Appendix 9: Underwater Noise Modelling Report - Rock Breaking (JASCO)

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Santos Barossa Darwin Pipeline Duplication

Acoustic Modelling for Assessing Marine Fauna Sound Exposure

JASCO Applied Sciences (Australia) Pty Ltd

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SER Component	Key Roles	Organisation	Name	Qualifications	Experience
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Executive Summary

JASCO Applied Sciences (JASCO) performed a modelling study of underwater sound levels associated with the Santos Barossa Darwin Pipeline Duplication (DPD). The modelling study considers trenching activity using two sources – the Xcentric Ripper, considered to be a non-impulsive noise source, and a hydraulic hammer, considered to be an impulsive noise source.

The study predicted ranges to acoustic thresholds that may result in injury to or behavioural disturbance of marine fauna. The corresponding thresholds used in this study represented the best available science for behavioural response or disturbance, temporary threshold shift (TTS), and permanent threshold shift (PTS) or injury depending upon the fauna group. The fauna considered included marine mammals, sea turtles, and fish.

The modelling methodology was to characterise the sound sources and then determine how the sounds propagated at a specific location considering the environmental properties that influence the propagation of underwater sound. The models considered source levels of the trenching devices, and range-dependent environmental properties. It was assumed that any of the activities could be performed at any time during the year, therefore the most conservative season for the sound speed profile was considered.

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 and noise sources. In this report, the duration period for SEL accumulation is defined as an 8-hour period over which sound energy is integrated; the level is specified with the abbreviation SEL_{24h}.

SEL_{24h} is a cumulative metric that reflects the dosimetric effect of noise levels within 24 hours, based on the assumption that a receiver (e.g., an animal) is consistently exposed to such noise levels at a fixed position. More realistically, marine animals would not stay in the same location for 24 hours (especially in the absence of location-specific habitat) but rather a shorter period, depending on the animal's behaviour and the source's proximity and movements. Therefore, a reported radius for the SEL_{24h} criteria does not mean that marine fauna travelling within this radius of the source will be impaired, but rather that an animal could be exposed to the sound level associated with impairment (either PTS or TTS) if it remained at that location for 24 hours.

Marine Mammals

- The maximum distance where the NOAA (2019) marine behavioural response criterion of 120 dB 1 µPa for non-impulsive noise is shown in Table 1 and 160 dB 1 µPa for impulsive noise is shown in Table 2.
- The results for marine mammal injury considered the criteria from Southall et al. (2019). The metric used in this assessment is SEL_{24h}. The SEL_{24h} 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. More realistically, marine mammals (and fish) would not stay in the same location for 24 hours. Therefore, a reported radius of SEL24h 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 source level associated with injury (either PTS or TTS) if it remained in that location for 24 hours.
- The distance to PTS and TTS was always farthest towards the offshore direction and is shown in Tables 1 and 2.

Table 1. Summary of maximum (R_{max}) horizontal distances (in km) from the Xcentric Ripper at the modelled site to behavioural response thresholds, temporary threshold shift (TTS), and permanent threshold shift (PTS) for marine mammals.

Hearing group	Modelled distance to effect threshold (R_{max})		
	Behavioural response[1]	Impairment: TTS[2]	Impairment: PTS[2]
LF cetaceans	14.7	3.83	0.18
HF cetaceans		0.16	–
Sirenians		0.11	–

Noise exposure criteria: [1] NOAA (2019) and [2] Southall et al. (2019)
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m)

Table 2. Summary of maximum (R_{max}) horizontal distances (in km) from the hydraulic hammer at the modelled site to behavioural response thresholds, temporary threshold shift (TTS), and permanent threshold shift (PTS) for marine mammals.

Hearing group	Modelled distance to effect threshold (R_{max})		
	Behavioural response[1]	Impairment: TTS[2]	Impairment: PTS[2]
LF cetaceans	0.27	20.1	5.78
HF cetaceans		2.44	0.20
Sirenians		2.78	0.23

Noise exposure criteria: [1] NOAA (2019) and [2] Southall et al. (2019)
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m)

Sea Turtles

- The maximum distance to the SEL_{24h} metrics from the modelled sites Finneran et al. (2017). As is the case with marine mammals, a reported radius fir SEL_{24h} criteria does not mean that sea turtles travelling within the radius of the source will be injured, but rather that an animal could be exposed to the sound level associated with either PTS or TTS if it remained in that location for 24 hours.
- Table 3 summarises the distances to where the criterion for behavioural response of sea turtles to 166 dB 1 µPa and the 175 dB 1 µPa threshold for behavioural disturbance could be exceed.

Table 3. *Xcentric Ripper*: summary of distances to sea turtle temporary threshold shift (TTS) and permanent threshold shift (PTS).

Hearing group	Modelled distance to effect threshold (R_{max})	
	Impairment: TTS[1]	Impairment: PTS[1]
Sea turtles	0.05	–

Noise exposure criteria: [1] Finneran et al. (2017)

Table 4. *Hydraulic hammer*: summary of distances to sea turtle behavioural response criteria, temporary threshold shift (TTS), and permanent threshold shift (PTS).

Hearing group	Modelled distance to effect threshold (R_{max})			
	Behavioural response[1]	Behavioural disturbance[1]	Impairment: TTS[2]	Impairment: PTS[2]
Sea turtles	0.09	0.27	1.18	0.12

Noise exposure criteria: [1] McCauley et al. (2000) and [2] Finneran et al. (2017)

NOTE: TTS and PTS for impulsive noise is considered as a dual metric with SEL_{24h} and peak thresholds and the longest range to threshold to be taken. Since the source levels were taken from measured data over 1 sec the time characteristics and hence peak could not be determined. Due to the noise source distance to thresholds is expected to be greater for SEL_{24h}

Fish, fish eggs, and fish larvae

- This modelling study assessed the ranges for qualitative criteria based on Popper et al. (2014) and considered SEL_{24h} metrics associated with mortality and potential mortal injury as well as impairment in the following groups:
  - Fish without a swim bladder (also appropriate for sharks in the absence of other information),
  - Fish with a swim bladder that do not use it for hearing,
  - Fish that use their swim bladders for hearing,
  - Fish eggs and fish larvae.
- Table 5 summarises distances to effect criteria for fish, fish eggs, and fish larvae.

Table 5. *Hydraulic Hammer*: Summary of maximum fish, fish eggs, and larvae injury and temporary threshold shift (TTS) onset distances for 24 h sound exposure level (SEL_{24h}) modelled scenarios.

Relevant hearing group	Effect Criteria	Modelled distance to effect threshold (R_{max})
Fish: No swim bladder	Recoverable injury	0.03
	TTS	4.27
Fish: swim bladder not involved in hearing and Swim bladder involved in hearing	Recoverable injury	0.34
	TTS	4.27
Fish eggs and larvae	Injury	0.09

1. Introduction

Jasco Applied Sciences (JASCO) performed a numerical estimation study of underwater sound levels associated with the planned trenching activities in relation to the Santos Barossa Darwin Pipeline Duplication (DPD) to assist in understanding the potential acoustic effect on receptors including marine mammals, sea turtles, and fish.

The modelling study predicted the distances at which underwater sound levels from operations reached noise effect thresholds and criteria. Due to the variety of species considered, there are several different thresholds for evaluating effects, including: mortality, injury, temporary reduction in hearing sensitivity, and behavioural disturbance.

The modelling methodology considered underwater acoustic propagation models used in conjunction with the parametrisation specific to modelled sources (source level, frequency content, and source directivity) and range-dependent environmental properties that effect the propagation of underwater sound. 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 either non-impulsive (Xcentric Ripper) or impulsive (hydraulic hammer) noise sources.

Section 1.1 outlines the specific details of modelling study. Section 2 details the metrics used to represent underwater acoustic fields and the associated effect criteria considered. Section 3 details the methodology for predicting the source levels and modelling the sound propagation, including source levels and environmental parameters required by the propagation models. Section 4 presents the results, which are then discussed in Section 5.

1.1. Modelling Scenarios

The acoustic modelling study for trenching activities for the Santos Barossa DPD considers sites within Darwin Harbour with a water depth approximately 10 m deep. The project components considered two sources for trenching at three different tide datums for consistency with previous work – Lowest Astronomical Tide (LAT), Mean Sea Level (MSL), and Highest Astronomical Tide (HAT). The modelled site and scenarios considered are detailed in Table 6 with an overview map of the area shown in Figure 1.

Table 6. Modelled site locations and source information.

Site	Source	Latitude (S)	Longitude (E)	MGA[1] Zone 52 (GDA94)		Datum	Water Depth (m)	Duration (h)
				X (m)	Y (m)			
1	Xcentric Ripper XR-60	12° 31' 39.87"	130° 51' 11.43"	701366	8614382	LAT	5.0	2 x 4 h
						MSL	9.2	
						HAT	13.1	
	Hydraulic Hammer					LAT	5.0	2 x 4 h
						MSL	9.2	
						HAT	13.1	

[1] Map Grid of Australia (MGA)
LAT: Lowest Astronomical Tide
MSL: Mean Sea Level
HAT: Highest Astronomical Tide

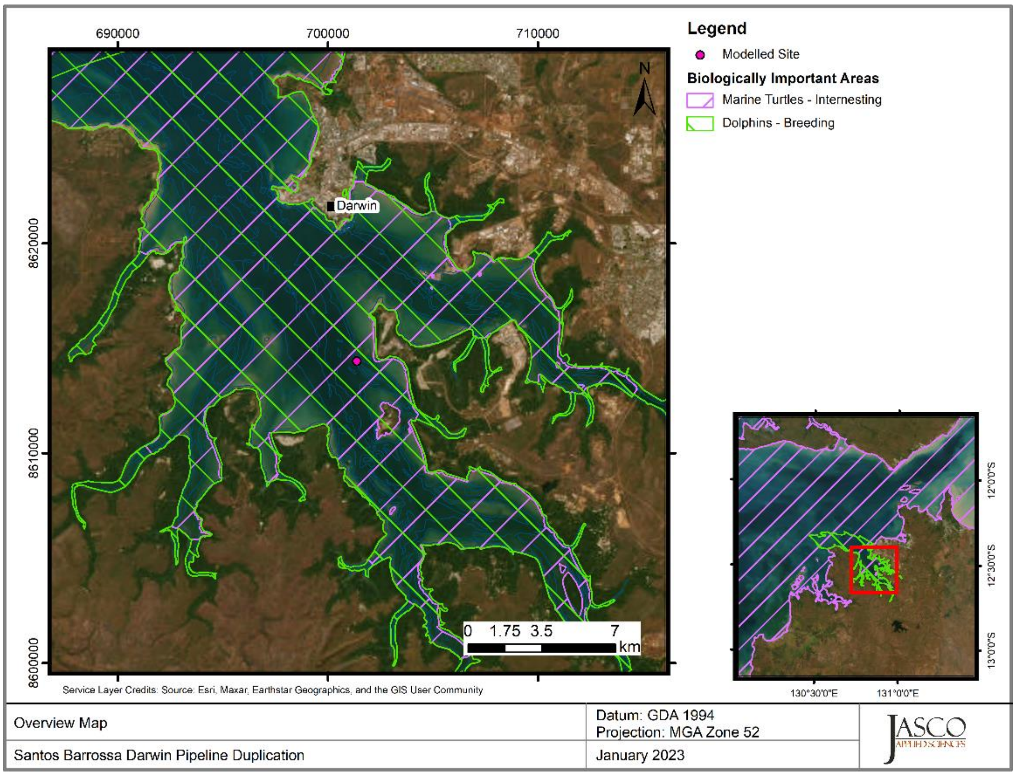

Figure 1. Overview of the modelled site and features associated with the Santos Barossa DPD.

2. Noise Effect Criteria

To assess the potential effects 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 effect 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), United States National Marine Fisheries Service (NMFS 2018) and Southall et al. (2019). The number of studies that investigate the level of behavioural disturbance to marine fauna by anthropogenic sound has also increased substantially.

Several impulsive metrics have been suggested to discern between impulsive and non-impulsive sounds for aerial and underwater sounds. Southall et al. (2007) proposed that regulations should use the Harris (1998) definition that says an impulse is present if there is more than a 3 dB difference between the impulse time weighted SPL and the slow-time weighted SPL (referred to here as the Harris impulse factor). Erdreich (1986) presented as an indicator of impulsiveness and demonstrated that kurtosis was a sensitive discriminator of the impulsiveness of noise. Kurtosis (β) (ISO 18405, 2017, Müller et al. 2020) is a statistical measure describing the distribution of acoustic energy across the frequency spectrum of a sound. It is a measure of the outliers in a given distribution (or time-series) relative to their occurrence in a normal distribution. Popper and Hawkins (2019) proposed kurtosis as a metric to distinguish impulsive sounds in the studies of fish and invertebrates. Martin et al. (2020) compared various types of impulsive and non-impulsive sounds in terms of their kurtosis, and the results strongly support using kurtosis for quantifying impulsiveness for future assessments and revised underwater noise regulations. The results also show that by applying this metric, it becomes irrelevant for assessing hearing impairment if impulsive signals seemingly merge into non-impulsive signals over distance due to dispersion as their kurtosis remains high (i.e., an indicator for impulsiveness). Guan et al. (2022) findings suggest that a simple dichotomy of classifying sounds as impulsive or non-impulsive may be overly simplistic for assessing auditory impacts (in marine mammals) and studies investigating the impacts from complex sound fields are needed.

The conclusions drawn in Guan et al. (2022) support the characterisation of the hydraulic hammer as an impulsive source while the Xcentric Ripper is used as a non-impulsive source. For these sound sources SPL and SEL are the relevant metrics. The period of accumulation associated with SEL is defined, with this report referencing either a “strikes in 1 sec” assessment or over 24 h. The acoustic metrics in this report reflect the ISO standard for acoustic terminology, ISO/DIS 18405:2017 (2017).

The following thresholds and guidelines for this study were chosen because they represent the best available science, and sound levels presented in literature for fauna with no defined thresholds:

1. Marine mammals:
    a. Marine mammal behavioural thresholds based on the current interim U.S. National Oceanic and Atmospheric Administration (NOAA) (2019) unweighted criterion for marine mammals of 120 dB re 1 µPa (SPL; L_p) and 160 dB re 1 µPa (SPL; L_p) for non–impulsive and impulsive sound sources, respectively.
1. Fish, fish eggs, and larvae:
    a. Sound exposure guidelines for fish, fish eggs, and larvae (Popper et al. 2014).
2. Sea turtles (also applied to other marine reptiles including crocodiles):
    a. Frequency–weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Finneran et al. (2017) for the onset of PTS and TTS in turtles for non–impulsive and impulsive sound sources.
    b. Sea turtle behavioural response threshold of 166 dB re 1 µPa (SPL; L_p) for impulsive noise, along with a sound level associated with behavioural disturbance 175 dB re 1 µPa (SPL; L_p) (McCauley et al. 2000).

The following sections (Sections 2.1 and 2.2, along with Appendix A.4 and A.5), expand on the thresholds, guidelines and sound levels for all marine fauna.

2.1. Impulsive Noise

Hydraulic hammering activities have been assessed as impulsive noise source as consistent with the considered thresholds and guidelines.

2.1.1. Marine Mammals

The criteria applied in this study to assess possible effects of impulsive noise sources on marine mammals are summarised Table 7; cetaceans were identified as the hearing group requiring assessment. Details on thresholds related to auditory threshold shifts or hearing loss and behavioural response are provided in Appendix A.4, with frequency weighting explained in detail in Appendix A.5. Whilst the newly published Southall et al. (2021) provides recommendations and discusses the nuances of assessing behavioural response, the authors do not recommend new numerical thresholds for onset of behavioural responses for marine mammals. The criteria from the current interim U.S. National Oceanic and Atmospheric Administration (NOAA) (2019) has been applied.

Table 7. Acoustic effects of impulsive noise on marine mammals: Unweighted SPL, SEL_{24h}, and PK thresholds.

Hearing group	NOAA (2019)	Southall et al. (2019)			
	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 µPa²·s)	PK (L_{pk}; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	PK (L_{pk}; dB re 1 µPa)
Low–Frequency (LF) cetaceans	160	183	219	168	213
High–frequency (HF) cetaceans		185	230	170	224
Sirenians		190	226	175	220

* Dual metric acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS onset. If a non–impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds should also be considered.
L_p denotes sound pressure level period.
$L_{pk,flat}$ denotes peak sound pressure is flat weighted or unweighted.
L_E denotes cumulative sound exposure over a 24 h period.

2.1.2. Fish, Sea turtles, Fish Eggs, Fish Larvae

In 2006, the Working Group on the Effects of Sound on Fish and Sea Turtles was formed to continue developing noise exposure criteria for fish and sea 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 hair cell damage and minor haematoma, and

- TTS.

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 Tables 8 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. Sea turtles, fish eggs, and fish larvae are considered separately.

Impulsive noise from hydraulic hammering is assessed in this study based on the relevant effects thresholds from Popper et al. (2014) listed in Table 8. In general, whether an impulsive sound adversely effects fish behaviour depends on the species, the state of the individual exposed, and other factors.

The SEL metric integrates noise intensity over some period of exposure. Because the period of integration for regulatory assessments is not well defined for sounds that do not have a clear start or end time, or for very long–lasting exposures, an exposure evaluation time must be defined. Southall et al. (2007) defines the exposure evaluation time as the greater of 24 h or the duration of the activity. Popper et al. (2014) recommend a standard period of the duration of the activity; however, the publication also includes caveats about considering the actual exposure times if fish move. Integration times in this study for hammering have been applied as 24 h even though the operational time is less than a day (2x4 h) following Southall et al. (2007).

