Technical Report A

Marine ecology and water quality impact assessment

Part 2

Appendix A-1: Baseline Monitoring of Ambient Underwater Noise Environment

Viva Energy Gas Terminal Project Environment Effects Statement

JASCO Applied Sciences (Australia) Pty Ltd

26 November 2021

Submitted to:

AECOM

Contract Dated 21 July 2021

P001627-001

Document 02580

Version 1.0

Contents

Executive Summary 1

1. Introduction 2

1.1. Project Overview 2

1.2. Study Specific Introduction 2

1.3. Changes to Sound as it Travels in the Ocean 3

1.4. Ambient Ocean Soundscape 4

1.5. Anthropogenic Contributors to the Soundscape 5

2. Methods 7

2.1. Acoustic Data Acquisition 7

2.1.1. Deployment Locations 7

2.2. Automated Data Analysis 7

2.2.1. Total Ocean Sound Levels 8

2.2.2. Vessel Noise Detection 9

3. Results and Discussion 11

3.1. Soundscape Characterisation 11

3.1.1. Spectrograms and Statistical Analysis 11

3.1.2. Frequency Weighted Sound Exposure Levels 16

Acknowledgements 18

Glossary 19

Literature Cited 29

Appendix A. Underwater Acoustics A-1

Appendix B. Acoustic Data Analysis Methods B-1

Appendix C. Recorder Calibration C-1

Appendix D. Noise Effect Criteria D-1

Appendix E. Mooring Design E-1

Figures

Figure 1. Map of location of the acoustic recorder and proposed project features in Corio Bay............3
Figure 2. Wenz curves....................5
Figure 3. Vessel traffic off near Geelong for 2019 and 2020. 6
Figure 4. The Autonomous Multichannel Acoustic Recorder 7
Figure 5. Example of broadband and 40–315 Hz band sound pressure level (SPL), as well as the number of tonals detected per minute as a vessel approached a recorder, stopped, and then departed....................10
Figure 6. (Top) In-band sound pressure level (SPL) by decade band and (bottom) long-term spectral average (LTSA) of underwater sound (UTC+10)....................12
Figure 7. (Top) percentiles and mean of decidecade sound pressure level (SPL) and (bottom) percentiles and probability density (grayscale) of 1-min power spectral density levels....................13
Figure 8. SPL by decade band, showing mean levels and percentiles over entire recording duration. 13
Figure 9. Median SPL by time of day for entire recording duration. 14
Figure 10. Median SPLs by day of week for entire recording duration. 15
Figure 11. Spectrum of sound levels on 14 Sep 2021 (UTC). 15
Figure 12. Vessel detections by hour. 16
Figure 13. Auditory frequency weighted ambient noise (10 Hz and above) over the measurement period shown as daily sound exposure levels (SEL)....................17

Figure B-1. Major stages of the automated acoustic analysis process performed with JASCO's custom software suite. B-1
Figure B-2. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale....................B-4
Figure B-3. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient noise shown on a logarithmic frequency scale. B-4
Figure C-1. Split view of a G.R.A.S. 42AC pistonphone calibrator with an M36 hydrophone..............C-1
Figure D-1. Application of an auditory weighting function. D-2
Figure D-2. Auditory weighting functions for functional marine mammal hearing groups as recommended by NMFS (2018)....................D-4
Figure E-1. Mooring design for acoustic environment recordings. E-1

Tables

Table 1. Deployment details of the Autonomous Multichannel Acoustic Recorder (AMAR) deployed in Corio Bay....................7
Table 2. Statistical analysis of sound levels for full recording period. 14
Table 13. Daily sound exposure level (SEL, dB re 1 µPa²s) statistics for the hearing groups (NMFS 2018) relevant to the assessment over the entire measurement period. 17

Table B-1. Decidecade band frequencies (Hz)....................B-5
Table B-2. Decade-band frequencies (Hz)....................B-6
Table D-1. Criteria for effects of continuous noise exposure, including vessel noise, for marine mammals....................D-1
Table D-2. Marine mammal hearing groups (NMFS 2018). D-3
Table D-3. Parameters for the auditory weighting functions used in this project as recommended by NMFS (2018). D-4

Executive Summary

This technical report provides the results of underwater acoustic monitoring conducted to support an underwater noise impact assessment (Lucke and McPherson 2021) and inform underwater acoustic modelling (Green et al. 2021) which forms part of the Environment Effects Statement (EES) for the Viva Energy Gas Terminal Project (the project).

The measurement component of this program was completed to characterise the ambient environment, and to achieve this a single JASCO Autonomous Multichannel Acoustic Recorder (AMAR) was deployed in Corio Bay from Aug-Sep 2021 for a period of 37 days. The recorder collected data continuously over the frequency band of 10–32000 Hz, and thus captured the majority of anthropogenic contributions in the area, along with natural and biological contributors. These data were analysed with the goal being to present this the data in a manner that documents the baseline underwater sound conditions in Corio Bay and allows us to examine temporal variations, and to correlate with external factors that change sound levels such as weather and human activities.

The most substantial contribution to the soundscape in Corio Bay is from vessel noise occupying bands below approximately 1000 Hz, with many distinct tones related to vessel propulsion observable in the 30-200 Hz ranges of data representations such as spectrogram and percentiles. JASCO's vessel detector, optimised for larger vessels, demonstrates that these signals are present for a significant amount of time per day for the entire monitoring period.

The soundscape also includes a faint dusk and dawn invertebrate chorus, with the primary contributor likely being snapping shrimp. No automated detectors or manual review was conducted to determine the presence of marine mammals. The low tidal variation does not offer a strong contribution to the soundscape, and on occasion, a significant storm event was recorded.

The monitoring results demonstrate that when compared to long term recordings of other Australian harbours, such as Fremantle Inner Harbour (Salgado Kent et al. 2012), Corio Bay has higher median sound levels, and has a soundscape primarily defined by anthropogenic contributors, with shipping being the dominant factor.

1. Introduction

1.1. Project Overview

This technical report provides the results of underwater acoustic monitoring conducted to support an underwater noise impact assessment (Lucke and McPherson 2021) and inform underwater acoustic modelling (Green et al. 2021) which forms part of the Environment Effects Statement (EES) for the Viva Energy Gas Terminal Project (the project).

Viva Energy Gas Australia Pty Ltd (Viva Energy) is planning to develop a gas terminal using a ship known as a floating storage and regasification unit (FSRU), which would be continuously moored at Refinery Pier in Corio Bay, Geelong. The key objective of the project is to facilitate supply of a new source of gas for the south-east Australian gas market where there is a projected supply shortfall in coming years.

The FSRU would store liquefied natural gas (LNG) received from visiting LNG carriers (that would moor directly adjacent to the FSRU) and would convert LNG back into a gaseous state by heating the LNG using seawater (a process known as regasification) as required to meet industrial, commercial, and residential customer demand. A 7 km gas transmission pipeline would transfer the gas from the FSRU to the Victorian Transmission System (VTS) at Lara.

The project would be situated adjacent to, and on, Viva Energy's Geelong Refinery, within a heavily developed port and industrial area on the western shores of Corio Bay between the Geelong suburbs of Corio and North Shore. Co-locating the project with the existing Geelong Refinery and within the Port of Geelong offers significant opportunity to minimise potential environmental effects and utilise several attributes that come with the port and industrial setting.

In December 2020, the Victorian Minister for Planning determined that the project requires assessment through an EES under the *Environment Effects Act 1978* (Vic). The reasons for the decision were primarily related to the potential for significant adverse effects on the marine environment of Corio Bay and the potential for contributing to greenhouse gas emissions. Secondarily, the EES was required to assess the effects of the project on air quality, noise, land use, Aboriginal and historic heritage, native vegetation, groundwater, traffic, and transport as well as visual amenity.

In January 2021, the project was also determined to require assessment and approval under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) due to the potential for the project to have a significant impact on wetlands of international importance, listed threatened species and communities, and listed migratory species. The EES process is the accredited environmental assessment process for the controlled action decision under the EPBC Act in accordance with the bilateral agreement between the Commonwealth and Victorian governments.

1.2. Study Specific Introduction

The measurement component of this program was completed to characterise the ambient environment over a period of approximately one month. A single JASCO Autonomous Multichannel Acoustic Recorder (AMAR) was deployed in Corio Bay (Figure 1) from Aug-Sep 2021.

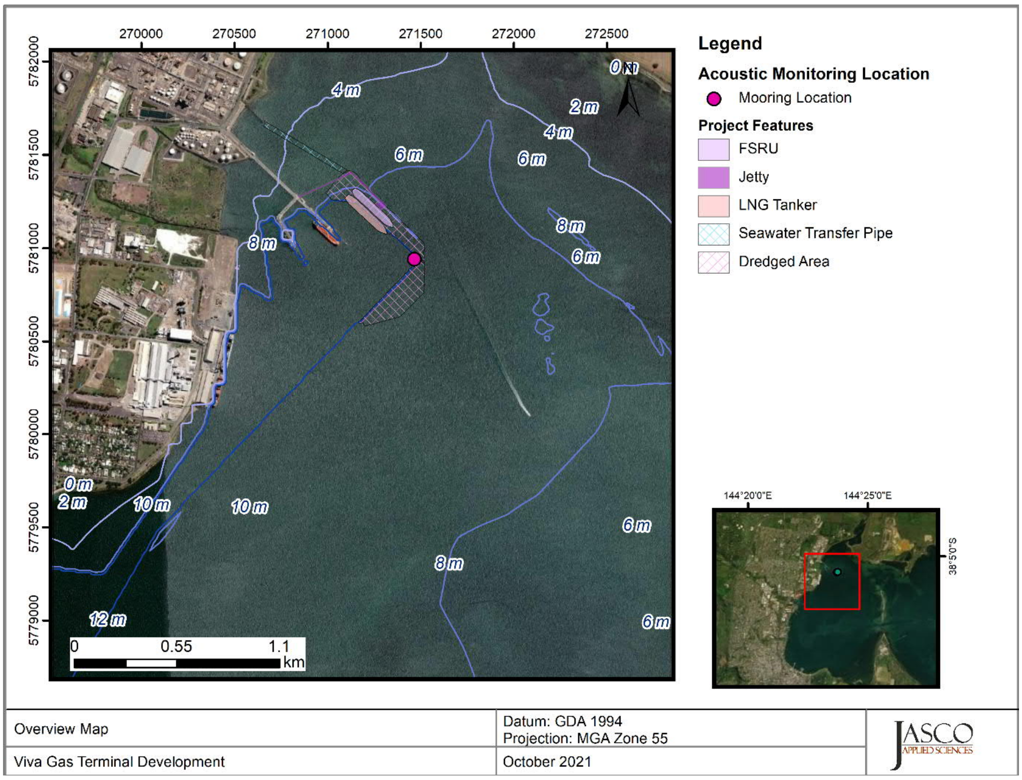


Figure 1. Map of location of the acoustic recorder and proposed project features in Corio Bay.

1.3. Changes to Sound as it Travels in the Ocean

A key question in the study of underwater sound is how a sound changes in nature as it propagates from its source to a receiver some distance away. Understanding and modelling sound propagation in the ocean is a complex topic that is the subject of numerous textbooks. This section provides a descriptive overview of key sound propagation concepts to assist with the results presented in this report. These concepts are integral to interpreting how sounds emitted by a source are transformed into those received some distance away. The sounds are transformed by 1) geometric spreading; 2) reflection, scattering and absorption at the seabed and sea surface; 3) refraction due to changes in sound speed with depth; and 4) absorption. This section does not address 3), as sound refraction plays only a minor role in shallow water.

At one extreme, the echolocation clicks of porpoises at 130 kHz travel only 500 m before becoming inaudible (Au et al. 1999). At the other extreme, sounds from fin whales (20 Hz) and low frequency energy from seismic airguns (5–100 Hz) can be detected thousands of km away under the right conditions (Nieukirk et al. 2012).

Geometric spreading losses: Sound levels from an omnidirectional point source in the water column are reduced with range, a process known as geometric spreading loss. As sound leaves the source, each spherical sound wave propagates outward and the sound energy is spread out over this ever-expanding sphere. The farther you are from the source, the lower the sound level you will receive. The received sound pressure levels at a recorder located a distance R (in m) from the source are 20log10R dB lower than the source level (SL) referenced to a standard range of 1 m. But the sound cannot spread uniformly in all directions forever. Once the waves interact with the sea surface and seabed, the spreading becomes cylindrical rather than spherical and is limited to the cylinder formed by the surface and seabed with a lower range-dependent decay of 10log10R dB. Thus, the water depth is a key factor in predicting spreading losses and thus received sound levels. These spherical and cylindrical spreading factors provide limits for quick approximations of expected levels from a given source. In very shallow waters, sound rapidly attenuates if the water depth is less than a quarter of a wavelength (Urick 1983).

Absorption, reflection, and scattering at the sea surface and seabed: If geometric spreading were the only factor governing sound attenuation in water, then at a given distance from a source, sound levels in shallow waters would almost always be higher than those in deep waters. In shallow water, however, the sound interacts more often with the seabed and sea surface than sound travelling in deep waters, and these interactions reflect, absorb, and scatter the sounds. The sea surface behaves approximately as a pressure release boundary, where incident sound is almost completely reflected with opposite phase. As a result, the sum of the incident and reflected sounds at the sea-surface is zero. At the seabed, many types of interactions can occur depending on the composition of the bottom. Soft silt and clay bottoms absorb sound, sand and gravel bottoms tend to reflect sound like a partially reflective mirror, and some hard yet elastic bottoms, such as limestone, reflect some of the sound while absorbing some of the energy by converting the compressional waves to elastic shear waves.

Absorption by sea water: As sound travels through the ocean, some of the energy is absorbed by molecular relaxation in the seawater, which turn the acoustic energy into heat. The amount of absorption that occurs is quantified by an attenuation coefficient, expressed in units of decibels per kilometre (dB/km). This absorption coefficient depends on the temperature, salinity, pH, and pressure of the water, as well as the sound frequency. In general, the absorption coefficient increases with the square of the frequency, so low frequencies are less affected. The absorption of acoustic wave energy has a noticeable effect (>0.05 dB/km) at frequencies above 1 kHz. For example, at 10 kHz the absorption loss over 10 km distance can exceed 10 dB, as computed according to the formulae of François and Garrison (1982a, b).

1.4. Ambient Ocean Soundscape

The ambient acoustic environment, or soundscape, consists of cumulative contributions from abiotic (geophonic), biotic (biophonic), and man-made (anthrophonic) sound sources (Krause 2008). Variation in soundscape characteristics over time and space can act as proxies for geographical, biological, and anthropogenic events occurring within an environment.

In the marine environment, geophonic elements of the soundscape commonly correlate with oceanographic conditions. Increased sea state and wind speed lead to higher sound intensities across frequencies ranging from 500 Hz to 30 kHz, via sound produced by breaking waves, cavitation, surface flow noise, and pressure changes (Knudsen et al. 1948, Wenz 1962) (Figure 2). Rainfall elevates sound levels in the 1–15 kHz frequency range, via surface impacts and bubble entrainment (Heindsmann et al. 1955, Bom 1969, Scrimger et al. 1987). The specific frequency band affected by rainfall depends on rain strength and droplet size. Abiotic acoustic contributions are often unpredictable or irregular (Urick 1983). For example, significant low frequency acoustic energy can be contributed to marine soundscapes by earthquakes and sea ice movement (Urick 1974, Matsumoto et al. 2014). On the other hand, biophonic contributions often feature seasonal and diel activity patterns (Hannay et al. 2013, Erbe et al. 2017). Water movement, or flow noise, is considered to be a pseudo-noise that results from eddies and vortices forming as water flows past an acoustic receiver, and is not considered to be part of a marine soundscape (Strasberg 1979).

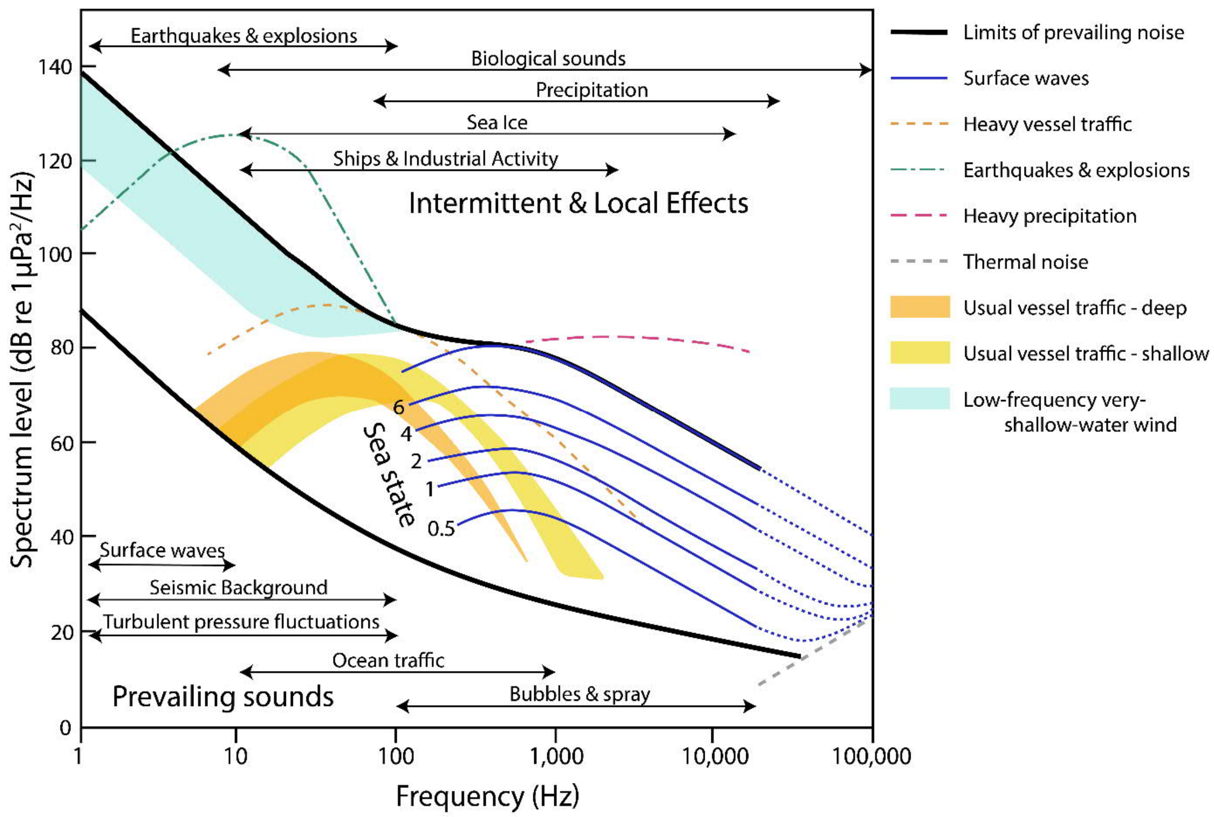


Figure 2. Wenz curves describing pressure spectral density levels of marine ambient sound from weather, wind, geologic activity, and commercial shipping (adapted from NRC 2003, based on Wenz 1962). Thick lines indicate limits of prevailing ambient sound.

1.5. Anthropogenic Contributors to the Soundscape

Anthropogenic (human-generated) sounds are relatively recent additions to soundscapes and, unlike biophonic contributors, often overlap in frequency, space, or time (Cato 1997, van Opzeeland and Boebel 2018). Anthrophonic contributors to global ocean noise include vessel traffic (commercial and recreational) at frequencies mainly in the frequency band 50–500 Hz. This sound can be a by-product of vessel operations, such as engine sound radiating through vessel hulls and cavitating propulsion systems, or it can be a product of active acoustic data collection with seismic surveys, military sonar, and depth sounding as the main contributors.

Marine construction projects involve vessel operations and project specific noise sources that can produce a range of both impulsive and non-impulsive noise. The contribution of anthropogenic sources to the ocean soundscape has increased from the 1950s to 2010, largely due to greater maritime shipping traffic (Ross 1976, Andrew et al. 2011). Oil and gas exploration with seismic airguns, marine pile driving, and oil and gas production platforms elevate sound levels over significant ranges when present (Bailey et al. 2010, Miksis-Olds and Nichols 2016, Delarue et al. 2018).The extent of seismic survey sounds has increased substantially following the expansion of oil and gas exploration into deep water, and seismic sounds have been detected across ocean basins (Nieukirk et al. 2004). Recent trends suggest that global sound levels are leveling off or potentially decreasing in some areas (Andrew et al. 2011, Miksis-Olds and Nichols 2016).

The main anthropogenic contributor to ambient sound in the present study was vessel noise. Vessels include large ships carrying goods to nearby ports, as well as smaller recreational boats. Figure 3 shows the vessel traffic over 2019 and 2020 of AIS-carrying vessels.

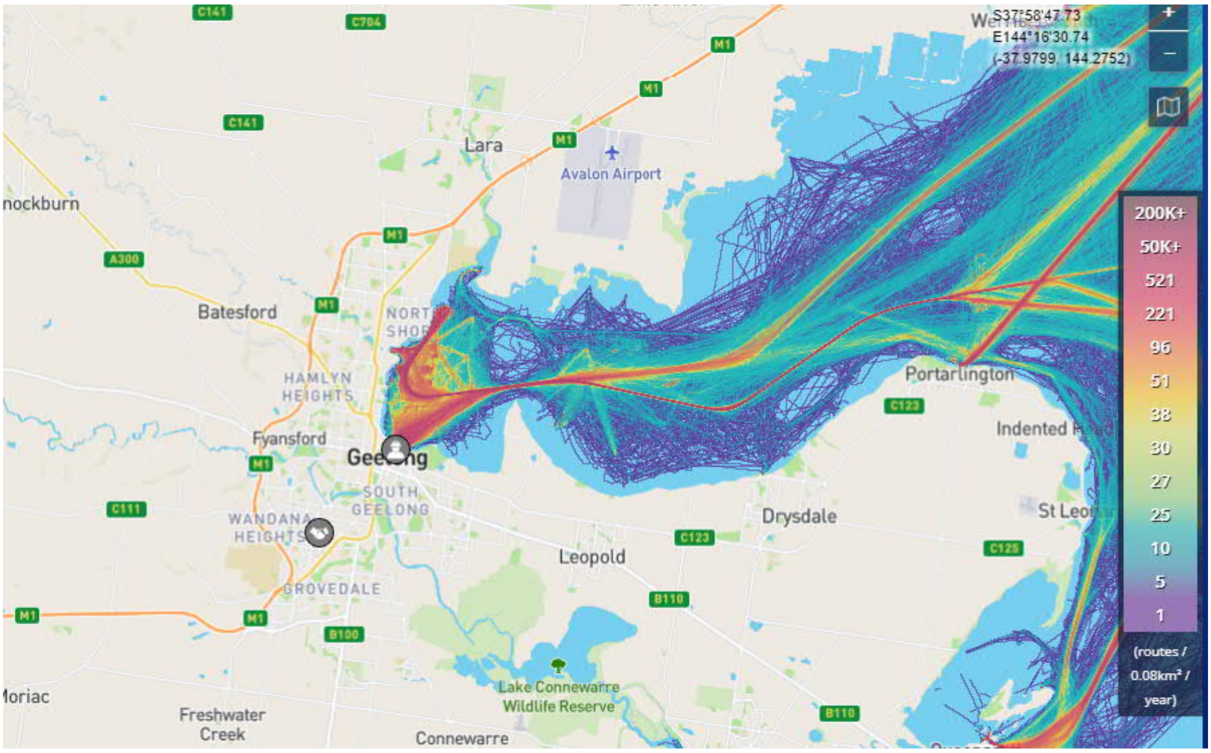


Figure 3. Vessel traffic near Geelong for 2019 and 2020. (source: marinetraffic.com; accessed 3 Nov 2021).

2. Methods

2.1. Acoustic Data Acquisition

Underwater sound was recorded with an Autonomous Multichannel Acoustic Recorder (AMAR, JASCO; Figure 4). The AMAR was fitted with an M36 omnidirectional hydrophone (GeoSpectrum Technologies Inc., −165 ± 3 dB re 1 V/µPa sensitivity). The AMAR hydrophone was protected by a hydrophone cage, and flow shields. The AMAR recorded continuously at 64 000 samples per second for a recording bandwidth of 10 Hz to 32 kHz, storing approximately 600 Gb of data; The recording channel had 24-bit resolution with a spectral noise floor of 20 dB re 1 µPa^2/Hz. Acoustic data were stored on 1TB of internal solid-state flash memory. Appendix C provides details about the calibration procedure.

Figure 4. The Autonomous Multichannel Acoustic Recorder (AMAR; JASCO) used to measure underwater sound Geelong Harbour.

2.1.1. Deployment Locations

The AMAR was deployed at one location (Figure 1) on the 25 Aug 2021 (Table 1) with the assistance of Consulting Environmental Engineers (CEE), as due to COVID restrictions, JASCO was unable to enter Victoria from Queensland. The AMAR was retrieved as planned on 30 Sep 2021 using grappling, also by CEE, and the retrieved AMAR recorded as planned from deployment until retrieval, for an average recording duration of 37 days. Appendix A provides details about the mooring design.

The AMAR location was determined through considering proximity to the project location, the requirement to place the recorder in the deepest water possible to achieve the best quality acoustic data (less influenced by wave / wind noise at the surface), and also staying as clear of shipping lanes as possible. The Geelong Harbour Master approved the mooring location.

Table 1. Deployment details of the Autonomous Multichannel Acoustic Recorder (AMAR) deployed in Corio Bay.

Station	Latitude	Longitude	Depth (m)	Deployment Date (UTC+10)	Retrieval Date (UTC+10)	Duration (days)
1	-38.090452	144.41069	13	26 Aug 2021	30 Sep 2021	37

2.2. Automated Data Analysis

The AMAR collected approximately 600 GB of acoustic data during this study. A specialised computing platform (PAMlab; JASCO) capable of processing acoustic data hundreds of times faster than real time was used. The system performed automated analysis of total ocean noise and sounds from vessels.

2.2.1. Total Ocean Sound Levels

The data collected at Corio Bay spans approximately one month, over the frequency band of 10–32000 Hz. The goal of the total ocean sound analysis is to present this expansive data in a manner that documents the baseline underwater sound conditions in Corio Bay and allows us to examine temporal variations, and to correlate with external factors that change sound levels such as weather and human activities.

The first stage of the total sound level analysis involves computing the peak pressure level (PK) and sound pressure level (SPL) for each minute of data. This reduces the data to a manageable size without compromising the value for characterising the soundscape (ISO 2017b, Ainslie et al. 2018, Martin et al. 2019). The SPL analysis is performed by averaging 120 fast-Fourier transforms (FFTs) that each include 1 s of data with a 50% overlap and that use the Hann window to reduce spectral leakage. The 1 minute average data were stored as power spectral densities (1 Hz resolution) and summed over frequency to calculate decidecade band SPL levels. Decidecade band levels are very similar to 1/3-octave-band levels. Table B-1 lists the decidecade band frequencies, and Table B-2 lists the decade-band frequencies. The decidecade analysis sums the frequency range from the 180,000 frequencies (representing the frequency range 1 Hz to 180 kHz) in the power spectral density data to a manageable set of 43 bands that approximate the critical bandwidths of mammal hearing. The decade bands further summarize the sound levels into four frequency bands for manageability. Detailed descriptions of the acoustic metrics and decidecade analysis can be found in Appendix B.

In Section 3, the total sound levels are presented as:

- **Band-level plots:** These strip charts show the averaged received sound pressure levels as a function of time within a given frequency band. We show the total sound levels (across the entire recorded bandwidth from 10 to 32,000 Hz) and the levels in the decade bands of 10–100, 100–1000, 1000–10,000, and 10,000–32,000 Hz. The 10–100 Hz band is associated with blue whales, large shipping vessels, flow and mooring noise. Sounds within the 100–1000 Hz band are generally associated with the physical environment such as wind and wave conditions but can also include both biological and anthropogenic sources such as southern right and humpback whales, fish, nearby vessels, and pile driving. Sounds above 1000 Hz include high-frequency components of humpback whale sounds, odontocete whistles and echolocation signals, snapping shrimp, wind- and wave-generated sounds, and sounds from human sources at close range including pile driving, vessels, seismic surveys, and sonars.
- **Long-term Spectral Averages (LTSAs)**: These colour plots show power spectral density levels as a function of time (*x*-axis) and frequency (*y*-axis). The frequency axis uses a logarithmic scale, which provides equal vertical space for each decade increase in frequency and allows the reader to equally see the contributions of low and high-frequency sound sources. The LTSAs are excellent summaries of the temporal and frequency variability in the data.
- **Decidecade box-and-whisker plots**: In these figures, the 'boxes' represent the middle 50% of the range of sound pressure levels measured, so that the bottom of the box is the sound level 25th percentile (L_{25}) of the recorded levels, the bar in the middle of the box is the median (L_{50}), and the top of the box is the level that exceeded 75% of the data (L_{75}). The whiskers indicate the maximum and minimum range of the data.
- **Spectral density level percentiles**: The decidecade box-and-whisker plots are representations of the histogram of each band's sound pressure levels. The power spectral density data has too many frequency bins for a similar presentation. Instead coloured lines are drawn to represent the L_{eq}, L_5, L_{25}, L_{50}, L_{75}, and L_{95} percentiles of the histograms. Shading is provided underneath these lines to provide an indication of the relative probability distribution. It is common to compare the power spectral densities to the results from Wenz (1962), which documented the variability of ambient spectral levels off the US Pacific coast as a function of frequency of measurements for a

range of weather, vessel traffic, and geologic conditions. The Wenz levels are appropriate for approximate comparisons only since the data were collected in deep water, largely before an increase in low-frequency sound levels (Andrew et al. 2011).

- **Daily sound exposure levels (SEL; $L_{E,24h}$)**: The SEL represents the total sound energy received over a 24 h period, computed as the linear sum of all 1-minute values for each day. It has become the standard metric for evaluating the probability of temporary or permanent hearing threshold shift. Long-term exposure to sound impacts an animal more severely if the sounds are within its most sensitive hearing frequency range. Therefore, during SEL analysis recorded sounds are typically filtered by the animal's auditory frequency weighting function before integrating to obtain SEL. For this analysis the 10 Hz and above SEL were computed as well as the SEL weighted by the marine mammal auditory filters (Appendix D (NMFS 2018), which are identical to the filters applied in Southall et al. (2019)). The SEL thresholds for possible hearing impacts from sound on marine mammals are provided in Appendix D, Lucke and McPherson (2021) and Green et al. (2021).

2.2.2. Vessel Noise Detection

Vessels are detected in two steps (Martin 2013):

1. Detect constant, narrowband tones produced by a vessel's propulsion system and other rotating machinery (Arveson and Vendittis 2000). These sounds are also referred to as tonals. We detect the tonals as lines in a 0.125 Hz resolution spectrogram of the data (8 s of data, Hann window, 2 s advance).
2. Assess the SPL for each minute in the 40–315 Hz shipping frequency band, which commonly contains most sound energy produced by mid-sized to large vessels. Background estimates of the shipping band SPL and system-weighted SPL are then compared to their mean values over a 12 h window, centred on the current time.

Vessel detections are defined by the following criterion (Figure 5):

1. SPL in the shipping band (40–315 Hz) is at least 3 dB above the 12 h mean for the shipping band for at least 5 min.
2. AND at least three shipping tonals (0.125 Hz bandwidth) are present for at least 1 min per 5 min window. Tonals are difficult to detect during turns and near the closest points of approach (CPA) due to Lloyds' mirror and Doppler effects.
3. AND SPL in the shipping band is within 12 dB of the system weighted SPL.

The duration where these constraints are valid is identified as a period with shipping present. A 10 min shoulder period before and after the detection period is also included in the shipping period. The shipping period is searched for the highest 1 min SPL in the vessel detection band, which is then identified as the closest point of approach (CPA) time. This algorithm is designed to find detectable shipping, meaning situations where the vessel noise can be distinguished from the background. It does not identify cases of two vessels moving together or cases of continuous noise from stationary platforms, such as oil and gas drilling and dynamic positioning operations. Those situations are easily identified from tools such as the daily SEL and long-term spectral average figures.

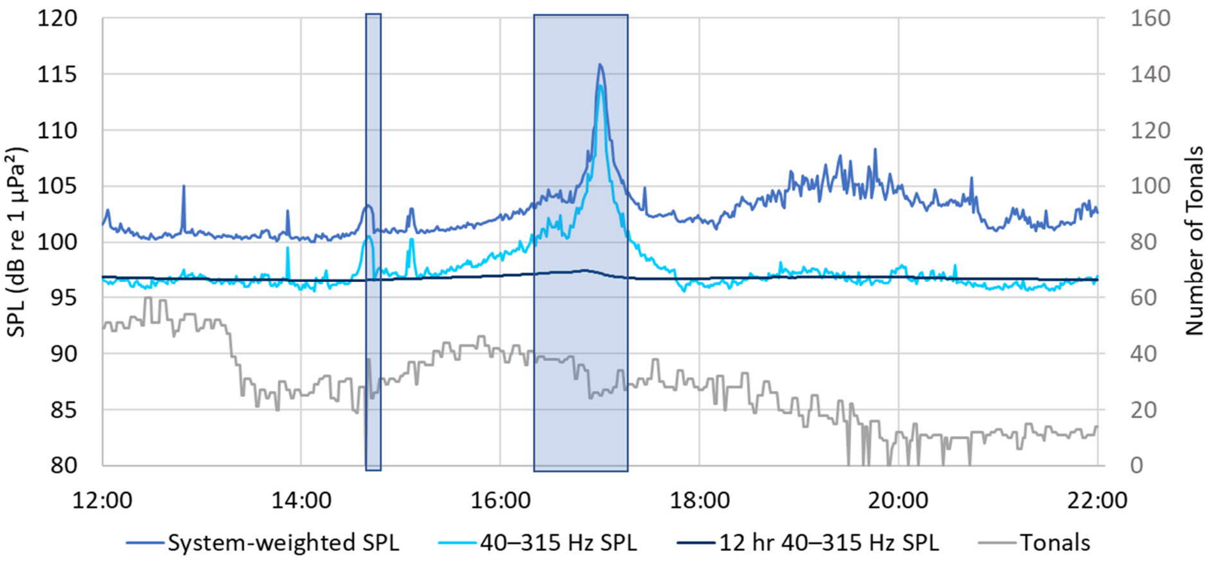


Figure 5. Example of broadband and 40–315 Hz band sound pressure level (SPL), as well as the number of tonals detected per minute as a vessel approached a recorder, stopped, and then departed. The shaded area is the period of shipping detection. Fewer tonals are detected at the vessel's closest point of approach (CPA) at 17:00 because of masking by broadband cavitation noise and due to Doppler shift that affects the tone frequencies.

3. Results and Discussion

3.1. Soundscape Characterisation

3.1.1. Spectrograms and Statistical Analysis

The band-level plots, spectrograms (Long-term Spectral Averages), decidecade box-and-whisker plots, spectral density level percentiles and decade band box-and-whiskers plots (Figures 6 and 8) provide an overview of the sound variability in time and frequency, which demonstrates the presence and level of contribution from different sources. The values for the statistics shown in Figures 8 are provided in Table 2. Short-term events appear as vertical stripes on the spectrograms and spikes on the band level plots. Long-term events affect (increasing or decreasing accordingly) the band level over the event period and appear in the spectrograms as horizontal bands of colour.

The most substantial contribution to the soundscape is from vessel noise occupying bands below approximately 1000 Hz, as shown in both the spectrogram of Figure 6, the percentiles in Figure 7 and the lower two decade bands of Figure 8. In the spectrogram (Figure 6), both the horizontal bands of long-term trends (particularly in the approximate 30-100 Hz range), as well as the vertical events can be attributed to vessel noise. Due to the shallow deployment depth, and therefore closer range to passing vessels, many distinct tones related to vessel propulsion can be observed in the 30-200 Hz ranges of both spectrogram and percentiles. Figure 11 shows a short-term spectrum including both consistent tones associated with vessels, as well as elevated broader-band sounds of a passing vessel. Figure 12 shows the results of the automated vessel detector by hour, including both detections of large vessels and that of smaller boats. It is possible that very small recreational boats may not be detected either due to masking from larger vessels or distance from recorder.

The median SPL by hour of day (Figure 9) and day of week (Figure 10) demonstrate reasonable consistency of sound levels with respect to time. There are a few subtle trends, however the overall conclusion is that vessel related noise is mostly present. Figure 9 shows a slight increase in low frequency levels between approximately 06:00 to 16:00 local time (20:00 – 04:00 UTC), indicating a slightly higher vessel presence during daytime hours. On a weekly basis (Figure 10), sound levels in the 100-1000 Hz band demonstrate a slight decrease after Friday, which would indicate a slightly lower vessel presence on weekends.

There is an interesting trend in both the daily and weekly figures for the highest decade band, which is the slight peak just after 18:00 and 06:00 (08:00 and 20:00 UTC) which is likely a dusk and dawn invertebrate chorus, with the local morning peak being greater than the evening. The predominant contributor is likely to be snapping shrimp (Erbe et al. 2016, McPherson et al. 2016), whose impulsive signals can be seen above approximately 1 kHz in Figure 11.

The tidal range in this area is less than 1 m, generally approximately 0.5 m. As such, flow noise does not offer a strong contribution to the soundscape, as supported by low sound levels below 30 Hz, where vessel noise begins. On 20 Sep 2021 there are slightly elevated broadband sound levels up to approximately 10 kHz, which may be because of a severe storm in the region which included wind speeds of up to 100 km/h, heavy rain, and thunder. Due to the shallow deployment, the wind, rain, thunder, and waves induced have a high likelihood of causing increased sound levels across many frequency bands. However, vessels may not have been operating during this storm time, and so the storm noise may be replacing the vessel noise, rather than adding to it.

The monitoring results demonstrate that Corio Bay is typically louder and exhibits less variation in the soundscape than Fremantle Inner Harbour (Salgado Kent et al. 2012). Five months of monitoring in Fremantle Inner Harbour determined this location has broadband noise levels typically between 110 and 140 dB re 1 µPa, and an approximately 10 dB diurnal variation, compared to a broadband median and 124.6 and a maximum of 153.3 dB re 1 µPa less than 5 dB average diurnal variation for Corio Bay.

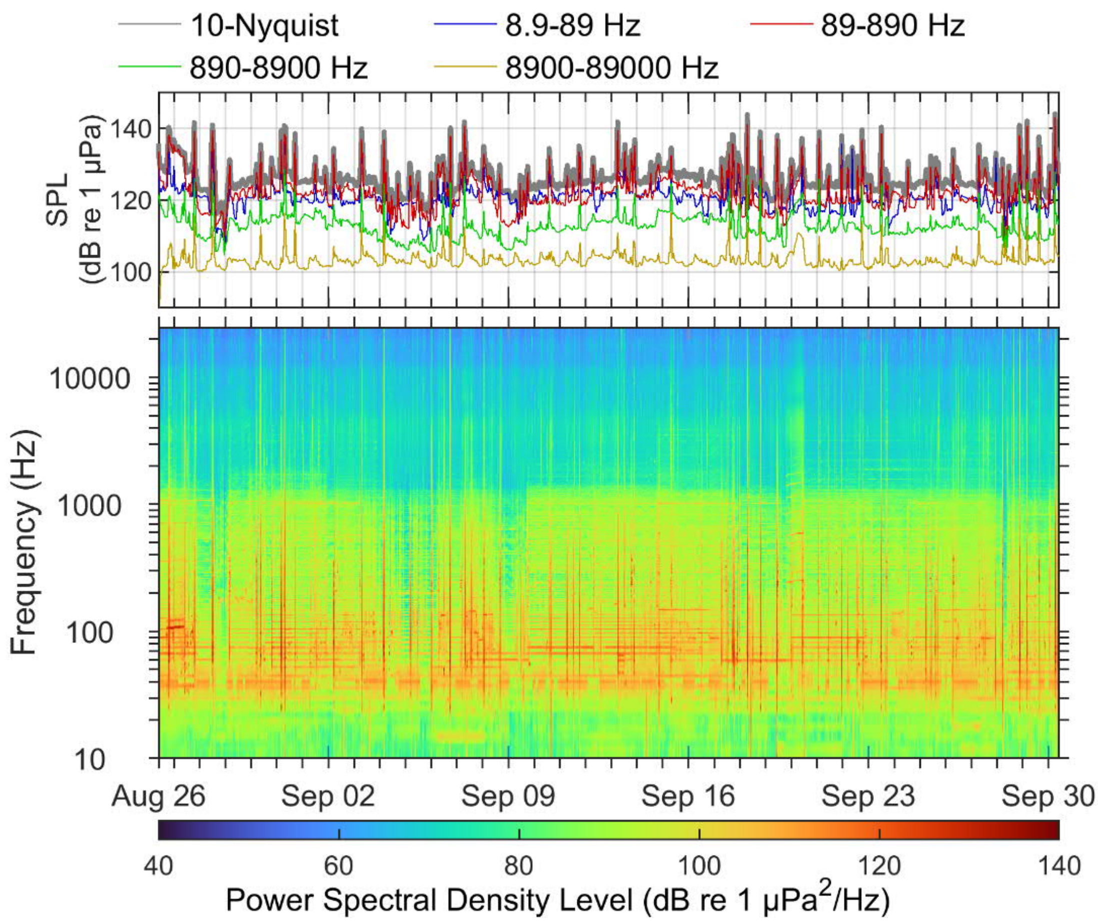


Figure 6. (Top) In-band sound pressure level (SPL) by decade band and (bottom) long-term spectral average (LTSA) of underwater sound (UTC+10).

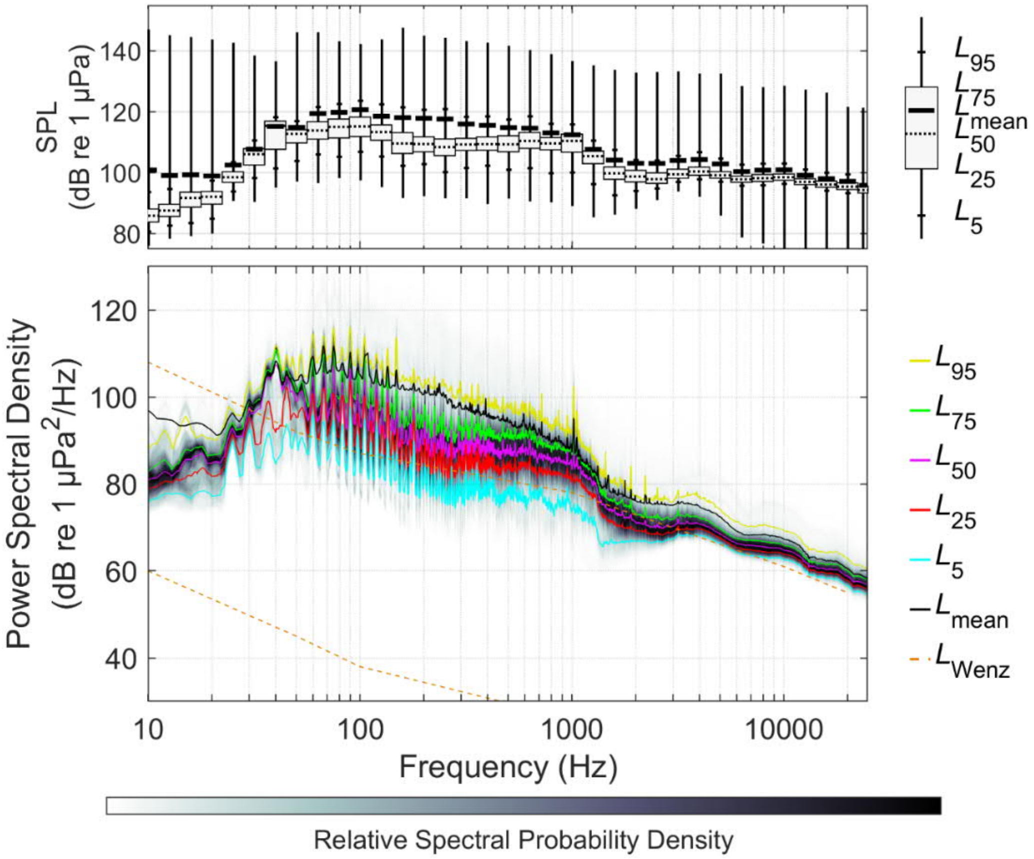


Figure 7. (Top) percentiles and mean of decidecade sound pressure level (SPL) and (bottom) percentiles and probability density (grayscale) of 1-min power spectral density levels, by station compared to the Wenz curve limits (coloured lines) of prevailing noise (Wenz 1962).

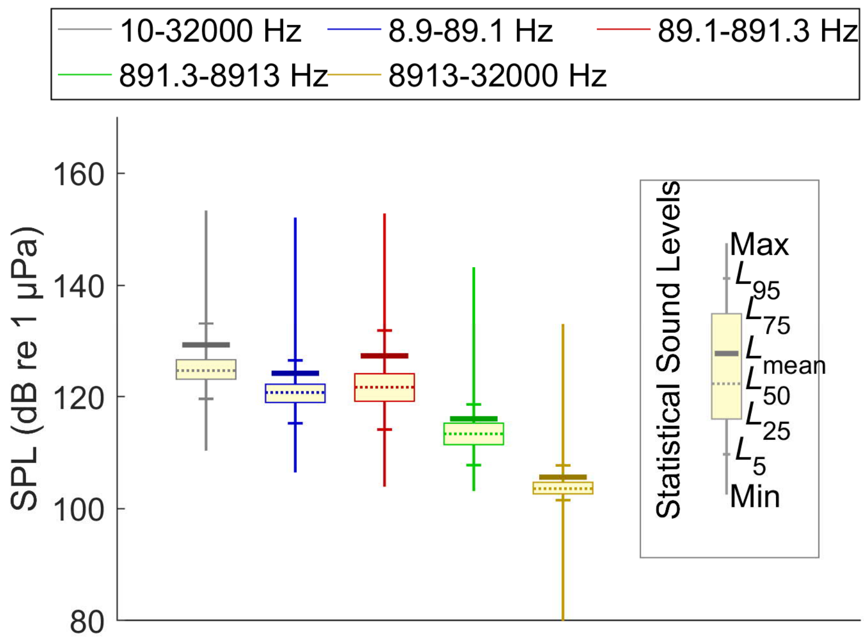


Figure 8. SPL by decade band, showing mean levels and percentiles over entire recording duration.

Table 2. Statistical analysis of sound levels for full recording period. SPL units: dB re 1 µPa.

Sound level statistic	Sound level				
	10-Nyquist	8.9-89 Hz	89-890 Hz	890-8900 Hz	8900-Nyquist Hz
Minimum	110.3	106.5	103.9	103.2	78.7
L_5	119.6	115.2	114.1	107.8	101.5
L_{25}	123.1	118.9	119.2	111.4	102.6
L_{50}	124.6	120.7	121.7	113.4	103.6
L_{75}	126.6	122.2	124.1	115.3	104.7
L_{95}	133.1	126.5	131.8	118.6	107.7
Maximum	153.3	152.1	152.8	143.2	133
Mean	129.2	124.2	127.3	116	105.6

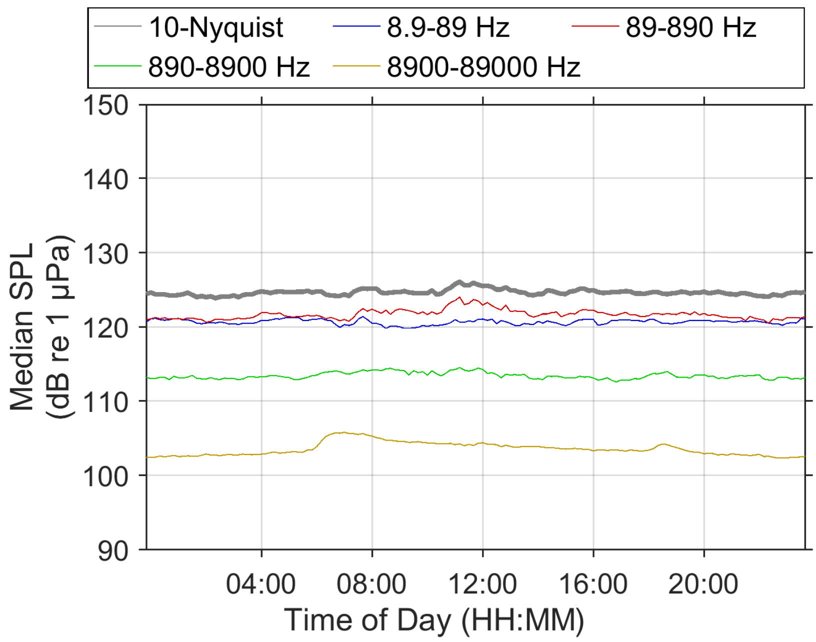


Figure 9. Median SPL by time of day for entire recording duration. Recording occurred during Australian Eastern Standard Time, UTC+10.

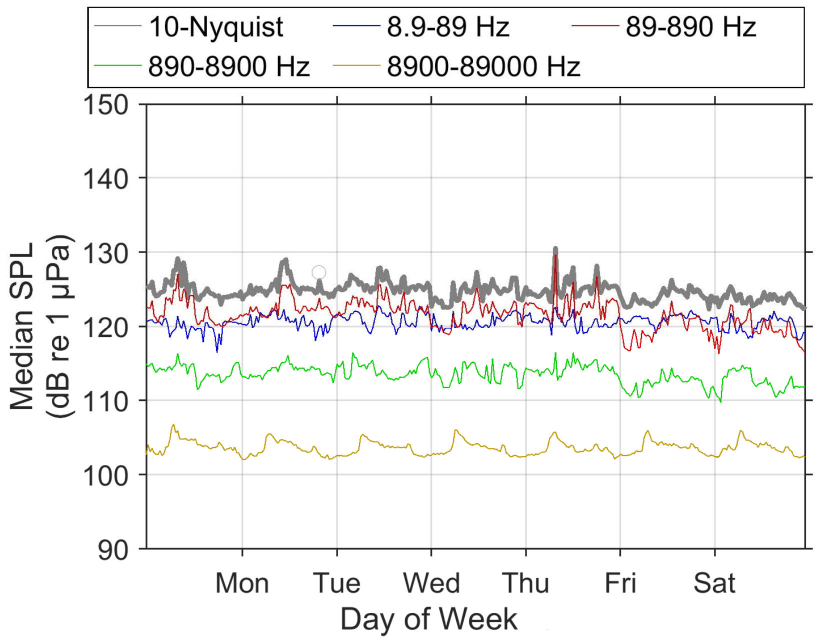


Figure 10. Median SPLs by day of week for entire recording duration. Recording occurred during Australian Eastern Standard Time, UTC+10.

