Broome Wharf Extension Project

Underwater Noise Modelling and Assessment

Prepared for O2 Marine

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2	Second issue, including clients' comments.	24/01/2024	IW		GB

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Introduction

This report summarises the outcomes of an underwater noise modelling study undertaken for the O2 Marine Broome Wharf Extension Project.

Aim

The aim of this study is to undertake underwater noise modelling of pilling noise emissions to determine the potential noise impacts on marine fauna within the proposed development area.

Scope

The report includes a summary of the methods and results of underwater noise modelling undertaken for the Broome Wharf Extension Project. The report focuses on impact piling as this is the most significant source of underwater noise identified for the Project. The report is limited to the assessment of impacts on dolphins, dugongs, whales, sawfish, turtles, sea snakes and salt-water crocodiles.

Applicable Documents

The following project document was used in support of the underwater noise study:

i. O2 Marine 2020 Kimberley Ports Authority: Port of Broome Marine Monitoring Program, Document Prepared for Kimberley Ports Authority: Ref T1800094
ii. Oceanica 2010, Broome Boating Facility at West Roebuck Bay ‑ Desktop Assessment of Environmental Issues. Prepared for Department of Transport by Oceanica Consulting Pty Ltd, Report No. 178_003/1, Perth, Western Australia, November 2010.
iii. Broome Boating Facility - Sediment Sampling and Analysis Plan Implementation Report WorleyParsons 2013; Report prepared for the Department of Transport, July 2013.
iv. BMT Oceanica (2017) Port of Broome Capital Dredging ‑ Sediment Analysis Plan Implementation Report. Prepared for BMT JFA Consultants Pty Ltd by BMT Oceanica Pty Ltd, Report No. 1382_00_003/1_Rev0, Perth, Western Australia, December 2017.

Academic references used for the underwater noise study are given in Appendix A and abbreviations and acronyms are given in Appendix B.

Project Background and Noise Sources

Overview

Kimberly Ports Authority (KPA) is proposing to undertake improvements and modifications (works) to the Broome Harbour Wharf Extension at the Port of Broome to maximise wharf space and facilities while assisting with safe and efficient operations. The Port is located near Entrance Point at the tip of the Broome Peninsula, north-west of Roebuck Bay and approximately 5 km south-west of the town of Broome (Figure 0-1).

The Port is the region's largest deep-water port and is managed by KPA. The wharf consists of a steel pile jetty extending out from Entrance Point into the deeper waters of the Bay.

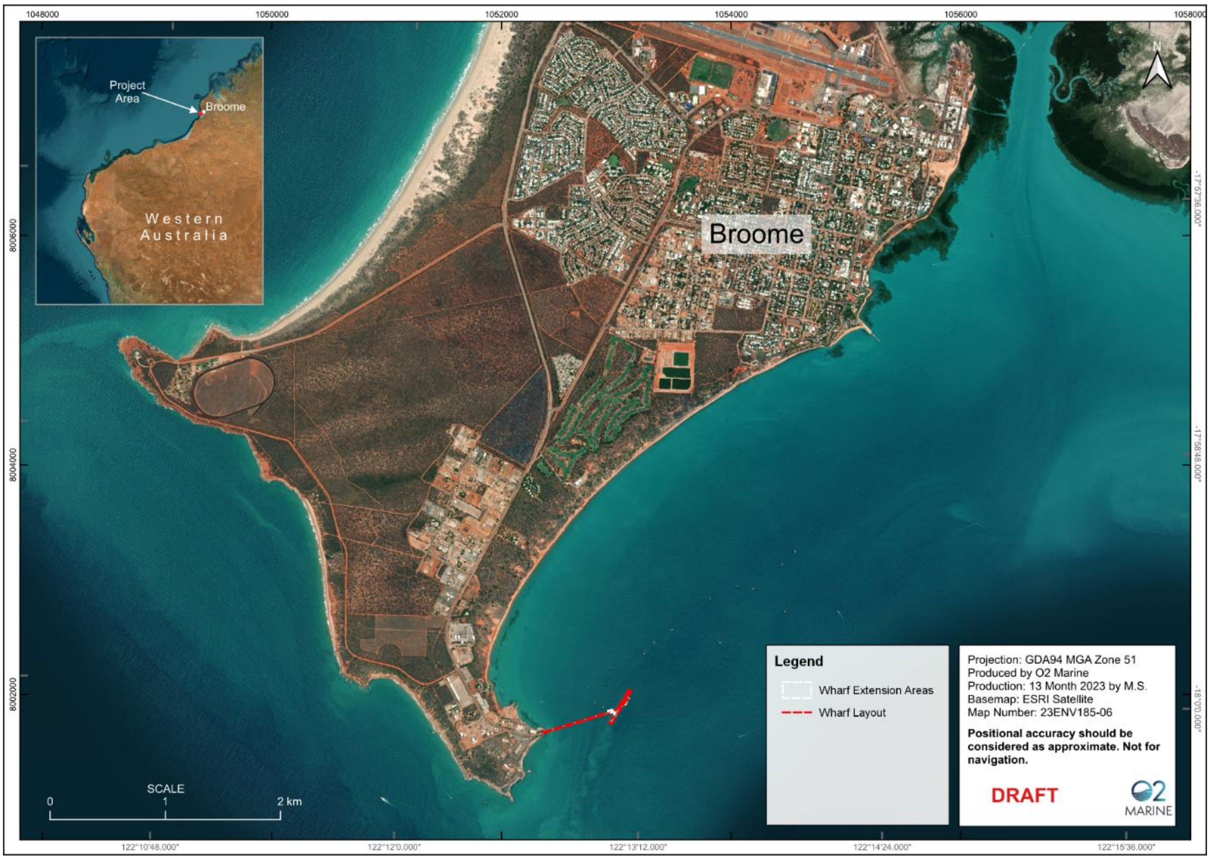

Figure 0-1 – Proposal Regional Location

Construction Overview

Construction will require piling of steel piles in the Broome Wharf area using a hydraulic hammer. Driving in piles is the most significant underwater noise source for construction.

Pile driving will only take place during daytime hours. It is anticipated only one pile will be driven in per day.

The process of piling requires the pile to be positioned and surveyed before it can be driven in. Once the pile is ready the hydraulic hammer will be raised and place on the top of the pile. When in place the hydraulic hammer will start driving the pile into the seabed. It is estimated that driving in the pile to the point of refusal will take between 30 and 60 minutes.

Figure 0-2 – Project Elements of the Proposed Broome Wharf Extension Project

Underwater Noise

Overview

The ocean soundscape consists of naturally produced sounds and anthropogenically generated noise. Natural underwater sound occurs from marine life and events such as waves, storms, and underwater earthquakes. Anthropogenic noise results from activities such as piling, vessel traffic, seismic exploration, marine construction, and military activities. Typical ambient sea noise levels in Australian waters are shown in Figure 0-1. Figure 0-2 shows typical deep ocean ambient noise levels from weather, wind, geologic activity, and commercial shipping.

The ambient underwater soundscape tends to be consistent and widespread across large areas of ocean, however, noise generated by anthropogenic activities can often be localised. If sufficiently loud, noise may be detrimental to certain marine species under some circumstances. The degree of impact is influenced by many factors including the sound's duration, amplitude, and frequency; the distance between the sound source and marine life; the total time that the marine life is exposed to the sound and the sensitivity of marine life to the site-specific combination of these factors [1].

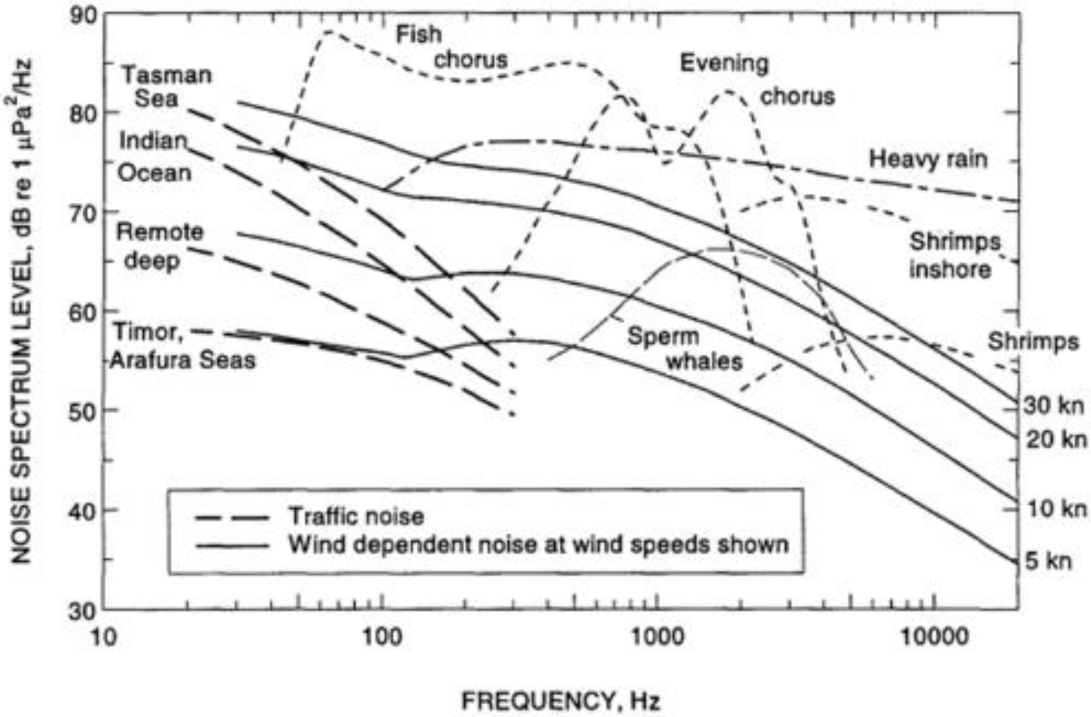

Figure 0-1 : Ambient Sea Noise in Australian Waters [6]

Sound travels further in the ocean than in air due to the natural duct created between the sea surface and the seabed, and the refractive properties of the water column. Additionally, the higher sound speeds in water result in longer wavelengths than in air, which result in low frequencies travelling further before they are absorbed to levels below ambient noise levels.

In shallow continental shelf water (< 200 m deep)[1], sound attenuates a lot faster than in the deeper, open ocean as the natural duct created between the sea surface and the seabed is very narrow, resulting in the acoustic pressure wave reflecting multiple times off the seabed and surface, with every reflection resulting in the pressure wave losing energy. Additionally, in very shallow water, low frequencies below a (depth dependant) cut-off frequency attenuate very quickly, thus not having any impact at distance from the source.

[1] In the field of ocean acoustics, "shallow water" commonly refers to coastal waters extending from the shoreline out to the edge of the continental shelf to a depth of about 200 metres, where the seafloor slope increases.

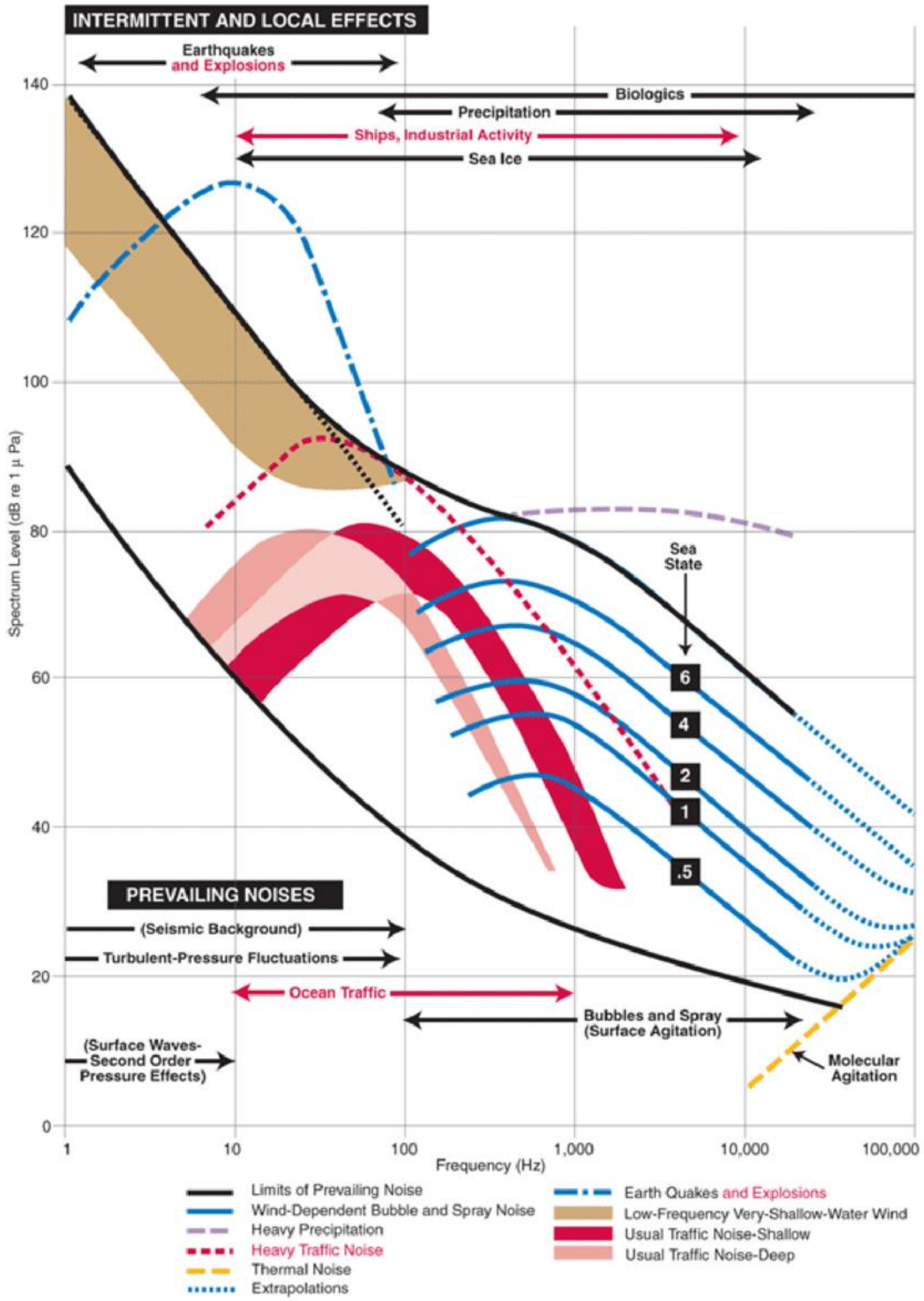

Figure 0-2 : Wenz curves: spectra and frequency distribution of underwater sound [35]

Key Metrics

Sound Pressure Level (Root Mean Square) (i.e. SPL(RMS)): SPL is a logarithmic scale (i.e. dB) used to measure the volume of a sound. SPL is a time averaged value taken over a time period. The RMS of a time averaged pressure (i.e. SPL) is a more accurate representation of the amount of power in a time varying waveform such as a sound pressure wave.

Sound Pressure Level (Peak) (i.e. SPL PK): SPL is a logarithmic scale (i.e. dB) used to measure the volume of a sound. SPL is a time averaged value taken over a time period. The Peak is the maximum excursion of the of the pressure wave over the time measured.

Sound Exposure Level (SEL): SEL is the equivalent of the total sound energy over a stated period (for this study the stated period is 24 hours). The unit of sound exposure (SI) is the $Pa^2 \cdot s$ (pascal-squared second). SEL is not time averaged, as a result the longer the exposure, the higher the SEL.

Marine Fauna

Assessment Criteria

Research has found that the noise levels at which Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS) occur is dependent on whether the noise being generated is classed as impulsive or non-impulsive. The Project is developing a new wharf with the most significant noise source being pile driving (which is classed as impulsive). Impulsive noise is defined as sounds that are typically transient, brief (less than one second), broadband and consist of high peak pressure with rapid rise and decay times [2]. Impulsive noise is associated with activities such as pile driving, seismic activities and underwater blasting and results in some of the most powerful sounds produced underwater [26], [27].

The assessment criteria for each fauna type are divided into noise levels that may result in TTS, PTS and Behavioural disturbance (see Table 0-1). To determine the levels at which TTS and PTS occurs the study has relied on the following:

- **Whales.** For low frequency cetaceans such as Humpback Whales, threshold levels for TTS and PTS for high frequency cetaceans defined in Southall et al [1]. Behavioural response for low and mid frequency cetaceans were also obtained from NOAA's 'Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing' Section 7 of [2].

- **Dolphins**. For dolphins, the threshold levels for TTS and PTS for high frequency cetaceans defined in Southall et al [1] and [2] respectively, are appropriate for this study. Behavioural threshold levels from NOAA's technical guidance [2], section 7 have been used.

- **Sirenians**. Sirenians (i.e. dugongs), the threshold levels for TTS and PTS defined in [1] and [2] respectively, are appropriate for this study. Behavioural threshold levels from Section 7 of [2] have been used.

- **Turtles.** The TTS and PTS criteria for turtles were based on the 'Criteria and Thresholds for U.S Navy Acoustics and Explosive Effect Analysis' [22].

- **Sawfish.** A study of elasmobranch fishes audiograms [4] indicates that their hearing bandwidths range from 10 to 1000 Hz. As the study area is very shallow it is expected that the very low frequencies will only exist as short duration evanescent waves. This implies that frequencies below 100 Hz will attenuate very quickly. With the lower frequencies removed the Sawfish will have a similar hearing bandwidth to that of turtles and it has therefore been assumed that their TTS levels will be similar to that of Turtles.

- **Sea-Snakes and Salt-water Crocodiles.** Very little is known about sea snake and crocodile underwater bioacoustics, including the sounds they make and their hearing capabilities. However, there are some studies that have been undertaken that provide an indication of Sea-Snake and Crocodilian hearing bandwidths:

  - **Sea-Snakes.** Studies of Sea-Snake hearing bandwidths have concluded that Sea snakes are sensitive to a bandwidth of 60-400 Hz, with a peak sensitivity detected around 100 Hz [41]. No impact threshold levels have been proposed for Sea Snakes.
  - **Crocodiles.** No studies have been carried out on crocodile hearing in Australia but a study on the hearing sensitivity of the spectacled caiman (*Caiman crocodilus*) found in Central and South America showed that these related species had highest sensitivity between 150 Hz and 3 kHz [40]. A more recent study on the American alligator (*Alligator mississipiensis*), which used auditory brainstem responses, showed that in-water responses were elicited from tones between 100 Hz and 2 kHz, with peak sensitivity at around 800 Hz [38][39]. It has been assumed that, because crocodile hearing bandwidths are most similar to turtles, the Behavioural/PTS/TTS threshold levels and hearing curves of these species are the same, and so will be assessed as such.

