Underwater Acoustic Modelling

Technical Report A - Annexure J

AGL Gas Import Jetty Facility

Underwater Acoustic Modelling

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Contents

Figures

Tables

Executive summary

Acoustic models were used to predict underwater noise levels to assist with the environment effects statement (EES) for the Gas Import Jetty and Pipeline Project. Acoustic models were used to estimate underwater sound emissions from the proposed Floating Storage and Regasification Unit (FSRU), a Liquid Natural Gas (LNG) carrier moored alongside the FSRU during offload, and the existing offload operations of liquid petroleum (motor spirit and automotive diesel) by United Petroleum Australia (United), at Berth 1 of Crib Point Jetty. The effects of range-dependent environmental properties on sound propagation in the study areas were accounted for by the numerical models. Limited to no suitable data in either grey or peer reviewed literature is available to determine monopole source levels for berthed FSRU, LNG and petroleum carriers, therefore a conservative proxy, derived from measurements of Floating Production Storage and Offload (FPSO) facilities, were applied.

Four scenarios were included in the study:

1. United Petroleum liquid petroleum carrier offloading, representing existing operations.
2. FSRU berthed, representing the operation of the new facility.
3. FSRU berthed and LNG carrier offloading, representing the operation of the new facility during regasification.
4. FSRU berthed, LNG carrier offloading and United petroleum carrier offloading, representing the cumulative noise from combination of existing operations and the new facility operating.

The study results are required for assessing the potential effects of noise exposure on marine mammals and fish near Crib Point. Sound levels are presented as sound pressure levels (SPL) and accumulated sound exposure levels (SEL) as appropriate for different noise effect criteria for continuous noise sources.

The analysis considered multiple effects criteria commonly used for vessel noise assessments. Key results of the modelling are summarised below.

Marine mammals

- The results for the U.S. National Marine Fisheries Service (NMFS) (2018) criteria applied for marine mammal permanent threshold shift (PTS) considers SEL for continuous sources with the maximum distances summarised in Table 1.
- The maximum distances at which the NMFS (2014) marine mammal behavioural response criterion of 120 dB re 1 µPa[1] (SPL) could be exceeded are summarised in Table 2.

Table 1. Summary of marine mammal PTS onset distances.

Hearing group	SEL_{24h} threshold (L_E; dB re 1 µPa²·s)	Distance R_{max} (km)			
		Petroleum carrier offloading	FSRU berthed	FSRU berthed, LNG carrier offloading	FSRU berthed, LNG carrier offloading, petroleum carrier offloading
Low-frequency cetaceans	199	0.03	0.03	0.08	0.08
Mid-frequency cetaceans	198	–	–	–	–
High-frequency cetaceans	173	0.02	<0.02	0.06	0.06
Phocid seals	201	<0.02	<0.02	0.06	0.06
Otariid seals	219	–	–	–	–

A dash indicates the level was not reached.

[1]decibels referenced to one micropascal

Table 2. Summary of marine mammal behavioural disturbance distances, derived from Table 9.

SPL (L_p; dB re 1 µPa	Distance R_{max} (km)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
120†	1.42	1.49	2.04	2.09

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).

Fish

- Sound produced by the vessels in the considered scenarios could cause physiological effects, and recoverable injury, to some fish species, but only if the animals are in very close proximity to the sound sources–within a maximum planar distance of 50 metres for 48 hours.

  Temporary impairment of their hearing sensitivity due to temporary threshold shift (TTS) could occur at similar distances if fish remain at the same point within the sound field for long periods of time (12 hours). The overall risk for TTS is low, the risk for auditory masking and behavioural reactions is range-dependant and varies from high at tens of meters to low at thousands of metres away from the source based on the appropriate relative risk criteria. For demersal fish, modelling predicts that neither of these thresholds will be reached at the seafloor.

1. Introduction

This study investigated underwater noise emissions from current and proposed operations at Crib Point to assist with the Environment Effects Statement (EES) for the Gas Import Jetty and Pipeline Project (the Project).

The study was intended to estimate underwater sound emission levels from the moored Floating Storage and Regasification Unit (FSRU) and associated liquefied natural gas (LNG) carrier during berthed operational activities, as well as liquid petroleum (motor spirit and automotive diesel) operations by United Petroleum Australia (United) at Berth 1 of the Crib Point Jetty. This report describes the applied underwater acoustic modelling approaches and presents the predicted underwater sound levels over the area surrounding the existing and proposed activities at the Crib Point Jetty. Estimated underwater acoustic levels are presented as sound pressure levels (SPL, L_p), and accumulated sound exposure levels (SEL, L_E) as appropriate for different noise effect criteria for continuous noise sources.

Acoustic modelling was performed to understand the propagation of noise emissions into nearby waters, JASCO's Marine Operations Noise Model (MONM) was used for this purpose. This model calculated noise levels in several frequency bands and produced broadband noise maps over a wide area. Distances to several noise thresholds were calculated, including thresholds used to predict marine mammal disturbance.

1.1. Study overview and purpose

The Port of Hastings is located approximately 50 kilometres southeast of Melbourne, Victoria. The Port of Hastings consists of four main facilities, Stony Point Jetty, Crib Point Jetty, Long Island Point Jetty, and Blue Scope Steel Wharves. The Crib Point Jetty is the site of a current liquid petroleum terminal, which receives petroleum carriers at Berth 1. Berth 2 is the proposed location of the FSRU that forms part of the Project. The jetty extends approximately 500 metres from shore into Western Port. The FSRU is proposed to be moored at Berth 2 of the jetty with visiting LNG carriers to dock alongside the FSRU during refilling operations.

The study purpose is to understand how noise generated by the FSRU-LNG loading systems and LNG carriers may ensonify the nearby waters of Western Port. The predicted noise levels may be used to understand potential zones of impact on marine fauna from noise emissions from the considered operational scenarios.

1.2. Modelling scenario details

To meet the assessment requirements, four operational scenarios associated with current use and proposed future use were considered for this study, as detailed in Table 3. The scenarios were comprised of combinations of three separate modelling sites for the different vessels as listed in Table 4, and shown in Figure 1. The sites were chosen as being approximate acoustic centres of the FSRU, and LNG and petroleum carriers.

For the purposes of this study, the FSRU and LNG carrier have both been assumed to be 300 metres long, and 45 metres wide, while the petroleum carrier has been assumed to be 250 metres long and 32 metres wide. These are nominal dimensions which based on specifications provided by AGL and dimensions of a typical petroleum carrier that currently visits the Crib Point Jetty. Each vessel was modelled using Monopole Source Level (MSL) values.

Table 3. Modelling scenarios and relevant modelling sites.

Scenario Number	Scenario Description	Included Modelling Sites in Scenario
1	Petroleum carrier offloading	Site 1
2	FSRU berthed (regasifying) and offloading	Site 2
3	FSRU berthed (regasifying) and LNG carrier offloading	Sites 2, 3
4	FSRU berthed(regasifying), LNG carrier offloading, petroleum carrier offloading	Sites 1, 2, 3

Table 4. Modelling sites.

Site Number	Vessel Type	Latitude (S)	Longitude (E)	MGA (GDA94), Zone 50		Water depth (m)
				X (m)	*Y* (m)	
1	Petroleum carrier	38° 20' 57.7"	145° 13' 34.2"	344998	5753933	16.2
2	FSRU	38° 21' 08.9"	145° 13' 35.1"	345027	5753589	15.9
3	LNG carrier	38° 21' 08.7"	145° 13' 37.1"	345076	5753594	16.2

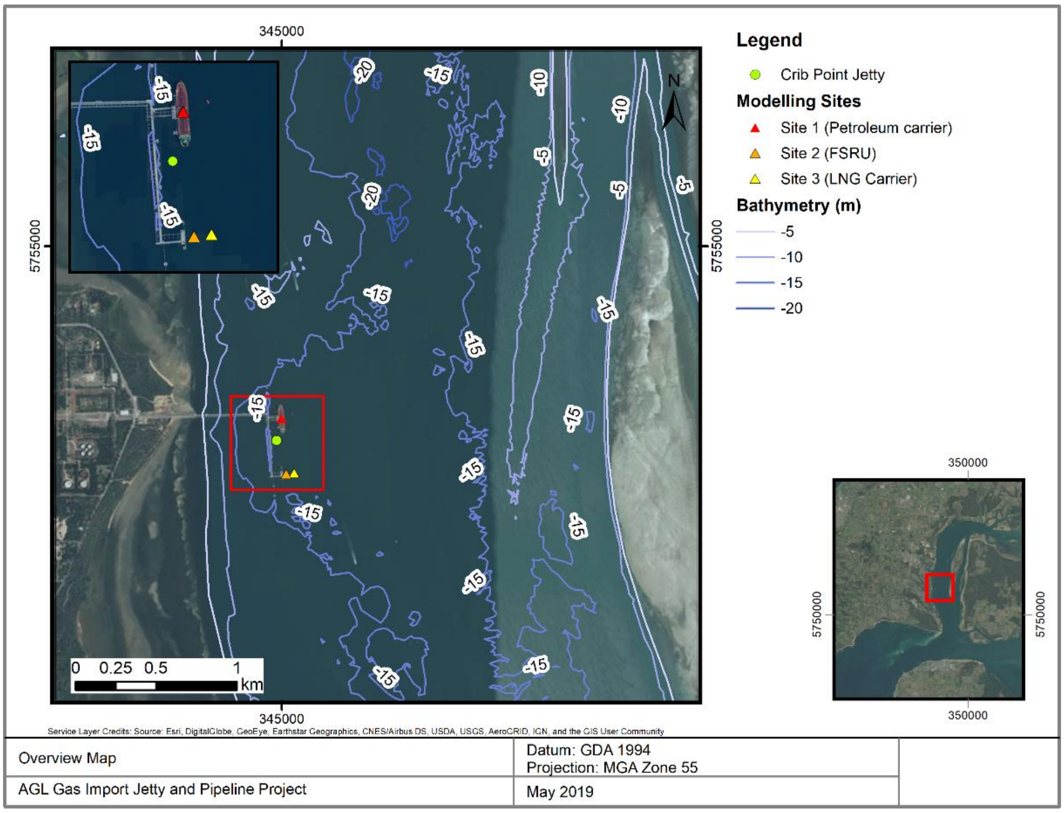

Figure 1: Map of Crib Point and modelling locations.