Table 8. Criteria for pile driving noise exposure for fish, 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)	> 219 dB SEL_{24h} or > 213 dB PK	> 216 dB SEL_{24h} or > 213 dB PK	>> 186 dB SEL_{24h}	Pile driving: (N) Moderate (I, F) Low Seismic: (N, I, F) Low	(N) High (I) Moderate (F) Low
Fish: Swim bladder not involved in hearing (particle motion detection)	210 dB SEL_{24h} or > 207 dB PK	203 dB SEL_{24h} or > 207 dB PK	>> 186 dB SEL_{24h}	Pile driving: (N) Moderate (I, F) Low Seismic: (N, I, F) Low	(N) High (I) Moderate (F) Low
Fish: Swim bladder involved in hearing (primarily pressure detection)	207 dB SEL_{24h} or > 207 dB PK	203 dB SEL_{24h} or > 207 dB PK	186 dB SEL_{24h}	Pile driving: (N, I) High (F) Moderate Seismic: (N, I) Low (F) Moderate	(N, I) High (F) Moderate
Fish eggs and fish larvae	> 210 dB SEL_{24h} or > 207 dB PK	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	Pile driving: (N) Moderate (I, F) Low Seismic: (N, I, F) Low	(N) Moderate (I, F) Low

Peak sound pressure level dB re 1 µPa; SEL_{24h} dB re 1µPa^{2}·s.
All criteria are presented as sound pressure even for fish without swim bladders since no data for particle motion exist.
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). Where near might be considered in the 10's of m, intermediate in the 100's of m and far in the 1000's of m.

There is a paucity of data regarding responses of turtles to acoustic exposure, and no studies of hearing loss due to exposure to loud sounds. Popper et al. (2014) suggested thresholds for onset of mortal injury (including PTS) and mortality for sea turtles and, in absence of taxon–specific information, adopted the levels for fish that do not hear well (suggesting that this likely would be conservative for sea turtles). Finneran et al. (2017) in turn presented revised thresholds for sea turtle injury and hearing impairment (TTS and PTS). Their rationale is that sea turtles have best sensitivity at low frequencies and are known to have poor auditory sensitivity (Bartol and Ketten 2006, Dow Piniak et al. 2012). Accordingly, TTS and PTS thresholds for turtles are likely more similar to those of fishes than to marine mammals (Popper et al. 2014).

McCauley et al. (2000) observed the behavioural response of caged sea turtles—green (*Chelonia mydas*) and loggerhead (*Caretta caretta*)—to an approaching seismic airgun. For received levels above 166 dB re 1 µPa (SPL), the sea turtles increased their swimming activity, and above 175 dB re 1 µPa they began to behave erratically, which was interpreted as an agitated state. The Recovery Plan for Marine Turtles in Australia (Department of the Environment and Energy et al. 2017) acknowledges the 166 dB re 1 µPa SPL reported (McCauley et al. 2000) as the level that may result in a behavioural response to marine turtles. The 175 dB re 1 µPa level from McCauley et al. (2000) is recommended as a criterion for behavioural disturbance.; these thresholds are shown in Table 9.

Table 9. Acoustic effects of impulsive noise on sea turtles: Unweighted sound pressure level (SPL), 24-hour sound exposure level (SEL_{24h}), and peak pressure (PK) thresholds

Effect type	Criterion	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	PK (L_{pk}; dB re 1 µPa)
Behavioural response	McCauley et al. (2000)	166	NA	
Behavioural disturbance		175		
PTS onset thresholds[1] (received level)	Finneran et al. (2017)	NA	204	232
TTS onset thresholds[1] (received level)			189	226

[1] Dual metric acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS and TTS onset. If a non–impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds should also be considered.
L_p denotes sound pressure level period and has a reference value of 1 µPa.
$L_{pk,flat}$ denotes peak sound pressure is flat weighted or unweighted and has a reference value of 1 µPa.
L_E denotes cumulative sound exposure over a 24 h period and has a reference value of 1 µPa²s.

2.2. Non-impulsive Noise

Xcentric Ripper operations have been assessed as non-impulsive noise source as consistent with the considered thresholds and guidelines.

2.2.1. Marine Mammals

The criteria applied in this study to assess possible effects of non-impulsive noise sources on marine mammals are summarised in Table 10.

Table 10. Criteria for effects of non–impulsive noise exposure for marine mammals: Unweighted SPL and SEL_{24h} thresholds.

Hearing group	NOAA (2019)	Southall et al. (2019)	
	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 µPa²·s)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)
Low–Frequency (LF) cetaceans	120	199	179
High–frequency (HF) cetaceans		198	178
Sirenians		206	186

L_p denotes sound pressure level period and has a reference value of 1 µPa.
L_E denotes cumulative sound exposure over a 24 h period and has a reference value of 1 µPa²·s.

2.2.2. Fish, Sea Turtles, Fish Eggs, and Fish Larvae

Non-impulsive noise from the Xcentric Ripper is assessed in this study based on the relevant effects thresholds from Popper et al. (2014). Table 11 lists the relevant effects thresholds from Popper et al. (2014) for Xcentric Ripper operational noise. Some evidence suggests that fish sensitive to acoustic pressure 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. Finneran et al. (2017) presented revised thresholds for turtle injury, considering frequency weighted SEL, which have been applied in this study for non-impulsive sound sources (Table 12).

Table 11. Criteria for non–impulsive noise exposure for fish, 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
Sea turtles	(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) 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). Where near might be considered in the 10's of m, intermediate in the 100's of m and far in the 1000's of m.

Table 12. Acoustic effects of non–impulsive noise on sea turtles, weighted SEL_{24h}, Finneran et al. (2017).

PTS onset thresholds (received level)	TTS onset thresholds (received level)
220	200

3. Methods

This section describes the methods used to characterise acoustic sources considered in this study, the Xcentric Ripper and the Hydraulic Hammer; as well as the acoustic propagation models and associated inputs used to make numerical predictions of acoustic fields.

3.1. Sources

3.1.1. Xcentric Ripper

The Xcentric Ripper is a hydraulic rock breaking tool which can be attached to an excavator. Underwater measurements of an Xcentric Ripper XR-60 were performed at Acheron Head in Otago Lawrence (2016) by Marshall Day Acoustics. The measurement consisted of three hydrophones at approximate measurement distances of 430, 950, and 2000 m. From Barham and East (2018) a fit equation of $N\log_{10}(r) - \alpha r$ curve was fit to the data, giving values of $N = 14.8$ and $\alpha = -0.0075$.

To determine source level the received levels from Lawrence (2016) were backpropagated using the following method. Using the spectral data from Lawrence (2016), the closest hydrophone (430 m away from source) was backpropagated using the fit curve above. At a range approximately equal to 1 water depth levels were further backpropagated using a $20\log_{10}(r)$ spreading loss. A broadband source level was then calculated as 184.8 dB re 1 µPa^{2}m^{2}s with the associated spectra shown in Figure 2.

The additional backpropagation step was applied since the fit curve may not be appropriate in the near-field region close to the source. In this region, there is little interaction with the seabed with loss almost entirely ascribed to spherical spreading loss thus we have used $20\log_{10}(r)$. More accurate source levels could be determined through backpropagation using a propagation model, however this isn’t possible with the information available.

Most acoustic energy from the Xcentric Ripper is output at frequencies in the hundreds to thousands of hertz. The sound produced was considered to be isotropic with the main source of noise a nominal 1 m above the seafloor.

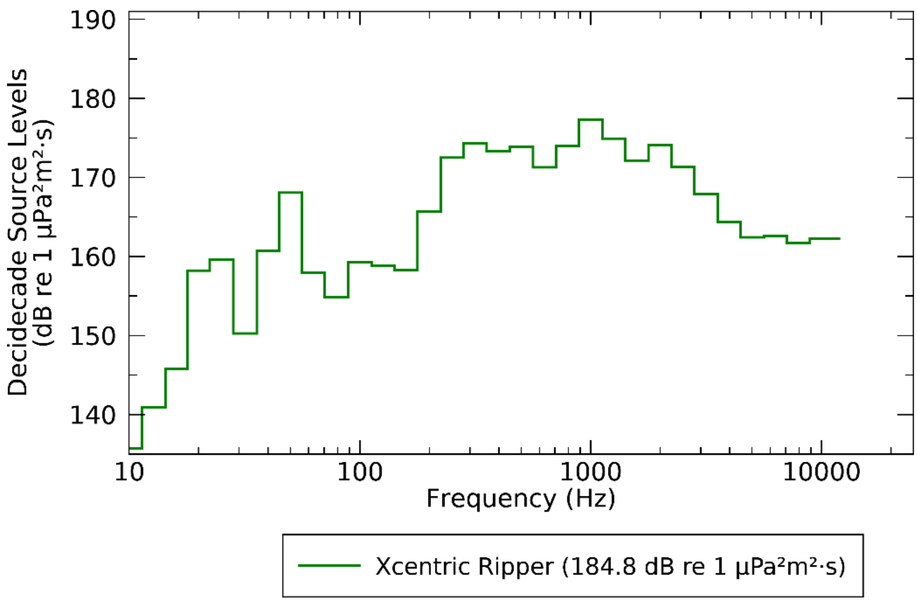

Figure 2. Source level spectra (in decidecade frequency-band) for the Xcentric Ripper.

3.1.2. Hydraulic Hammer

The Epiroc HB 10000 is a hydraulic rock breaking hammer tool, which can be attached to an excavator. Detailed measurements of the underwater source level were not available at the time of the study, therefore the source level spectra corresponding to Down-The-Hole (DTH) hydro-hammering were used as a proxy of the proposed hydraulic rock breaking hammer tool. DTH hydro-hammering is a percussive rotating drilling technique appropriate for hard rock formations. The proxy DTH levels correspond to a Numa Patriot 180 hammer, used to drive 24 inch (0.6 m) diameter piles at a ferry terminal at Kodiak, AK, USA (Denes et al. 2016). The acoustic signature for this activity was recorded at 10 to 30 m from the pile. The measured sound levels (in decidecade frequency bands) were adjusted to determine the levels at the pile, (i.e., backpropagated using spherical spreading) and averaged to provide the representative decidecade frequency-band energy source level (ESL) seen in Figure 3. This source level spectrum yields a broadband ESL of 192 dB 1 μPa^2·s m^2.

Depending on several factors, mainly the repetition rate, hydraulic hammer tool could be impulsive or non-impulsive. Since the hydraulic rock breaking hammer tool operates at a repetition rate between 250-380 strikes/min we consider it an impulsive source, in a similar fashion to the DTH tool presented in Guan et al. (2022). However, it is close to the threshold where it may be considered quasi-continuous. While the hydraulic hammer tool is considered as impulsive, the measurements from Denes et al. (2016) give only a source level and spectra over 1 sec. The report does not provide enough temporal information needed to determine peak levels. The noise effect criteria for TTS and PTS (Section 2.1) are dual metrics which require the longest distance to threshold between peak and SEL_{24h}; however, based on JASCO's experience it is expected that SEL_{24h} will produce greater distances to threshold than peak pressure level for this source. It is unlikely that PK thresholds will be exceeded except within the close vicinity of the source.

Most acoustic energy from the hydraulic hammer tool is output at frequencies in the hundreds to thousands of hertz. The sound produced was considered to be isotropic with the main source of noise a nominal 1 m above the seafloor.

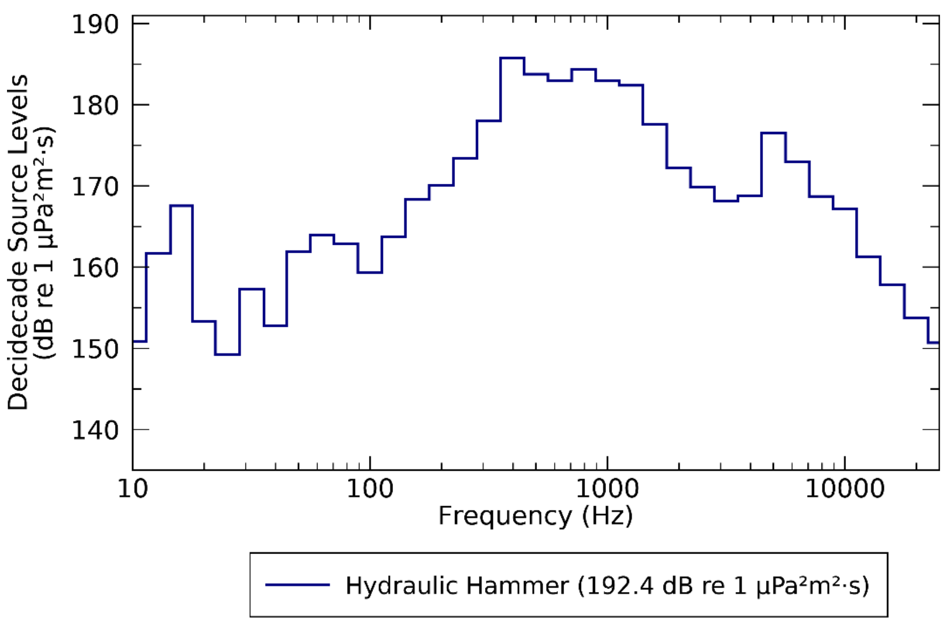

Figure 3. Source level spectra (in decidecade frequency-band) for the Hydraulic Hammer.

3.2. Geometry and Modelled Regions

To predict sound levels with MONM-BELLHOP was used to calculate propagation losses up to distances of 40 km from the source, with a horizontal separation of 20 m between receiver points along all modelled radials. The sound fields were modelled with a horizontal angular resolution of $\Delta\theta$ = 2.5° for a total of *N* = 144 radial planes. Receiver depths were chosen to span the entire water column over the modelled area, from 2 m to a maximum of 100 m, with step sizes that increased with depth. To supplement the MONM results, high-frequency results for propagation loss were modelled using BELLHOP for frequencies from 1.25 to 25 kHz. The MONM and Bellhop results were combined to produce results for the full frequency range of interest.

3.3. Accumulated Modelling

For both sources, the source levels were measured over a 1 sec period. As such SPL is equivalent to the SEL over the same duration. Modelling results were converted to SEL_{24h} by the duration of the measurement. As SEL was assessed over 8 h, the conversion from SEL over 1 second was obtained by increasing the levels by $10*\log_{10}(T)$, where T is 28,800 (the number of seconds in 8 h). Additional modelling times of 2, 4, and 6 h for the hydraulic hammer are presented in Appendix F.

4. Results

The results below are split into two sections Xcentric Ripper and hydraulic hammer. For the results and tables presented below where a dash is used in place of a horizontal distance, these thresholds may or may not be reached due to the discreetly sampled radial increments of the modelled sound fields. A dash therefore is an indication that effect levels for the associated metric may only be reached within a very close proximity to a given source.

4.1. Xcentric Ripper (non-impulsive sound source)

Table 13 presents the maximum and 95% distances to SPL. The SPL sound footprints presented represent the instantaneous sound field and do not depend on the accumulation time. Table 14 presents the maximum distances to frequency-weighted SEL_{24h} thresholds, as well as total ensonified area.

4.1.1. Tabulated Results

Table 13. *Xcentric Ripper*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) to sound pressure level (SPL). A dash indicates the threshold is not reached within the limits of the modelled resolution (20 m).

SPL (L_p; dB re 1 µPa)	LAT		MSL		HAT	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
180	–	–	–	–	–	–
170[a]	–	–	–	–	–	–
160	0.06	0.06	0.05	0.05	0.03	0.03
158[b]	0.09	0.08	0.06	0.06	0.05	0.05
150	0.35	0.31	0.28	0.25	0.23	0.21
140	1.52	1.33	1.30	1.15	1.20	1.04
130	6.86	4.99	4.97	4.19	4.71	3.91
120[c]	14.7	11.5	14.0	11.0	13.1	11.1

[a] 48 h threshold for recoverable injury for fish with a swim bladder involved in hearing (Popper et al. 2014).
[b] 12 h threshold for TTS for fish with a swim bladder involved in hearing (Popper et al. 2014).
[c] Threshold for marine mammal behavioural response to non-impulsive noise (NOAA 2019).

Table 14. *Xcentric Ripper:* Maximum (R_{max}) horizontal distances (in km) to frequency-weighted SEL_{24h} PTS and TTS thresholds based on Southall et al. (2019) and Finneran et al. (2017) from the most appropriate location for considered sources per scenario, and ensonified area (km^2). A dash indicates the level was not reached within the limits of the modelled resolution (20 m). A slash indicates that the area is less than an area associated with the modelled resolution (0.0013 km^2). Scenario descriptions are given in Table 6.

Hearing group	Frequency-weighted SEL_{24h} threshold ($L_{E,24h}$; dB re 1 µPa²·s)	LAT		MSL		HAT	
		R_{max} (km)	Area (km^2)	R_{max} (km)	Area (km^2)	R_{max} (km)	Area (km^2)
PTS							
LF cetaceans	199	0.18	0.06	0.10	0.03	0.09	0.02
HF cetaceans	198	–	–	–	–	–	–
Sirenians	206	–	–	–	–	–	–
Sea Turtles	220	–	–	–	–	–	–
TTS							
LF cetaceans	179	3.83	12.27	3.02	11.59	2.68	10.8
HF cetaceans	178	0.16	0.06	0.10	0.03	0.09	0.02
Sirenians	186	0.11	0.03	0.07	0.02	0.06	0.01
Sea Turtles	200	0.05	0.01	0.04	0.01	0.03	\

4.1.2. Sound Field Maps

SPL maps are presented as maximum-over-depth sound level contour in Figures 4-6 and as vertical slice plots shown in Figures 7-9 for selected azimuths. SEL_{24h} maps are shown in Figures 10-12 with LF cetacean contour maps shown for context in Appendix E.1.