Note: Behavioural disturbance levels are not based on cumulative exposure or SEL[2], but on a Root Mean Square (RMS) Sound Pressure Level (SPL[3]).

Table 0-1 : TTS, PTS (24-hour[4]) and Behavioural Disturbance onset thresholds

Marine Fauna Type	Marine Mammal Hearing Group	Hearing Bandwidth	Possible Behavioural Disturbance	SEL Onset (Weighted)			
				TTS		PTS	
			SPL (RMS) (dB re 1μ Pa[5])	Weighted SEL_{24} (dB re 1 μPa²·s)	SPL_{PK} (dB re 1μPa)	Weighted SEL_{24} (dB re 1 μPa²·s)	SPL_{PK} (dB re 1μPa)
Impulsive							

[2] Sound exposure levels (SEL) is the cumulative level of energy contained within underwater noise and is typically used to assess health and welfare impacts. This is also referred to as the "noise dose".

[3] Sound Pressure Level (SPL) is the measure of the amplitude of acoustic pressure compared to 1 µPa.

[4] PTS and TTS sound exposure levels are calculated over a 24 hour period [1].

[5] NOTE: (N) = Near, (I) = Intermediate and (F) = Far Distances for Relative Risk (high, moderate, low).

Marine Fauna Type	Marine Mammal Hearing Group	Hearing Bandwidth	Possible Behavioural Disturbance	SEL Onset (Weighted)			
				TTS		PTS	
			SPL (RMS) (dB re 1µ Pa[5])	Weighted SEL_{24} (dB re 1 µPa²·s)	SPL_{PK} (dB re 1µPa)	Weighted SEL_{24} (dB re 1 µPa²·s)	SPL_{PK} (dB re 1µPa)
Whales	Low frequency (LF)	7Hz to 35kHz	160[6]	168[7]	213[7]	183[7]	219[7]
Dolphins	High frequency (HF)	150Hz to 160kHz	160[6]	170[7]	224[7]	185[7]	230[7]
Sirenians	SI – Low Frequency	100Hz to 50kHz	160[6]	175[7]	220[7]	190[7]	226[7]
Turtles + Sawfish + Crocodiles	N/A	100Hz to 2 kHz	175[8]	189[9]	226[9]	204[9]	232[9]

Methodology

Overview

This study has been undertaken using a computer noise model to simulate underwater noise emissions. The underwater software calculation kernel utilises the Monterey Miami Parabolic Equation (MMPE [36]) which was developed by the University of Miami and Naval Postgraduate School Monterey in the USA. This kernel has been rigorously tested at the Shallow Water Acoustic Modelling (SWAM) Workshop and has undergone infield verification for both deep and shallow water [32]. The model can predict transmission loss from multiple noise emission sources simultaneously in both broadband and narrowband frequency ranges.

Underwater propagation models require inputs including bathymetric data, geo-acoustic information, and oceanographic parameters to produce three-dimensional (3D) estimates of the acoustic field at any depth and distance from the source. As with any model, the quality of the prediction is directly related to the quality of the environmental information used in the model.

[6] NOAA 2019 [2]

[7] Southall et al. 2019 [1]

[8] McCauley et al. (2000b)

[9] Finneran et al. 2017

Noise Sources

Overview

Minimal engineering information was available from the Project as a result the source selection was based on the best possible match to the activities and on previous marine piling projects using similar pile diameters. The noise source levels used for modelling have therefore been calculated based on a combination of Project data and source levels from an in-house database of underwater noise sources which have been developed from publicly available data. The source level includes overall and spectral levels.

Impact Piling Noise Source Level (Impulsive Source)

The noise emanating from a pile is a function of its material type, size, the force applied to it and the characteristics of the substrate into which it is being driven. The action of driving a pile into the seabed excites waves in the pile that propagate along the length of the pile and transfer into the water and seabed (Figure 0-1).

The noise that is generated by an impact hammer hitting the top of the pile is short in duration lasting approximately 90 milliseconds (ms) and can therefore be described as impulsive noise. The pile driving specifications that have been used to calculate the source levels for modelling are given in Table 0-1.

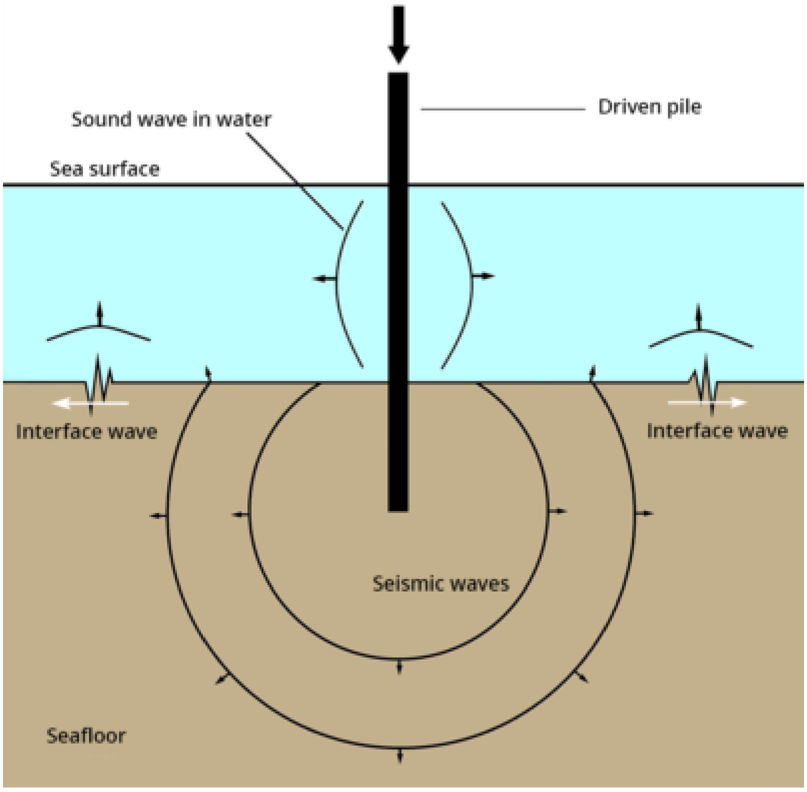

Figure 0-1 : Sound waves generated in water, in seabed and interface wave from pile driving (source Sound in the Sea [38])

Table 0-1 : Pile driving specifications.

Parameter	Value
Pile diameter	1200 mm
Hammer Type and Weight	Hydraulic
Hammer Energy (max)	250 kJ
Blow rate	30 bpm
Number of piles per 24 hours	1

The expected hydraulic hammer energy profile (Figure 0-2) shows that the hammer energies start off low and only achieve maximum energy in the last stages of piling before the point of refusal[10]. This results in a cumulative increase in SEL at the source (Figure 0-3).

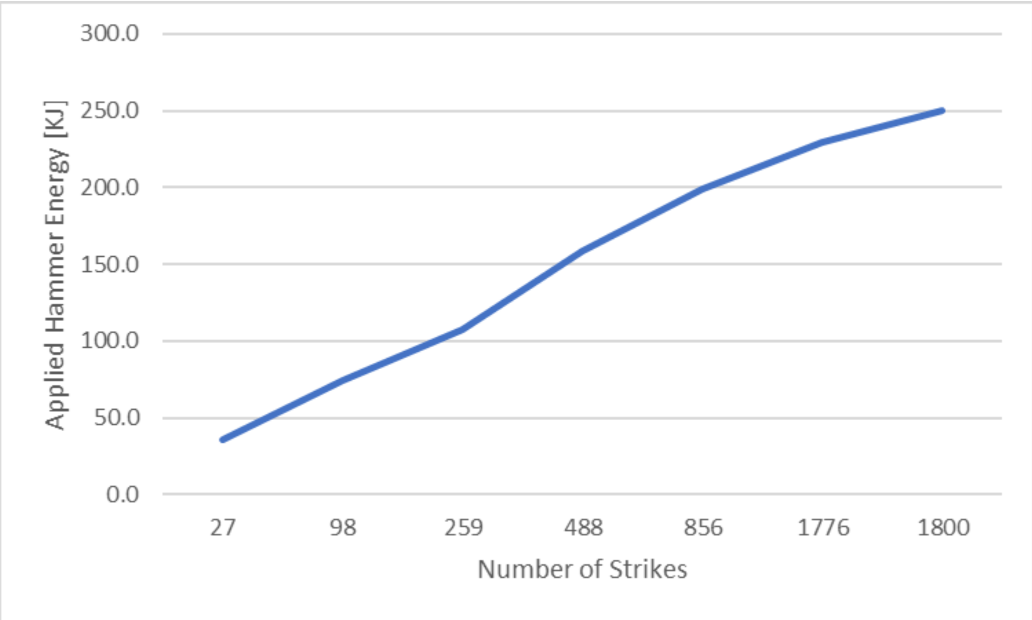

Figure 0-2 Applied hammer energy versus number of hammer strikes.

[10] As the Project has not undertaken a piling drivability assessment at the time of the study the hammer energy profile has been based on piling logs and publicly available data.

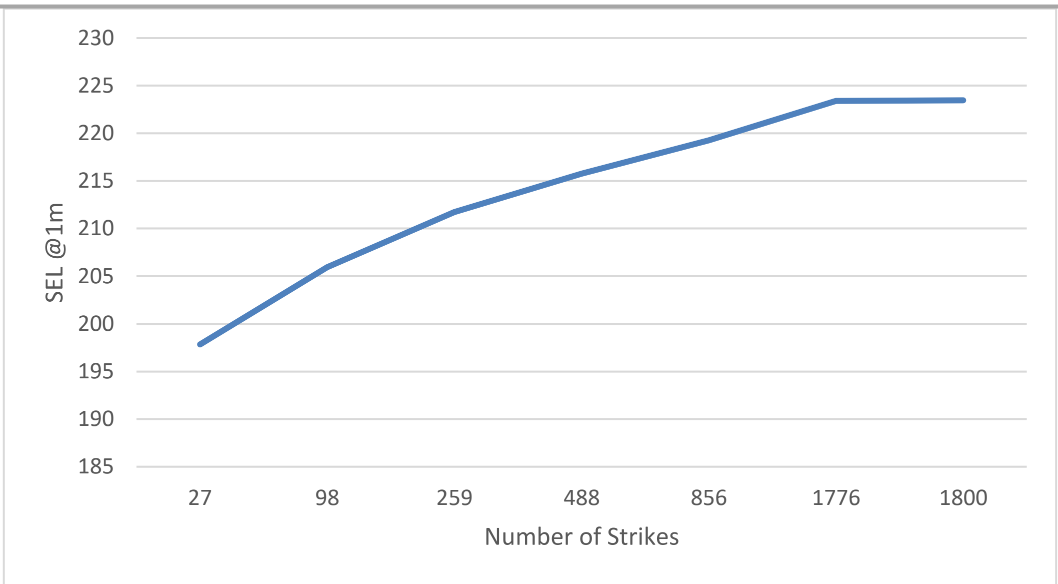

Figure 0-3: Cumulative growth of source SEL with varying hammer energy and hammer strikes.

The cumulative impacts from piling have been determined using the source level and the number of hammer strikes to determine the Cumulative SEL[11] at the source for driving a single pile into the seabed (Figure 0-3).

Peak pressures associated with the piling have been determined using a combination of scaled modelling data (as described in 2010 ICA proceedings [39]), measured data from Caltrans ([22],[40]) and the E&P Sound and Marine Life Review [23].

Table 0-2 : Piling noise source level for maximum hammer energy.

SEL for a single strike	Cumulative SEL
192 dB re 1µPa^2.s @ 1m	223 dB re 1µPa^2.s @ 1m

The spectrum of the piling noise source is shown in Figure 0-4.

[11] 10*log10(N) where N is the number of hammer strikes.

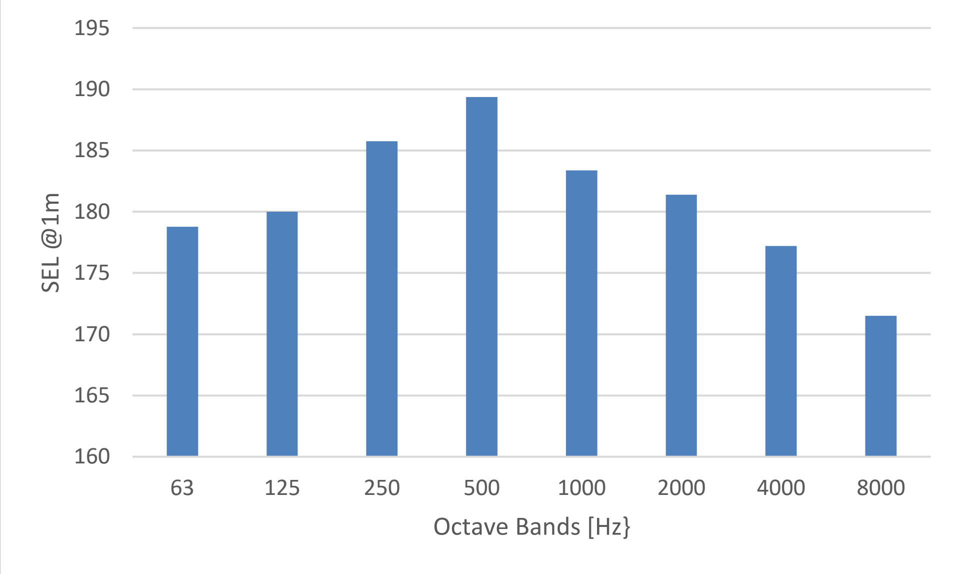

Figure 0-4 : Pile Driving source spectral characteristics (250KJ).

Modelled Scenarios

A scenario has been created in the model that includes a pile modelled in deep water (~20m) for Highest Astronomical Tide (HAT) (i.e. ~2.5m above mean Sea Level (MSL)) and Lowest Astronomical Tide (LAT) (i.e. ~2.5m below MSL)[12].

Table 0-3 : Noise Source Model locations (MGA zone 51 – UTM Coordinates)

Location Name	Easting	Northing
Pile Location (N)	417188.24	8009507.86
Pile Location (S)	417157.00	8009426.00

Figure 0-5 : Modelled Noise Source Locations

Bathymetry

The bathymetry applied to the model for the Broome area was provided by O2 Marine. The bathymetry details a submarine channel known as Roebuck Deep with a maximum depth of ~ 110 m as shown in Figure 0-6.

[12] Determined from project drawing "PA3421-RHD-00-DR-MA-0010, Rev A"

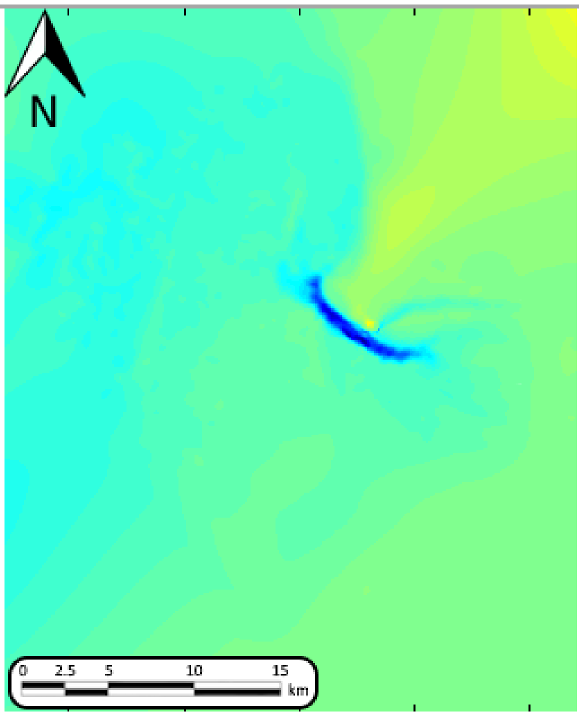

Figure 0-6 : Bathymetry (Mean Australian Sea Level)

Sound Speed Profile

All construction activities for the Project will be undertaken in shallow water (~20m) and the temperature profile in the water column is expected to be well mixed and isothermal. As the water becomes deeper the temperature gradient changes and will result in a Sound Speed Profile as shown in Figure 0-7.

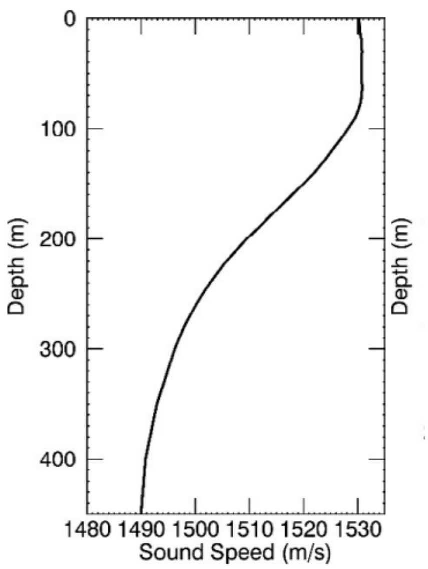

Figure 0-7 : Sound speed profile calculated from temperature and salinity profiles from Generalized Digital Environmental Model for the Northwest Shelf

Seabed Types

Roebuck Bay is comprised of mainly fine to medium sands with a small portion of silt, clay and gravel (see applicable documents ii, iii and iv). A predominately sandy seabed (see Table 0-4 for seabed properties) has been assumed for the greater Roebuck Bay area. This is a conservative assumption because sand is more reflective in shallow water environments (i.e. shallow grazing angles) than limestone due to the excitation of both compression and shear waves in the material.

Table 0-4 : Seabed geo-acoustic properties used in the model [34]

Type	Sound Speed (m/s)	Density (g/cm³)	Sound attenuation (dB/m/kHz)		Shear Speed (m/s)
			Compression	Shear	
Fine to medium sand	1650	1.90	0.374	0	0

Hearing Threshold Weighting Curves

Hearing weighting curves for Low Frequency (LF) and High Frequency (HF) marine mammal species, as well as Sirenians have been applied to all predicted received levels in accordance with NOAA's technical guidance (See Appendix G) [2]. For Turtles and Sawfish, the weighting curves from [22] have been used.