2. Noise effect criteria

To assess the potential impacts of a sound-producing activity, it is necessary to first establish exposure criteria (thresholds) for which sound levels may be expected to have a negative impact on animals. Whether acoustic exposure levels might injure or disturb marine fauna is an active research topic. Since 2007, several expert groups have developed SEL-based assessment approaches for evaluating auditory injury, with key works including Southall et al. (2007), Finneran and Jenkins (2012), Popper et al. (2014), and NMFS (2018). The number of studies that investigate the level of behavioural disturbance to marine fauna by anthropogenic sound has also increased substantially.

The perceived loudness of vessel noise depends on the duration of emissions of the noise source and the signals' frequency content. Several sound level metrics, such as SPL, and SEL, are commonly used to evaluate noise and its effects on marine life. The time period of accumulation of SEL is defined as 24 hours and appropriate subscripts to the metrics indicate any applied auditory frequency weighting (Appendix A.3). The acoustic metrics in this report reflect the updated American National Standards Institute (ANSI) and International Organization for Standardization (ISO) standards for acoustic terminology, ANSI-ASA S1.1 (R2013) and ISO/DIS 18405.2:2017 (2017).

This study applies the following noise criteria, chosen for their acceptance by regulatory agencies and because they represent current best available science (Sections 2.1–2.2 and Appendix A.2):

1. Frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from the U.S. National Oceanic and Atmospheric Administration (NOAA) Technical Guidance (NMFS 2018) for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in marine mammals.
2. Marine mammal behavioural threshold based on the current interim U.S. National Marine Fisheries Service (NMFS) criterion NMFS (2014) for marine mammals of 120 dB re 1 µPa[2] SPL (L_p) for non-impulsive sound sources.
3. Sound exposure guidelines for fish, fish eggs and larvae (Popper et al. 2014).

[2] decibels referenced to one micropascal

2.1. Marine mammals

The criteria applied in this study to assess possible effects of vessel noise on marine mammals are summarised in Table 5, and detailed in Section 2.1.1 and 2.1.2 with frequency weighting explained in Appendix A.3. Marine mammal species occurring in the study area could include otariid and phocid seals along with mysticetes and odontocetes (low- and mid-frequency cetaceans), such as humpback, southern right whales and common bottlenose dolphins.

Non-impulsive noise sources, referred to here as continuous noise sources, are described in NMFS (2018) to 'produce sounds that can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent) and typically do not have a high peak sound pressure with rapid rise/decay time that impulsive sounds do (NIOSH 1998, ANSI S12.7-1986 R2006)'.

Table 5. Acoustic effects of continuous noise on marine mammals: Unweighted SPL and SEL_{24h} thresholds.

Hearing group	NMFS (2014)	NMFS (2018)	
	Behaviour	PTS onset thresholds (received level)	TTS onset thresholds (received level)
	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s)
Low-frequency (LF) cetaceans (baleen whales)	120	199	179
Mid-frequency (MF) cetaceans (dolphins, plus toothed, beaked, and bottlenose whales, river dolphins)		198	178
High-frequency (HF) cetaceans (true porpoises, *Kogia*, cephalorhynchid, *Lagenorhynchus cruciger* and *L. australis*)		173	153
Phocid seals (true seals)		201	181
Otariid seals (eared seals)		219	199

L_p-denotes sound pressure level period and has a reference value of 1 µPa.
L_E - denotes cumulative sound exposure over a 24-hour period and has a reference value of 1 µPa²s.

2.1.1. Auditory injury and hearing sensitivity changes

There are two categories of auditory threshold shifts or hearing loss: permanent threshold shift (PTS), a physical injury to an animal's hearing organs; and temporary threshold shift (TTS), a temporary reduction in an animal's hearing sensitivity as the result of receptor hair cells in the cochlea becoming fatigued.

To assist in assessing the potential for injuries to marine mammals this report applies the criteria recommended by NMFS (2018), considering both PTS and TTS, to help assess the potential for injuries to marine mammals (Table 5). Appendix A.2 provides more information about the NMFS (2018) criteria.

2.1.2. Behavioural response

Numerous studies on marine mammal behavioural responses to sound exposure have not resulted in consensus in the scientific community regarding the appropriate metric for assessing behavioural reactions. However, it is recognised that the context in which the sound is received affects the nature and extent of responses to a stimulus (Southall et al. 2007, Ellison and Frankel 2012, Southall et al. 2016). Because of the complexity and variability of marine mammal behavioural responses to acoustic exposure, NMFS has not yet released technical guidance on behaviour thresholds for use in calculating animal exposures (NMFS 2018). The NMFS currently uses a step function to assess behavioural impact.

The NMFS (2018) noise criterion for non-impulsive (continuous) sounds was selected for this assessment because it is both suitable to the sound sources and represents the most commonly applied behavioural response criterion by regulators for continuous noise sources. The distances at which behavioural responses could occur were therefore determined to occur in areas ensonified above an unweighted SPL of 120 dB re 1 µPa (NMFS 2014).

2.2. Fish, fish eggs, and fish larvae

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

- mortality, including injury leading to death;
- recoverable injury, including injuries unlikely to result in mortality, such as auditory hair cell damage and minor haematoma;
- temporary threshold shift (TTS).

Auditory masking and behavioural effects can be assessed qualitatively, by assessing relative risk rather than by specific sound level thresholds. However, as these depend upon activity-based subjective ranges, these effects are not addressed in this report and are included in Table 6 for completeness only. Because the presence or absence of a swim bladder has a role in hearing, fish's susceptibility to injury from noise exposure depends on the species and the presence and possible role of a swim bladder in hearing. Thus, different thresholds were proposed for fish without a swim bladder (also appropriate for sharks and applied to whale sharks in the absence of other information), fish with a swim bladder not used for hearing, and fish that use their swim bladders for hearing. Fish eggs, and fish larvae are considered separately.

Table 6 lists the relevant effects thresholds from Popper et al. (2014) for shipping and continuous noise. There is some evidence to suggest that acoustic pressure sensitive fish show a recoverable loss in hearing sensitivity, or injury when exposed to high levels of noise (Scholik and Yan 2002, Amoser and Ladich 2003, Smith et al. 2006); this is reflected in the SPL thresholds for fish with a swim bladder involved in hearing.

Table 6. Criteria for continuous noise exposure for fish and turtles, adapted from Popper et al. (2014).

Type of animal	Mortality and Potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: No swim bladder (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder not involved in hearing (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder involved in hearing (primarily pressure detection)	(N) Low (I) Low (F) Low	170 dB SPL for 48 h	158 dB SPL for 12 h	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Fish eggs and fish larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

Sound pressure level dB re 1 µPa.
Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F). The near, intermediate and far relative distances may be considered respectively as, tens of metres, hundreds of metres and thousands of metres away from the source.

3. Acoustic modelling methods

3.1. Modelling overview

JASCO's combined Marine Operations Noise Model (MONM) and gaussian beam acoustic ray-trace model (BELLHOP) were used to predict the acoustic field at frequencies of 10 (hertz) Hz to 25 kilohertz (kHz) for all modelled sources.

Due to a limited information, A representative proxy vessel was used for noise modelling (Table 7). Furthermore, where uncertainties exist due to a lack of available information, a conservative approach has been adopted in the noise modelling.

The SEL modelling results were converted from SPL by the duration of the assessment, which is appropriate for a continuous noise source. As SEL was assessed over 24 hours, the conversion to SPL was 10*log10(T), where T is 86,400, the number of seconds in 24 hours. This conversion factor is based on vessels in continuous operation for 24 hours.

Environmental information (ocean floor geoacoustics, bathymetry, sound speed profile, average water salinity and temperature), representative of the sites, was gathered and used as inputs to the predictive acoustic models. These environmental parameters are detailed in Section 3.3 and Appendix C.

3.2. Acoustic source parameters for vessel operations

Noise from the considered operational scenarios is likely to be associated with pumps, generators, and associated machinery within the three vessels. Furthermore, the FSRU may also generate underwater noise associated with the seawater discharge from regasification process. During regasification operations seawater used for converting LNG back to a gaseous state will be discharged from six discharge ports located below the water line.

Upon review, no suitable data in either grey or peer reviewed literature is available to determine monopole source levels (MSL) for berthed FSRU, LNG and petroleum carriers. Therefore, a single MSL derived from measured levels of two Floating Production Storage and Offload (FPSO) facilities detailed in Erbe et al. (2013) was applied as a proxy for each vessel considered in this study. This selection was based upon comparable vessel sizes and similarity in vessel operations. While a complete list of operations details on FPSO vessels is described in Erbe et al. (2013), it should be noted that during measurement programs, the FPSO facilities were moored on a turret, and operations as described in vessel logs include:

- water disposal from process cooling;
- de-ballasting;
- general processes involving fluid pumps, and
- gas turbines for power generation.

The MSL for each vessel in this study, derived from considering a vessel of similar size and purpose therefore represents the best estimate given the current information available at this time. Each of the monopole sources were located at mid-water depth for two reasons,

1. To approximate an average of hull radiated noise from the submerged hull of each vessel.
2. Optimal noise propagation is expected for sources in the middle of the water column.

The acoustic source parameters are summarised in Table 7. The averaged 1/3-octave-band spectrum for the proxy source used to represent all modelled sources is shown in Figure 2.

Table 7. Summary of proxy vessel used in the noise modelling study.