4.1.2.1. SPL Sound level contour maps

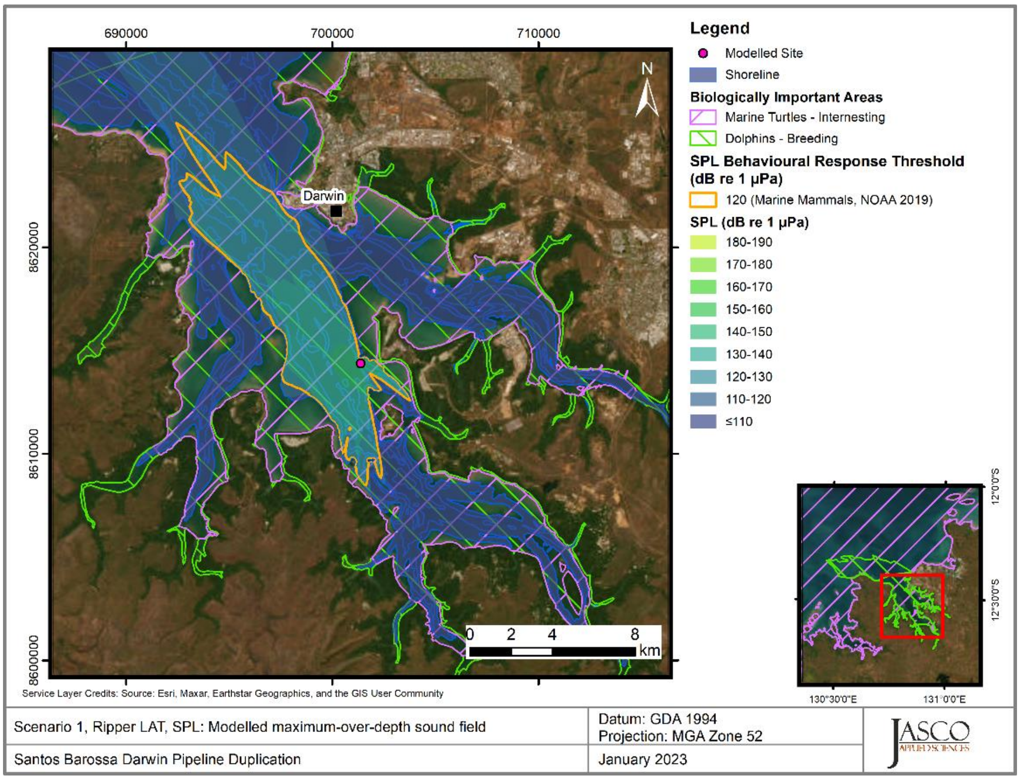

Figure 4. *Xcentric Ripper, LAT, SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural thresholds for marine mammals.

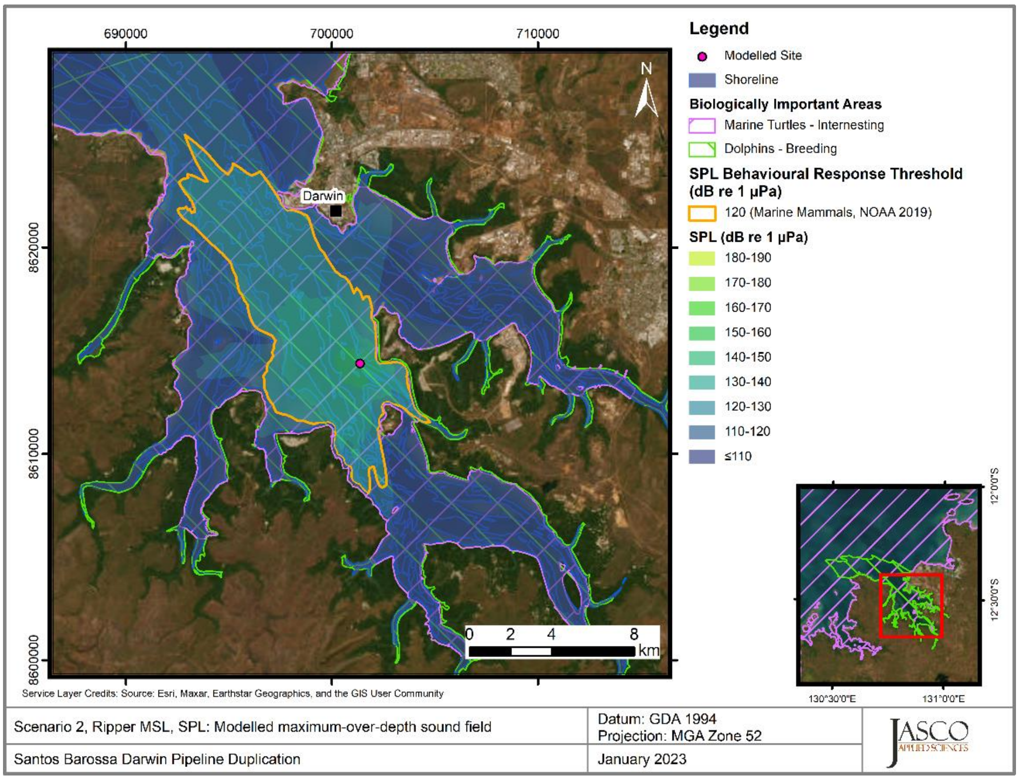

Figure 5. *Xcentric Ripper, MSL, SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural thresholds for marine mammals.

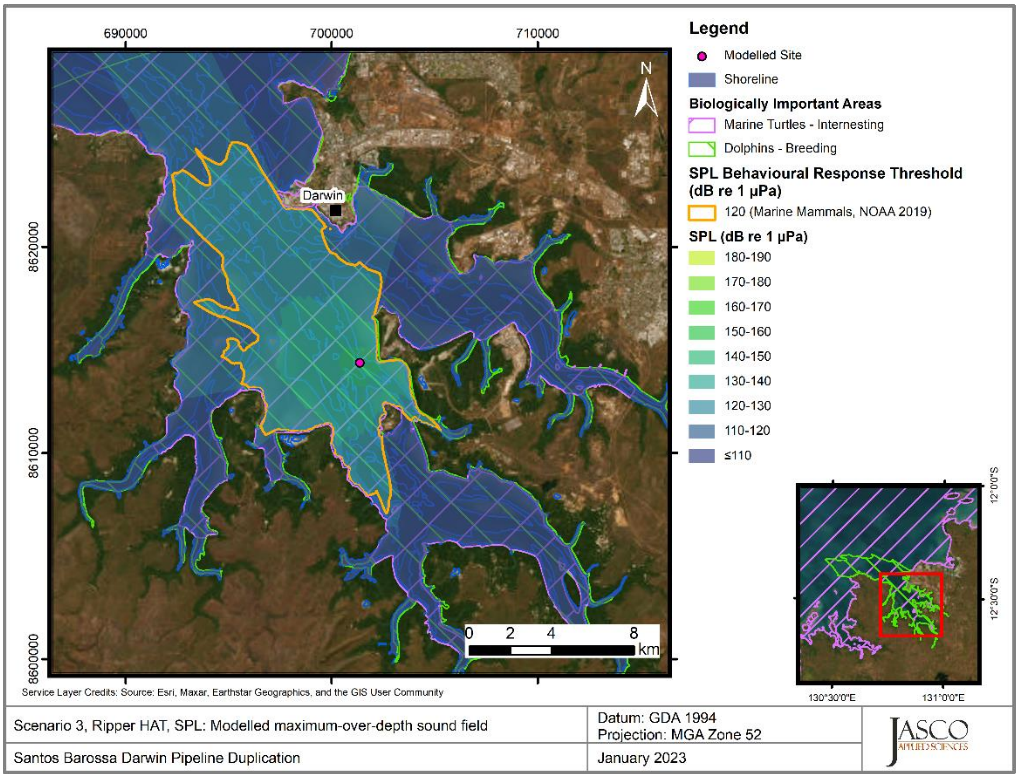

Figure 6. *Xcentric Ripper, HAT, SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural thresholds for marine mammals.

4.1.2.2. SPL Vertical slice plots

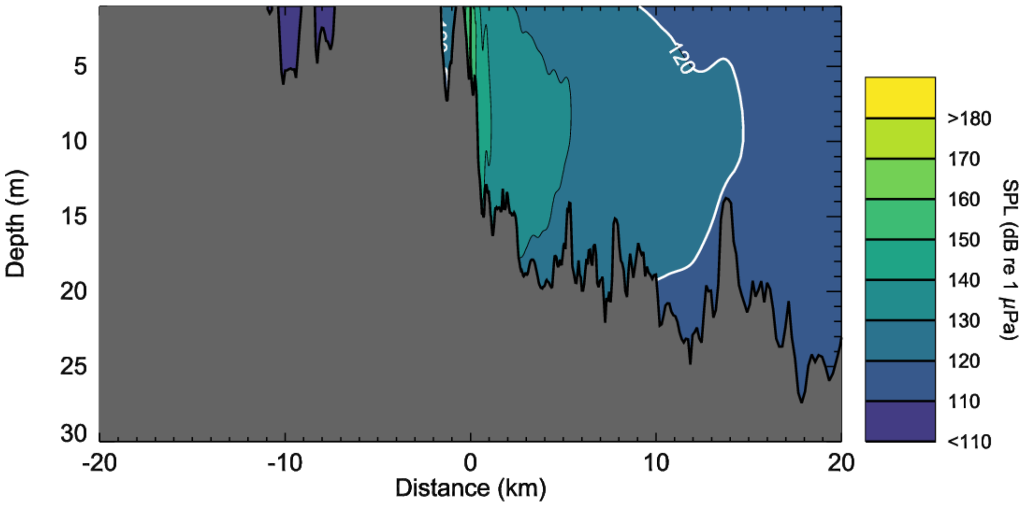

Figure 7. *Xcentric Ripper, LAT, SPL*: Vertical slice plot showing variations with depth and distance from the source with the isopleth for behavioural threshold for marine mammals. The seabed is shown in dark grey. Cross sections are along the 142/322° transect.

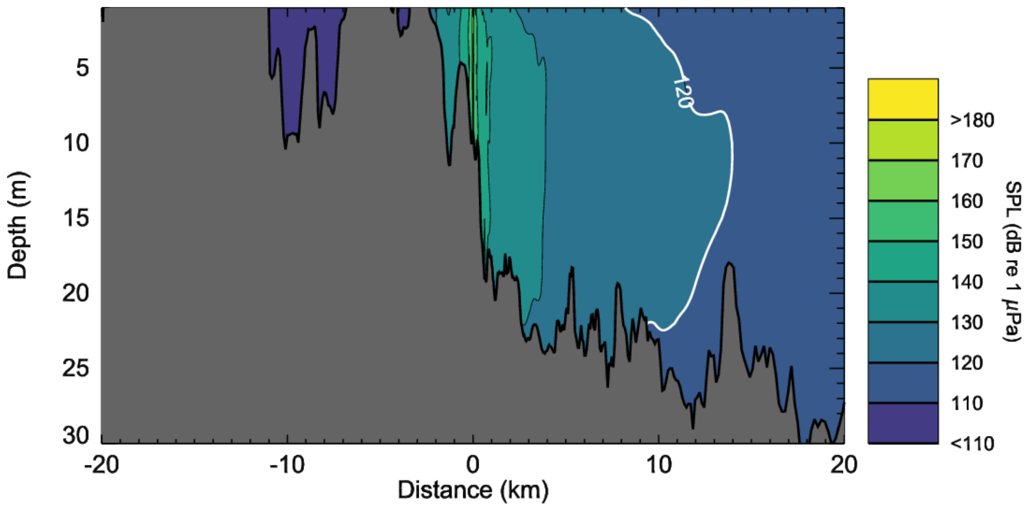

Figure 8. *Xcentric Ripper, MSL, SPL*: Vertical slice plot showing variations with depth and distance from the source with the isopleth for behavioural threshold for marine mammals. The seabed is shown in dark grey. Cross sections are along the 142/322° transect.

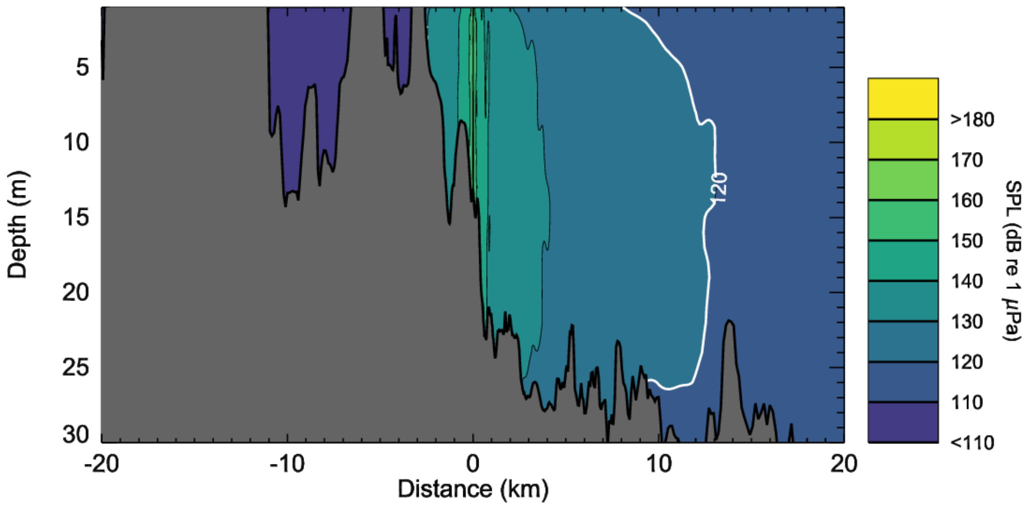

Figure 9. *Xcentric Ripper, HAT, SPL*: Vertical slice plot showing variations with depth and distance from the source with the isopleth for behavioural threshold for marine mammals. The seabed is shown in dark grey. Cross sections are along the 142/322° transect.

4.1.2.3. Accumulated SEL_{24h} sound level contour maps

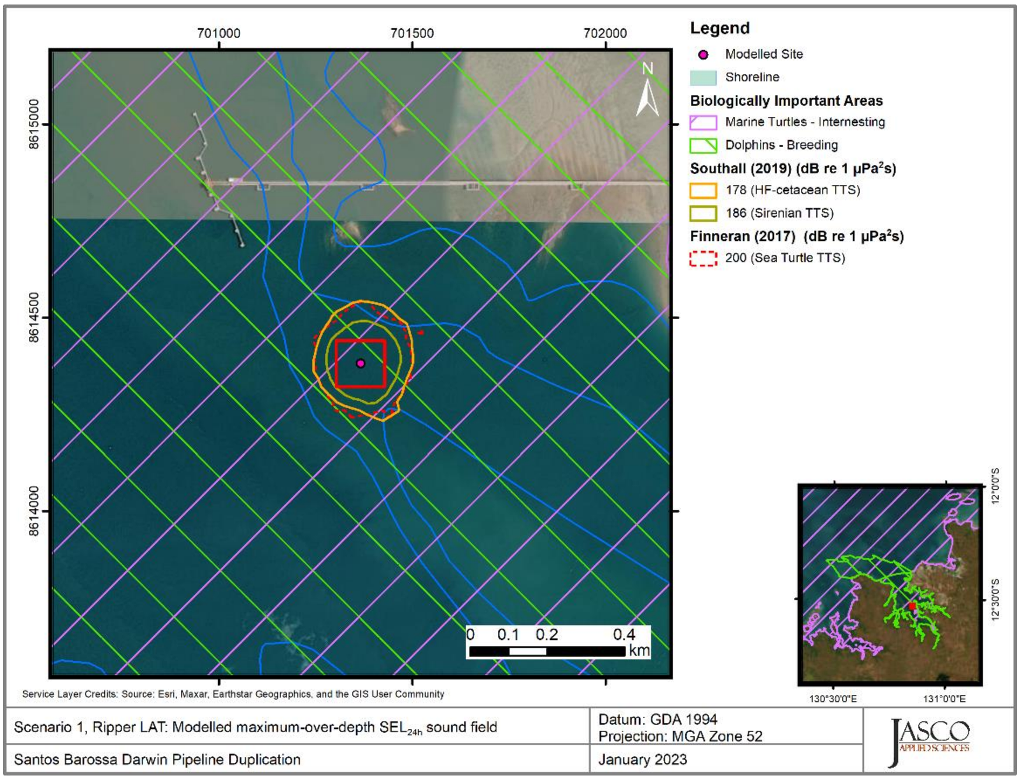

Figure 10. *Xcentric Ripper, LAT:* sound level contour map isopleths for HF cetaceans, sirenians and sea turtles. Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

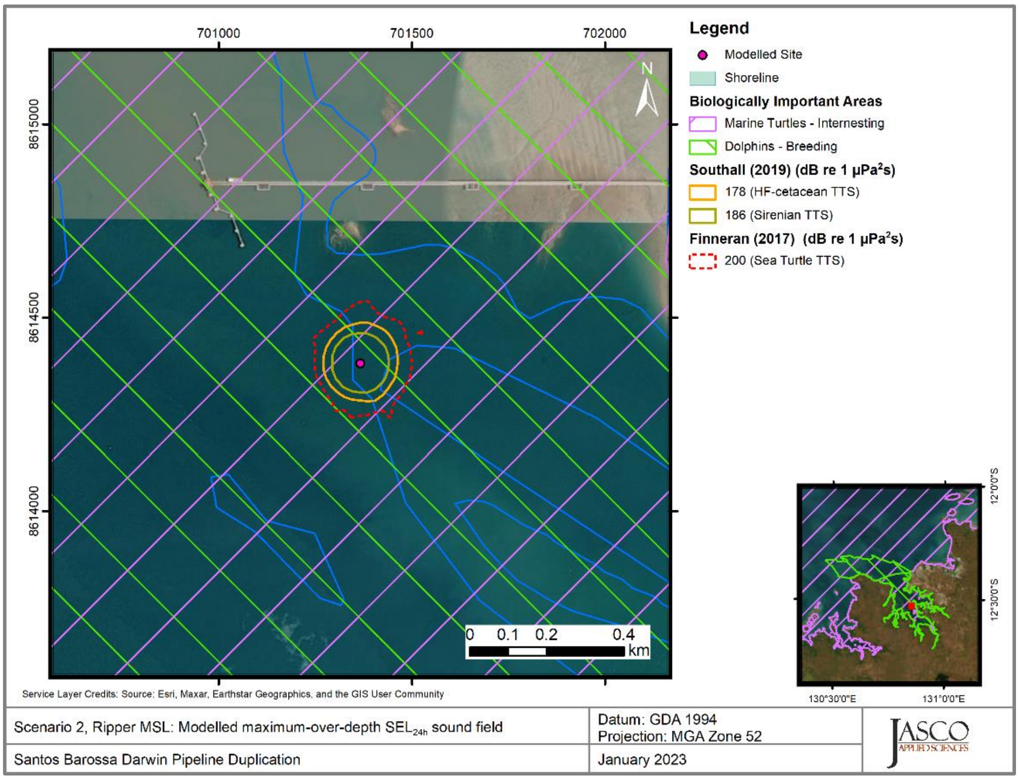

Figure 11. *Xcentric Ripper, MSL:* sound level contour map isopleths for HF cetaceans, sirenians and sea turtles.

Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

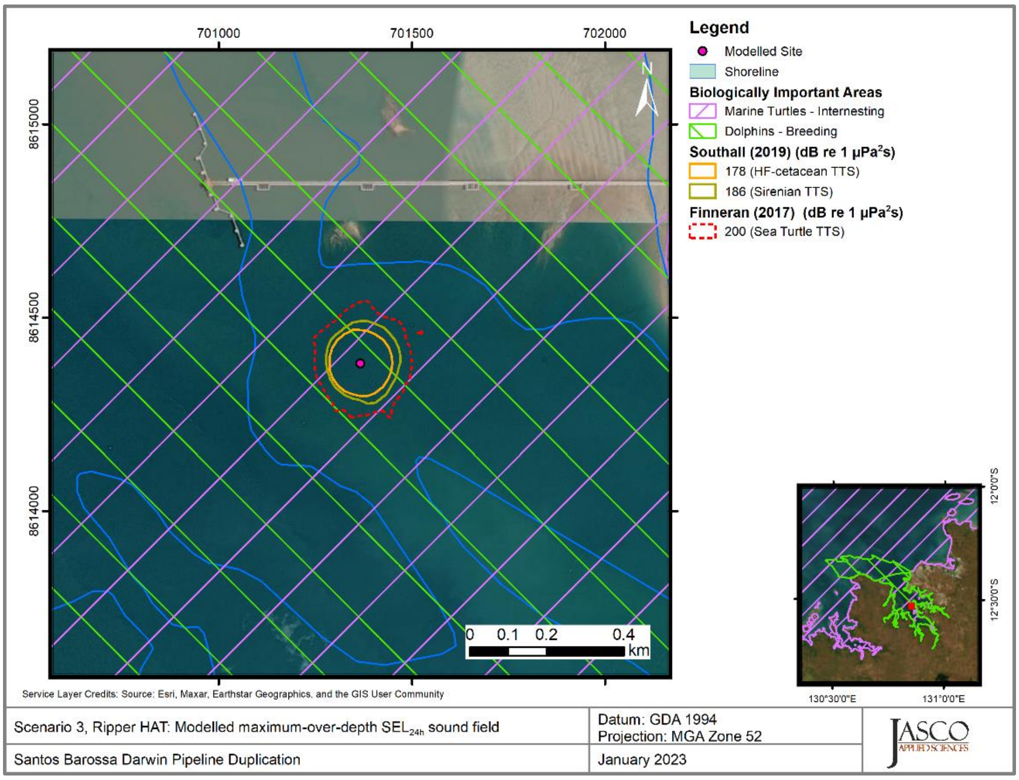

Figure 12. *Xcentric Ripper, HAT:* sound level contour map isopleths for HF cetaceans, sirenians and sea turtles.

Thresholds omitted here not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

4.2. Hydraulic Hammer (impulsive sound source)

Table 15 presents the maximum and 95% distances to SPL. The SPL sound footprints presented represent the instantaneous sound field and do not depend on the accumulation time. Table 16 presents the maximum distances to frequency-weighted SEL_{24h} thresholds, as well as total ensonified area. Additional modelling times of 2, 4, and 6 h for the hydraulic hammer are presented in Appendix F.

4.2.1. Tabulated Results

Table 15. *Hydraulic Hammer: modelled maximum–over–depth per–strike SPL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km).

SPL (L_p; dB re 1 µPa)	Hydraulic Hammer					
	LAT		MSL		HAT	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
180	–	–	–	–	–	–
175[1]	–	–	–	–	–	–
170	0.04	0.04	0.03	0.03	0.02	0.02
166[2]	0.09	0.08	0.06	0.06	0.06	0.06
160[3]	0.27	0.24	0.22	0.20	0.17	0.15
150	1.21	1.07	0.96	0.84	0.90	0.75
140	4.83	3.80	4.25	3.39	3.82	3.12
130	11.3	8.48	11.1	8.62	12.6	8.75
120	26.6	22.7	29.3	24.3	29.3	25.0

[1] Threshold for turtle behavioural disturbance from impulsive noise (McCauley et al. 2000).
[2] Threshold for turtle behavioural response to impulsive noise (McCauley et al. 2000).
[3] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (40 km).

Table 16. *Hydraulic Hammer:* Maximum (R_{max}) horizontal distances (in km) to frequency-weighted SEL_{24h} PTS and TTS thresholds based on Southall et al. (2019) and Finneran et al. (2017) from the most appropriate location for considered sources per scenario, and ensonified area (km^2). A dash indicates the level was not reached within the limits of the modelled resolution (20 m). A slash indicates that the area is less than an area associated with the modelled resolution (0.0013 km^2). Scenario descriptions are given in Table 6.

Hearing group	Frequency-weighted SEL_{24h} threshold ($L_{E,24h}$; dB re 1 µPa²·s)	LAT		MSL		HAT	
		R_{max} (km)	Area (km^2)	R_{max} (km)	Area (km^2)	R_{max} (km)	Area (km^2)
PTS							
LF cetaceans	183	5.78	19.0	4.71	22.56	4.39	24.14
HF cetaceans	185	0.20	0.08	0.13	0.04	0.10	0.03
Sirenians	190	0.23	0.11	0.16	0.06	0.12	0.04
Sea Turtles	204	0.12	0.03	0.10	0.02	0.06	0.01
TTS							
LF cetaceans	168	20.1	69.75	24.2	102.9	19.9	133.2
HF cetaceans	170	2.44	4.81	1.83	5.36	1.63	5.04
Sirenians	175	2.78	8.33	2.50	7.06	1.94	6.62
Sea Turtles	189	1.18	1.90	0.95	1.68	0.90	1.61

Table 17. *Hydraulic Hammer:* distances to 24 h sound exposure level (SEL_{24h}) based fish criteria in the water column. A dash indicates the level was not reached within the limits of the modelled resolution (20 m). A slash indicates that the area is less than an area associated with the modelled resolution (0.0013 km^2). Scenario descriptions are given in Table 6.

Marine fauna group	Threshold SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Maximum-over-depth					
		LAT		MSL		HAT	
		R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)
Mortality and potential mortal injury							
I	219	–	–	–	–	–	–
II, fish eggs and fish larvae	210	0.09	0.03	0.06	0.01	0.06	0.01
III	207	0.20	0.07	0.16	0.04	0.09	0.03
Fish recoverable injury							
I	216	0.03	\	0.02	\	–	–
II, III	203	0.34	0.24	0.28	0.17	0.24	0.12
Fish temporary threshold shift (TTS)							
I, II, III	186	4.27	14.43	3.44	14.67	3.13	13.75

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.2.2. Sound Field Maps

Maps for SPL are presented as maximum-over-depth sound level contours in Figures 13-15 and as vertical slice plots shown in Figures 16-18 for selected azimuths. SEL_{24h} contour maps are shown in Figures 19–24 for HF cetaceans, sirenians, sea turtles, and fish. While the LF cetacean contours are shown for context in Appendix E.1.

4.2.2.1. SPL Sound level contour maps

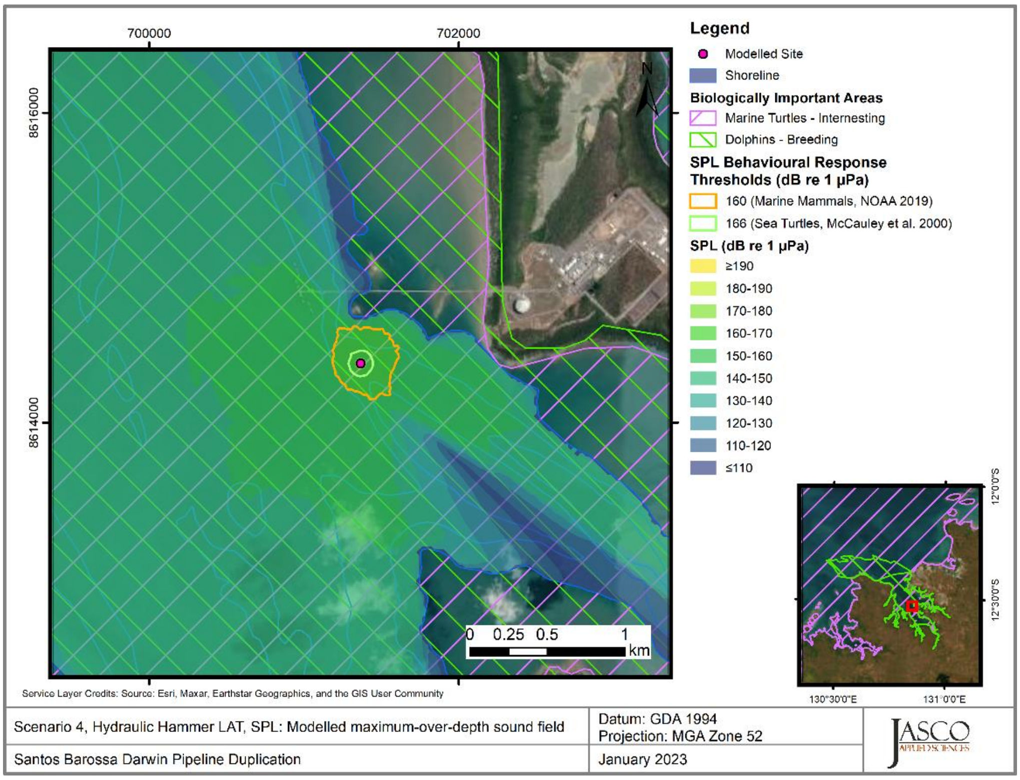

Figure 13. *Hydraulic Hammer, LAT, SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural thresholds for marine mammals and sea turtles.

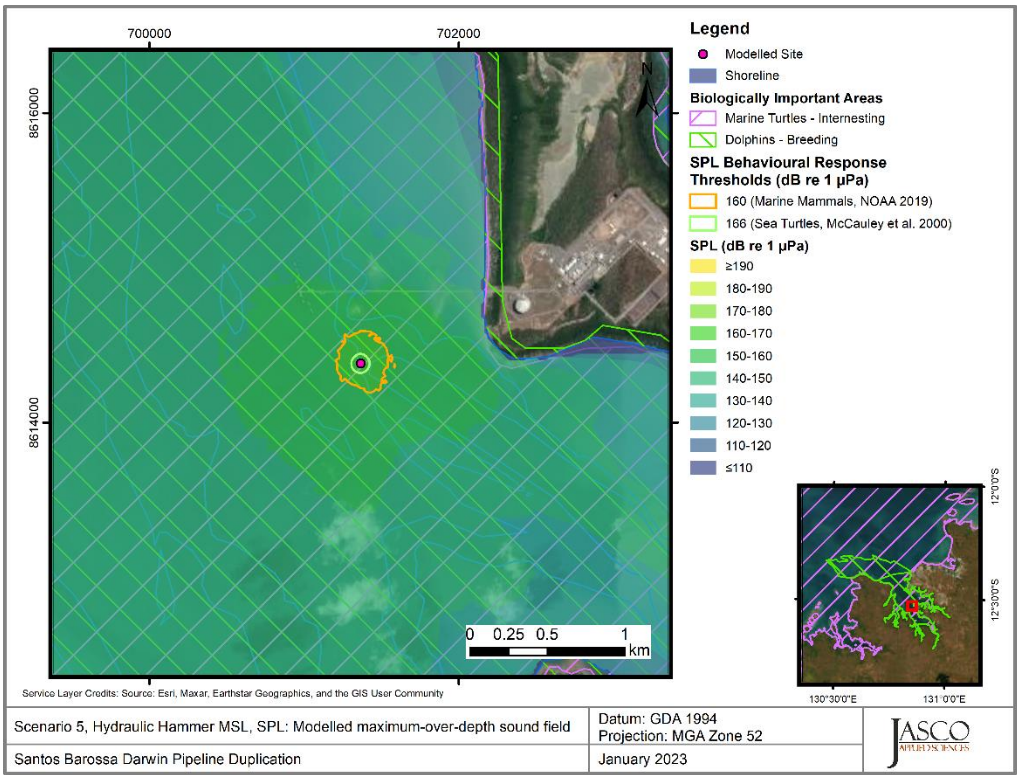

Figure 14. *Hydraulic Hammer, MSL, SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural thresholds for marine mammals and sea turtles.

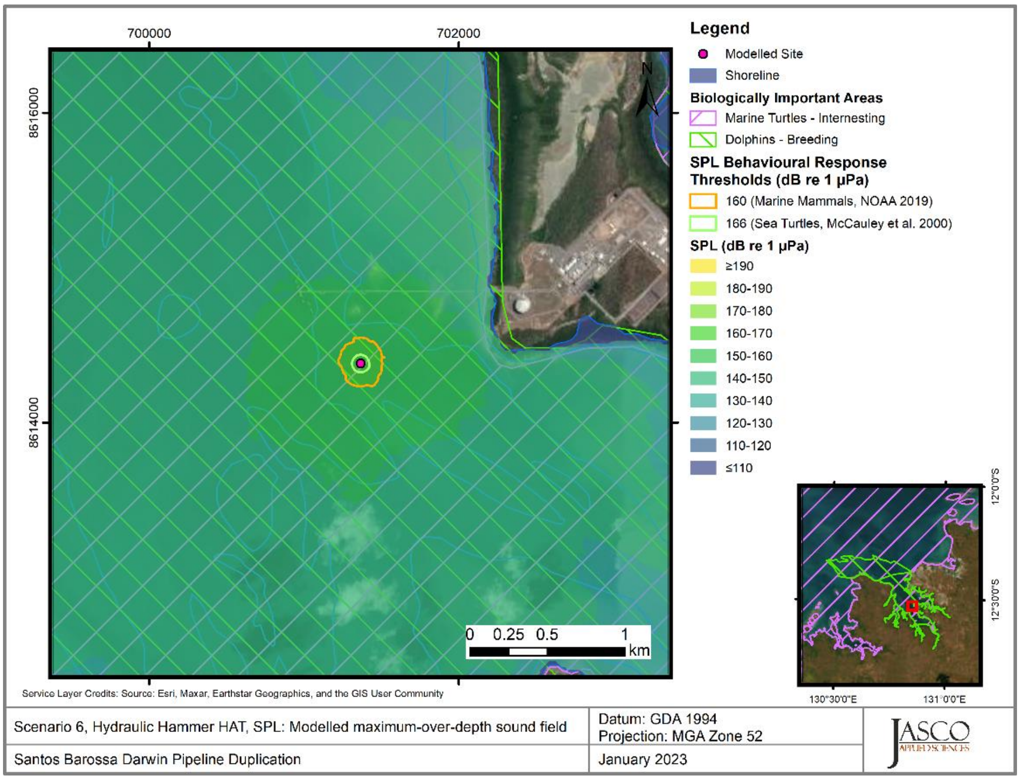

Figure 15. *Hydraulic Hammer, HAT, SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural thresholds for marine mammals and sea turtles.

4.2.2.2. SPL Vertical slice plots

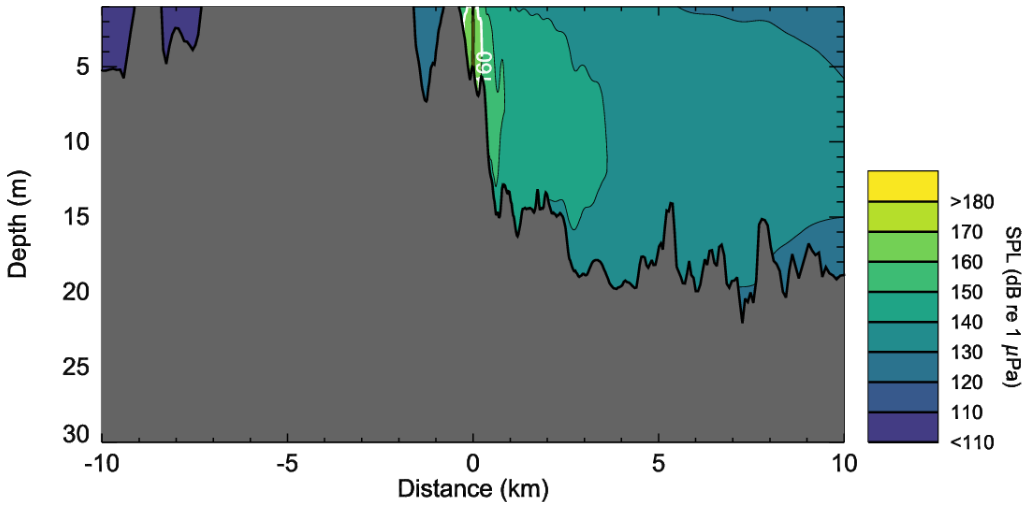

Figure 16. *Hydraulic Hammer, LAT, SPL*: Vertical slice plot showing variations with depth and distance from the source with the isopleth for behavioural threshold for marine mammals. The seabed is shown in dark grey. Cross sections are along the 142/322° transect.

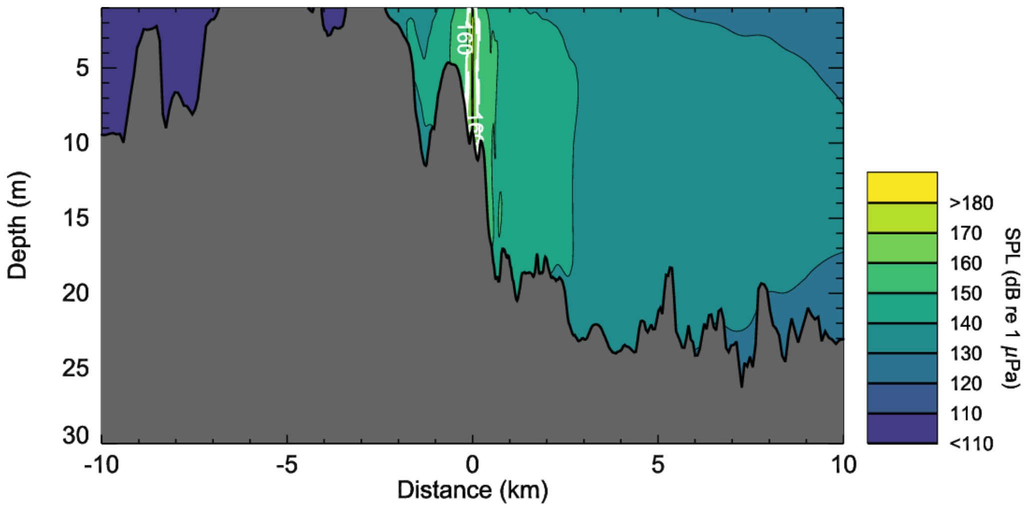

Figure 17. *Hydraulic Hammer, MSL, SPL*: Vertical slice plot showing variations with depth and distance from the source with the isopleth for behavioural threshold for marine mammals. The seabed is shown in dark grey. Cross sections are along the 142/322° transect.