These have been applied to predicted received noise levels to reflect the sensitivity of a particular marine fauna's auditory systems to different frequencies of sound. They are applied to help understand which frequency ranges may have more significant consequences for marine fauna and inform mitigation strategies to minimize adverse effects.

Data and Model Limitations

The following limitations apply to the noise modelling:

- **Reflection** – Specular reflection due to rough seabed surface and wave action is not accounted for in the model. Specular reflection will result in a reduction in received noise levels.
- **Airborne Noise** – A small component of the airborne noise generated above the sea surface will be transferred into the water column, however this has not been accounted for in the model.
- **Bathymetry** – For near shore modelling, both bathymetry and topography were used in the model. The bathymetry is based on Mean Sea Level (MSL). A 2.5m high tide above MSL, and 2.5m low tide below MSL was used in the model.

Noise Model Results and Discussion

The model outputs have been used to develop noise maps and determine distances from the noise source at which PTS, TTS and behavioural disturbance is predicted to exceed the threshold levels in Table 0-1. PTS and TTS exceedance distances are based on the animal remaining at a distance for the duration of the piling. Behavioural ranges are based on the Sound Pressure Level (RMS) found to affect faunal behaviour, while PTS and TTS ranges are based on a 24-hour exposure level from the piling activities.

Table 0-1 shows the furthest distances from piling activities at which behavioural disturbance is likely to occur. Whales were found to have the furthest distances ranging from 350 to 500 m depending on the tide. Behavioural Sound Pressure Level (RMS) noise maps for whales can be found in Appendix D. Whale noise maps have been selected for the report as they are the furthest predicted distances (i.e. most conservative) at which behavioural disturbance occurs. Detailed SPL(RMS) graphs versus distance graphs that also show the behavioural disturbance threshold for each fauna type can be found in Appendix F.

PTS and TTS 24-hour exposure distances from the source are given in Table 0-2. Whales were found to have the largest exposure ranges with TTS distances of just under 10 km. All other TTS distances were found to be ≤ 500m. It is noted that the TTS and PTS exposure ranges for whales are more than the behavioural disturbance ranges shown in Table 0-1. To understand why this is the case the following is applicable:

- PTS and TTS use a cumulative exposure metric over 24 hours (i.e. SEL) while behavioural disturbance uses a time averaged metric (i.e. SPL(RMS)).
- The recommended SPL(RMS) threshold level for whales is 160 dB re 1µPa (see Table 0-1). Typical background noise levels are ~120 dB re 1µPa. The threshold is therefore 40 dB above typical background noise (i.e. it is significantly louder than background noise).
- If the threshold levels where 140 dB re 1µPa the behavioural disturbance range for whales would be ~8km and if the threshold levels where 120 dB re 1µPa the range would be between 14 and 20km.

Peak TTS and PTS exposure distances, as shown in Table 0-3, were <20 m from the pile. Detailed SEL range graphs versus distance that also show the TTS and PTS thresholds for each fauna type can be found in Appendix E.

Table 0-1 – Behavioural (SPL-RMS) ranges for piling at different tide levels.

Species	Source	Behavioural Threshold Levels	Tidal Level	Behavioural Range (m)
Whales (LF)	Pile Location (N)	160 dB	HAT	500
			MSL	400
			LAT	350
	Pile Location (S)		HAT	500
			MSL	475
			LAT	375
Dolphins (HF)	Pile Location (N)	160 dB	HAT	<50
			MSL	<50
			LAT	<50
	Pile Location (S)		HAT	<50
			MSL	<50
			LAT	<50
Sirenians	Pile Location (N)	160 dB	HAT	<50
			MSL	<50
			LAT	<50
	Pile Location (S)		HAT	<50
			MSL	<50
			LAT	<50
Turtles + Sawfish + Crocodiles	Pile Location (N)	175 dB	HAT	75
			MSL	70
			LAT	70
	Pile Location (S)		HAT	70
			MSL	75
			LAT	65

Table 0-2 – TTS and PTS 24hour exposure ranges for piling at different tide levels.

Species	Source	Threshold Levels (dB)	Tidal Level	PTS Range (m)	TTS Range (m)
Whales (LF)	Pile Location (N)	TTS = 168 PTS = 183	HAT	1,550	9,550
			MSL	1,400	8,350
			LAT	1,200	5,450
	Pile Location (S)		HAT	1,350	8,290
			MSL	1,280	6,275
			LAT	1,260	5,100
Dolphins (HF)	Pile Location (N)	TTS = 170 PTS = 185	HAT	70	185
			MSL	70	180
			LAT	65	170
	Pile Location (S)		HAT	75	185
			MSL	65	165
			LAT	65	155
Sirenians	Pile Location (N)	TTS = 175 PTS = 190	HAT	<50	95
			MSL	<50	90
			LAT	<50	85
	Pile Location (S)		HAT	<50	95
			MSL	<50	85
			LAT	<50	80
Turtles + Sawfish + Crocodiles	Pile Location (N)	TTS = 189 PTS = 204	HAT	95	500
			MSL	90	440
			LAT	85	370
	Pile Location (S)		HAT	90	470
			MSL	85	390
			LAT	80	340

Table 0-3 – SPL Pk TTS and PTS 24hour exposure ranges for piling at different tide levels.

Species	SPL Peak Levels (dB)	Source	Tide Level	TTS Range (m)	PTS Range (m)
Whales (LF)	$TTS_{PK} = 213$ $PTS_{PK} = 219$	Pile (N)	HAT	<20	<20
			MSL	<20	<20
			LAT	<20	<20
		Pile (S)	HAT	<20	<20
			MSL	<20	<20
			LAT	<20	<20
Dolphins (HF)	$TTS_{PK} = 224$ $PTS_{PK} = 230$	Pile (N)	HAT	<10	<10
			MSL	<10	<10
			LAT	<10	<10
		Pile (S)	HAT	<10	<10
			MSL	<10	<10
			LAT	<10	<10
Sirenians	$TTS_{PK} = 220$ $PTS_{PK} = 226$	Pile (N)	HAT	<10	<10
			MSL	<10	<10
			LAT	<10	<10
		Pile (S)	HAT	<10	<10
			MSL	<10	<10
			LAT	<10	<10
Turtles + Sawfish + Crocodiles	$TTS_{PK} = 226$ $PTS_{PK} = 232$	Pile (N)	HAT	<10	<10
			MSL	<10	<10
			LAT	<10	<10
		Pile (S)	HAT	<10	<10
			MSL	<10	<10
			LAT	<10	<10

Conclusions and Recommendations

Conclusions

An underwater noise model has been developed to predict noise levels and impacts from piling noise sources associated with construction of the Broome Wharf Extension Project. The noise sources modelled are based on Project information available at the time of the study and previous marine piling projects using similar pile diameters. A reasonably conservative approach has been adopted in the study.

The model has been used to develop noise maps and determine distances from the piling at which PTS, TTS and behavioural disturbance is predicted to exceed threshold levels. The modelling results and ranges are summarised in Table 0-1 to Table 0-3.

It was found that whales TTS threshold exceedance had the largest impact ranges. The TTS distances were found to be between 5-10km. These distances are not manageable using Marine Fauna Observers (MFO's) and as a result additional control measures including avoiding the peak whale season or using bubble curtains should be used. All other species were found to have distances <600 m. These distances can be effectively managed using MFOs.

Recommendations

It is recommended that the following noise management approaches be considered:

- **Avoidance**. Key sensitive ecological windows should be avoided by scheduling works outside of those periods (i.e. outside of whale migration season between July to September). If piling does coincide with whale season bubble curtains will be used. Bubble curtains are to be of appropriate design to ensure 15 dB reduction in piling noise levels (this will potentially reduce whale PTS and TTS ranges to ~200m and ~1km respectively). Piling contractors are to be appropriately trained and supervised in the use of the bubble curtain. Should the bubble curtain fail at any time during a piling operation the piling operation should cease until the bubble curtain is operational.
- **Piling Soft Starts**. Soft starts require low hammer energies to be applied at the beginning of piling. This is not always an effective strategy to follow as in some cases fauna have been seen to move towards a piling operation during the soft start.
- **Hammer Energy Management**. Hammer energies should be managed so that the lowest required hammer energy be applied to drive the pile through the sediment (i.e. depending on the resistivity of the sediment on the pile wall, lower energies be used to drive piles through marine clay and other soft sediments).
- **Drill/Pile/Drill.** A drill/pile/drill approach could be considered by the Project. In this approach a drill is used if rock substrate is encountered during the piling campaign. This will result in reducing the use of the hydraulic hammer and as a result the SEL.
- **Observation and exclusion Zones**. MFOs can be used to manage exclusions zones. Usually, two zones are selected for observation and exclusion (Table 0-1). The first zone is based on TTS distances and construction activities can only commence when no marine fauna has been observed within this range. The second zone is only relevant once the activity commences. It is based on the PTS distances and the activity stops if a species comes inside of its PTS distance. Piling can only recommence once the animal has moved outside of its PTS distance.
- **Monitoring.** It is recommended that the Project undertake infield monitoring at the beginning of the piling programme to ensure that the management zones are appropriate.

Table 0-1 : Observation and exclusion zones

Type	Distance Informed by	Purpose
Observation	TTS 24hour exposure ranges	Piling can only commence when all marine fauna are outside of their respective TTS ranges.
Exclusion	PTS 24hour exposure ranges	Piling stops if a species comes inside of its PTS distance.

APPENDIX A

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APPENDIX B

dB	Decibel
CMST	Centre of Marine Science and Technology
HAT	Highest Astronomical Tide
HF	High Frequency
Hz	Hertz
kHz	Kilo Hertz
LAT	Lowest Astronomical Tide
LE,24h	Sound Exposure Level Cumulative 24 hours
LF	Low Frequency
PK	Peak Sound Pressure Level
M	Metre
MSL	Mean Sea Level
ms	Milliseconds
NOAA	National Oceanic and Atmospheric
Pa	Pascals
PTS	Permanent Threshold Shift
RMS	Root Mean Square
s	Seconds
SEL	Sound Exposure Level [dB re 1µPa^2.s]
SELcum	Cumulative Sound Exposure Level
SL	Source Level [dB re 1µPa @ 1m] or [dB re 1µPa^2.s @ 1m]
SPL	Sound Pressure Level [dB re 1µPa]
TTS	Temporary Threshold Shift
µPa	Micro Pascal
µPa^2 s	Micro Pascal Square Second
W(f)	Weighting function