Proxy vessel name	Proxy vessel type	Source depth (m)	Broadband MSL (dB re 1 re 1 µPa²m²)
Ngujima and *Nganhurra*	FPSO	7	173.9

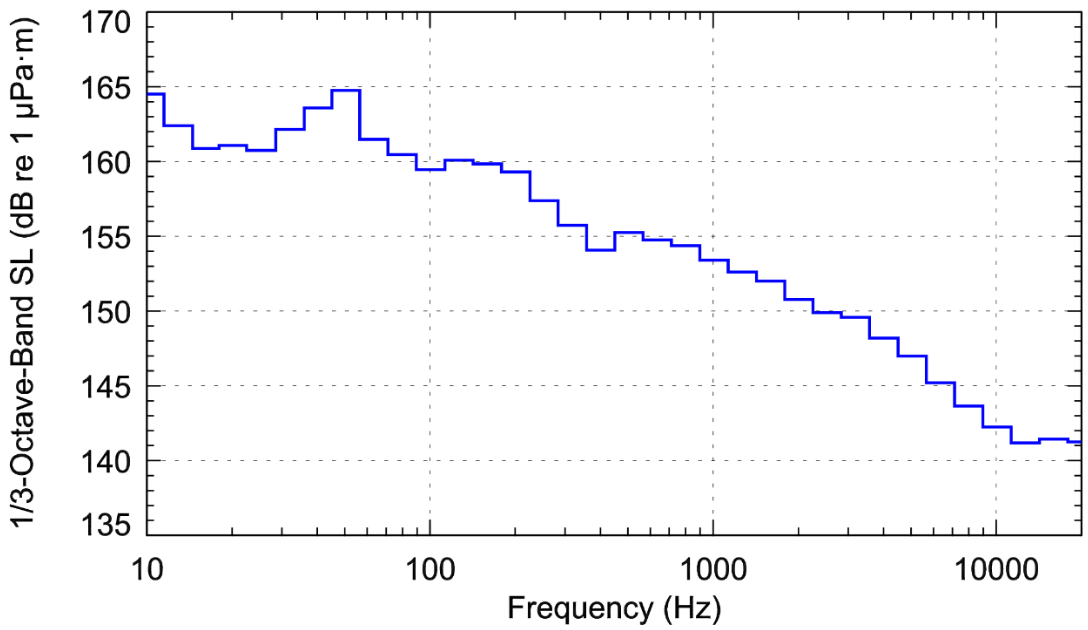

Figure 2: One-third-octave-band monopole source levels of the proxy vessel, derived from an average of the FPSO's *Nugujima* and *Nganhurra*.

3.3. Environmental parameters

The environmental parameters used in the propagation models summarised here are described in detail in Appendix C.

A single sound speed profile for July was considered for modelling scenarios; this was identified as the seasonal period that would provide the largest seabed reflection and therefore greatest propagation potential (Appendix C.2.2). The geological composition of the seabed was derived from geotechnical data. The profile was determined to consist of layer of unconsolidated sediment, overlying a layer increasingly consolidated sediment, over a bounding a siltstone basement (Appendix C.2.3)

The following geological profile was used for all modelling sites:

- unconsolidated mixture of sand, silt and clay, with a thickness of 3.25 metres
- consolidated mixture of silty sand, with a thickness of 31.75 metres
- bedrock basement composed of siltstone.

3.4. Geometry and modelled regions

To predict sound levels, the sound field modelling calculated propagation losses up to distances of 15 kilometres from the source, with a horizontal separation of 10 metres between receiver points along the modelled radials. The sound fields were modelled with a horizontal angular resolution of $\Delta\theta = 1°$ for a total of N = 359 radial planes. Receiver depths were chosen to span the entire water

column over the modelled areas, from one metre to a maximum of 40 metres. To supplement the MONM results, high-frequency results for propagation loss were modelled using BELLHOP for frequencies from 2.5 to 25 kHz. The MONM and BELLHOP results were combined to produce results for the full frequency range of interest.

The results are presented in two formats: i) as noise contour maps (also referred to as sound level isopleth maps), and ii) as distances to broadband noise thresholds. To produce maps of received sound level distributions and to calculate distances to specified sound level thresholds, the maximum-over-depth level is calculated at each modelled easting and northing position within the considered region. The radial grids of maximum-over-depth levels are then resampled (by linear triangulation) to produce a regular Cartesian grid at a resolution of 20 m. The contours and threshold ranges are calculated from these flat Cartesian projections of the modelled acoustic fields.

Because the noise isopleths are not circular, the distances to each sound level threshold depends on the direction from the source position see Appendix C for more detail. We calculated two distance metrics:

1) The maximum distance to the threshold in any direction
2) The 95% threshold, representing the minimum radius containing 95% of the area ensonified above the threshold.

4. Results

4.1. Tabulated results

Sound field results for the four modelling scenarios are presented in Tables 8 and 9 for SEL_{24h} and SPL. Tables 10 and Table 11 list the estimated distances for the various applicable maximum-over-depth and seafloor noise effects criteria for marine mammals and fish, respectively.

Table 8. Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the specified vessels to modelled maximum-over-depth unweighted SEL_{24h} isopleths. The scenarios are defined in Table 3.

SEL_{24h} (L_E; dB re 1 µPa²·s)	**Scenario 1**		**Scenario 2**		**Scenario 3**		**Scenario 4**	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.03	0.03	0.03	0.03	0.08	0.08	0.08	0.08
190	0.07	0.07	0.07	0.07	0.13	0.12	0.13	0.12
180	0.34	0.32	0.35	0.32	0.51	0.47	0.87	0.79
170	1.36	1.11	1.40	1.19	1.87	1.59	2.37	1.98
160	3.70	2.84	3.69	3.05	4.79	4.03	6.27	4.65

Table 9. Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the specified vessels to modelled maximum-over-depth unweighted SPL isopleths. The scenarios are defined in Table 3.

SPL (L_p; dB re 1 µPa	**Scenario 1**		**Scenario 2**		**Scenario 3**		**Scenario 4**	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
170	<0.02	<0.02	<0.02	<0.02	0.05	0.05	0.05	0.05
160	0.03	0.03	0.03	0.03	0.08	0.08	0.08	0.08
150	0.03	0.03	0.03	0.03	0.08	0.08	0.08	0.08
140	0.08	0.07	0.08	0.08	0.14	0.13	0.44	0.43
130	0.37	0.35	0.39	0.36	0.55	0.51	0.92	0.83
120†	**1.42**	**1.21**	**1.49**	**1.29**	**2.04**	**1.7**	**2.42**	**2.09**

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).

Table 10. *Marine mammal SEL_{24h} thresholds*: Maximum (R_{max}) horizontal distances (km) from the vessels to modelled maximum-over-depth isopleths based on the NOAA Technical Guidance (NMFS 2018) for marine mammals. The scenarios are defined in Table 3.

Hearing group	SEL_{24h} threshold (L_E; dB re 1 µPa²·s)	Distance R_{max} (km)			
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Low-frequency cetaceans (PTS)	199	0.03	0.03	0.08	0.08
Low-frequency cetaceans (TTS)	179	0.20	0.20	0.38	0.65
Mid-frequency cetaceans (PTS)	198	–	–	–	–
Mid-frequency cetaceans (TTS)	178	0.02	<0.02	0.06	0.06
High-frequency cetaceans (PTS)	173	0.02	<0.02	0.06	0.06
High-frequency cetaceans (TTS)	153	0.41	0.41	0.66	1.05
Phocids (PTS)	201	<0.02	<0.02	0.06	0.06
Phocids (TTS)	181	0.04	0.04	0.08	0.08
Otariids (PTS)	219	–	–	–	–
Otariids (TTS)	199	<0.02	<0.02	0.06	0.06

A dash indicates the level was not reached.

Table 11. Maximum (R_{max}) horizontal distances (km) from the vessels to modelled maximum-over-depth (MOD) and seafloor SPL thresholds based on the quantifiable thresholds for fish (Popper et al. 2014). The scenarios are defined in Table 3.

Hearing group	SPL threshold (L_p; dB re 1 µPa)	Distance R_{max} (km)							
		Scenario 1		Scenario 2		Scenario 3		Scenario 4	
		MOD	Seafloor	MOD	Seafloor	MOD	Seafloor	MOD	Seafloor
Fish: Swim bladder not involved in hearing (particle motion detection): recoverable injury	170 dB for 48 h	<0.02	–	<0.02	–	0.05	–	0.05	–
Fish: Swim bladder not involved in hearing (particle motion detection): TTS	158 dB for 12 h	0.03	–	0.03	–	0.08	–	0.08	–

A dash indicates the level was not reached.

4.2. Sound field maps

Maps of the estimated sound fields, threshold contours, and isopleths of interest for SEL_{24h} and SPL sound fields have been presented for all modelling scenarios (detailed in Table 3), are shown below in Figures 3–14.

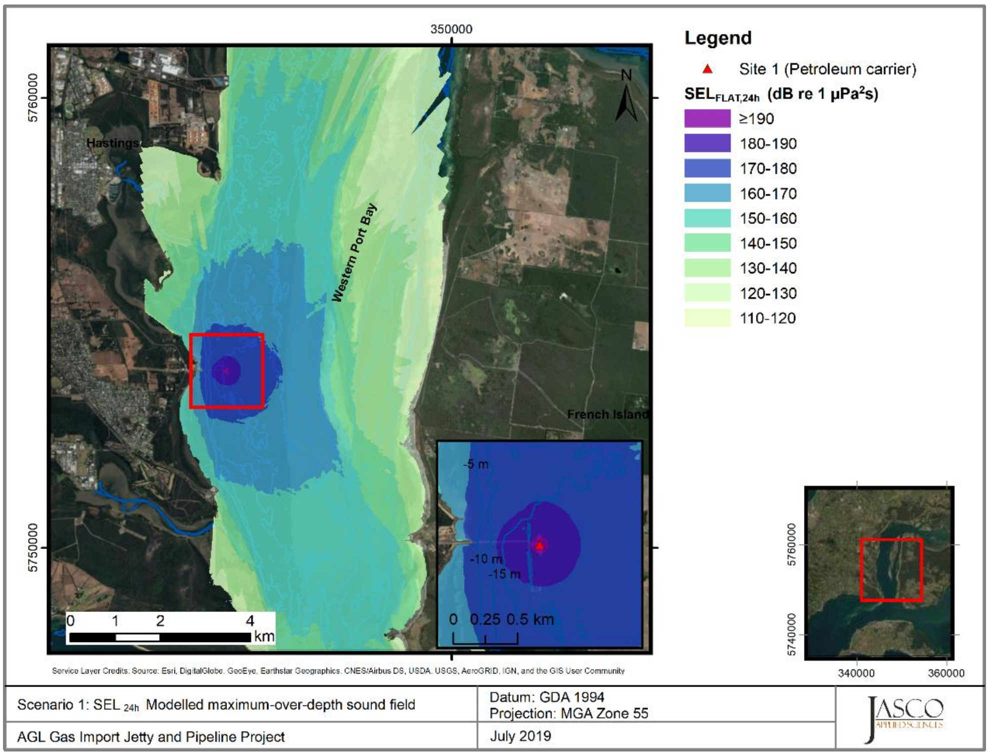

Figure 3. *Scenario 1 – Petroleum carrier, SEL24h*: Sound level contour map showing maximum-over-depth results.