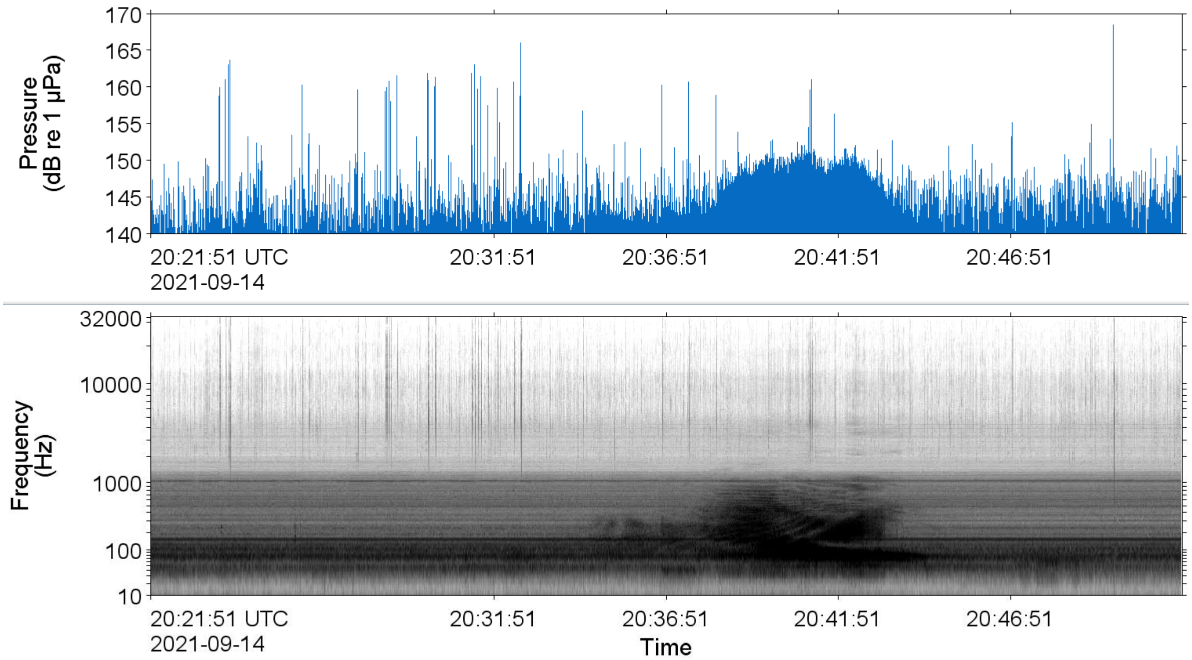


Figure 11. Spectrum of sound levels on 14 Sep 2021 (UTC). Demonstrates sound level contributions from consistent vessel tones and passing vessel.

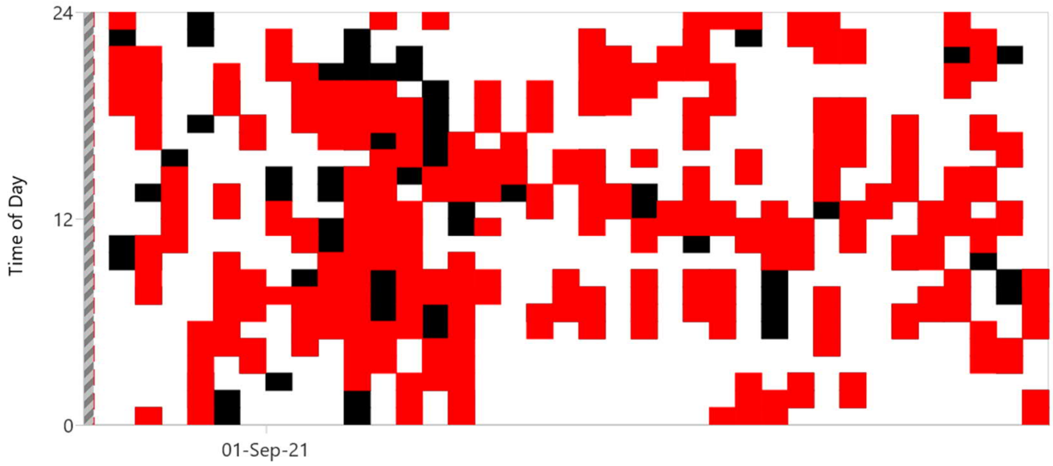


Figure 12. Vessel detections by hour. Red indicates a large vessel detection, and black indicates a smaller boat.

3.1.2. Frequency Weighted Sound Exposure Levels

The perception of underwater sound depends on the hearing sensitivity of the receiving animal in the frequency bands of the sound. Hearing sensitivity in animals, however, varies over the frequency band of their hearing (the hearing curve (audiogram) usually resembling a U-shaped form). The frequency range of hearing and hearing sensitivity differ between species, resulting in the fact that different species will perceive underwater sound differently. Auditory (frequency) weighting functions (Appendix D) are applied to account for this difference as they reflect an animal's ability to hear a sound, emphasising the frequency band of best sensitivity over frequencies animals do not hear well. Figure 13 shows the difference between perceived ambient noise by cetaceans and seals. The hearing groups of relevance to the Viva Energy Gas Terminal project are mid-frequency cetaceans (referred to as high-frequency cetaceans in Southall et al. (2019)) and otariid seals, statistics for these species are provided in Table 3.

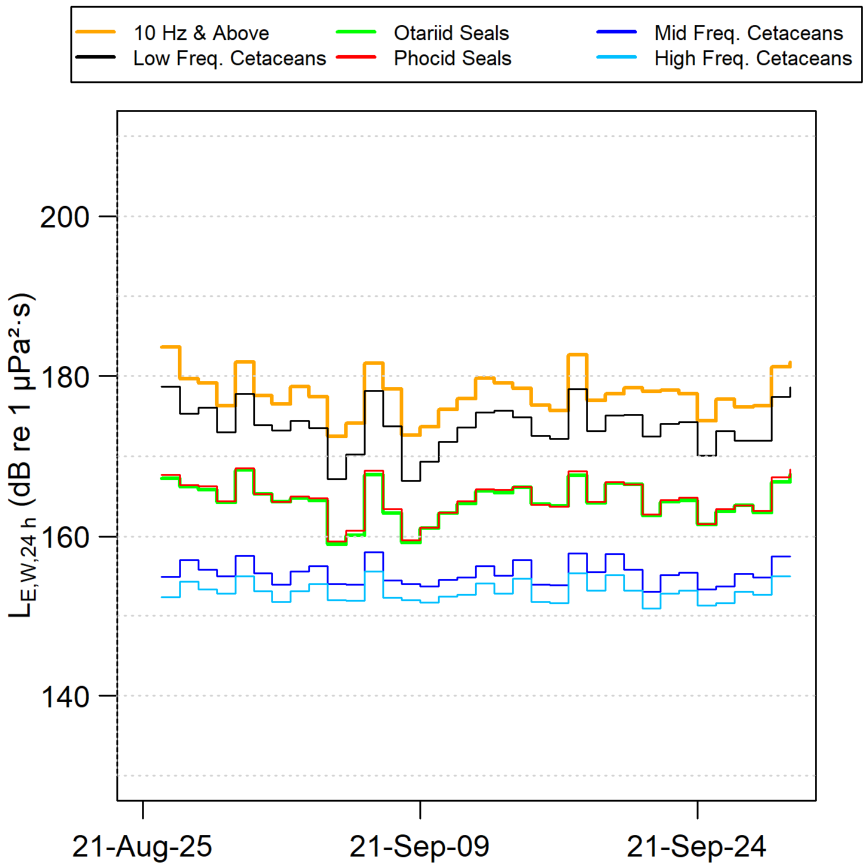


Figure 13. Auditory frequency weighted ambient noise (10 Hz and above) over the measurement period shown as daily sound exposure levels (SEL) (NMFS 2018).

Table 3. Daily sound exposure level (SEL, dB re 1 µPa²s) statistics for the hearing groups (NMFS 2018) relevant to the assessment over the entire measurement period.

Sound level statistic	Unweighted	Mid-Frequency Cetacean	Otariid Seals
Minimum	172.5	153.0	159.0
Median	177.8	155.1	164.3
Maximum	183.6	158.0	168.3

The data presented in this report will be used to inform an assessment of potential underwater noise impacts for the Viva Energy Gas Terminal project.

Acknowledgements

JASCO would like to thank Nick Goodwin and the team at Consulting Environmental Engineers for their assistance with deployment and retrieval of the acoustic recording equipment.

Glossary

1/3-octave

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

1/3-octave-band

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

90%-energy time window

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

90% sound pressure level (90% SPL)

The sound pressure level calculated over the 90%-energy time window of a pulse.

absorption

The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

acoustic noise

Sound that interferes with an acoustic process.

acoustic self-noise

Sound at a receiver caused by the deployment, operation, or recovery of a specified receiver, and its associated platform.

ambient sound

Sound that would be present in the absence of a specified activity, 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.

audiogram

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

auditory frequency weighting

The process of applying an auditory frequency weighting function. In human audiometry, C-weighting is the most commonly used 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. Example hearing groups are low-, mid-, and high-frequency cetaceans, phocid and otariid pinnipeds.

automated detection

The output of an **automated detector**.

automated detector

An algorithm that includes both the **automated detection** of a sound of interest based on how it stands out from the background and its automated classification based on similarities to templates in a library of reference signals.

background noise

Combination of ambient sound, acoustic self-noise, and sonar reverberation. Ambient sound detected, measured, or recorded with a signal is part of the background noise.

bandwidth

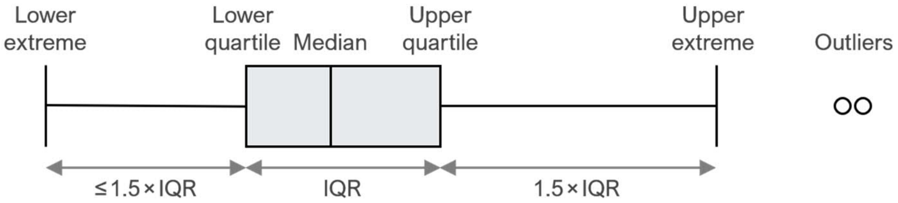
The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., seismic airguns, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI S1.13-2005 (R2010)).

bar

Unit of pressure equal to 100 kPa, which is approximately equal to the atmospheric pressure on Earth at sea level. 1 bar is equal to 10^5 Pa or 10^{11} µPa.

box-and-whisker plot

A plot that illustrates the centre, spread, and overall range of data from a visual 5-number summary. The box is the interquartile range (IQR), which shows the middle 50% of the data—from the lower quartile (25th percentile) to the upper quartile (75th percentiles). The line inside the box is the median (50th percentile). The whiskers show the lower and upper extremes excluding outliers, which are data points that fall more than 1.5 × IQR beyond the upper and lower quartiles.



boxcar averaging

A signal smoothing technique that returns the averages of consecutive segments of a specified width.

broadband level

The total level measured over a specified frequency range.

cavitation

A rapid formation and collapse of vapor cavities (i.e., bubbles or voids) in water, most often caused by a rapid change in pressure. Fast-spinning vessel propellers typically cause cavitation, which creates a lot of noise.

cetacean

Any animal in the order Cetacea. These are aquatic species and include whales, dolphins, and porpoises.

conductivity-temperature-depth (CTD)

Measurement data of the ocean's conductivity, temperature, and depth; used to compute sound speed and salinity.

continuous sound

A sound whose sound pressure level remains above ambient sound during the observation period . A sound that gradually varies in intensity with time, for example, sound from a marine vessel.

decade

Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 80000-3:2006).

decidecade

One tenth of a decade. *Note*: An alternative name for decidecade (symbol ddec) is “one-tenth decade”. A decidecade is approximately equal to one third of an octave (1 ddec ≈ 0.3322 oct) and for this reason is sometimes referred to as a “one-third octave”.

decidecade band

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

decibel (dB)

Unit of level used to express the ratio of one value of a power quantity to another on a logarithmic scale. Unit: dB.

delphinid

Family of oceanic dolphins, or Delphinidae, composed of approximately thirty extant species, including dolphins, porpoises, and killer whales.

duty cycle

The time when sound is periodically recorded by an acoustic recording system.

energy source level

A property of a sound source obtained by adding to the sound exposure level measured in the far field 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 f_1 to f_2. In equation form, the energy spectral density E_f is given by:

$$E_f = \frac{2\int_{f_1}^{f_2} |X(f)|^2 \, \mathrm{d}f}{f_2 - f_1},$$

where $X(f)$ is the Fourier transform of the field variable $x(t)$

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

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, sound particle velocity, or sound particle 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

The factor of two on the right-hand 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 (2017a).

energy spectral density level

The level ($L_{E,f}$) of the **energy spectral density** (E_f). Unit: decibel (dB).

$$L_{E,f} := 10 \log_{10}\left(E_f / E_{f,0}\right) \text{ dB} .$$

The frequency band and integration time should be specified.

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

energy spectral density source level

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

ensonified

Exposed to sound.

Fourier transform (or Fourier synthesis)

A mathematical technique which, although it has varied applications, is referenced in the context of this report 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 fast Fourier transform (FFT).

flat weighting

Term indicating that no frequency weighting function is applied. Synonymous with unweighted.

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. For sound of a given frequency, the frequency weighting function is the ratio of output power to input power of a specified filter, sometimes expressed in decibels. Examples include the following:

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

geoacoustic

Relating to the acoustic properties of the seabed.

Global Positioning System (GPS)

A satellite based navigation system providing accurate worldwide location and time information.

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 example, the second harmonic of a sound has a frequency that is double the fundamental frequency of the sound.

hearing group

Category of animal species when classified according to their hearing sensitivity and to the susceptibility to sound. Examples for marine mammals include very low-frequency (VLF) cetaceans, low-frequency (LF) cetaceans, mid-frequency (MF) cetaceans, high-frequency (HF) cetaceans, very high-frequency (VHF) cetaceans, otariid pinnipeds in water (OPW), phocid pinnipeds in water (PPW), sirenians (SI), other marine carnivores in air (OCA), and other marine carnivores in water (OCW) (NMFS 2018, Southall et al. 2019). See **auditory frequency weighting functions**, which are often applied to these groups. Examples 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).

hearing threshold

The sound pressure level for any frequency of the hearing group that is barely audible for a given individual for specified background noise during a specific percentage of experimental trials.

hertz (Hz)

A unit of frequency defined as one cycle per second.

high-frequency (HF) cetacean

See **hearing group**.

hydrophone

An underwater sound pressure transducer. A passive electronic device for recording or listening to underwater sound.

intermittent sound

A sound whose level abruptly drops below the background noise level several times during an observation period.

impulsive sound

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

knot

One nautical mile per hour. Symbol: kn.

level

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

low-frequency (LF) cetacean

See **hearing group**.

masking

Obscuring of sounds of interest by sounds at similar frequencies.

median

The 50th percentile of a statistical distribution.

mid-frequency (MF) cetacean

See **hearing group**.

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-like (monopole) sound source. Also see **radiated noise level**.

Monte Carlo simulation

The method of investigating the distribution of a non-linear multi-variate function by random sampling of all of its input variable distributions.

multiple linear regression

A statistical method that seeks to explain the response of a dependent variable using multiple explanatory variables.

mysticete

A suborder of cetaceans that use baleen plates to filter food from water. Members of this group include rorquals (Balaenopteridae), right whales (Balaenidae), and grey whales (*Eschrichtius robustus*).

N percent exceedance level

The sound level exceeded *N*% of the time during a specified time interval. Also see **percentile level**.

non-impulsive sound

Sound that is not an impulsive sound. A non-impulsive sound is 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

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

otariid

A common term used to describe members of the Otariidae, eared seals, commonly called sea lions and fur seals. Otariids are adapted to a semi-aquatic life; they use their large fore flippers for propulsion. Their ears distinguish them from phocids. Otariids are one of the three main groups in the superfamily Pinnipedia; the other two groups are phocids and walrus.

otariid pinnipeds in water (OPW)

See **hearing group**.

other marine carnivores in air (OCA)

See **hearing group**.

other marine carnivores in water (OCW)

See **hearing group**.

peak sound pressure level (zero-to-peak sound pressure level)

The level ($L_{p,pk}$ or L_{pk}) of the squared maximum magnitude of the sound pressure (p_{pk}^2). Unit: decibel (dB). Reference value (p_0^2) for sound in water: 1 µPa².

$$L_{p,\text{pk}} := 10\log_{10}\left(p_{\text{pk}}^2/p_0^2\right)\text{ dB} = 20\log_{10}\left(p_{\text{pk}}/p_0\right)\text{ dB}$$

The frequency band and time window should be specified. Abbreviation: PK or Lpk.

peak-to-peak sound pressure

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

percentile level

The sound level not exceeded *N*% of the time during a specified time interval. The *N*th percentile level is equal to the (100−*N*)% exceedance level. Also see ***N* percent exceedance level**.

permanent threshold shift (PTS)

An irreversible loss of hearing sensitivity caused by excessive noise exposure. PTS is considered auditory injury.

phocid

A common term used to describe all members of the family Phocidae. These true/earless seals are more adapted to in-water life than are otariids, which have more terrestrial adaptations. Phocids use their hind flippers to propel themselves. Phocids are one of the three main groups in the superfamily Pinnipedia; the other two groups are otariids and walrus.

phocid pinnipeds in water (PPW)

See **hearing group**.

pinniped

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

point source

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

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:

$$P_f = \frac{E_f}{\Delta t}.$$

Power spectral density can be expressed in terms of various field variables (e.g., sound pressure, sound particle displacement).

power spectral density level

The level ($L_{P,f}$) of the **power spectral density** (P_f). Unit: decibel (dB).

$$L_{P,f} := 10 \log_{10}\left(P_f / P_{f,0}\right) \text{ dB}.$$

The frequency band and integration time should be specified.

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 field variable.

power spectral density source level

A property of a sound source obtained by adding to the power spectral density level of the sound pressure measured in the far field 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.

pressure, acoustic

The deviation from the ambient pressure caused by a sound wave. Also called sound pressure. Unit: pascal (Pa).

pressure, hydrostatic

The pressure at any given depth in a static liquid that is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid. Unit: pascal (Pa).

propagation loss (PL)

Difference between a source level (SL) and the level at a specified location, PL(x) = SL − L(x). Also see **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 and seabed. Also see **monopole source level**.

received level

The level measured (or that would be measured) at a defined location. The type of level should be specified.

reference values

standard underwater references values used for calculating sound **levels**, e.g., the reference value for expressing sound pressure level in decibels is 1 μPa.

Quantity	Reference value
Sound pressure	1 μPa
Sound exposure	1 μPa^2 s
Sound particle displacement	1 pm
Sound particle velocity	1 nm/s
Sound particle acceleration	1 $\mu m/s^2$

rms

abbreviation for root-mean-square.

sound

A time-varying disturbance in the pressure, stress, or material displacement of a medium propagated by local compression and expansion of the medium.

sound exposure

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

sound exposure level

The level (L_E) of the sound exposure (E). Unit: decibel (dB). Reference value (E_0) for sound in water: 1 μPa^2 s.

$$L_E := 10 \log_{10}(E/E_0) \text{ dB} = 20 \log_{10}\left(E^{1/2}/E_0^{1/2}\right) \text{ dB}$$

The frequency band and integration time should be specified. Abbreviation: SEL.

sound exposure spectral density

Distribution as a function of frequency of the time-integrated squared sound pressure per unit bandwidth of a sound having a continuous spectrum. Unit: Pa^2 s/Hz.

sound field

Region containing sound waves.

sound pressure

The contribution to total pressure caused by the action of sound.

sound pressure level (rms sound pressure level)

The level ($L_{p,\mathrm{rms}}$) of the time-mean-square sound pressure (p_{rms}^2). Unit: decibel (dB). Reference value (p_0^2) for sound in water: 1 μPa².

$$L_{p,\mathrm{rms}} := 10\log_{10}(p_{\mathrm{rms}}^2/p_0^2)\ \mathrm{dB} = 20\log_{10}(p_{\mathrm{rms}}/p_0)\ \mathrm{dB}$$

The frequency band and averaging time should be specified. Abbreviation: SPL or Lrms.

sound speed profile

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

soundscape

The characterization of the ambient sound in terms of its spatial, temporal, and frequency attributes, and the types of sources contributing to the sound field.

source level (SL)

A property of a sound source obtained by adding to the sound pressure level measured in the far field the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 μPa²m².

spectrogram

A visual representation of acoustic amplitude compared with time and frequency.

spectrum

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

surface duct

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

temporary threshold shift (TTS)

Reversible loss of hearing sensitivity. TTS can be caused by noise exposure.

transmission loss (TL)

The difference between a specified level at one location and that at a different location, TL(x1,x2) = L(x1) − L(x2). Also see **propagation loss**.

unweighted

Term indicating that no frequency weighting function is applied. Synonymous with flat weighting.

wavelength

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

Literature Cited

[ANSI] American National Standards Institute and [ASA] Acoustical Society of America. S1.1-2013. *American National Standard: Acoustical Terminology*. NY, USA. https://webstore.ansi.org/Standards/ASA/ANSIASAS12013.

[ANSI] American National Standards Institute and [ASA] Acoustical Society of America. S1.13-2005 (R2010). *American National Standard: Measurement of Sound Pressure Levels in Air*. NY, USA. https://webstore.ansi.org/Standards/ASA/ANSIASAS1132005R2010.

[ISO] International Organization for Standardization. 2006. *ISO 80000-3:2006 Quantities and units – Part 3: Space and time*. https://www.iso.org/standard/31888.html.

[ISO] International Organization for Standardization. 2017a. *ISO 18405:2017. Underwater acoustics – Terminology*. Geneva. https://www.iso.org/standard/62406.html.

[ISO] International Organization for Standardization. 2017b. *ISO 18406:2017(E). Underwater acoustics – Measurement of radiated underwater sound from percussive pile driving*. Geneva. https://www.iso.org/obp/ui/#iso:std:iso:18406:ed-1:v1:en.

[NMFS] National Marine Fisheries Service (US). 2016. *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts*. US Department of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-55. 178 p.

[NMFS] National Marine Fisheries Service (US). 2018. *2018 Revision to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts*. US Department of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-59. 167 p. https://www.fisheries.noaa.gov/webdam/download/75962998.

[NOAA] National Oceanic and Atmospheric Administration (US). 2019. *ESA Section 7 Consultation Tools for Marine Mammals on the West Coast* (webpage), 27 Sep 2019. https://www.fisheries.noaa.gov/west-coast/endangered-species-conservation/esa-section-7-consultation-tools-marine-mammals-west. (Accessed 10 Mar 2020).

[NRC] National Research Council (US). 2003. *Ocean Noise and Marine Mammals*. National Research Council (US), Ocean Studies Board, Committee on Potential Impacts of Ambient Noise in the Ocean on Marine Mammals. The National Academies Press, Washington, DC, USA. https://doi.org/10.17226/10564.

Ainslie, M.A., J.L. Miksis-Olds, S.B. Martin, K.D. Heaney, C.A.F. de Jong, A.M. von Benda-Beckmann, and A.P. Lyons. 2018. *ADEON Underwater Soundscape and Modeling Metadata Standard*. Version 1.0. Technical report by JASCO Applied Sciences for ADEON Prime Contract No. M16PC00003. https://doi.org/10.6084/m9.figshare.6792359.v2.

Andrew, R.K., B.M. Howe, and J.A. Mercer. 2011. Long-time trends in ship traffic noise for four sites off the North American West Coast. *Journal of the Acoustical Society of America* 129(2): 642-651. https://doi.org/10.1121/1.3518770.

Bailey, H., G. Clay, E.A. Coates, D. Lusseau, B. Senior, and P.M. Thompson. 2010. Using T-PODs to assess variations in the occurrence of coastal bottlenose dolphins and harbour porpoises. *Aquatic Conservation: Marine and Freshwater Ecosystems* 20(2): 150-158. https://doi.org/10.1002/aqc.1060.

Bom, N. 1969. Effect of rain on underwater noise level. *Journal of the Acoustical Society of America* 45(1): 150-156. https://doi.org/10.1121/1.1911351.

Cato, D.H. 1997. Ambient sea noise in Australian waters. *5th International Congress on Sound and Vibration*. Volume 5, 15-18 Dec 1997, Adelaide, Australia. pp. 2813-2818.

Delarue, J.J.-Y., K.A. Kowarski, E.E. Maxner, J.T. MacDonnell, and S.B. Martin. 2018. *Acoustic Monitoring Along Canada's East Coast: August 2015 to July 2017*. Document Number 01279, Environmental Studies

Research Funds Report Number 215, Version 1.0. Technical report by JASCO Applied Sciences for Environmental Studies Research Fund, Dartmouth, NS, Canada. 120 pp + appendices.

Erbe, C., R.D. McCauley, A. Gavrilov, S. Madhusudhana, and A. Verma. 2016. The underwater soundscape around Australia. *ACOUSTICS 2016*. 9-11 Nov 2016, Brisbane, Australia.

Erbe, C., R. Dunlop, K.C.S. Jenner, M.-N.M. Jenner, R.D. McCauley, I. Parnum, M. Parsons, T. Rogers, and C. Salgado-Kent. 2017. Review of underwater and in-air sounds emitted by Australian and Antarctic marine mammals. *Acoustics Australia*. https://doi.org/10.1007/s40857-017-0101-z.

Finneran, J.J. and A.K. Jenkins. 2012. *Criteria and thresholds for U.S. Navy acoustic and explosive effects analysis*. SPAWAR Systems Center Pacific, San Diego, CA, USA. 64 p.

Finneran, J.J. 2015. *Auditory weighting functions and TTS/PTS exposure functions for cetaceans and marine carnivores*. Technical report by SSC Pacific, San Diego, CA, USA.

Finneran, J.J. 2016. *Auditory weighting functions and TTS/PTS exposure functions for marine mammals exposed to underwater noise*. Technical Report for Space and Naval Warfare Systems Center Pacific, San Diego, CA, USA. 49 p. https://apps.dtic.mil/dtic/tr/fulltext/u2/1026445.pdf.

Green, M.C., M. Wood, and C. McPherson. 2021. *Viva Energy Gas Terminal: Underwater Acoustic Modelling*. Technical report by JASCO Applied Sciences for AECOM. Document Number 02534, Version 1.0.

Hannay, D.E., J.J.-Y. Delarue, X. Mouy, S.B. Martin, D. Leary, J.N. Oswald, and J. Vallarta. 2013. Marine mammal acoustic detections in the northeastern Chukchi Sea, September 2007–July 2011. *Continental Shelf Research* 67: 127-146. https://doi.org/10.1016/j.csr.2013.07.009.

Heindsmann, T.E., R.H. Smith, and A.D. Arneson. 1955. Effect of rain upon underwater noise levels [Letter to the editor]. *Journal of the Acoustical Society of America* 27(2): 378-379. https://doi.org/10.1121/1.1907897.

Houser, D.S., W. Yost, R. Burkard, J.J. Finneran, C. Reichmuth, and J. Mulsow. 2017. A review of the history, development and application of auditory weighting functions in humans and marine mammals. *Journal of the Acoustical Society of America* 141(3): 1371-1413. https://doi.org/10.1121/1.4976086.

Knudsen, V.O., R.S. Alford, and J.W. Emling. 1948. Underwater ambient noise. *Journal of Marine Research* 7: 410-429.

Krause, B. 2008. Anatomy of the Soundscape: Evolving Perspectives. *Journal of the Audio Engineering Society* 56(1/2): 73-80. http://www.aes.org/e-lib/browse.cfm?elib=14377.

Lucke, K. and C. McPherson. 2021. *Appendix [X]: Underwater Noise Impact Assessment: Viva Energy Gas Terminal Project Environment Effects Statement*. Document Number 02558, Version 1.0 DRAFT. Technical report by JASCO Applied Sciences for AECOM.

Martin, B. 2013. Computing cumulative sound exposure levels from anthropogenic sources in large data sets. *Proceedings of Meetings on Acoustics* 19(1): 9. https://doi.org/10.1121/1.4800967.

Martin, S.B., C. Morris, K. Bröker, and C. O'Neill. 2019. Sound exposure level as a metric for analyzing and managing underwater soundscapes. *Journal of the Acoustical Society of America* 146(1): 135-149. https://doi.org/10.1121/1.5113578.

Martin, S.B., B.J. Gaudet, H. Klinck, P.J. Dugan, J.L. Miksis-Olds, D.K. Mellinger, D.A. Mann, O. Boebel, C.C. Wilson, et al. 2021. Hybrid millidecade spectra: A practical format for exchange of long-term ambient sound data. *JASA Express Letters* 1(1). https://doi.org/10.1121/10.0003324.

Matsumoto, H., D.R. Bohnenstiehl, J. Tournadre, R.P. Dziak, J.H. Haxel, T.K.A. Lau, M. Fowler, and S.A. Salo. 2014. Antarctic icebergs: A significant natural ocean sound source in the Southern Hemisphere. *Geochemistry, Geophysics, Geosystems* 15(8): 3448-3458. https://doi.org/10.1002/2014GC005454.

McPherson, C.R., B. Martin, J.T. MacDonnell, and C.J. Whitt. 2016. Examining the value of the acoustic variability Index in the characterisation of Australian marine soundscapes. *ACOUSTICS 2016*. 9-11 Nov 2016, Brisbane, Australia. p. 13. https://www.acoustics.asn.au/conference_proceedings/AASNZ2016/papers/p19.pdf.

Miksis-Olds, J.L. and S.M. Nichols. 2016. Is low frequency ocean sound increasing globally? *Journal of the Acoustical Society of America* 139(1): 501-511. https://doi.org/10.1121/1.4938237.

Nedwell, J.R. and A.W. Turnpenny. 1998. The use of a generic frequency weighting scale in estimating environmental effect. *Workshop on Seismics and Marine Mammals*. 23–25 Jun 1998, London, UK.

Nedwell, J.R., A.W. Turnpenny, J. Lovell, S.J. Parvin, R. Workman, J.A.L. Spinks, and D. Howell. 2007. *A validation of the dB$_{ht}$ as a measure of the behavioural and auditory effects of underwater noise*. Document Number 534R1231 Report prepared by Subacoustech Ltd. for Chevron Ltd, TotalFinaElf Exploration UK PLC, Department of Business, Enterprise and Regulatory Reform, Shell UK Exploration and Production Ltd, The Industry Technology Facilitator, Joint Nature Conservation Committee, and The UK Ministry of Defence. 74 p. https://tethys.pnnl.gov/sites/default/files/publications/Nedwell-et-al-2007.pdf.

Nieukirk, S.L., K.M. Stafford, D.K. Mellinger, R.P. Dziak, and C.G. Fox. 2004. Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic Ocean. *Journal of the Acoustical Society of America* 115(4): 1832-1843. https://doi.org/10.1121/1.1675816.

Popper, A.N., A.D. Hawkins, R.R. Fay, D.A. Mann, S. Bartol, T.J. Carlson, S. Coombs, W.T. Ellison, R.L. Gentry, et al. 2014. *Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI*. ASA S3/SC1.4 TR-2014. SpringerBriefs in Oceanography. ASA Press and Springer. https://doi.org/10.1007/978-3-319-06659-2.

Ross, D. 1976. *Mechanics of Underwater Noise*. Pergamon Press, NY, USA.

Salgado Kent, C.P., R.D. McCauley, I.M. Parnum, and A.N. Gavrilov. 2012. Underwater noise sources in Fremantle inner harbour: Dolphins, pile driving and traffic. *Acoustics 2012*. 21-23 Nov 2012, Fremantle, Australia.

Scrimger, J.A., D.J. Evans, G.A. McBean, D.M. Farmer, and B.R. Kerman. 1987. Underwater noise due to rain, hail, and snow. *Journal of the Acoustical Society of America* 81(1): 79-86. https://doi.org/10.1121/1.394936.

Southall, B.L., A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Greene, Jr., D. Kastak, D.R. Ketten, J.H. Miller, et al. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. *Aquatic Mammals* 33(4): 411-521. https://doi.org/10.1578/AM.33.4.2007.411.

Southall, B.L., J.J. Finneran, C.J. Reichmuth, P.E. Nachtigall, D.R. Ketten, A.E. Bowles, W.T. Ellison, D.P. Nowacek, and P.L. Tyack. 2019. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. *Aquatic Mammals* 45(2): 125-232. https://doi.org/10.1578/AM.45.2.2019.125.

Strasberg, M. 1979. Nonacoustic noise interference in measurements of infrasonic ambient noise. *Journal of the Acoustical Society of America* 66(5): 1487-1493. https://doi.org/10.1121/1.383543.

Urick, R.J. 1974. Sea-bed motion as a source of the ambient noise background of the sea. *Journal of the Acoustical Society of America* 56(3): 1010-1011. https://doi.org/10.1121/1.1903363.

Urick, R.J. 1983. *Principles of Underwater Sound*. 3rd edition. McGraw-Hill, New York, London. 423 p.

van Opzeeland, I. and O. Boebel. 2018. Marine soundscape planning: Seeking acoustic niches for anthropogenic sound. *Journal of Ecoacoustics* 2(5GSNT). https://doi.org/10.22261/JEA.5GSNT8.

Wenz, G.M. 1962. Acoustic Ambient Noise in the Ocean: Spectra and Sources. *Journal of the Acoustical Society of America* 34(12): 1936-1956. https://doi.org/10.1121/1.1909155.

Appendix A. Underwater Acoustics

A.1. Acoustic Metrics Mathematical Definitions

Sound levels with individual metrics defined below, are presented as:

- Broadband and approximate-decade-band SPL over time for these frequency bands for the 64 kHz sample rate: 8.9 Hz–32 kHz, 8.9–89 Hz, 89 Hz to 891 Hz, 891 Hz–8.91 kHz, and 8.91 kHz–32 kHz.
- Spectrograms: Ambient noise at each station was analysed by Hamming-windowed fast Fourier transforms (FFTs), with 1 Hz resolution and 50% window overlap. The 120 FFTs performed with these settings are averaged to yield 1 min average spectra.
- Statistical distribution of SPL in each decidecade. The boxes of the statistical distributions indicate the first (L_5), second (L_{50}), and third (L_{75}) quartiles. The whiskers indicate the maximum and minimum range of the data. The solid line indicates the sound pressure level (SPL) or L_{eq} in each decidecade.
- Spectral level percentiles: Histograms of each frequency bin per 1 min of data. The L_{eq}, L_5, L_{25}, L_{50}, L_{75}, and L_{95} percentiles are plotted. The L_5 percentile curve is the frequency-dependent level exceeded by 95% of the 1 min averages. Equivalently, 5% of the 1 min spectral levels are above the 95th percentile curve.
- Daily cumulative sound exposure levels (SEL (24 h)): computed for the total received sound energy. The SEL (24 h) is the linear sum of the 1 min sound exposure levels (SEL). These SEL values were weighted to mimic different functional hearing groups according to the marine mammal frequency-weighted curves described in Appendix D.

Sound is most commonly described using the sound pressure level (SPL) metric. Underwater sound amplitude levels are commonly measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa.

SPL (dB re 1 μPa) is the decibel level of the rms pressure in a stated frequency band over a time window (*T; s*) containing the acoustic event:

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

The SPL is a measure of the effective pressure level over the duration of an acoustic event, such as the emission of one acoustic pulse or sweep. Because the window length, *T*, is the divisor, events more spread out in time have a lower SPL even though they may have similar total acoustic energy density.

Power spectral density (PSD) level is a description of how the acoustic power is distributed over different frequencies within a spectrum. It is expressed in dB re 1 μPa^2/Hz.

The sound exposure level (SEL, dB re 1 μPa^2·s) is a measure of the total acoustic energy contained in one or more acoustic events. The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (T_{100}):

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

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

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

$$\mathrm{SPL} = \mathrm{SEL} - 10\log_{10}(T) \tag{A-3}$$

Sound level statistics, namely percentiles, were used to quantify the distribution of recorded sound levels. The *n*th percentile level (L_n) is the level (i.e., PSD level, SPL, or SEL) *n*% of the data are below this level. L_{eq} is the linear arithmetic mean of the sound power, which can be substantially different from the median sound level L_{50}. SPL can also be referred to as L_{eq}, which stands for 'equivalent level'. The two terms are used interchangeably throughout. L_{95}, the level exceeded by only 5% of the data, represents the highest typical sound levels measured. Sound levels between L_5 and L_{99} are generally from very close passes of vessels, very intense weather events, and other infrequent conditions. L_5 represents the quietest typical conditions.

Appendix B. Acoustic Data Analysis Methods

The data sampled at 64 and 128 kHz was processed for ambient sound analysis, vessel noise detection, and detection of all marine mammal vocalisations. This section describes the ambient, vessel, and marine mammal detection algorithms employed (Figure B-1).

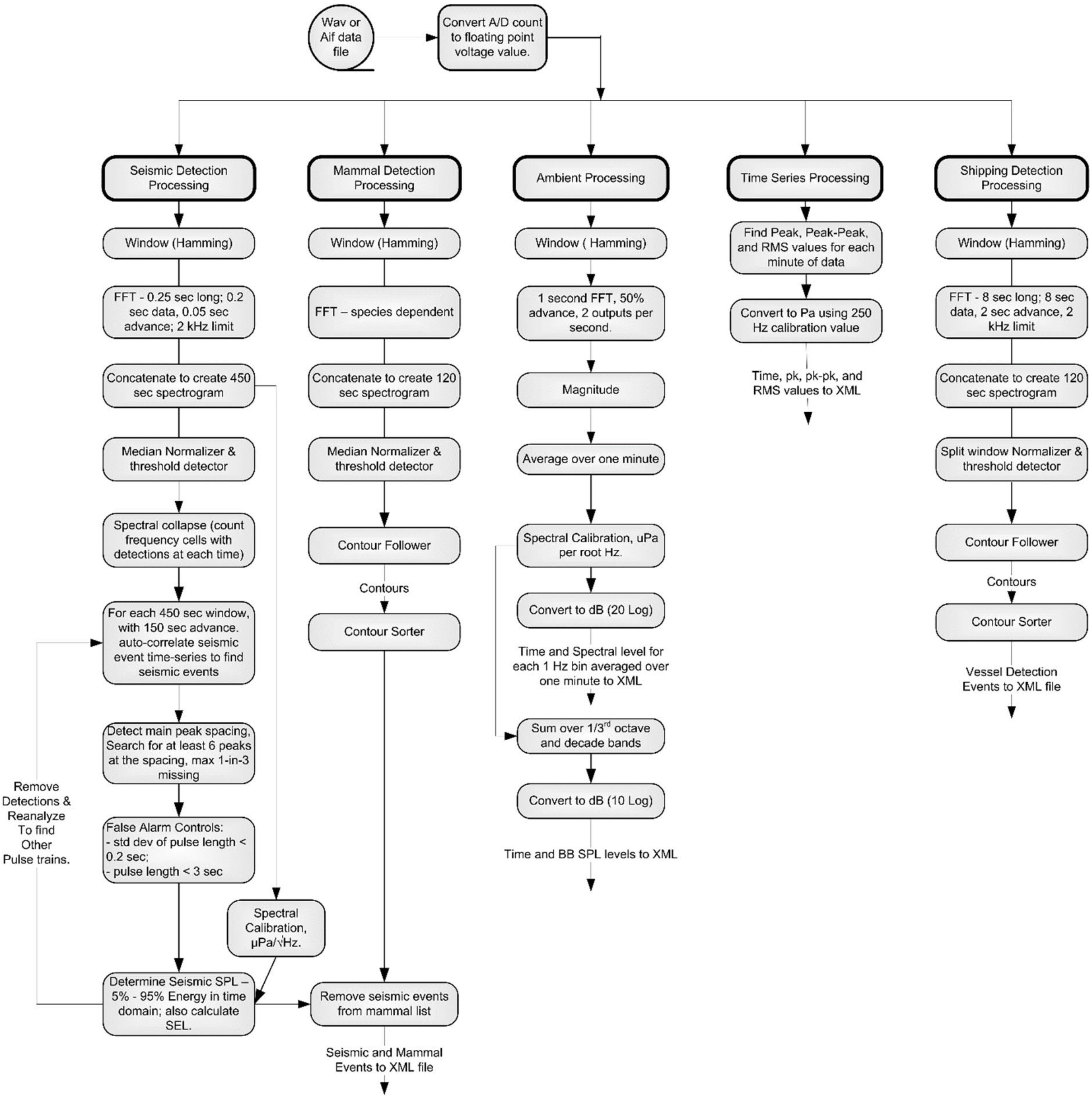


Figure B-1. Major stages of the automated acoustic analysis process performed with JASCO's custom software suite.

B.1. Total Ambient Sound Levels

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa. Because the perceived loudness of sound, especially impulsive noise such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate noise and its effects on marine life. We provide specific definitions of relevant metrics used in this report. Where possible we follow the ANSI and ISO standard definitions and symbols for sound metrics, but these standards are not always consistent.

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

$$\mathrm{PK} = L_{p,\mathrm{pk}} = 10\log_{10}\frac{\max|p^2(t)|}{p_0^2} \tag{B-1}$$

PK is often included as criterion for assessing whether a sound is potentially injurious; however, because it does not account for the duration of a noise event, it is generally a poor indicator of perceived loudness.

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

$$\mathrm{SPL} = L_p = 10\log_{10}\left[\frac{1}{T}\int_T p^2(t)\,dt \Big/ p_0^2\right] \tag{B-2}$$

The SPL represents a nominal effective continuous sound over the duration of an acoustic event, such as the emission of one acoustic pulse, a marine mammal vocalisation, the passage of a vessel, or over a fixed duration. Because the window length, T, is the divisor, events with similar sound exposure level (SEL), but more spread out in time have a lower SPL.

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

$$\mathrm{SEL} = L_E = 10\log_{10}\left[\int_T p^2(t)\,dt \Big/ T_0 p_0^2\right] \tag{B-3}$$

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

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

$$L_{E,N} = 10\log_{10}\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}} \tag{B-4}$$

To compute the SPL(T_{90}) and SEL of acoustic events in the presence of high levels of background noise, equations B-1 and B-2 are modified to subtract the background noise contribution:

$$\mathrm{SPL}(T_{90}) = L_{p90} = 10\log_{10}\left[\frac{1}{T_{90}}\int_{T_{90}}\left(p^2(t)-\overline{n^2}\right)dt\Big/p_0^2\right] \quad \text{(B-5)}$$

$$L_E = 10\log_{10}\left[\int_{T}\left(p^2(t)-\overline{n^2}\right)dt\Big/T_0 p_0^2\right] \quad \text{(B-6)}$$

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

Because the SPL(T_{90}) and SEL are both computed from the integral of square pressure, these metrics are related numerically by the following expression, which depends only on the duration of the time window T:

$$L_p = L_E - 10\log_{10}(T) \quad \text{(B-7)}$$

$$L_{p90} = L_E - 10\log_{10}(T_{90}) - 0.458 \quad \text{(B-8)}$$

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

Energy equivalent SPL (dB re 1 µPa) denotes the SPL of a stationary (constant amplitude) sound that generates the same SEL as the signal being examined, $p(t)$, over the same period of time, T:

$$L_{\mathrm{eq}} = 10\log_{10}\left[\frac{1}{T}\int_{T} p^2(t)\,dt\Big/p_0^2\right] \quad \text{(B–9)}$$

The equations for SPL and the energy-equivalent SPL are numerically identical; conceptually, the difference between the two metrics is that the former is typically computed over short periods (typically of 1 s or less) and tracks the fluctuations of a non-steady acoustic signal, whereas the latter reflects the average SPL of an acoustic signal over times typically of one minute to several hours.

B.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. These values directly compare to the Wenz curves, which represent typical deep ocean sound levels (Figure 2) (Wenz 1962). 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, $f_{\mathrm{c}}(i)$, is defined as:

$$f_{\mathrm{c}}(i) = 10^{\frac{i}{10}}\ \mathrm{kHz} \quad \text{(B-1)}$$

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

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

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure B-2).

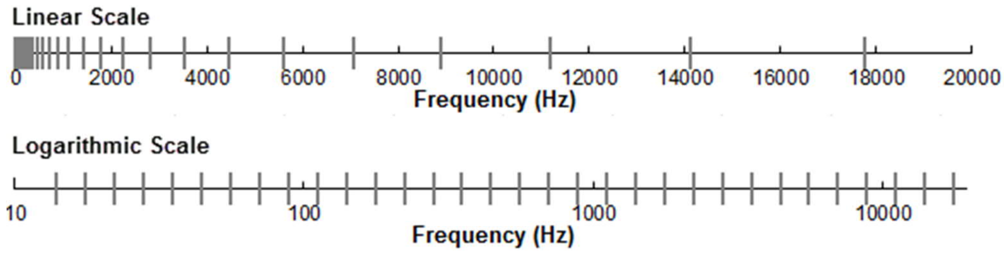


Figure B-2. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale.

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

$$L_{p,i} = 10 \log_{10} \int_{f_{\mathrm{lo},i}}^{f_{\mathrm{hi},i}} S(f)\, df \tag{B-3}$$

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

$$\text{Broadband SPL} = 10 \log_{10} \sum_{i} 10^{\frac{L_{p,i}}{10}} \tag{B-4}$$

Figure B-3 shows an example of how the decidecade band sound pressure levels compare to the sound pressure spectral density levels of an ambient noise signal. Because the decidecade bands are wider with increasing frequency, the decidecade band SPL is higher than the spectral levels at higher frequencies. Decidecade band analysis is applied to continuous and impulsive noise sources. For impulsive sources, the decidecade band SEL is typically reported.

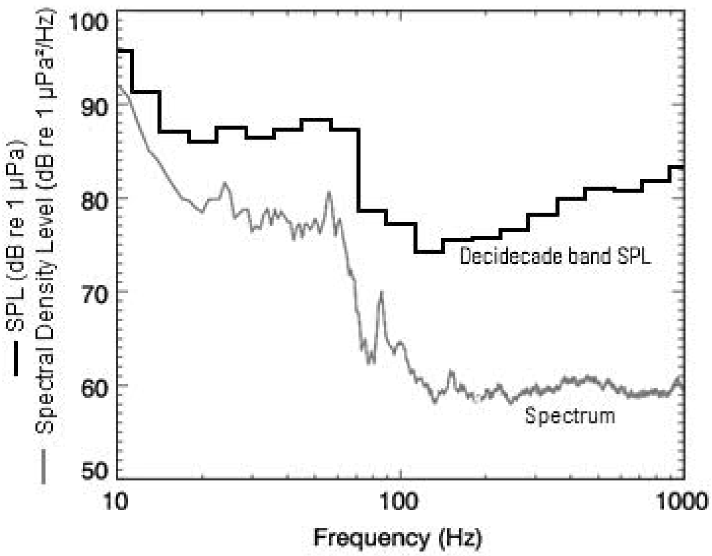


Figure B-3. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient noise shown on a logarithmic frequency scale.

Table B-1. Decidecade band frequencies (Hz)

Band	Lower frequency	Nominal centre frequency	Upper frequency
10	8.9	10.0	11.2
11	11.2	12.6	14.1
12	14.1	15.8	17.8
13	17.8	20.0	22.4
14	22.4	25.1	28.2
15	28.2	31.6	35.5
16	35.5	39.8	44.7
17	44.7	50.1	56.2
18	56.2	63.1	70.8
19	70.8	79.4	89.1
20	89.1	100.0	112.2
21	112	126	141
22	141	158	178
23	178	200	224
24	224	251	282
25	282	316	355
26	355	398	447
27	447	501	562
28	562	631	708
29	708	794	891
30	891	1000	1122
31	1122	1259	1413
32	1413	1585	1778
33	1778	1995	2239
34	2239	2512	2818
35	2818	3162	3548
36	3548	3981	4467
37	4467	5012	5623
38	5623	6310	7079
39	7079	7943	8913
40	8913	10000	11220
41	11220	12589	14125
42	14260	16000	17952
43	17825	20000	22440
44	22281	25000	28050
45	28074	31500	35344

Table B-2. Decade-band frequencies (Hz)

Decade band	Lower frequency	Nominal centre frequency	Upper frequency
A	8.9	50	89.1
B	89.1	500	891
C	891	5000	8910
D	8910	50000	89100 (Here limited to 64000)

B.3. Millidecade Band Analysis

JASCO Applied Sciences has adopted a hybrid millidecade spectrum system to store and exchange passive acoustic spectral data to optimise data resolution while minimising data size, described in Martin et al. (2021).

Millidecades are logarithmically spaced frequency bands but have a bandwidth equal to 1/1000th of a decade. This frequency resolution is high enough to support many types of analysis, including analysing different types of soundscapes, computing weighted sound exposure levels, and summing the millidecades to find decidecades, 1/3-octave, and other desired frequency bands. The size of the millidecade files greatly compresses the acoustic data compared to 1 Hz resolution, such that data from long-term, multiple-station, high-sampling frequency projects can easily be stored at a single location. For example, there are 1,000 millidecades in each frequency decade, where a decade is an increase in the frequency by a factor of 10. A pure millidecade presentation of a spectrum from 1–100,000 Hz has 5,000 bands rather than 100,000 1 Hz bands, which results in a 20:1 decrease in the amount of data required for storage or exchange. For a 256 kHz spectrum, which is becoming a common size for recorders sampling at 512 kHz, there are 3,206 hybrid millidecades resulting in a compression ratio of 80:1.

The format uses 1-Hz resolution up to 455 Hz and millidecades frequency bands above 455 Hz. The lowest millidecades over-resolve (bin sizes <1 Hz) the space between 1–435 Hz for nearly all soundscape applications. To address this, a hybrid solution was applied that uses 1 Hz bands up to 455 Hz, where the millidecades are 1 Hz wide.