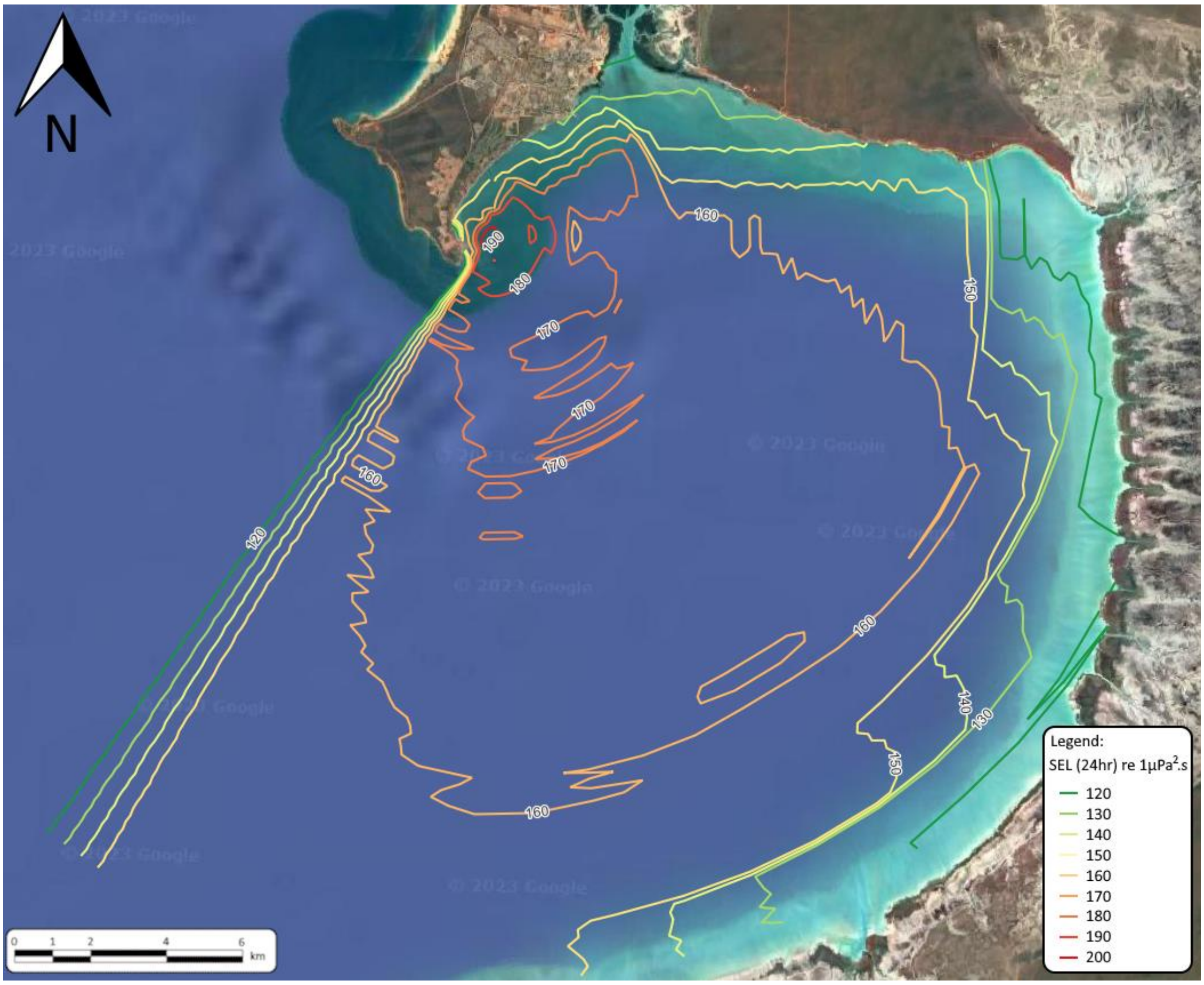


Figure C-1 : Noise Contour Map – Pile (N) – Cumulative – HAT – Whales

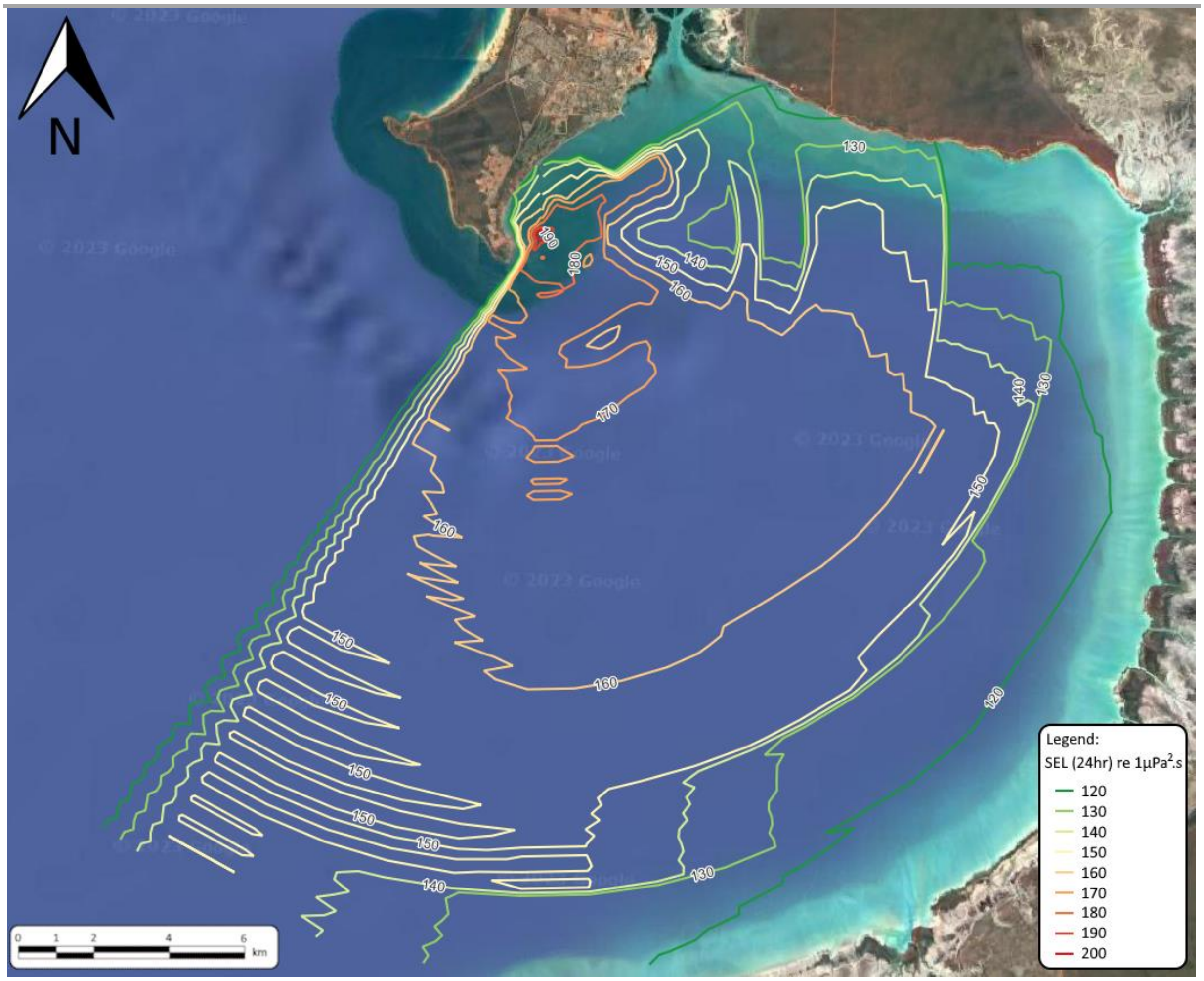


Figure C-2 : Noise Contour Map – Pile (N) – Cumulative – MSL – Whales

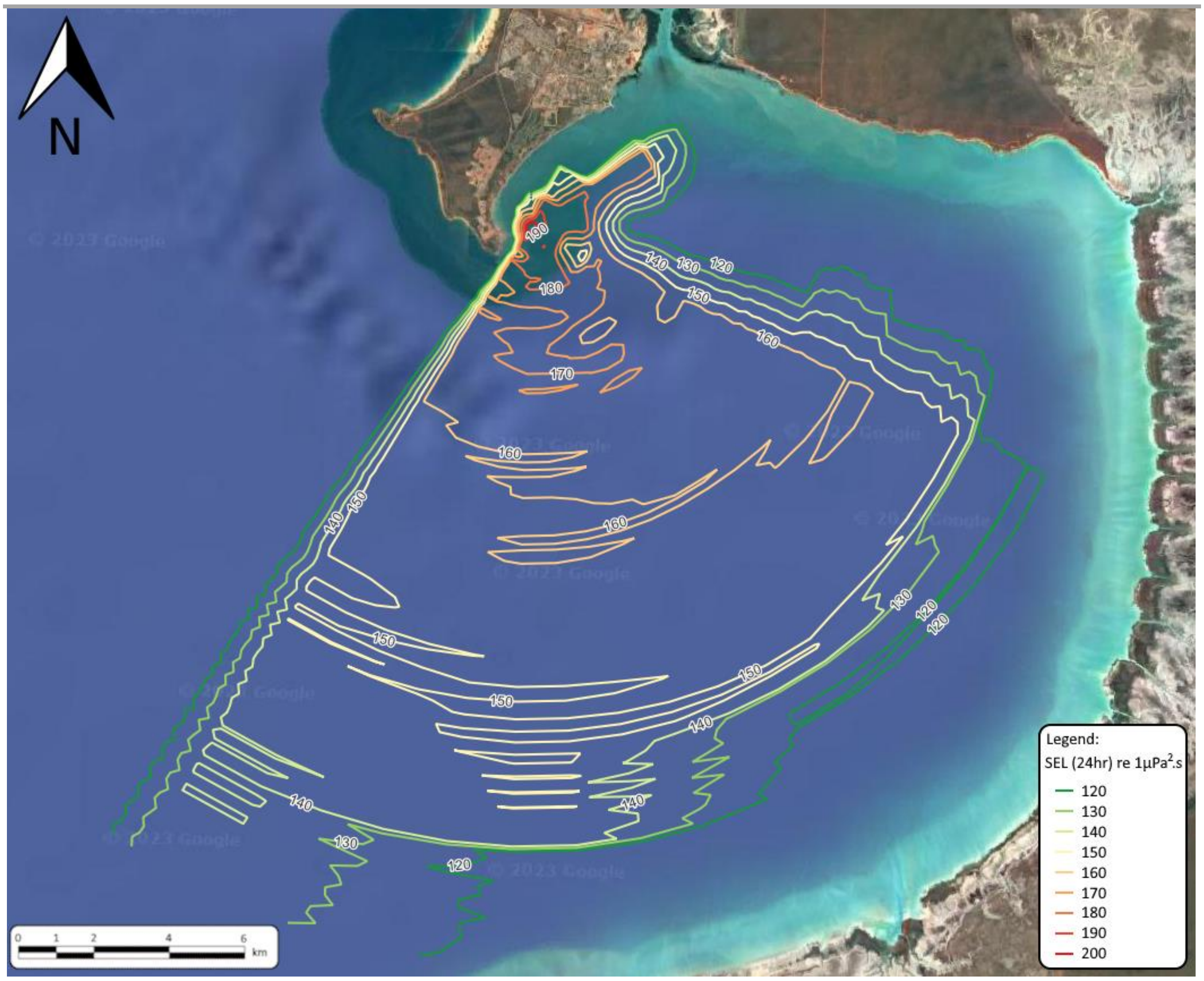


Figure C-3 : Noise Contour Map – Pile (N) – Cumulative – LAT – Whales

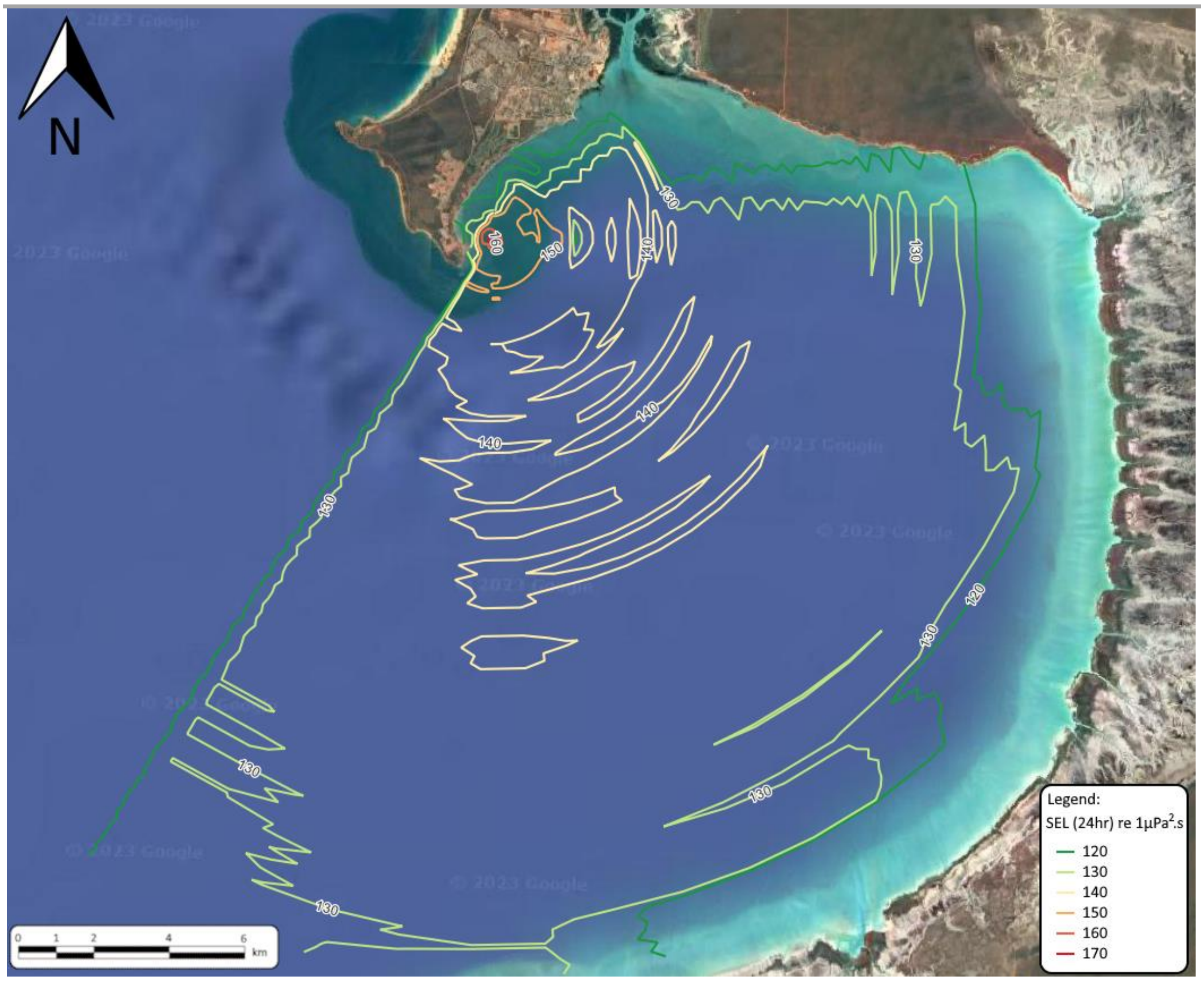


Figure C-4 : Noise Contour Map – Pile (N) – Cumulative – HAT – Dolphins

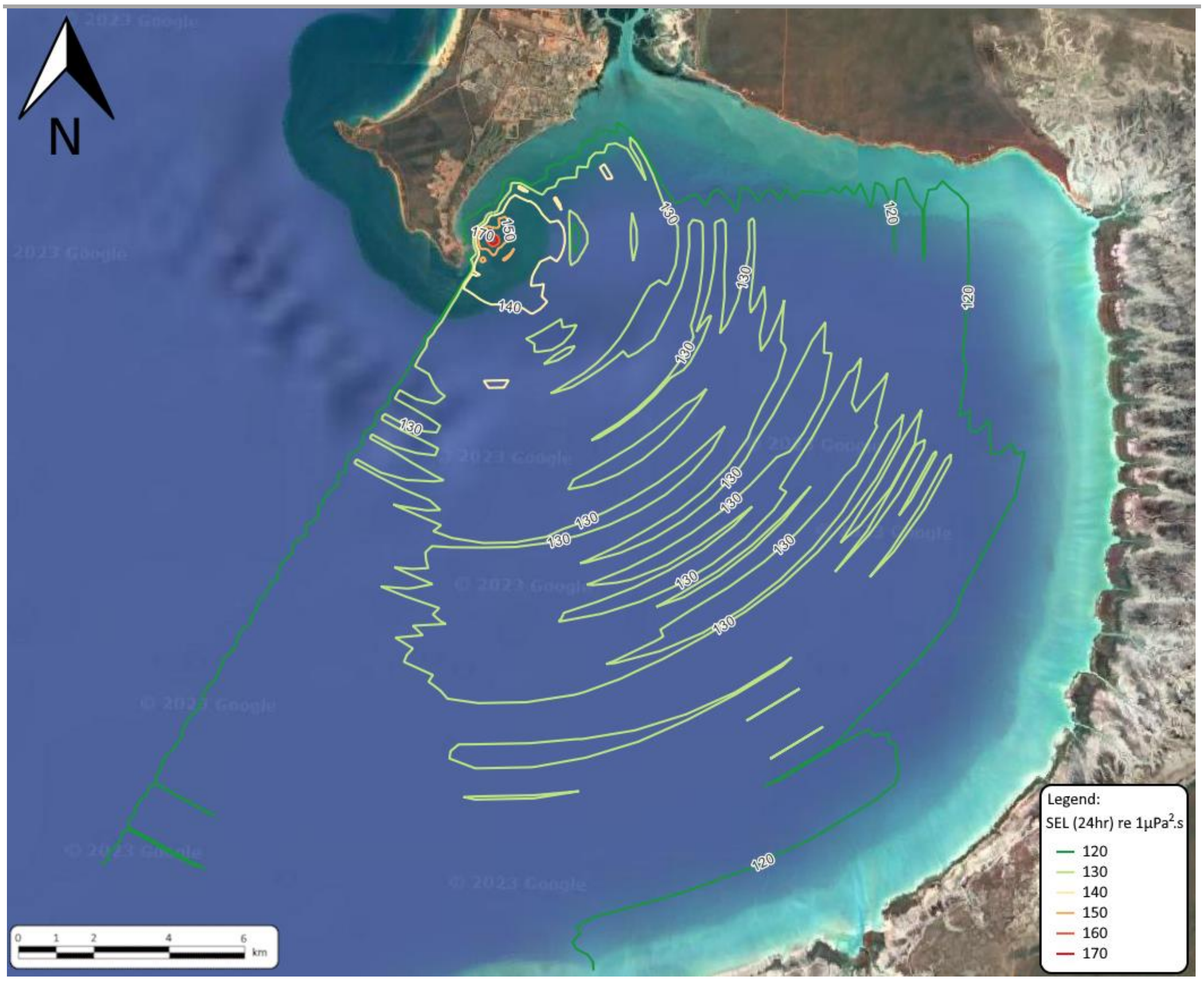


Figure C-5 : Noise Contour Map – Pile (N) – Cumulative – HAT – Sirenians

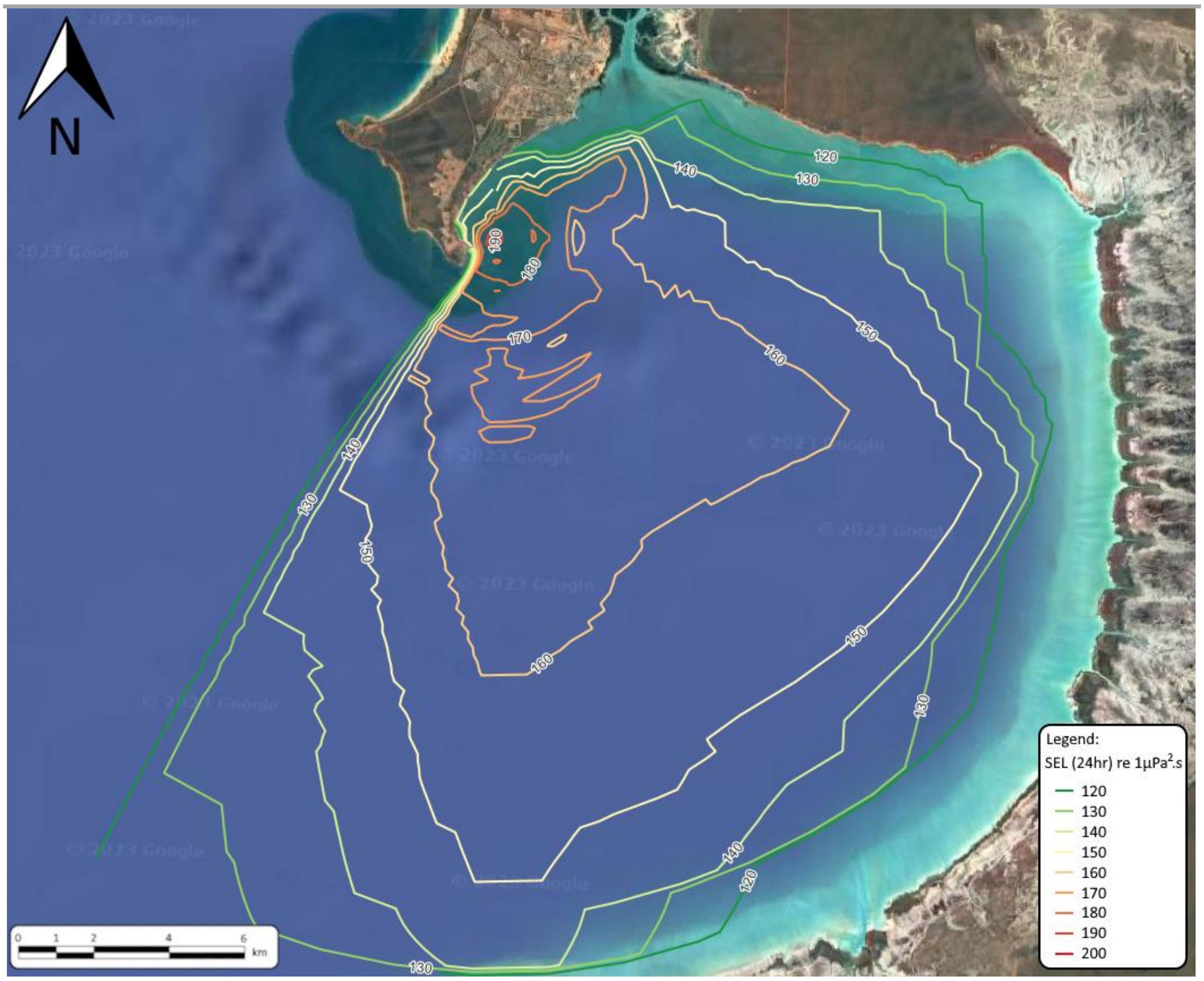


Figure C-6 : Noise Contour Map – Pile (N) – Cumulative – HAT – Turtles / Sawfish / Crocodiles