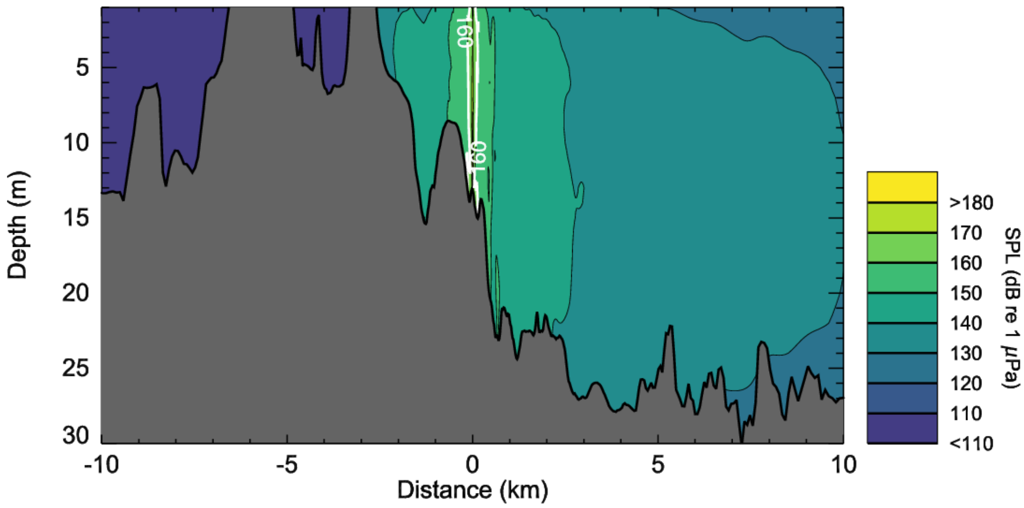

Figure 18. *Hydraulic Hammer, HAT, SPL*: Vertical slice plot showing variations with depth and distance from the source with the isopleth for behavioural threshold for marine mammals. The seabed is shown in dark grey. Cross sections are along the 142/322° transect.

4.2.2.3. Accumulated SEL_{24h} sound level contour maps

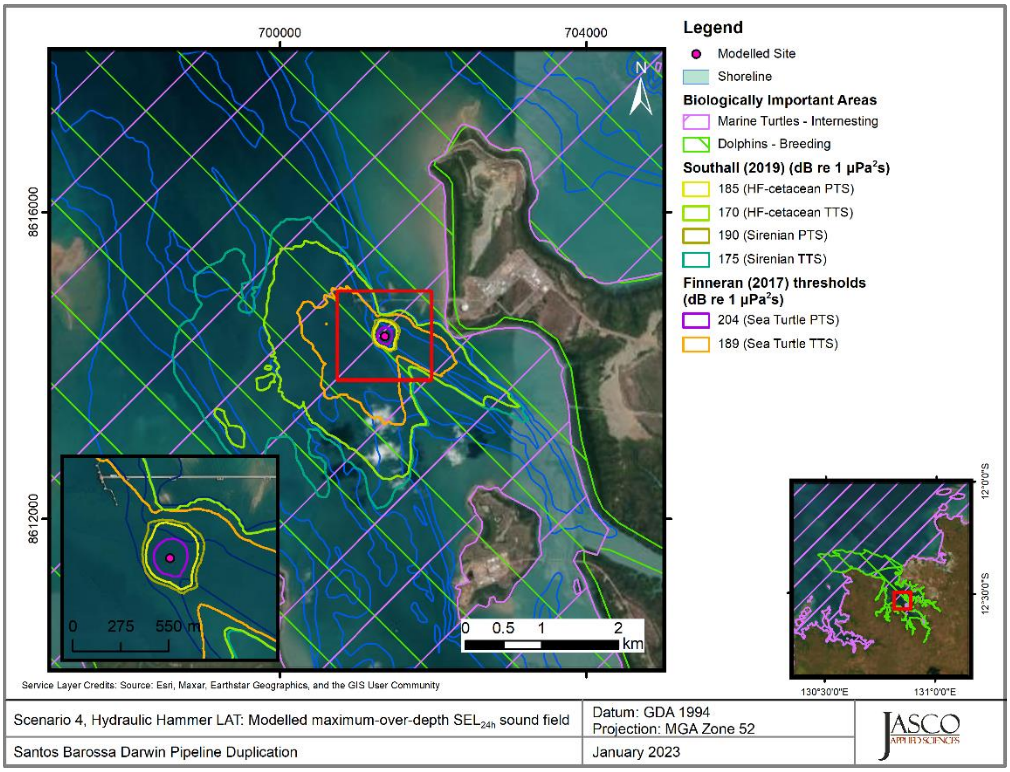

Figure 19. *Hydraulic Hammer, LAT:* isopleths for HF cetaceans, sirenians, and sea turtles. Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

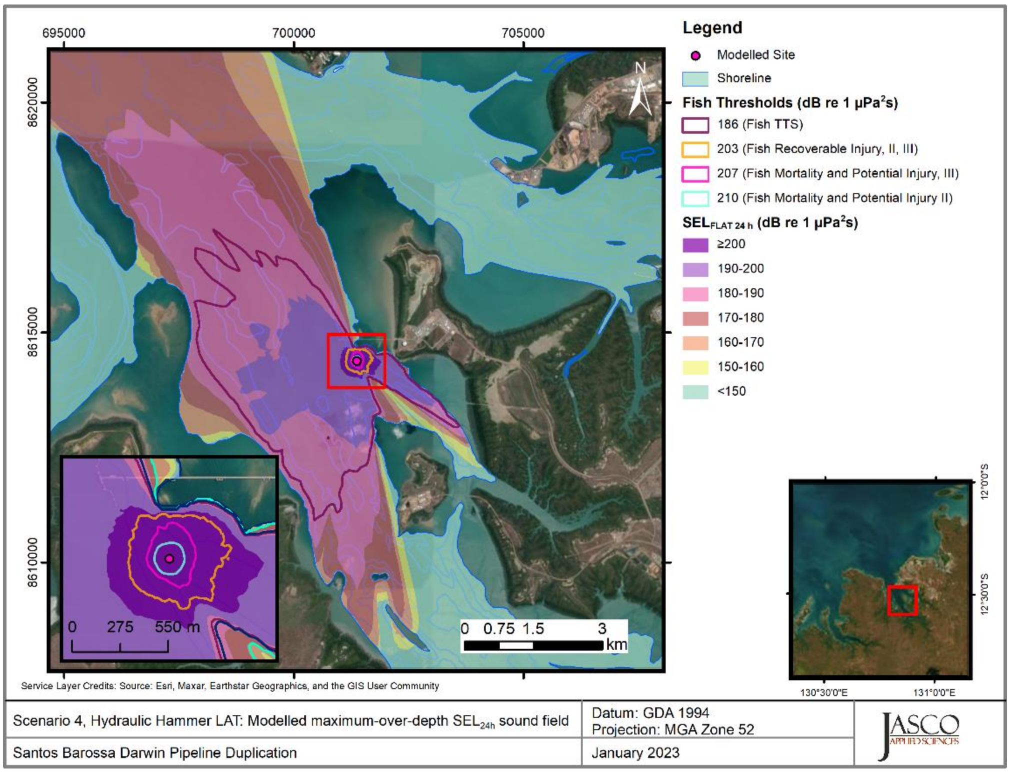

Figure 20. *Hydraulic Hammer, LAT:* sound level contour map of unweighted maximum-over-depth SEL_{24h} results, along with isopleths for fish. Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

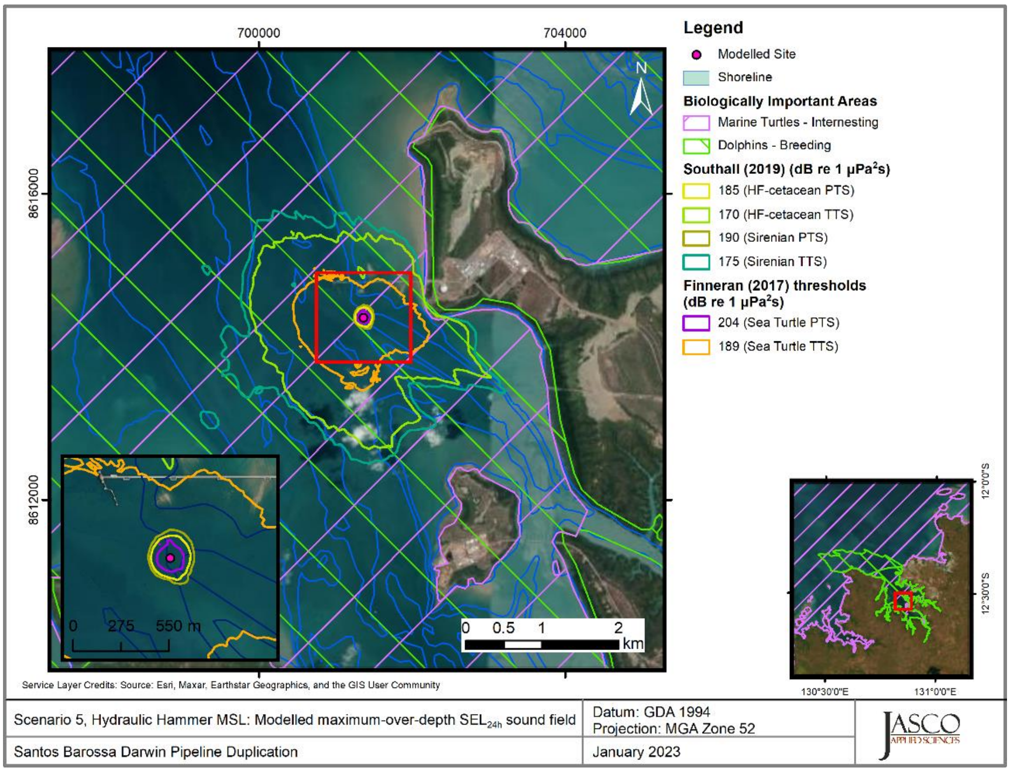

Figure 21. *Hydraulic Hammer, MSL:* isopleths for HF cetaceans, sirenians, and sea turtles. Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

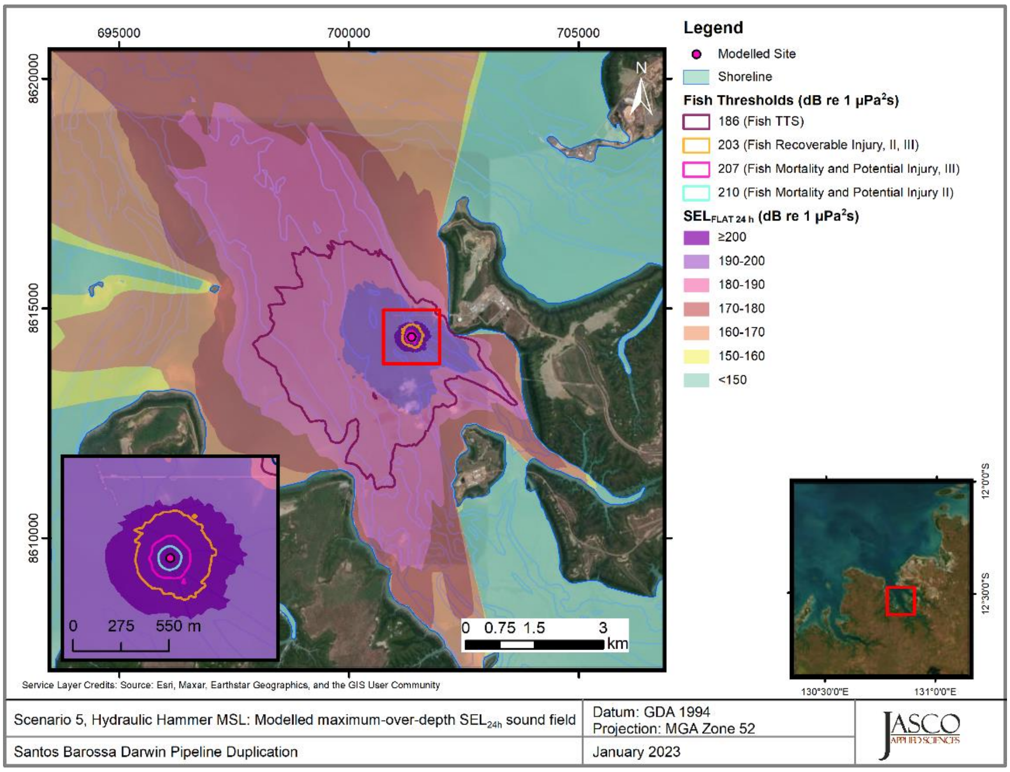

Figure 22. *Hydraulic Hammer, MSL:* sound level contour map of unweighted maximum-over-depth SEL_{24h} results, along with isopleths for fish. Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

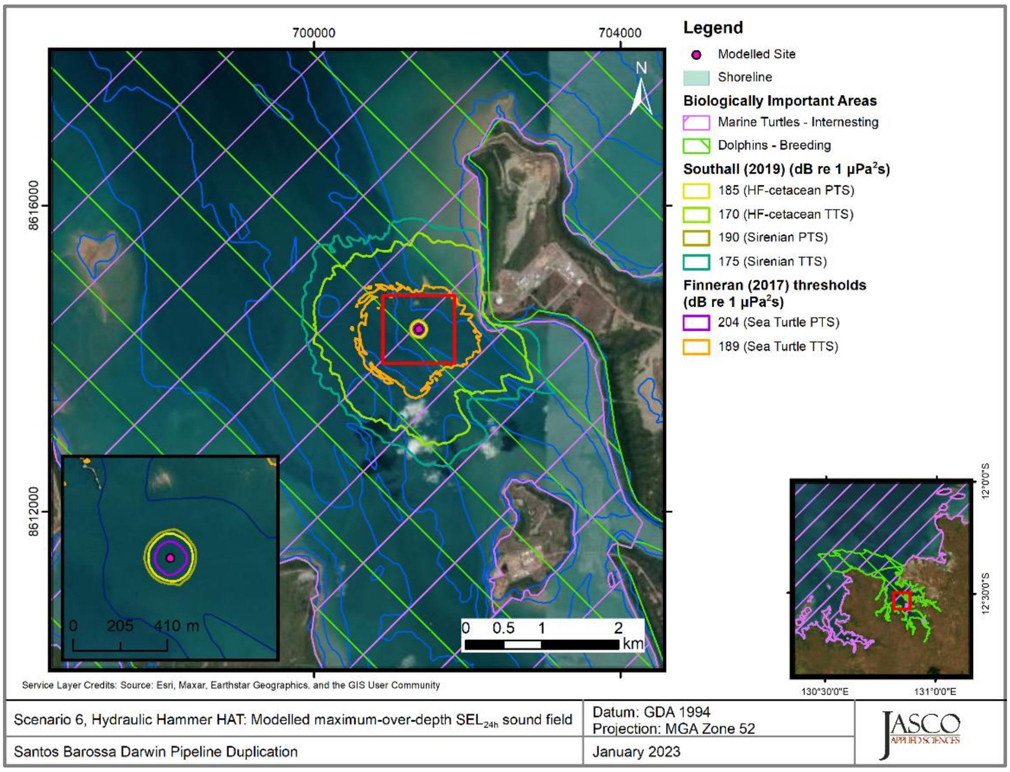

Figure 23. *Hydraulic Hammer, HAT:* isopleths for HF cetaceans, sirenians, and sea turtles. Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

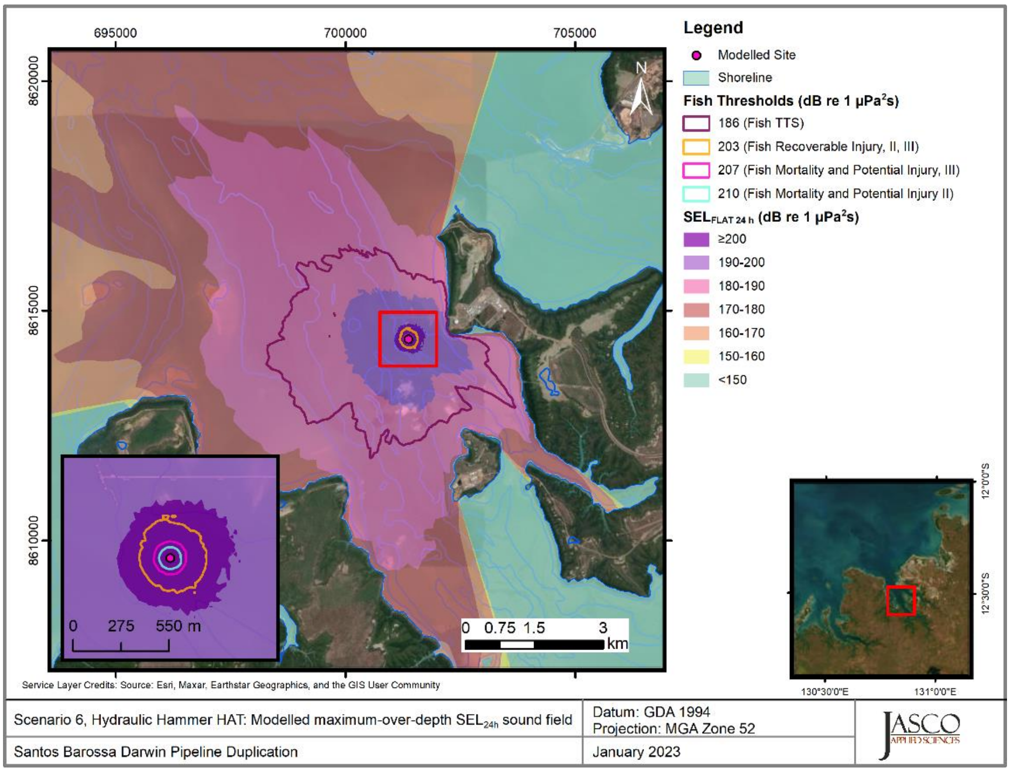

Figure 24. *Hydraulic Hammer, HAT:* sound level contour map of unweighted maximum-over-depth SEL_{24h} results, along with isopleths for fish. Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

5. Discussion and Conclusion

The modelling study predicted underwater sound levels associated with rock breaking activities for the Santos Darwin DPD. The underwater sound field was modelled for two types of rock breakers, the Xcentric Ripper and a hydraulic hammer. The source levels for each of these rock breakers were selected from measurement studies. However, a surrogate source (see Section 3.1.2) has been proposed to represent the potential spectral characteristics for the hydraulic hammer. No reliable information could be found on the underwater noise levels of this tool at the time of this study. The measurement of the hydraulic hammer source and subsequent use in re-modelling would increase accuracy of the estimates of distances to thresholds presented above.