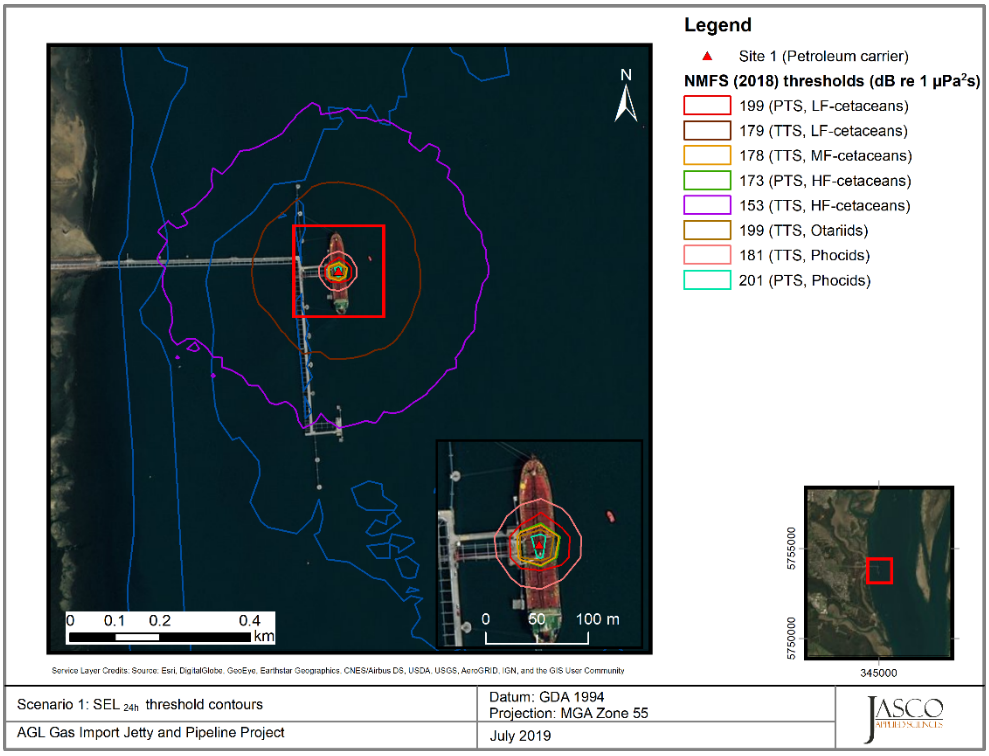

Figure 4. *Scenario 1 – Petroleum carrier, SEL24h*: Sound level threshold map for maximum-over-depth results. PTS threshold for mid–frequency cetaceans and otariids was not reached.

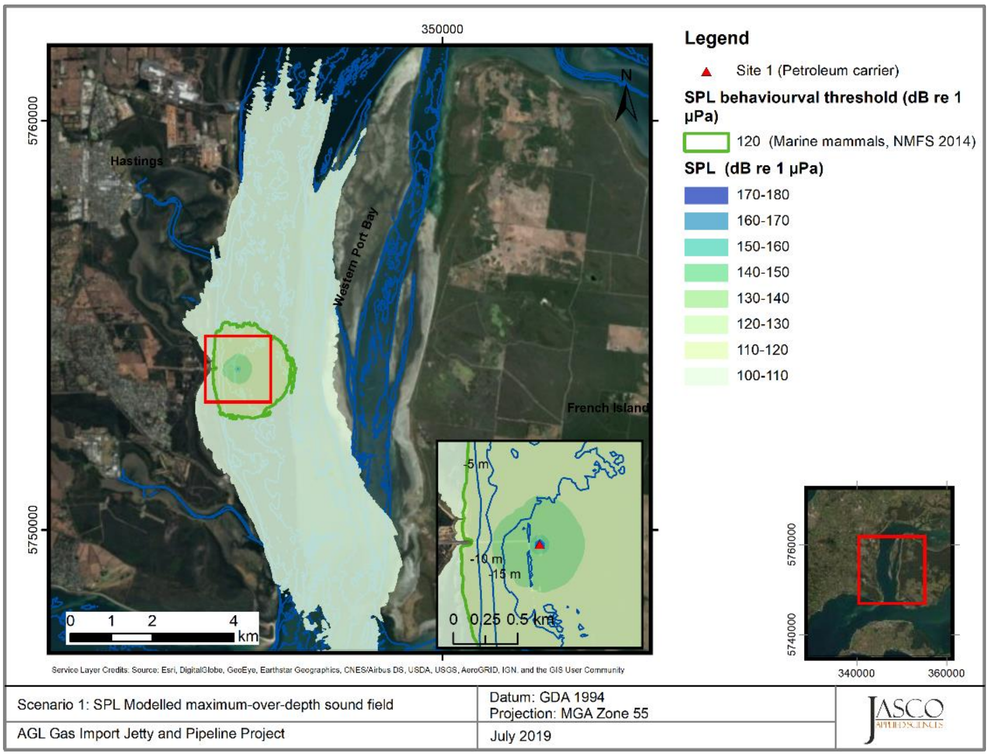

Figure 5. *Scenario 1 – Petroleum carrier, SPL*: Sound level contour map showing unweighted maximum-over-depth results. Isopleth for marine mammal (120 dB re 1 µPa) behavioural criteria is shown.

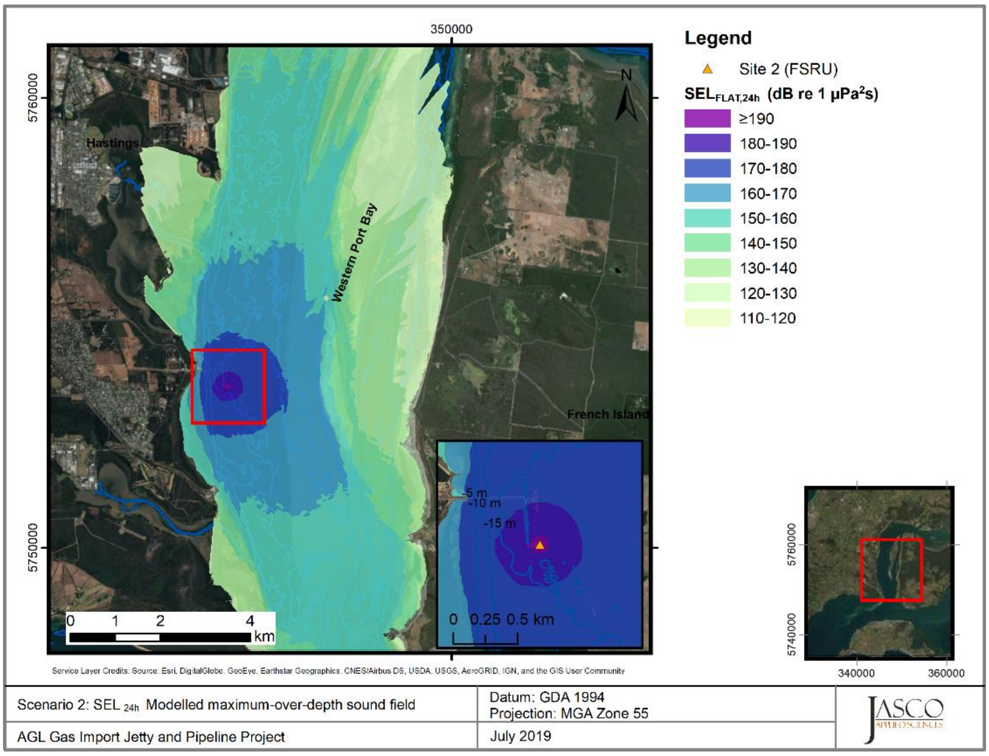

Figure 6. *Scenario 2 – FSRU, SEL_{24h}:* Sound level contour map showing maximum-over-depth results.

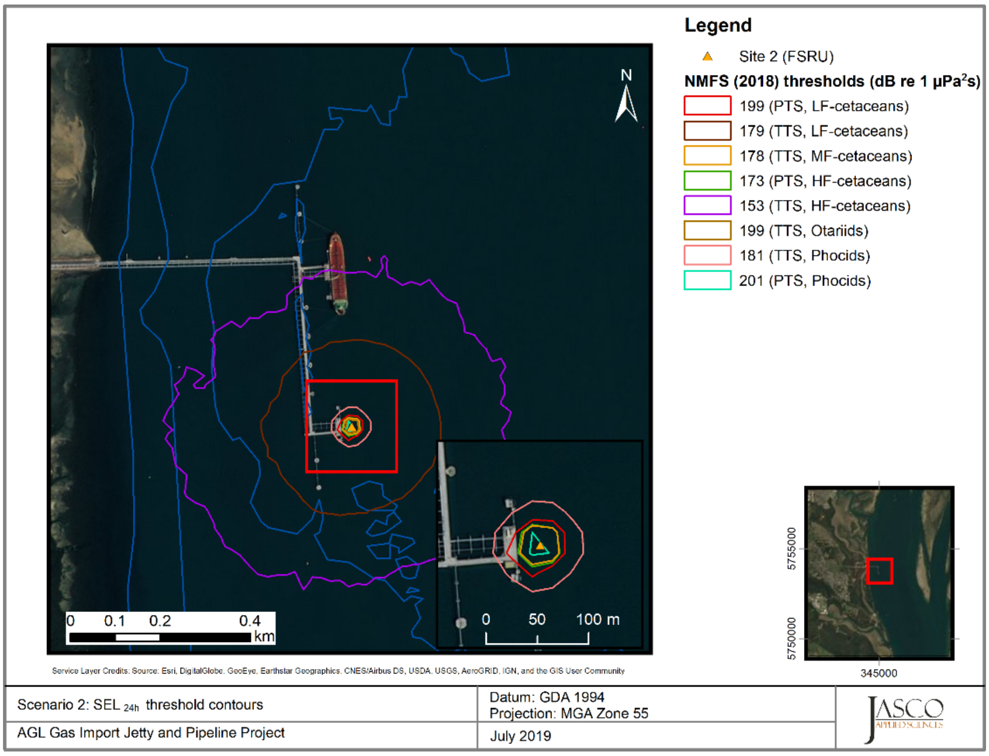

Figure 7. *Scenario 2 – FSRU, SEL24h:* Sound level threshold map for maximum-over-depth results. PTS threshold for mid–frequency cetaceans and otariids was not reached