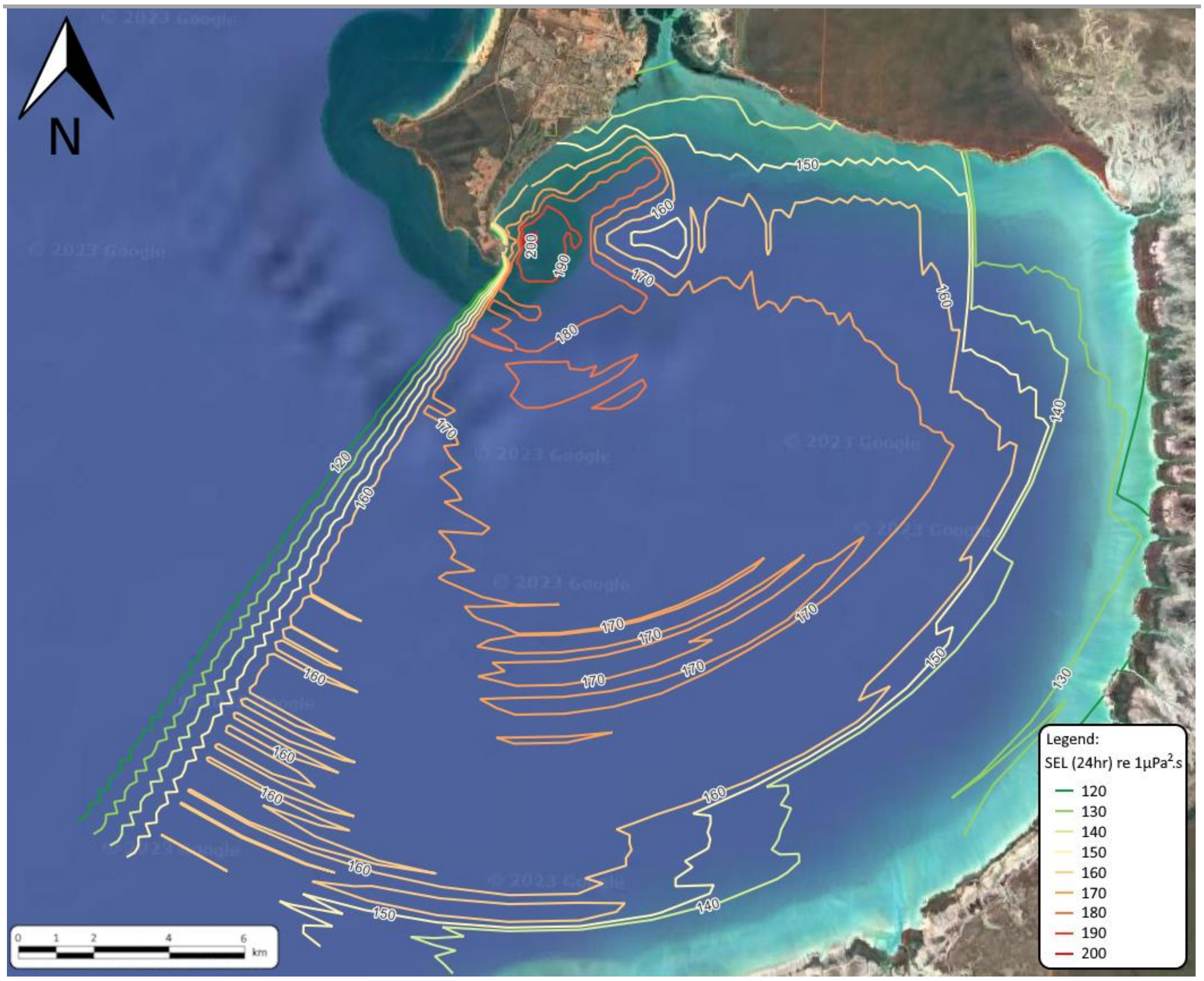


Figure C-7 : Noise Contour Map – Pile (S) – Cumulative – HAT – Whales

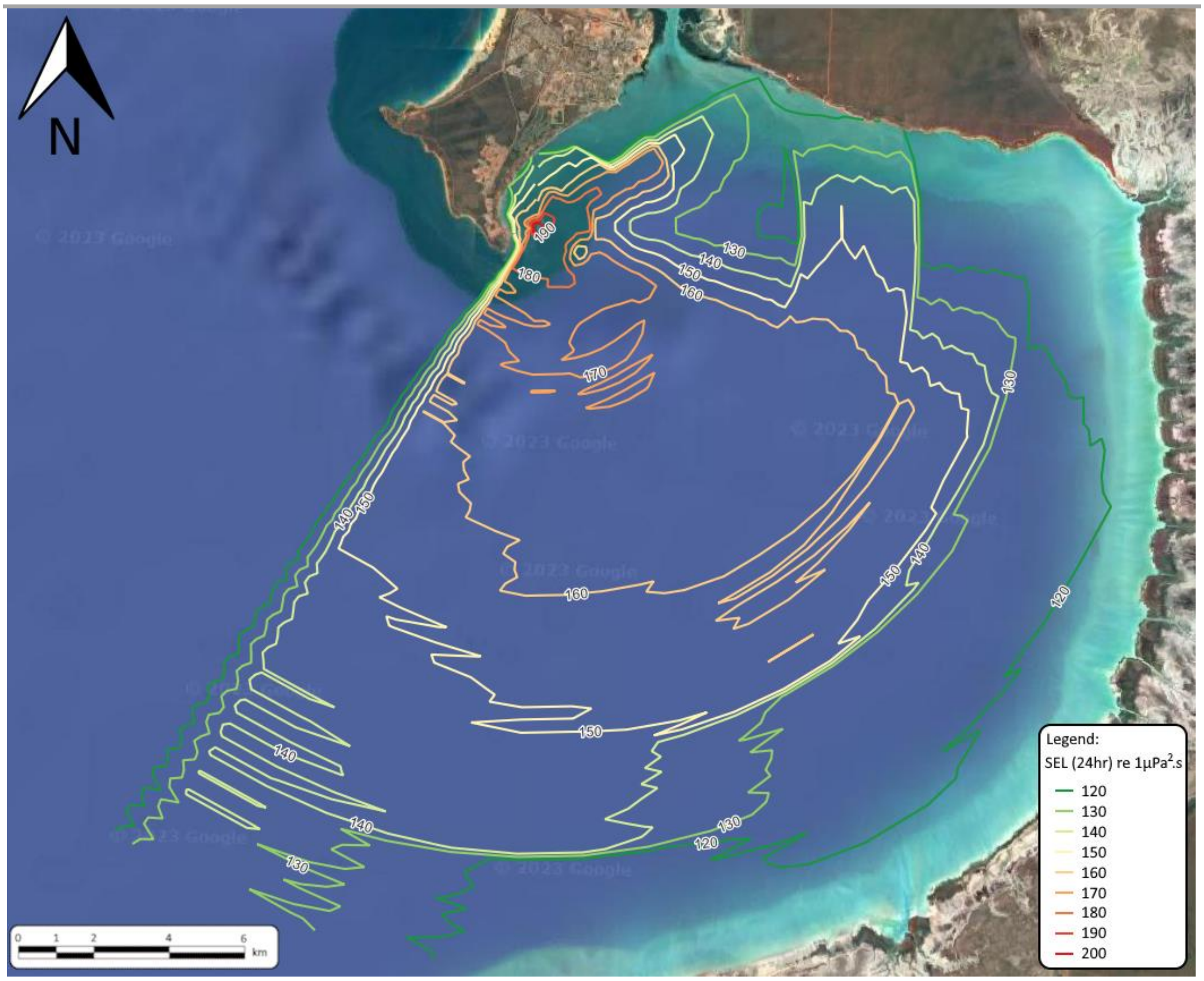


Figure C-8 : Noise Contour Map – Pile (S) – Cumulative – MSL – Whales

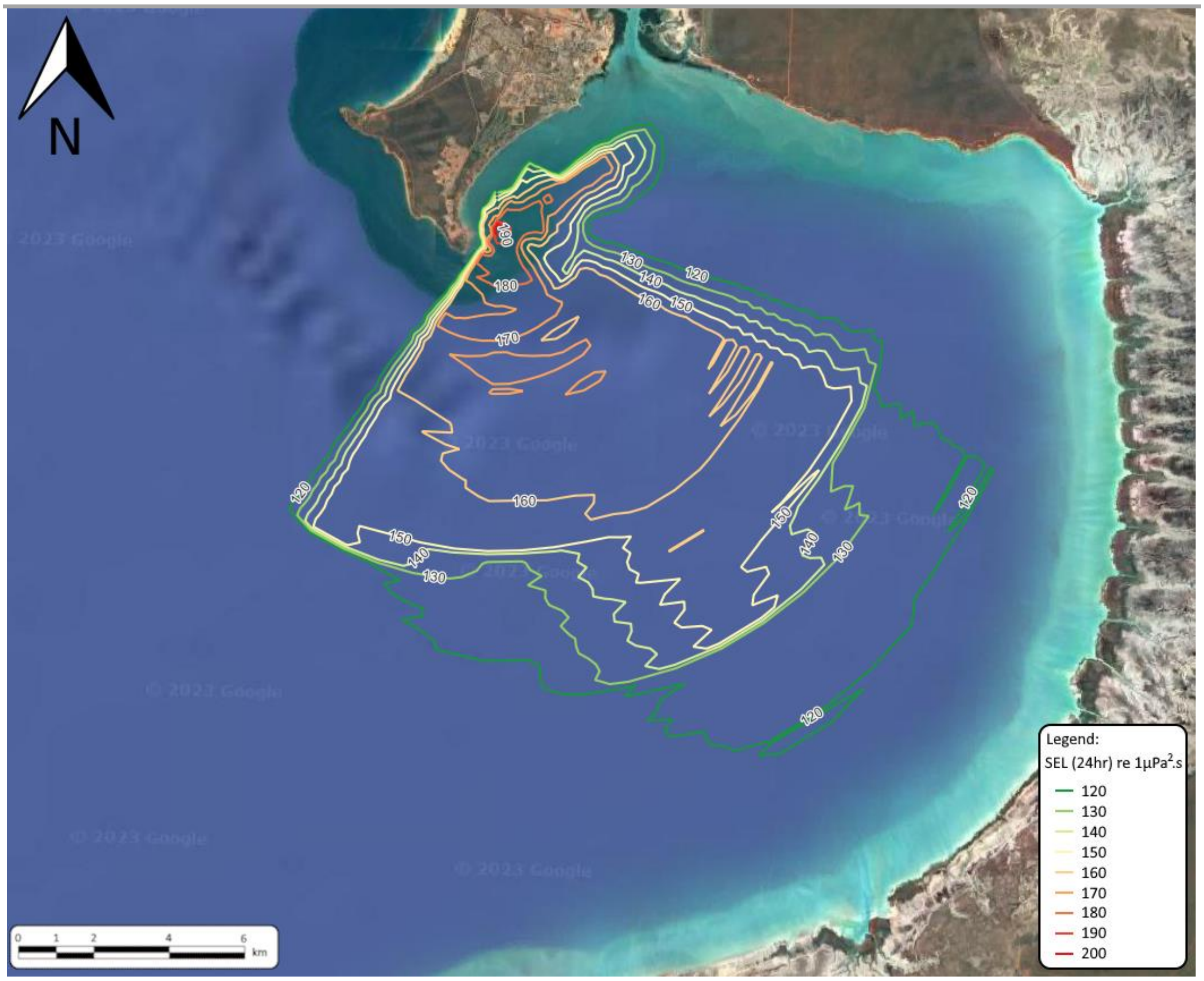


Figure C-9 : Noise Contour Map – Pile (S) – Cumulative – LAT – Whales

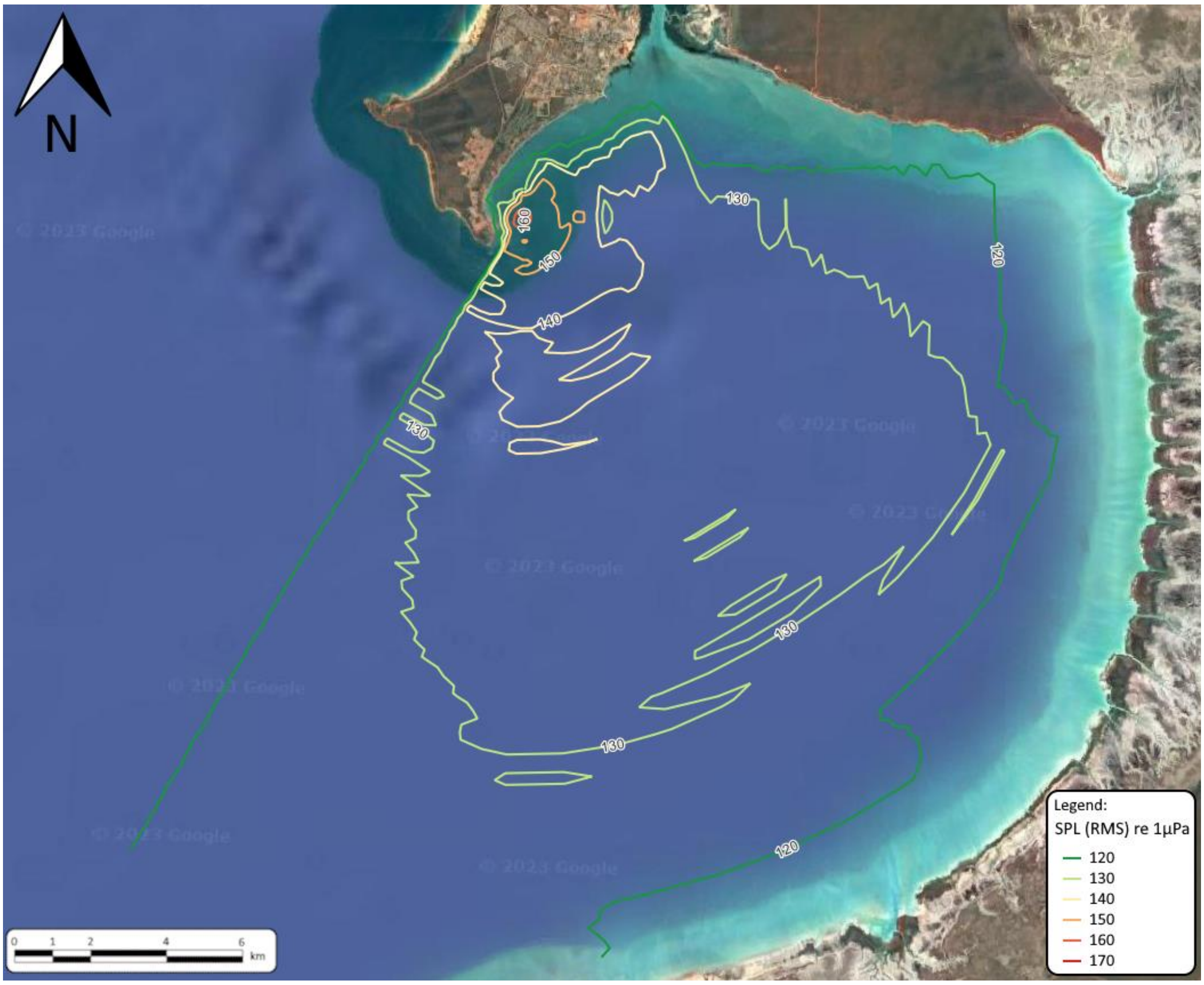


Figure D-1 : Noise Contour Map – Pile (N) – Behavioural – HAT – Whales

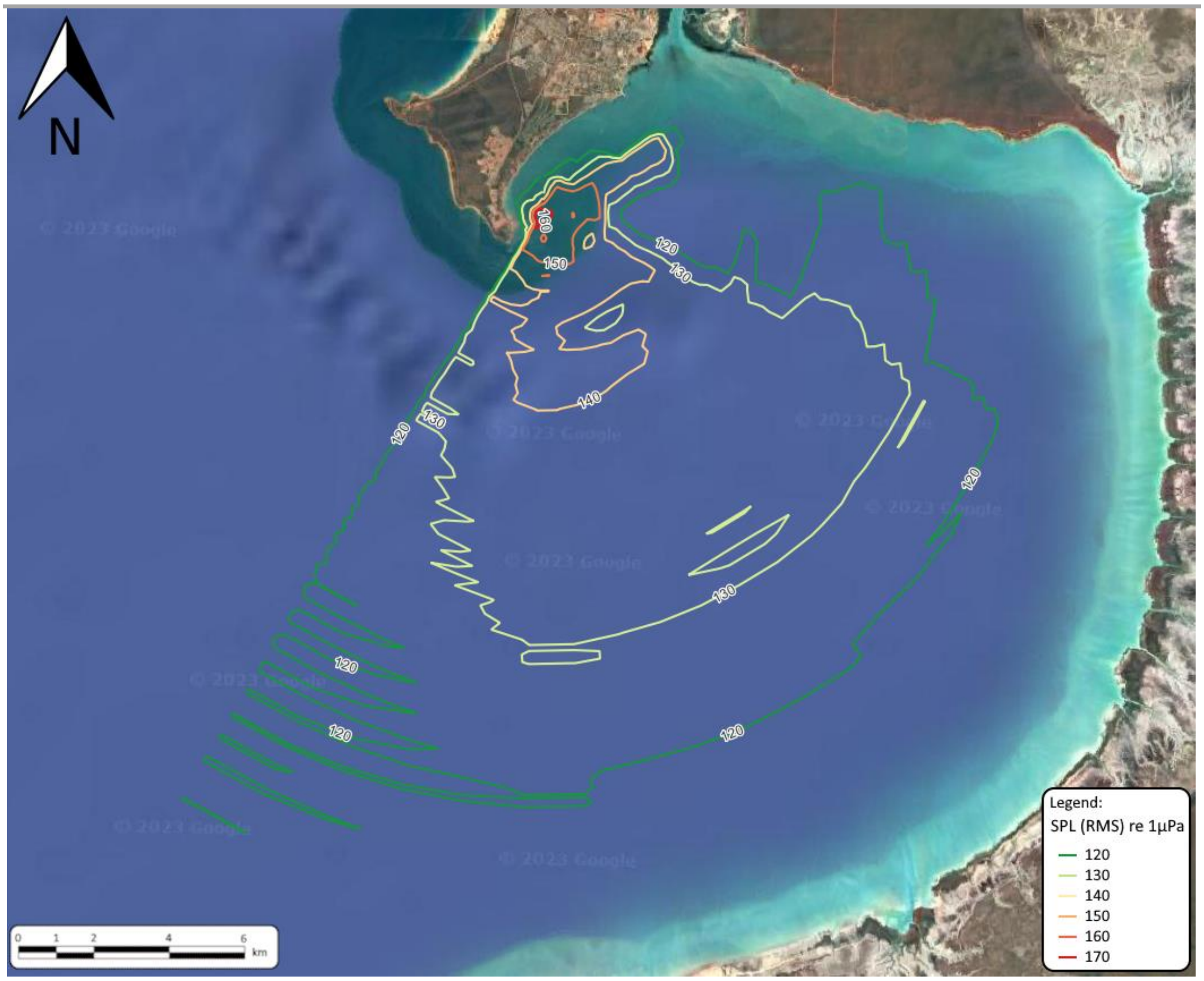