Similar to decidecades, the centre frequency for the i^{th} millidecade (f_{c_i}) is defined as

$$f_{c\_i} = 10^{i/1{,}000}\ \text{(Hz)} \tag{10}$$

and the lower (f_{lo_i}) and upper (f_{hi_i}) bounds for each millidecade are

$$f_{lo\_i} = f_{c\_i} \cdot 10^{-1/2{,}000}\ \text{(Hz)} \tag{11}$$

$$f_{hi\_i} = f_{c\_i} \cdot 10^{1/2{,}000}\ \text{(Hz)}\ . \tag{12}$$

Appendix C. Recorder Calibration

The AMAR was calibrated before deployment with a pistonphone type 42AC precision sound source (G.R.A.S. Sound & Vibration A/S; Figure C-1). Due to the unforeseen delay of the retrieval the battery life was exhausted which prevented a calibration after retrieval. The pistonphone calibrator produces a constant tone at 250 Hz at a fixed distance from the hydrophone sensor in an airtight space with known volume. The recorded level of the reference tone on the AMAR yields the system gain for the AMAR and hydrophone. To determine absolute sound pressure levels, this gain was applied during data analysis. Typical calibration variance using this method is less than 0.7 dB absolute pressure.

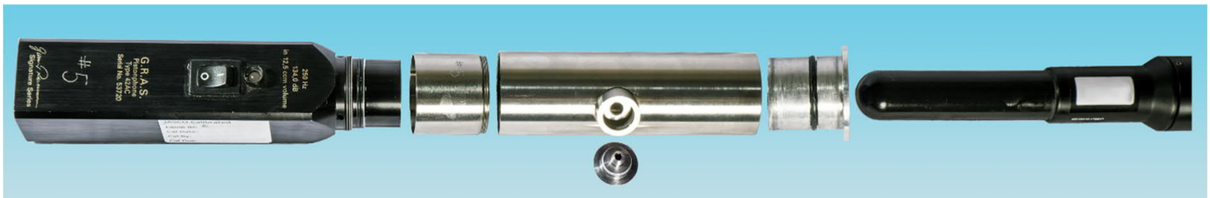


Figure C-1. Split view of a G.R.A.S. 42AC pistonphone calibrator with an M36 hydrophone.

Appendix D. Noise Effect Criteria

D.1. Noise Effect Criteria

To assess the potential effects of a sound-producing activity, it is first necessary to 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 sound exposure level (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.

Two sound level metrics, sound pressure level (SPL), and SEL (Appendix A), are commonly used to evaluate non-impulsive noise and its effects on marine life. In this report, the duration of the SEL accumulation is defined as integrated over a 24 h time period. Appropriate subscripts indicate any applied frequency weighting applied. The acoustic metrics in this report reflect the amended ANSI and ISO standards for acoustic terminology, ANSI S1.1 (S1.1-2013), and ISO 18405:2017 (2017a).

The following thresholds were chosen because they represent the best available science:

1. Frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from the US National Oceanic and Atmospheric Administration (NOAA) Technical Guidance (NMFS 2018) for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in marine mammals for non-impulsive sources.
2. Marine mammal behavioural threshold based on the current interim U.S. National Oceanic and Atmospheric Administration (NOAA) (2019) criterion for marine mammals of 120 dB re 1 µPa (SPL; L_p) for non-impulsive sound sources.

The criteria applied in this study to assess possible effects of vessel noise on marine mammals are summarised in Table D-1, with frequency weighting explained in Appendix D.2.

Table D-1. Criteria for effects of continuous noise exposure, including vessel noise, for marine mammals: Unweighted sound pressure level (SPL) and 24 h sound exposure level (SEL_{24h}) thresholds.

Hearing group	NOAA (2019)	NMFS (2018)	
	Behaviour	PTS onset thresholds (received level)	TTS onset thresholds (received level)
	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 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
Very high-frequency (VHF) cetaceans		173	153
Phocid seals		201	181
Otariid seals		219	199

L_p denotes sound pressure level period and has a reference value of 1 µPa.
L_E denotes cumulative sound exposure over a 24 h period and has a reference value of 1 µPa^{2}s.

D.2. Auditory Frequency Weighting Functions

The potential for anthropogenic sounds to impact marine mammals is largely dependent on whether the sound occurs at frequencies that an animal can hear well, unless the sound pressure level is so high that it can cause physical tissue damage regardless of frequency. Auditory (frequency) weighting functions reflect an animal's ability to hear a sound (Nedwell and Turnpenny 1998, Nedwell et al. 2007). Houser et al (2017) provide an example illustrating the effect of applying a weighting function to a (hypothetical) sound (Figure D-1).

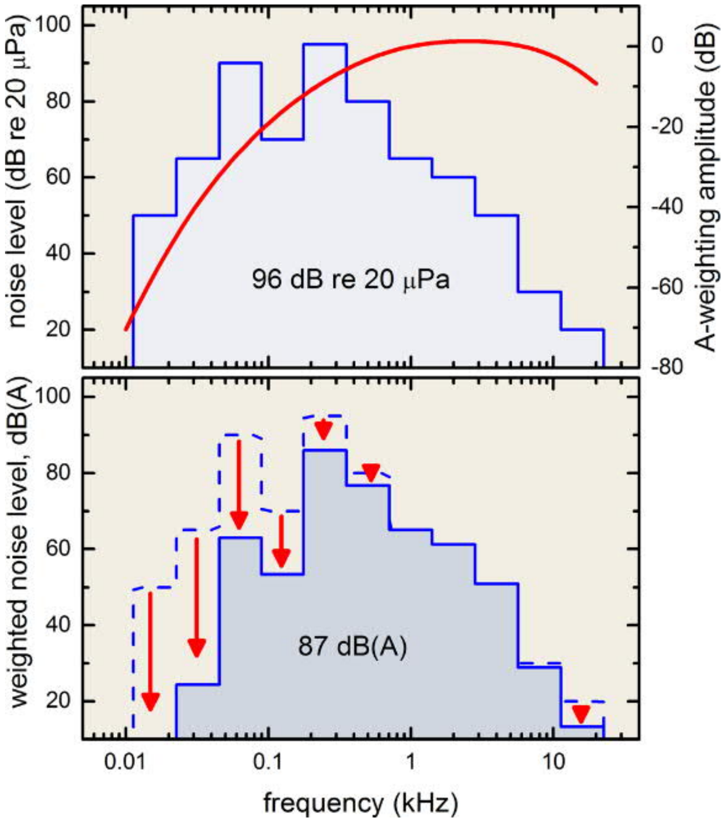


Figure D-1. Application of an auditory weighting function. Blue line shows a hypothetical, octave-band sound pressure spectrum in air, with a total sound pressure level (integrated over all octave-bands) of 96 dB re 20 µPa (This example uses in air-noise levels; therefore, a different reference pressure (20 µPa) applies. The principle is identical to underwater sound where a reference pressure of 1 µPa applies). (Top) Red line shows the human A-weighting function amplitude (A-weighting applies only to human hearing). (Bottom) To determine the weighted exposure level, the A-weighting amplitude at each frequency is added to the sound pressure level at each frequency (red arrows). The weighted spectrum has lower amplitude at the frequencies where the A-weighting function amplitudes are negative. The values from 1–4 kHz do not change substantially, because the weighting function is flat (i.e., the weights are near zero). The weighted SPL is calculated by integrating the weighted spectrum across all octave-bands; the result is 87 dBA, meaning a sound pressure level of 87 dB re 20 µPa after applying the human A-weighting function (Source: Houser et al. 2017).

To better reflect the auditory similarities between phylogenetically closely related species, but also significant differences between species groups among the marine mammals, the extant marine mammal species are assigned to functional hearing groups based on their hearing capabilities and sound production (NMFS 2018) (Table D-2). This division into broad categories is intended to provide a realistic number of categories for which individual noise exposure criteria were developed and the categorisation as such has proven to be a scientifically justified and useful approach in developing auditory frequency weighting functions and deriving noise exposure criteria for marine mammals.

Table D-2. Marine mammal hearing groups (NMFS 2018).

Hearing group	*Generalised hearing range**
Low-frequency (LF) cetaceans (mysticetes or baleen whales)	7 Hz to 35 kHz
Mid-frequency (MF) cetaceans (odontocetes: delphinids, beaked whales)	150 Hz to 160 kHz
High-frequency (HF) cetaceans (other odontocetes)	275 Hz to 160 kHz
Phocid pinnipeds (PW) (underwater)	50 Hz to 86 kHz
Otariid pinnipeds (OW) (underwater)	60 Hz to 39 kHz

* The generalised hearing range for all species within a group. Individual hearing will vary.

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).

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

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

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid-, and high-frequency cetaceans, phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA's technical guidance that assesses noise impacts on marine mammals (NMFS 2016, NMFS 2018). Table D-3 lists the frequency-weighting parameters for each hearing group; Figure D-2 shows the resulting frequency-weighting curves.

Table D-3. Parameters for the auditory weighting functions used in this project as recommended by NMFS (2018).

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

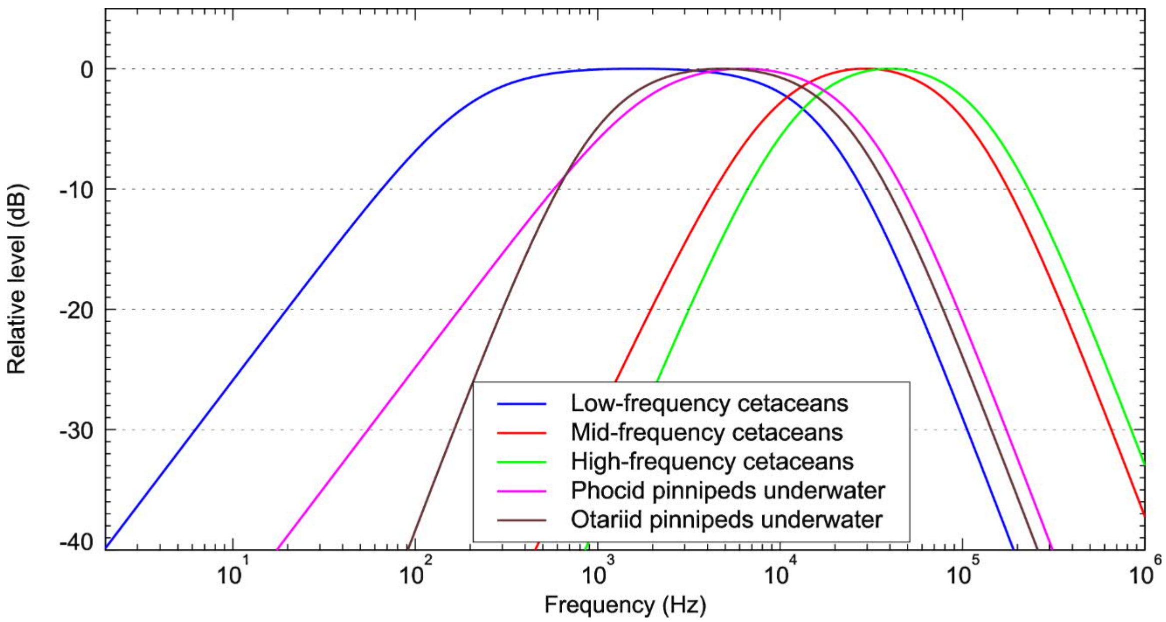


Figure D-2. Auditory weighting functions for functional marine mammal hearing groups as recommended by NMFS (2018).

Appendix E. Mooring Design

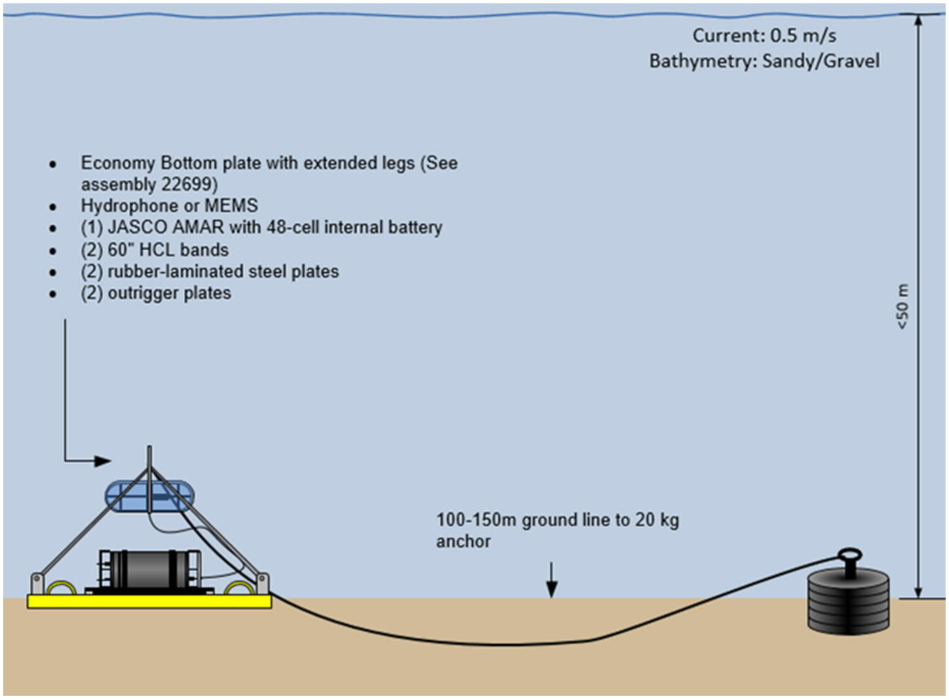


Figure E-1. Mooring design for acoustic environment recordings.

Appendix A-2: Underwater Noise Modelling

Viva Energy Gas Terminal Project Environment Effects Statement

JASCO Applied Sciences (Australia) Pty Ltd

4 February 2022

Submitted to:

AECOM

Contract Dated 21 July 2021

P001627-001
Document 02534
Version 2.0

Contents

Executive Summary 1
Pile Driving 2
Vessels 4
Berthing 5
1. Introduction 6
1.1. Project Overview 6
1.2. Study Specific Introduction 6
1.3. Modelling Scenario Details 7
2. Noise Effect Criteria 9
2.1. Marine Mammals 10
2.2. Fish, Fish Eggs, and Fish Larvae 11
2.3. Diving Birds 13
3. Methods 14
3.1. Environmental Parameters 14
3.2. Acoustic Source Parameters 14
3.2.1. Scenario 1 - Impact Pile Driving 14
3.2.2. Scenario 2 – Dredging 16
3.2.3. Scenario 3 – FSRU and LNG Carrier Operations 17
3.2.4. Scenario 4 – LNG Carrier Berthing 17
3.3. Modelling Sound Propagation 19
3.3.1. Impulsive Sources 19
3.3.2. Non-impulsive Sources 19
4. Results 20
4.1. Scenario 1 - Pile Driving 20
4.1.1. Tables 21
4.1.2. Sound Field Maps 23
4.1.3. Vertical Slice Plots 27
4.2. Scenarios 2 and 3 – Vessels 29
4.2.1. Tables 29
4.2.2. Sound Field Maps 31
4.3. Scenario 4 – Berthing 35
4.3.1. Tables 35
4.3.2. Sound Field Maps 36
5. Discussion 38
5.1. Scenario 1 38
5.2. Scenarios 2 and 3 38
5.3. Scenario 4 39
Glossary 40

Literature Cited 46
Appendix A. Additional Methods and Parameters A-1
Appendix B. Underwater Acoustic Metrics B-1
Appendix C. Sound Source and Propagation Models C-1

Figures

Figure 1. Map of the study area indicating modelled sound source locations for Scenarios 1 to 3. 8
Figure 2. Map of the Scenario 4 indicating modelled source positions and line of approach. 8
Figure 3. Forcing functions at the top of the pile for the pile-driving scenarios. 15
Figure 4. Modelled vertical displacement of the head and toe of the pile in Scenario 1a at 15m penetration. 15
Figure 5. Modelled vertical displacement of the head and toe of the pile in Scenario 1b at 4m penetration. 15
Figure 6. Maximum-over-depth decidecade band SELs at a receiver 10 m horizontally from the modelled pile driving sources. 16
Figure 7. Decidecade band monopole source levels for vessel sources. 17
Figure 8. Estimated decidecade energy source level (ESL) spectra of the *Britoil 51*, used for both escort and berthing tugs. Dashed line indicates extrapolated portion of spectrum. 18
Figure 9. Unweighted maximum-over-depth SEL for the complete driving of a single pile in Scenario 1a 23
Figure 10. Unweighted maximum-over-depth SEL for the complete driving of three piles in Scenario 1a. 24
Figure 11. Maximum-over-depth SPL levels in Scenario 1a. 24
Figure 12. Unweighted maximum-over-depth SEL levels for the complete driving of a single pile in Scenario 1b. 25
Figure 13. Unweighted maximum-over-depth SEL levels for the complete driving of four piles in Scenario 1b 26
Figure 14. Maximum-over-depth per-strike SPL levels in Scenario 1b. 26
Figure 15. *SPL, dolphin pile*: Vertical slice of the predicted SPL sound field for a single impact strike along azimuths 135° and 315° for Scenario 1a. 27
Figure 16. *SPL, dolphin pile*: Vertical slice of the predicted SPL sound field for a single impact strike along azimuths 0° and 180° for Scenario 1a. 27
Figure 17. *SPL, Lascelles Wharf pile*: Vertical slice of the predicted SPL sound field for a single impact strike along azimuths 135° and 315° for Scenario 1b. 28
Figure 18. *SPL, Lascelles Wharf pile*: Vertical slice of the predicted SPL sound field for a single impact strike along azimuths 0° and 180° for Scenario 1b. 28
Figure 19. Unweighted maximum-over-depth SEL levels for Scenario 2a. 31
Figure 20. Maximum-over-depth SPL levels for Scenario 2a. 31
Figure 21. Unweighted maximum-over-depth SEL levels for Scenario 2b. 32
Figure 22. Maximum-over-depth SPL levels for Scenario 2b. 32
Figure 23. Unweighted maximum-over-depth SEL levels for Scenario 3a. 33
Figure 24. Maximum-over-depth SPL levels for Scenario 3a. 33
Figure 25. Unweighted maximum-over-depth SEL levels for Scenario 3b. 34
Figure 26. Maximum-over-depth SPL levels for Scenario 3b. 34
Figure 27. Maximum-over-depth SPL levels for Scenario 4a. 36

Figure 28. Maximum-over-depth SPL levels for Scenario 4b. 36
Figure 29. Maximum-over-depth SPL levels for Scenario 4c. 37
Figure 30. Unweighted maximum-over-depth SEL levels for Scenario 4. 37

Figure A.1. Simplified overview of composite bathymetry data. A-2
Figure A.2 Sound speed profile used in this study. A-3
Figure A.3. R_{max} and $R_{95\%}$ ranges shown for two contrasting scenarios A-4
Figure B.1. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale. B-3
Figure B.2. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient sound shown on a logarithmic frequency scale. B-3
Figure B.3. Auditory weighting functions for functional marine mammal hearing groups used in this project. B-6
Figure C.1 Underwater sound propagation paths associated with pile driving C-1
Figure C.2. Physical model geometry for impact driving of a cylindrical pile C-2
Figure C.3. The N×2-D and maximum-over-depth modelling approach used by MONM. C-3
Figure C.4. Example of synthetic pressure waveforms computed for this project by FWRAM at multiple ranges. C-4

Tables

Table 1. Summary of maximum (R_{max}) horizontal distances (in km) from piling modelled sites to behavioural response thresholds, temporary threshold shift (TTS) and permanent threshold shift (PTS) for marine mammals. Where dual criteria are used, the metric applied is that which is associated with the longer distance. 2
Table 2. Summary of maximum fish, fish eggs, and larvae injury and temporary threshold shift (TTS) onset distances for single impulse and 24-hour sound exposure level (SEL_{24h}) modelled scenarios. 3
Table 3. Summary of maximum (R_{max}) horizontal distances (in km) from piling modelled sites to behavioural response threshold, temporary threshold shift (TTS) and permanent threshold shift (PTS) for diving birds. 3
Table 4. Summary of temporary threshold shift (TTS) and behavioural response distances for marine mammals in the continuous sound scenarios (Scenarios 2 and 3). 4
Table 5. Maximum distances to recommended sound level thresholds by Popper et al. (2014) for fish with a swim bladder involved in hearing exposed to vessel noise (Scenarios 2 and 3). 4
Table 6. Summary behavioural response distances for marine mammals in Scenario 4. 5
Table 7. Maximum distances to recommended sound level thresholds by Popper et al. (2014) for fish with a swim bladder involved in hearing exposed to vessel noise (Scenario 4). 5
Table 8. Scenarios modelled in this study and associated source locations. 7
Table 9. Criteria for effects of non-impulsive noise exposure including vessel noise, for marine mammals 10
Table 10. Acoustic effects of impulsive noise on marine mammals. 10
Table 11. Criteria for pile driving noise exposure for fish 12
Table 12. Criteria for non-impulsive (vessel) noise exposure for fish 12
Table 13. Geoacoustic profile based on Port of Geelong geotechnical data. 14
Table 14. Parameters for the pile geometry used in the impact piling modelling scenarios. 14
Table 15. Parameters for the hammer used in the impact piling modelling scenarios. 15

Table 16. *Piling, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from the dolphin pile (Scenario 1a) and mooring pile (dolphin pile (Scenario 1b) to modelled maximum-over-depth peak pressure level (PK) PTS and TTS thresholds for marine mammals (Southall et al. 2019) and fish (Popper et al. 2014). 21

Table 17. *Piling, SPL*: Maximum (R_{max}) horizontal distances (km) from the dolphin pile (Scenario 1a) and mooring pile (Scenario 1b) to maximum-over-depth per-strike SPL isopleths. 21

Table 18. *Piling, PTS and TTS SEL thresholds*: Maximum (R_{max}) horizontal distances (m) from the dolphin pile (Scenario 1a) and mooring pile (Scenario 1b) to maximum-over-depth weighted SEL isopleths for marine mammals and diving birds (Southall et al. 2019). 22

Table 19. *Piling, thresholds for effects on fish*: maximum and 95% distances to maximum-over-depth unweighted SEL isopleths for fish (Popper et al. 2014). 22

Table 20. Vessels, SPL: Maximum (R_{max}) horizontal distances (km) from dredging (Scenario 2) and FSRU (Scenario 3) scenarios to maximum-over-depth SPL isopleths. 29

Table 21. *Vessels, TTS SEL thresholds* 30

Table 22. Berthing Scenario, SPL: Maximum (R_{max}) horizontal distances (km) from three modelled locations representing an LNG carrier berthing operation to maximum-over-depth SPL isopleths. 35

Table 23. Berthing Scenario, TTS SEL Thresholds: Maximum (R_{max}) horizontal distances (m) from the berthing scenario line to maximum-over-depth weighted SEL isopleths for marine mammals (Southall et al. 2019). PTS thresholds were also not exceeded. 35

Table B-1. Parameters for the auditory weighting functions used in this project (Southall et al. 2019). B-6

Executive Summary

This technical report provides the results of underwater acoustic modelling conducted to support an underwater noise impact assessment which forms part of the Environment Effects Statement (EES) for the Viva Energy Gas Terminal Project (the project).

This underwater acoustic modelling study presents the outputs from models of underwater noise resulting from the construction phase and future operations of the Viva Gas Energy Terminal in Corio Bay. Acoustic models were used to simulate four main scenarios, each with a number of sub-scenarios, as follows:

1. Pile driving:
    a. Dolphin pile, part of the construction of the pier extension for the gas terminal.
    b. Mooring piles at Lascelles Wharf.
2. Dredging:
    a. Localised dredging at Refinery Pier to enable the FSRU and LNG carriers to berth at the pier extension.
    b. Installation of seawater transfer piping.
3. Future operations:
    a. FSRU berthed
    b. FSRU berthed and LNG carrier offloading
4. Future berthing:
    a. LNG carrier approaching (4 knots)
    b. LNG carrier approaching (2 knots)
    c. LNG carrier berthing (0.5 knots)

The study results are required for assessing the potential effects of noise exposure on marine mammals, fish (including eggs and larvae), and diving birds in the vicinity of the project. Due to the variety of species considered, there are several different thresholds for evaluating effects, including those associated with mortality, injury, temporary reduction in hearing sensitivity, and behavioural disturbance.

The modelling methodology considered scenario specific source levels and range-dependent environmental properties. Estimated underwater acoustic levels for non-impulsive (continuous) noise sources are presented as sound pressure levels (SPL, L_p), and as accumulated sound exposure levels (SEL, L_E). Estimated underwater acoustic levels for impulsive noise sources (piling) are presented as sound pressure levels, zero-to-peak pressure levels (PK, L_{pk}), and either single-impulse (i.e., per-pulse) or accumulated sound exposure levels as appropriate for different noise effect criteria. In this report, the duration of the SEL accumulation is defined as being integrated over a 24-hour period, which includes multiple piles being installed per day. SEL_{24h} is a cumulative metric that reflects the dosimetric impact of noise levels over 24 hours, based on the assumption that an animal is consistently exposed to such noise levels whilst remaining static for the period.

The modelling results predict very little sound transmission beyond Corio Bay and the Port of Geelong due to the local bathymetry.

Pile Driving

For impulsive sources, the SEL accumulates with each strike. Conservative estimates of SEL_{24h} for pile driving were calculated based on the assumption that a maximum of three piles could be driven per day for the dolphin pile at the pier extension, and four piles per day for the smaller mooring piles. Accumulated levels are based on the modelled sound emissions of a single mid-sequence strike at each location.

Marine Mammals:

The results for marine mammal injury used the criteria from Southall et al. (2019), which requires two metrics (PK and SEL_{24h}) to be considered when assessing marine mammal Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS). The longest distance associated with either metric should be applied.

Table 1 summarises the results from the modelling in terms of R_{max}, which represents the largest distances from the sound source to the indicated sound level thresholds. It includes the distances to the NOAA (2019) marine mammal behavioural response criterion of 160 dB re 1 µPa (SPL), and temporary threshold shift (TTS) based on the Southall et al. (2019) criteria. No criterion associated with permanent threshold shift (PTS) or peak pressure was exceeded within the resolution of the models.

Table 1. Summary of maximum (R_{max}) horizontal distances (in km) from piling modelled sites to behavioural response thresholds, temporary threshold shift (TTS) and permanent threshold shift (PTS) for marine mammals. Where dual criteria are used, the metric applied is that which is associated with the longer distance.

Hearing group	Modelled distance to effect threshold (R_{max})		
	Behavioural response[a]	Impairment: TTS[b]	Impairment: PTS[b]
1a) Dolphin pile			
High-frequency (HF) cetaceans	0.80	0.07	—
Otariid pinnipeds (OCW)		0.10	—
1b) Mooring pile			
High-frequency (HF) cetaceans	0.26	—	—
Otariid pinnipeds (OCW)		—	—

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

Fish, fish eggs, and fish larvae:

This modelling study assessed the ranges for quantitative criteria based on Popper et al. (2014) and considered both PK and SEL_{24h} metrics associated with mortality, potential mortal injury, and 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 2 summarises distances to effect criteria for fish, fish eggs, and fish larvae along with the metric associated with the longest distance.

Table 2. Summary of maximum fish, fish eggs, and larvae injury and temporary threshold shift (TTS) onset distances for single impulse and 24-hour sound exposure level (SEL_{24h}) modelled scenarios. Where dual criteria are used, the metric applied is that which is associated with the longer distance.

Hearing group	1a – Dolphin pile		1b – Mooring pile	
	Metric	R_{max} (km)	Metric	R_{max} (km)
Injury/recoverable injury[a]				
Fish: No swim bladder	n/a	—	n/a	—
Fish: Swim bladder not involved in hearing and Swim bladder involved in hearing	SEL_{24h}	0.02	n/a	—
Fish eggs, and larvae	SEL_{24h}	0.02	n/a	—
TTS*				
Fish: No swim bladder Swim bladder not involved in hearing and Swim bladder involved in hearing	SEL_{24h}	0.87	SEL_{24h}	0.11

Noise exposure criteria: [a] Popper et al. (2014).
A dash indicates the threshold was not reached within the limits of the modelling resolution.

Diving birds:

There are no regulatory thresholds or criteria established to assess potential behavioural responses by diving birds to underwater noise. To assess possible impacts, a frequency-weighted onset criterion for behavioural responses of diving birds of 120 dB re 1 µPa (SPL) for impulsive sources was chosen based on information from Sørensen et al. (2020). Table 3 shows results determined to assist with assessing the potential effects on diving birds.

Table 3. Summary of maximum (R_{max}) horizontal distances (in km) from piling modelled sites to behavioural response threshold, temporary threshold shift (TTS) and permanent threshold shift (PTS) for diving birds.

Hearing group	Effect	1a – Dolphin pile		1b – Mooring pile	
		Metric	R_{max} (km)	Metric	R_{max} (km)
Diving birds	PTS[a]	n/a	—	n/a	—
	TTS[a]	SEL_{24h}	0.10	n/a	—
	Behavioural response[b]	SPL	4.90	SPL	3.62

Noise exposure criteria: [a] Southall et al. (2019) (Otariid pinnipeds (OCW) as a proxy), and [b] Sørensen et al. (2020)
A dash indicates the threshold was not reached within the limits of the modelling resolution.

Vessels

For continuous sources, the SEL accumulates over the duration the source is active. To calculate SEL$_{24h}$ for the dredging and the FSRU operations, each were considered to be in continuous operation over 24 hours.

Marine Mammals:

The study investigated sound level thresholds associated with auditory impairment in high-frequency cetaceans and otariid pinnipeds. No relevant PTS levels were exceeded in these scenarios, therefore the table presents the longest distances to recommended threshold levels for TTS onset (Southall et al. 2019) and relevant behavioural thresholds (NOAA 2019) are shown in Table 4.

Table 4. Summary of temporary threshold shift (TTS) and behavioural response distances for marine mammals in the continuous sound scenarios (Scenarios 2 and 3).

Hearing group	Metric	2a – Dredging berth and swing basin	2b – Dredging seawater piping	3a – FSRU	3b – FSRU + LNG Carrier
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS[a]					
High-frequency cetaceans	SEL$_{24h}$	—	—	—	—
Otariid pinnipeds	SEL$_{24h}$	—	—	—	—
TTS[a]					
High-frequency cetaceans	SEL$_{24h}$	0.01	0.01	0.01	0.04
Otariid pinnipeds	SEL$_{24h}$	<0.01	0.01	—	0.03
Behavioural response[b]					
Marine mammals	SPL	1.55	1.84	1.10	1.46

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

Fish:

The maximum distances to recommended sound level thresholds for fish (Popper et al. 2014) are shown in Table 5. For continuous sounds, sound level thresholds are only provided for fish with a swim bladder involved in hearing. In terms of recoverable injury onset levels, the maximum distance is less than 10 m from the acoustic centre of the source in Scenario 2a only (48-hour exposure). The maximum distance to the TTS onset threshold level is 30 m in Scenario 3b (12-hour exposure). Additional investigations were carried out for demersal fish for which the modelling predicts that neither the recoverable injury or TTS onset thresholds will be reached at the seafloor.

Table 5. Maximum distances to recommended sound level thresholds by Popper et al. (2014) for fish with a swim bladder involved in hearing exposed to vessel noise (Scenarios 2 and 3).

Hearing group	Effect	2a) Dredging – berth & swing basin	2b) Dredging – seawater piping	3a) FSRU	3b) FSRU + LNG carrier
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
Fish: Swim bladder involved in hearing	Recoverable injury	<0.01	—	—	—
	TTS	0.01	0.01	<0.01	0.03

A dash indicates the threshold was not reached within the limits of the modelling resolution.

Berthing

For the berthing scenario, the SEL accumulates over the equivalent length of time the sources are present at each point on a defined approach path.

Marine Mammals:

In this scenario, no relevant PTS or TTS levels were exceeded, therefore Table 6 presents relevant behavioural thresholds only.

Table 6. Summary behavioural response distances for marine mammals in Scenario 4.

Hearing group	Metric	4a – 4 knots	4b – 2 knots	4c – 0.5 knots
		R_{max} (km)	R_{max} (km)	R_{max} (km)
Marine mammals	SPL	3.84	3.84	4.27

Noise exposure criteria: NOAA (2019).

Fish:

The maximum distances to recommended sound level thresholds for fish (Popper et al. 2014) are shown in Table 7. Again, as these sounds are non-impulsive, thresholds are only provided for fish with a swim bladder involved in hearing.

Table 7. Maximum distances to recommended sound level thresholds by Popper et al. (2014) for fish with a swim bladder involved in hearing exposed to vessel noise (Scenario 4).

Hearing group	Effect	4a – 4 knots	4b – 2 knots	4c – 0.5 knots
		R_{max} (km)	R_{max} (km)	R_{max} (km)
Fish: Swim bladder involved in hearing	Recoverable injury	<0.01	<0.01	0.04
	TTS	0.02	0.02	0.04

The maximum distance to both recoverable injury and TTS onset levels is 40 m from the acoustic centre of the sources in Scenario 4c, however, since these metrics are for 48-hour and 12-hour exposures, respectively, these will not be exceeded in the time taken to complete the berthing operation.

1. Introduction

1.1. Project Overview

This technical report provides the results of underwater acoustic modelling conducted to support an underwater noise impact assessment (Lucke and McPherson 2021) which forms part of the Environment Effects Statement (EES) for the Viva Energy Gas Terminal Project (the project).

Viva Energy Gas Australia Pty Ltd (Viva Energy) is planning to develop a gas terminal using a ship known as a floating storage and regasification unit (FSRU), which would be continuously moored at Refinery Pier in Corio Bay, Geelong. The key objective of the project is to facilitate supply of a new source of gas for the south-east Australian gas market where there is a projected supply shortfall in coming years.

The FSRU would store liquefied natural gas (LNG) received from visiting LNG carriers (that would moor directly adjacent to the FSRU) and would convert LNG back into a gaseous state by heating the LNG using seawater (a process known as regasification) as required to meet industrial, commercial, and residential customer demand. A 7 km gas transmission pipeline would transfer the gas from the FSRU to the Victorian Transmission System (VTS) at Lara.

The project would be situated adjacent to, and on, Viva Energy's Geelong Refinery, within a heavily developed port and industrial area on the western shores of Corio Bay between the Geelong suburbs of Corio and North Shore. Co-locating the project with the existing Geelong Refinery and within the Port of Geelong offers significant opportunity to minimise potential environmental effects and utilise several attributes that come with the port and industrial setting.

In December 2020, the Victorian Minister for Planning determined that the project requires assessment through an EES under the *Environment Effects Act 1978* (Vic). The reasons for the decision were primarily related to the potential for significant adverse effects on the marine environment of Corio Bay and the potential for contributing to greenhouse gas emissions. Secondarily, the EES was required to assess the effects of the project on air quality, noise, land use, Aboriginal and historic heritage, native vegetation, groundwater, traffic, and transport as well as visual amenity.

In January 2021, the project was also determined to require assessment and approval under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) due to the potential for the project to have a significant impact on wetlands of international importance, listed threatened species and communities, and listed migratory species. The EES process is the accredited environmental assessment process for the controlled action decision under the EPBC Act in accordance with the bilateral agreement between the Commonwealth and Victorian governments.

1.2. Study Specific Introduction

The scope of this study covers sound emissions caused both by the construction of new facilities and those caused by the operation of the moored FSRU and associated LNG carrier during berthed operational activities. This report describes the underwater acoustic modelling approaches and presents the predicted underwater sound levels over the area surrounding the proposed activities at the Geelong Refinery. Estimated underwater acoustic levels are presented as sound pressure levels (SPL, L_p), zero-to-peak pressure levels (PK, L_{pk}), and accumulated sound exposure levels (SEL, L_E), as appropriate for noise effect criteria for continuous and impulsive noise sources.

Acoustic modelling was performed to estimate the propagation of sound into nearby waters using JASCO's Marine Operations Noise Model (MONM), and full waveform range-dependent model (FWRAM), across the entire relevant frequency spectrum. Maps and metrics were produced describing distances at which sound levels could cause fish, diving birds, and marine mammal disturbance or injury.

1.3. Modelling Scenario Details

Four main scenarios associated with the construction and use of new facilities were considered for this study. These are detailed in Table 8. Modelled source locations for Scenarios 1 to 3 are mapped with context in Figure 1, with a map of Scenario 4 shown in Figure 2. Monopole source locations for the FSRU and LNG carriers were based on approximate acoustic centres of the vessels, both of which were assumed to be 300 metres long and 45 metres wide.

Table 8. Scenarios modelled in this study and associated source locations.

Scenario		Description	Latitude (S)	Longitude (E)	MGA Zone 55		Water depth (m)
					Easting (m)	Northing (m)	
1	a	Impact piling (dolphin)	38° 5.318’	144° 23.600’	271 397.5	5 781 142.2	8.3
	b	Impact piling (Lascelles Wharf)	38° 5.452’	144° 22.995’	270 521.1	5 780 869.2	4.6
2	a	Dredging (new berth & swing basin)	38° 5.535’	144° 23.585’	271 386.9	5 780 740.5	9.4
	b	Dredging (seawater piping)	38° 5.097’	144° 23.253’	270 881.0	5 781 536.1	5.4
3	a	FSRU	38° 5.275’	144° 23.493’	271 240.2	5 781 217.9	10.4
	b	FSRU + LNG carrier offloading	38° 5.293’	144° 23.468’	271 204.9	5 781 183.5	12.3
4	a	LNG carrier berthing (4 knots)	38° 5.738′	144° 23.178′	270 803.2	5 780 348.4	12.0
	b	LNG carrier berthing (2 knots)	38° 5.494′	144° 23.499′	271 259.5	5 780 811.5	12.0
	c	LNG carrier berthing (0.5 knots)	38° 5.356′	144° 23.533′	271 302.7	5 781 068.3	12.0

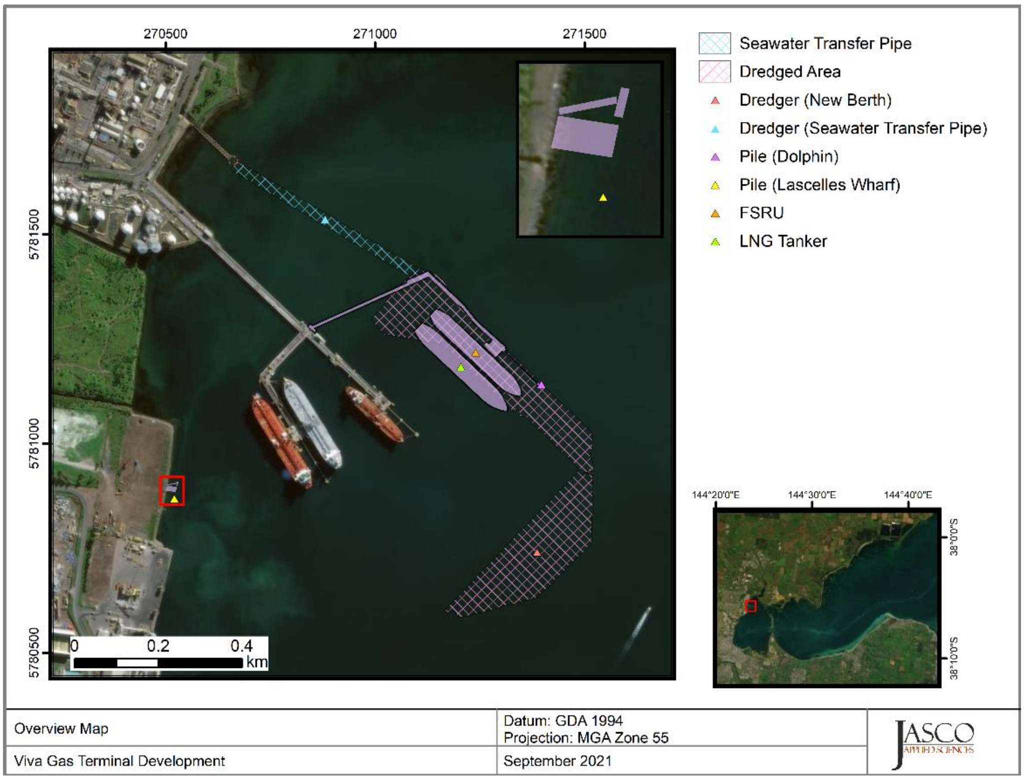


Figure 1. Map of the study area indicating modelled sound source locations for Scenarios 1 to 3.

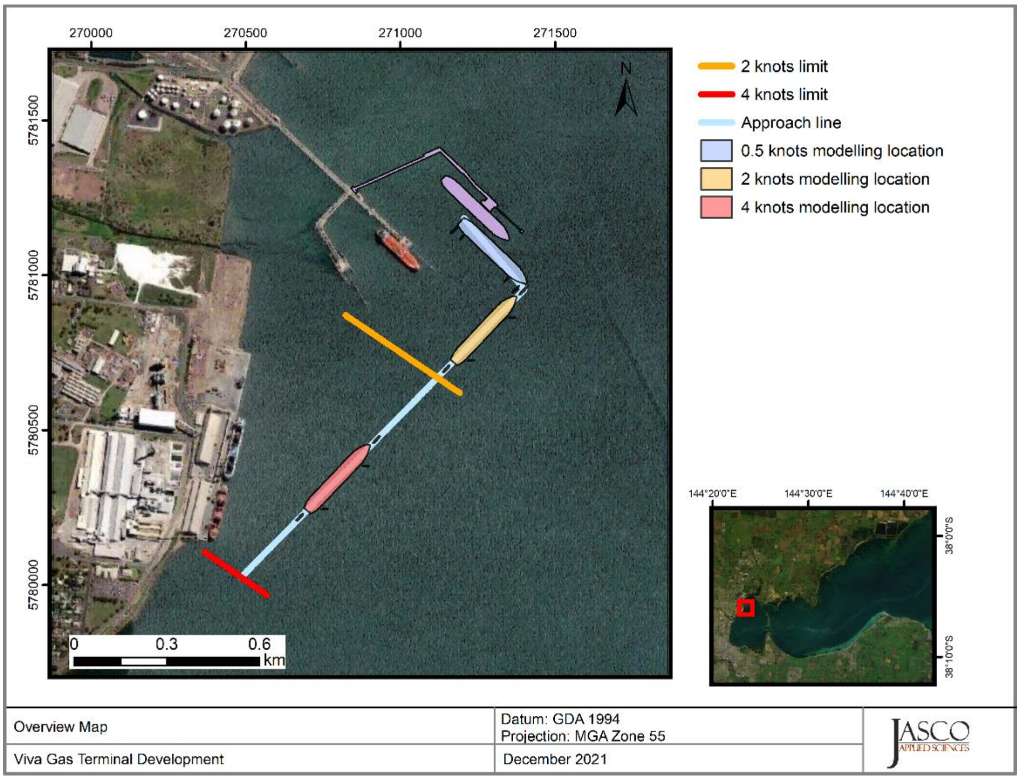


Figure 2. Map of the Scenario 4 indicating modelled source positions and line of approach.

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.

Two sound level metrics, SPL, and SEL, are commonly used to evaluate non-impulsive noise and its effects on marine life. In this report, the duration of the SEL accumulation is defined as integrated over a 24-hour time period. Appropriate subscripts indicate any frequency weighting applied (Appendix B.3). The acoustic metrics in this report reflect the updated ANSI and ISO standards for acoustic terminology, ANSI S1.1 (2013) and ISO 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. Peak pressure levels (PK; L_{pk}) and frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24\text{h}}$) from Southall et al. (2019) for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in marine mammals, including high-frequency (HF) cetaceans and otariid pinnipeds (as a proxy for diving birds – see Section 2.3).
2. Marine mammal behavioural threshold based on the current interim U.S. National Oceanic and Atmospheric Administration (NOAA 2019) 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.
3. Sound exposure guidelines for fish, fish eggs, and larvae from Popper et al. (2014).
4. Behavioural response to impulsive sound of 120 dB re 1 µPa (SPL; L_p) for diving birds based on information from Sørensen et al. (2020).

The following sections (Sections 2.1 and 2.2, along with Appendix B.3), expand on the thresholds, guidelines and sound levels for marine mammals, fish, fish eggs, fish larvae, and diving birds.

2.1. Marine Mammals

The criteria applied in this study to assess possible effects of non-impulsive and impulsive noise sources on marine mammals are summarised in Tables 9 and 10. High-frequency cetaceans and otariid seals were identified as the only mammalian hearing groups requiring assessment. Details on thresholds related to auditory threshold shifts or hearing loss and behavioural response are provided in Appendix B.3, with frequency weighting explained in detail in Appendix B.4. Note, that whilst the latest publication by Southall et al. (2021) provides recommendations and discusses the nuances of assessing behavioural response, the authors do not recommend new numerical thresholds for the onset of behavioural responses for marine mammals.

Table 9. Criteria for effects of non-impulsive noise exposure including vessel noise, for marine mammals considered in this study: 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 µPa²s)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²s)
High-frequency (HF) cetaceans	120	198	178
Otariid seals		219	199

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

Table 10. Acoustic effects of impulsive noise on marine mammals considered in this study: Unweighted SPL, SEL_{24h}, and PK thresholds.

Hearing group	NOAA (2019)	Southall et al. (2019)			
	Behaviour	PTS onset thresholds [a] (received level)		TTS onset thresholds [a] (received level)	
	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²s)	PK (L_{pk}; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²s)	PK (L_{pk}; dB re 1 µPa)
High-frequency (HF) cetaceans	160	185	230	170	224
Otariid seals		203	232	188	226

[a] 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-hour period.

2.2. Fish, Fish Eggs, and 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, following work began by a NOAA panel two years earlier. The group developed guidelines with specific thresholds for different levels of effects for several species groups (Popper et al. 2014), and 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.
- Temporary threshold shift.

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 11 and 12 for completeness only. Because the presence or absence of a swim bladder has a role in hearing, fish susceptibility to injury from noise exposure depends on the species as well as the presence and role of a swim bladder in hearing. Thus, different thresholds were proposed for fish without a swim bladder (also appropriate for sharks and applied to whale sharks in the absence of other information), fish with a swim bladder not used for hearing, and fish that use their swim bladders for hearing. Fish eggs, and fish larvae are considered separately.

Impulsive noise from pile driving is assessed in this study based on the relevant effect thresholds from Popper et al. (2014), listed in Table 11. In general, whether an impulsive sound adversely affects fish behaviour depends on the species and the state of the fish exposed, amongst other factors.

The SEL metric integrates sound energy over a specified period of exposure. Because the period of integration for regulatory assessments is not well defined for very long-lasting exposures or sounds that do not have a clear start or end time, an exposure evaluation time must be defined. NMFS (2018) defines the exposure evaluation time as the lesser of 24 hours or the duration of the activity. Popper et al. (2014) recommend a standard period of the duration of the activity, but also include caveats regarding consideration of the actual exposure times if fish move. In this study, integration times for piling have been applied over both the time taken to drive a single pile, and the total number of piles expected to be driven per day.

Table 11. 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}	(N) Moderate (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}	(N) Moderate (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}	(N, I) High (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	(N) Moderate (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).

Table 12 lists the relevant effects thresholds from Popper et al. (2014) for vessel noise. Some studies suggest 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.

Table 12. Criteria for non-impulsive (vessel) 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
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).

2.3. Diving Birds

There are no regulatory thresholds or criteria established to assess potential behavioural responses by diving birds (penguins, flying seabirds, swans) to underwater noise. This section provides a short overview of the proposed noise exposure criteria which are applied to model potential impact ranges in this report; Lucke and McPherson (2021) present more comprehensive background information and discuss the rationale for the chosen noise exposure criteria.

In a controlled exposure experiment, Sørensen et al. (2020) exposed captive gentoo penguins (*Pygoscelis papua*) to impulsive signals, and the majority of animals showed strong aversive reactions at received levels above 120 dB re 1 µPa (SPL). In a study on free-ranging African penguins (*Spheniscus demersus*) Pichegru et al. (2017) investigated their behavioural response to seismic surveys within 100 km of their colony in South Africa. The authors documented strong avoidance by penguins over long distances, thereby corroborating the relatively low threshold for onset of behavioural responses measured by Sørensen et al. in principle.

To apply this onset criterion to project-related noise emission, it must be frequency-weighted to reflect the difference of bird hearing over the frequency band of their hearing. In the absence of frequency weighting functions for birds, the function for other carnivores in water (OCW) from Southall et al. (2019) is used as a proxy.

There is also insufficient information available to determine the onset thresholds of behavioural responses of diving birds from non-impulsive noise such as vessel or dredger noise; therefore, this assessment has not considered potential effects from non-impulsive noise on behaviour of diving birds.

There are also no regulatory thresholds for the onset of hearing impairment for penguins or any other bird, or any phylogenetically or anatomically related species. To allow for assessing the noise-induced impact risk of the pile driving on penguins, other carnivores in water (OCW), from Southall et al. (2019), is once again recommended as a proxy due to the similarity in hearing sensitivity in the frequency band of underwater hearing for the two species groups. This is a conservative approach as otariids are considered more sensitive to underwater sound at higher frequencies than penguins.

3. Methods

3.1. Environmental Parameters

Bathymetry for the project was taken mainly from high-resolution survey data provided by the client, combined with depth soundings from Australian Hydrographic Office (AHO) survey AU439144. Many additional sources were required to fill in missing details, and these are covered in Appendix A.1.

A single sound speed profile for the month of May was used in all scenarios. This profile is largely flat, varying between 1505.7 m/s and 1506.0 m/s for all depths of interest, see expanded details in Appendix A.2.

Geoacoustics were derived from a geotechnical report provided by the client (Coffey Services Australia Pty Ltd 2021). Based on this, a two-layer system was used as the geoacoustic profile in this study with material properties taken from Hamilton (1980), and is outlined in Table 13. Whittaker et al. (2013) indicates that the bedrock at the modelled location is at a depth of 2.5 km, which is distant enough to disregard as part of the acoustic models in this study.

Table 13. Geoacoustic profile based on Port of Geelong geotechnical data. Within each depth range, each parameter varies linearly within the stated range. The compressional wave is the primary wave. The shear wave is the secondary wave.