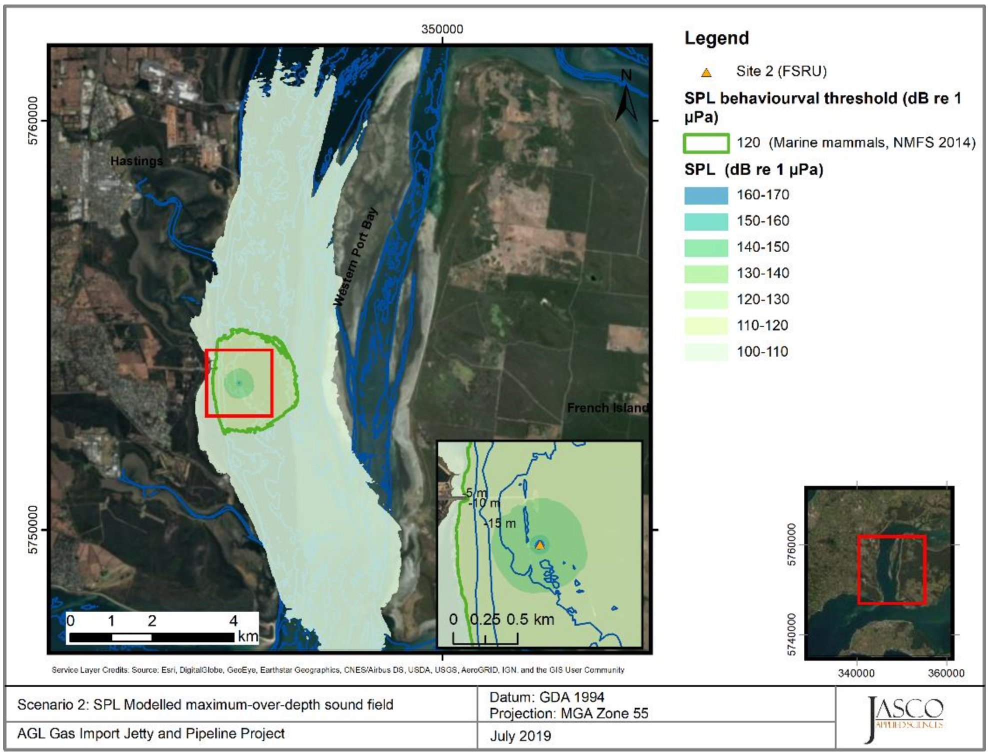

Figure 8. *Scenario 2– FSRU*, *SPL*: Sound level contour map showing unweighted maximum-over-depth results. Isopleth for marine mammal (120 dB re 1 µPa) behavioural criteria is shown.

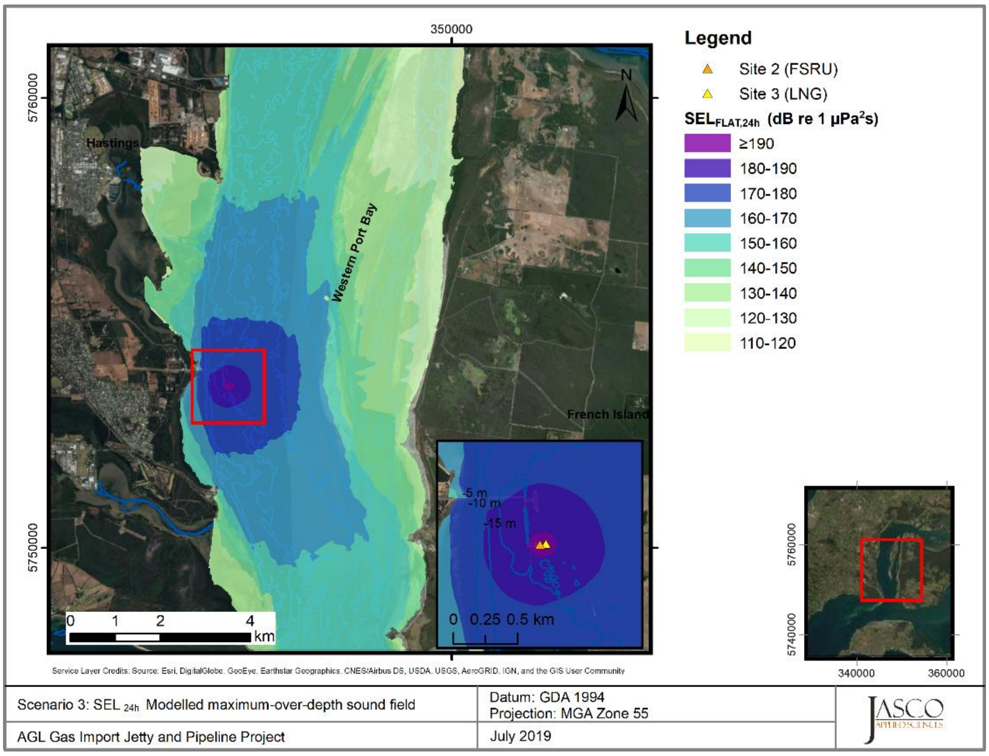

Figure 9. *Scenario 3 – FSRU + LNG Carrier, SEL_{24h}*: Sound level contour map showing maximum-over-depth results.

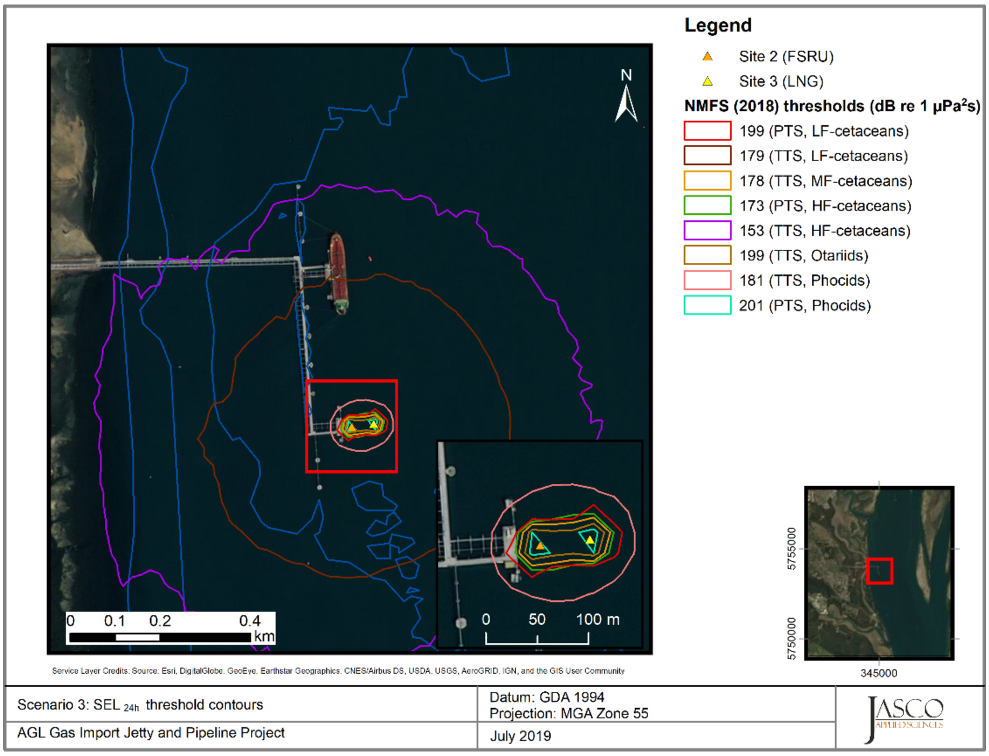

Figure 10. *Scenario 3 – FSRU + LNG Carrier, SEL_{24h}*: Sound level threshold map for maximum-over-depth results. PTS threshold for mid–frequency cetaceans and otariids was not reached

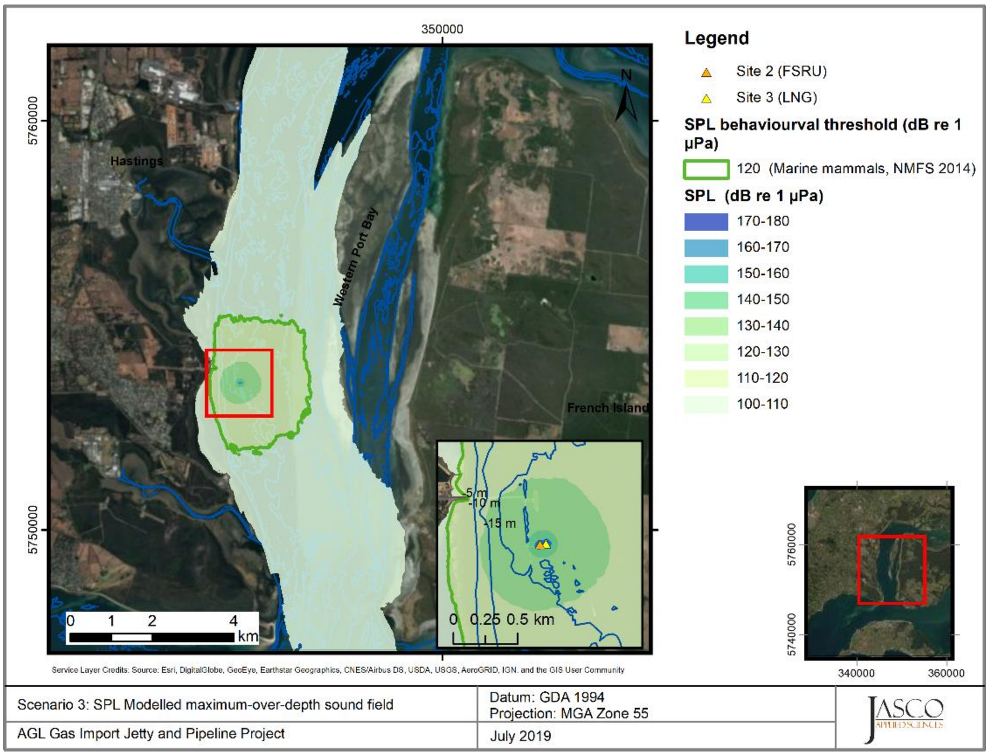

Figure 11. *Scenario 3 – FSRU + LNG Carrier, SPL*: Sound level contour map showing unweighted maximum-over-depth results. Isopleth for marine mammal (120 dB re 1 µPa) behavioural criteria is shown.