Figure D-2 : Noise Contour Map – Pile (N) – Behavioural – MSL – Whales

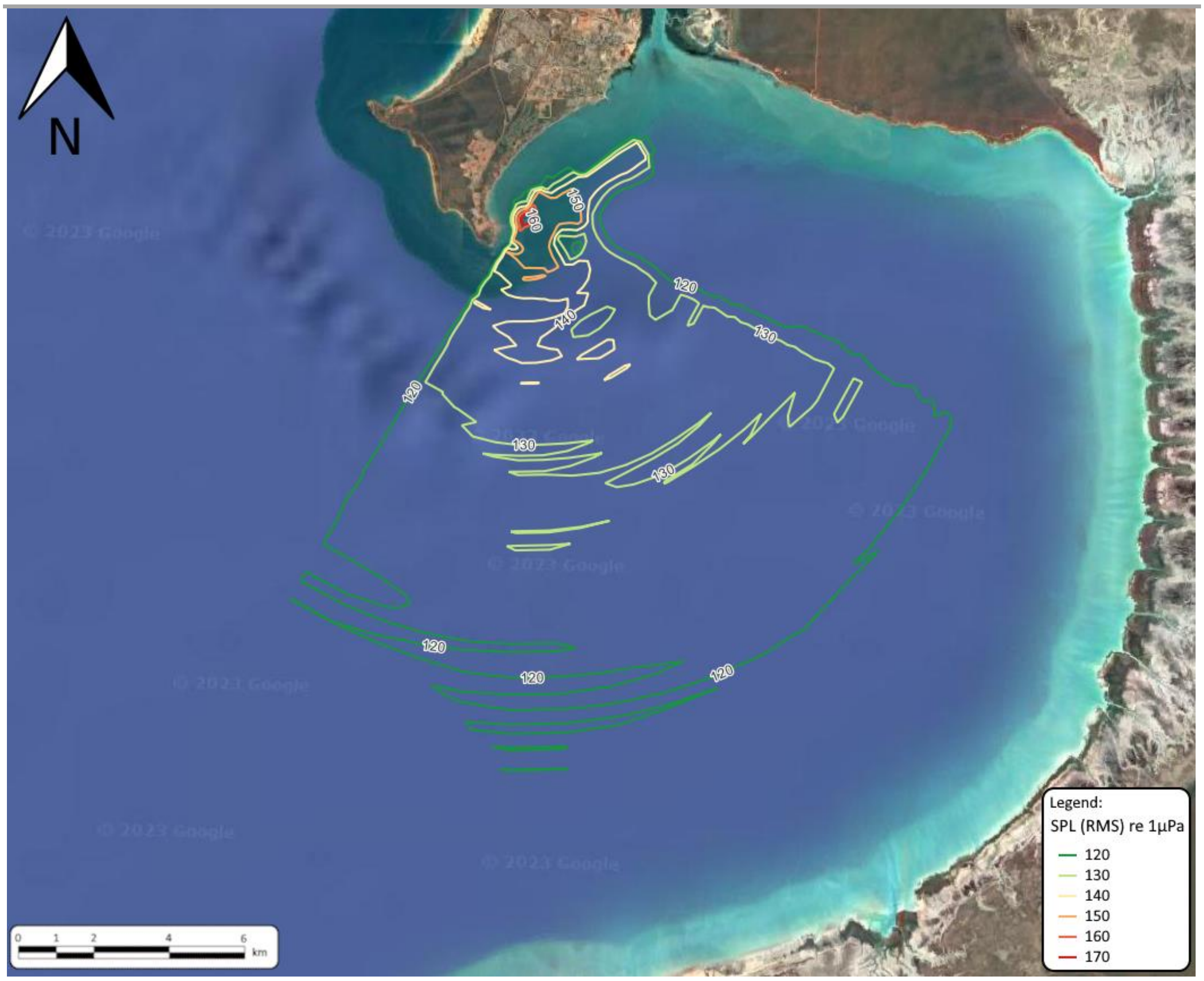


Figure D-3 : Noise Contour Map – Pile (N) – Behavioural – LAT – Whales

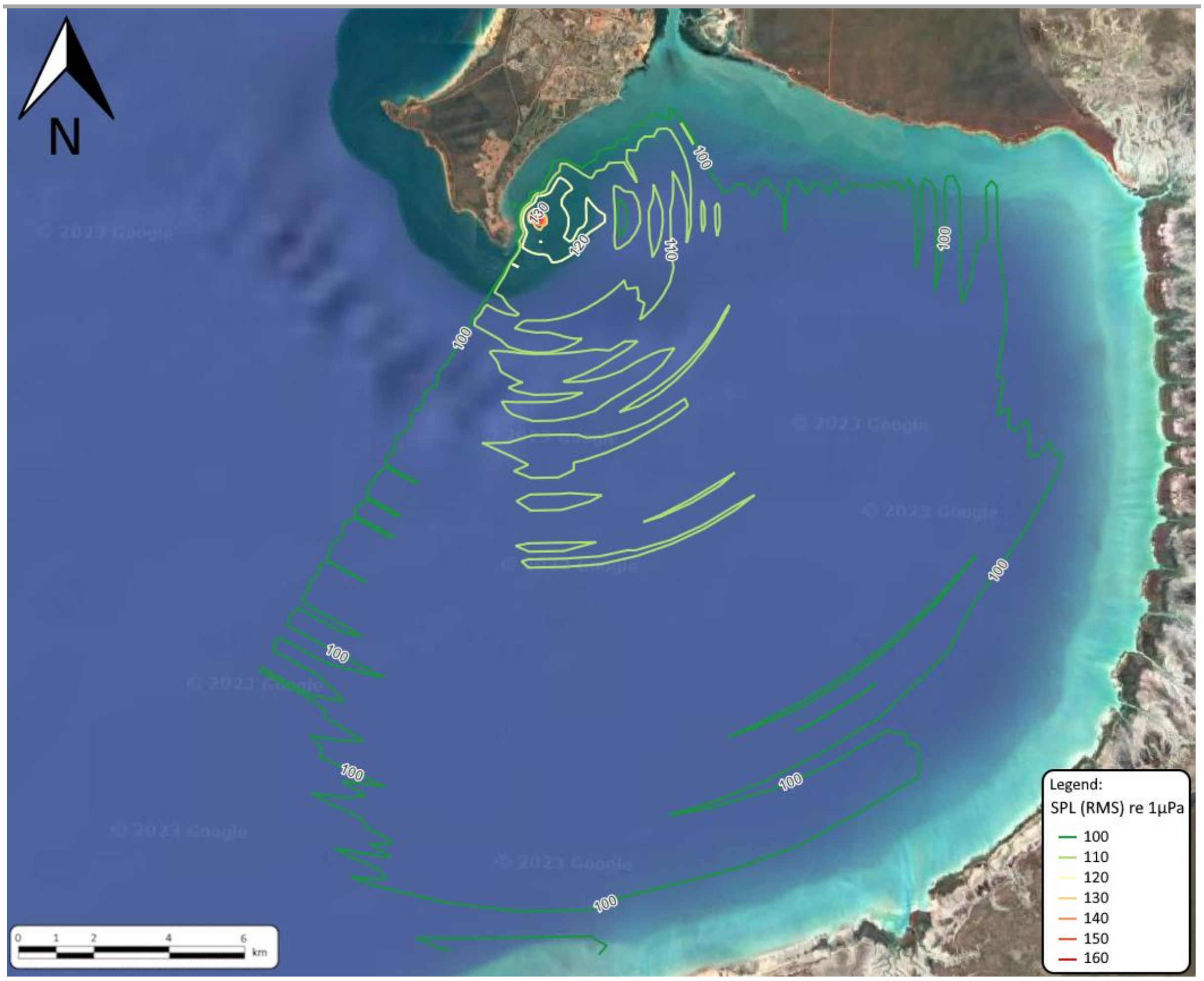


Figure D-4 : Noise Contour Map – Pile (N) – Behavioural – HAT – Dolphins

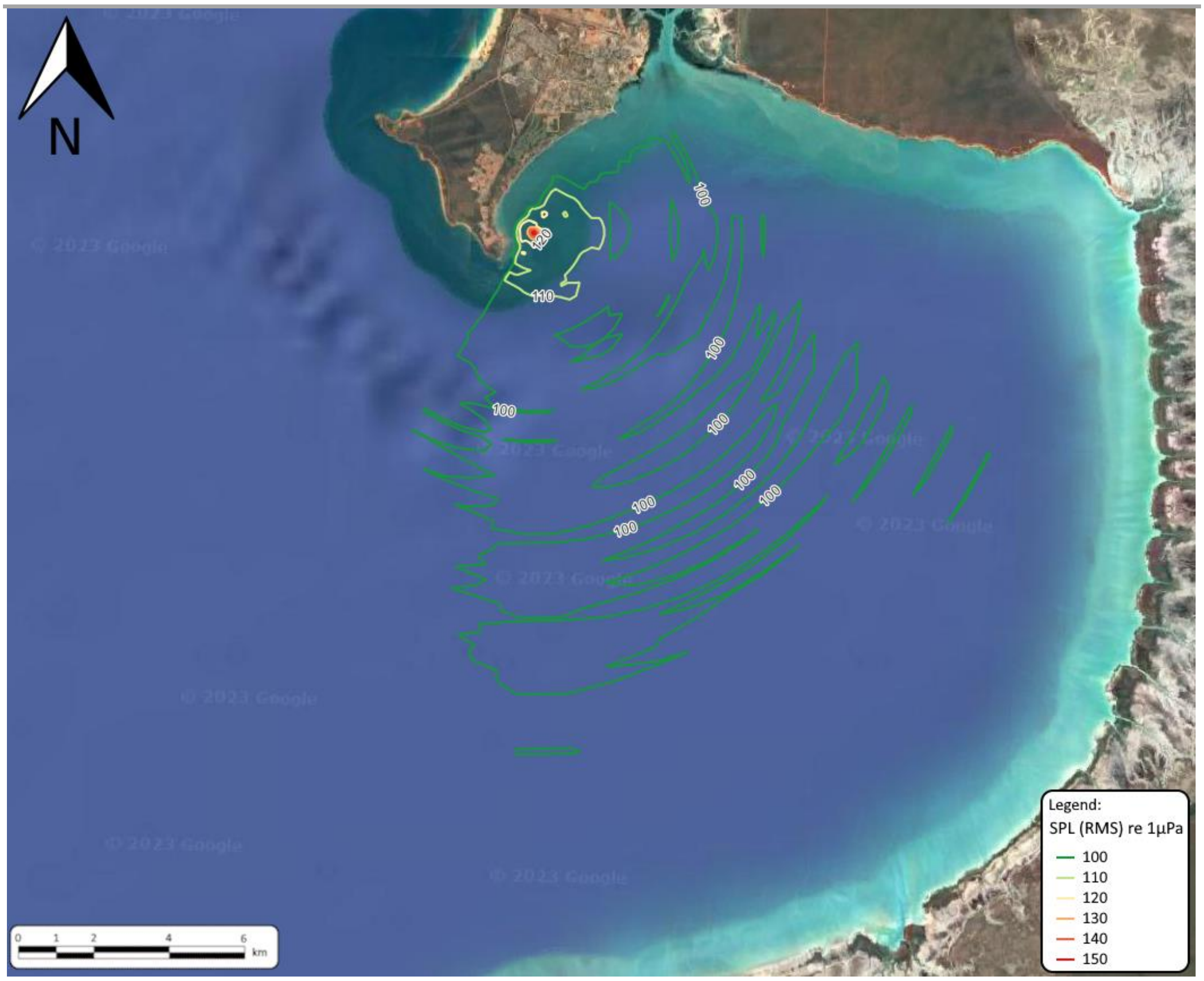


Figure D-5 : Noise Contour Map – Pile (N) – Behavioural – HAT – Sirenians

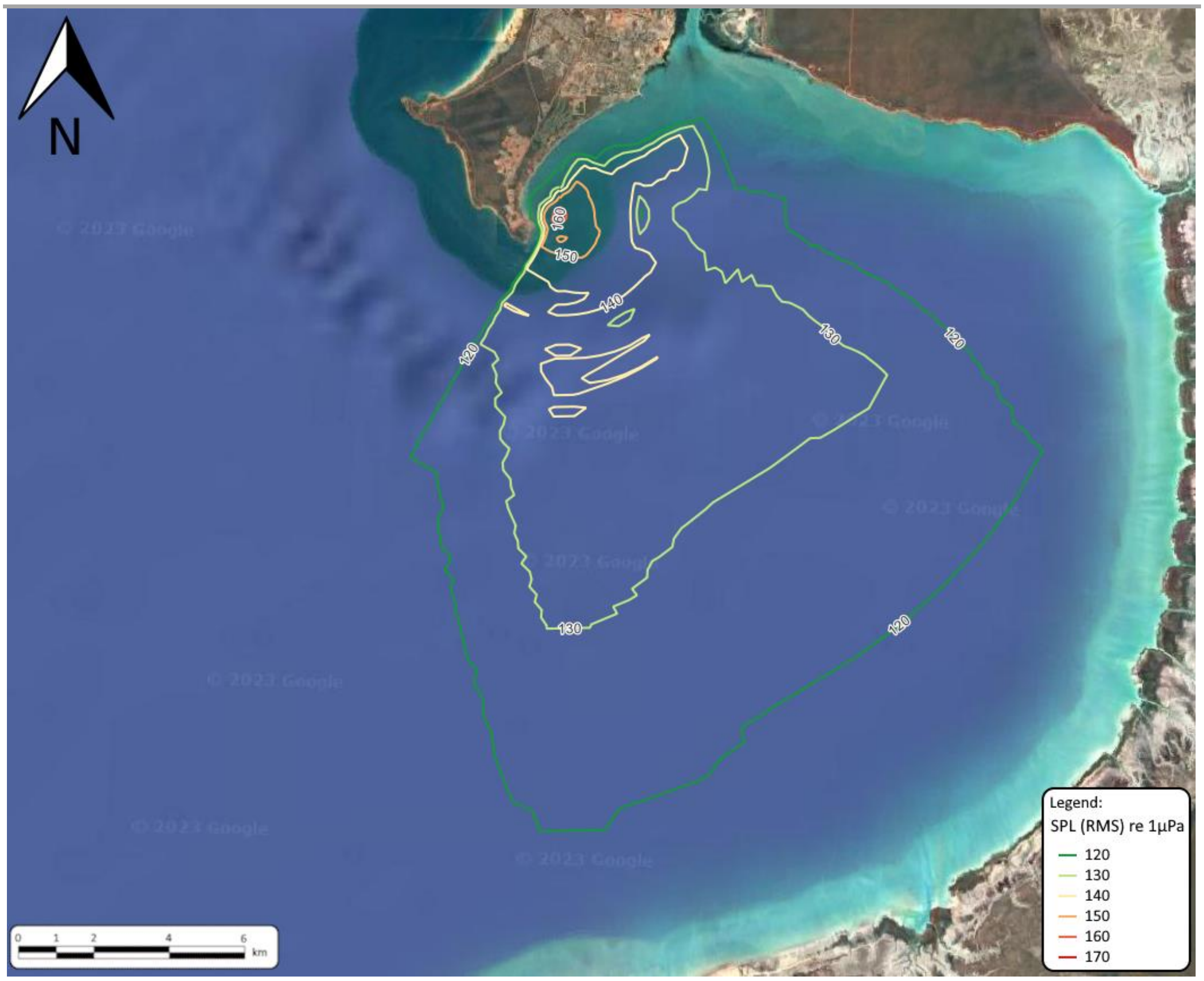


Figure D-6 : Noise Contour Map – Pile (N) – Behavioural – HAT – Turtles / Sawfish / Crocodiles