Depth below seafloor (m)	Material	Compressional wave		Shear wave	
		Speed (m/s)	Attenuation (dB/ λ)	Speed (m/s)	Attenuation (dB/ λ)
0–16.5	Sand-silt-clay	1555–1584	0.23–0.37	283	1.36
16.5–200	Silty Sand	1648–1876	1.23–0.86		

3.2. Acoustic Source Parameters

3.2.1. Scenario 1 - Impact Pile Driving

JASCO's pile driving source model (PDSM, MacGillivray 2014) was used in conjunction with the GRLWEAP 2010 wave equation model (Pile Dynamics 2010) to predict source levels associated with impact pile driving activities. Further detail on PDSM is included in Appendix C.1.2. GRLWEAP, which includes a database of commercial impact hammers, was used to model a forcing function at the top of the pile. This model accounts for several parameters that describe the pile and hammer, along with the penetration depth. Based on information provided by the client, these parameters were set as shown in Tables 14 and 15. The resultant hammer forcing functions are shown in Figure 3.

Table 14. Parameters for the pile geometry used in the impact piling modelling scenarios.

Scenario	Pile type	Diameter (m)	Wall thickness (m)	Length (m)	Modelled penetration depth (m)
1a	Cylindrical steel	1.400	0.0250	56.0	15.0
1b		1.063	0.0254	21.0	4.0

Table 15. Parameters for the hammer used in the impact piling modelling scenarios.

Hammer model	Maximum energy (kJ)	Stroke (m)	Helmet weight (kN)	Helmet stiffness (kN/mm)
S-150	150	2.02	22.46	963

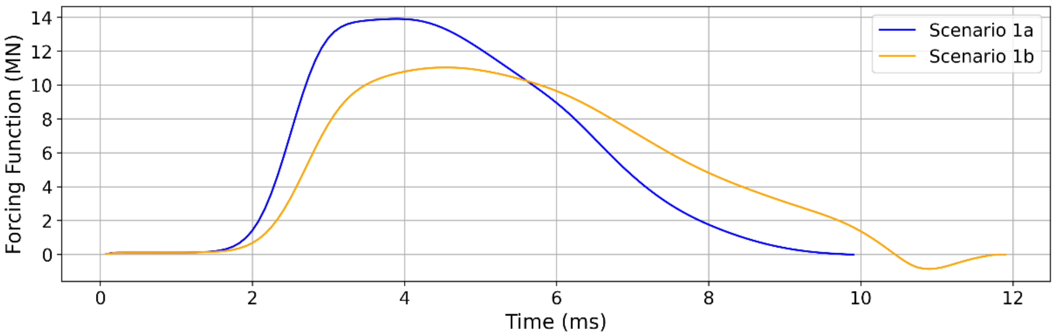


Figure 3. Forcing functions at the top of the pile for the pile-driving scenarios.

Another key factor affecting the source model and eventual calculation of cumulative sound exposure metrics is the pile penetration rate, which is the distance the pile embeds into the sediment as a result of a single hammer impact. Based on specifications and sediment data provided, this was estimated at 25 mm per strike. For Scenario 1a, a stress wave reflection coefficient of 0.3 was used in order to match this vertical pile displacement estimate, whilst the coefiicient for Scenario 1b was 0.17; the resultant displacement estimates as a function of time after impact are shown in Figures 4 and 5.

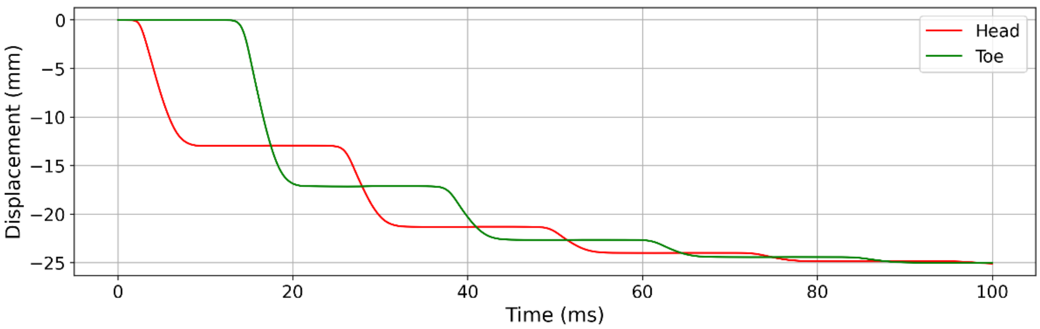


Figure 4. Modelled vertical displacement of the head and toe of the pile in Scenario 1a at 15m penetration.

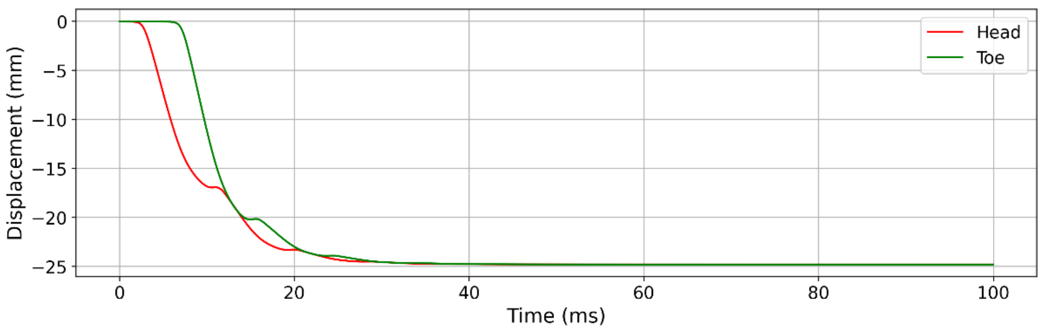


Figure 5. Modelled vertical displacement of the head and toe of the pile in Scenario 1b at 4m penetration.

Given that piles are distributed and directional sources (Appendix C.1), they cannot be accurately approximated by a point source. The sound radiating from the piles was therefore simulated using vertical arrays of discrete point sources, as described in Appendix C.1.2.

For the purposes of comparison, it is possible to inspect the levels received a short distance from the modelled source. Figure 6 shows the maximum-over-depth decidecade band received levels for a single strike in the two pile-driving scenarios, at a horizontal range of 10 m from the centre of the pile. The levels above 1 kHz were extrapolated using a 20 dB/decade decay rate to match acoustic measurements of impact pile driving of similarly sized piles (Illingworth & Rodkin 2007, Matuschek and Betke 2009).

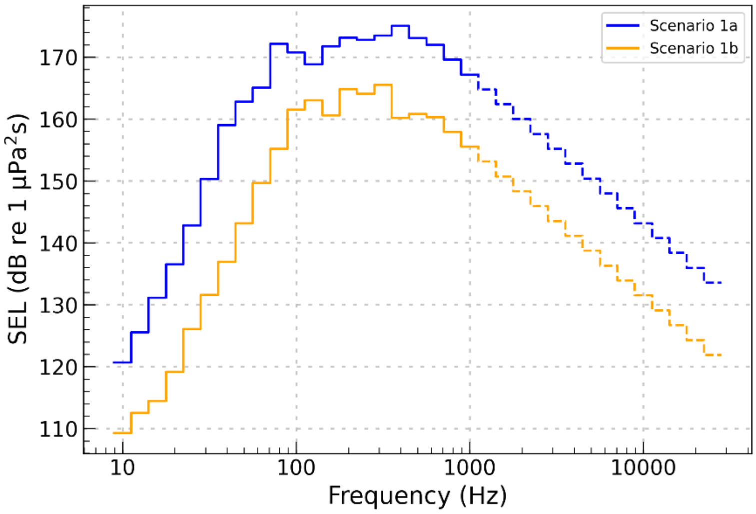


Figure 6. Maximum-over-depth decidecade band SELs at a receiver 10 m horizontally from the modelled pile driving sources. Dashed line indicates extrapolated portions of the spectra.

3.2.2. Scenario 2 – Dredging

Specifications for multiple backhoe dredging vessels were supplied as representative of the type of vessel to be used on this project. The vessel with the largest specified excavator engine power (3356 kW), *Magnor*, was chosen as the source to be modelled. Since there are no measured source levels (SLs) available for this particular dredger, levels reported by Reine et al. (2014) for the backhoe dredger *New York* were used as a proxy. Since *New York* has an excavator power of 2565 kW, the following equation was used to calculate a source level offset Δ_{L_p} to account for the difference in power:

$$\Delta_{L_p} = 10 \log\left(\frac{P}{P_{ref}}\right) \tag{1}$$

where P_{ref} and P are the power of the proxy vessel and the target vessel respectively. In this case, an offset of 1.17 dB was calculated and applied to the proxy source levels, giving a broadband level of 176.3 dB re 1 μPa^{2}m^{2}s. Source levels were linearly extrapolated to cover the modelled frequency range. Figure 7 shows the resultant source level in decidecade bands from 10 Hz to 25 kHz, alongside source levels for the FSRU and LNG Carrier (see Section 3.2.3).

A modelled source depth of 2.37 m was used based on 0.7 × ship draft (3.39 m for *Magnor*), as specified in ISO 17208-1 (2016).

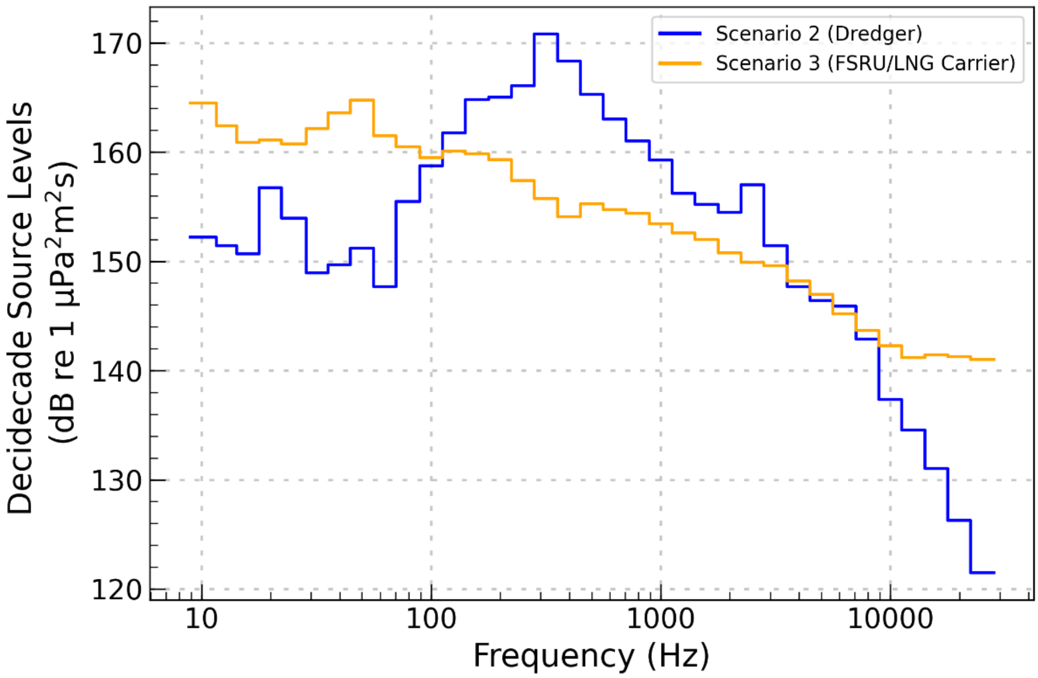


Figure 7. Decidecade band monopole source levels for vessel sources. *Magnor* derived from the backhoe dredger *New York* (Reine et al. 2014), and FSRU and LNG carrier derived by averaging the *Nganhurra* and *Ngujima Yin* (Erbe et al. 2013).

Scenario 3 – FSRU and LNG Carrier Operations

Scenario 3 investigates radiated sound from the FSRU and LNG carrier. As the FSRU would be continuously moored and the LNG carrier would be berthed alongside, noise from the considered operational scenarios is likely to be associated with pumps, generators, and other machinery within the vessels, rather than the propeller cavitation typically associated with vessels underway. There is at present no literature describing measured SLs for either FSRUs or berthed LNG carriers. Erbe et al. (2013), however, includes measured SLs from two Floating Production Storage and Offload (FPSO) facilities, the *Nganhurra* and the *Ngujima Yin*. Given the similarity in vessel sizes and operations, an average of these two measured SLs, with a broadband level of 173.9 dB re 1 µPa^{2}m^{2}s, was used as a proxy for both the FSRU and LNG carrier in this study. Figure 7 shows the source level in decidecade bands from 10 Hz to 25 kHz, alongside levels for the dredger (see Section 3.2.1).

A source depth of 6 m for both vessels was chosen to approximate an average of hull-radiated noise from the submerged hull of each vessel. As the depth of the newly dredged channel will be just over 12 m, this corresponds to the middle of the water column, a location expected to give optimal noise propagation and therefore a reasonable estimate for the maximum likely threshold distances.

3.2.4. Scenario 4 – LNG Carrier Berthing

Scenario 4 consists of an LNG carrier approaching the proposed new berth, accompanied by two escort tug boats and two berthing tug boats. The final part of the berthing sequence was modelled, as the carrier and tugs move through defined zones at 4 knots, 2 knots, and finally 0.5 knots for the berthing. Single points in the middle of these three areas were modelled to calculate SPL-based metrics, and these three points were translated to ‘footprint’ locations at 50 m increments along a defined line of approach in order to calculate accumulated SEL metrics. Figure 2 shows an overview of the scenario, showing modelled SPL locations and the approach line along which the 50 m SEL footprints were distributed.

The SEL sound field at any given point p along the approach line is dependent upon the duration of exposure, which with a fixed footprint spacing Δ_p depends upon the modelled speed of the vessel at each point. The SPL modelling results at each point for each vessel were therefore converted to SEL according to the following equation:

$$L_{E,p} = L_E + 10\log_{10}\left(\frac{\Delta_p}{c}\right) \quad (2)$$

where c represents the vessel speed. This equated to an addition of 13.86 dB at points in the 4 knots zone, 16.87 dB at points in the 2 knots zone, and 22.89 dB at points in the 0.5 knots final berthing zone.

The escort and berthing tug models in this scenario were based on the Damen ASD Tug 3212 (6865 hp) and Damen ASD Tug 2312 (5172 hp), respectively, following information provided by the client. These two types of tugs were both modelled using recorded source levels from the *Britoil 51*, an anchor handling tug of similar size and power, travelling at half speed (6.5 knots). Since *Britoil 51* has a power of 6600 hp, Equation 1 was used to calculate source level offsets to account for the differences in power for the two types of modelled vessels. Offsets of 0.17 dB and -1.06 dB were calculated and applied to the source levels for the escort and berthing tugs, respectively. As the 6.5 knot speed of *Britoil 51* for these recorded SLs is slightly higher than the highest speed modelled in this scenario, these SLs should be considered a conservative estimate.

The SLs for *Britoil 51* do not include information above 10 kHz, so levels at frequencies above this were linearly extrapolated from the level reduction between the 8 kHz and 10 kHz bands. The decidecade energy source level (ESL) spectra for the *Britoil 51* is shown in Figure 8, with the extrapolated portion shown as a dashed line. The broadband ESL (5 Hz to 25 kHz) is 190.8 dB re 1 µPa^{2}m^{2}s.

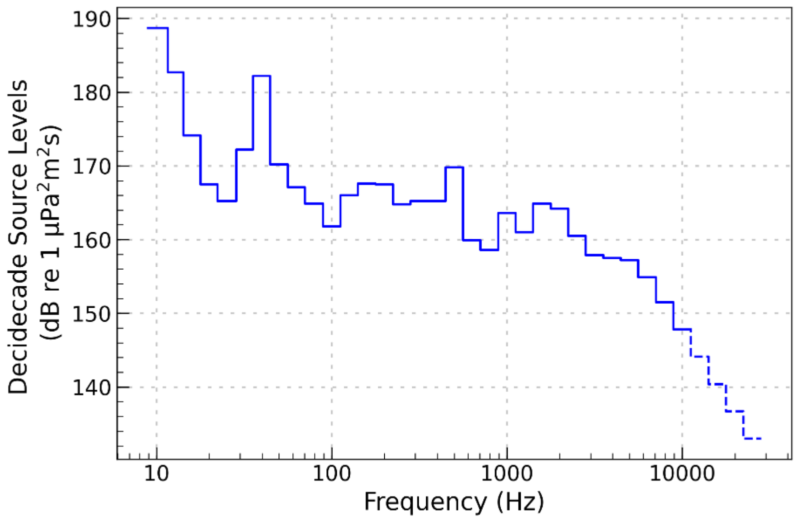


Figure 8. Estimated decidecade energy source level (ESL) spectra of the *Britoil 51*, used for both escort and berthing tugs. Dashed line indicates extrapolated portion of spectrum.

Due to uncertainty in terms of how much the LNG carrier's propulsion system would be contributing at such slow speeds relative to the tugs, no propulsion has been modelled for the carrier, and instead the measured SLs from FPSOs *Nganhurra* and *Ngujima Yin* were once again used for this vessel.

A source depth of 6 m was again used for the carrier, whilst a depth of 3.85 m (0.7 × ship draft) was used for the tugs, as both tug models have a draft of 5.5 m.

3.3. Modelling Sound Propagation

3.3.1. Impulsive Sources

For the impulsive impact pile driving sources, JASCO's full waveform range-dependent model (FWRAM - see Appendix C.3) was used to model sound propagating away from the driven pile along radial planes at 1° separation. The maximum modelled distance was 12 km for Scenario 1a, and 25 km for Scenario 1b, with a 10 m range step increasing with distance from the source. Receiver depths spanned the entire water column over the modelled areas.

Given respective final pile penetration depths of 30 m and 8 m, it can be estimated that the complete driving of a single pile in Scenario 1a will take 1200 strikes, and a single pile in Scenario 1b will take 320 strikes. For the purposes of this study, the SEL over the operation is calculated based on a single mid-sequence strike, rather than separate models for various penetration depths. The SELs over the complete sequence were therefore calculated using the following equation:

$$L_{E,\text{cumulative}} = L_E + 10\log_{10}(N) \tag{3}$$

where L_E is the per-strike energy source level and N is the number of strikes. Values of N = 1200 and N = 320 were used for single-pile estimates, and N = 3600 and N = 1280 for estimates assuming the maximum number of piles driven per day. In this study, all piling is modelled at a single location for each scenario.

3.3.2. Non-impulsive Sources

For the non-impulsive vessel sources in Scenarios 2 and 3, JASCO's combined Marine Operations Noise Model (MONM) and gaussian beam acoustic ray-trace model (BELLHOP) were used to predict the acoustic field at frequencies from 10 Hz to 25 kHz; details on these models are included in Appendix C.2. The SEL over 24 hours was calculated using the following equation:

$$L_{E,24h} = L_E + 10\log_{10}(T) \tag{4}$$

where L_E is the per-second energy source level and T is the total number of operational seconds in a 24-hour period. Assuming constant operation over 24 hours, this amounts to an offset of 49.3 dB.

4. Results

This section contains the results from the models of the scenarios described in the previous section. These are presented as tables of distances, and contour maps showing the directivity and range to maximum-over-depth sound levels, with isopleths showing various relevant noise effect thresholds for marine mammals, diving birds, and fish. Vertical slice plots showing per-strike sound propagation are also included for the pile driving sources.

The monitoring report, Wilson and McPherson (2021), determined that the soundscape was primarily defined by anthropogenic contributors, with shipping being the dominant factor. The sound level statistics used in this report are the median broadband sound level (L_p = 124.6 dB re 1 μPa), the 5th percentile (L_p = 119.6 dB re 1 μPa) and median measured unweighted ambient level (L_E = 178 dB re 1 μPa²s).

4.1. Scenario 1 - Pile Driving

This section presents the sound fields for the two pile driving operations in terms of maximum-over-depth PK, SPL, and SEL. Metrics are presented as follows:

- PK metrics within the water column, relevant to thresholds and guidelines for marine mammals, fish, fish eggs and larvae (as well as plankton) (see Sections 2.1 and 2.2).
- SPL sound fields, used to determine the distances to marine mammal and penguin behavioural thresholds (see Sections 2.1 and 2.3).
- SEL sound fields (per-pile and 24 h), relevant to thresholds and guidelines for marine mammals, fish, fish eggs and larvae, and penguins (Section 2).

Maximum distances to PK thresholds were calculated for both piles, with maximum-over-depth results presented in Table 16. The maximum and 95% distances for SEL and SPL metrics (calculated as detailed in Appendix A.3) are presented in Tables 17 and 18.

The SEL and SPL sound fields and distances to relevant isopleths, are visualised on the contour maps presented in Figures 9 to 14. SEL maps show contours down to the median measured unweighted ambient level (L_E = 178 dB re 1 μPa²s), whilst SPL maps show contours including median (L_p = 124.6 dB re 1μPa) and 5th percentile (L_p = 119.6 dB re 1μPa) ambient levels, averaged from decidecade band levels. The SPL sound fields are also presented as vertical slices for both piles with the sound field on either side of the pile shown (Figures 14–18). Note that the measured ambient SPL in the area is higher than the diving bird behavioural threshold, therefore the diving bird behavioural threshold distances are included for completeness.

4.1.1. Tables

Table 16. *Piling, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from the dolphin pile (Scenario 1a) and mooring pile (dolphin pile (Scenario 1b) to modelled maximum-over-depth peak pressure level (PK) PTS and TTS thresholds for marine mammals (Southall et al. 2019) and fish (Popper et al. 2014).

Hearing group	PK threshold (L_{pk}; dB re 1 µPa)	Distance R_{max} (km)	
		1a – Dolphin pile	1b – Mooring pile
PTS			
High-frequency cetaceans	230	—	—
Otariid pinnipeds in water	232	—	—
TTS			
High-frequency cetaceans	224	—	—
Otariid pinnipeds in water	226	—	—
Mortal Injury			
Fish: No swim bladder	213	—	—
Fish: Swim bladder not involved in hearing; swim bladder involved in hearing; and fish eggs, and larvae	207	—	—

A dash indicates the threshold was not reached within the limits of the modelling resolution.

Table 17. *Piling, SPL*: Maximum (R_{max}) horizontal distances (km) from the dolphin pile (Scenario 1a) and mooring pile (Scenario 1b) to maximum-over-depth per-strike SPL isopleths.

SPL (L_p; dB re 1 µPa)	1a – Dolphin pile		1b – Mooring pile	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
180	0.03	0.03	–	–
170	0.26	0.24	0.05	0.05
160[a]	**0.80**	**0.71**	**0.26**	**0.23**
150	2.00	1.48	1.05	0.93
140	4.04	2.69	2.20	1.91
130	5.12	4.23	3.70	3.23
124.6[b]	6.04	5.10	4.58	3.92
120	6.60	5.65	5.42	4.58
119.6[c]	6.64	5.68	5.46	4.62
120[d]	**5.76**	**4.90**	**4.30**	**3.62**

[a] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[b] Median ambient level
[c] 5th percentile ambient level
[d] Diving bird behavioural response threshold (OCW weighted) for impulsive noise (Sørensen et al. 2020).
A dash indicates the threshold was not reached within the limits of the modelling resolution.

Table 18. *Piling, PTS and TTS SEL thresholds*: Maximum (R_{max}) horizontal distances (m) from the dolphin pile (Scenario 1a) and mooring pile (Scenario 1b) to maximum-over-depth weighted SEL isopleths for marine mammals and diving birds (Southall et al. 2019).

Hearing group	SEL_{24h} threshold ($L_{E,\ weighted}$; dB re 1 µPa²s)	1a – Dolphin pile				1b – Mooring pile			
		Single pile		3 piles		Single pile		4 piles	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS									
HF cetaceans	185	—	—	—	—	—	—	—	—
Otariid pinnipeds and diving birds	203	—	—	—	—	—	—	—	—
TTS									
HF cetaceans	170	0.03	0.03	0.07	0.07	—	—	—	—
Otariid pinnipeds and diving birds	188	0.04	0.04	0.10	0.09	—	—	—	—

A dash indicates the threshold was not reached within the limits of the modelling resolution.

Table 19. *Piling, thresholds for effects on fish*: maximum and 95% distances to maximum-over-depth unweighted SEL isopleths for fish (Popper et al. 2014).

Hearing group	SEL_{24h} threshold (L_E; dB re 1 µPa²s)	1a – Dolphin pile				1b – Mooring pile			
		Single pile		3 piles		Single pile		4 piles	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Mortal Injury									
Fish: No swim bladder	219	—	—	—	—	—	—	—	—
Fish: Swim bladder not involved in hearing; and eggs and larvae	210	—	—	0.02	0.02	—	—	—	—
Fish: Swim bladder involved in hearing	207	0.02	0.02	0.03	0.03	—	—	—	—
Recoverable Injury									
Fish: No swim bladder	216	—	—	—	—	—	—	—	—
Fish: Swim bladder not involved in hearing; and swim bladder involved in hearing	203	0.03	0.03	0.06	0.06	—	—	—	—
TTS									
Fish: No swim bladder; swim bladder not involved in hearing; and swim bladder involved in hearing	186	0.52	0.48	0.87	0.77	0.05	0.05	0.11	0.10

A dash indicates the threshold was not reached within the limits of the modelling resolution.

4.1.2. Sound Field Maps

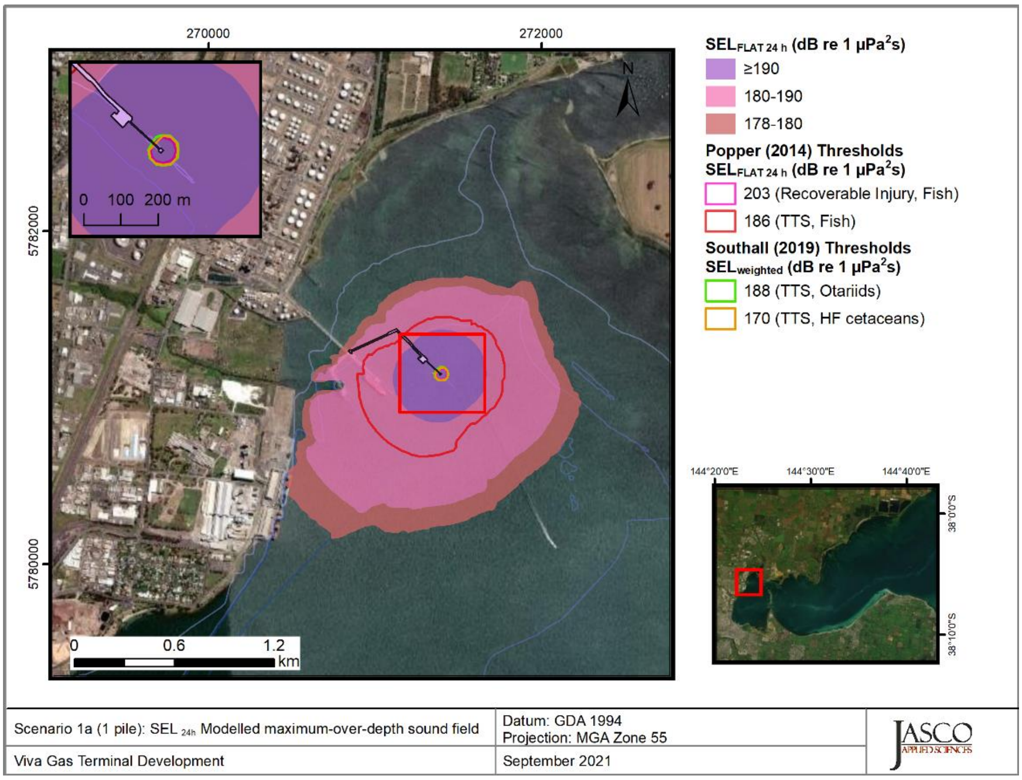


Figure 9. Unweighted maximum-over-depth SEL for the complete driving of a single pile in Scenario 1a. Isopleths show distances to temporary threshold shift onset levels for high-frequency cetaceans and otariids, based on weighted levels for impulsive sources, and unweighted levels relevant to fish.

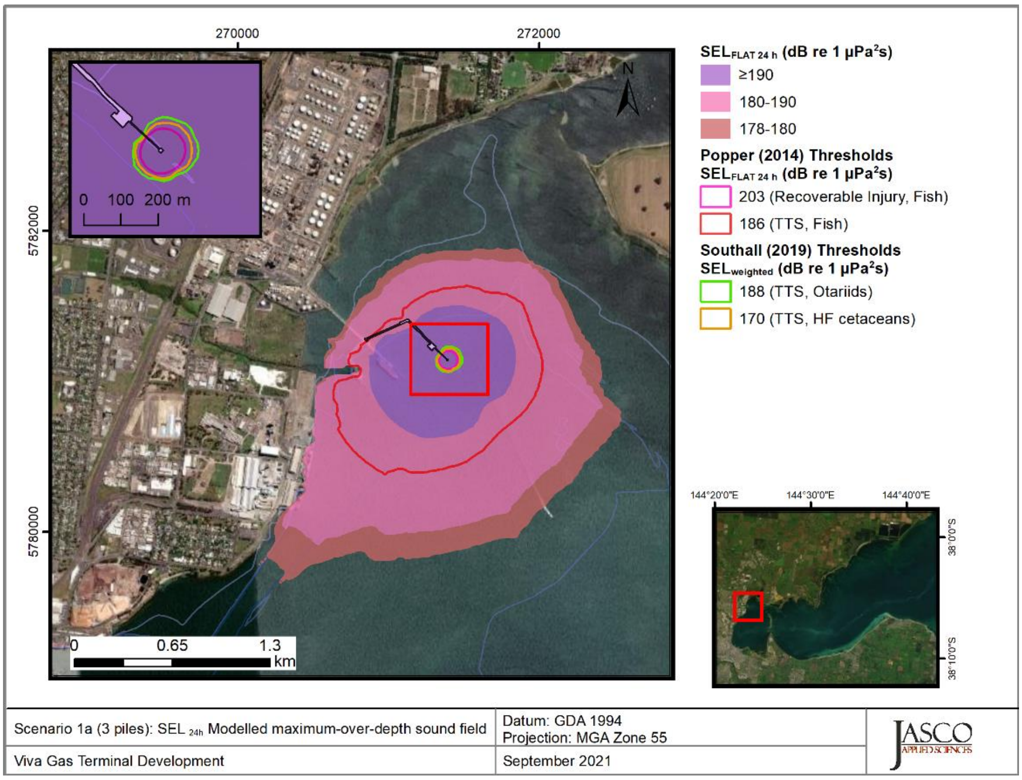


Figure 10. Unweighted maximum-over-depth SEL for the complete driving of three piles in Scenario 1a. Isopleths show distances to temporary threshold shift onset levels for high-frequency cetaceans and otariids, based on weighted levels for impulsive sources, and unweighted levels relevant to fish.

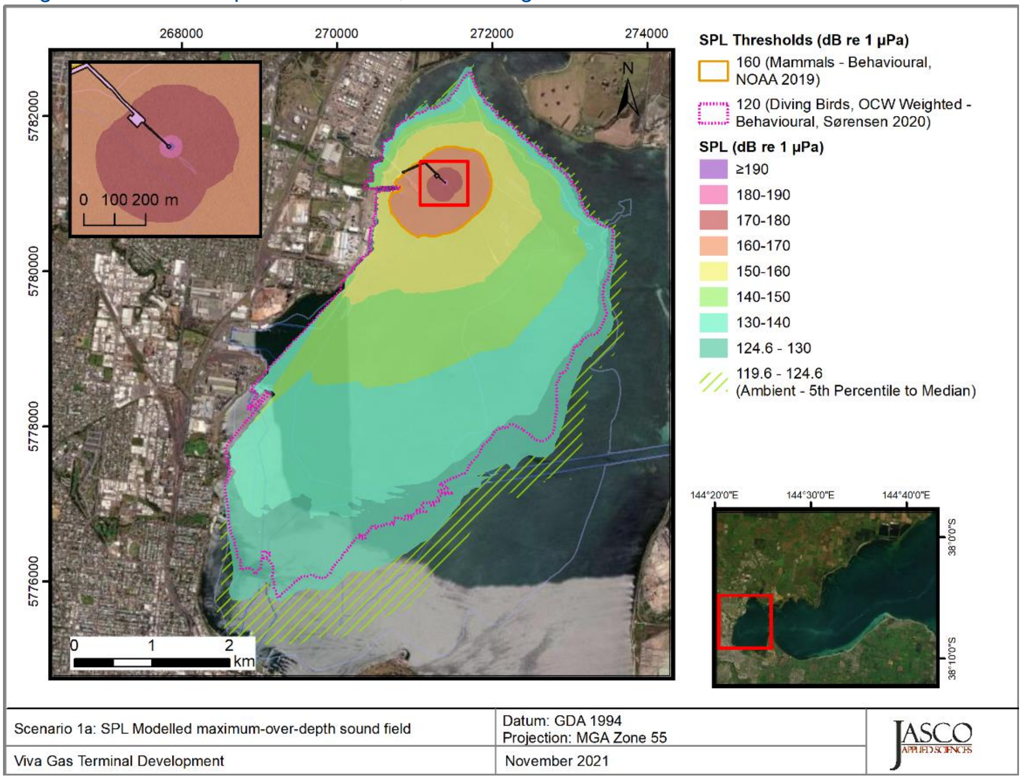


Figure 11. Maximum-over-depth SPL levels in Scenario 1a. Isopleths show distances to behavioural effect onset levels in marine mammals and diving birds.

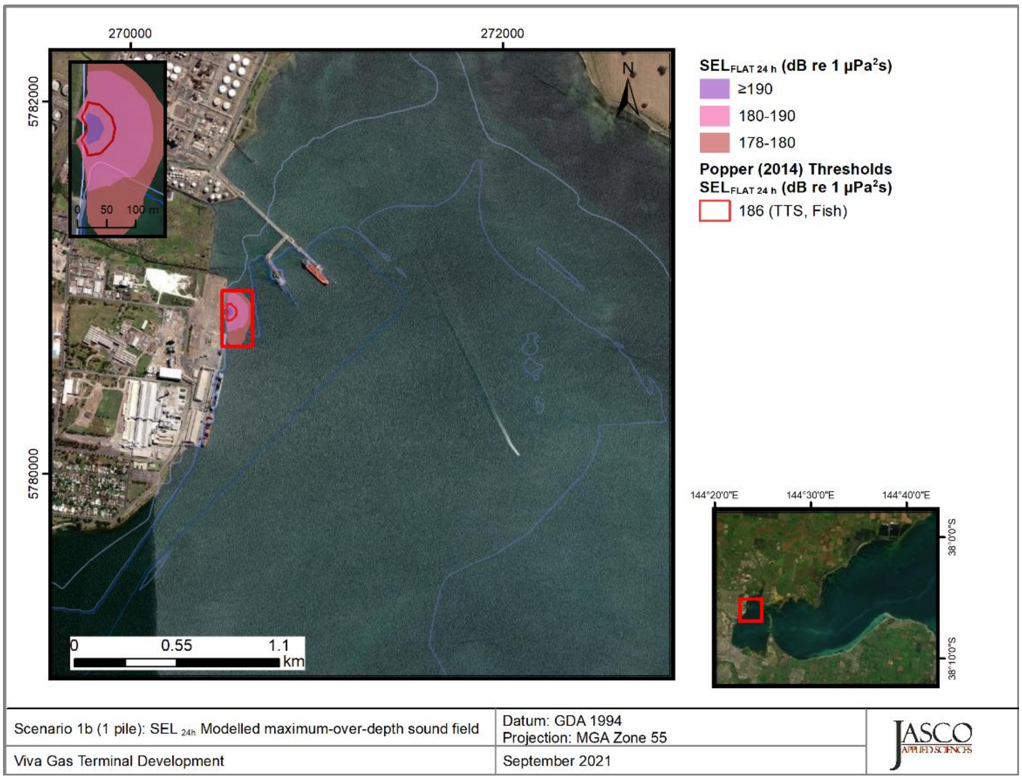


Figure 12. Unweighted maximum-over-depth SEL levels for the complete driving of a single pile in Scenario 1b. Isopleths shows distance to temporary threshold shift onset level for fish based on unweighted levels.

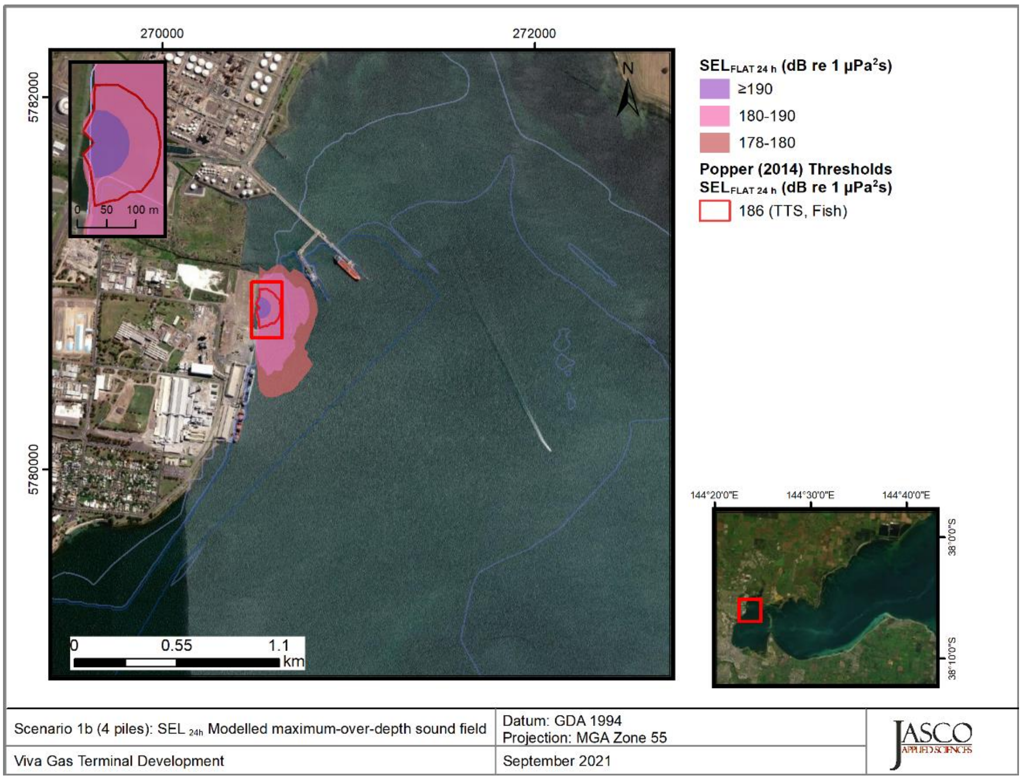


Figure 13. Unweighted maximum-over-depth SEL levels for the complete driving of four piles in Scenario 1b. Isopleths shows distance to temporary threshold shift onset level for fish based on unweighted levels.

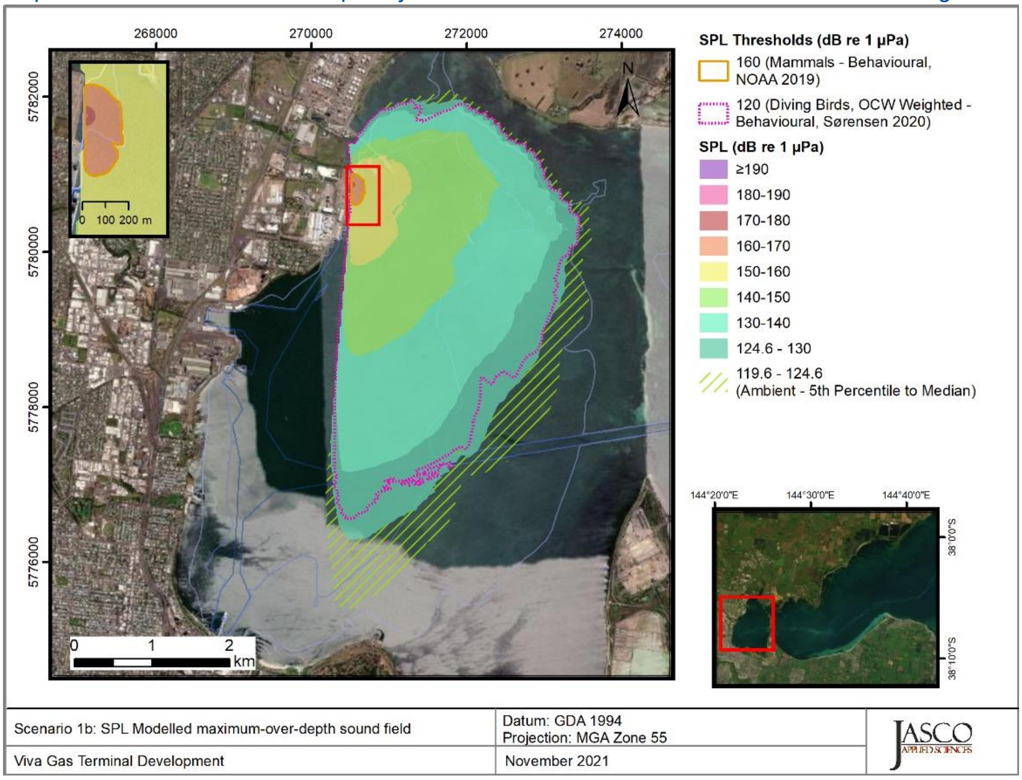


Figure 14. Maximum-over-depth per-strike SPL levels in Scenario 1b. Isopleths show distances to behavioural effect onset levels in marine mammals and diving birds.

4.1.3. Vertical Slice Plots

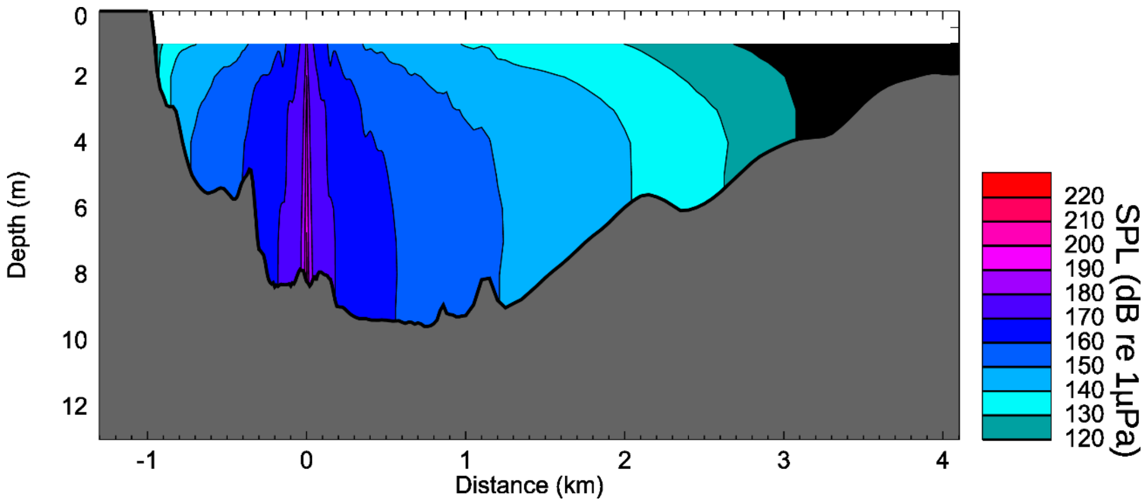


Figure 15. *SPL, dolphin pile*: Vertical slice of the predicted SPL sound field for a single impact strike along azimuths 135° and 315° for Scenario 1a.

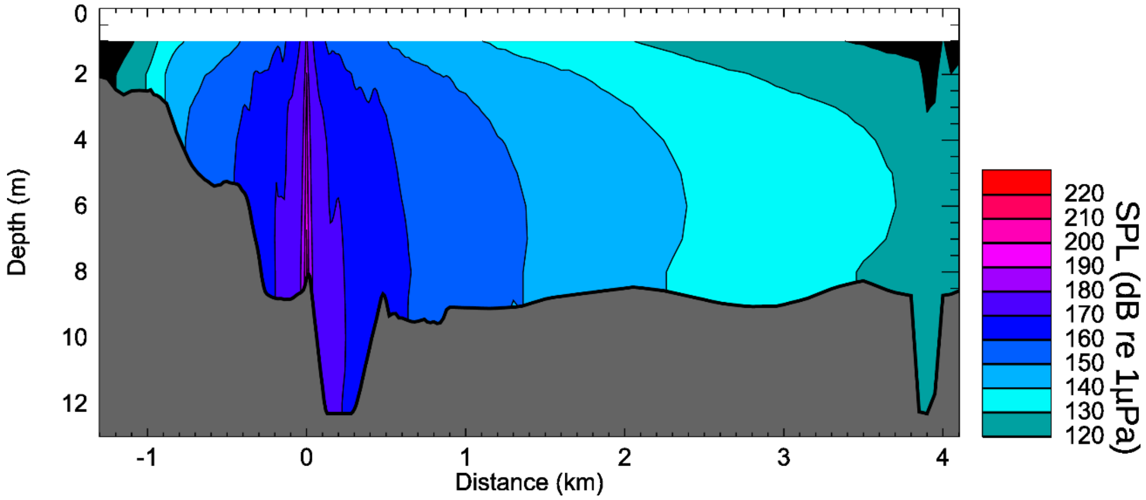


Figure 16. *SPL, dolphin pile*: Vertical slice of the predicted SPL sound field for a single impact strike along azimuths 0° and 180° for Scenario 1a.

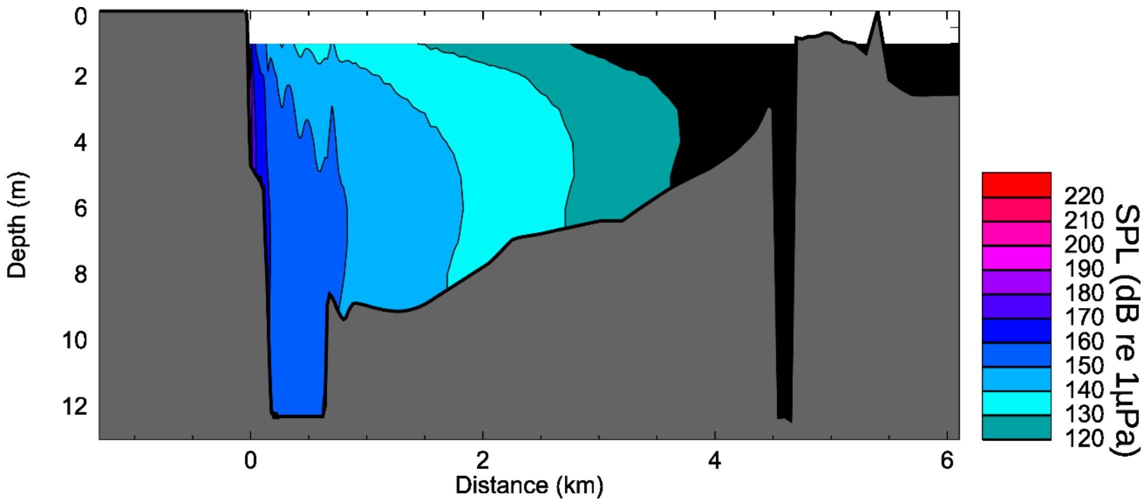


Figure 17. *SPL, Lascelles Wharf pile*: Vertical slice of the predicted SPL sound field for a single impact strike along azimuths 135° and 315° for Scenario 1b.

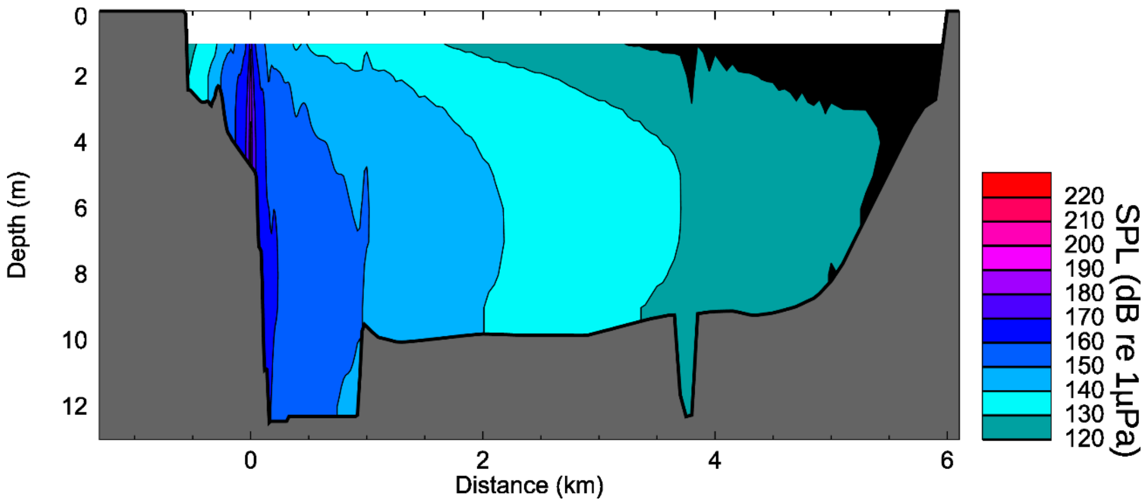


Figure 18. *SPL, Lascelles Wharf pile*: Vertical slice of the predicted SPL sound field for a single impact strike along azimuths 0° and 180° for Scenario 1b.

4.2. Scenarios 2 and 3 – Vessels

This section presents the sound fields for the dredging and FSRU and LNG carrier scenarios in terms of maximum-over-depth SPL and SEL. Metrics are presented as follows:

- SPL sound fields, used to determine the distances to marine mammal behavioural thresholds (Section 2.1).
- SEL sound fields (24 h), relevant to thresholds and guidelines for marine mammals, fish, fish eggs and larvae (Section 2.1).

The maximum and 95% distances (calculated as detailed in Appendix A.3) for SEL and SPL metrics are presented in Tables 20 and 21. The SEL and SPL sound fields and distances to relevant isopleths are visualised on the contour maps presented in Figures 19 to 26. SEL maps show contours down to the median measured unweighted ambient level (L_E = 178 dB re 1 µPa²s), whilst SPL maps show contours including median (L_p = 124.6 dB re 1µPa) and 5th percentile (L_p = 119.6 dB re 1µPa) ambient levels, averaged from decidecade band levels. Note that the measured ambient SPL in the area is higher than the marine mammal behavioural threshold, at 120 dB re 1µPa.