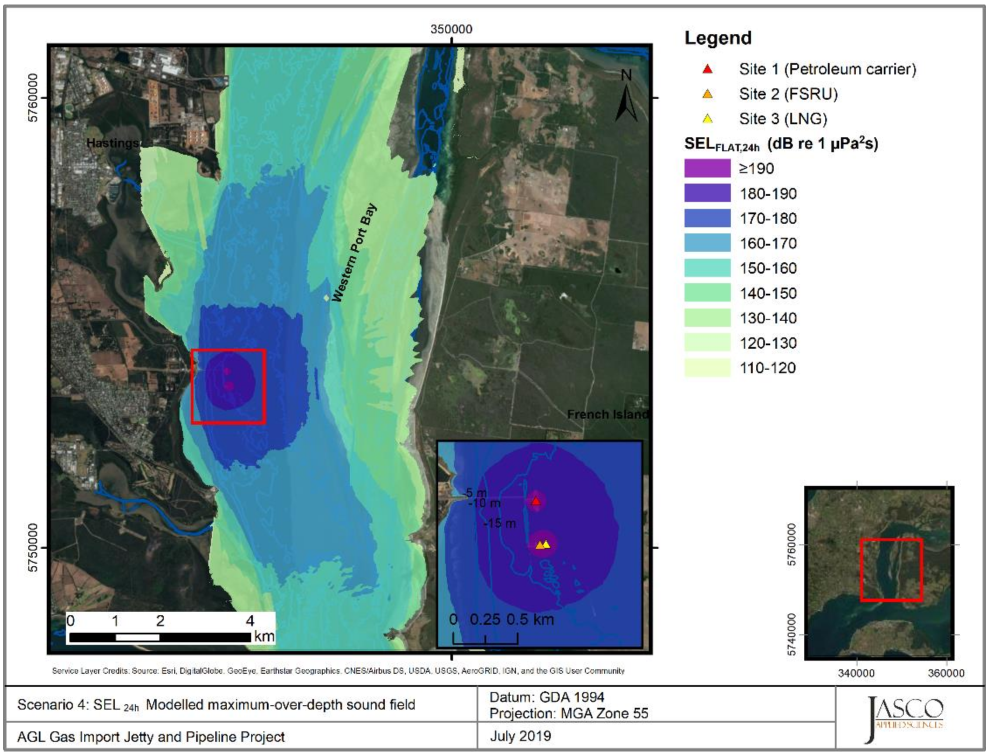

Figure 12. *Scenario 4 – Petroleum carrier + FSRU + LNG Carrier, SEL_{24h}:* Sound level contour map showing maximum-over-depth results.

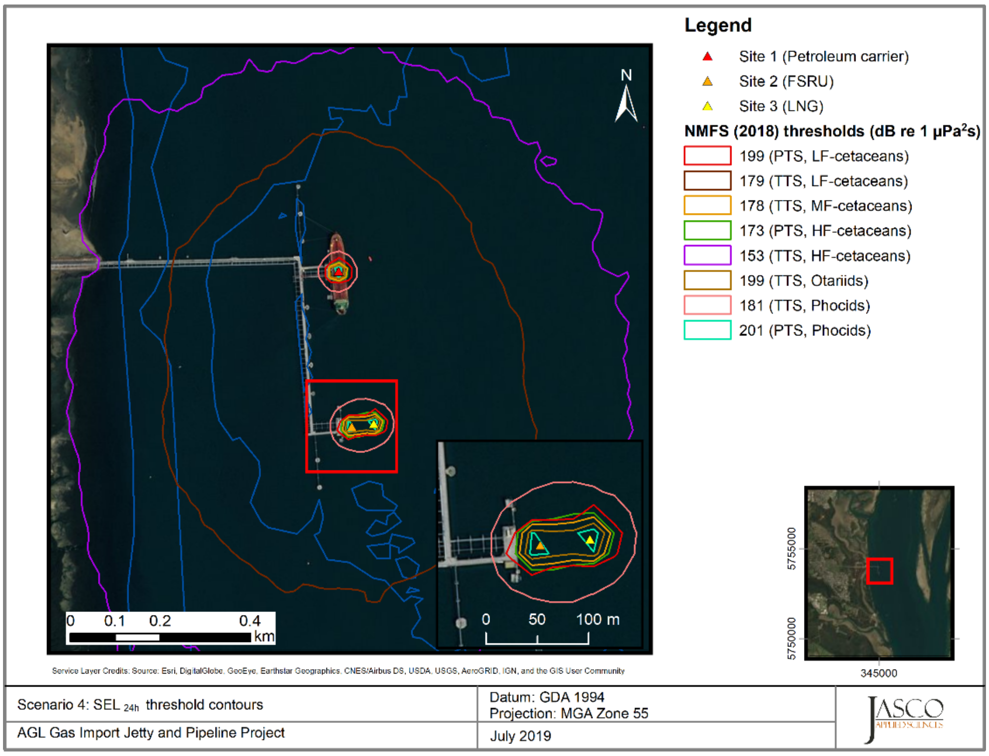

Figure 13. *Scenario 4 – Petroleum carrier + FSRU + LNG Carrier, SEL24h*: Sound level threshold map for maximum-over-depth results. PTS threshold for mid–frequency cetaceans and otariids was not reached

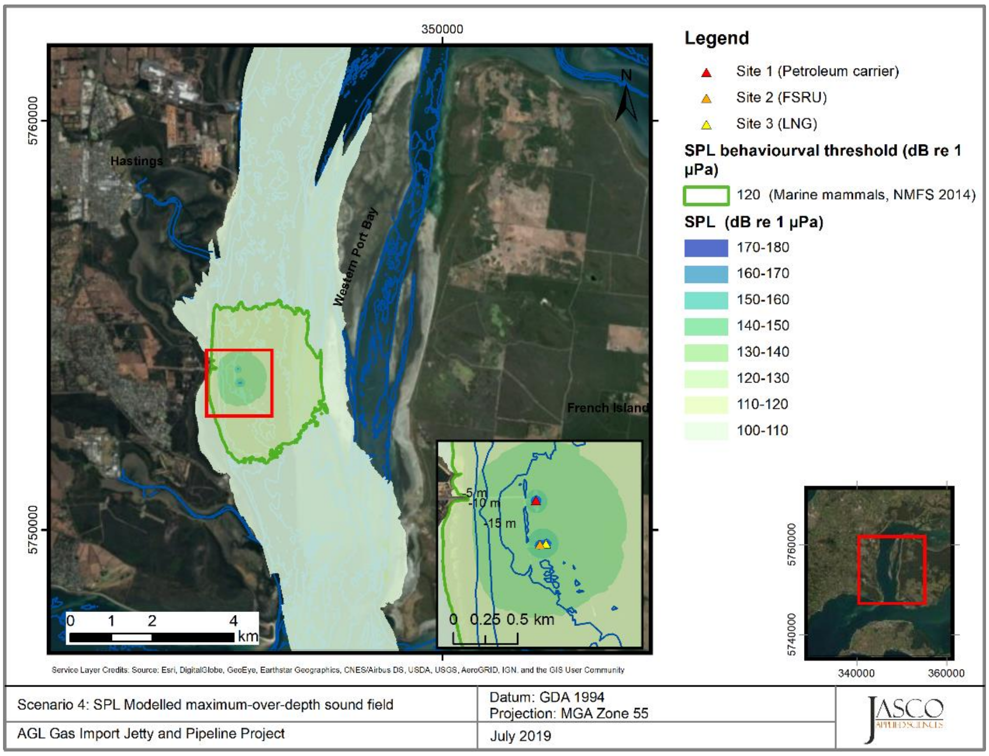

Figure 14. *Scenario 4 – Petroleum carrier + FSRU + LNG Carrier, SPL*: Sound level contour map showing unweighted maximum-over-depth results. Isopleth for marine mammal (120 dB re 1 µPa) behavioural criteria is shown.

5. Discussion and summary

5.1. Noise emissions and propagation

The modellings sites, which were used to model operations from the Crib Point Jetty were located in water on the western edge of Western Port with approximate water depth of 15 metres. The average water depth within the Western Port Bay channel to the east of the modelling sites was approximately 20 metres. There are significant variations in the bathymetric profile as the bay area wraps around French Island and intersect with the coastal areas. Bathymetry had a considerable effect on propagation at longer distances, with larger lobes of sound energy extending into the deeper waters within the channel to the southeast and northeast of the modelling sites. In the onshore direction to the east and west of the modelling sites the rapid decrease in water depth as the water intersects with the land significantly attenuated the sound fields. This effect can be seen in the SEL_{24h} contour plots (Figures 3, 6, 9 and 12).

Because of the attenuating effect of bathymetry, the maximum ranges to thresholds, summarised below, were predicted to occur within the deeper waters of the channel to the southeast and northeast of the Crib Point Jetty. Ranges to impact thresholds in other directions will be smaller than these R_{max} values.

Furthermore, due to the magnitude and frequency content of the MSL used for modelling, ranges to the injury thresholds, particularly for low-frequency cetaceans, are confined to ranges near the source as low frequency energy does not propagate well in shallow water depths. This effect can be described in terms of the “cut-off frequency (f_c)”. The cut-off frequency is a single number that describes how much acoustic energy can propagate with minimal loss between then sea-surface and seafloor interfaces. For a given acoustic signal, frequencies below f_c are subject to higher loss compared to frequencies above the f_c (Jensen et al. 2011). For a source located in 15 metre of water the “cut-off frequency (f_c)” is approximately 60 Hz. Therefore, the low frequency content of the MSL spectrum, which contain the majority of the energy below 60 Hz, are subject to higher rates of loss as distance from the source increases.

5.2. Marine mammals

The results for the NMFS (2018) criteria applied for marine mammal PTS considers SEL for continuous sources with the maximum distances summarised in Table 12.

The 24-h SEL is a cumulative metric that reflects the dosimetric impact of noise levels within 24 hours based on the assumption that an animal is consistently exposed to such noise levels at a fixed position. The corresponding SEL_{24h} radii represent an unlikely worst-case scenario. More realistically, marine mammals (and fish) would not stay in the same location for 24 hours. Therefore, a reported radius for SEL_{24h} criteria does not mean that marine fauna travelling within this radius of the source will be injured, but rather that an animal could be exposed to the sound level associated with injury (either PTS or TTS) if it remained in that location for 24 hours.

The maximum distances at which the NMFS (2014) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) could be exceeded are summarised in Table 13.

Table 12. Summary of marine mammal PTS onset distances, derived from Table 10, the scenarios are defined in Table 3.