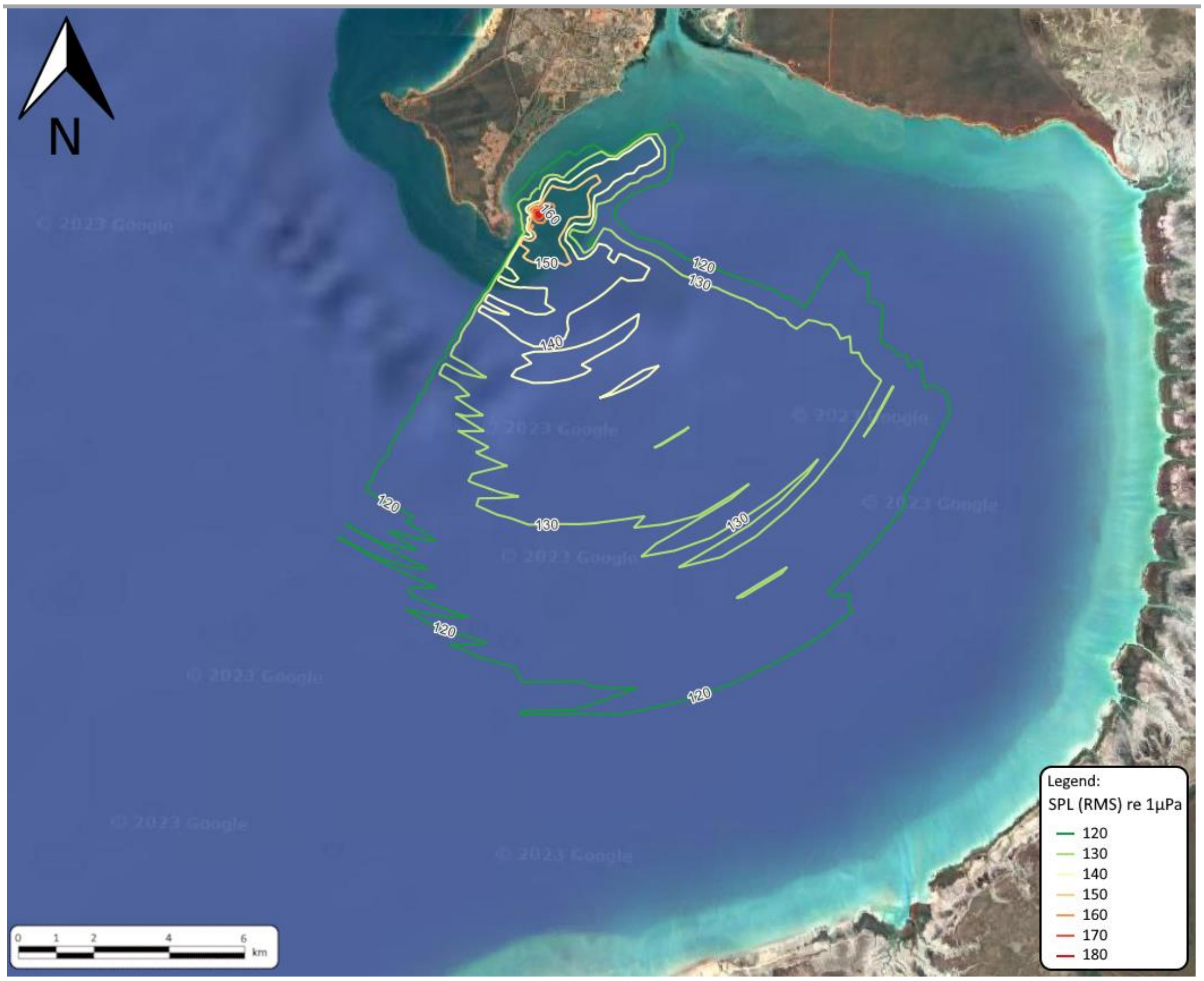


Figure D-7 : Noise Contour Map – Pile (S) – Behavioural – HAT – Whales

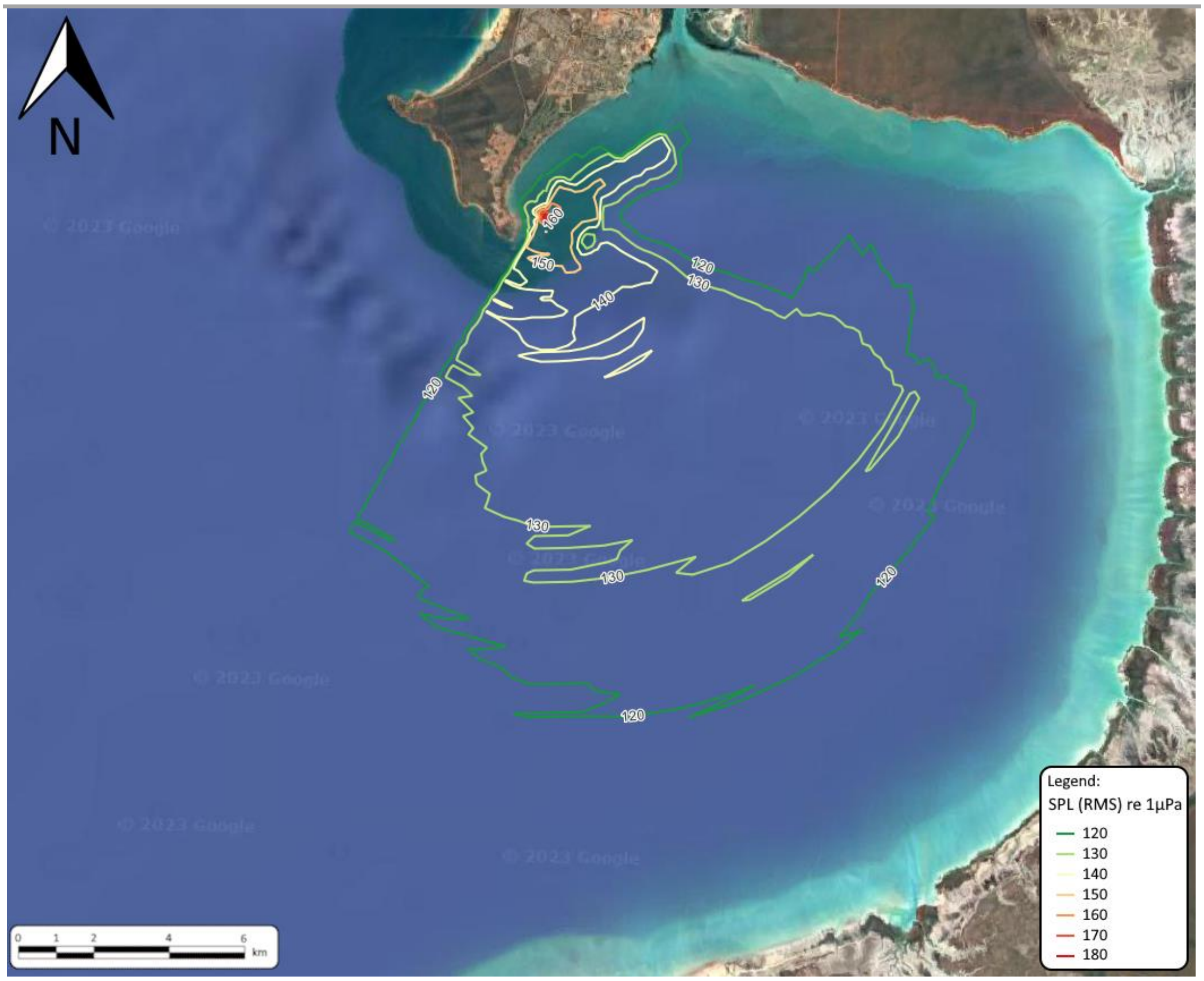


Figure D-8 : Noise Contour Map – Pile (S) – Behavioural – MSL – Whales

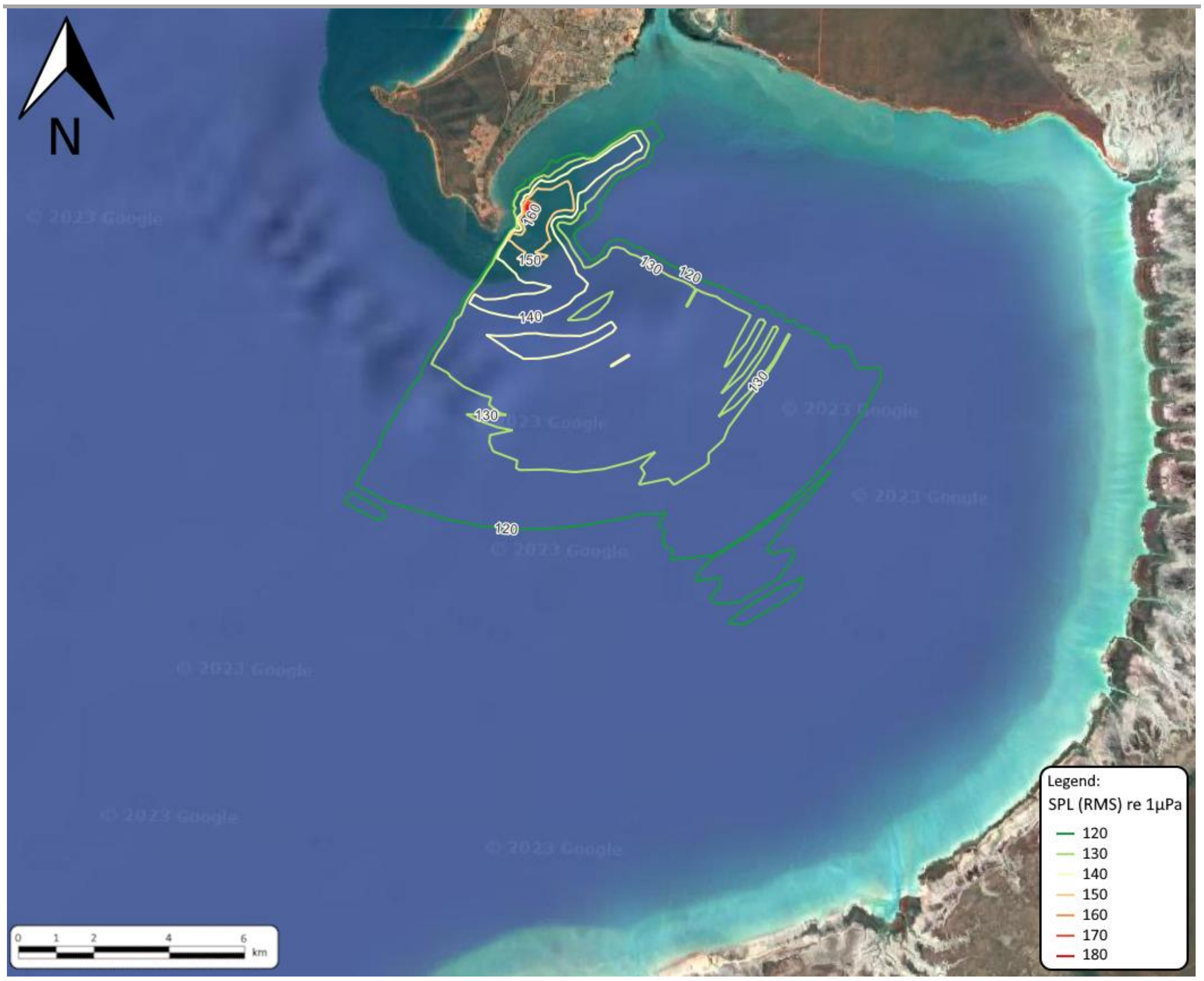


Figure D-9 : Noise Contour Map – Pile (S) – Behavioural – LAT – Whales

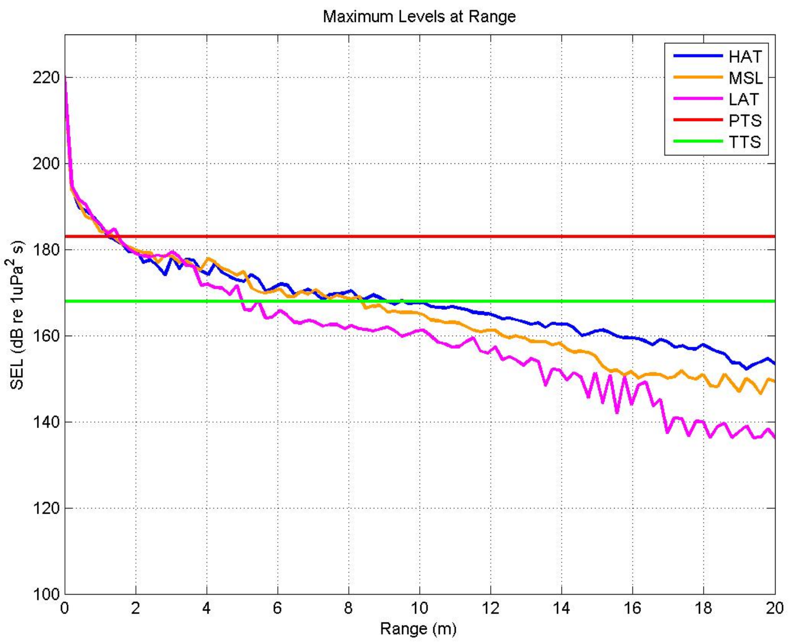


Figure E-1 : PTS & TTS Range Graph – Pile (N) – Whales

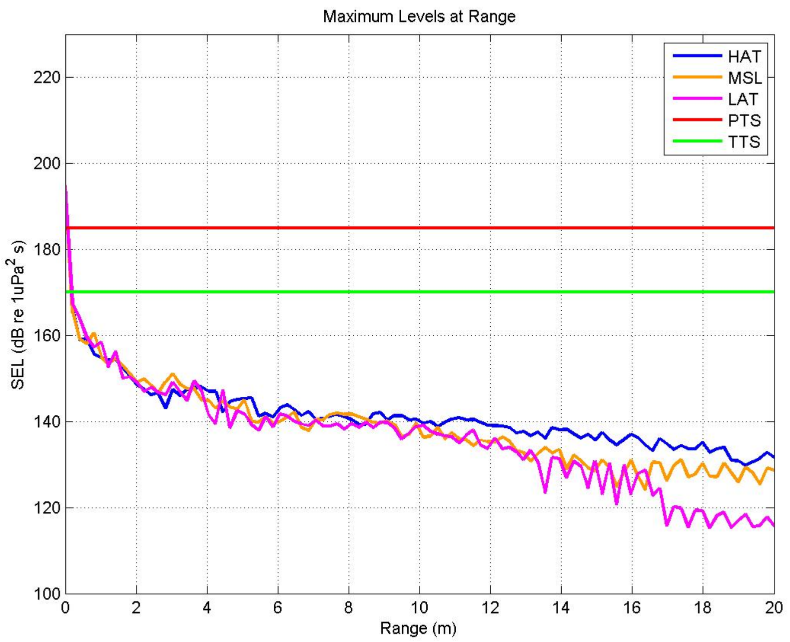


Figure E-2 : PTS & TTS Range Graph – Pile (N) – Dolphins

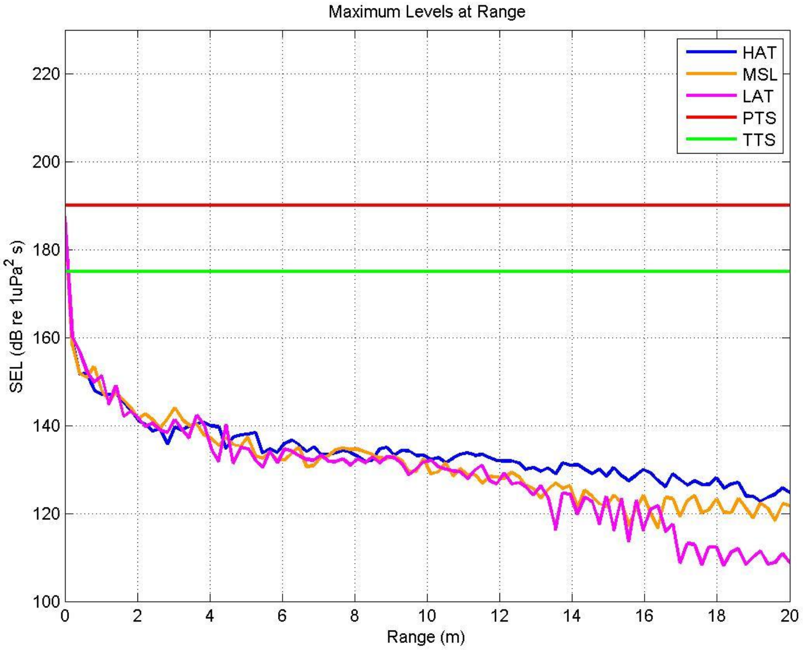


Figure E-3 : PTS & TTS Range Graph – Pile (N) – Sirenians

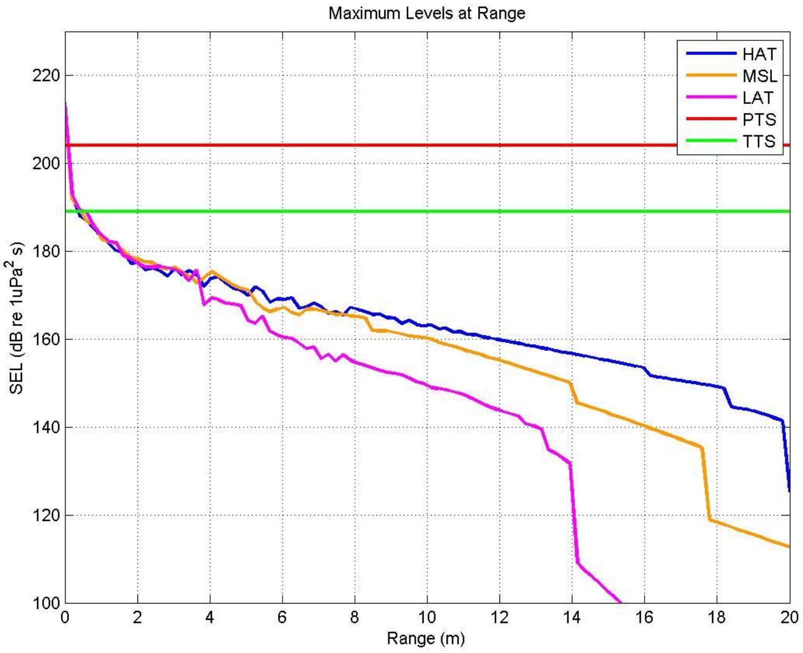


Figure E-4 : PTS & TTS Range Graph – Pile (N) – Turtles / Sawfish / Crocodiles

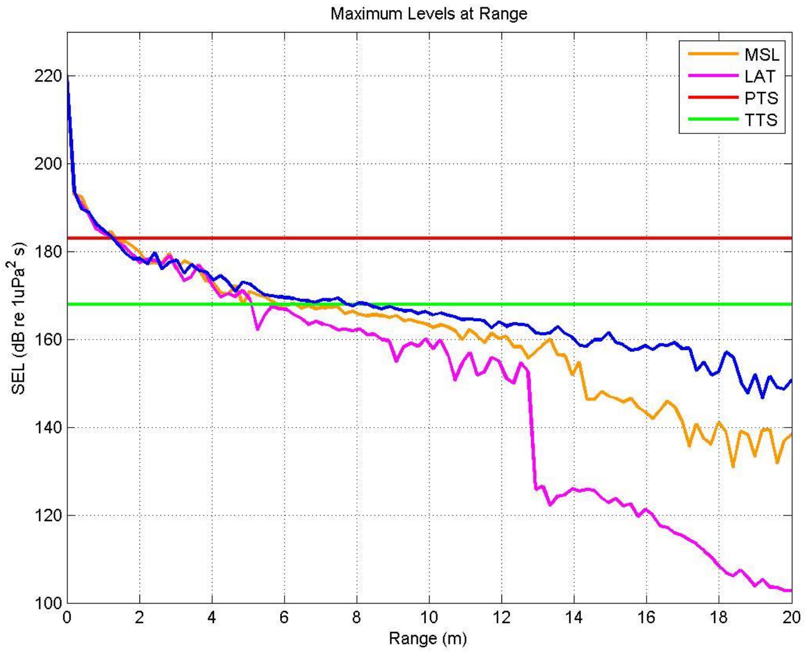


Figure E-5 : PTS & TTS Range Graph – Pile (S) – Whales

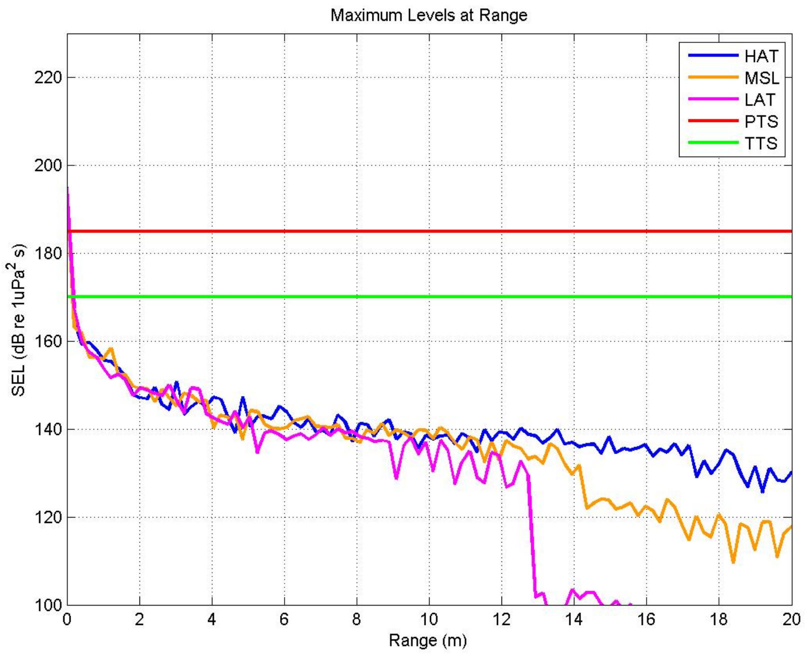


Figure E-6 : PTS & TTS Range Graph – Pile (S) – Dolphins

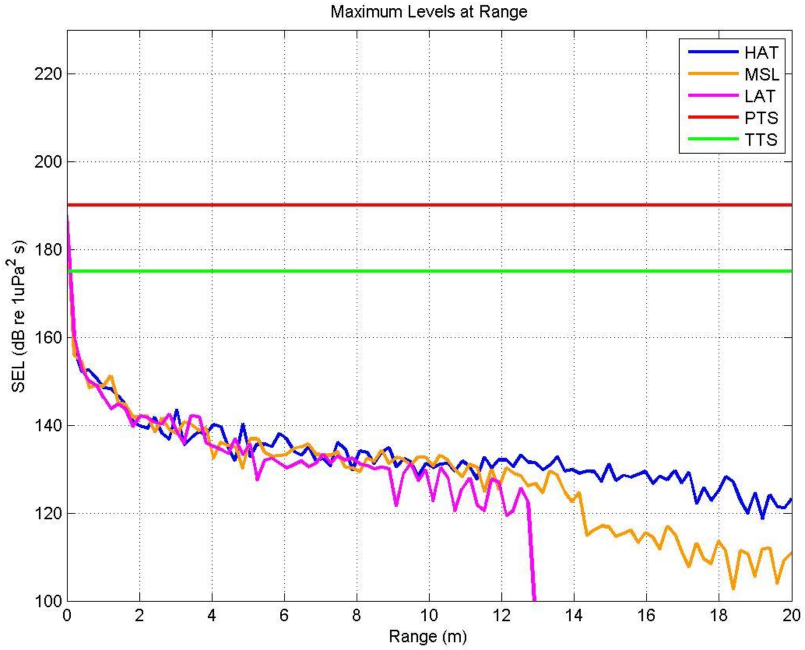


Figure E-7 : PTS & TTS Range Graph – Pile (S) – Sirenians

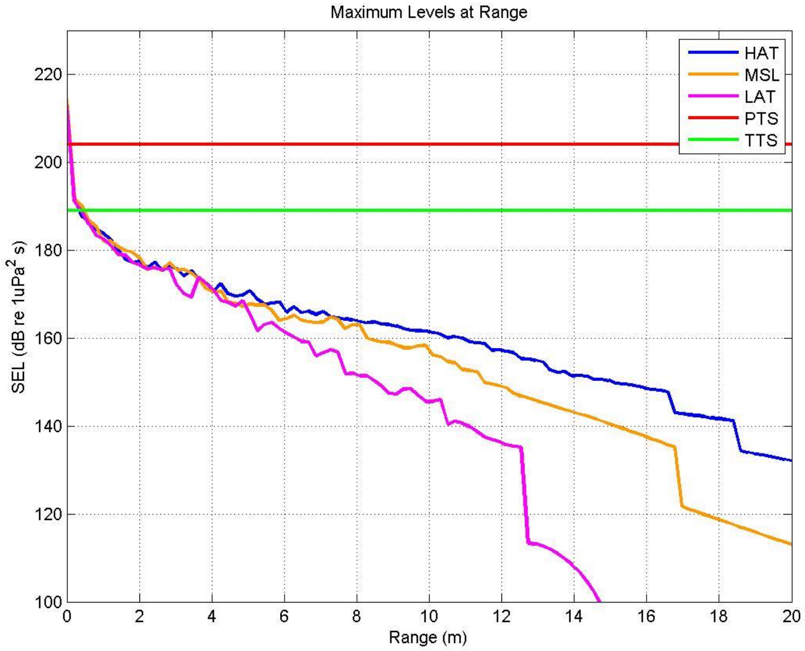


Figure E-8 : PTS & TTS Range Graph – Pile (S) – Turtles / Sawfish / Crocodiles

APPENDIX F

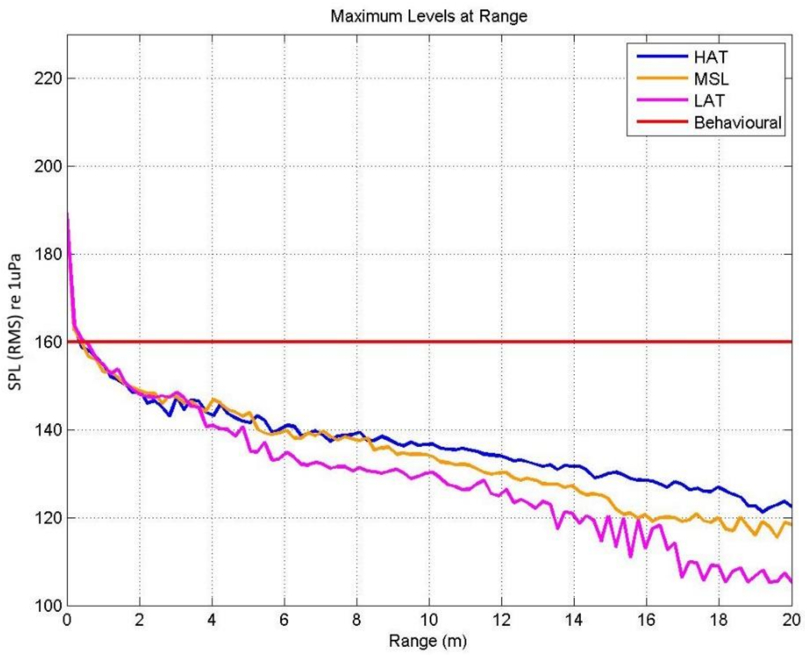
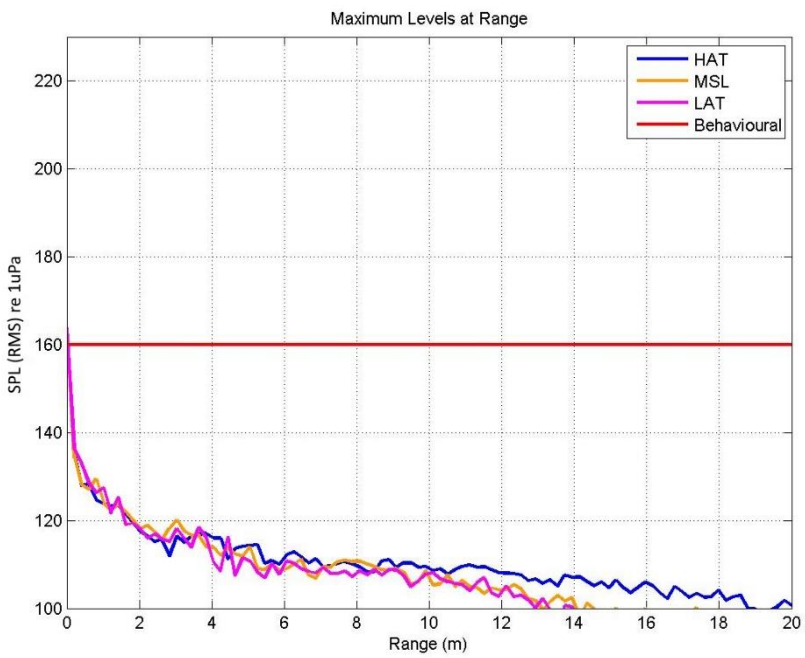


Figure F-1 : Behavioural Range Graph – Pile (N) – Whales



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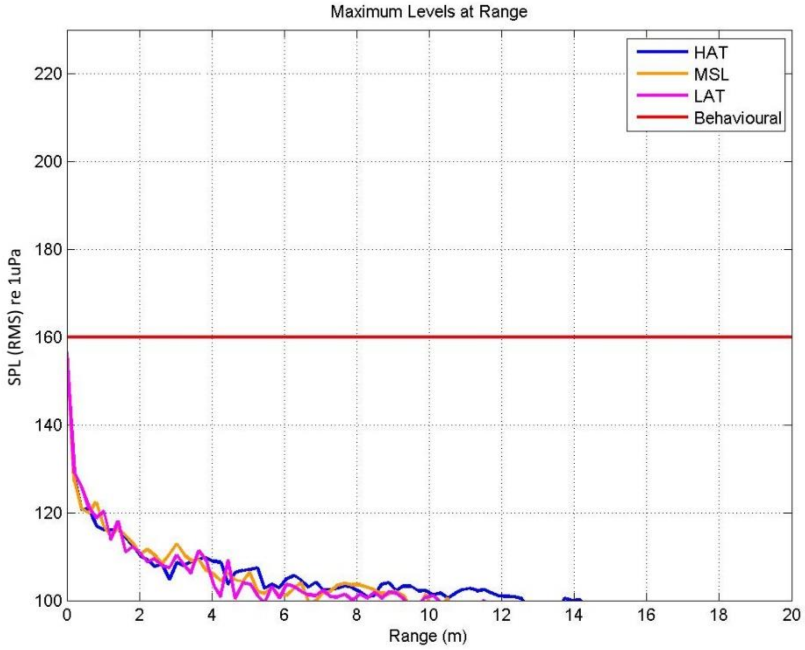

Figure F-3 : Behavioural Range Graph – Pile (N) – Sirenians

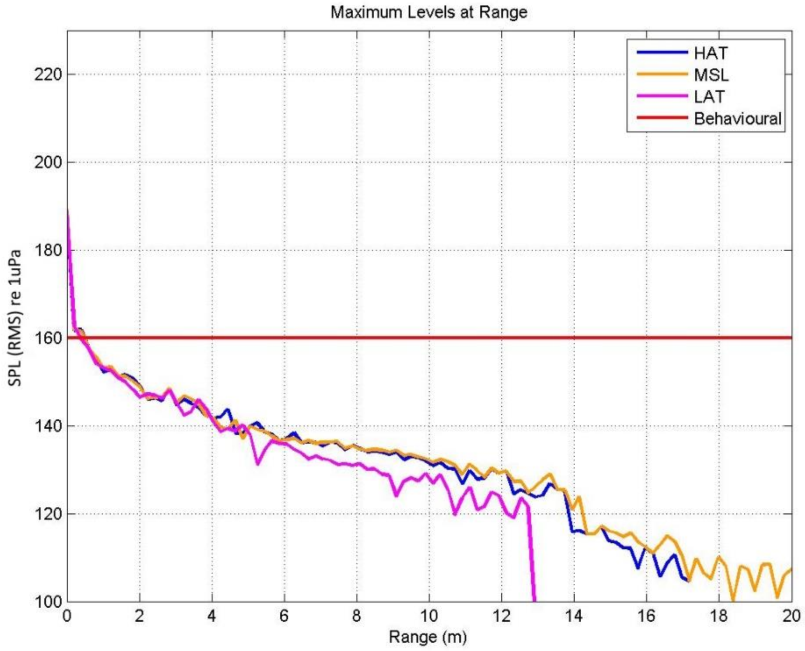