4.2.1. Tables

Table 20. Vessels, SPL: Maximum (R_{max}) horizontal distances (km) from dredging (Scenario 2) and FSRU (Scenario 3) scenarios to maximum-over-depth SPL isopleths.

SPL (L_p; dB re 1 µPa)	2a – Berth & swing basin dredging		2b – Seawater pipe dredging		3a – FSRU		3b – FSRU + LNG carrier	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
170[a]	**<0.01**	**<0.01**	—	—	—	—	—	—
160	0.01	0.01	0.01	0.01	<0.01	<0.01	0.03	0.03
158[b]	**0.01**	**0.01**	**0.01**	**0.01**	**<0.01**	**<0.01**	**0.03**	**0.03**
150	0.04	0.04	0.03	0.03	0.02	0.02	0.04	0.04
140	0.12	0.11	0.15	0.14	0.06	0.05	0.09	0.08
130	0.80	0.64	0.51	0.47	0.31	0.27	0.44	0.38
124.6[c]	1.11	1.01	1.16	1.00	0.65	0.57	0.90	0.76
119.6[d]	1.60	1.47	1.90	1.66	1.14	1.03	1.52	1.30
120[e]	**1.55**	**1.43**	**1.84**	**1.60**	**1.10**	**0.98**	**1.46**	**1.26**

[a] Recoverable injury threshold for fish, 48 hours exposure (Popper et al. 2014).
[b] Temporary threshold shift in fish, 12 hours exposure (Popper et al. 2014).
[c] Median ambient level.
[d] 5th percentile ambient level.
[e] Marine mammal (NOAA 2019) behavioural threshold (non-impulsive sources).
A dash indicates the threshold was not reached within the limits of the modelling resolution.

Table 21. *Vessels, TTS SEL thresholds*: Maximum (R_{max}) horizontal distances (m) from the dredging (Scenario 2) and FSRU (Scenario 3) scenarios to maximum-over-depth weighted SEL isopleths for marine mammals (Southall et al. 2019). PTS thresholds were not exceeded.

Hearing group	SEL_{24h} threshold ($L_{E,\ weighted}$; dB re 1 µPa²s)	2a – Berth & swing basin dredging		2b – Seawater pipe dredging		3a – FSRU		3b – FSRU + LNG carrier	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
HF cetaceans	178	0.01	0.01	0.01	0.01	0.01	0.01	0.04	0.04
Otariid pinnipeds	199	<0.01	<0.01	0.01	0.01	—	—	0.03	0.03

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

4.2.2. Sound Field Maps

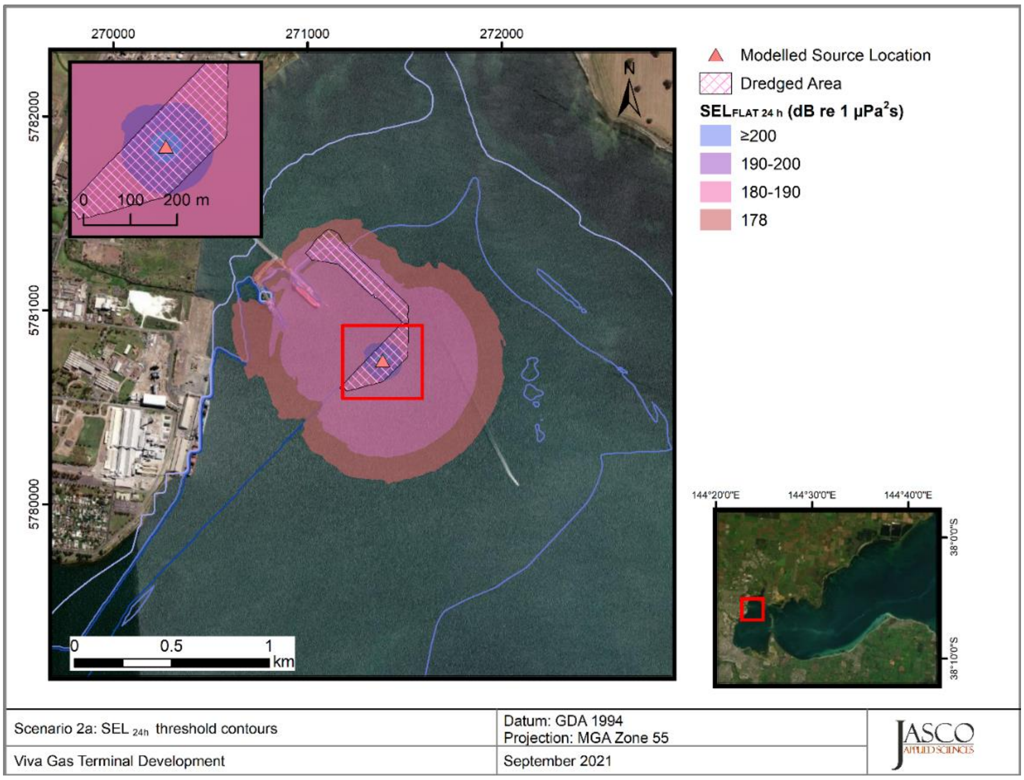


Figure 19. Unweighted maximum-over-depth SEL levels for Scenario 2a. No relevant thresholds were exceeded within the modelling resolution.

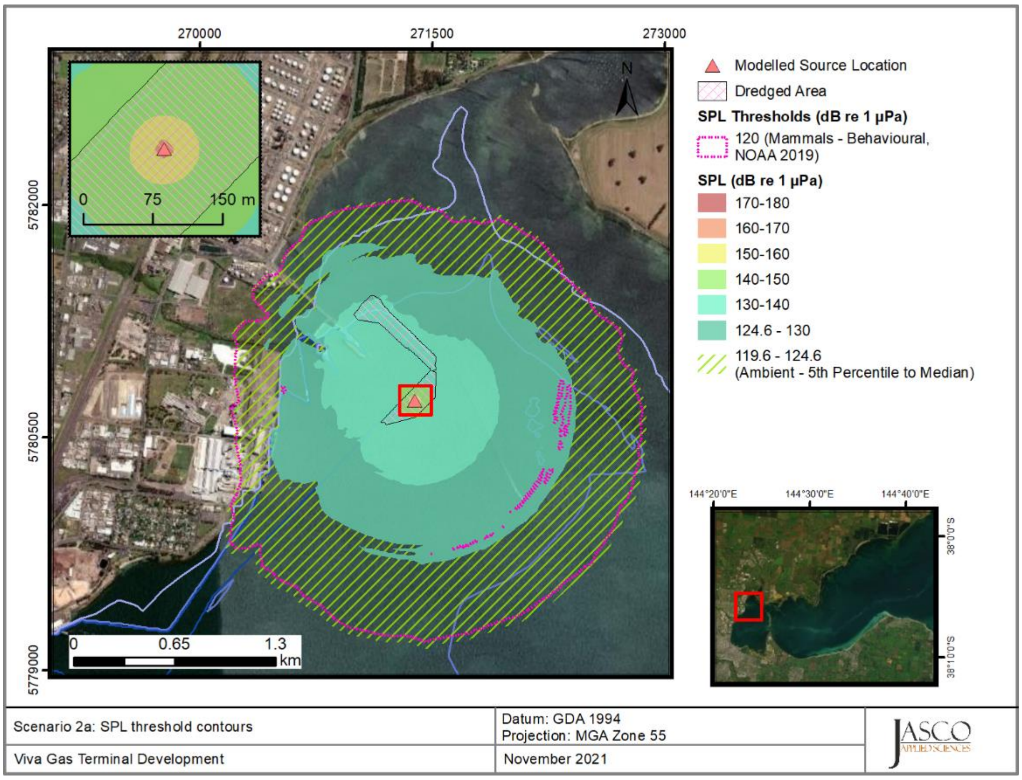


Figure 20. Maximum-over-depth SPL levels for Scenario 2a. Isopleth shows distance to behavioural effect onset level for marine mammals.

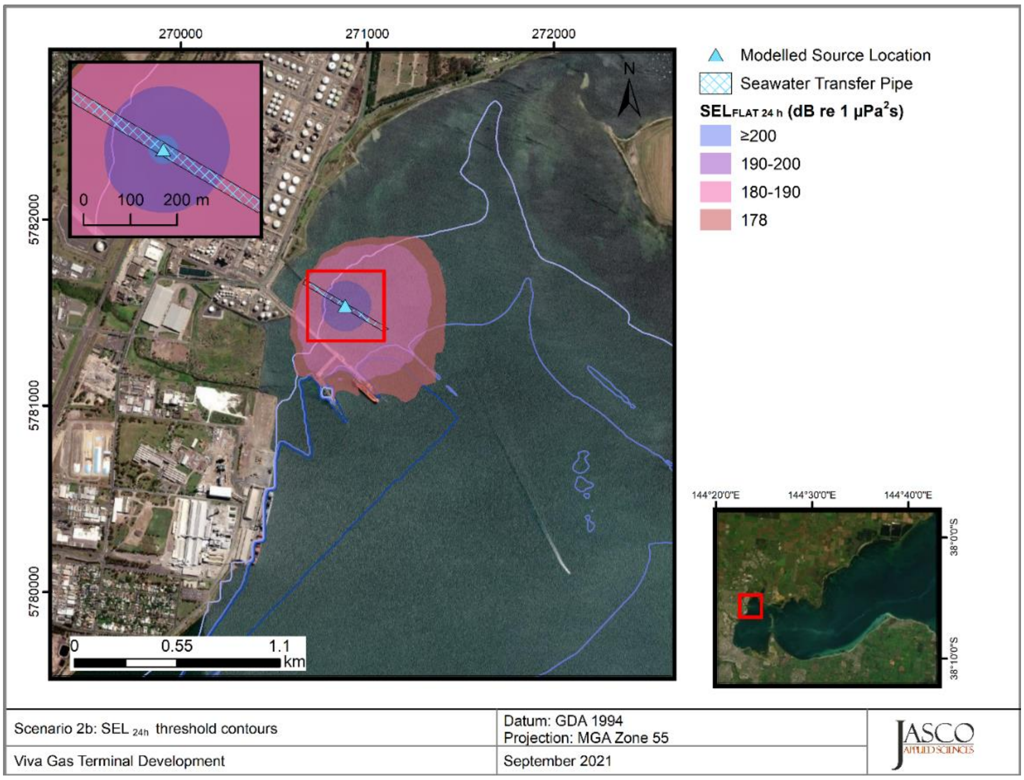


Figure 21. Unweighted maximum-over-depth SEL levels for Scenario 2b. No relevant thresholds were exceeded within the modelling resolution.

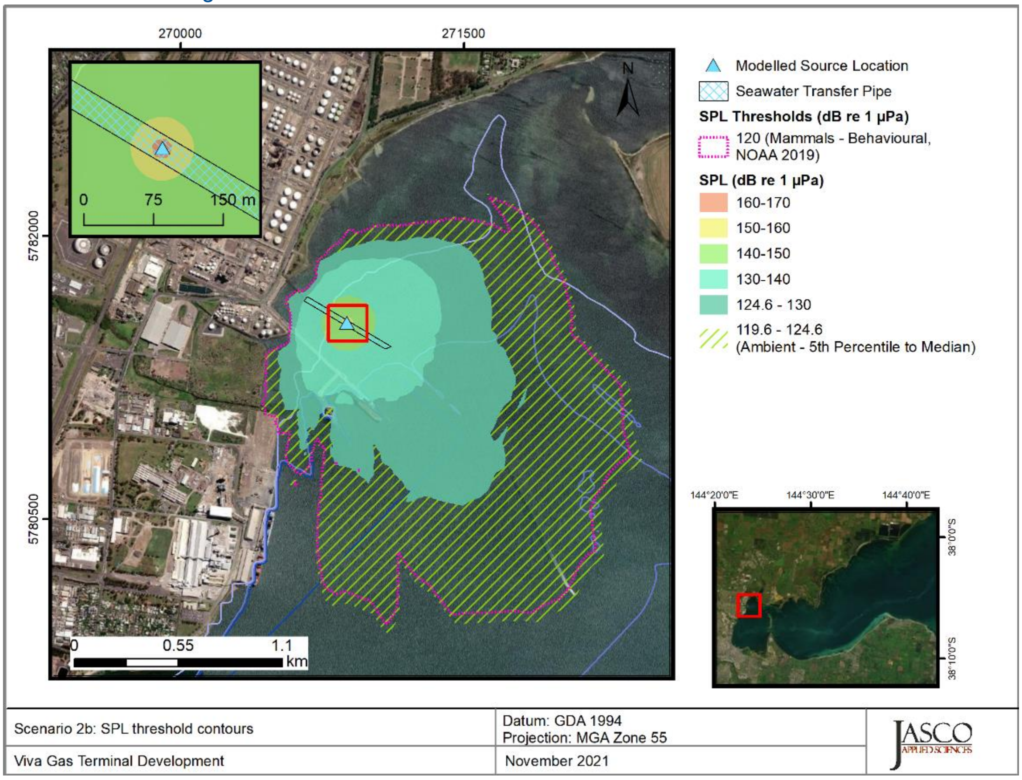


Figure 22. Maximum-over-depth SPL levels for Scenario 2b. Isopleth shows distance to behavioural effect onset level for marine mammals.

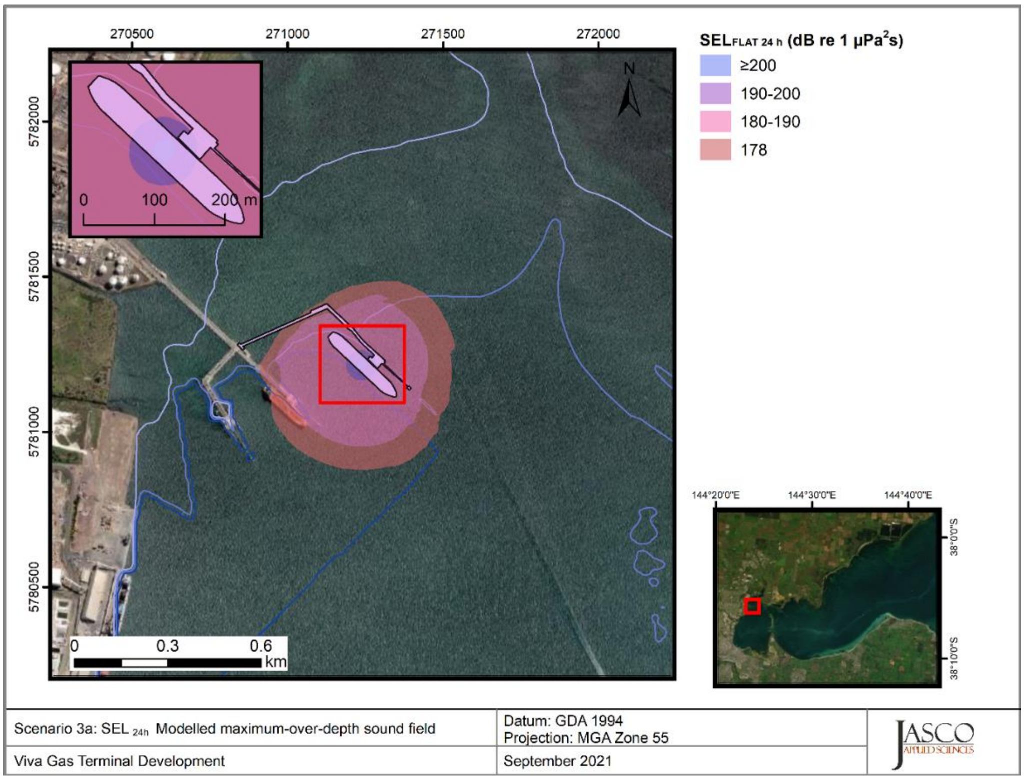


Figure 23. Unweighted maximum-over-depth SEL levels for Scenario 3a. No relevant thresholds were exceeded within the modelling resolution.

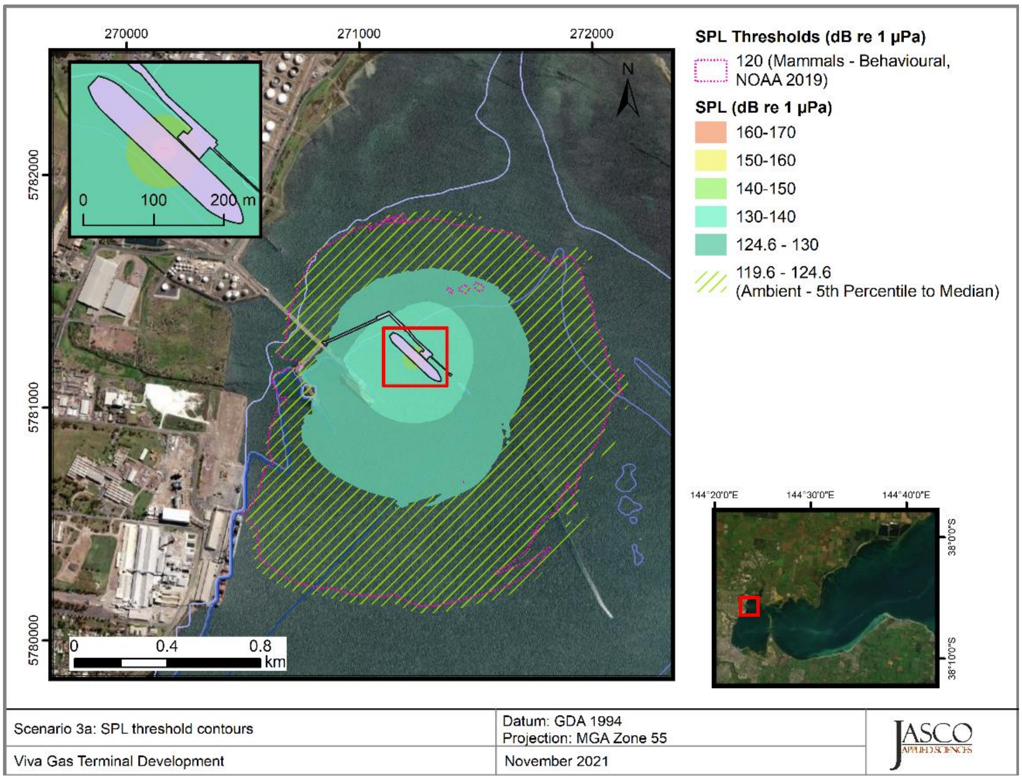


Figure 24. Maximum-over-depth SPL levels for Scenario 3a. Isopleth shows distance to behavioural effect onset level for marine mammals.

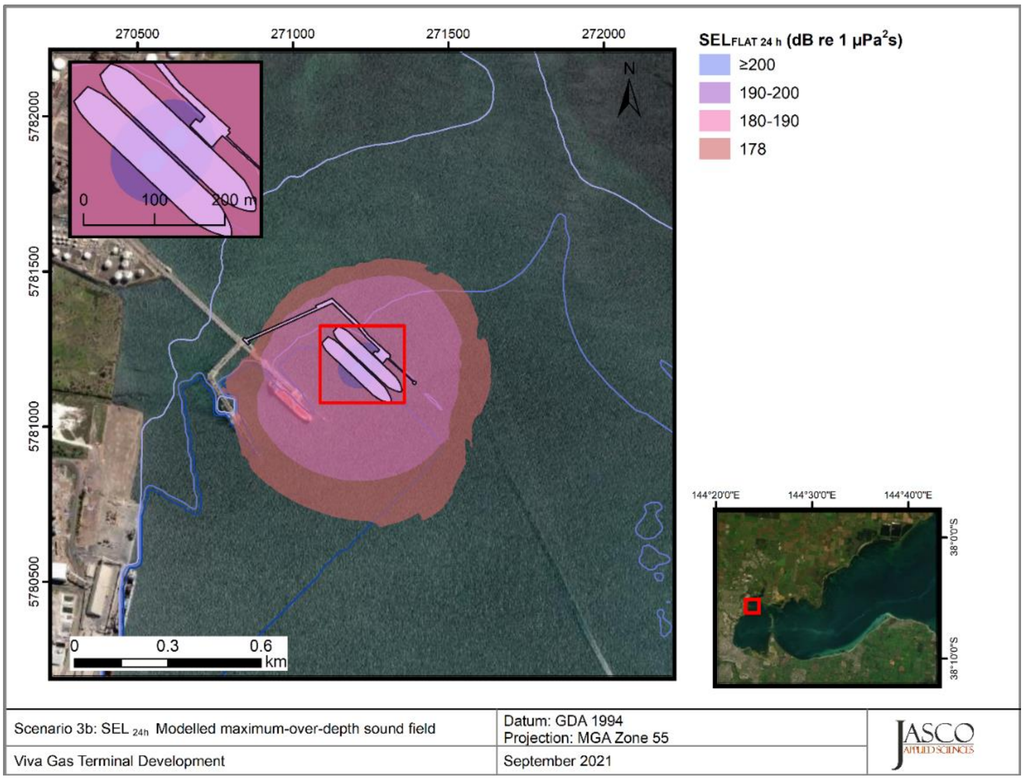


Figure 25. Unweighted maximum-over-depth SEL levels for Scenario 3b. No relevant thresholds were exceeded within the modelling resolution.

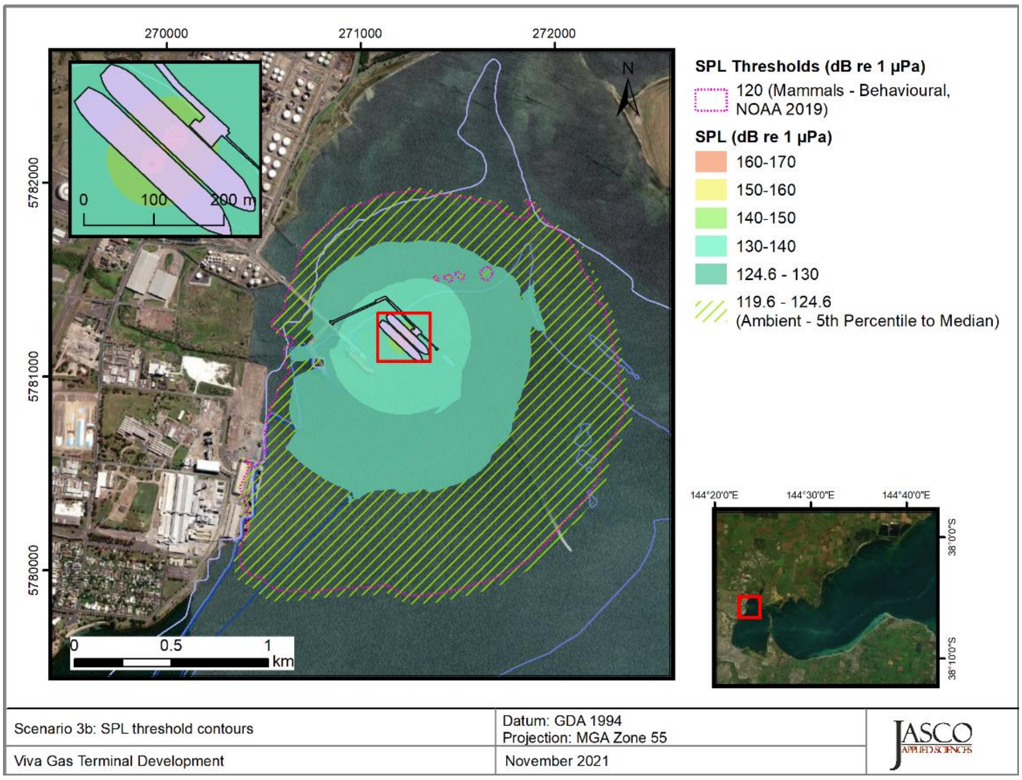


Figure 26. Maximum-over-depth SPL levels for Scenario 3b. Isopleth shows distance to behavioural effect onset level for marine mammals.

4.3. Scenario 4 – Berthing

This section presents the sound fields for LNG carrier berthing scenario in terms of maximum-over-depth SPL and SEL. Metrics presented are to those in Section 4.2.

4.3.1. Tables

Table 22. Berthing Scenario, SPL: Maximum (R_{max}) horizontal distances (km) from three modelled locations representing an LNG carrier berthing operation to maximum-over-depth SPL isopleths.

SPL (L_p; dB re 1 µPa)	4a – 4 knots		4b – 2 knots		4c – 0.5 knots	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
170[a]	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**0.04**	**<0.01**
160	0.02	0.02	0.02	0.02	0.04	0.02
158[b]	**0.02**	**0.02**	**0.02**	**0.02**	**0.04**	**0.02**
150	0.06	0.05	0.06	0.05	0.07	0.06
140	0.45	0.33	0.43	0.36	0.47	0.36
130	1.43	1.22	1.45	1.14	1.59	1.27
124.6[c]	2.49	2.23	2.61	2.02	2.75	2.21
119.6[d]	3.99	3.30	3.99	3.21	4.33	3.58
120[e]	**3.84**	**3.23**	**3.84**	**3.11**	**4.27**	**3.47**

[a] Recoverable injury threshold for fish, 48 hours exposure (Popper et al. 2014).
[b] Temporary threshold shift in fish, 12 hours exposure (Popper et al. 2014).
[c] Median ambient level.
[d] 5th percentile ambient level.
[e] Marine mammal (NOAA 2019) behavioural threshold (non-impulsive sources).

Table 23. Berthing Scenario, TTS SEL Thresholds: Maximum (R_{max}) horizontal distances (m) from the berthing scenario line to maximum-over-depth weighted SEL isopleths for marine mammals (Southall et al. 2019). PTS thresholds were also not exceeded.

Hearing group	SEL_{24h} threshold ($L_{E,\,weighted}$; dB re 1 µPa²s)	R_{max} (km)	$R_{95\%}$ (km)
HF cetaceans	178	—	—
Otariid pinnipeds	199	—	—

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

4.3.2. Sound Field Maps

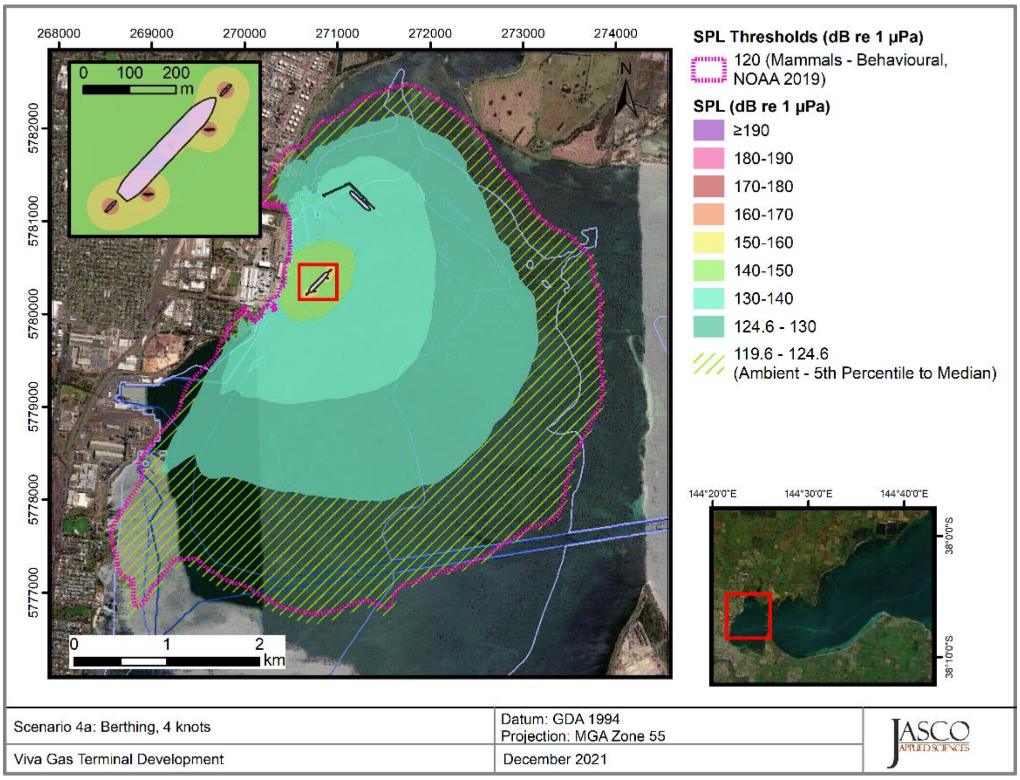


Figure 27. Maximum-over-depth SPL levels for Scenario 4a. Isopleth shows distance to behavioural effect onset level for marine mammals.

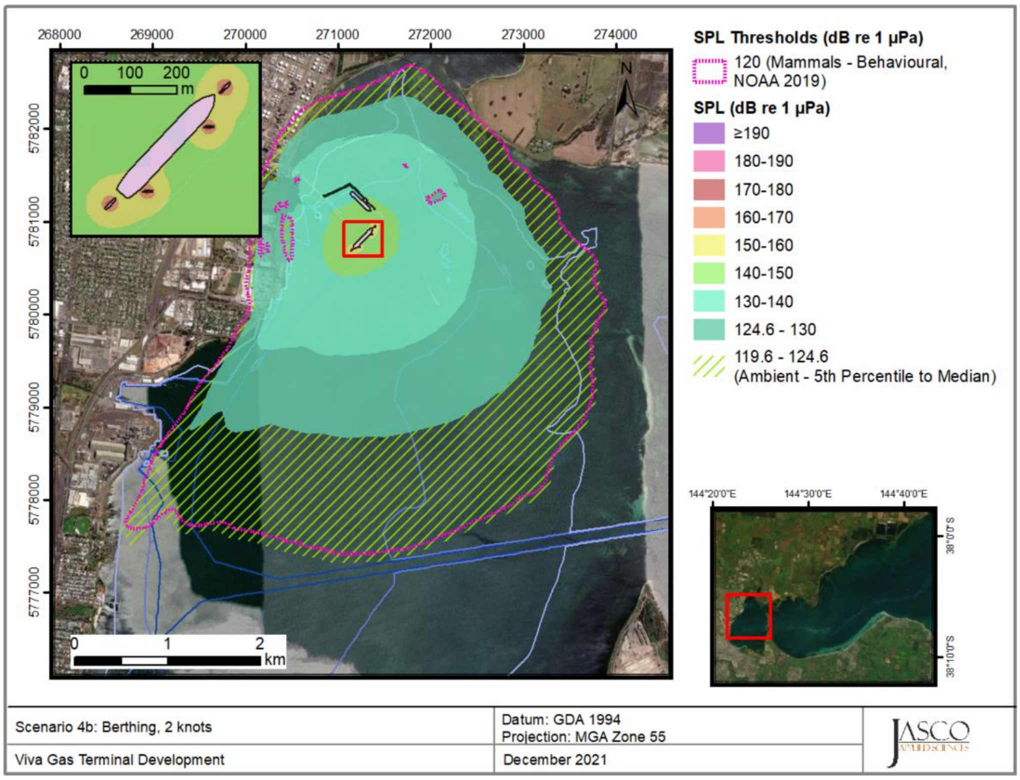


Figure 28. Maximum-over-depth SPL levels for Scenario 4b. Isopleth shows distance to behavioural effect onset level for marine mammals.

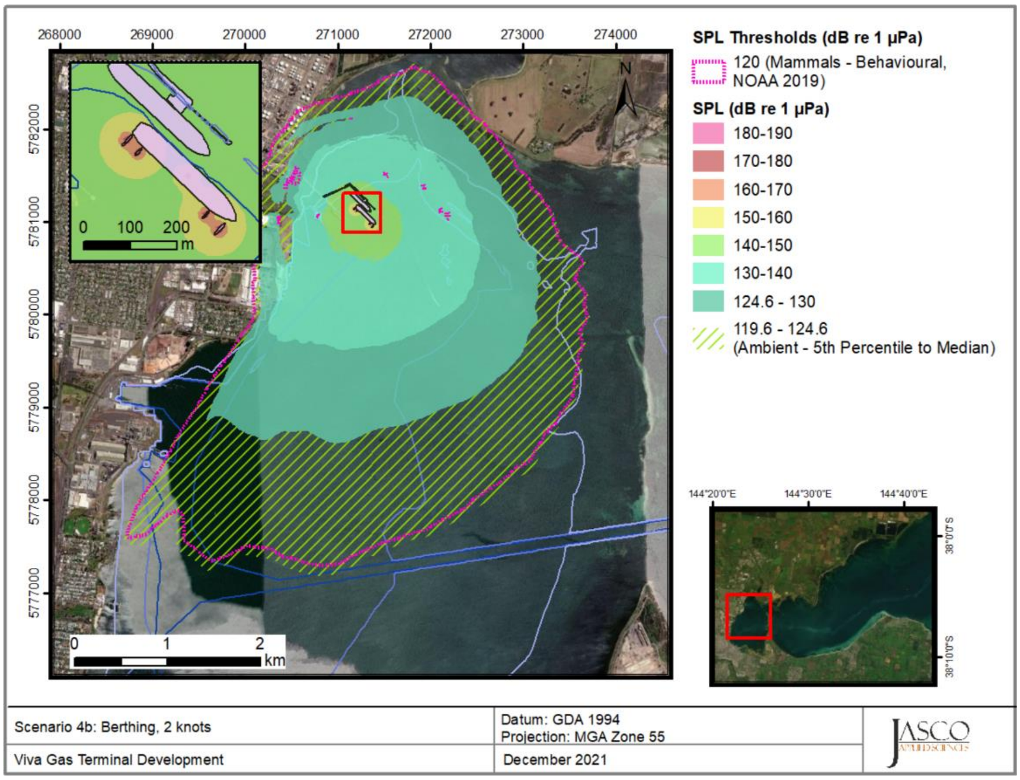


Figure 29. Maximum-over-depth SPL levels for Scenario 4c. Isopleth shows distance to behavioural effect onset level for marine mammals.

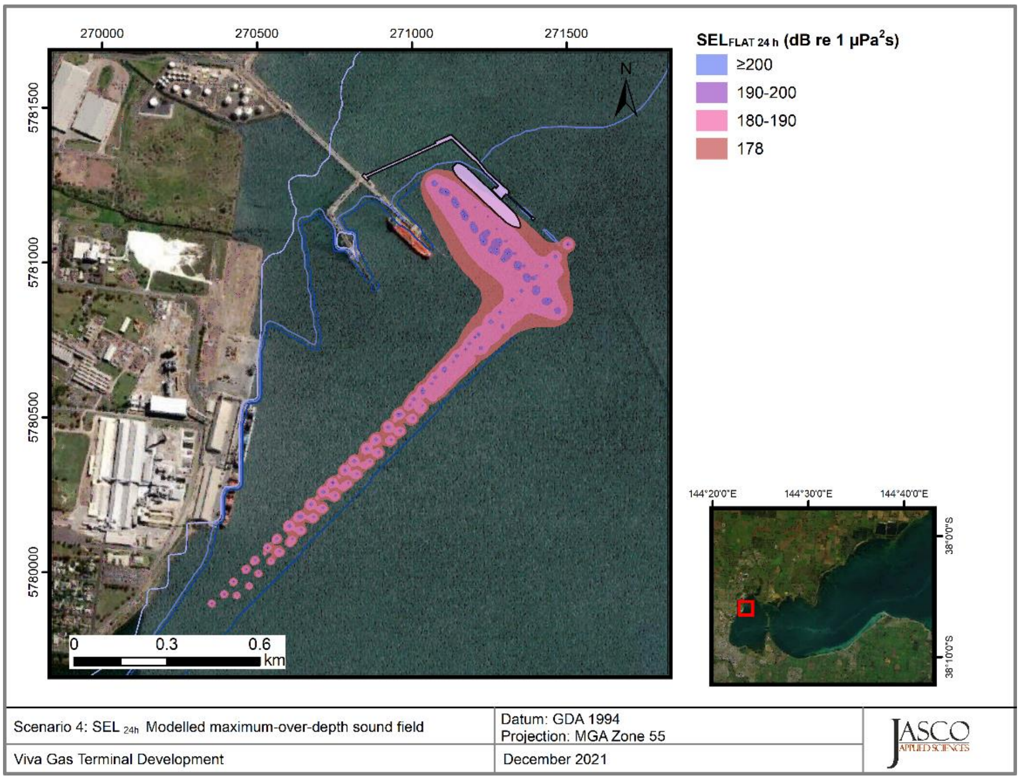


Figure 30. Unweighted maximum-over-depth SEL levels for Scenario 4. No relevant thresholds were exceeded within the modelling resolution.

5. Discussion

The modelling in this report shows sound field predictions from activities associated with construction and operational activities at the Viva Energy Gas Terminal. Scenario 1 considers impulsive radiated sound from two impact piling operations, while Scenarios 2 and 3 consider the continuous radiated sound propagation from dredging operations and FSRU operations, respectively.

5.1. Scenario 1

Scenario 1 describes the modelling of two pile driving operations: a dolphin pile to be driven as part of the construction of the pier extension for the gas terminal (Scenario 1a), and a smaller mooring pile driven at Lascelles Wharf (Scenario 1b) for the temporary loadout facility. The received spectra at 10 m from the pile central axes (Figure 6) show that the pile driven in Scenario 1a generates higher sound levels close to the source than that in Scenario 1b. This is likely to be due to the dolphin pile having a larger radiating (pile wall) area in the water column due to the larger water depth at its location (8.2 m) than the Lascelles Wharf pile (4.6 m).

The resulting sound fields for Scenarios 1a and 1b are shown in Figures 9 to 11 and Figures 12 to 14 respectively. Given the identical geoacoustic and sound speed properties between the modelled locations, the dominant influence on the variation in sound propagation between these sites is the bathymetry. The presence of the land blocks sound propagation to the north and west, and the shallow water depth (maximum of 12 m in inlet) serves to attenuate sound energy rapidly, especially at lower frequencies.

Across the sources studied in this report, the pile driving generates the highest source levels. Despite this, because of the shallow bathymetry, there is little sound propagation beyond the immediate vicinity of Geelong Inner Harbour. The influence of the bathymetry can be seen in the sound propagation results for Scenario 1a, visualised in Figures 9 and 10, which show slightly increased propagation in the south-westerly direction, likely due to the presence of the Geelong shipping channel. Conversely, south-westerly propagation for Scenario 1b is entirely blocked due to the proximity of the source to the shoreline (see Figure 17).

With regards to the recommended impact thresholds, none were exceeded when considering the PK levels (Table 16). The distances to SPL thresholds, shown in Table 17, indicate the maximum distance to the behavioural response onset level in marine mammals (NOAA 2019) is 0.80 km for Scenario 1a and 0.26 km in Scenario 1b. The largest distances at which the behavioural response onset threshold in diving birds was exceeded was 4.90 km in Scenario 1a, and 3.62 km in Scenario 1b.

The cumulative assessments consider radiated sound energy over the course of a single piling operation, and for all piling over a 24-hour period. For marine mammals and diving birds (Table 18), no PTS onset threshold level was reached for the studied auditory groups. Sound levels exceeding TTS onset levels were reached only for the dolphin pile (Scenario 1a), with a maximum distance of 0.10 km (otariid pinnipeds and diving birds) for piling operations over 24 hours.

Results for cumulative levels for fish are shown in Table 19. Sound levels associated with injury in fish with a swim bladder are exceeded up to 0.06 km from the pile in Scenario 1a, and not at all in Scenario 1b. Maximum distances to TTS onset levels are 0.87 and 0.11 km for piling operations over 24 hours for Scenarios 1a and 1b respectively.

5.2. Scenarios 2 and 3

Scenarios 2 and 3 describe the modelling of continuous noise from vessel sources. Scenario 2 comprises dredging activities as part of construction of the new berth (Scenario 2a) and for the seawater transfer pipe (Scenario 2b). Scenario 3 comprises activities associated with the FSRU alone (Scenario 3a), and in conjunction with an offloading LNG carrier (Scenario 3b).

Results shown in Tables 20 and 21, and Figures 19 to 26, indicate that the two dredging operations in Scenario 2 generally result in slightly larger ensonified areas than the FSRU operations in Scenario 3, despite the fact that Scenario 3b features two simultaneous vessel sources. This is due to the source level of the dredger being higher than that of the FSRU and LNG carrier at frequencies that will be attenuated less rapidly given the shallow bathymetry (see Figure 7). The source spectrum used for the dredger has a peak in level between 100 and 1000 Hz, whereas the FSRU and LNG carrier sources peak below 100 Hz; this is reflected in the fact that in Scenario 3 the vessels are berthed, so there will be no high-frequency cavitation noise from propellers. Shallow waters act as a high-pass filter. The low-frequency cut-off f_c can be estimated as:

$$f_c \approx \frac{c_w}{4D\sqrt{1-(c_w/c_b)^2}} \tag{5}$$

where D is depth, c_w is a single-value estimate for the speed of sound in the water column, and c_b is a single-value estimate for the speed of sound in the sediment (Jensen et al. 2011). Using figures from the environmental parameters specified in Section 3.1, and D = 12 m, it can be estimated that for the area of concern in this study, the cut-off frequency is approximately 125 Hz. Thus, the majority of the low frequency sound, which is to say the most prevalent portion of the spectrum emanating from the FSRU and LNG carrier sources, is rapidly absorbed into the sediment, and the ensonified area is small.

Table 20 shows that marine mammal behavioural thresholds are exceeded up to a range of 1.84 km in Scenario 2b, and between 1.1 km and 1.6 km for other vessel scenarios. It should be noted, however, that the median ambient level exceeds the behavioural threshold. It can be seen from Table 21 that weighted TTS levels are only exceeded at very short distances from any of the vessel sources, with PTS levels not exceeded at all within the 20 m resolution of the models used in this study. As shown in Figures 21 to 26, there is no propagation further than the vicinity of Geelong Inner Harbour.

5.3. Scenario 4

Scenario 4 describes the final part of an approach and berthing of an LNG carrier at the proposed new berth. This involves the approach of the LNG carrier accompanied by two escort tugs and two berthing tugs.

Results presented in Table 22 and Figures 27 to 29 show that this berthing operation results in significantly larger ensonified areas than any of the other vessel scenarios due to the high source levels of the four tugs. Maximum distances to marine mammal behavioural response thresholds are between 3.8 km and 4.3 km. Since the berthing operation takes place over a shorter time scale than the other modelled vessel operations, however, marine mammals that may be present will not experience these elevated levels for as long as in other scenarios. It should also be noted that, for this reason, although the TTS and recoverable injury thresholds for fish are exceeded at very short distances, since these measures are for 12-hour and 48-hour exposures, respectively, these are effectively not exceeded in practise.

This short operational duration is also reflected in the SEL results. As seen in Figure 30, exposure levels are only elevated over the ambient noise over relatively short distances, and no relevant injury thresholds are exceeded.

Glossary

Unless otherwise stated in an entry, these definitions are consistent with ISO 80000-3 (2017).

absorption

The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

ambient sound

Sound that would be present in the absence of a specified activity, 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.

auditory frequency weighting

The process of applying an auditory frequency weighting function. In human audiometry, C-weighting is the most commonly used 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. Example hearing groups are low-, mid-, and high-frequency cetaceans, phocid and otariid pinnipeds.

azimuth

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

bandwidth

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

broadband level

The total level measured over a specified frequency range.

cavitation

A rapid formation and collapse of vapor cavities (i.e., bubbles or voids) in water, most often caused by a rapid change in pressure. Fast-spinning vessel propellers typically cause cavitation, which creates a lot of noise.

cetacean

Any animal in the order Cetacea. These are aquatic species and include whales, dolphins, and porpoises.

compressional wave

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

continuous sound

A sound whose sound pressure level remains above ambient sound during the observation period. A sound that gradually varies in intensity with time, for example, sound from a marine vessel.

decade

Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 80000-3:2006).

decidecade

One tenth of a decade. *Note*: An alternative name for decidecade (symbol ddec) is “one-tenth decade”. A decidecade is approximately equal to one third of an octave (1 ddec ≈ 0.3322 oct) and for this reason is sometimes referred to as a “one-third octave”.

decidecade band

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

decibel (dB)

Unit of level used to express the ratio of one value of a power quantity to another on a logarithmic scale. Unit: dB.

energy source level

A property of a sound source obtained by adding to the sound exposure level measured in the far field the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 $\mu Pa^2 m^2 s$.

ensonified

Exposed to sound.

far field

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

Fourier transform (or Fourier synthesis)

A mathematical technique which, although it has varied applications, is referenced in the context of this report 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 fast Fourier transform (FFT).

flat weighting

Term indicating that no frequency weighting function is applied. Synonymous with unweighted.

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. For sound of a given frequency, the frequency weighting function is the ratio of output power to input power of a specified filter, sometimes expressed in decibels. Examples include the following:

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

geoacoustic

Relating to the acoustic properties of the seabed.

hearing group

Category of animal species when classified according to their hearing sensitivity and to the susceptibility to sound. Examples for marine mammals include very low-frequency (VLF) cetaceans, low-frequency (LF) cetaceans, mid-frequency (MF) cetaceans, high-frequency (HF) cetaceans, very high-frequency (VHF) cetaceans, otariid pinnipeds in water (OPW), phocid pinnipeds in water (PPW), sirenians (SI), other marine carnivores in air (OCA), and other marine carnivores in water (OCW) (NMFS 2018, Southall et al. 2019). See **auditory frequency weighting functions**, which are often applied to these groups. Examples 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).

hertz (Hz)

A unit of frequency defined as one cycle per second.

high-frequency (HF) cetacean

See **hearing group**.

impulsive sound

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

isopleth

A line drawn on a map through all points having the same value of some quantity.

level

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

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-like (monopole) sound source. Also see radiated noise level.

M-weighting

See **auditory frequency weighting function** (as proposed by Southall et al. 2007).

non-impulsive sound

Sound that is not an impulsive sound. A non-impulsive sound is 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.

otariid

A common term used to describe members of the Otariidae, eared seals, commonly called sea lions and fur seals. Otariids are adapted to a semi-aquatic life; they use their large fore flippers for propulsion. Their ears distinguish them from phocids. Otariids are one of the three main groups in the superfamily Pinnipedia; the other two groups are phocids and walrus.

other marine carnivores in water (OCW)

See **hearing group**.

parabolic equation method

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

peak sound pressure level (zero-to-peak sound pressure level)

The level ($L_{p,pk}$ or L_{pk}) of the squared maximum magnitude of the sound pressure (p^2_{pk}). Unit: decibel (dB). Reference value (p^2_0) for sound in water: 1 µPa^2.

$$L_{p,\mathrm{pk}} := 10\log_{10}\left(p^2_{\mathrm{pk}}/p^2_0\right)\,\mathrm{dB} \;= 20\log_{10}\left(p_{\mathrm{pk}}/p_0\right)\,\mathrm{dB}$$

The frequency band and time window should be specified. Abbreviation: PK or L_{pk}.

permanent threshold shift (PTS)

An irreversible loss of hearing sensitivity caused by excessive noise exposure. PTS is considered auditory injury.

phocid

A common term used to describe all members of the family Phocidae. These true/earless seals are more adapted to in-water life than are otariids, which have more terrestrial adaptations. Phocids use their hind flippers to propel themselves. Phocids are one of the three main groups in the superfamily Pinnipedia; the other two groups are otariids and walrus.

pinniped

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

point source

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

pressure, acoustic

The deviation from the ambient pressure caused by a sound wave. Also called sound pressure. Unit: pascal (Pa).

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 and seabed. Also see **monopole source level**.

received level

The level measured (or that would be measured) at a defined location. The type of level should be specified.

rms

root-mean-square.

shear wave

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

sound

A time-varying disturbance in the pressure, stress, or material displacement of a medium propagated by local compression and expansion of the medium.

sound exposure

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

sound exposure level

The level (L_E) of the sound exposure (E). Unit: decibel (dB). Reference value (E_0) for sound in water: 1 μPa^2 s.

$$L_E := 10 \log_{10}(E/E_0)\ \mathrm{dB}\ = 20 \log_{10}\left(E^{1/2}/E_0^{1/2}\right)\ \mathrm{dB}$$

The frequency band and integration time should be specified. Abbreviation: SEL.

sound field

Region containing sound waves.

sound pressure

The contribution to total pressure caused by the action of sound.

sound pressure level (rms sound pressure level)

The level ($L_{p,\mathrm{rms}}$) of the time-mean-square sound pressure (p^2_{rms}). Unit: decibel (dB). Reference value (p^2_0) for sound in water: 1 μPa^2.

$$L_{p,\mathrm{rms}} := 10\log_{10}(p^2_{\mathrm{rms}}/p^2_0)\ \mathrm{dB}\ = 20\log_{10}(p_{\mathrm{rms}}/p_0)\ \mathrm{dB}$$

The frequency band and averaging time should be specified. Abbreviation: SPL or Lrms.

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 obtained by adding to the sound pressure level measured in the far field 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

An acoustic signal represented in terms of its power, energy, mean-square sound pressure, or sound

temporary threshold shift (TTS)

Reversible loss of hearing sensitivity. TTS can be caused by noise exposure.

unweighted

Term indicating that no frequency weighting function is applied. Synonymous with flat weighting.

Literature Cited

[AHO] Australian Hydrographic Office. 2021. *AU439144* (webpage), 27 Sep 2021. https://www.hydro.gov.au/webapps/jsp/charts/encDetails.jsp?chart=AU439144.

[HESS] High Energy Seismic Survey. 1999. *High Energy Seismic Survey Review Process and Interim Operational Guidelines for Marine Surveys Offshore Southern California*. Prepared for the California State Lands Commission and the United States Minerals Management Service Pacific Outer Continental Shelf Region by the High Energy Seismic Survey Team, Camarillo, CA, USA. 98 p. https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/PB2001100103.xhtml.

[ISO] International Organization for Standardization. 2006. *ISO 80000-3:2006. Quantities and Units – Part 3: Space and time*. https://www.iso.org/standard/31888.html.

[ISO] International Organization for Standardization. 2016. *ISO 17208-1:2016. Underwater acoustics – Quantities and procedures for description and measurement of underwater sound from ships – Part 1: Requirements for precision measurements in deep water used for comparison purposes*. https://www.iso.org/standard/62408.html.