Hearing group	SEL_{24h} threshold (L_E; dB re 1 µPa²·s)	Distance R_{max} (km)			
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Low-frequency cetaceans	199	0.03	0.03	0.08	0.08
Mid-frequency cetaceans	198	–	–	–	–
High-frequency cetaceans	173	0.02	<0.02	0.06	0.06
Phocids	201	<0.02	<0.02	0.06	0.06
Otariids	219	–	–	–	–

A dash indicates the level was not reached.

Table 13. Summary of marine mammal behavioural disturbance distances, derived from Table 9, the scenarios are defined in Table 3.

SPL (L_p; dB re 1 µPa	Distance R_{max} (km)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
120†	1.42	1.49	2.04	2.09

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).

5.3. Fish

Sound produced by the vessels in the considered scenarios could cause physiological effects, and recoverable injury, to some fish species, but only if the animals are in very close proximity to the sound sources–within a maximum planar distance of 50 m for 48 hours. Temporary impairment due to TTS could occur at similar distances if fish remain at the same point within the sound field for long periods of time (12 h). The overall risk for TTS is low, the risk for auditory masking and behavioural reactions is range-dependant and varies from high at tens of meters to low at thousands of metres away from the source based on the appropriate relative risk criteria (Table 6). For demersal fish, modelling predicts that neither of these thresholds will be reached at the seafloor.

Glossary

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

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

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

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

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

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

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).

ensonified
Exposed to sound.

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

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

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

geoacoustic
Relating to the acoustic properties of the seabed.

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

high-frequency (HF) cetacean
The functional cetacean hearing group that represents those odontocetes (toothed whales) specialized for hearing high frequencies.

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

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

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

mid-frequency (MF) cetacean
The functional cetacean hearing group that represents those odontocetes (toothed whales) specialized for mid-frequency hearing.

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.

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.

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

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

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

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

rms
root-mean-square.

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

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

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

sound exposure level (SEL)
A cumulative measure related to the sound energy in one or more pulses. Unit: dB re 1 µPa²·s. SEL is expressed over the summation period (e.g., per-pulse SEL [for airguns], single-strike SEL [for pile drivers], 24-hour SEL).

sound exposure spectral density
Distribution as a function of frequency of the time-integrated squared sound pressure per unit bandwidth of a sound having a continuous spectrum (ANSI S1.1-1994 R2004). Unit: µPa²·s/Hz.

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

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

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

source level (SL)
The sound level measured in the far-field and scaled back to a standard reference distance of 1 metre from the acoustic centre of the source. Unit: dB re 1 µPa·m (pressure level) or dB re 1 µPa²·s·m² (exposure level).

spectral density level
The decibel level ($10 \cdot \log_{10}$) of the spectral density of a given parameter such as SPL or SEL, for which the units are dB re 1 µPa²/Hz and dB re 1 µPa²·s/Hz, respectively.

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

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

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

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Appendix A. Acoustic metrics

A.1. Pressure related acoustic metrics

Underwater sound pressure 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. We provide specific definitions of relevant metrics used in the accompanying report. Where possible we follow the ANSI and ISO standard definitions and symbols for sound metrics, but these standards are not always consistent.

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

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

The SPL represents a nominal effective continuous sound 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 over a fixed duration. Because the window length, T, is the divisor, events with similar sound exposure level (SEL) but more spread out in time have a lower SPL. A fixed window length of 0.125 seconds (critical duration defined by Tougaard et al. (2015)) is used in this study for impulsive sounds.

The sound exposure level (SEL; L_E; $L_{E,p}$; dB re 1 µPa²·s) is a measure related to the acoustic energy contained in one or more acoustic events (N). The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (T):

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

where T_0 is a reference time interval of one second. The SEL continues to increase with time when non-zero pressure signals are present. It therefore can be construed as a dose-type measurement, so the integration time used must be carefully considered in terms of relevance for impact to the exposed recipients.

SEL can be calculated over periods with multiple acoustic events or over a fixed duration. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, the SEL can be computed by summing (in linear units) the SEL of the N individual events:

$$L_{E,N} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right). \tag{A-3}$$

If applied, the frequency weighting of an acoustic event should be specified, as in the case of weighted SEL (e.g., $L_{E,LF,24h}$; Appendix A.3). The use of fast, slow, or impulse exponential-time-averaging or other time-related characteristics should else be specified.

A.2. Marine mammal impact criteria

It has been long recognised 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, Nedwell and Turnpenny 1998, HESS 1999, Ellison and Stein 1999). In the years since these early workshops, a variety of thresholds have been proposed for both injury and disturbance. The following sections summarize the recent development of thresholds; however, this field remains an active research topic.

A.2.1. Injury

In recognition of shortcomings of the SPL-only based injury criteria, in 2005 NMFS sponsored the Noise Criteria Group to review literature on marine mammal hearing to propose new noise exposure criteria. Some members of this expert group published a landmark paper (Southall et al. 2007) that suggested assessment methods similar to those applied for humans. The resulting recommendations introduced dual acoustic injury criteria for impulsive sounds that included peak pressure level thresholds and SEL_{24h} thresholds, where the subscripted 24h refers to the accumulation period for calculating SEL. The peak pressure level criterion is not frequency weighted whereas the SEL_{24h} is frequency weighted according to one of four marine mammal species hearing groups: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively) and Pinnipeds in Water (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 implies a 3 dB exchange rate).

Wood et al. (2012) refined Southall et al.'s (2007) thresholds, suggesting lower injury values for LF and HF cetaceans while retaining the filter shapes. Their revised thresholds were based on TTS-onset levels in harbour porpoises from Lucke et al. (2009), which led to a revised impulsive sound PTS threshold for HF cetaceans 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 LF cetaceans on results obtained from MF cetacean 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 LF cetaceans of 192 dB re 1 $\mu Pa^2 \cdot s$.

As of 2019, an optimal approach is not apparent. There is consensus in the research community that an SEL-based method is preferable either separately or in addition to an SPL-based approach to assess the potential for injuries. In August 2016, after substantial public and expert input into three draft versions and based largely on the above-mentioned literature (NOAA 2013, 2015, 2016), NMFS finalised technical guidance for assessing the effect of anthropogenic sound on marine mammal hearing (NMFS 2016). The guidance describes injury criteria with new thresholds and frequency weighting functions for the five hearing groups described by Finneran and Jenkins (2012). The latest revision to this work was published in 2018; only the peak sound level pressure PK criteria defined in NMFS (2018) are applied in this report.

A.3. Marine mammal frequency weighting

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. Marine mammal frequency weighting functions

In 2015, a U.S. Navy technical report by Finneran (2015) recommended new auditory weighting functions. The overall shape of the auditory weighting functions is similar to human A-weighting functions, which follows the sensitivity of the human ear at low sound levels. The new frequency-weighting function is expressed as:

$$G(f) = K + 10\log_{10}\left[\left(\frac{(f/f_{lo})^{2a}}{\left[1+(f/f_{lo})^2\right]^a\left[1+(f/f_{hi})^2\right]^b}\right)\right] \quad \text{(A-4)}$$

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid-, and high-frequency cetaceans, phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA's technical guidance that assesses noise impacts on marine mammals (NMFS 2016, NMFS 2018). Table A-1 lists the frequency-weighting parameters for each hearing group; Figure A-1 shows the resulting frequency-weighting curves.

Table A-1. Parameters for the auditory weighting functions used in this project as recommended by NMFS (2018).

Hearing group	a	b	f_{lo} (Hz)	f_{hi} (kHz)	K (dB)
Low-frequency cetaceans (baleen whales)	1.0	2	200	19,000	0.13
Mid-frequency cetaceans (dolphins, plus toothed, beaked, and bottlenose whales)	1.6	2	8,800	110,000	1.20
High-frequency cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* and *L. australis*)	1.8	2	12,000	140,000	1.36
Phocid seals in water	1.0	2	1,900	30,000	0.75
Otariid seals in water	2.0	2	940	25,000	0.64

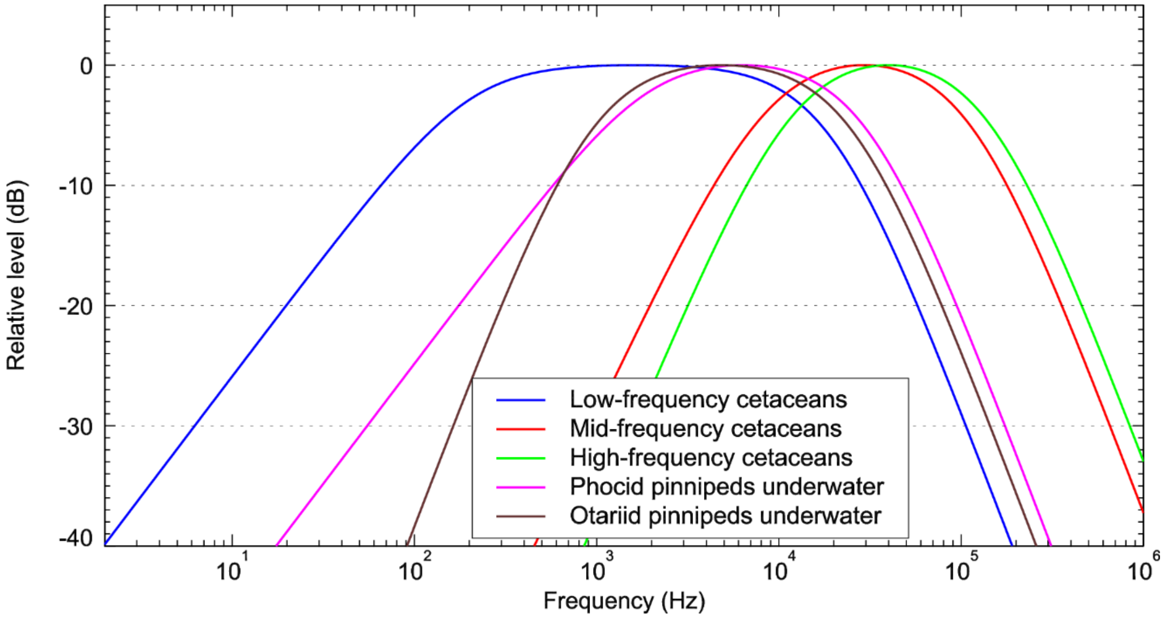

Figure A-1. Auditory weighting functions for functional marine mammal hearing groups used in this project as recommended by NMFS (2018)

Appendix B. Sound propagation models

B.1. MONM-BELLHOP

Long-range sound fields were computed using JASCO's Marine Operations Noise Model (MONM). This model computes sound propagation at frequencies of 10 Hz to 1.25 kHz 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). MONM computes sound propagation at frequencies > 1.25 kHz via the BELLHOP Gaussian beam acoustic ray-trace model (Porter and Liu 1994).