An analysis of seasonal sound speed profiles indicates that April is the month most conducive to sound propagation; as such it was selected to ensure a conservative estimation of distances to received sound level thresholds (Appendix C.2.2). Modelling also accounted for site-specific bathymetric variations at three vertical height datums, LAT, MSL, and HAT (Appendix C.2.1) and local geoacoustic properties (Appendix C.2.3).The April sound speed profile was primarily slightly upward refracting between the sea surface and the sea floor due to the shallow water depth and the high surface temperature. The profile had a minimum sound speed at approximately 1532 m/s at the sea surface. The seafloor and sea surface create a waveguide which only allows energy of certain frequencies to be trapped.

Considering the activity location in shallow water within Darwin Harbour the bathymetry was used at three different vertical datums, LAT, MSL, and HAT, which results in a difference in water depth between LAT and HAT of ~8.1 m. These different datums also changed the water depth at the source location from 5.0 m to 8.2, and 13.1 m and these changes can influence the waveguide physics of propagating sound. For successive reflections between the sea surface and the seafloor energy is stripped from the water column mainly due to multiple interactions with the seabed. For shallow water environments, underwater sound propagation is generally better than free-field propagation at short and intermediate ranges but worse at longer ranges due to the increased number of interaction with the seabed at long range (see result for the hydraulic hammer tool, Section 4.2.1). However, this is not the case for the Xcentric Ripper (see Section 4.1.1). These can be understood by considering optimum propagation. Shallow water environment tend to have a high optimum propagation frequency than a deeper counter parts (Jensen et al. 2011), and if the source spectra overlaps with the optimum propagation frequencies then shallower water depths may lead to slightly higher levels at distance. The radii associated with sound level contours for LAT datum were marginally longer and persisted to longer ranges compared to the HAT scenario.

The vertical slice plots assist in demonstrating the propagation characteristics of the different water depths (Sections 4.1.2.2 and 4.2.2.2).

Glossary

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

1/3-octave

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

1/3-octave-band

Frequency band whose bandwidth is one 1/3-octave. *Note*: The bandwidth of a 1/3-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. Used to compute the 90 % sound pressure level. Unit: second (s). Symbol: T_{90}.

90 % sound pressure level (90 % SPL)

The sound pressure level calculated over the 90 % energy time window of a pulse. Unit: decibel (dB).

absorption

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

acoustic impedance

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

acoustic noise

Sound that interferes with an acoustic process.

ambient sound

Sound that would be present in the absence of a specified activity (ISO 18405:2017). It is usually a composite of sound from many sources near and far, e.g., shipping vessels, seismic activity, precipitation, sea ice movement, wave action, and biological activity.

attenuation

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

auditory frequency weighting

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

auditory frequency-weighting function

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

azimuth

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

bandwidth

A range within a continuous band of frequencies. Unit: hertz (Hz).

broadband level

The total level measured over a specified frequency range. If the frequency range is unspecified, the term refers to the entire measured frequency range.

cetacean

Member of the order Cetacea. Cetaceans are aquatic mammals and include whales, dolphins, and porpoises.

compressional wave

A mechanical vibration wave in which the direction of particle motion is parallel to the direction of propagation. Also called a longitudinal wave. In seismology/geophysics, it's called a primary wave or P-wave. Shear waves in the seabed can be converted to compressional waves in water at the water-seabed interface.

continuous sound

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

decade

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

decibel (dB)

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

decidecade

One tenth of a decade. Approximately equal to one third of an octave (1 ddec ≈ 0.3322 oct), and for this reason sometimes referred to as a 1/3-octave.

decidecade band

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

delphinid

Member of the family of oceanic dolphins (Delphinidae), composed of approximately 35 extant species, including dolphins, porpoises, and killer whales.

energy source level

A property of a sound source equal to the sound exposure level measured in the far field plus the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 μPa^2 m^2 s.

energy spectral density

Ratio of energy (time-integrated square of a specified field variable) to bandwidth in a specified frequency band from f_1 to f_2. In equation form, the energy spectral density E_f is given by: $E_f = 2\int_{f_1}^{f_2} |X(f)|^2 \, \mathrm{d}f / (f_2 - f_1)$ where $X(f)$ is the Fourier transform of the field variable $x(t)$:

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

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

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

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

energy spectral density level

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

energy spectral density source level

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

ensonified

Exposed to sound.

equal-loudness-level contour

Curve that shows, as a function of frequency, the sound pressure level required to produce a given loudness for a listener having normal hearing, listening to a specified kind of sound in a specified manner (ANSI S1.1-2013).

far field

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

Fourier transform, Fourier synthesis

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

frequency

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

frequency weighting

The process of applying a frequency-weighting function.

frequency-weighting function

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

- *Auditory frequency-weighting function*: compensatory frequency-weighting function accounting for a species' (or functional hearing group's) frequency-specific hearing sensitivity.

functional hearing group

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

geoacoustic

Relating to the acoustic properties of the seabed.

harmonic

A sinusoidal sound component that has a frequency that is an integer multiple of the frequency of a sound to which it is related. For a sound with a fundamental frequency of f, the harmonics have frequencies of $2f$, $3f$, $4f$, etc.

hearing threshold

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

hertz (Hz)

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

high-frequency (HF) cetaceans

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

impulsive sound

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

isopleth

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

knot (kn)

Unit of vessel speed equal to 1 nautical mile per hour.

level

A measure of a quantity expressed as the logarithm of the ratio of the quantity to a specified reference value of that quantity. For example, a value of sound pressure level with reference to 1 μPa^2 can be written in the form *x* dB re 1 μPa^2.

low-frequency (LF) cetaceans

See functional hearing group.

median

The 50th percentile of a statistical distribution.

mid-frequency (MF) cetaceans

See functional hearing group. *Note*: The mid-frequency cetaceans group proposed by Southall et al. (2007) was renamed high-frequency cetaceans by Southall et al. (2019).

monopole source level (MSL)

A source level that has been calculated using an acoustic model that accounts for the effect of the sea-surface and seabed on sound propagation, assuming a point source (monopole). Often used to quantify source levels of vessels or industrial operations from measurements. See also radiated noise level.

M-weighting

A set of auditory frequency-weighting functions proposed by Southall et al. (2007).

mysticete

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

non-impulsive sound

Sound that is not an impulsive sound. Not necessarily a continuous sound.

octave

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

odontocete

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

parabolic equation method

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

permanent threshold shift (PTS)

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

point source

A source that radiates sound as if from a single point.

power spectral density

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

power spectral density level

The level ($L_{P,f}$) of the power spectral density (P_f) in a stated frequency band and time window. Defined as: $L_{P,f} = 10\log_{10}(P_f/P_{f,0})$. Unit: decibel (dB).

As with power spectral density, power spectral density level can be expressed in terms of various field variables (e.g., sound pressure, sound particle displacement). The reference value ($P_{f,0}$) for power spectral density level depends on the nature of the field variable.

power spectral density source level

A property of a sound source equal to the power spectral density level of the sound pressure measured in the far field plus the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 μPa^2 m^2/Hz.

propagation loss (PL)

Difference between a source level (SL) and the level at a specified location, $\mathrm{PL}(x) = \mathrm{SL} - L(x)$. Unit: decibel (dB). See also transmission loss.

radiated noise level (RNL)

A source level that has been calculated assuming sound pressure decays geometrically with distance from the source, with no influence of the sea-surface or seabed. Often used to quantify source levels of vessels or industrial operations from measurements. See also monopole source level.

received level

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

reference value

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

Quantity	Reference value
Sound pressure	p_0^2 = 1 μPa^2 or p_0 = 1 μPa
Sound exposure	E_0 = 1 μPa^2 s
Sound particle displacement	δ_0^2 = 1 pm^2
Sound particle velocity	u_0^2 = 1 nm^2/s^2
Sound particle acceleration	a_0^2 = 1 μm^2/s^4

shear wave

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

sirenians (SI)

Members of the order Sirenia, which includes several manatee species and the dugong. See also functional hearing group.

sound

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

sound exposure

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

sound exposure level (SEL)

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

sound field

Region containing sound waves.

sound pressure

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

sound pressure level (SPL), rms sound pressure level

The level (L_p) of the time-mean-square sound pressure ($p^2_{\rm rms}$) in a stated frequency band and time window: $L_p = 10\log_{10}(p^2_{\rm rms}/p^2_0) = 20\log_{10}(p_{rms}/p_0)$, where rms is the abbreviation for root-mean-square. Unit: decibel (dB). Reference value (p^2_0) for sound in water: 1 μPa^2. SPL can also be expressed in terms of the root-mean-square (rms) with a reference value of p_0 = 1 μPa. The two definitions are equivalent.

sound speed profile

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

source level (SL)

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

spectrum

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

surface duct

The upper portion of a water column within which the gradient of the sound speed profile causes sound to refract upward and therefore reflect repeatedly off the surface resulting in relatively long-range sound propagation with little loss.

temporary threshold shift (TTS)

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

transmission loss (TL)

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

unweighted

Term indicating that no frequency-weighting function is applied.

very high-frequency (VHF) cetaceans

See functional hearing group.

wavelength

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

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Appendix A. Acoustic Metrics

This section describes in detail the acoustic metrics, impact criteria, and frequency weighting relevant to the modelling study.

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 pulsed sound such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate sound and its effects on marine life. Here we provide specific definitions of relevant metrics used in the accompanying report. Where possible, we follow International Organization for Standardization definitions and symbols for sound metrics (e.g., ISO 2017, ANSI S1.1-2013).

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

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

where $g(t)$ is an optional time weighting function. In many cases, the start time of the integration is marched forward in small time steps to produce a time-varying SPL function.

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

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

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

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

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

If applied, the frequency weighting of an acoustic event should be specified, as in the case of weighted SEL (e.g., $L_{E,LFC,24h}$; Appendix A.5). The use of fast, slow, or impulse exponential-time-averaging or other time-related characteristics should also be specified.

A.2. Decidecade Band Analysis

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

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

$$f_c(i) = 10^{\frac{i}{10}}\ \text{kHz} \qquad \text{(A-4)}$$

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

$$f_{lo,i} = 10^{\frac{-1}{20}} f_c(i) \quad \text{and} \quad f_{hi,i} = 10^{\frac{1}{20}} f_c(i) \qquad \text{(A-5)}$$

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure A-1). The acoustic modelling spans from band 10 ($f_c(10)$ = 10 Hz) to band 44 ($f_c(44)$ = 25 kHz).

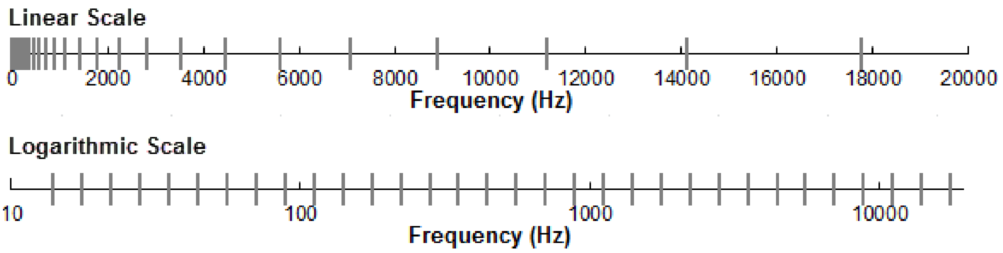

Figure A-1. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale.

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

$$L_{p,i} = 10\, log_{10} \int_{f_{lo,i}}^{f_{hi,i}} S(f)\, df\ \ \text{dB} \qquad \text{(A-6)}$$

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

$$\text{Broadband SPL} = 10 \log_{10} \sum_i 10^{\frac{L_{p,i}}{10}}\ \text{dB} \qquad \text{(A-7)}$$

Figure A-2 shows an example of how the decidecade band sound pressure levels compare to the sound pressure spectral density levels of an ambient sound signal. Because the decidecade bands are wider than 1 Hz, the decidecade band SPL is higher than the spectral levels at higher frequencies. Acoustic modelling of decidecade bands requires less computation time than 1 Hz bands and still resolves the frequency-dependence of the sound source and the propagation environment.

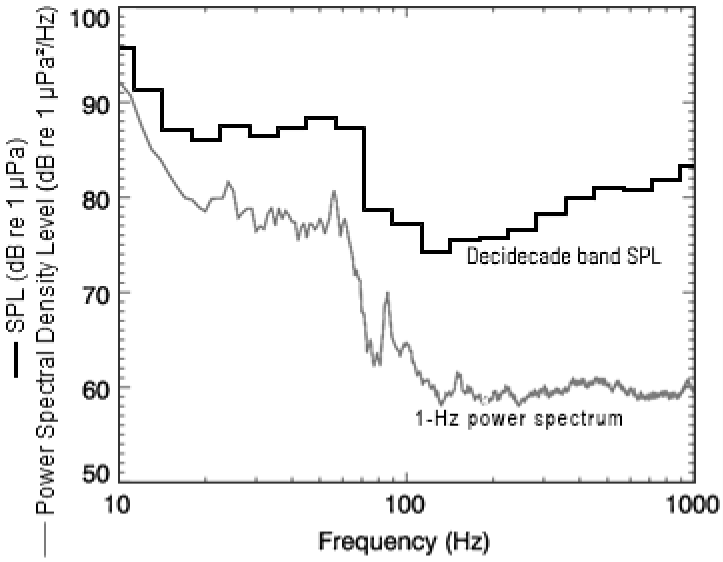

Figure A-2. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient noise shown on a logarithmic frequency scale.Because the decidecade bands are wider with increasing frequency, the decidecade band SPL is higher than the power spectrum.

A.3. Marine Mammal Noise Effect Criteria – Non-impulsive

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

A.3.1. Injury and Hearing Sensitivity Changes

In recognition of shortcomings of the SPL-only based auditory injury criteria, in 2005 NMFS sponsored the Noise Criteria Group to review literature on marine mammal hearing to propose new noise exposure criteria. Some members of this expert group published a landmark paper (Southall et al. 2007) that suggested assessment methods similar to those applied for humans. The resulting recommendations introduced dual auditory injury criteria for impulsive sounds that included peak pressure level thresholds and SEL24h thresholds, where the subscripted 24h refers to the accumulation period for calculating SEL. The peak pressure level criterion is not frequency weighted whereas SEL24h 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 humans; see Appendix A.5). The SEL24h 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 PTS and TTS 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 µPa^2·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 the 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 µPa^2·s.

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

A.3.2. 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).

NMFS currently uses step function (all-or-none) threshold of 120 dB re 1 µPa SPL (unweighted) for non-impulsive sounds to assess and regulate noise-induced behavioural impacts on marine mammals (NOAA 2019). The 120 dB re 1 µPa threshold is associated with continuous sources and was derived based on studies examining behavioural responses to drilling and dredging (NOAA 2018), referring to Malme et al. (1983), Malme et al. (1984), and Malme et al. (1986), which were considered in Southall et al. (2007). Malme et al. (1986) found that playback of drillship noise did not produce clear evidence of disturbance or avoidance for levels below 110 dB re 1 µPa (SPL), possible avoidance occurred for exposure levels approaching 119 dB re 1 µPa. Malme et al. (1984) determined that measurable reactions usually consisted of rather subtle short-term changes in speed and/or heading of the whale(s) under observation. It has been shown that both received level and proximity of the sound source is a contributing factor in eliciting behavioural reactions in humpback whales (Dunlop et al. 2017, Dunlop et al. 2018).

A.4. Marine Mammal Impact Criteria – Impulsive

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.4.1. 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 0). 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 present, 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; with the criteria defined in NMFS (2018). The latest criteria are from Southall et al. (2019) which is applied in this report.

A.4.2. 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).

For impulsive noise, NMFS currently uses step function thresholds of 160 dB re 1 µPa SPL (unweighted) to assess and regulate noise-induced behavioural impacts for marine mammals (NOAA 2018, NOAA 2019). The threshold for impulsive sound is derived from the High-Energy Seismic Survey (HESS) panel (HESS 1999) report that, in turn, is based on the responses of migrating mysticete whales to airgun sounds (Malme et al. 1984). The HESS team recognised that behavioural responses to sound may occur at lower levels, but significant responses were only likely to occur above a SPL of 140 dB re 1 µPa. Southall et al. (2007) found varying responses for most marine mammals between a SPL of 140 and 180 dB re 1 µPa, consistent with the HESS (1999) report, but lack of convergence in the data prevented them from suggesting explicit step functions.

A.5. 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.5.1. Marine Mammal Frequency Weighting Functions

In 2015, a US 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:

$$G(f) = K + 10\log_{10}\left[\left(\frac{(f/f_{lo})^{2a}}{\left[1+(f/f_{lo})^2\right]^a\left[1+(f/f_{hi})^2\right]^b}\right)\right] \qquad \text{(A-8)}$$

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively), phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA's technical guidance that assesses acoustic impacts on marine mammals (NMFS 2018), and in the latest guidance by Southall (2019). The updates did not affect the content related to either the definitions of frequency-weighting functions or the threshold values, however, the terminology for mid- and high-frequency cetaceans was changed to high- and very high-frequency cetaceans. Table A-1 lists the frequency-weighting parameters for each hearing group relevant to this assessment, and Figure A-3 shows the resulting frequency-weighting curves.