[ISO] International Organization for Standardization. 2017. *ISO 18405:2017. Underwater acoustics – Terminology*. Geneva. https://www.iso.org/standard/62406.html.

[NAVO] Naval Oceanography Office (US). 2003. *Database description for the Generalized Digital Environmental Model (GDEM-V) (U)*. Document Number MS 39522-5003. Oceanographic Data Bases Division, Stennis Space Center.

[NMFS] National Marine Fisheries Service (US). 1998. *Acoustic Criteria Workshop*. Dr. Roger Gentry and Dr. Jeanette Thomas Co-Chairs.

[NMFS] National Marine Fisheries Service (US). 2016. *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts*. US Department of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-55. 178 p.

[NMFS] National Marine Fisheries Service (US). 2018. *2018 Revision to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts*. US Department of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-59. 167 p. https://www.fisheries.noaa.gov/webdam/download/75962998.

[NOAA] National Oceanic and Atmospheric Administration (US). 2013. *Draft guidance for assessing the effects of anthropogenic sound on marine mammals: Acoustic threshold levels for onset of permanent and temporary threshold shifts*. National Oceanic and Atmospheric Administration, U. Department of Commerce, and NMFS Office of Protected Resources, Silver Spring, MD, USA. 76 p.

[NOAA] National Oceanic and Atmospheric Administration (US). 2015. *Draft guidance for assessing the effects of anthropogenic sound on marine mammal hearing: Underwater acoustic threshold levels for onset of permanent and temporary threshold shifts*. NMFS Office of Protected Resources, Silver Spring, MD, USA. 180 p.

[NOAA] National Oceanic and Atmospheric Administration (US). 2016. *Document Containing Proposed Changes to the NOAA Draft Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Threshold Levels for Onset of Permanent and Temporary Threshold Shifts*. National Oceanic and Atmospheric Administration and US Department of Commerce. 24 p.

[NOAA] National Oceanic and Atmospheric Administration (US). 2018. Takes of Marine Mammals Incidental to Specified Activities; Taking Marine Mammals Incidental to Marine Site Characterization Surveys off of Delaware. *Federal Register* 83(65): 14417-14443. https://www.federalregister.gov/d/2018-12225.

[NOAA] National Oceanic and Atmospheric Administration (US). 2019. *ESA Section 7 Consultation Tools for Marine Mammals on the West Coast* (webpage), 27 Sep 2019. https://www.fisheries.noaa.gov/west-coast/endangered-species-conservation/esa-section-7-consultation-tools-marine-mammals-west. (Accessed 10 Mar 2020).

[ONR] Office of Naval Research. 1998. *ONR Workshop on the Effect of Anthropogenic Noise in the Marine Environment*. Dr. R. Gisiner Chair.

[VRCA] Victoria Regional Channels Authority. 2020. *Vic Tides*. https://vrca.vic.gov.au/wp-content/uploads/2020/02/Tides-Tables-2020-web.pdf.

Aerts, L.A.M., M. Blees, S.B. Blackwell, C.R. Greene, Jr., K.H. Kim, D.E. Hannay, and M.E. Austin. 2008. *Marine mammal monitoring and mitigation during BP Liberty OBC seismic survey in Foggy Island Bay, Beaufort Sea, July-August 2008: 90-day report*. Document Number P1011-1. Report by LGL Alaska Research Associates Inc., LGL Ltd., Greeneridge Sciences Inc., and JASCO Applied Sciences for BP Exploration Alaska. 199 p. ftp://ftp.library.noaa.gov/noaa_documents.lib/NMFS/Auke%20Bay/AukeBayScans/Removable%20Disk/P1011-1.pdf.

Amoser, S. and F. Ladich. 2003. Diversity in noise-induced temporary hearing loss in otophysine fishes. *Journal of the Acoustical Society of America* 113(4): 2170-2179. https://doi.org/10.1121/1.1557212.

ANSI S1.1-2013. 2013. *American National Standard Acoustical Terminology*. American National Standards Institute, NY, USA.

ANSI/ASA S1.13-2005. R2010. *American National Standard Measurement of Sound Pressure Levels in Air*. American National Standards Institute and Acoustical Society of America, NY, USA.

Buehler, D., R. Oestman, J.A. Reyff, K. Pommerenck, and B. Mitchell. 2015. *Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish*. Report Number CTHWANP-RT-15-306.01.01. California Department of Transportation (CALTRANS), Division of Environmental Analysis. 532 p. http://www.dot.ca.gov/hq/env/bio/files/bio_tech_guidance_hydroacoustic_effects_110215.pdf.

Carnes, M.R. 2009. *Description and Evaluation of GDEM-V 3.0*. US Naval Research Laboratory, Stennis Space Center, MS. NRL Memorandum Report 7330-09-9165. 21 p. https://apps.dtic.mil/dtic/tr/fulltext/u2/a494306.pdf.

Christopherson, A. and J. Lundberg. 2013. *Underwater Sound Attenuation in Construction Projects: Applying Science to Pile Driving Permits*. Deep Foundations Institute. Article #1629. OneMine.org. 6 p.

Coffey Services Australia Pty Ltd. 2021. *Geelong LNG Regasification Terminal Project*. Technical report by Coffey Services Australia Pty Ltd for Viva Energy Australia Pty Ltd. Geotechnical Factual Report 754-MELGE271165AD_Rev2.

Collins, M.D. 1993. A split-step Padé solution for the parabolic equation method. *Journal of the Acoustical Society of America* 93(4): 1736-1742. https://doi.org/10.1121/1.406739.

Collins, M.D., R.J. Cederberg, D.B. King, and S. Chin-Bing. 1996. Comparison of algorithms for solving parabolic wave equations. *Journal of the Acoustical Society of America* 100(1): 178-182. https://doi.org/10.1121/1.415921.

Coppens, A.B. 1981. Simple equations for the speed of sound in Neptunian waters. *Journal of the Acoustical Society of America* 69(3): 862-863. https://doi.org/10.1121/1.382038.

Dunlop, R.A., M.J. Noad, R.D. McCauley, L. Scott-Hayward, E. Kniest, R. Slade, D. Paton, and D.H. Cato. 2017. Determining the behavioural dose–response relationship of marine mammals to air gun noise and source proximity. *Journal of Experimental Biology* 220(16): 2878-2886. https://jeb.biologists.org/content/220/16/2878.

Dunlop, R.A., M.J. Noad, R.D. McCauley, E. Kniest, R. Slade, D. Paton, and D.H. Cato. 2018. A behavioural dose-response model for migrating humpback whales and seismic air gun noise. *Marine Pollution Bulletin* 133: 506-516. https://doi.org/10.1016/j.marpolbul.2018.06.009.

Ellison, W.T. and P.J. Stein. 1999. *SURTASS LFA High Frequency Marine Mammal Monitoring (HF/M3) Sonar: Sustem Description and Test & Evaluation*. Under U.S. Navy Contract N66604-98-D-5725. http://www.surtass-lfa-eis.com/wp-content/uploads/2018/02/HF-M3-Ellison-Report-2-4a.pdf.

Ellison, W.T. and A.S. Frankel. 2012. A common sense approach to source metrics. *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life*. Springer, New York. pp. 433-438.

Erbe, C., R. McCauley, C.R. McPherson, and A. Gavrilov. 2013. Underwater noise from offshore oil production vessels. *Journal of the Acoustical Society of America* 133(6): EL465-EL470. https://doi.org/10.1121/1.4802183.

Finneran, J.J. and C.E. Schlundt. 2010. Frequency-dependent and longitudinal changes in noise-induced hearing loss in a bottlenose dolphin (*Tursiops truncatus*). *Journal of the Acoustical Society of America* 128(2): 567-570. https://doi.org/10.1121/1.3458814.

Finneran, J.J. and A.K. Jenkins. 2012. *Criteria and thresholds for U.S. Navy acoustic and explosive effects analysis*. SPAWAR Systems Center Pacific, San Diego, CA, USA. 64 p.

Finneran, J.J. 2015. *Auditory weighting functions and TTS/PTS exposure functions for cetaceans and marine carnivores*. Technical report by SSC Pacific, San Diego, CA, USA.

Finneran, J.J. 2016. *Auditory weighting functions and TTS/PTS exposure functions for marine mammals exposed to underwater noise*. Technical Report for Space and Naval Warfare Systems Center Pacific, San Diego, CA, USA. 49 p. http://www.dtic.mil/dtic/tr/fulltext/u2/1026445.pdf.

Fisher, F.H. and V.P. Simmons. 1977. Absorption of sound in sea water. *Journal of the Acoustical Society of America* 62(S13): 558-564. https://doi.org/10.1121/1.2015423.

Funk, D., D.E. Hannay, D.S. Ireland, R. Rodrigues, and W.R. Koski (eds.). 2008. *Marine mammal monitoring and mitigation during open water seismic exploration by Shell Offshore Inc. in the Chukchi and Beaufort Seas, July–November 2007: 90-day report*. LGL Report P969-1. Prepared by LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Research Ltd. for Shell Offshore Inc., National Marine Fisheries Service (U.S.), and U.S. Fish and Wildlife Service. 218 p.

Hamilton, E.L. 1980. Geoacoustic modeling of the sea floor. *Journal of the Acoustical Society of America* 68(5): 1313-1340. https://doi.org/10.1121/1.385100.

Hannay, D.E. and R.G. Racca. 2005. *Acoustic Model Validation*. Document Number 0000-S-90-04-T-7006-00-E, Revision 02. Technical report by JASCO Research Ltd. for Sakhalin Energy Investment Company Ltd. 34 p.

Illingworth & Rodkin, Inc. 2007. Appendix I. Compendium of pile driving sound data. *In Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish*.

Illingworth & Rodkin, Inc. for the California Department of Transportation, Sacramento, CA, Sacramento, CA. p. 129. www.dot.ca.gov/hq/env/bio/files/pile_driving_snd_comp9_27_07.pdf.

Ireland, D.S., R. Rodrigues, D. Funk, W.R. Koski, and D.E. Hannay. 2009. *Marine mammal monitoring and mitigation during open water seismic exploration by Shell Offshore Inc. in the Chukchi and Beaufort Seas, July–October 2008: 90-Day Report*. Document Number P1049-1. 277 p.

Jensen, F.B., W.A. Kuperman, M.B. Porter, and H. Schmidt. 2011. *Computational Ocean Acoustics*. 2nd edition. AIP Series in Modern Acourics and Signal Processing. AIP Press - Springer, New York. 794 p.

Lucke, K., U. Siebert, P. Lepper, A., and M.-A. Blanchet. 2009. Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. *Journal of the Acoustical Society of America* 125(6): 4060-4070. https://doi.org/10.1121/1.3117443.

Lucke, K. and C. McPherson. 2021. *Appendix [X]: Underwater Noise Impact Assessment: Viva Energy Gas Terminal Project Environment Effects Statement*. Document Number 02558, Version 1.0 DRAFT. Technical report by JASCO Applied Sciences for AECOM.

MacGillivray, A.O. and N.R. Chapman. 2012. Modeling underwater sound propagation from an airgun array using the parabolic equation method. *Canadian Acoustics* 40(1): 19-25. https://jcaa.caa-aca.ca/index.php/jcaa/article/view/2502/2251.

MacGillivray, A.O. 2014. A model for underwater sound levels generated by marine impact pile driving. *Proceedings of Meetings on Acoustics* 20(1). https://doi.org/10.1121/2.0000030

Malme, C.I., P.R. Miles, C.W. Clark, P. Tyak, and J.E. Bird. 1983. *Investigations of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Migrating Gray Whale Behavior*. Report Number 5366. http://www.boem.gov/BOEM-Newsroom/Library/Publications/1983/rpt5366.aspx.

Malme, C.I., P.R. Miles, C.W. Clark, P.L. Tyack, and J.E. Bird. 1984. *Investigations of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Migrating Gray Whale Behavior. Phase II: January 1984 migration*. Report Number 5586. Report prepared by Bolt, Beranek and Newman Inc. for the US Department of the Interior, Minerals Management Service, Cambridge, MA, USA. 357 p. https://www.boem.gov/BOEM-Newsroom/Library/Publications/1983/rpt5586.aspx.

Malme, C.I., B. Würsig, J.E. Bird, and P.L. Tyack. 1986. *Behavioral responses of gray whales to industrial noise: Feeding observations and predictive modeling*. Document Number 56. Final Reports of Principal Investigators. 393-600 p.

Martin, B., K. Bröker, M.-N.R. Matthews, J.T. MacDonnell, and L. Bailey. 2015. Comparison of measured and modeled air-gun array sound levels in Baffin Bay, West Greenland. *OceanNoise 2015*. 11-15 May 2015, Barcelona, Spain.

Matuschek, R. and K. Betke. 2009. Measurements of construction noise during pile driving of offshore research platforms and wind farms. *NAG-DAGA 2009 International Conference on Acoustics*. Rotterdam, Netherlands. pp. 262-265.

Nedwell, J.R. and A.W. Turnpenny. 1998. The use of a generic frequency weighting scale in estimating environmental effect. *Workshop on Seismics and Marine Mammals*. 23–25 Jun 1998, London, UK.

Nedwell, J.R., A.W. Turnpenny, J. Lovell, S.J. Parvin, R. Workman, J.A.L. Spinks, and D. Howell. 2007. *A validation of the dB_{ht} as a measure of the behavioural and auditory effects of underwater noise*. Document Number 534R1231 Report prepared by Subacoustech Ltd. for the UK Department of Business, Enterprise and Regulatory Reform under Project No.

RDCZ/011/0004. 74 p. https://tethys.pnnl.gov/sites/default/files/publications/Nedwell-et-al-2007.pdf.

O'Neill, C., G. Warner, and D.E. Hannay. 2010. Verification of a Bubble Curtain Model Using an Impulse Response Function for a Towed Source. *Canadian Acoustics* 38(3): 68-69. https://jcaa.caa-aca.ca/index.php/jcaa/article/view/2248/1996.

Payne, R. and D. Webb. 1971. Orientation by means of long range acoustic signaling in baleen whales. *Annals of the New York Academy of Sciences* 188: 110-142. https://doi.org/10.1111/j.1749-6632.1971.tb13093.x.

Pichegru, L., R. Nyengera, A.M. McInnes, and P. Pistorius. 2017. Avoidance of seismic survey activities by penguins. *Scientific Reports* 7: 16305. https://doi.org/10.1038/s41598-017-16569-x.

Pile Dynamics, Inc. 2010. GRLWEAP.

Popper, A.N., A.D. Hawkins, R.R. Fay, D.A. Mann, S. Bartol, T.J. Carlson, S. Coombs, W.T. Ellison, R.L. Gentry, et al. 2014. *Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI*. ASA S3/SC1.4 TR-2014. SpringerBriefs in Oceanography. ASA Press and Springer. https://doi.org/10.1007/978-3-319-06659-2.

Porter, M.B. and Y.-C. Liu. 1994. Finite-element ray tracing. *In*: Lee, D. and M.H. Schultz (eds.). *International Conference on Theoretical and Computational Acoustics*. Volume 2. World Scientific Publishing Co. pp. 947-956.

Racca, R.G., A.N. Rutenko, K. Bröker, and M.E. Austin. 2012a. A line in the water - design and enactment of a closed loop, model based sound level boundary estimation strategy for mitigation of behavioural impacts from a seismic survey. *11th European Conference on Underwater Acoustics*. Volume 34(3), Edinburgh, UK.

Racca, R.G., A.N. Rutenko, K. Bröker, and G. Gailey. 2012b. Model based sound level estimation and in-field adjustment for real-time mitigation of behavioural impacts from a seismic survey and post-event evaluation of sound exposure for individual whales. *In*: McMinn, T. (ed.). *Acoustics 2012 Fremantle: Acoustics, Development and the Environment. Proceedings of the Annual Conference of the Australian Acoustical Society*. Fremantle, Australia. http://www.acoustics.asn.au/conference_proceedings/AAS2012/papers/p92.pdf.

Reine, K.J., D. Clarke, and C. Dickerson. 2014. Characterization of underwater sounds produced by hydraulic and mechanical dredging operations. *Journal of the Acoustical Society of America* 135(6): 3280-3294. https://doi.org/10.1121/1.4875712.

Scholik, A.R. and H.Y. Yan. 2002. Effects of boat engine noise on the auditory sensitivity of the fathead minnow, *Pimephales promelas*. *Environmental Biology of Fishes* 63(2): 203-209. https://doi.org/10.1023/A:1014266531390.

Smith, M.E., A.B. Coffin, D.L. Miller, and A.N. Popper. 2006. Anatomical and functional recovery of the goldfish (*Carassius auratus*) ear following noise exposure. *Journal of Experimental Biology* 209(21): 4193-4202. http://jeb.biologists.org/content/209/21/4193.abstract.

Sørensen, K., C. Neumann, M. Dähne, K.A. Hansen, and M. Wahlberg. 2020. Gentoo penguins (Pygoscelis papua) react to underwater sounds. *Royal Society Open Science* 7(2): 191988.

Southall, B.L., A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Greene, Jr., D. Kastak, D.R. Ketten, J.H. Miller, et al. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. *Aquatic Mammals* 33(4): 411-521. https://doi.org/10.1080/09524622.2008.9753846.

Southall, B.L., D.P. Nowaceck, P.J.O. Miller, and P.L. Tyack. 2016. Experimental field studies to measure behavioral responses of cetaceans to sonar. *Endangered Species Research* 31: 293-315. https://doi.org/10.3354/esr00764.

Southall, B.L., J.J. Finneran, C. Reichmuth, P.E. Nachtigall, D.R. Ketten, A.E. Bowles, W.T. Ellison, D.P. Nowacek, and P.L. Tyack. 2019. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. *Aquatic Mammals* 45(2): 125-232. https://doi.org/10.1578/AM.45.2.2019.125.

Southall, B.L., D.P. Nowacek, A.E. Bowles, V. Senigaglia, L. Bejder, and P.L. Tyack. 2021. Marine Mammal Noise Exposure Criteria: Assessing the Severity of Marine Mammal Behavioral Responses to Human Noise. *Aquatic Mammals* 47(5): 421-464.

Teague, W.J., M.J. Carron, and P.J. Hogan. 1990. A comparison between the Generalized Digital Environmental Model and Levitus climatologies. *Journal of Geophysical Research* 95(C5): 7167-7183. https://doi.org/10.1029/JC095iC05p07167.

Warner, G.A., C. Erbe, and D.E. Hannay. 2010. Underwater Sound Measurements. (Chapter 3) *In* Reiser, C.M., D. Funk, R. Rodrigues, and D.E. Hannay (eds.). *Marine Mammal Monitoring and Mitigation during Open Water Shallow Hazards and Site Clearance Surveys by Shell Offshore Inc. in the Alaskan Chukchi Sea, July-October 2009: 90-Day Report*. LGL Report P1112-1. Report by LGL Alaska Research Associates Inc. and JASCO Applied Sciences for Shell Offshore Inc., National Marine Fisheries Service (US), and Fish and Wildlife Service (US). pp. 1-54.

Whittaker, J.M., A. Goncharov, S.E. Williams, R.D. Müller, and G. Leitchenkov. 2013. Global sediment thickness data set updated for the Australian-Antarctic Southern Ocean. *Geochemistry, Geophysics, Geosystems* 14(8): 3297-3305. https://doi.org/10.1002/ggge.20181.

Wilson, C.C. and C. McPherson. 2021. *Viva Energy Gas Terminal Project: Baseline Monitoring of Ambient Environment*. Document Number 02580, Version 1.0 DRAFT. Technical report by JASCO Applied Sciences for AECOM.

Wood, J., B.L. Southall, and D.J. Tollit. 2012. *PG&E offshore 3-D Seismic Survey Project Environmental Impact Report–Marine Mammal Technical Draft Report*. SMRU Ltd. 121 p. https://www.coastal.ca.gov/energy/seismic/mm-technical-report-EIR.pdf.

Zhang, Z.Y. and C.T. Tindle. 1995. Improved equivalent fluid approximations for a low shear speed ocean bottom. *Journal of the Acoustical Society of America* 98(6): 3391-3396. https://doi.org/10.1121/1.413789.

Appendix A. Additional Methods and Parameters

A.1. Bathymetry

Water depths for the modelled area were extracted from a number of sources:

- Survey data for distances from the source location on the order of 1-2 km, supplied by the client. This data has ~1 m resolution in the area immediately around the proposed FSRU mooring, reducing to ~25 m, then ~50 m resolution as the distance from this area increases.
- Depth soundings from Australian Hydrographic Office (AHO) survey AU439144, which have a resolution of ~250 m.
- Lower resolution (on the order of kilometres) depth contours provided by the client.
- Shapefile for Geelong shipping channel from an Australian government source.
- Post-dredge depths of the area to be dredged as part of this project in Scenario 2a, provided by the client.

The main source of bathymetry for the majority of the modelled area was the AU439144 survey (AHO 2021). This data was, however, missing the northeast corner of Port Philip, so the low-resolution depth contours were used to fill in this area, with a 250 m buffer to smooth the transition between the two datasets. The area around the modelled source locations was replaced by the high-resolution survey data, with a 20 m buffer to smooth between this and the AU439144 data.

All of these datasets are referenced to chart datum, which is -0.58 m offset from Australian height datum (AHD). Mean higher high water (MHHW) for the port is reported as AHD + 0.42 m (VRCA 2020). The combined bathymetry was therefore adjusted to MHHW by adding 1 m. The Geelong shipping channel was then added to the bathymetry by manually creating a zone at a depth of 12.3 m (the channel depth at MHHW according to the AU439144 metadata) in areas based on the channel shapefile. The final composite bathymetry data was re-gridded onto a Map Grid of Australia (MGA) coordinate projection (Zone 55 south) with a regular grid spacing of 10 m. Figure A.1 shows a simplified overview of the composite bathymetry, highlighting the different data sources.

Scenario 2a was modelled using bathymetry as described above, as it was reasoned that a pre-dredged bathymetry would be more representative for this dredging operation. For all other scenarios, the post-dredged depths were also added to the composite bathymetry.

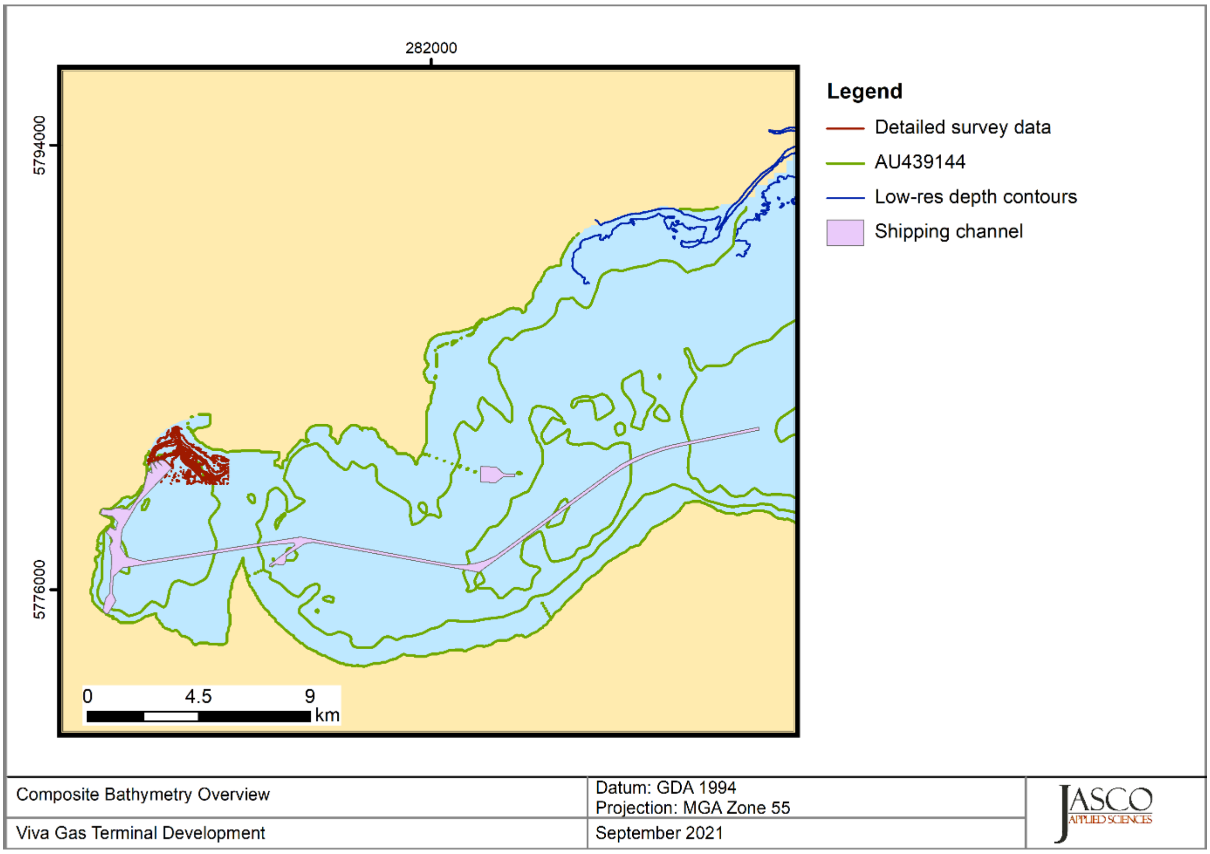


Figure A.1. Simplified overview of composite bathymetry data.

A.2. Sound Speed Profile

The sound speed profile (SSP) for the modelled site was derived from temperature and salinity data from the US Naval Oceanographic Office's *Generalized Digital Environmental Model V 3.0* (Teague et al. 1990, NAVO 2003, 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 data were converted to sound speed profiles according to Coppens (1981).

The SSP used in this study was generated using extracted temperature and salinity data for May from 38°S, 144.5°E, up to a depth of 4 m. This was combined with data from 38.25°S, 144.5°E to extend the profile to 45 m. Ultimately, no modelled scenarios resulted in sound propagating beyond the immediate vicinity of the sources, so sound speed data for depths greater than this was not required. The resultant SSP is largely flat, varying between 1505.7 m/s and 1506.0 m/s for all depths of interest in this study, as shown in Figure A.2

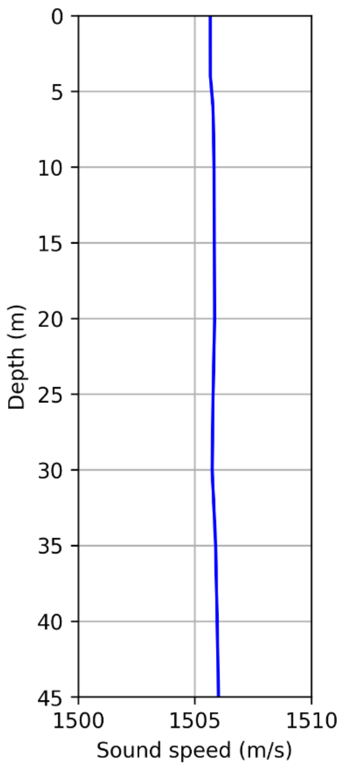


Figure A.2 Sound speed profile used in this study.

A.3. Estimating Ranges to Threshold 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 seafloor for each location in the modelled region. The predicted distances to specific levels were computed from these contours. Two distances relative to the source are reported for each sound level: R_{max}, the maximum range to the given sound level over all azimuths, and $R_{95\%}$, the range to the given sound level after the 5% farthest points were excluded (see examples in Figure A.3).

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 Figure A.3a. In cases such as this, where relatively few points are excluded in any given direction, R_{max} can misrepresent the area of the region exposed to such effects, and $R_{95\%}$ is considered more representative. In contrast, in strongly radially asymmetric cases such as shown in Figure A.3b, $R_{95\%}$ neglects to account for substantial protrusions in the footprint. In such cases, R_{max} might better represent the region of effect in specific directions. Cases such as this are usually associated with bathymetric features that affect propagation. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the non-uniformity of the acoustic environment.

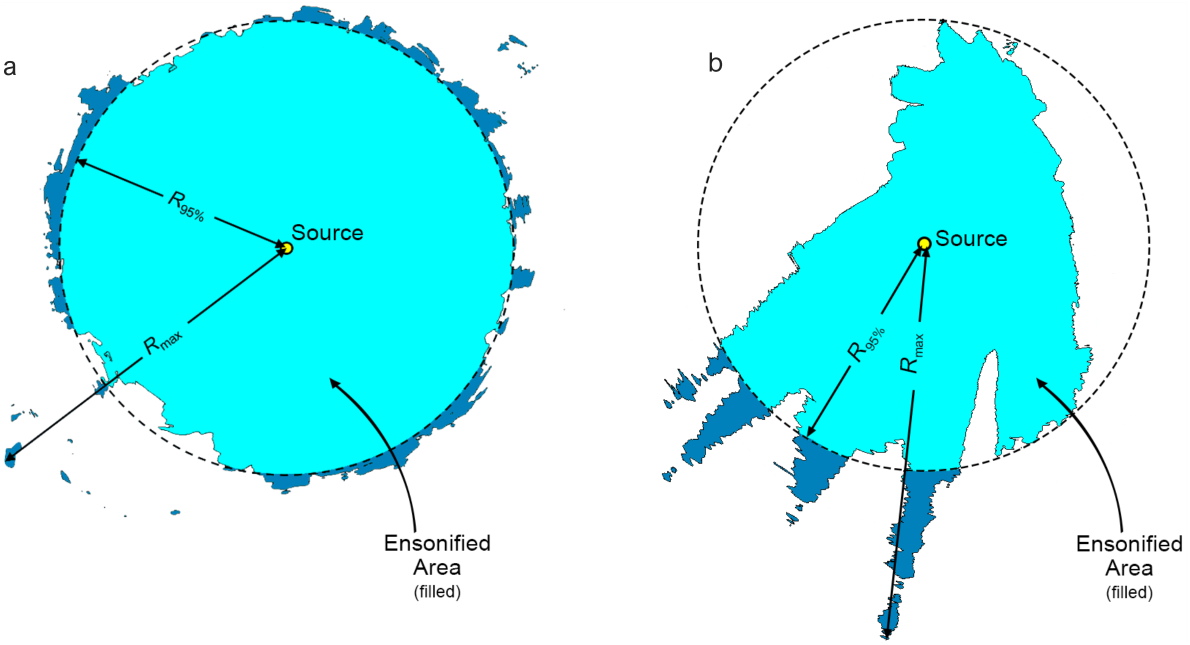


Figure A.3. R_{max} and $R_{95\%}$ ranges shown for two contrasting scenarios. Cyan indicates the ensonified areas bounded by $R_{95\%}$, whilst dark blue indicates the ensonified areas beyond $R_{95\%}$ that determine R_{max}.

Appendix B. Underwater Acoustic Metrics

B.1. Level 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 (ANSI 2013, e.g., ISO 2017).

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

$$L_{p,\mathrm{pk}} = 10\log_{10}\frac{\max|p^2(t)|}{p_0^2} = 20\log_{10}\frac{\max|p(t)|}{p_0} \tag{B-1}$$

PK is often included as a criterion for assessing whether a sound is potentially injurious; however, because it does not account for the duration of an acoustic event, it is generally a poor indicator of perceived loudness.

The sound pressure level (SPL or L_p; dB re 1 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:

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

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. For short acoustic events, such as sonar pulses and marine mammal vocalizations, it is important to choose an appropriate time window that matches the duration of the signal. For in-air studies, when evaluating the perceived loudness of sounds with rapid amplitude variations in time, the time weighting function $g(t)$ is often set to a decaying exponential function that emphasizes more recent pressure signals. This function mimics the leaky integration nature of mammalian hearing. For example, human-based fast time-weighted SPL ($L_{p,fast}$) applies an exponential function with time constant 125 ms. A related simpler approach used in underwater acoustics sets $g(t)$ to a boxcar (unity amplitude) function of width 125 ms; the results can be referred to as $L_{p,boxcar\ 125ms}$. Another approach, historically used to evaluate SPL of impulsive signals underwater, defines $g(t)$ as a boxcar function with edges set to the times corresponding to 5% and 95% of the cumulative square pressure function encompassing the duration of an impulsive acoustic event. This calculation is applied individually to each impulse signal, and the results have been referred to as 90% SPL ($L_{p,90\%}$).

The sound exposure level (SEL or L_E; dB re 1 µPa² s) is the time-integral of the squared acoustic pressure over a duration (T):

$$L_E = 10\log_{10}\left(\int_T p^2(t)\,dt \Big/ T_0 p_0^2\right)\ \text{dB} \tag{B-3}$$

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:

$$L_{E,N} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right)\ \text{dB} \tag{B-4}$$

Energy equivalent SPL (L_{eq}; dB re 1 µPa) denotes the SPL of a stationary (constant amplitude) sound that generates the same SEL as the signal being examined, $p(t)$, over the same time period, T:

$$L_{\text{eq}} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)\,dt \Big/ p_0^2\right) \tag{B-5}$$

The equations for SPL and the energy-equivalent SPL are numerically identical. Conceptually, the difference between the two metrics is that the SPL is typically computed over short periods (typically of 1 s or less) and tracks the fluctuations of a non-steady acoustic signal, whereas the L_{eq} reflects the average SPL of an acoustic signal over time periods typically of 1 min to several hours.

B.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, $f_{\text{c}}(i)$, is defined as:

$$f_{\text{c}}(i) = 10^{\frac{i}{10}}\ \text{kHz} \tag{B-6}$$

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

$$f_{\text{lo},i} = 10^{\frac{-1}{20}} f_{\text{c}}(i) \quad \text{and} \quad f_{\text{hi},i} = 10^{\frac{1}{20}} f_{\text{c}}(i) \tag{B-7}$$

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure B.1). The acoustic modelling spans from $f_c(1) = 10$ Hz to $f_c(35) = 25119$ Hz.

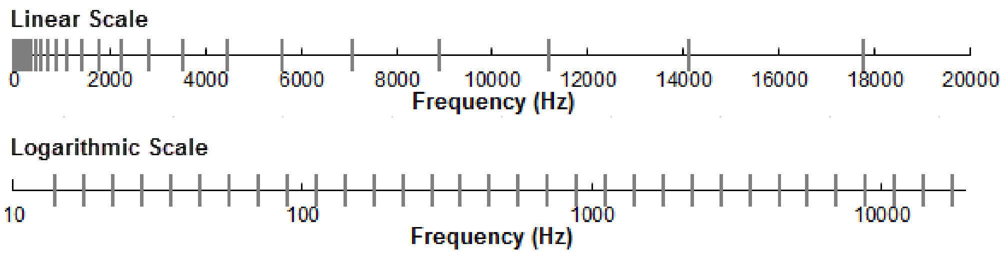


Figure B.1. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale.

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

$$L_{p,i} = 10 \log_{10} \int_{f_{\text{lo},i}}^{f_{\text{hi},i}} S(f)\, \mathrm{d}f \;\; \text{dB} \tag{B-8}$$

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

$$\text{Broadband SPL} = 10 \log_{10} \sum_i 10^{\frac{L_{p,i}}{10}} \;\; \text{dB} \tag{B-9}$$

Figure B.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.

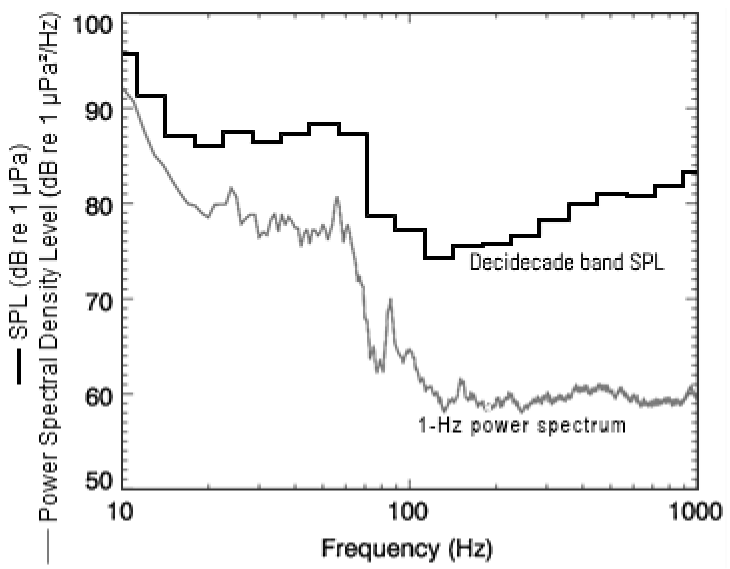


Figure B.2. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient sound shown on a logarithmic frequency scale.Because the decidecade bands are wider with increasing frequency, the 1/3-octave-band SPL is higher than the power spectrum.

B.3. Marine Mammal Noise Effect Criteria

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.

B.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 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 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 humans; see Appendix B.3). The SEL_{24h} thresholds were obtained by extrapolating measurements of onset levels of Temporary Threshold Shift (TTS) in belugas by the amount of TTS required to produce Permanent Threshold Shift (PTS) in chinchillas. The Southall et al. (2007) recommendations do not specify an exchange rate, which suggests that the thresholds are the same regardless of the duration of exposure (i.e., it implies a 3 dB exchange rate).

Wood et al. (2012) refined Southall et al.'s (2007) thresholds, suggesting lower 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 $\mu Pa^2 \cdot s$. 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 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 $\mu Pa^2 \cdot s$.

As of 2017, 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).

B.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, Southall et al. 2021).

B.3.2.1. Non-Impulsive Noise

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, 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).

B.3.2.2. Impulsive Noise

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.

B.4. 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).

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:

$$G(f) = K + 10\log_{10}\left(\frac{\left(\frac{f}{f_{lo}}\right)^{2a}}{\left(1+\left(\frac{f}{f_{lo}}\right)^{2}\right)^{a}\left(1+\left(\frac{f}{f_{hi}}\right)^{2}\right)^{b}}\right) \tag{B-10}$$

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid-, and high-frequency cetaceans, phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA's technical guidance that assesses noise impacts on marine mammals (NMFS 2016, NMFS 2018). A further update to these weighting functions is presented in Southall (2019), whereby mid- and high- frequency cetaceans are now known as high- and very-high-frequency cetaceans.

Table B-1 lists the frequency-weighting parameters for each hearing group, and Figure B.3 shows the resulting frequency-weighting curves.

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

Hearing group	a	b	f_{lo} (Hz)	f_{hi} (kHz)	K (dB)
High-frequency cetaceans	1.6	2.0	8,800	110,000	1.2
Otariid seals in water	2.0	2.0	940	25,000	0.64

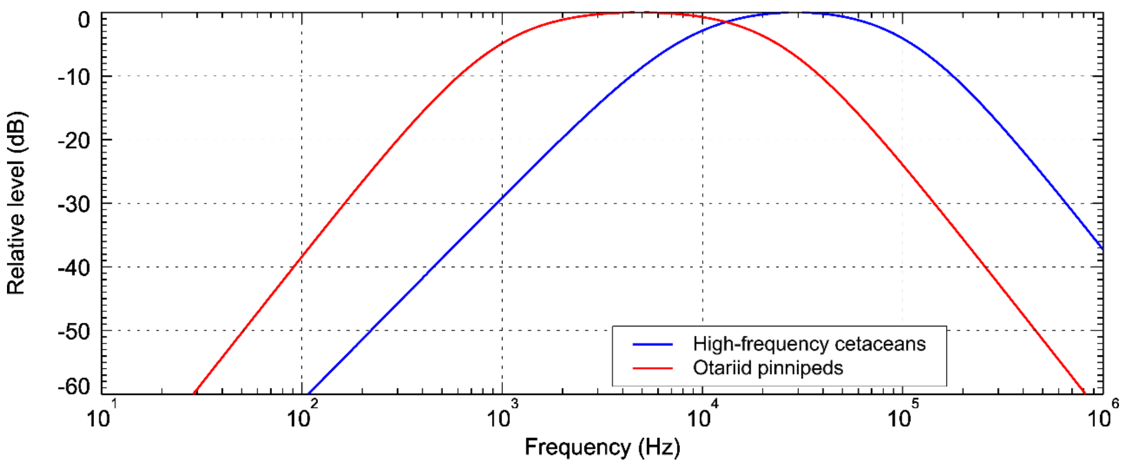


Figure B.3. Auditory weighting functions for functional marine mammal hearing groups used in this project.

Appendix C. Sound Source and Propagation Models

C.1. Pile Driving

C.1.1. Source Properties

For most projects involving pile driving in shallow-water environments, there is potential for direct transmission from the sound source to biological receivers, and there are reflected sound paths from the water's surface and bottom that may be perceived by marine fauna (megafauna and fish), and people. Normally, ground-radiated sound is dominated by low frequencies that cannot propagate efficiently through shallow water. When pile driving is the sound source, there is the potential for substrate-borne sound caused by the hammer's action on the pile to be re-radiated back into the water where it may reach a biological receiver. For pile driving, energy transmission through water depends on the following factors (Christopherson and Lundberg 2013):

1. Direct contact between the pile and the water,
2. The depth of the water column,
3. The size of the pile,
4. The type of hammer,
5. The hammer energy, and
6. The addition of re-radiation of substrate-borne sound.

The way sound propagates in water is affected by obstructions (barges, breakwater walls, other piles, etc.) and the bathymetric characteristics (Buehler et al. 2015). Figure C.1 illustrates these basic propagation concepts.

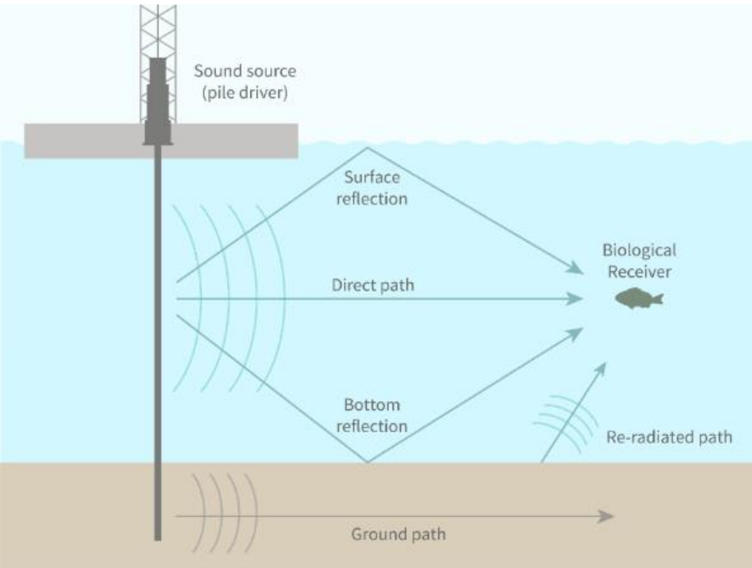


Figure C.1 Underwater sound propagation paths associated with pile driving (Buehler et al. 2015).

C.1.2. Source Model

A physical model of pile vibration and near-field sound radiation is used to calculate source levels of piles. The physical model employed in this study computes the underwater vibration and sound radiation of a pile by solving the theoretical equations of motion for axial and radial vibrations of a cylindrical shell. These equations of motion are solved subject to boundary conditions, which describe the forcing function of the hammer at the top of the pile and the soil resistance at the base of the pile, as shown in Figure C.2. Damping of the pile vibration due to radiation loading is computed for Mach waves emanating from the pile wall. The equations of motion are discretised using the finite difference (FD) method and are solved on a discrete time and depth mesh.

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

The sound radiating from the pile itself is simulated using a vertical array of discrete point sources. The point sources are centred on the pile axis. Their amplitudes are derived using an inverse technique, such that their collective particle velocity, calculated using a near-field wave-number integration model, matches the particle velocity in the water at the pile wall. The sound field propagating away from the vertical source array is then calculated using a time-domain acoustic propagation model (see Appendix C.3). MacGillivray (2014) describes the theory behind the physical model in more detail.

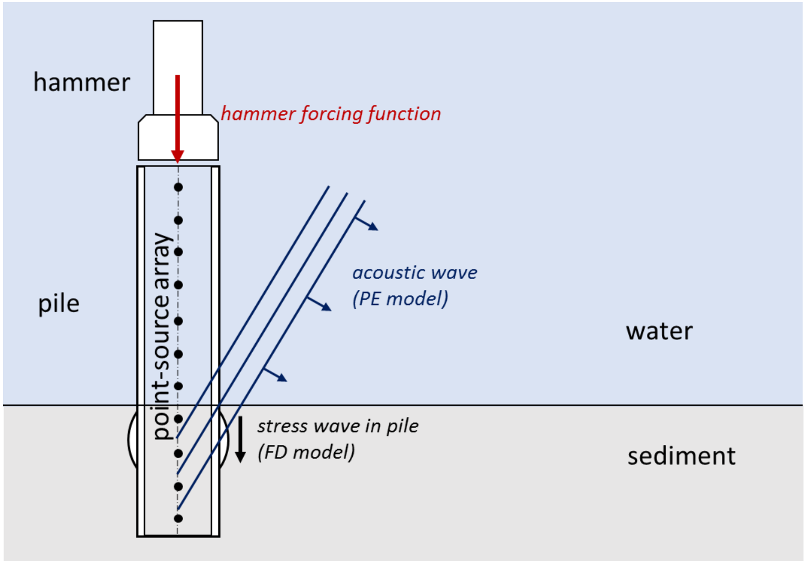


Figure C.2. Physical model geometry for impact driving of a cylindrical pile(vertical cross-section). The hammer forcing function is used with the finite difference (FD) model to compute the stress wave vibration in the pile. A vertical array of point sources is used with the parabolic equation (PE) model to compute the acoustic waves that the pile wall radiates.

C.2. Marine Operations Noise Model

Underwater sound propagation (i.e., transmission loss) at frequencies of 10 Hz to 2 kHz was predicted with JASCO's Marine Operations Noise Model (MONM). MONM computes received per-pulse SEL for directional impulsive sources, and SEL over 1 s for non-impulsive sources, at a specified source depth. Sound propagation at frequencies greater than 2.5 kHz was computed via the BELLHOP Gaussian beam acoustic ray-trace model (Porter and Liu 1994).

MONM computes acoustic propagation via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the US Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed (Zhang and Tindle 1995). The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996).

MONM accounts for the additional reflection loss at the seabed, which results from partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. MONM incorporates the following site-specific environmental properties: a bathymetric grid of the modelled area, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor. Additionally, BELLHOP accounts for sound attenuation due to energy absorption through ion relaxation and viscosity of water (Fisher and Simmons 1977). This type of sound attenuation is important 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\times$2-D. These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding $N = 360°/\Delta\theta$ number of planes (see Figure C.3).

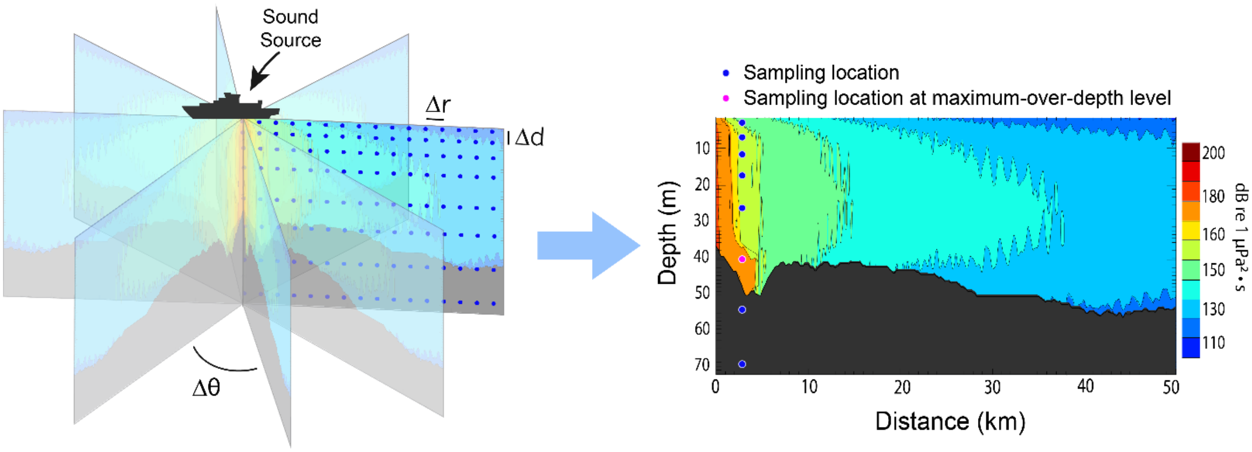


Figure C.3. The $N\times$2-D and maximum-over-depth modelling approach used by MONM.

MONM treats frequency dependence by computing acoustic transmission loss at the centre frequencies of decidecade bands. Sufficiently many decidecade frequency, 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 received per-pulse SEL are computed by subtracting the band propagation loss values from the directional source level in that frequency band. Composite broadband received per-pulse SEL are then computed by summing the received decidecade levels.

The received per-pulse SEL sound field within each vertical radial plane is sampled at various ranges from the source, generally with a fixed radial step size (Δr in Figure C.3). At each sampling range along the surface, the sound field is sampled at various depths (Δd in Figure C.3) 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 for the sound speed profile. For areas with deep water, sampling is not performed at depths beyond those reachable by marine mammals. The received per-pulse SEL at a surface sampling location is taken as the maximum value that occurs over all samples within the water column, i.e., the maximum-over-depth received per-pulse SEL. These maximum-over-depth per-pulse SEL are presented as colour contours around the source.

MONM's predictions have been validated against experimental data from several underwater acoustic measurement programs conducted by JASCO (Hannay and Racca 2005, Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010, Racca et al. 2012a, Racca et al. 2012b, Martin et al. 2015).

C.3. Full Waveform Range-dependent Model

For impulsive sounds from impact pile driving, time-domain representations of the pressure waves generated in the water are required for calculating SPL and peak pressure level. Furthermore, the pile must be represented as a distributed source to accurately characterise vertical directivity effects in the near-field zone.

FWRAM is a time-domain acoustic model based on the same wide-angle parabolic equation (PE) algorithm as MONM. FWRAM computes synthetic pressure waveforms versus range and depth for range-varying marine acoustic environments, and it takes the same environmental inputs as MONM (bathymetry, water sound speed profile, and seabed geoacoustic profile). Unlike MONM, FWRAM computes pressure waveforms via Fourier synthesis of the modelled acoustic transfer function in closely spaced frequency bands.