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.

This version of MONM accounts for sound attenuation due to energy absorption through ion relaxation and viscosity of water in addition to acoustic attenuation due to reflection at the medium boundaries and internal layers (Fisher and Simmons 1977). The former type of sound attenuation is significant for frequencies higher than 5 kHz and cannot be neglected without noticeably affecting the model results.

MONM 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 B-1).

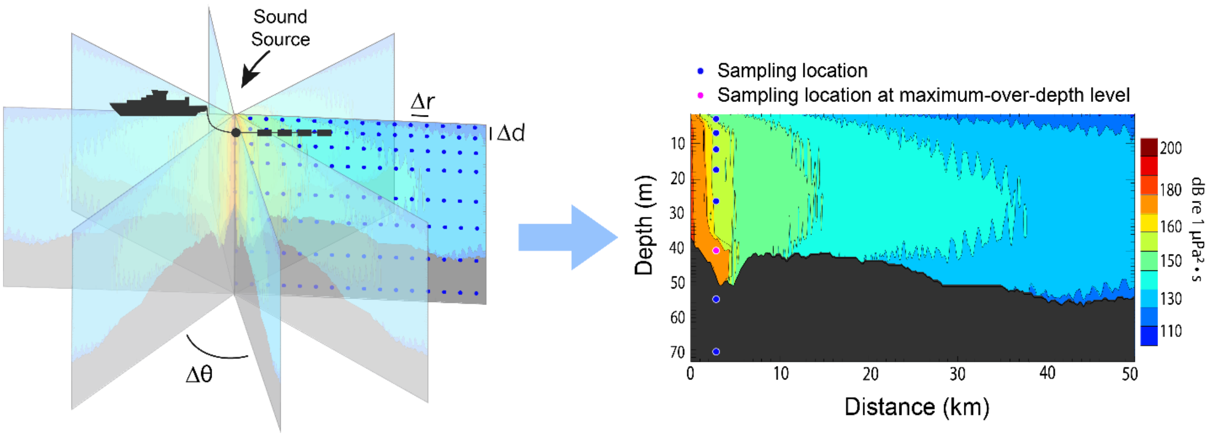

Figure B-1. The N×2-D and maximum-over-depth modelling approach used by MONM.

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

The received per-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 are presented as colour contours around the source.

An inherent variability in measured sound levels is caused by temporal variability in the environment and the variability in the signature of repeated acoustic impulses (sample sound source verification results is presented in Figure B-2). While MONM's predictions correspond to the averaged received levels, cautionary estimates of the threshold radii are obtained by shifting the best fit line (solid line, Figure B-2) upward so that the trend line encompasses 90% of all the data (dashed line, Figure B-2).

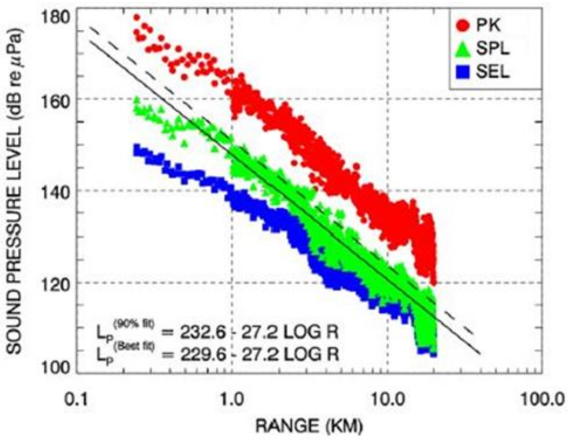

Figure B-2. PK and SPL and per-pulse SEL versus range from a 20 in^3 seismic source. Solid line is the least squares best fit to SPL. Dashed line is the best fit line increased by 3.0 dB to exceed 90% of all SPL values (90th percentile fit) (Ireland et al. 2009, Figure 10).

Appendix C. Methods and parameters

This section describes the specifications of the seismic source that was used at all sites and the environmental parameters used in the propagation models.

C.1. Estimating range to thresholds levels

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

The $R_{95\%}$ is used because sound field footprints are often irregular in shape. In some cases, a sound level contour might have small protrusions or anomalous isolated fringes. This is demonstrated in the image in Figure C-1(a). In cases such as this, where relatively few points are excluded in any given direction, R_{max} can misrepresent the area of the region exposed to such effects, and $R_{95\%}$ is considered more representative. In strongly asymmetric cases such as shown in Figure C-1(b), on the other hand, $R_{95\%}$ neglects to account for significant protrusions in the footprint. In such cases R_{max} might better represent the region of effect in specific directions. Cases such as this are usually associated with bathymetric features affecting propagation. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the non-uniformity of the acoustic environment.

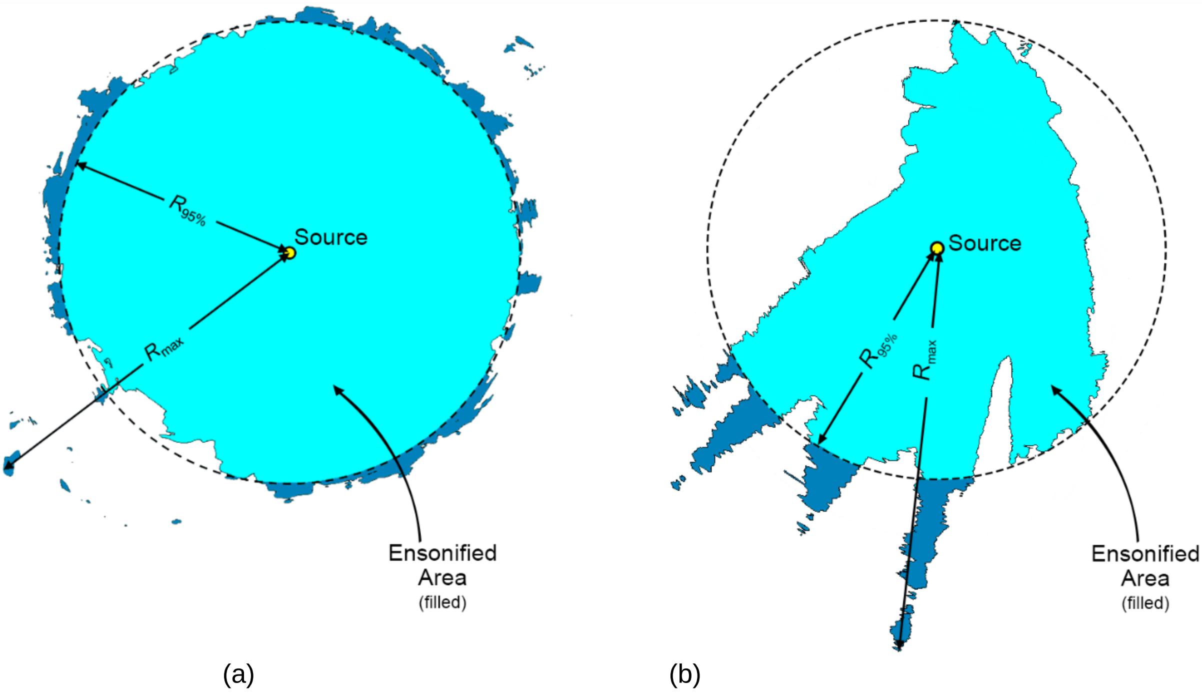

Figure C-1. Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ ranges shown for two different scenarios. (a) Largely symmetric sound level contour with small protrusions. (b) Strongly asymmetric sound level contour with long protrusions. Light blue indicates the ensonified areas bounded by $R_{95\%}$; darker blue indicates the areas outside this boundary which determine R_{max}.

C.2. Environmental parameters

C.2.1. Bathymetry

Water depths throughout the modelled area were extracted from data supplied by the client. Bathymetry data were extracted and re-gridded onto a Map Grid of Australia (MGA) coordinate projection (Zone 55) with a regular grid spacing of 10 by 10 metres. The water depths were also adjusted for highest astronomical tide (HAT) through the addition of 1.62 metres (https://www.regionalchannels.vic.gov.au/images/documents/2019/Tides%20Tables%202019.pdf).

C.2.2. Sound speed profile

The sound speed profiles for the modelled sites were derived from temperature and salinity data provided by the client. Data were provided in monthly averages from 2007 to 2010 and were assumed to represent an average profile throughout the water columns. The temperature-salinity profiles were converted to sound speed profiles according to Coppens (1981).

Table C-1.Monthly averaged temperature-salinity data

Month	Salinity (ppm)	Temperature (ºC)
Jan	37	21.1
Feb	37	21.0
Mar	36.7	18.8
Apr	36.8	16.8
May	36	14.4
June	35.8	12.1
Jul	**35.6**	**11.2**
Aug	35.3	11.5
Sep	35.1	12.6
Oct	35.4	15.9
Nov	36	17.1
Dec	35.7	19.0

C.2.3. Geoacoustics

Acoustic propagation loss modelling requires the geoacoustic properties of the seabed and sub-bottom to be as representative of the modelling area as possible. The modelling area is located in the Port of Hastings. The geology data for the Port of Hasting was derived from geologic core data found in GHD (2017), which describes the depositional environment and lithology for the region. Because the modelled area is large and geoacoustic information is limited, a single simplified geoacoustic profile was constructed to represent the major features of the sediment column at the modelled sites.

Based on this layer information and generic properties for marine sediments and sedimentary rocks from Hamilton (1980) and (Mavko 2005) the geoacoustic profile in Table C-2 was derived.

Table C-2. Estimated geoacoustic profile. For modelling using MONM-BELLHOP, only the surficial S-wave properties are considered. The compressional wave is the primary wave and the shear wave is the secondary wave.

Depth below seafloor (m)	Material	Density (g/cm3)	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0.0–3.25	Sand-silt-clay (unconsolidated)†	1.60	1579–1583	0.22	310–315	4.2
3.25–35.0	Silty Sand (consolidated)	1.77	1650–1691	0.77–0.98	396–414	5.3–5.5
≥35.0	Siltstone	2.10	2045	0.96	633	2.2

C.3. Model validation information

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

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