Table A-1. Parameters for the auditory weighting functions used in this project as recommended by Southall et al. (2019).

Hearing group	a	b	flo (Hz)	fhi (kHz)	K (dB)
Low-frequency cetaceans *(baleen whales)*	1.0	2	200	19,000	0.13
High-frequency cetaceans *(most dolphins, plus sperm, beaked, and bottlenose whales)*	1.6	2	8,800	110,000	1.20
Sirenians *(Dugongs, manatees)*	1.8	2	12,000	140,000	1.36

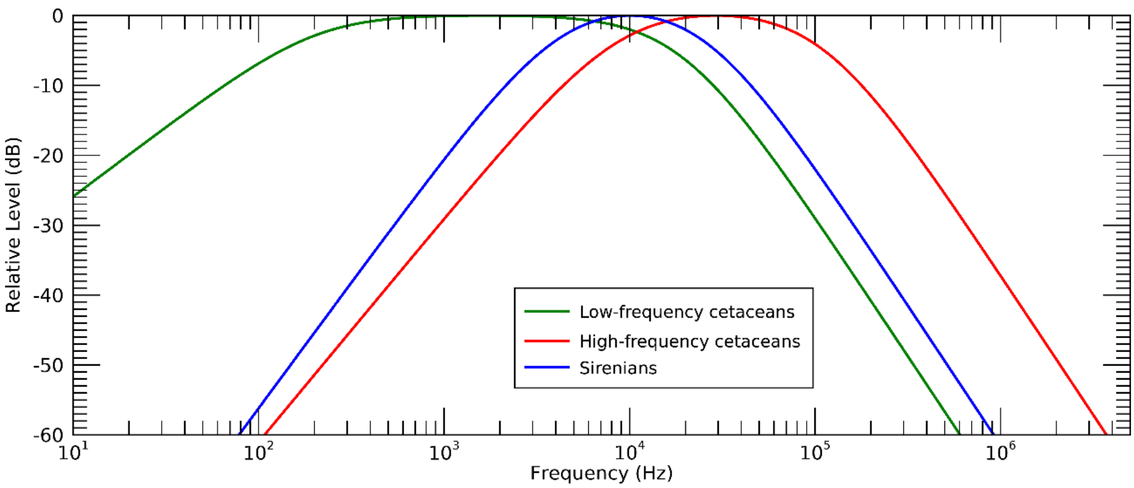

Figure A-3. Auditory weighting functions for functional marine mammal hearing groups used in this project as recommended by Southall et al. (2019).

Appendix B. Sound Propagation Models

B.1. MONM-BELLHOP

Long-range sound fields were computed using JASCO's Marine Operations Noise Model (MONM). MONM is well suited for effective long-range estimation. This model computes sound propagation at frequencies of 5 Hz to 1 kHz via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the US Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed (Zhang and Tindle 1995). MONM computes sound propagation at frequencies >1 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).

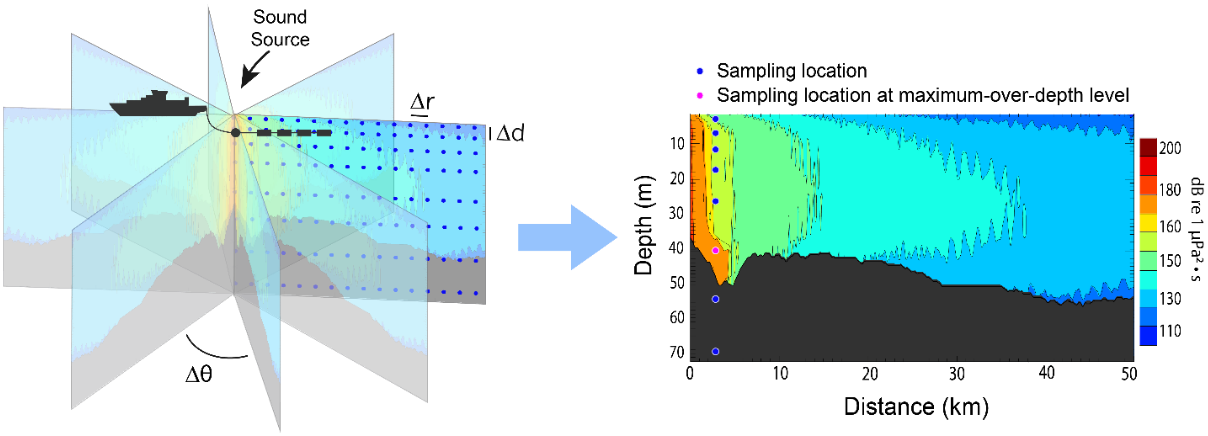

Figure B-1. The N×2-D and maximum-over-depth modelling approach used by MONM.

MONM treats frequency dependence by computing acoustic transmission loss at the centre frequencies of decidecade bands. Sufficiently many decidecade 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 decidecade band received per-1s, for impulsive and non-impulsive noise sources respectively, SEL are computed by subtracting the band transmission loss values from the directional source level in that frequency band. Composite broadband received per-1s SEL are then computed by summing the received decidecade band levels.

The received per-1s 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. The maximum received per-1s SEL at many sampling depths are taken over all samples within the water column, i.e., the maximum-over-depth received per-pulse SEL. These maximum-over-depth per-1s SEL are presented as contours around the source.

Appendix C. Methods and Parameters

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.

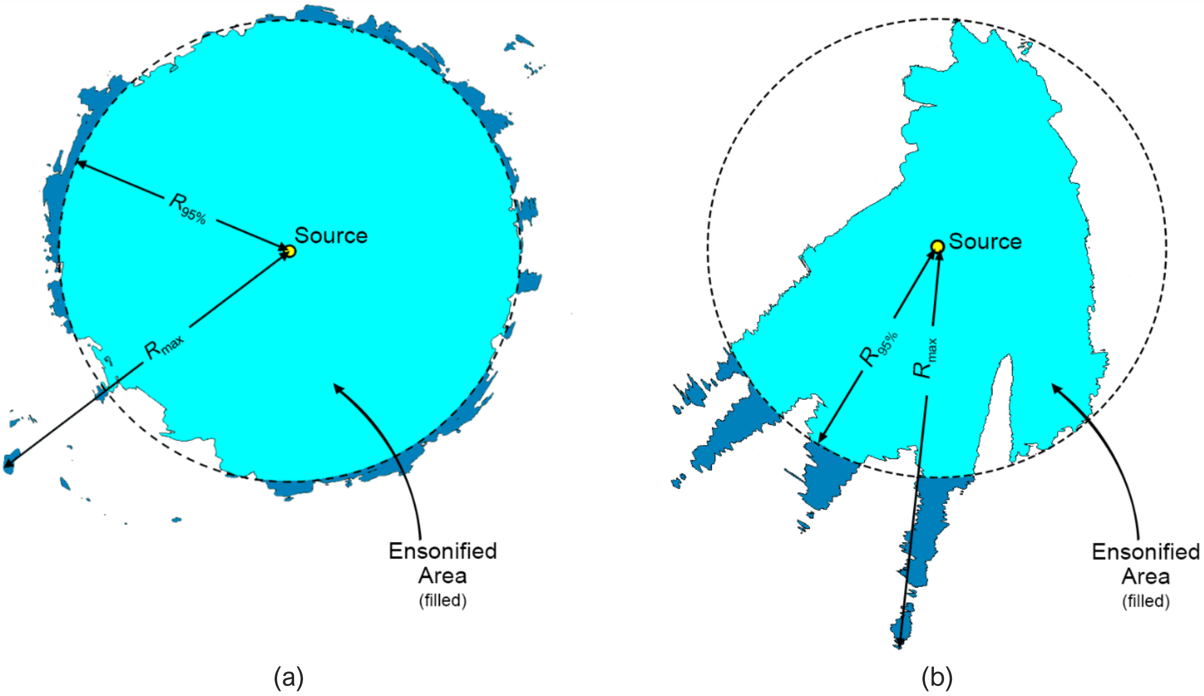

Figure C-1. Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ ranges shown for two scenarios. (a) Largely symmetric sound level contour with small protrusions. (b) Strongly asymmetric sound level contour with long protrusions. Light blue indicates the ensonified areas bounded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

C.2. Environmental Parameters

C.2.1. Bathymetry

Bathymetry throughout the modelled area was extracted from two sources, Darwin Inner Harbour with 1 m resolution (Geoscience Australia 2017) and where required this was supplemented with the high-resolution depth model for Northern Australia, a ~30 m grid rendered for Northern Australia (Beaman 2018) for the region shown in Figure 1. Bathymetry data were re-gridded and combined onto a Map Grid of Australia (MGA) coordinate projection (Zone 52) with a regular grid spacing of 40 × 40 m (Figure C-2). Bathymetry data is used at three different vertical height datums at lowest astronomical tide, mean sea level, and highest astronomical tide. For a reference level for LAT at 0.0 m, MSL is 3.2, and HAT at 8.1 m from Australian hydrographic charts AUS25 and AUS26.

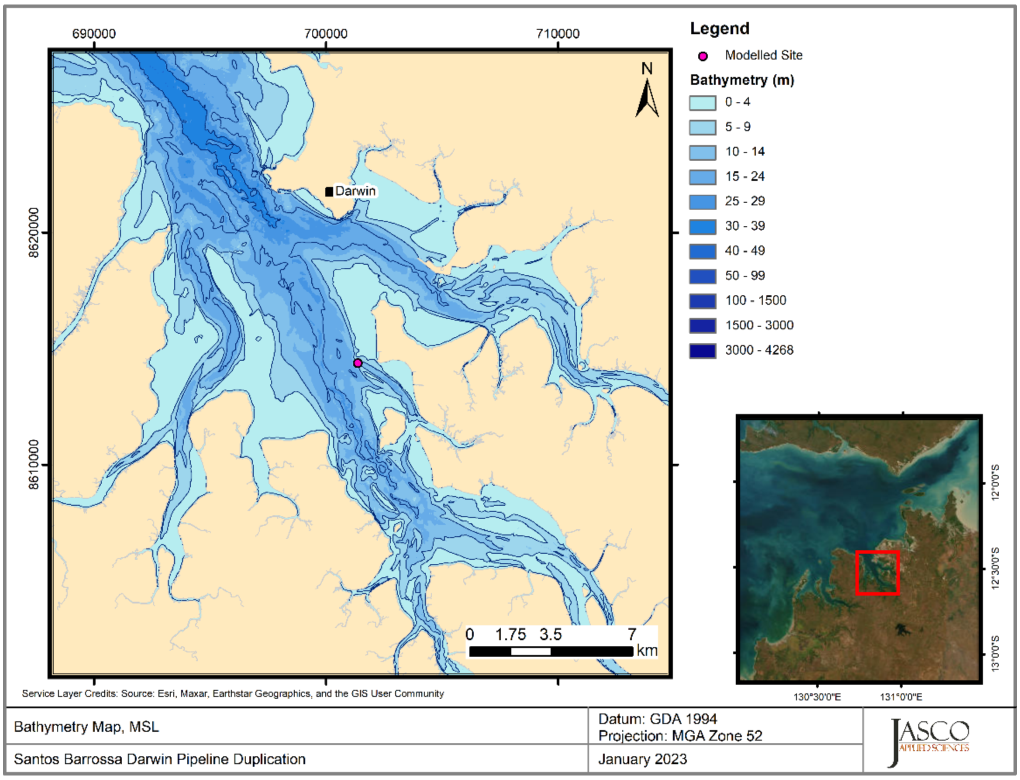

Figure C-2. Bathymetry in the modelled area.

C.2.2. Sound Speed Profile

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

Mean monthly sound speed profiles were derived from the GDEM profiles within a 40 km box radius encompassing each of the three areas. To determine the sound speed profile that is expected to be most favourable to longer-range sound propagation during the proposed survey time frame, each month was modelled for each area and the ranges were compared. As such, April was selected for sound propagation modelling to ensure precautionary estimates of distances to received sound level thresholds. Figure C-3 shows the resulting profile used as input to the sound propagation modelling.

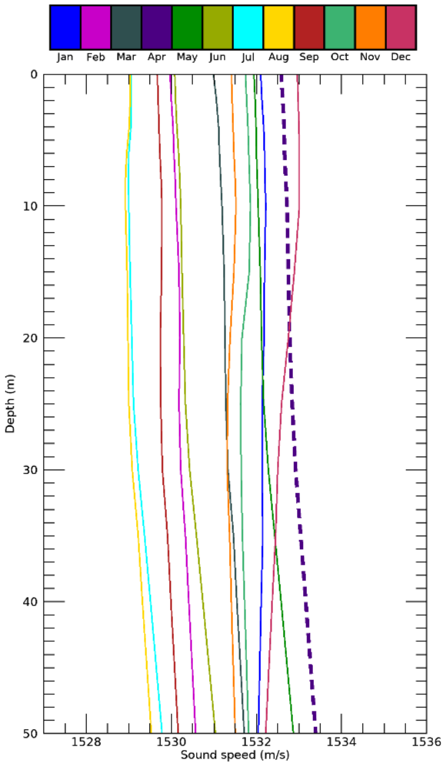

Figure C-3. The modelling sound speed profile corresponding to April is shown as the dotted line The profile is calculated from temperature and salinity profiles from Generalized Digital Environmental Model V 3.0 (GDEM; Teague et al. 1990, Carnes 2009).

C.2.3. Geoacoustics

The geoacoustic profile in this area was constructed using client-supplied geotechnical reports. Multiple bore holes near the modelled site were considered such that the geologic profile that was most representative of the seabed within Darwin Harbour was chosen. The geology was modelled as thin layer of sand, over a layer of silt, underlain with increasingly consolidated sandstone. Representative grain sizes and porosity were used in the grain-shearing model proposed by Buckingham (2005) to estimate the geoacoustic parameters required by the sound propagation models.

Table C-1. Geoacoustic profile for Darwin Harbour.

Depth below seafloor (m)	Material	Density (g/cm³)	P-wave speed (m/s)	P-wave attenuation (dB/λ)	S-wave speed (m/s)	S-wave attenuation (dB/λ)
0–1.5	Fine to coarse Sand with clay and gravel	2.09	1695–1910	0.18–0.92	283	3.65
1.5–5	Silt	2.01	1702–1754	0.40–0.59		
5–100	Sandstone	2.09	2039–2926	1.26–2.49		

Appendix D. Model Validation Information

Predictions from JASCO’s 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 that 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, Austin et al. 2018, Beach Energy Limited 2020).

Appendix E. Additional Maps

E.1. Accumulated SEL$_{24h}$ sound level contour maps

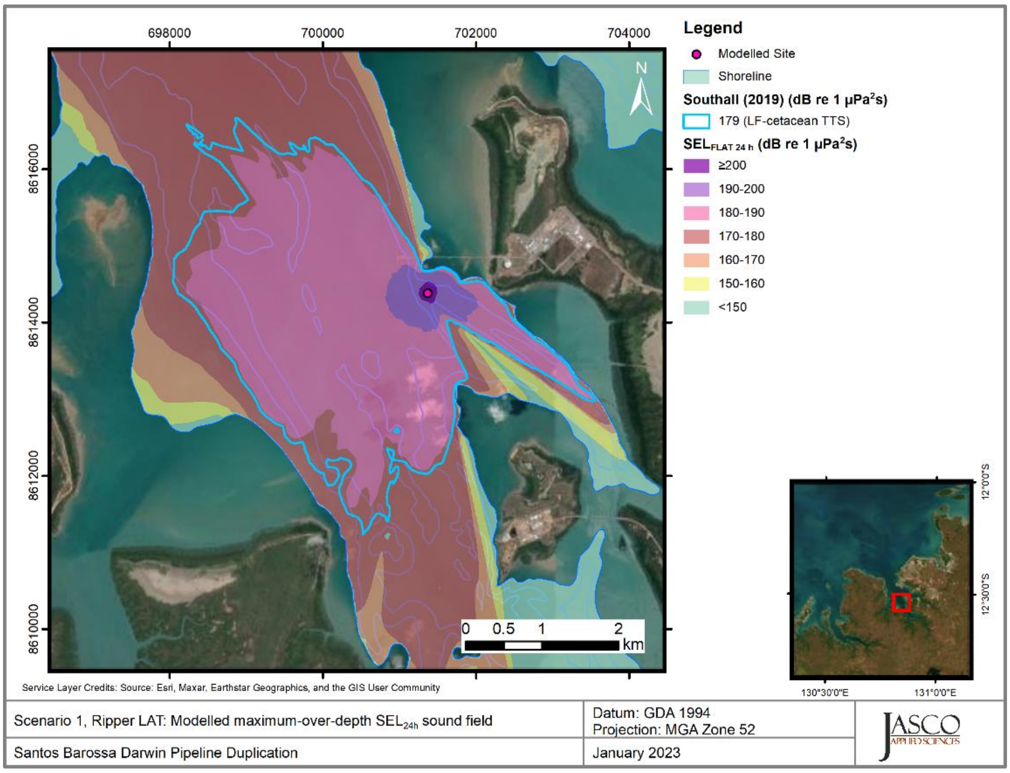

Figure E-1. *Xcentric Ripper, LAT:* sound level contour map of unweighted maximum-over-depth SEL$_{24h}$ results, along with isopleths for LF cetaceans. Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