Figure F-4 : Behavioural Range Graph – Pile (N) – Turtles / Sawfish / Crocodiles

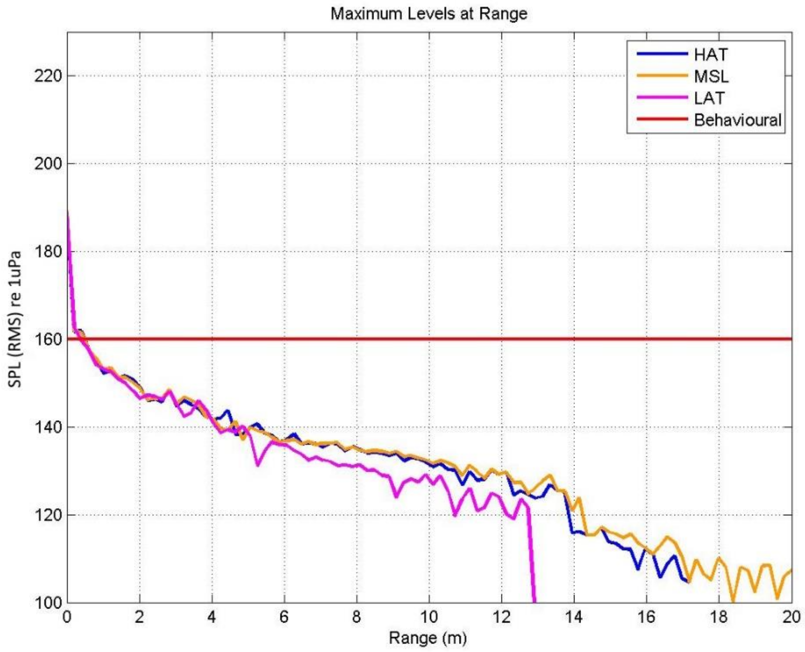

Figure F-5 : Behavioural Range Graph – Pile (S) – Whales

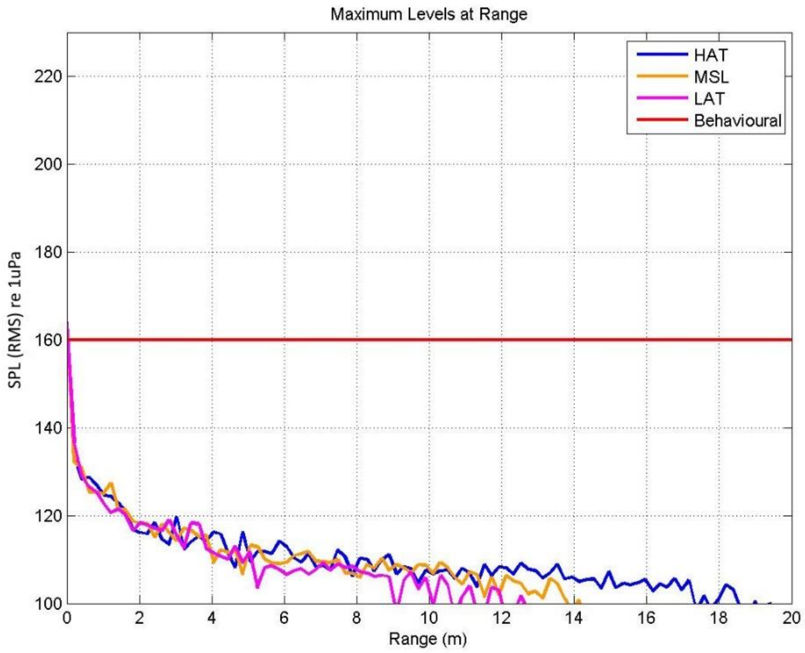

Figure F-6 : Behavioural Range Graph – Pile (S) – Dolphins

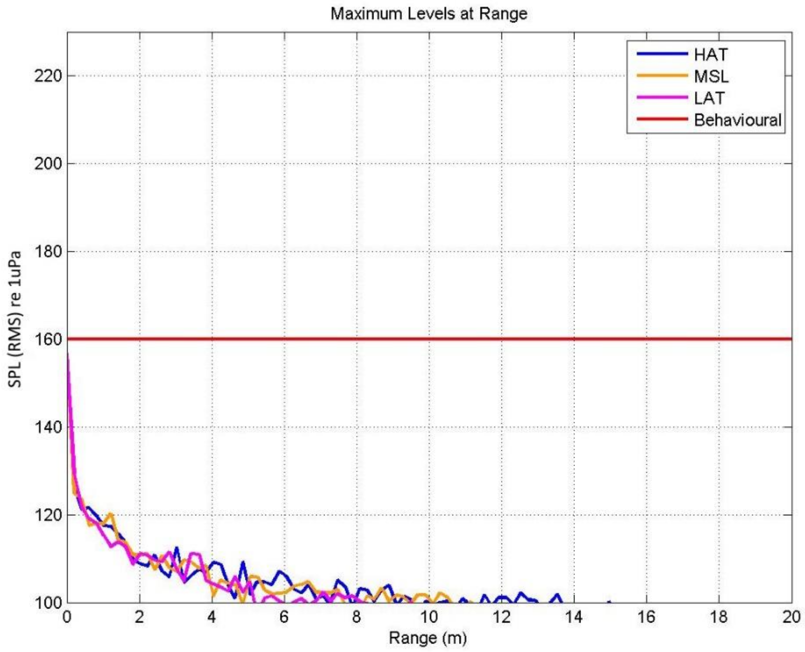

Figure F-7 : Behavioural Range Graph – Pile (S) – Sirenians

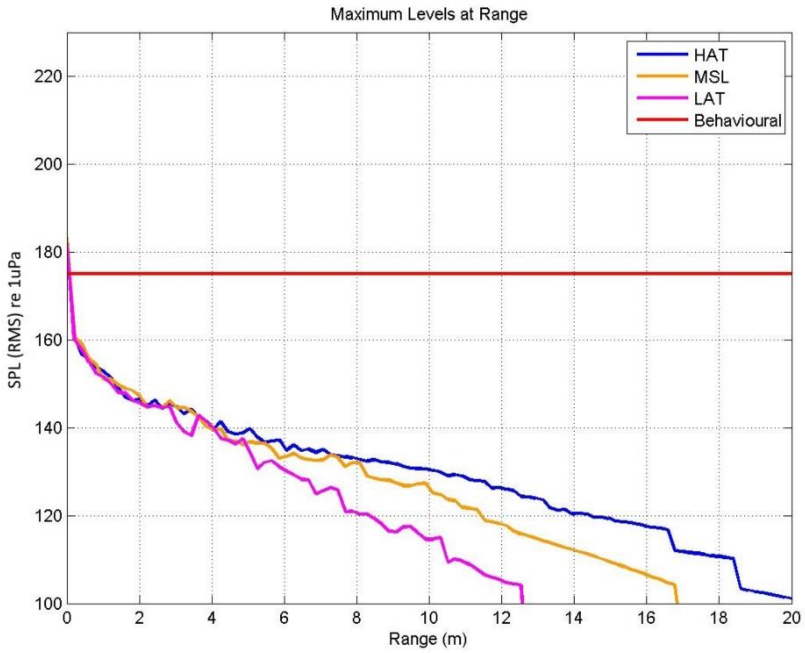

Figure F-8 : Behavioural Range Graph – Pile (S) – Turtles / Sirenians / Crocodiles

APPENDIX G

Note: All of the following equations use SI units: Pascals, metres, seconds, and kilograms. For clarity, units are not included in every equation and constant.

Hearing Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	K (dB)
Low-frequency (LF) cetaceans	1.0	2	0.2	19	0.13	179
High-frequency (HF) cetaceans	1.6	2	8.8	110	1.20	177
Very High-frequency (HF) cetaceans	1.8	2	12	140	1.36	152

* Equations associated with Technical Guidance's auditory weighting ($W_{aud}(f)$) and exposure functions ($E_{aud}(f)$):

$$W_{aud}(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a[1+(f/f_2)^2]^b}\right\}$$

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

Assets | Engineering | Environment | Noise | Spatial | Waste

Talis Consultants
ABN 85 967 691 321

Head Office
Level 1, 604 Newcastle Street,
Leederville
Western Australia 6007

PO Box 454,
Leederville
Western Australia 6903

NSW Office
76 Bridge Road, Nowra
New South Wales, 2541

PO Box 1189, Nowra
New South Wales, 2541