FWRAM employs the array starter method to accurately model sound propagation from a spatially distributed source (MacGillivray and Chapman 2012). Synthetic pressure waveforms are modelled over the frequency range 10 Hz to 1123 Hz inside a one-second time window. An example of these waveforms at increasing distance from the source is shown in Figure C.4. The synthetic pressure waveforms are post-processed, after applying a travel time correction, to calculate standard SPL and SEL metrics versus range and depth from the source.

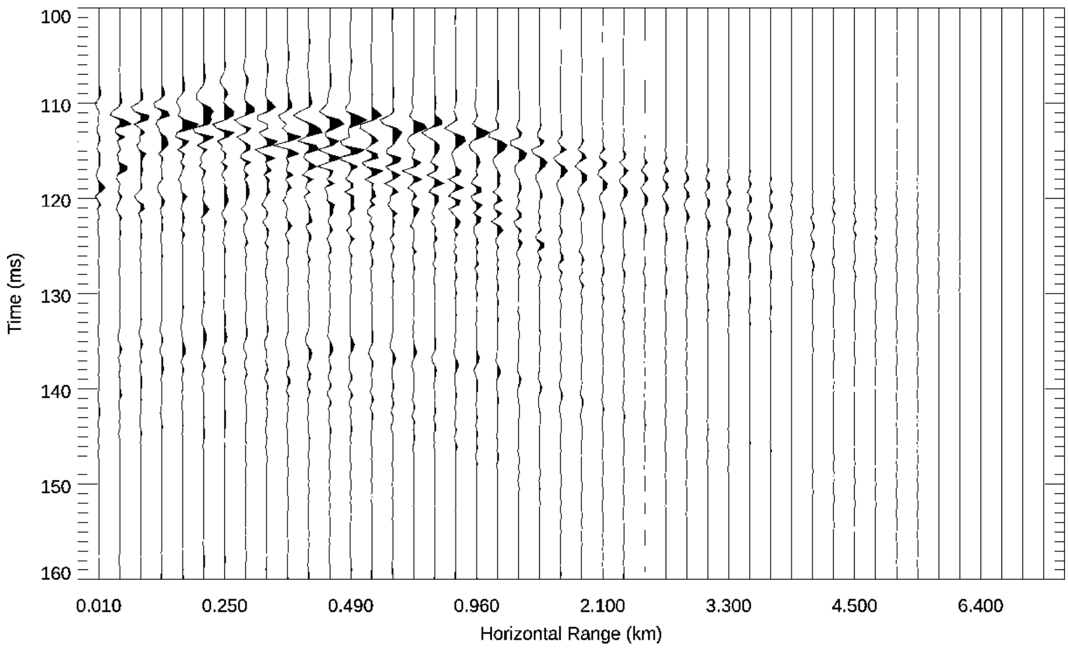


Figure C.4. Example of synthetic pressure waveforms computed for this project by FWRAM at multiple ranges.

Appendix A-3: Underwater Noise Impact Assessment

Viva Energy Gas Terminal Project Environment Effects Statement

JASCO Applied Sciences (Australia) Pty Ltd

26 November 2021

Submitted to:

AECOM

Contract Dated 21 July 2021

P001627-001
Document 02558
Version 2.0

Contents

Executive Summary 1

1. Introduction 5

1.1. Purpose 5
1.2. Why Understanding Underwater Noise is Important 6
1.3. Project Area 6
1.4. Project Description 9
1.4.1. Key Construction Activities 9
1.4.2. Key Operation Activities 11
1.4.3. Key Decommissioning Activities 11
1.4.4. Project Activities Relevant to the Assessment 11

2. Scoping Requirements 12

3. Legislation, Policy, and Guidelines 13

3.1. Key Environmental Legislation 13
3.2. Noise Impacts and Exposure Thresholds 13
3.2.1. Acoustic Metrics 14
3.2.2. Marine Mammals 15
3.2.3. Fishes 16
3.2.4. Invertebrates 18
3.2.5. Avifauna 18

4. Methodology 20

4.1. Existing Conditions Assessment Method 20
4.1.1. Study Area 20
4.1.2. Existing Noise Conditions 21
4.2. Underwater Sound 21
4.3. Underwater Hearing Sensitivity of Marine Animals 22
4.3.1. Marine Mammals 23
4.3.2. Fishes 24
4.3.3. Invertebrates 25
4.3.4. Avifauna 27
4.4. Impact of Underwater Noise on Marine Fauna 27
4.4.1. Physiological Stress 29
4.4.2. Behavioural Responses 30
4.4.3. Acoustic Masking 32
4.4.4. Hearing Impairment 33
4.4.5. Mortality 34
4.5. Risk Screening Method 34
4.5.1. Criteria and Consequence Ratings 35
4.5.2. Risk Screening Results 37
4.6. Impact Assessment Method 37
4.7. Stakeholder and Community Engagement 37

4.8. Assumptions and Limitations 38
4.8.1. Assumptions 38
4.8.2. Limitations 38
4.8.3. Linkages to Other EES Technical Studies 39
5. Existing Conditions 40
5.1. Areas of Wildlife Conservation Value in the Project Area 40
5.2. Marine Fauna occurring in the Project Area 40
6. Construction Impacts 42
6.1. Noise Emissions of Construction Related Activities 43
6.1.1. Pile driving 43
6.1.2. Dredging 44
6.2. Marine Mammals 44
6.2.1. Pile Driving 44
6.2.2. Dredging 47
6.3. Fishes 49
6.3.1. Pile Driving 49
6.3.2. Dredging 52
6.4. Invertebrates 53
6.4.1. Pile Driving 53
6.4.2. Dredging 55
6.5. Avifauna 56
6.6. Summary of Residual Construction Impacts 58
7. Operation Impacts 60
7.1. Marine Mammals 60
7.2. Fishes 63
7.3. Invertebrates 64
7.4. Avifauna 66
7.5. Summary of Residual Operation Impacts 67
8. Decommissioning Impacts 68
8.1. Summary of Residual Decommissioning Impacts 68
9. Recommended Mitigation Measures 69
10. Conclusion 71
10.1. Residual Impacts 71
Abbreviations and Glossary of Terms 72
Literature Cited 74
Supplement A. Physical Characteristics of Underwater Sound A-1

Figures

Figure 1. Project overview. 8
Figure 2. Overview map of the project and assessment area. 20
Figure 3. Maximum-over-depth SPL levels in Scenario 1a. Isopleths show distances to behavioural effect onset levels in marine mammals and penguins 21
Figure 4. Auditory weighting functions for the functional marine mammal hearing groups assessed in this report (Southall et al. 2019). 24
Figure 5. Fish audiograms obtained under open sea, free-field conditions; species representing different categories as classified by Popper et al. (2014) (source: Popper et al. 2019). 25
Figure 6. Conceptual relationship between the distances from a noise source and the overlapping effects on hearing and behaviour 28
Figure 7. Maximum-over-depth decidecade band sound exposure level (SEL) at a receiver 10 m horizontally from the modelled pile driving sources. 43
Figure 8. Decidecade band monopole source levels for dredging and vessel operations (FSRU/LNG carrier). 44

Tables

Table 1. Scoping requirements relevant to underwater noise. 12
Table 2. Primary environmental legislation and associated information 13
Table 3. Acoustic metrics used in this impact assessment as compared to other publications. 14
Table 4. Summary of relevant permanent threshold shift (PTS) and temporary threshold shift (TTS) onset acoustic thresholds (Southall et al. 2019). 16
Table 5. Noise exposure criteria for pile driving noise exposure for fishes, fish eggs and larvae, adapted from Popper et al. (2014). 17
Table 6. Noise exposure criteria for vessel noise exposure for fishes, fish eggs and larvae, adapted from Popper et al. (2014). 17
Table 7. Marine mammal hearing groups (Southall et al. 2019). 23
Table 8. Issues screening criteria and consequence ratings. 35
Table 9. Issue investigation categories. 36
Table 10. Underwater noise issues screening result. 37
Table 11. List of marine fauna species potentially occurring in the project area. 41
Table 12. Recommended mitigation measures. 70
Table 13. Behavioural impact ranges for pile driving; horizontal distances (m) from the dolphin pile (Scenario 1a) and mooring pile (dolphin pile (Scenario 1b) to maximum-over-depth per-strike SPL isopleths based on noise exposure criteria for non-impulsive sounds (NOAA 2019) 46
Table 14. TTS ranges for marine mammals for pile driving noise based on noise exposure criteria for impulsive sounds (Southall et al. 2019); maximum (R_{max}) horizontal distances (m) from the dolphin pile (Scenario 1a) and mooring pile (dolphin pile, Scenario 1b) to maximum-over-depth weighted SEL isopleths for marine mammals (Southall et al. 2019) 46
Table 15. Behavioural impact ranges for marine mammals for dredging noise based on noise exposure criteria for non-impulsive sounds (NOAA 2019); horizontal distances (m) from the dredger (Scenario 2a Channel dredging; Scenario 2b: Seawater pipe dredging) to maximum-over-depth per-strike SPL isopleths are given 48
Table 16. TTS ranges for marine mammals for dredging noise based on noise exposure criteria for non-impulsive sounds (Southall et al. 2019); maximum horizontal distances (m) from the dredging scenarios (Scenarios 2a and b) to maximum-over-depth weighted SEL isopleths are given. 48

Table 17. Impact ranges for fishes for pile driving noise; horizontal distances (m) from the pile driving site (Scenario 1a Dolphin pile; Scenario 1b: Mooring pile) to maximum-over-depth unweighted SEL isopleths for fish (Popper et al. 2014) 51
Table 18. Impact ranges for fishes for dredging noise; horizontal distances (m) from the dredger (Scenario 2a Channel dredging; Scenario 2b: Seawater pipe dredging) to maximum-over-depth per-strike SPL isopleths based on noise exposure criteria for vessel noise 52
Table 19. Behavioural impact ranges for diving birds for pile driving; horizontal distances (m) from the dolphin pile (Scenario 1a) and mooring pile (dolphin pile (Scenario 1b) to maximum-over-depth per-strike SPL isopleths 57
Table 20. TTS ranges for diving birds for dredging noise based on noise exposure criteria for non-impulsive sounds (Southall et al. 2019). 58
Table 21. Behavioural impact ranges for fishes for operational noise; horizontal distances (m) from the FSRU and LNG carrier (Scenario 3a: FSRU; Scenario 3b: FSRU + LNG carrier) to maximum-over-depth per-strike SPL isopleths based on noise exposure criteria for vessel noise. 62
Table 22. TTS ranges for marine mammals for operational noise based on noise exposure criteria for non-impulsive sounds (Southall et al. 2019 horizontal distances (m) from the FSRU and LNG carrier (Scenario 3a: FSRU; Scenario 3b: FSRU + LNG carrier) to maximum-over-depth weighted SEL isopleths are given. 62
Table 23. Impact ranges for fishes for operational noise; horizontal distances (m) from the dredger (Scenario 3a: FSRU; Scenario 3b: FSRU + LNG carrier) to maximum-over-depth per-strike SPL isopleths based on noise exposure criteria for vessel noise 64
Table 24. TTS ranges for diving birds for dredging noise based on noise exposure criteria for other carnivores in water for non-impulsive sounds (Southall et al. 2019). 66

Executive Summary

This technical report provides an underwater noise impact assessment conducted to support the Environment Effects Statement (EES) for the Viva Energy Gas Terminal Project (the project).

In December 2020, the Victorian Minister for Planning determined that the project requires assessment through an EES under the Environment Effects Act 1978 (Vic). The reasons for the decision were primarily related to the potential for significant adverse effects on the marine environment of Corio Bay and the potential for contributing to greenhouse gas emissions. Secondarily, the EES was required to assess the effects of the project on air quality, noise, land use, Aboriginal and historic heritage, native vegetation, groundwater, traffic, and transport as well as visual amenity.

In January 2021, the project was also determined to require assessment and approval under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) due to the potential for the project to have a significant impact on wetlands of international importance, listed threatened species and communities, and listed migratory species. The EES process is the accredited environmental assessment process for the controlled action decision under the EPBC Act in accordance with the bilateral agreement between the Commonwealth and Victorian governments.

Overview

Viva Energy Gas Australia Pty Ltd (Viva Energy) is planning to develop a gas terminal using a ship known as a floating storage and regasification unit (FSRU), which would be continuously moored at Refinery Pier in Corio Bay, Geelong. The key objective of the project is to facilitate supply of a new source of gas for the south-east Australian gas market where there is a projected supply shortfall in coming years.

The FSRU would store liquefied natural gas (LNG) received from visiting LNG carriers (that would moor directly adjacent to the FSRU), and regasify the LNG as required to meet industrial, commercial, and residential customer demand. A 7 km gas transmission pipeline would transfer the gas from the FSRU to the Victorian Transmission System (VTS) at Lara.

The gas terminal would be located adjacent to, and on, Viva Energy's Geelong Refinery in a heavily industrialised setting and would benefit from Viva Energy's experience and capability as an existing Major Hazard Facility (MHF) operator and potential synergies between the two facilities such as reuse of the FSRU seawater discharge within the refinery operations.

Existing conditions

Underwater acoustic monitoring was conducted in Corio Bay for a period of 37 days (Wilson and McPherson 2021) to characterise the ambient acoustic environment. Data were collected continuously over the frequency band of 10–32000 Hz, and thus captured the majority of anthropogenic contributions to the underwater sound field in the area, along with natural and biological contributors. These data document the baseline underwater sound conditions in Corio Bay and allow examination of temporal variations, and to correlate with external factors that change sound levels such as weather and other human activities.

The most substantial contribution to the soundscape in Corio Bay is from vessel noise occupying frequency bands below approximately 1000 Hz, with many distinct tones related to vessel propulsion observed in the 30-200 Hz range; these signals are present for a significant amount of time per day for the entire monitoring period.

The soundscape also includes a faint dusk and dawn invertebrate chorus, with the primary contributor likely being snapping shrimp.

The monitoring results demonstrate that when compared to long term recordings of other Australian harbours, such as Fremantle Inner Harbour (Salgado Kent et al. 2012), Corio Bay has higher median sound levels, and has a soundscape primarily defined by anthropogenic contributors, with shipping being the dominant factor.

Methodology

The marine fauna that could be exposed to underwater noise from project-related activities in Corio Bay comprises all taxonomic groups, from invertebrates to marine mammals and also includes birds. Several species permanently or potentially occurring in the project area are listed under the EPBC Act or the Flora and Fauna Guarantee Act 1988 (FFG Act), however, the study found that these species would not be significantly impacted as a result of the project. Potential noise-induced effects on marine fauna can range from increased stress, behavioural responses, and acoustic masking to hearing impairment or non-auditory injuries and therefore it is important to understand the predicted underwater noise emissions from the project to determine potential effects. There are substantial differences in sensitivity to underwater sound and ecological relevance of the potential impacts between species groups. The potential impacts are assessed in this report based on the already existing (ambient) noise as well as the modelled noise environment created by the project activities. In general, there is a widespread lack of quantitative information on noise-induced impacts on marine fauna. Where possible, relevant noise exposure criteria are used to determine the exceedance of these criteria by the construction activities and future operation of the FSRU and to quantify the impact ranges for each species group.

Impact of construction activities and future operations

Noise monitoring conducted as part of this study indicates that the existing ambient noise level in the project area is high and adding another noise source such as project related activities including dredging, pile driving and operation of the FSRU, would lead to a localised increase in levels in the vicinity of the project area and for the duration of these activities.

In an unmitigated ‘worst-case’ scenario, the most significant impacts to be expected are temporary behavioural responses over a range of several hundred meters for most species (fish and marine mammals) and for diving birds (when submerged) up to several kilometres from the project area. The impact ranges presented in this assessment indicate the onset of behavioural responses which are likely of little or no ecological relevance at their lowest level of severity and only become more severe and relevant the closer the animals are to the sound source(s). It can be expected that at received levels above the threshold, animals would react by subtly altering their behaviour. At higher received levels, i.e., closer to the sound source, where noise levels are generally higher, it is likely that animals would abandon current behaviour. Ultimately, at the highest received levels animals would avoid the area for the duration of the sound-producing activity. The potential avoidance zones are comparatively small relative to the overall habitat of the marine mammals, birds and fishes and being excluded from these areas is not likely to have any ecologically significant consequences for the animals. It is likely that the animals would gradually return into the area after the noise emissions have ceased or abated.

Pile driving during construction represents the most significant anthropogenic change to the existing soundscape in Corio Bay due to the impulsiveness of the signals, as compared to the ambient noise which is dominated by continuous noise. Dolphins and fur seals are expected to respond behaviourally to pile driving noise over a range of up to 800 m and diving birds (when submerged) over more than five kilometres for the duration of the activity. Pile driving noise is expected to exceed the noise exposure thresholds for recoverable injury for fishes at a distance of up to 60 m and the threshold for onset of Temporary Threshold Shift (TTS) at a distance of up to 870 m from the sound source. While temporary behavioural responses for most fish species are likely in the range of 10–100 m, there is a moderate likelihood that Australian anchovy, the only fish species in the project area with high sensitivity to underwater sound, would show responses at ranges exceeding 1 km.

Dredging, and vessel movement, during construction generates continuous sounds similar in their acoustic characteristics to the already existing ambient sound field. The noise generated by these activities is likely to temporarily exceed the onset threshold for behavioural responses of dolphins and fur seals at ranges of up to 1.84 km. There is a moderate likelihood that fish species in the project area would be temporarily exposed to noise levels generated by these activities exceeding their threshold for onset of behavioural responses at ranges up to 100 m.

Operating the FSRU would also generate continuous sound similar in its acoustic characteristic to the existing ambient soundscape. The noise generated by this activity is likely to exceed the onset threshold for behavioural responses of dolphins and fur seals at ranges within 1.1 km. There is a moderate likelihood that fish species in the project area would be temporarily exposed to noise levels generated by these activities exceeding their threshold for onset of behavioural responses at ranges up to 100 m.

More severe effects are not likely to occur. Stress and acoustic masking, while not quantifiable per se, can be assumed to occur at the same ranges as (ecologically relevant) behavioural responses. Applying recommended mitigation measures has the potential to avoid, minimise and manage potential impacts related to underwater noise and this is discussed below.

Residual impacts

Applying mitigation measures has the potential of reducing the noise levels emitted by the construction activities and future operation and lead to reducing the severity and range of the noise-induced impacts. The level of noise reduction is specific to each measure but not every measure can or should be applied to every activity; rather a differentiated approach is necessary, accounting for the proportionality principle. The potential noise-induced impacts for marine fauna arising from the planned project activities are not considered severe. However, a well-designed mitigation concept, such as reducing noise at the source, deterring animals from the construction area and noise awareness training, would reduce or even eliminate the risk of behavioural responses with the exception of the immediate vicinity of the activities. Due to the high existing acoustic conditions in the area, it is very likely that the animals are already accustomed (habituated) to living in a noisy environment and those individuals more sensitive to noise have long left the area.

The most efficient methods to mitigate the noise exposure for marine mammals and diving birds is implementing and enforcing a safety zone around sound sources and constant visual monitoring of the surrounding area during noise-critical activities. Moreover, a soft start of the pile driving activities and the spatially and temporally limited use of acoustic deterrent devices prior to commencing the pile driving would reduce the likelihood of strong behavioural responses of listed species such as dolphins or penguins.

With a reasonable (proportional) set of mitigation measures implemented, the underwater noise emissions generated by the construction and operation of the FSRU are not expected to have unacceptable impacts on the marine fauna in Corio Bay.

Decommissioning

It is anticipated that the FSRU would leave Corio Bay after the end of the project and that the infrastructure would be retained. While decommissioning activities may be subject to change and subject to legislative requirements at the time, it is assumed that no additional underwater noise would be emitted during the decommissioning phase and underwater noise would return to levels similar to those measured prior to its construction once the decommissioning phase is completed.

Population level effects

There is no information available about abundance or densities of marine organisms in the project area as compared to Port Phillip Bay which makes it difficult to assess the potential population effects. Based on the relatively small acoustic and impact footprint of the activities it is justifiable to assume that, especially in a mitigated scenario, the ecological effects would be restricted to individuals and would not affect populations negatively.

1. Introduction

This technical report provides an underwater noise impact assessment conducted to support the Environment Effects Statement (EES) for the Viva Energy Gas Terminal Project (the project).

Viva Energy Gas Australia Pty Ltd (Viva Energy) is planning to develop a gas terminal using a ship known as a floating storage and regasification unit (FSRU), which would be continuously moored at Refinery Pier in Corio Bay, Geelong. The key objective of the project is to facilitate supply of a new source of gas for the south-east Australian gas market where there is a projected supply shortfall in coming years.

The FSRU would store liquefied natural gas (LNG) received from visiting LNG carriers (that would moor directly adjacent to the FSRU) and would convert LNG back into a gaseous state by heating the LNG using seawater (a process known as regasification) as required to meet industrial, commercial, and residential customer demand. A 7 km gas transmission pipeline would transfer the gas from the FSRU to the Victorian Transmission System (VTS) at Lara.

The project would be situated adjacent to, and on, Viva Energy's Geelong Refinery, within a heavily developed port and industrial area on the western shores of Corio Bay between the Geelong suburbs of Corio and North Shore. Co-locating the project with the existing Geelong Refinery and within the Port of Geelong offers significant opportunity to minimise potential environmental effects and utilise several attributes that come with the port and industrial setting.

In December 2020, the Victorian Minister for Planning determined that the project requires assessment through an EES under the *Environment Effects Act 1978* (Vic). The reasons for the decision were primarily related to the potential for significant adverse effects on the marine environment of Corio Bay and the potential for contributing to greenhouse gas emissions. Secondarily, the EES was required to assess the effects of the project on air quality, noise, land use, Aboriginal and historic heritage, native vegetation, groundwater, traffic, and transport as well as visual amenity.

In January 2021, the project was also determined to require assessment and approval under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) due to the potential for the project to have a significant impact on wetlands of international importance, listed threatened species and communities, and listed migratory species. The EES process is the accredited environmental assessment process for the controlled action decision under the EPBC Act in accordance with the bilateral agreement between the Commonwealth and Victorian governments.

1.1. Purpose

This underwater noise impact assessment identifies, assesses, and characterises potential environmental impacts on underwater noise associated with the construction, operation, and eventual decommissioning of the project to inform the preparation of the EES required for the project.
The report identifies and recommends mitigation measures to avoid, minimise and manage potential impacts which will inform the development of an Environmental Management Framework (EMF) for the project. The mitigation measures listed in the EMF would be implemented in the approvals and management plans for the project.

1.2. Why Understanding Underwater Noise is Important

Underwater noise has the potential to affect a wide range of marine fauna receptors. Potential noise-induced effects on marine fauna can range from increased stress, behavioural responses, and acoustic masking to hearing impairment or non-auditory injuries and therefore it is important to understand the predicted underwater noise emissions from the project to determine potential effects

Marine fauna uses sound for important life functions such as communication, locating prey and navigation. The hearing systems of some taxa such as cetaceans and pinnipeds are highly adapted and sensitive to perceiving underwater sound but also very susceptible to noise-induced impacts.

While increased airborne noise from existing shore based or nearshore boating activities (not related to the project) has already been identified as risk to waterbirds in the Ramsar site (DELWP 2020), underwater noise has not been considered so far for any marine fauna species. The potential for underwater noise to impact an animal (the 'receiver') depends on the occurrence of the receiver in the project area, the temporal and spectral characteristics of the emitted sound, the distance and sound propagation environment between the source and the receiver, and the sensitivity of the receiver to sound.

An introduction to the specific terminology used in describing underwater sound (underwater 'noise' being the unwanted part of underwater 'sound') is provided in Section 4.2 and Supplement A information. This provides important background information for non-experts to understand the technical terms and specific considerations related to measuring and assessing underwater noise and its impacts. Moreover, a definition of many acoustic terms can be found in the Glossary and the acoustic metrics are explained in greater detail in Section 3.2.1.

1.3. Project Area

The project would be located at, and adjacent to, the Geelong Refinery and Refinery Pier in the City of Greater Geelong, 75 kilometres (km) south-west of Melbourne. The project area is within a heavily developed port and industrial area on the western shores of Corio Bay between the Geelong suburbs of Corio and North Shore. The Geelong central business district is located approximately 7 km south of the project.

Corio Bay is the largest bay in the south-west corner of Port Phillip Bay and is a sheltered, shallow basin at the western end of the Geelong Arm, with an area of 44 square kilometres (km^2). The Point Wilson/Limeburners Bay section of the Port Phillip Bay (Western Shoreline) and Bellarine Peninsula Ramsar site is located along the northern shoreline of Corio Bay, approximately one kilometre to the north-east of the project.

The Port of Geelong has been in operation for over 150 years and is the largest industrial bulk cargo port in Victoria, attracting over 600 ship visits and handling more than 14 million tonnes of product annually. Geelong's shipping channels extend 18 nautical miles through Corio Bay from Point Richards through to Refinery Pier. Ports Victoria (formerly the Victoria Regional Channels Authority (VRCA)) manages commercial navigation in the port waters in and around Geelong and is responsible for the safe and efficient movement of shipping, and for maintaining shipping channels and navigation aids. The channels are man-made having been deepened and widened through periodic dredging to support port trade development.

Refinery Pier is the primary location within the Port of Geelong for movement of bulk liquids. Vessels up to 265 metres in length currently utilise the four berths at Refinery Pier which service Viva Energy refinery operations. Most ship visits to the port are to Refinery Pier, with Viva Energy accounting for over half of the trade through the Port of Geelong.

The Geelong Refinery has been operating since 1954 with both the refinery and the co-located Lyondell Bassell plant being licensed Major Hazard Facilities (MHFs). A range of industrial activities are situated in the Port environs including wood fibre processing and chemical, fertiliser and cement manufacturing.

To the north of the Geelong Refinery, along the proposed underground pipeline corridor, the area is predominantly rural. There are several other existing Viva Energy-owned underground pipelines running between the refinery and the connection point to the South West Pipeline (SWP) at Lara. The proposed pipeline route follows already disturbed pipeline corridors, where possible, through a mix of land uses.

The project area is shown in Figure 1.

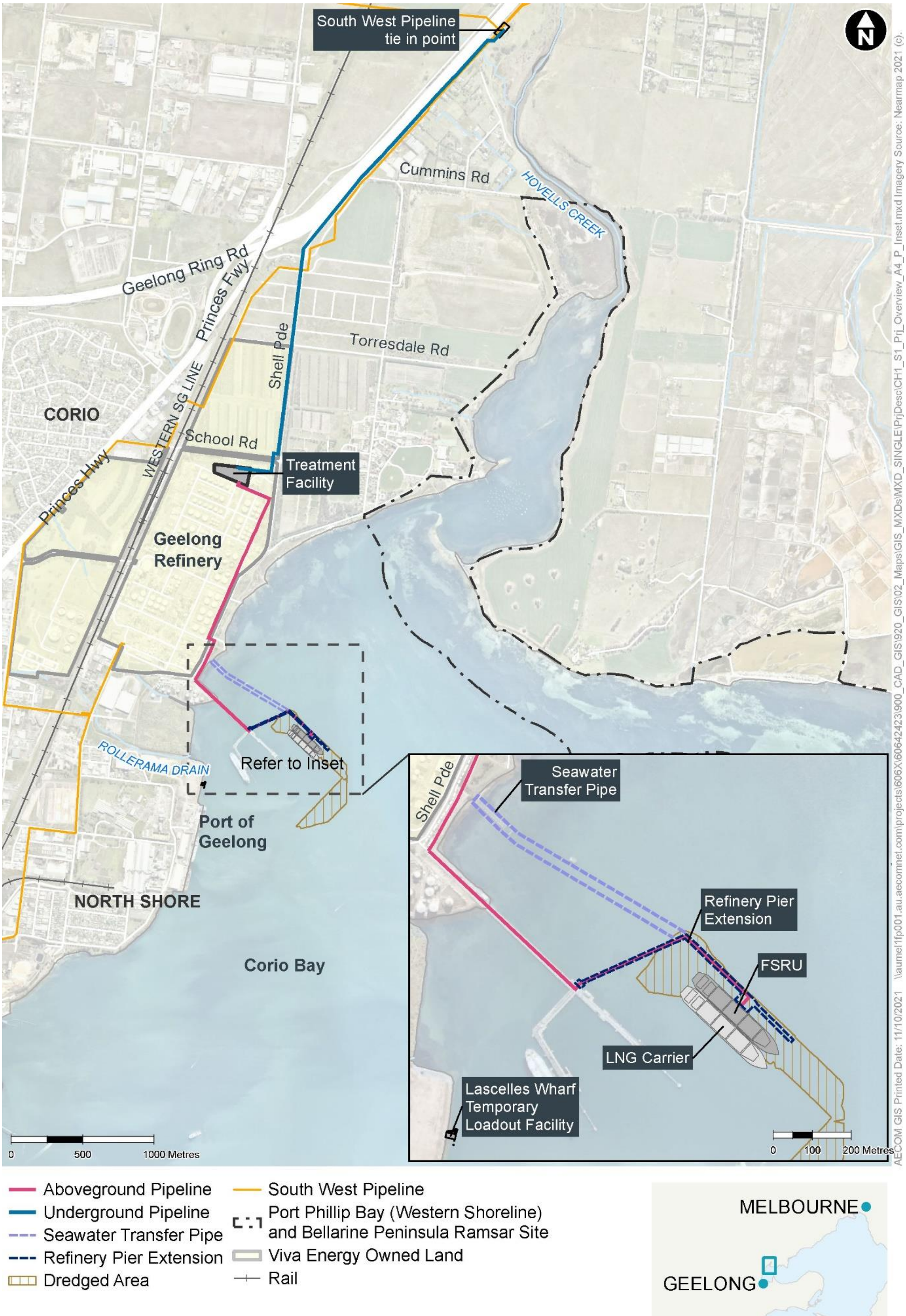


Figure 1. Project overview.

1.4. Project Description

This section summarises the project as described in Chapter 4 *Project description*. Key components of the project include:

- Extension of the existing Refinery Pier with an approximately 570 metre (m) long angled pier arm, new berth and ancillary pier infrastructure including high pressure gas marine loading arms (MLAs) and transfer lines connecting the seawater discharge points on the FSRU to the refinery seawater intake
- Continuous mooring of an FSRU at the new Refinery Pier berth to store and convert LNG into natural gas. LNG carriers would moor alongside the FSRU and unload the LNG
- Construction and operation of approximately 3 km of aboveground gas pipeline on the pier and within the refinery site connecting the FSRU to the new treatment facility
- Construction and operation of a treatment facility on refinery premises including injection of nitrogen and odorant (if required)
- Construction and operation of an underground gas transmission pipeline, approximately 4 km in length, connecting to the SWP at Lara.

The Refinery Pier extension would be located to the north-east of Refinery Pier No. 1. The new pier arm would be positioned to allow for sufficient clearance between an LNG carrier berthed alongside the FSRU and a vessel berthed at the existing Refinery Pier berth No. 1. Dredging of approximately 490,000 cubic metres of seabed sediment would be required to allow for the new berth pocket and swing basin.

The FSRU vessel would be up to 300 m in length and 50 m in breadth, with the capacity to store approximately 170,000 cubic metres (m^3) of LNG. The FSRU would receive LNG from visiting LNG carriers and store it onboard in cryogenic storage tanks at about -160 °C.

The FSRU would receive up to 140 PJ per annum (approximately 45 LNG carriers) depending on demand. The number of LNG carriers would also depend on their storage capacity, which could vary from 140,000 to 170,000 m^3.

When gas is needed, the FSRU would convert the LNG back into a gaseous state by heating the LNG using seawater (a process known as regasification). The natural gas would then be transferred through the aboveground pipeline from the FSRU to the treatment facility where odorant and nitrogen would be added, where required, to meet Victorian Transmission System (VTS) gas quality specifications. Nitrogen injection would occur when any given gas cargo needs to be adjusted (diluted) to meet local specifications. Odorant is added as a safety requirement so that the normally odourless gas can be smelt when in use. From the treatment facility, the underground section of the pipeline would transfer the natural gas to the tie-in point to the SWP at Lara.

1.4.1. Key Construction Activities

Construction of the project would occur over a period of 18 to 24 months. The key construction activities relate to:

- Localised dredging of seabed sediments to enable the FSRU and LNG carriers to berth at Refinery Pier and excavation of a shallow trench for the seawater transfer pipe.
- Construction of the new pier arm and berthing infrastructure, and aboveground pipeline along Refinery Pier and through the refinery.
- Construction of the treatment facility on a laydown area at the northern boundary of the refinery site.

- Construction of the buried pipeline.
- Construction at the tie-in point to the SWP at Lara.

There are no construction activities required for the FSRU component of the project. The vessel would be built, commissioned and all production and safety systems verified prior to being brought to site.

An estimated 490,000 cubic metres (m^3) of dredging would be required over an area of approximately 12 hectares (ha) adjacent to the existing shipping channel to provide sufficient water depth at the new berth and within the swing basin for visiting LNG carriers to turn. Dredging within the new berth would be undertaken to a depth of 13.1 metres and the swing basin would be dredged to a depth of 12.7 metres. The dredging footprint is shown in Figure 1. It is planned to deposit the dredged material within Ports Victoria's existing dredged material ground (DMG) in Port Phillip Bay to the east of Point Wilson, approximately 26 km from Refinery Pier.

Construction of the pier arm would be carried out once dredging was complete, primarily from the water using barge-mounted cranes. Steel piles would be driven into the seabed by cranes mounted on floating barges and pre-cast concrete and prefabricated steel components would be transported to site by barge and lifted into position. The installation of pier infrastructure such as the marine loading arms (MLAs), piping from the FSRU to the existing refinery seawater intake (SWI) and aboveground pipeline would also be undertaken from the water using barge-mounted cranes and construction support boats.

Installation of the 3 km above ground pipeline along the pier and through the refinery is anticipated to take 3.5 months to complete. The above ground pipeline would run along the pier to the existing pipe track east of Shell Parade within the pier foreshore compound. It would then pass through a road under-crossing to the existing refinery pipe track. The pipeline would then run north along the existing refinery pipe track to an existing laydown area where the treatment facility would be located.

The treatment facility would be located within an existing laydown area in the refinery site and cover an area of approximately 80m x 120m. Construction of the treatment facility would take approximately 6 months and would be undertaken by specialist crews across distinct phases of work. These would include initial earthworks and civil construction, mechanical installation and electrical and instrumentation works.

The 4 km underground pipeline would be installed in stages over an approximate four-month period within a corridor which has been selected to avoid the need for trenchless construction beneath watercourses or other environmental sensitivities. Firstly, a construction right of way (ROW) would be established, clearly identified, and fenced off where required. Typically, this would be between 15 and 20m wide, and minimised where possible to reduce disturbance. Once the construction ROW is established, vegetation would be removed, and a trench excavated to a maximum depth of 2m and a maximum width of 1m for the pipeline to be placed. Following the placement of the pipeline, the construction ROW would be rehabilitated to its pre-existing condition as far as practicable.

Trenchless construction (including thrust boring or horizontal directional drilling (HDD)) would be used to install the underground pipeline in areas that are not suited to open trenching techniques, such as at intersections with major roads. Trenchless construction would involve boring or drilling a hole beneath the ground surface at a shallow angle and then pushing or pulling a welded length of pipe through the hole without disturbing the surface. It is anticipated that the maximum depth of the trenchless section would be 25 m.

Construction at the tie-in point to the SWP at Lara would be undertaken by specialist crews across the distinct phases of works, as with the treatment facility.

1.4.2. Key Operation Activities

The project is expected to be in operation for 20 years. Key activities relating to project operation include:

- Receipt of up to 45 LNG carriers each year at Refinery Pier – the number and frequency of LNG carriers arriving each year would depend on their storage capacity and gas demand.
- Regasification of LNG onboard the FSRU using seawater as a heat source, which would then be reused within the refinery as cooling water.
- Injection of nitrogen and odorant into the gas prior to distribution via the VTS.
- Monitoring and maintenance of the pipeline easement.

1.4.3. Key Decommissioning Activities

The FSRU, which continues to be an ocean-going vessel throughout the operation of the project, would leave Corio Bay on completion of the project life to be used elsewhere.

It is anticipated that the Refinery Pier berth and facilities would be retained for other port related uses. The underground pipeline would likely remain in situ subject to landholder agreements and either decommissioned completely or placed into care and maintenance arrangements.

Decommissioning activities may be subject to change, subject to legislative requirements at the time and potential repurposing of the infrastructure at the end of the project.

1.4.4. Project Activities Relevant to the Assessment

The following construction and operational activities are relevant to the underwater noise impact assessment:

- localised dredging of seabed sediments to enable the FSRU and LNG carriers to berth at Refinery Pier and excavation of seabed sediments for installation of the seawater transfer pipe
- construction of a temporary loadout facility at Lascelles Wharf to enable construction overwater to occur and construction of the new pier arm and berthing infrastructure

The operation activities relevant to the underwater noise impact assessment relate to the continuous mooring of the FSRU and receipt of up to 45 LNG carriers each year at the pier.

The decommissioning activities relevant to the underwater noise impact assessment include the departure (i.e., removal) of the FSRU.

2. Scoping Requirements

The scoping requirements for the EES set out the specific environmental matters to be investigated in the EES. The scoping requirements include a set of draft evaluation objectives. These objectives identify the desired outcomes to be achieved in managing the potential impacts of constructing and operating the project.

The following evaluation objective is relevant to the underwater noise impact assessment:

- **Water and catchment values** – To minimise adverse effects on water (in particular wetland, estuarine, intertidal, and marine) quality and movement, and to the ecological character of the Port Phillip Bay (Western Shoreline) and Bellarine Peninsula Ramsar site.

The scoping requirements of relevance to this underwater noise impact assessment and where they are addressed in the report are shown in Table 1.

Table 1. Scoping requirements relevant to underwater noise.

Aspect	Scoping requirement	Section addressed
Key issues	Noise-induced effects on marine fauna and birds	3.2
Existing environment	Industrial and recreational activities in the project area producing an already disturbed soundscape	5
Likely effects	Adverse effects on relevant behaviours, life functions and health or marine fauna and exclusion from important habitats	6 and 7
Mitigation measures	Various noise abatement measures that can be implemented to reduce or avoid underwater noise and mitigate its effects	9
Performance objectives	Reduction of underwater noise generated by the project activities to acceptable levels	**Error! Reference source not found.**

3. Legislation, Policy, and Guidelines

3.1. Key Environmental Legislation

Table 2 summarises the key environmental legislation and policy that apply to the project in the context of this underwater noise impact assessment, as well as the implications for the project and the required approvals (if any). Additional guidelines and technical criteria relevant to underwater noise are described in Section 3.2.

Table 2. Primary environmental legislation and associated information

Legislation/policy	Description	Implications for the project	Approval required
Commonwealth			
Legislation			
Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act)	The EPBC Act identifies Matters of National Environmental Significance (MNES) that need to be protected.	EES process conducted to assess potential impacts on MNES listed under EPBC Act	Decision by Commonwealth Minister or delegate
Victoria			
Legislation			
Victorian Fauna and Flora Guarantee Act 1988 / Flora and Fauna Guarantee Amendment Act 2019	This Act identifies threatened species and communities and processes that require management to minimise threats to those species and communities.	EES process conducted to assess potential impacts	
Policy			
Department of Environment, Land, Water and Planning 2018 Port Phillip Bay (Western Shoreline) and Bellarine Peninsula Ramsar Site Management Plan	Port Phillip Bay (Western Shoreline) and Bellarine Peninsula Ramsar site is a wetland of international importance and is identified as a MNES under the EPBC Act. The site management plan identifies priority threats to be addressed.	EES process conducted to assess potential impacts	

3.2. Noise Impacts and Exposure Thresholds

The most extensive research on the effects of noise has been conducted on humans where noise has been shown to have cardiovascular, endocrinological, neurological and auditory effects (Basner et al. 2014). Among marine fauna, marine mammals have received most scientific attention regarding potential auditory effects of underwater noise, while studies on other noise effects (stress, acoustic masking) and for marine taxa or birds are scarce. In general, underwater noise can impact marine fauna in six principal ways:

- Inducing stress, which can be acute or chronic and affect health and behaviour.
- Masking or interfering with other biologically important sounds (including vocal communication, echolocation, signals, and sounds produced by predators or prey).
- Causing disturbance that leads to behavioural changes or displacement of fauna. The occurrence and intensity of disturbance is highly variable and depends on a range of factors relating to the animal and situation.

- Causing injury to hearing or other organs. Hearing loss may manifest as temporary threshold shift (TTS) or permanent threshold shift (PTS).
- Causing mortality and mortal injury, that is, immediate or delayed death either due to injury or substantially reduced fitness.
- Causing cumulative or chronic effects, whereby repeated or long-term exposure to noise leads to additive severity of noise-induced impacts.

The disparity that exists in empirical information on noise-induced effects for different taxa and in the understanding of different source-effect relationships is also reflected in the availability and level of detail provided in regulatory guidance on exposure of marine fauna to underwater noise.
Ideally, noise exposure criteria should consider the auditory susceptibility of the receiving animals to different types of noise in terms of physiological, behavioural, and physical impacts. Detailed noise exposure criteria, including thresholds and frequency weighting functions, aimed at reducing the risk of hearing impairment have been promulgated for marine mammals and, to some extent, for fishes. None exist for marine invertebrates or birds.

3.2.1. Acoustic Metrics

The publication of ISO 18405 Underwater Acoustics – Terminology (ISO 2017) provides a dictionary of underwater bioacoustics terms that builds and expands on previous standards (IEC 1994, ANSI/ASA S1.1-2013).The present document follows the definitions and conventions of ISO (2017), unless directly referring to definitions of metrics used in published literature.

The US National Marine Fisheries Service (NMFS) issued a Technical Guidance document providing regulatory criteria for noise exposure of marine mammals (NMFS 2018). The Technical Guidance uses a slightly different notation for the acoustic metrics (Table 3) with a dual criterion for assessing injurious exposures, including a peak (unweighted/flat) sound pressure level metric PK (L_{pk}) and a cumulative sound exposure level SEL_{cum} metric with frequency weighting. The acoustic metric terminology used in Southall et al. (2019) is equivalent to this guidance. Following the ISO standard, the L_{pk} as used by NMFS and Southall et al. (2019) is denoted as PK in impact assessment. The SEL_{cum} metric as used by NMFS and Southall et al. (2019) describes the sound energy received by a receptor over 24 h. Following the ISO (2017) standard, this is denoted as SEL_{24h} in this impact assessment.

Table 3. Acoustic metrics used in this impact assessment as compared to other publications.

Metric	NMFS (2018) and Southall et al. (2019)	Impact assessment (as per ISO 2017)		Unit
		Abbreviation in main text	Symbol in equations/tables	
Sound pressure level	Not applicable	SPL	L_p	decibel (dB) re 1 micropascal (μPa)
Peak sound pressure level	PK	PK	L_{pk}	dB re 1 μPa
Sound exposure level (per pulse)	Not applicable	Per-pulse SEL	L_E	dB re 1 μPa²·s
Sound exposure level (accumulated over time), SEL time-period	SELcum	SEL24h	$L_{E,24h}$	dB re 1 μPa²·s
Source level	SL	SL	$L_{S,pk}$ $L_{S,p}$ $L_{S,E}$	dB re 1 μPa·m (peak source pressure level, SPL source level) or dB 1 μPa²m²s (per-pulse source SEL)

3.2.2. Marine Mammals

Stress and Acoustic Masking

To date, there are no exposure criteria for the onset of stress or acoustic masking in marine mammals. Due to the limited information about acoustically induced stress responses in marine fauna, a precautionary approach would be to assume that any physical effect (e.g., hearing loss, hearing impairment) or significant behavioural response is also associated with a stress response.

Behavioural responses

Because of the complexity and variability of marine mammal behavioural responses to acoustic exposure, few countries have developed and implemented thresholds for the noise-induced onset of behavioural reactions. The Australian regulation of underwater noise exposure to marine fauna is non-prescriptive and, accordingly, no behavioural thresholds are promulgated. Instead, the current US National Marine Fisheries Service (NMFS) noise criteria for impulsive and non-impulsive sounds (NOAA 2019) were selected for this assessment because they represent the most commonly applied behavioural response criteria by regulators for impulsive sound sources (such as impact pile driving) and non-impulsive sound sources (such as vessels). The distances at which behavioural responses could occur were therefore determined from the areas ensonified above an unweighted SPL of 120 dB re 1 µPa for non-impulsive sounds and 160 dB re 1 µPa for impulsive sounds (NOAA 2019).

These behavioural criteria, however, are conservative estimates. Moreover, they vary between functional hearing groups and species due to differences in hearing sensitivity and they will vary with the behavioural context (see details in Section 4.4.2).

There are data for marine mammals that indicate the received sound levels at which TTS occurs, so the onset of PTS is extrapolated from the TTS onset level and an assumed growth function (Southall et al. 2007, NMFS 2018, Southall et al. 2019). US NMFS issued a Technical Guidance document that provides acoustic thresholds for the onset of TTS and PTS in marine mammal hearings for all sound sources (NMFS 2018). NMFS also provided guidance on the use of weighting functions when applying hearing impairment criteria (see Section 3.2). The NMFS Guidance recommends applying a dual criterion for assessing injurious exposures, including an unweighted (flat) peak sound pressure level metric peak sound pressure (PK; L_{pk}) levels and a sound exposure level SELcum ($L_{E,24\text{h}}$) metric with frequency weighting. Both acoustic criteria and weighting function application are different for the marine mammal functional hearing groups and types of noise. Southall et al. (2019) published an updated set of criteria for onset of TTS and PTS in marine mammals. While the proposed thresholds and weighting functions for exposure to underwater sound do not differ in effect from those promulgated by NMFS (2018), the authors propose a new nomenclature and classification for the marine mammal functional hearing groups[1] based on the most recent information about hearing sensitivity in marine mammal species. As this represents the most up-to-date information, this impact assessment follows the criteria and nomenclature proposed by Southall et al. (2019). These criteria incorporate also the best available science to estimate PTS onset in marine mammals from either sound energy accumulated over 24 h (SEL), or very loud, instantaneous PK levels. These dual threshold criteria of SEL and PK are used to calculate marine mammal exposures (Table 4).

[1] The new nomenclature for functional marine mammals hearing groups proposed by Southall et al. (2019) has not yet been adopted by NMFS.

Table 4. Summary of relevant permanent threshold shift (PTS) and temporary threshold shift (TTS) onset acoustic thresholds (Southall et al. 2019).

Hearing group	PTS onset thresholds[1] (received level)		TTS onset thresholds[1] (received level)	
	Impulsive	Non-impulsive	Impulsive	Non-impulsive
Low-frequency (LF) cetaceans	$L_{pk,\,flat}$: 219 dB $L_{E,\,LF,\,24h}$: 183 dB	$L_{E,\,LF,\,24h}$: 199 dB	L_{pk}: 213 dB $L_{E,\,LF}$: 168 dB	$L_{E,\,LF}$: 179 dB
High-frequency (HF) cetaceans	$L_{pk,\,flat}$: 230 dB $L_{E,\,HF}$, 24h: 185 dB	$L_{E,\,HF,\,24h}$: 198 dB	L_{pk}: 224 dB L_{E}, HF: 170 dB	$L_{E,\,HF}$: 178 dB
Very High-frequency (VHF) cetaceans	$L_{pk,\,flat}$: 202 dB $L_{E,\,VHF,\,24h}$: 155 dB	$L_{E,\,VHF,\,24h}$: 173 dB	L_{pk}: 196 dB $L_{E,\,VHF}$: 140 dB	$L_{E,\,VHF}$: 153 dB
Phocid Marine Carnivores (water) (PCW)	$L_{pk,\,flat}$: 218 dB $L_{E,PCW,\,24h}$: 185 dB	$L_{E,\,PCW,\,24h}$: 201 dB	L_{pk}: 212 dB $L_{E,\,PCW}$: 170 dB	$L_{E,\,PCW}$: 181 dB
Other Marine Carnivores (water) (OCW)	$L_{pk,\,flat}$: 232 dB $L_{E,\,OCW,\,24h}$: 203 dB	$L_{E,\,OCW,\,24h}$: 219 dB	L_{pk}: 226 dB $L_{E,\,OCW}$: 188 dB	$L_{E,\,OCW}$: 199 dB

[1] 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_{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 µPa^2·s. The subscript associated with cumulative sound exposure level thresholds indicates the designated marine mammal auditory weighting.

3.2.3. Fishes

The US Working Group on the Effects of Sound on Fish and Turtles developed guidelines with specific thresholds for different levels of effects for several species groups (Popper et al. 2014). The guidelines define quantitative thresholds for three types of immediate effects:

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

Tables 5 and 6 lists the relevant effects thresholds from Popper et al. (2014) for pile driving and vessel noise. Some evidence suggests that fish species 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 fishes with a swim bladder involved in hearing.

The noise impact criteria for marine mammals (Section 3.2.2) and the criteria proposed by Popper et al. (2014) are, in fact, the only sets of criteria regulating the potential of underwater noise to cause hearing impairment (TTS or PTS) for any marine faunal group.

Table 5. Noise exposure criteria for pile driving noise exposure for fishes, fish eggs and larvae, adapted from Popper et al. (2014).

Category and type of animal	Mortality and Potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
I. Fish: No swim bladder[1] (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	(N) High (I) Moderate (F) Low
II. 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	(N) High (I) Moderate (F) Low
III. Fish: Swim bladder involved in hearing[2] (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	(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	(N) Moderate (I, F) Low

SPL, Sound pressure level dB re 1 µPa.

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

[1] The swim bladder is missing in some bottom-dwelling and deep-sea bony fishes (teleosts) and in all cartilaginous fishes (sharks, skates, and rays).

[2] The group includes some of the squirrelfish (Holocentridae), drums and croakers (Sciaenidae), herrings (Clupeidae), and the large group of Otophysan fishes (a non-taxonomic) group consisting of four distinct orders: Cypriniformes (minnows), Characiformes (characins), Siluriformes (catfish) and Gymnotiformes (knifefish).

Table 6. Noise exposure criteria for vessel noise exposure for fishes, fish eggs and larvae, adapted from Popper et al. (2014).