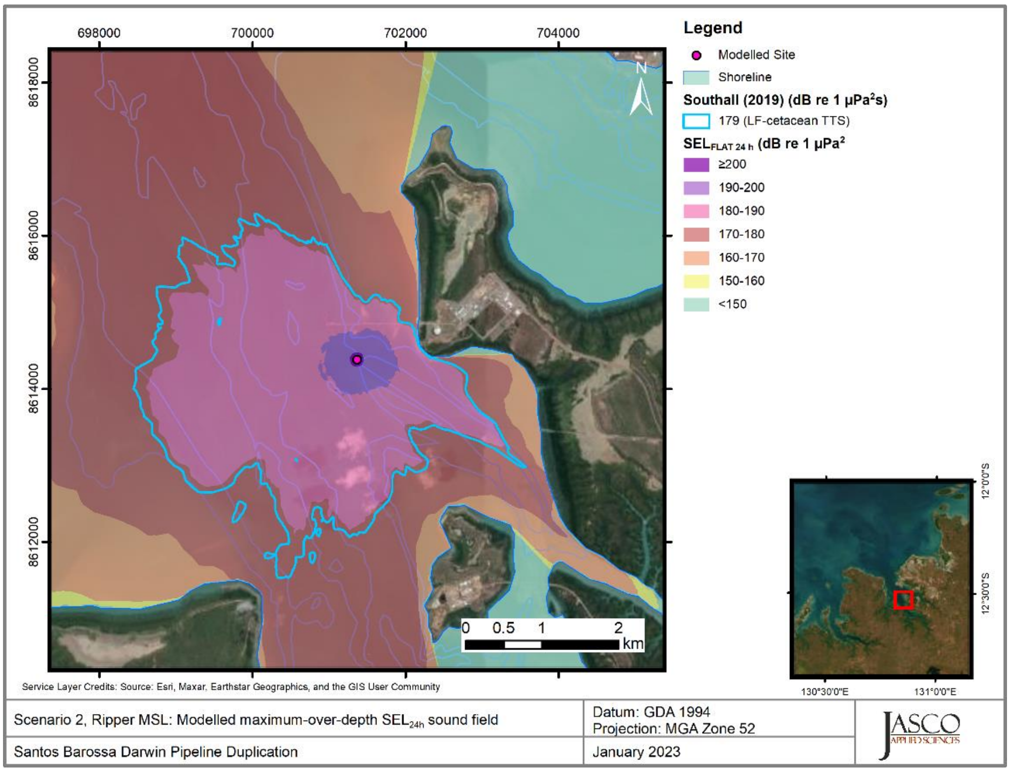

Figure E-2. *Xcentric Ripper, MSL:* sound level contour map of unweighted maximum-over-depth SEL_{24h} results, along with isopleths for LF cetaceans. Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

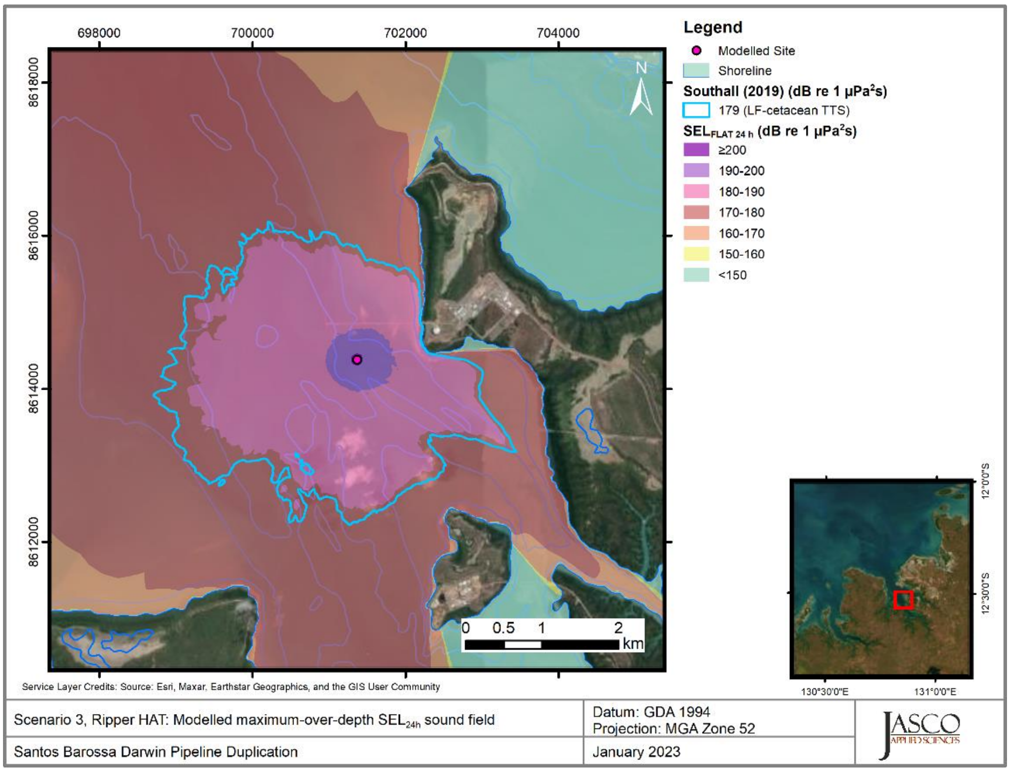

Figure E-3. *Xcentric Ripper, HAT:* sound level contour map of unweighted maximum-over-depth SEL_{24h} results, along with isopleths for LF cetaceans. Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

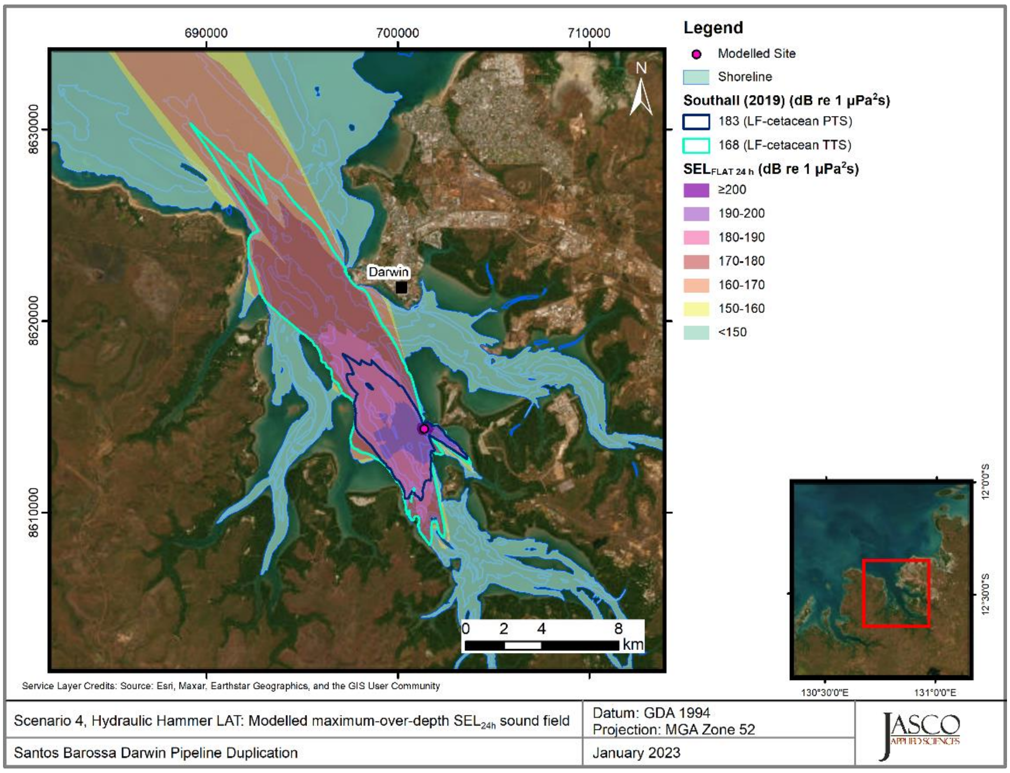

Figure E-4. *Hydraulic Hammer, LAT:* sound level contour map of unweighted maximum-over-depth SEL_{24h} results, along with isopleths for LF cetaceans. Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

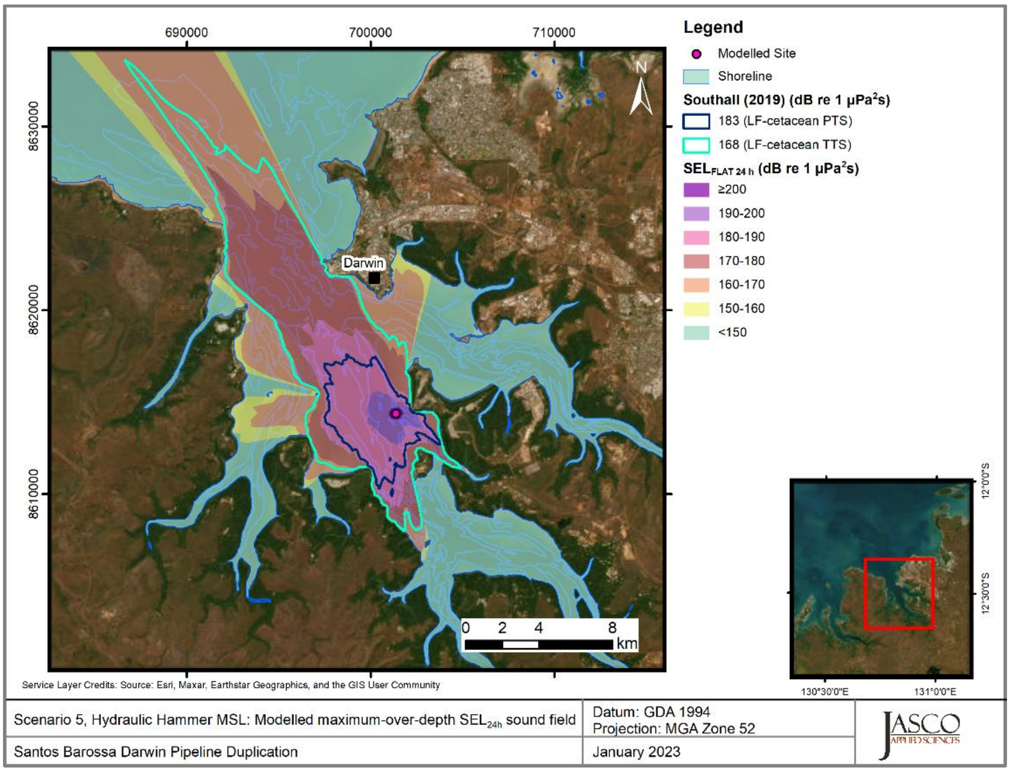

Figure E-5. *Hydraulic Hammer, MSL:* sound level contour map of unweighted maximum-over-depth SEL_{24h} results, along with isopleths for LF cetaceans. Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

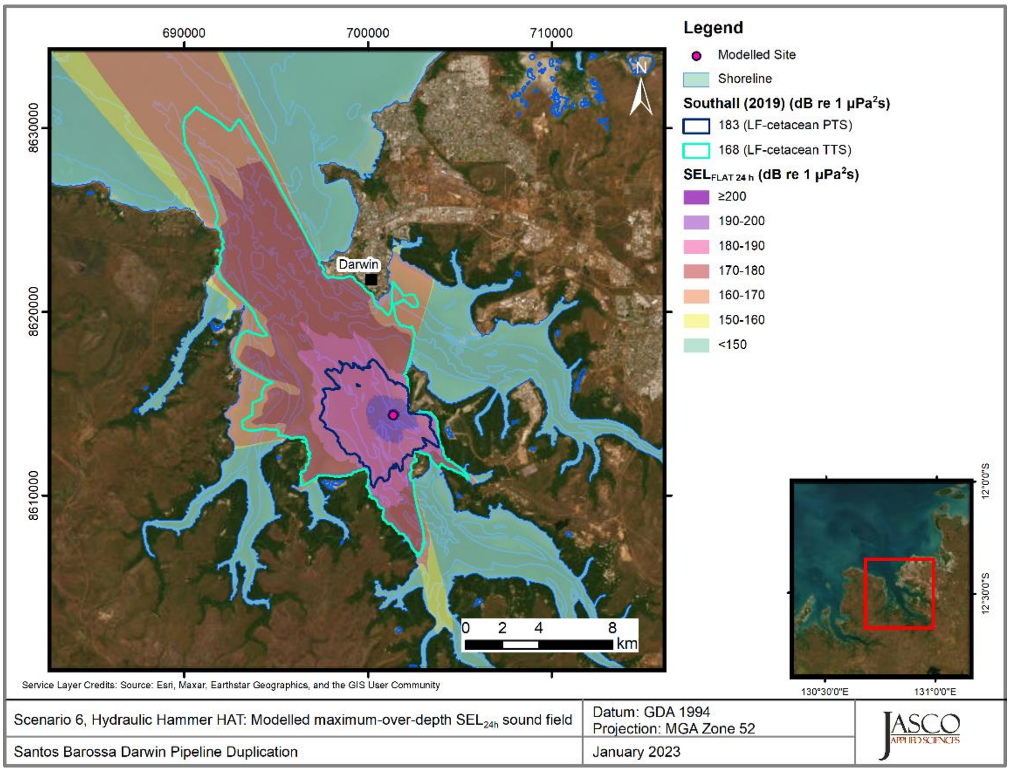

Figure E-6. *Hydraulic Hammer, HAT:* sound level contour map of unweighted maximum-over-depth SEL_{24h} results, along with isopleths for LF cetaceans. Thresholds omitted here were not reached or not large enough to display graphically. Refer to Table 14 for threshold distances.

Appendix F. Hydraulic hammer operational time per day

This section outlines the effect that the operation duration of the hydraulic hammer has on the range to threshold for accumulated SEL. Table F-1 to Table F-5 outline the range to PTS and TTS for the considered hearing groups over operation times of 2, 4, 6, and 8 h.

Table F-1. *Hydraulic Hammer*: Summary of maximum (R_{max}) horizontal distances (in km) to frequency-weighted SEL_{24h} TTS for HF cetaceans, Sirenians, and Sea Turtles based on Southall et al. (2019) and Finneran et al. (2017) for different operation durations.

Operation Duration (h)	HF Cetacean TTS			Sirenians TTS			Sea Turtle TTS		
	LAT	MSL	HAT	LAT	MSL	HAT	LAT	MSL	HAT
	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
2	0.89	0.67	0.57	1.14	0.84	0.67	0.48	0.38	0.34
4	1.39	1.20	0.98	1.65	1.41	1.20	0.70	0.58	0.53
6	1.70	1.51	1.33	2.37	1.79	1.58	1.04	0.74	0.69
8	2.44	1.83	1.63	2.78	2.50	1.94	1.18	0.95	0.90

Table F-2. *Hydraulic Hammer 2 h:* Maximum (R_{max}) horizontal distances (in km) to frequency-weighted SEL_{24h} PTS and TTS thresholds based on Southall et al. (2019) and Finneran et al. (2017) from the most appropriate location for considered sources per scenario, and ensonified area (km^2). A dash indicates the level was not reached within the limits of the modelled resolution (20 m). A slash indicates that the area is less than an area associated with the modelled resolution (0.0013 km^2).

Hearing group	Frequency-weighted SEL_{24h} threshold ($L_{E,24h}$; dB re 1 µPa²·s)	LAT		MSL		HAT	
		R_{max} (km)	Area (km^2)	R_{max} (km)	Area (km^2)	R_{max} (km)	Area (km^2)
PTS							
LF cetaceans	183	2.75	7.51	1.88	5.62	1.7	5.49
HF cetaceans	185	0.05	0.01	0.03	\	0.03	\
Sirenians	190	0.06	0.01	0.05	0.01	0.03	\
Sea Turtles	204	0.03	\	0.03	\	–	–
TTS							
LF cetaceans	168	11.8	39.9	11.47	58.0	12.5	71.5
HF cetaceans	170	0.89	0.94	0.67	0.90	0.57	0.75
Sirenians	175	1.14	1.45	0.84	1.21	0.67	0.99
Sea Turtles	189	0.48	0.4	0.38	0.33	0.34	0.28

Table F-3. *Hydraulic Hammer 4 h:* Maximum (R_{max}) horizontal distances (in km) to frequency-weighted SEL_{24h} PTS and TTS thresholds based on Southall et al. (2019) and Finneran et al. (2017) from the most appropriate location for considered sources per scenario, and ensonified area (km^2).

Hearing group	Frequency-weighted SEL_{24h} threshold ($L_{E,24h}$; dB re 1 µPa²·s)	LAT		MSL		HAT	
		R_{max} (km)	Area (km^2)	R_{max} (km)	Area (km^2)	R_{max} (km)	Area (km^2)
PTS							
LF cetaceans	183	4.15	13.8	3.34	13.4	3.03	12.5
HF cetaceans	185	0.10	0.03	0.06	0.01	0.06	0.01
Sirenians	190	0.12	0.04	0.08	0.02	0.06	0.01
Sea Turtles	204	0.06	0.01	0.05	0.01	0.05	0.01
TTS							
LF cetaceans	168	15.5	54.5	15.5	78.4	14.8	96.9
HF cetaceans	170	1.39	2.57	1.20	2.42	0.98	2.07
Sirenians	175	1.65	3.35	1.41	3.32	1.20	2.87
Sea Turtles	189	0.70	0.78	0.58	0.68	0.53	0.64

Table F-4. *Hydraulic Hammer 6 h:* Maximum (R_{max}) horizontal distances (in km) to frequency-weighted SEL_{24h} PTS and TTS thresholds based on Southall et al. (2019) and Finneran et al. (2017) from the most appropriate location for considered sources per scenario, and ensonified area (km^2).

Hearing group	Frequency-weighted SEL_{24h} threshold ($L_{E,24h}$; dB re 1 µPa²·s)	LAT		MSL		HAT	
		R_{max} (km)	Area (km^2)	R_{max} (km)	Area (km^2)	R_{max} (km)	Area (km^2)
PTS							
LF cetaceans	183	4.86	16.9	4.25	18.8	3.80	18.9
HF cetaceans	185	0.15	0.05	0.09	0.03	0.07	0.02
Sirenians	190	0.18	0.07	0.11	0.04	0.09	0.03
Sea Turtles	204	0.09	0.02	0.06	0.01	0.06	0.01
TTS							
LF cetaceans	168	17.3	63.1	17.9	89.3	17.6	117.1
HF cetaceans	170	1.70	3.79	1.51	4.00	1.33	3.58
Sirenians	175	2.37	4.67	1.79	5.13	1.58	4.79
Sea Turtles	189	1.04	1.40	0.74	1.05	0.69	1.00