Category and type of animal	Mortality and Potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
I. Fish: No swim bladder[1] (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
II. 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
III. Fish: Swim bladder involved in hearing[2] (primarily pressure detection)	(N) Low (I) Low (F) Low	170 dB SPL for 48 h	158 dB SPL for 12 h	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Fish eggs and fish larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

SPL, Sound pressure level dB re 1 µPa.

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

[1] The swim bladder is missing in some bottom-dwelling and deep-sea bony fishes (teleosts) and in all cartilaginous fishes (sharks, skates, and rays).

[2] Group includes some of the squirrelfish (Holocentridae), drums and croakers (Sciaenidae), herrings (Clupeidae), and the large group of Otophysan fishes (a non-taxonomic) group consisting of four distinct orders: Cypriniformes (minnows), Characiformes (characins), Siluriformes (catfish) and Gymnotiformes (knifefish).

3.2.4. Invertebrates

There is no regulatory guidance with respect to setting criteria for particle motion impact. Few particle motion measurements have been collected in conditions typically encountered in monitoring situations. This is due in part to limitations in the available instrumentation and a general lack of experience in recording this quantity.

3.2.5. Avifauna

There are no regulatory thresholds or criteria established in Australia or anywhere else in the world to assess potential behavioural responses by diving birds (penguins, flying seabirds, swans) to underwater noise. While the main bird species of concern in the EES are migratory waders and other waterbirds, particularly in the Ramsar wetland which is approximately 1.3 km from the FSRU and construction activity, these species are not expected to be impacted by underwater noise. Noise impacts can only occur if an animal's body is fully submerged in the water or, if at least partially immersed in the water, impacts are only possible if the body parts contain pressure sensitive organs such as ears or lungs; the waders' beaks or legs which are immersed in the water are not known to be sensitive to underwater sound. Moreover, sound propagation is substantially reduced in shallow water and near the surface and sound generated by the FSRU and construction activities is not expected to be transmitted into near-shore very shallow areas at relevant levels; accordingly, the focus in the study being on diving birds.

In a controlled exposure experiment, Sørensen et al. (2020) exposed gentoo penguins (*Pygoscelis papua*) to underwater noise bursts (impulsive signals), and the animals showed a graded reaction depending on received sound levels. The researchers conducted this study on captive animals, and results may not be a true representation of the behavioural responses in free-ranging animals. Pichegru et al. (2017) investigated the behavioural response of African penguins (*Spheniscus demersus*) to seismic surveys within 100 km of their colony in South Africa. Penguins showed a strong avoidance of their preferred foraging areas during seismic activities; foraging took place significantly farther from the survey vessel when in operation, increasing the overall foraging effort and energy expenditure. The birds reverted to normal behaviour when the operation ceased. While Pichegru et al. (2017) did not provide quantitative information on the noise levels corresponding to the observed behavioural responses, their study on wild animals corroborates the finding by Sørensen et al. (2020) which indicates a high susceptibility of penguins to noise-induced behavioural responses. Therefore, to enable assessing the potential for noise impacts, an onset criterion for behavioural responses of penguins and flying seabirds of 120 dB re 1 µPa (SPL) for impulsive sources was chosen based on information from Sørensen et al. (2020).

There is also insufficient information available to determine the onset thresholds of behavioural responses of diving birds from non-impulsive noise. In the absence of relevant information, the behavioural noise exposure criterion for impulsive noise is applied.

To apply this onset criterion to any project-related noise emission, it must be frequency-weighted to reflect the variation of penguin auditory acuity over the frequency band of their hearing. However, there is limited information on hearing sensitivity and frequency band of hearing of diving birds (see Section 4.3 for more details). Although these results are still insufficient for generating a full audiogram for diving birds, the hearing sensitivity values in the frequency range tested are comparable to those of otariid seals over the equivalent frequency range. As relevant information on frequency-weighting is available only for marine mammals, the weighting function from Southall et al. (2019) for the least sensitive marine mammal hearing group, other carnivores in water (OCW), is recommended as a proxy. This hearing group has been selected due to similar hearing sensitivity in the frequency band of underwater hearing for diving birds and otariid pinnipeds, which are included in the group.

There are also no regulatory thresholds for the onset of hearing impairment for penguins or any other diving bird species, or any phylogenetically or anatomically related species. The only scientifically robust noise exposure thresholds in this context exist for marine mammals. To allow assessing the noise-induced impact risk of the pile driving on penguins, the criterion from Southall et al. (2019) for other carnivores in water (OCW) is recommended as a proxy due to the similarity in hearing sensitivity in the frequency band of underwater hearing for the two species groups. Since otariids are considered more sensitive to underwater sound at frequencies above the frequency range tested for diving birds, using the frequency weighted otariid thresholds likely overestimates the sensitivity of diving birds and can be considered a conservative approach.

4. Methodology

This section describes how the underwater noise assessment was conducted to understand the existing environment and potential impacts of the project on underwater noise. The following sections outline the study methodology, background information on underwater sound, and impacts of noise on marine fauna that are equally important to understand and follow the assessment.

4.1. Existing Conditions Assessment Method

4.1.1. Study Area

The core project area is the inner harbour area in Corio Bay, but the study area extends also into the adjacent outer harbour area. The exact delineation of the study area is defined by the results of the noise propagation modelling study (Green et al. 2021) as the study indicates the ranges over which marine fauna can be exposed to project-related noise levels above the relevant exposure threshold levels.

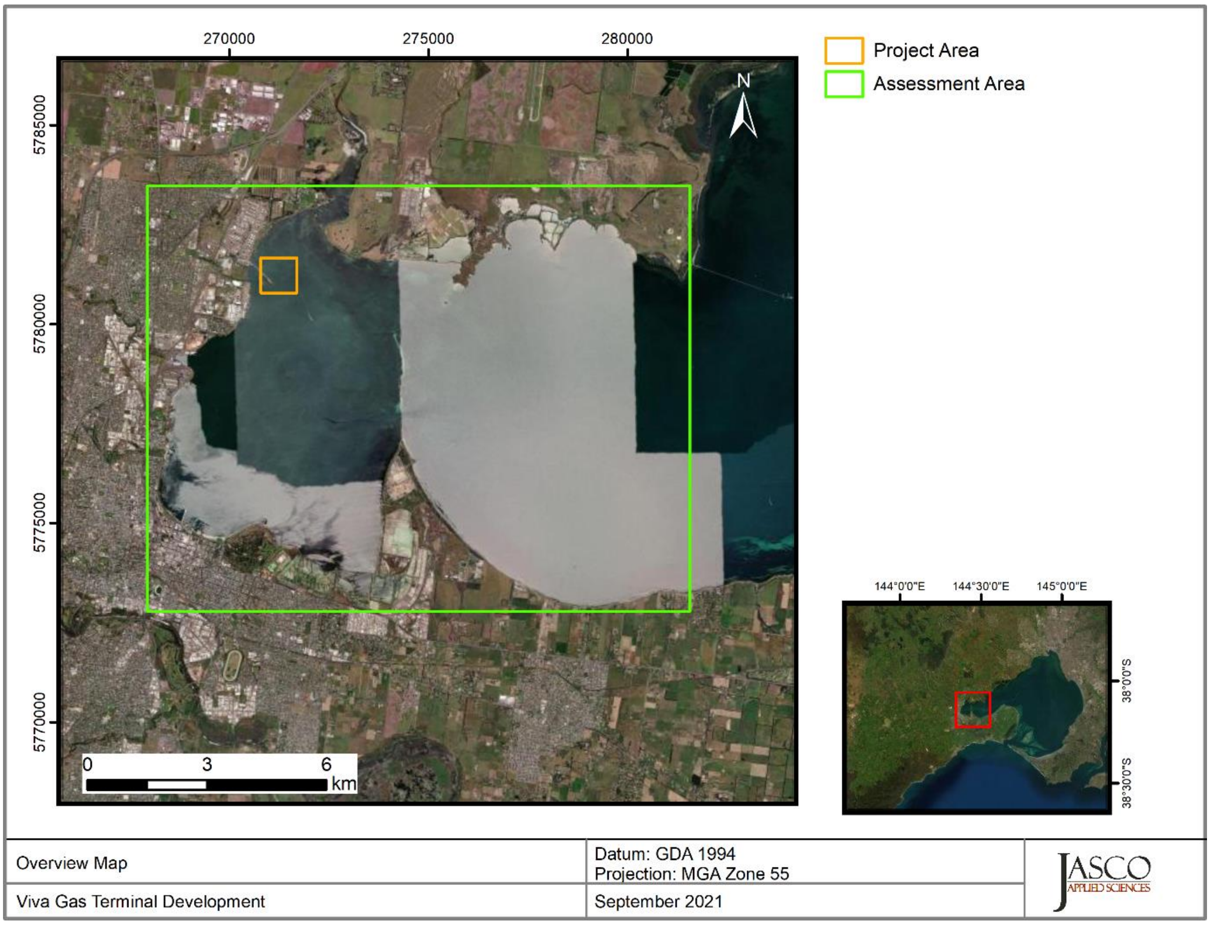


Figure 2. Overview map of the project and assessment area.

4.1.2. Existing Noise Conditions

As the project would be situated within a heavily developed port and industrial area, many currently operational water-based activities in Corio Bay will already cause emission of noise into the water as an unwanted by-product, e.g., noise from vessels and pumps. Land-based activities directly adjacent to the water could also contribute to the sound field in Corio Bay, though to a lesser extent.

Prior to this EES, there was no information available on the existing sound field with its temporal changes and spatial variations. To provide relevant baseline information, underwater noise was recorded in a sound monitoring study (Wilson and McPherson 2021). The results of this study are used to assess the existing acoustic exposure of marine fauna and birds to natural and anthropogenic noise before the project-related construction and operations begin.

The noise propagation modelling for the pile driving and dredging activities and operation of the FSRU predicts very limited sound transmission beyond Corio Bay and the Port of Geelong, mainly due to the local bathymetry (Green et al. 2021). The ambient noise in Corio Bay varies over a daily basis and also shows longer-term fluctuations, with a lowest (5th percentile) ambient noise SPL of 119.6 dB re 1 µPa and a median noise SPL of 124.6 dB re 1 µPa (Figure 3). The ambient noise levels thus even exceed some of the noise exposure criteria (Wilson and McPherson 2021).

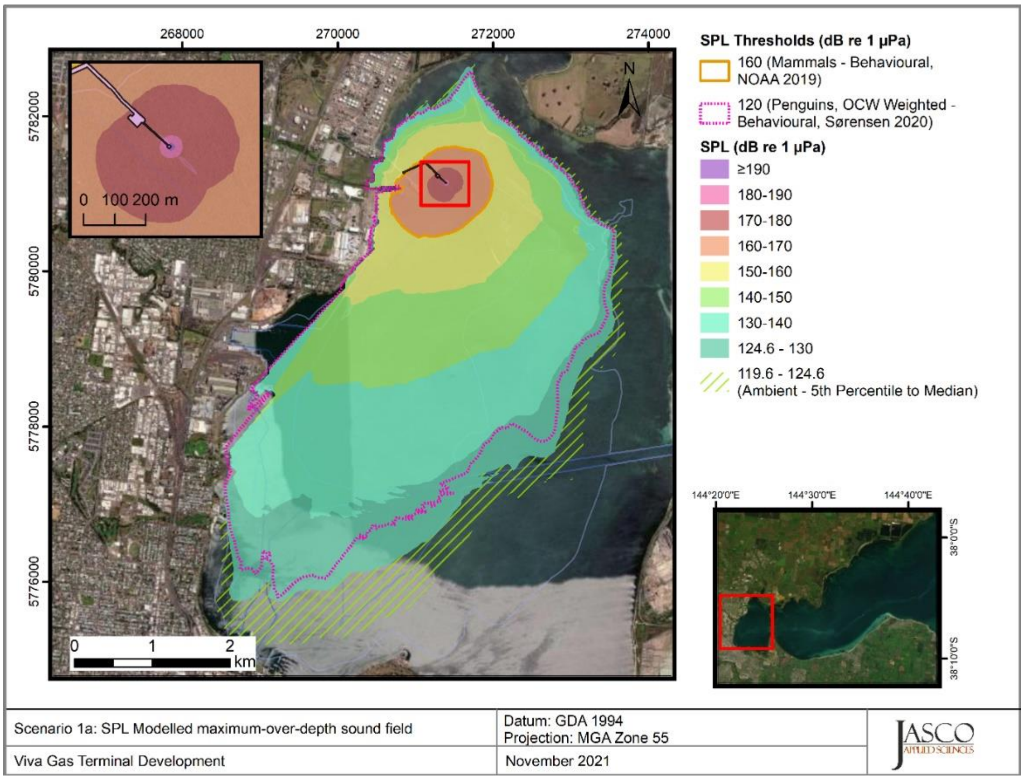


Figure 3. Maximum-over-depth SPL levels in Scenario 1a. and ambient noise levels. Isopleths show distances to behavioural effect onset levels in marine mammals and penguins (taken from Green et al. 2021).

4.2. Underwater Sound

Sound is always present in the underwater environment. It is naturally caused by biological sources such as marine fauna (e.g., snapping shrimp) and by meteorological and oceanographical sources (such as rain, wind driven waves, and currents). The existing sound in an environment is known as the ambient sound or soundscape. While the term ‘sound’ is objective, the term ‘noise’ can be defined subjectively as the ‘unwanted’ sound, i.e., sound that has an impact on a receptor. Anthropogenic sound is emitted by almost all activities at sea, either intentionally (e.g., operating an echosounder) or as a by-product (e.g., shipping or pile driving). A sound wave can be detected underwater and classified by the pressure fluctuation (compression and rarefaction of the supporting medium). However, when pressure and density change, the particles that comprise the media also move (Nedelec et al. 2016). Pressure and particle motion, the two components of sound, serve as input to the sensory systems in marine animals.

Sounds types can be classified as impulsive and non-impulsive sounds and are primarily distinguished by their temporal pattern. Impulsive or 'pulsed' sounds can be described as discrete (single pulses) and sometimes repetitive sounds (multiple pulses) produced by sources such as pile driving. These sounds, sometimes also termed transients, are typically brief signals reaching high peak sound pressure with a rapid rise time and a rapid decay (NIOSH 1998).

Non-impulsive sounds, which can be intermittent or continuous, are produced by sound sources such as ships and pumps. Non-impulsive sounds have longer durations than impulsive ones and usually do not have the high peak sound pressure and rapid rise/decay time that impulsive sounds do (NIOSH 1998). However, especially in respect to their auditory effects, the term non-impulsive does not imply long duration signals. All vessel operations are considered non-impulsive sound sources.

Assessing the impact of anthropogenic underwater noise on marine receptors requires an understanding of the basic physical principles of the sound pressure and particle motion components of underwater sound, which are presented in detail in Supplement A.

4.3. Underwater Hearing Sensitivity of Marine Animals

Marine mammals use sound for important life functions such as communicating, locating prey, and navigating. The hearing system of cetaceans is highly adapted to perceiving underwater sound. Their hearing range and frequencies of best sensitivity are species-specific. Toothed whales (odontocetes) are usually quite sensitive to high frequency sounds while baleen whales are assumed to be sensitive to very low frequency sounds. All cetacean species can theoretically be affected by acute or chronic exposure to sound depending on their susceptibility to sound effects, and the temporal and acoustic characteristics of the sound.

The sounds that marine animals hear and generate vary in characteristics, such as dominant frequency, bandwidth, energy, temporal pattern, and directivity. Just as many terrestrial animals integrate multiple stimuli from their visual landscape, marine life must discriminate a signal (meaningful sound) among multiple stimuli in their marine soundscape. Anthropogenic sounds can interfere with auditory (i.e., hearing related) processes in various ways.

Different species (or taxa) developed sensors for either the pressure or the particle motion components of sound, and some are sensitive to both. Many fish species and all invertebrate species studied to date do not have hearing organs that detect pressure differences due to sound pressure waves. Instead, they use receptors that sense particle motion in the water column to detect sound. The relevant exposure metric for most fishes and all invertebrates is therefore particle motion.

Marine animals only respond to or are impacted by acoustic signals they can detect. The sensitivity of an individual's auditory (i.e., hearing) system is described as a function of sound frequency. The lowest intensity of a sound at a particular frequency that an individual can hear describes its hearing threshold. The graphical representation of these thresholds over the range of frequencies that are audible to the individual is called its hearing curve or audiogram. Only a few individuals in a small number of marine species have been tested for their hearing sensitivity in all taxonomic groups of marine animals.

4.3.1. Marine Mammals

Acoustic signals have evolved as the principal mode of information transmission for many marine species. It is well known that cetaceans (whales, dolphins, and porpoises) use sound passively when listening to the environment and actively when communicating and foraging.

Current data and predictions on hearing sensibility show that marine mammal species differ in their hearing capabilities, in absolute hearing sensitivity, as well as their frequency band of hearing (Richardson et al. 1995, Wartzok and Ketten 1999, Southall et al. 2007). While hearing measurements are available for a small number of species based on captive animal studies, no direct measurements exist for many odontocetes and any mysticetes. As a result, hearing ranges for many odontocetes are grouped with similar species, and predictions for mysticetes are based on other methods, such as anatomical studies and modelling (Houser et al. 2001, Parks et al. 2007, Tubelli et al. 2012, Cranford and Krysl 2015), vocalizations (see reviews in Richardson et al. 1995, Wartzok and Ketten 1999, Au and Hastings 2008b), taxonomy, and behavioural responses to sound (Dahlheim and Ljungblad 1990).

4.3.1.1. Marine Mammal Hearing Groups

Southall et al. (2007) assigned the extant marine mammal species to functional hearing groups based on their hearing capabilities and sound production to better reflect the auditory similarities between phylogenetically closely related species but also the significant differences between species groups among the marine mammals,. This division into broad categories was intended to provide a realistic number of categories for which individual noise exposure criteria were developed. These groups were revised by Southall et al. (2019) (Table 7), but the categorisation as such has proven to be a scientifically justified and useful approach in developing auditory weighting functions and deriving noise exposure criteria for marine mammals.

Table 7. Marine mammal hearing groups (Southall et al. 2019).

Hearing group	Generalized hearing range*
Low-frequency (LF) cetaceans (mysticetes or baleen whales)	7 Hz to 35 kHz
High-frequency (HF) cetaceans (odontocetes: delphinids, beaked whales)	150 Hz to 160 kHz
Very High-frequency (VHF) cetaceans (other odontocetes)	275 Hz to 160 kHz
Phocid Carnivores in Water (PCW)	50 Hz to 86 kHz
Other Carnivores in Water (OCW)	60 Hz to 39 kHz

* The generalized hearing range for all species within a group. Individual hearing will vary.

4.3.1.2. Marine Mammal Weighting Functions

The potential for anthropogenic sounds to impact marine mammals is largely dependent on whether the sound occurs at frequencies that an animal can hear well unless the sound pressure level is so high that it can cause physical tissue damage regardless of frequency. Auditory (frequency) weighting functions reflect an animal’s ability to hear a sound (Nedwell and Turnpenny 1998, Nedwell et al. 2007). To better reflect the auditory similarities between phylogenetically closely related species, hearing ranges for cetaceans and pinnipeds are grouped with similar species via anatomical analyses and/or modelling studies. Southall et al. (2007, 2019) assigned the extant cetacean and pinniped species to functional hearing groups based on their hearing capabilities and sound production. Marine mammal auditory weighting functions published by Finneran (2016) are included in the NMFS (2018) Technical Guidance for use in conjunction with corresponding PTS (injury) onset acoustic criteria.

Figure 4 shows the resulting frequency-weighting curves proposed by Southall et al. (2007, 2019) which are identical to promulgated by NMFS (2018).

Applying marine mammal auditory weighting functions emphasizes the importance of making measurements and characterizing sound sources in terms of their overlap with biologically-important frequencies (e.g., frequencies of environmental signals, communication, or the detection of predators or prey), and not only the frequencies of dominant concern for the sound-producing activity such as a vessel (i.e., context of sound source; NMFS 2018).

Knowledge of the auditory capabilities of marine mammals is necessary for understanding their acoustic ecology, how they sense their environment, over what ranges they remain in acoustic contact, whether they can detect predators and prey, and how they receive ambient and anthropogenic noise.

While hearing measurements are available for a small number of species based on captive animal studies, direct measurements of many species do not exist. Current data and predictions on hearing sensitivity show that marine mammal species differ in their hearing capabilities, both in their absolute sensitivity to sound and in their frequency band of hearing (Wartzok and Ketten 1999, Southall et al. 2019).

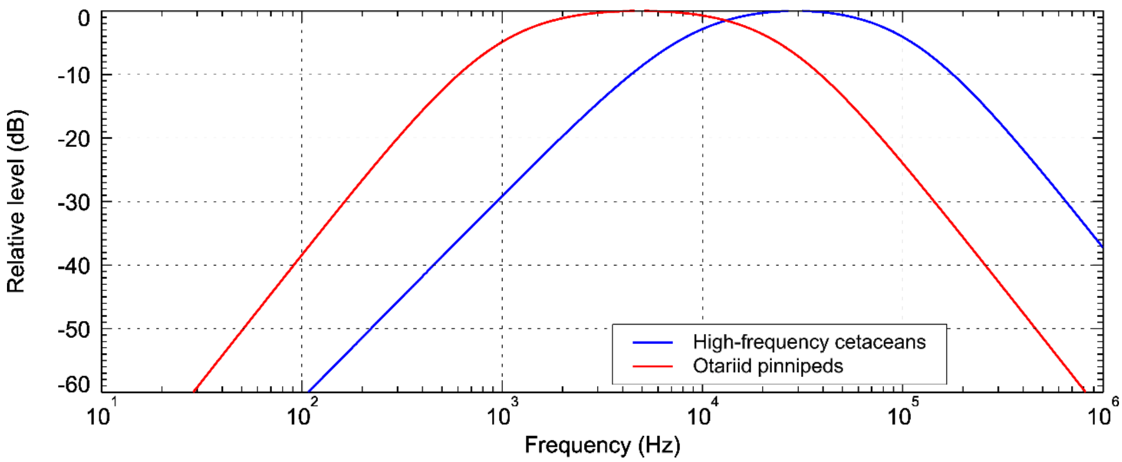


Figure 4. Auditory weighting functions for the functional marine mammal hearing groups assessed in this report (Southall et al. 2019).

4.3.2. Fishes

Although hearing ranges and sensitivities vary substantially between species (e.g., Ladich and Fay 2013), all fish species tested to date can hear (Dale et al. 2015). Fishes have developed two sensory mechanisms for detecting, localising, and interpreting underwater sounds and vibrations: the inner ear, which is tuned to sound detection, and the lateral line system, which allows them to detect vibration and water flow. Inter-specific variations in hearing range and sensitivity result from the different adaptations in these systems for perceiving sound pressure and particle motion information (Popper and Fay 2011).

The critical issue for understanding if an anthropogenic sound affects hearing is whether the sound is within the hearing (sound pressure) or detection (particle motion) frequency range of a fish and whether the sound is loud enough to be detected above the fish’s hearing threshold.

Sensitivity to sound pressure seems to be functionally correlated in fishes to the presence and absence of gas-filled chambers in the sound transduction system. These chambers enable fishes to detect sound pressure and to extend their hearing abilities to lower sound levels and higher frequencies (Ladich and Popper 2004, Braun and Grande 2008).

Based on their morphology, the Popper et al. (2014) classifications into three categories can be assigned to the following families or species of fish, common in Australian waters (see Figure 5 for hearing curves ('audiograms') of representatives of each group):

I) Fishes with swim bladders or other gas volumes, whose hearing does not directly involve the swim bladder, e.g., snappers, emperors, groupers and rock cods (Lutjanids and Lethrinids such as *Pristipomoides* spp., *Lethrinus* spp., *Lutjanus* spp., and family Serranidae), and some species of tuna (*Thunnus sp*.) (Tavolga and Wodinsky 1963, Bertrand and Josse 2000, Ramcharitar et al. 2006, Braun and Grande 2008, Engineering-Environmental Management 2008, Song et al. 2008, Caiger et al. 2012);

II) Fishes whose hearing does directly involve a swim bladder or other gas volume, e.g., family Clupeidae (herrings, sardines, pilchards, and shads), family Gadidae (true cods such as whiting), and potentially some nearshore/reef species relevant to tropical Australia, including some Pomacentridae (damsel fish and clown fish), some Holocentridae (soldierfish and squirrelfish), and some Haemulidae (grunters and sweetlips) (Nedwell et al. 2004, Braun and Grande 2008, Popper et al. 2014); and

III) Fishes without a swim bladder (e.g., mackerel, *Scomberomorus spp*., some tuna species, *Thunnus spp*, and sharks, including whale sharks, *Rhincodon typus*) (Casper et al. 2012a, Popper et al. 2014, Carroll et al. 2017).

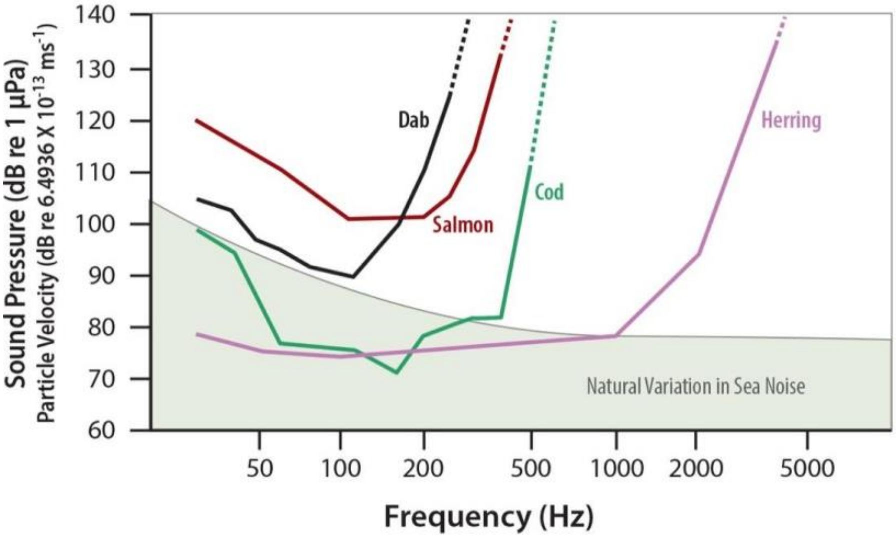


Figure 5. Fish audiograms obtained under open sea, free-field conditions; species representing different categories as classified by Popper et al. (2014) (source: Popper et al. 2019). Salmon (*Salmo salar*) have a swim bladder that does appear to play a role in hearing (category I), cod (*Gadus morhua*) and herring (*Clupea harengus*) have special structures mechanically linking the swim bladder to the ear (category II) and dab (*Limanda limanda*) are bottom-living fishes with no swim bladder (category III).

4.3.3. Invertebrates

Available literature suggests that particle motion, rather than sound pressure, is the most important factor for marine invertebrate hearing. At the seafloor interface, marine invertebrates are subject to particle motion stimuli from several acoustic or acoustically induced waves. These include the particle motion associated with an impinging sound pressure wave in the water column (the incident, reflected, and transmitted portions), substrate acoustic waves, and interface waves (such as Scholte waves, which are propagating at a water-sediment interface (Vinh 2013)). However, it is unclear which aspect(s) of these waves is/are most relevant to animals, either when the animals normally sense the environment or their physiological responses to loud sounds.

A few studies provide quantitative information on the sensitivity thresholds of marine invertebrates to sound. Electrophysiological studies measuring auditory evoked potentials (AEP) showed that cephalopods are capable of perceiving sound between 10 and 400 Hz (Packard et al. 1990, Parks et al. 2007, Hu et al. 2009, Mooney et al. 2010, Hughes et al. 2014). In a behavioural study, Mooney et al. (2016) showed that squid (*Doryteuthis pealeii*) can perceive sound pressure of signals as low as 80 Hz and have their optimal hearing range between 200–400 Hz. Lovell et al. (2005) measured AEP responses in prawns (*Palaemon serratus*) between 100 Hz to 3 kHz, and Pye and Watson (2004) tested lobster (*Homarus americanus*) up to 5 kHz using the AEP technique. However, as pointed out by several authors (Ladich 2013, Popper et al. 2014, Hawkins et al. 2015, Sisneros et al. 2016), studies employing the AEP technique may not reflect the true sensitivity to acoustic stimuli as the studies fail to incorporate natural soundscapes and processing at higher cortical levels.

Packard et al. (1990) used a classical conditioning approach to test low-frequency hearing in cephalopods (*Sepia sp.*, *Octopus sp*., and *Loligo sp*.) and found the best sensitivities at 10 Hz and below. Other studies obtained perception thresholds (using reflex movements of antennae or legs as proxy) for underwater sound in species such as the brown shrimp (*C. crangon*) (Heinisch and Wiese 1987, Berghahn et al. 1995), hermit crab (*Pagurus bernhardus*) (Roberts et al. 2016), common littoral crab (*Carcinus maenas*) (Barth 1980), and northern prawn (*Pandalus borealis*) (Klages et al. 2002). The studies revealed these species are sensitive to acoustic or vibratory stimuli at frequencies below 400–500 Hz.

Moreover, detection of substrate-borne low-frequency vibration (<200 Hz) has been demonstrated to induce behavioural responses in some crustacean and bivalve species (Roberts et al. 2015, Roberts and Elliott 2017).

Most studies on marine invertebrates do not differentiate between pressure and particle motion. If conducted in tanks, the resulting thresholds and high-frequency ranges (e.g., Pye and Watson 2004, Lovell et al. 2005) may be artefacts, possibly resulting from acoustic interferences in the confines of the test environment (Sisneros et al. 2016, Carroll et al. 2017). These experiment outcomes should be applied to impact assessments with caution, due to the aspects regarding study design and representation of true hearing sensitivity (see above).

Mooney et al. (2010) quantified the acoustic sensitivity of the longfin squid (*Loligo pealeii*) using near-field acoustic and shaker-generated acceleration stimuli. Sound field pressure and particle motion components were measured from 30 to 10,000 Hz. Acceleration stimuli were measured from 20 to 1000 Hz. Their results suggest that squid detect the acceleration and particle motion components of a sound field up to frequencies of ~500 Hz.

Jézéquel et al. (2021) corroborated the conclusion that crustaceans can sense particle motion but not sound pressure. In their study of sound detection in American lobster (*Homarus americanus*), they determined thresholds for particle acceleration levels (PAL_{rms}, in dB re. 1 m s^{-2}) ranging between −35 dB re 1 m·s^{-2} at 80 Hz and –30.2 dB re 1 m·s^{-2} at 220 Hz. The animals' best sensitivity ranged from 80–120 Hz and was limited to an upper frequency of 250 Hz.

Jézéquel et al. (2021) reported the important finding that statocysts, a long-proposed auditory structure in crustaceans, are not the sensory organs responsible for lobster sound detection. This raises doubt about studies investigating the noise-induced impact on statocysts in crustaceans and their conclusions regarding the ecological effects of the documented statocyst impairment or damage.

Irrespective of the sensory modality for sound perception, marine invertebrates produce, detect, and respond to sound as shown in a review by Edmonds et al. (2016), thus indicating that these species are susceptible to effects from underwater sound. While research in this area is limited, the sensitivity of invertebrates to water-borne particle motion and substrate vibration across a broad range of frequencies may potentially impact marine invertebrates through physical effects (Solé et al. 2017) and behaviour disruption (Solan et al. 2016).

However, due to the relative novelty in scientific understanding of invertebrate detection of and sensitivity to underwater sound, there are currently no established detection thresholds for this taxonomic group.

4.3.4. Avifauna

Hearing in birds has been tested predominantly in terrestrial species (Dooling 2010). There are only two studies providing information on the underwater hearing sensitivity of a (pursuit) diving bird species, the great cormorant (*Phalacrocorax carbo*) (Johansen et al. 2016, Anderson-Hansen et al. 2017). These studies show that the birds have underwater hearing sensitivity over the range of at least 1–4 kHz, with greatest sensitivity of 70 dB SPL found at 2 kHz. This suggests that their hearing capabilities in water are better than what would be expected for a purely in-air adapted bird’s ear (Johansen et al. 2016). Mooney et al. (2019) found comparable results for two seabird species, the common murre (*Uria aalge*) and the Atlantic puffin (*Fratercula arctica*). A behavioural response conducted on Gentoo penguins (*Pygoscelis papua*) (Sørensen et al. 2020) similarly indicates that underwater hearing may be important for penguins and that their auditory system is adapted for the underwater environment.

Best hearing sensitivity for in-air sound was measured at 2 kHz for the puffin and 1 kHz for the murre. The overall hearing range was highest for the puffin including frequencies between 0.5 to 6 kHz. Wever et al. (1969) investigated the hearing of African (black-footed) penguins (*Pheniscus demersus*) and documented a similar hearing range for this species. Apart from this, there are limited data on the hearing range or sound-induced effects for birds underwater.

In the absence of data on auditory information for most seabird species, information sensitivity can be drawn from the animals’ vocalisations. Of the penguin and flying seabird species, to date only the Macaroni penguin (*Eudyptes chrysolophus*) has been proven to produce sound underwater. Markov (1977) documented that their vocalisation frequencies range from 2.5 to 7 kHz, but the functionality of these sounds and therefore the role acoustic cues play for birds underwater remains unclear.

4.4. Impact of Underwater Noise on Marine Fauna

The audibility of a sound does not represent an impact per se but is the necessary condition for any direct effects to occur, i.e., sound becomes relevant in the context of this impact assessment only if it exceeds the threshold for any of the impacts listed in Section 3.2.

The potential for noise to impact marine fauna depends on the acoustic characteristics of the sound, the sound propagation characteristics of the physical environment, and biological factors such as hearing sensitivity and behavioural context (Southall et al. 2007, Ellison et al. 2012, Southall et al. 2016). Noise can have a variety of impacts on marine animals depending on its characteristics, including the sound intensity, temporal pattern, directivity, bandwidth, frequency range, and whether it is impulsive or not. Typically, the negative effects of noise are directly related to the type of noise and its level, which usually decreases with distance of the receptor from the noise source. A conceptual model describing the spatial extent of four theoretical zones of acoustic influence on marine life was proposed by Richardson et al. (1995) (Figure 6). With the highest levels of sound at the sound source at the centre of the model, the noise level and severity of noise-induced impacts decline with increasing distance from the source.

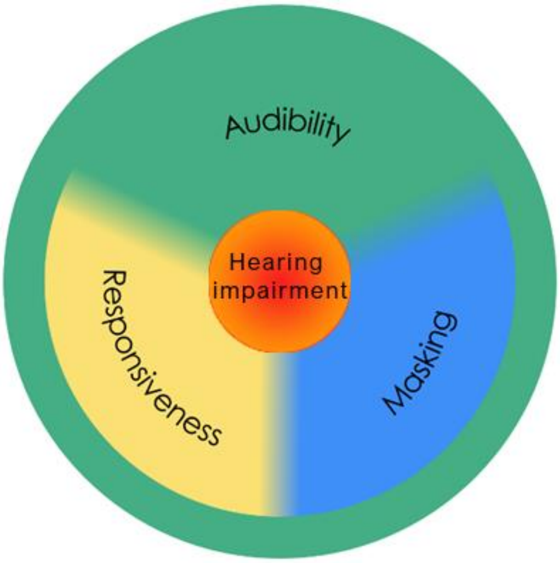


Figure 6. Conceptual relationship between the distances from a noise source and the overlapping effects on hearing and behaviour; (not to scale). Adapted from Richardson et al. (1995).

The four categories are described below in increasing severity of effect:

1. Audibility–Signal source levels decrease with range from a source due to propagation losses; their audibility is limited by the signal dropping either below the animal's hearing threshold or below ambient sound levels.
1. Responsiveness–The zone of behavioural response is generally smaller than the zone of audibility, as an animal is not likely to respond to a sound that is just detectable.
2. Masking–The zone overlaps with zone of responsiveness; masking occurs when a noise impedes the ability of the animal to perceive a biologically relevant signal.
3. Hearing impairment–Physical injury, temporary or permanent impairment of the auditory (hearing) system.

When the receptor is close to the noise source, all four categories of effects can occur simultaneously if the noise exposure is sufficiently intense. As the receptor moves away from the noise source, the effects become systematically less prominent. When the noise source is far enough away, only behavioural and/or physiological effects remain as possible responses to noise, as the very perception of a sound can cause a physiological stress response in the receiving animal. The direct impacts of anthropogenic noise on marine fauna are described in more detail below.

An effect of sound on certain marine species that is not defined in a zonal sense is the potential reduction in prey availability, for example, when prey responds to anthropogenic sound and is displaced from a particular feeding area. This is considered an indirect or secondary effect. The consequences of indirect effects, such as reduced food availability, on an individual or species are often difficult to determine. For most marine animals, the abundance of prey species near a source of impact (e.g., construction site) would, if reduced at all due to sound exposure, likely remain so only for a short duration (hours to days) past the end of the activity. Post noise exposure the area would likely be repopulated by the same animals or unaffected animals from adjacent waters. In some extreme cases, recovery of the habitat or prey resources could occur over a longer time frame (days to weeks). It is important to note that indirect impacts likely differ among species, as well as on spatial and temporal scales.

4.4.1. Physiological Stress

Stress is an integral and necessary part of the body's homeostasis, and certain stress levels are tolerable. At higher levels, if repeated too often or continued over long durations, stress can; however, become deleterious by creating an allostatic load to the body. This is expressed and can be measured as imbalances in the autonomic nervous system, central nervous system, neuroendocrine system, and immune system, and/or result in changes in growth rate, disruption of diurnal rhythms, and behavioural changes. Marine animals of all taxa may not show overt signs of responding to an increase in noise but may nonetheless show physiological changes (e.g., Slabbekoorn et al. 2010, Kight and Swaddle 2011, Slabbekoorn et al. 2019). Symptomatic stress responses include acute changes in respiration rate, oxygen consumption, excretion, and food consumption rates, or chronic effects such as immune suppression. The effects of increased stress levels (acute or chronic) can be expressed through various metabolic and/or physiological factors. The imbalance caused by stress in these factors can lead to immune suppression and/or result in altered growth rate, disrupted diurnal rhythms, and behavioural changes. This cascade of effects may reduce an individual's fitness through impacts on reproduction (e.g., Sierra-Flores et al. 2015) and, ultimately, survival (see review by Slabbekoorn et al. 2010).

While physiological responses such as increased heart rate or startle response can be difficult to measure in the field, they often accompany more easily measured reactions such as behavioural responses. A startle is a reflex characterized by rapidly increasing heart rate, shutting down nonessential functions, and mobilising glucose reserves. Habituation keeps animals from expending energy and wasting attention on harmless stimuli, but the physiological component might not habituate completely (Bowles 1995).

A strong and consistent physiological response does not necessarily indicate negative consequences to individuals or to populations (Larkin et al. 1996). Many reported physiological responses to in-air noise, e.g., are usually within the range of normal adaptive responses to external stimuli, such as predation. In many cases, individuals would return to homeostasis[2] or a stable equilibrium almost immediately after exposure. The individual's overall metabolism and energy budgets would not be affected if it had time to recover before being exposed again. If the individual does not have the opportunity to recover, however, physiological responses could be cumulative and lead to reduced fitness.

The difficulty of assessing noise-induced stress in marine animals is exemplified by a carefully controlled exposure experiment conducted by Houser et al. (2020) who exposed trained bottlenose dolphins (*Tursiops truncatus*) to 1-s tones at different SPL. Their results show that stress-related hormones were either below detection limits (aldosterone) or levels did not show a consistent relationship with received levels (cortisol nor epinephrine). Stress responses may be species- and context-specific and depend on previous exposures (sensitisation/habituation, see Section 4.4.2) and the (lack of) results in the study by Houser et al. (2020) may reflect the fact that these animals had been exposed to artificial underwater sound before. However, it also gives reason to question if marine mammals interpret high-level anthropogenic sound as stressful and whether behavioural responses to sound can be equated to a physiological (endocrine) response.

[2] The state of steady conditions of living organisms where they are optimally functioning.

4.4.2. Behavioural Responses

The intensity of behavioural responses of marine fauna to sound exposure does range from subtle responses, which may be difficult to observe and have little implication for the affected animal, to obvious responses, such as avoidance or panic reactions. Behavioural responses to hearing a sound include (in approximate order of increasing severity but decreasing likelihood):

1. Looking or increased alertness;
2. Minor behavioural responses;
3. Cessation of feeding or social interactions;
4. Temporary avoidance behaviour;
5. Modification of group structure or activity state;
6. Habitat abandonment; and
7. Injury or death from direct response.

The context in which the sound is received by an animal affects the nature and extent of responses to a stimulus. The threshold for elicitation of behavioural responses depends on received sound level, as well as multiple contextual factors such as the activity state of animals exposed to different sounds, the type of sound, spatial relations between a sound source and receiving animals, the gender, age, and reproductive status of the receiving animal and the and novelty of or previous exposure to the sound (Ellison et al. 2012). This means that individual animals will react differently depending on their previous experience, their life stage (e.g., mother-calf pairs versus solitary adult males), and the motivation to continue an ongoing activity such as feeding.

In general, noise exposure may result in alterations in the behaviour of marine fauna, particularly those individuals in closer proximity to the sound sources. The likely potential consequences for marine fauna are:

- Changes in species composition near the project site, with less noise-tolerant species moving farther away;
- Selection for more noise-tolerant individuals within the populations of species closer to the project site; and
- Habituation of some species and individuals to the noise impacts.

The differences in behavioural responsiveness that exist between individuals and species can furthermore change over time due to habituation or sensitisation to (repeated) exposure to the noise. Previous exposure to a sound can influence the severity of a behavioural response, leading to an increased or decreased tolerance to the sound. A novel acoustic stimulus may initially provoke a substantial anti-predator response (Voellmy et al. 2016). Behavioural habituation is the relative persistent waning of a response as a result of repeated stimulation to that novel stimulus (Thorpe 1963, Bejder et al. 2009). Habituation is a process involving a reduction in response over time as individuals learn that there are neither adverse nor beneficial consequences of the occurrence of the stimulus. Sensitisation refers to the opposite phenomenon, an increasing “behavioural responsiveness over time when animals learn that a repeated or ongoing stimulus has significant consequences for the animal” (Richardson et al. 1995). Individuals that are sensitised to acoustic stimuli (such as emitted by anthropogenic activities) will thus exhibit a progressive intensification of their response to these stimuli, e.g., by fleeing farther and faster when they encounter the stimulus or by responding at progressively lower stimulus intensities. Since habituation and sensitisation constitute learning processes that are ongoing, they reflect an individual’s cumulative experience with anthropogenic activities, including the number and outcome of its exposures to anthropogenic stimuli over the course of its lifetime (Knight and Temple 1995). Tolerance describes the “intensity of disturbance that an individual […] tolerates without responding in a defined way” (Nisbet 2000 p. 315).

In fishes, noise exposure can lead to behavioural effects such as reduced foraging, shelter or nest maintenance, and predator avoidance (Engås et al. 1996, Popper et al. 2003, Picciulin et al. 2010, Bruintjes and Radford 2013, Hawkins et al. 2014, Simpson et al. 2015). Not all studies, however, report an impact. For example, Nedwell et al. (2003) reported no apparent behavioural impacts or injuries to caged brown trout (*Salmo trutta*), located 400 m from pile driving operations where they were exposed to estimated received levels of 134 dB re 1 µPa (PK). Likewise, Ruggerone et al. (2008) reported no injury or behavioural changes in caged coho salmon (*Oncorhynchus kisutch*) located up to 15 m from pile driving activity.

Small-scale avoidance of noise is unlikely to have any long-lasting effects on fitness. If noise was to occur in breeding or feeding grounds, then fishes might relocate to other areas. More research is required to assess this possibility. Other behavioural effects include increased motility (Buscaino et al. 2010), reduced feeding efficiency (Voellmy et al. 2014), and masking of communication signals (Codarin et al. 2009).

To date, there have been few studies regarding behavioural responses by seabirds to impulsive underwater sound sources. Stemp (1985; as cited in Golde and Houtman (2012)) conducted observations on the effects of impulsive sounds generated by a seismic exploration on seabirds and did not observe any negative effects. Lacroix et al. (2003) investigated the effect of near shore seismic surveys on moulting long-tailed ducks (*Clangula hyemalis*) in the Beaufort Sea, Alaska, and found no noticeable impacts on the movements or diving behaviour of ducks.

Pichegru et al. (2017) investigated the behavioural response of breeding endangered African penguins (*Spheniscus demersus*) to seismic surveys within 100 km of their colony in South Africa. Penguins showed a strong avoidance of their preferred foraging areas during seismic activities; foraging took place significantly farther from the survey vessel when in operation, while increasing their overall foraging effort and energy expenditure. The birds reverted to normal behaviour when the operation ceased.

In a controlled exposure experiment, Sørensen et al. (2020) exposed seven gentoo penguins (*Pygoscelis papua*) to underwater noise bursts (i.e., impulsive signals) and documented that the animals showed a graded reactions ranging from no reactions at 100 dB re 1 µPa SPL to strong reactions in more than 60% of the playbacks at 120 dB re 1 µPa SPL.

It can be expected that pursuit-diving birds react to underwater sound emissions depending on the received noise level and possibly respond differently to different types of noise; most likely a behavioural response to onset of noise emissions will manifest itself as altering or abandoning a foraging pursuit; it remains unclear if or at what received levels and under what contextual circumstances birds entering an already existing sound field, i.e., with ongoing construction or operational activities, will avoid the area. Penguins, however, seem more prone to respond to acoustic disturbance than the other bird species and can be assumed to avoid ensonified areas for the duration of a sound-producing activity before returning to their habitat. However, the limited scientific information on behavioural responses of seabirds (including penguins) to underwater sound indicates that the response are likely species- and context-specific

4.4.3. Acoustic Masking

Auditory masking is the process by which the threshold of hearing for one sound is raised by the presence of another (masking) sound (Erbe and Farmer 1998, Erbe 2008, Erbe et al. 2016). This describes the reduction in audibility for one sound (termed 'signal') caused by the simultaneous presence of another sound (termed 'noise'). For this to occur, the sound must be loud enough, have similar frequency content to the signal, and must happen at the same time.

Masking is a complex phenomenon, and the onset levels and severity are difficult to predict for any given combination of sender, environment, and receiver characteristics (Erbe et al. 2016b). Masking depends on the spectral and temporal characteristics of signal and noise and is reduced if the signal and noise (masker) are separated in time, frequency, or direction (space). It can occur if the noise happens shortly before or after the signal (forward and backward masking).

The severity and extent of auditory masking depends on the spectral and temporal characteristics of both the signal and the noise. The zone of auditory masking can maximally be as large as the zone of audibility, i.e., a faint noise might mask a faint signal. However, auditory masking ends immediately after the masking sound ceases.

Masking sound can interfere with the perception of communication between conspecifics and echolocation signals and the detection of environmental, predator and prey sounds. These acute masking effects can have cascading consequences for communities through altered species interactions (Francis et al. 2009). Auditory masking can lead to disruption of a behaviour, lack of appropriate behavioural reactions, increased vulnerability to predators, reduced access to prey, reduced communication or listening space (Clark et al. 2009, Pine et al. 2018a, Pine et al. 2018b), changes in vocal behaviour, disruption of spawning activities, and stress (Houser et al. 2020).

The masking effect can be reduced or remedied by various active or passive mechanisms for masking-release, such as spatial or temporal release from masking (for more information, see Erbe et al. 2016, Popov et al. 2020). The masking effect can be reduced if the signal and noise are separated in time, frequency, or direction (space).

The biological significance of acoustic masking is directly linked to the duration of the masking sound. Both anthropogenic and natural marine sound can affect hearing and partially or completely reduce an individual's ability to effectively communicate. Auditory masking is likely occurring for all marine fauna; however, masking is most frequently associated with marine mammals. Masking in fishes or other taxa has not been studied in detail.

Repeating a signal or lengthening it may reduce the amount of masking because whales seem most reactive when the sound level is increasing and at the onset of a sound. Although limited, data suggest that stationary industrial activities producing non-impulsive sounds (such as dredging, drilling, and oil-production-related activities) result in less dramatic vocal reactions by cetaceans than do moving sound sources, particularly ships (Richardson et al. 1995). Masking and the potential effects of masking on communication and listening space of marine mammals are not fully understood and remain an area of active research (Terhune et al. 1979, Cunningham and Mountain 2014, Tennessen and Parks 2016, Cholewiak et al. 2018, Dunlop 2018, Gabriele et al. 2018, Putland et al. 2018, Dunlop 2019).

4.4.4. Hearing Impairment

Exposure to sufficiently intense sound may lead to an increased hearing threshold in any living animal capable of perceiving acoustic stimuli (Finneran 2015). If this shift is reversed and the hearing threshold returns to normal, the effect is called a temporary threshold shift (TTS). The onset of TTS is often defined as threshold shift of 6 dB above the normal hearing threshold (Southall et al. 2019). If the threshold shift does not return to normal, the residual shift is called a permanent threshold shift (PTS). Both TTS and PTS are hearing impairments that are considered an injury (DAWE 2021).

Hearing loss occurs naturally in marine mammals and possibly also in other taxa, most likely explained by advancing age, diseases, or congenital defects (Ridgway and Carder 1997, Mulsow et al. 2011). Threshold shifts can also be caused by acoustic trauma from a very intense sound of short duration, as well as from exposure to lower level sounds over longer time periods (Houser et al. 2017). Injury to the hearing apparatus of a marine animal may result from a fatiguing stimulus measured in terms of sound exposure level (SEL), which considers the sound level and duration of the exposure signal. Intense sounds may also damage the hearing apparatus independent of duration, so an additional metric of peak pressure (PK) is needed to assess acoustic exposure injury risk. Noise-induced effects mediated by particle motion have not been studied to date, and it is unclear what the exposure thresholds for marine animals sensitive to particle motion are.

The severity of TTS is a function of recovery time and is expressed as the magnitude of the shift in hearing sensitivity relative to pre-exposure sensitivity and the duration of hearing impairment. TTS occurs at lower sound levels than PTS. Though the relationship between the onset levels of TTS and the onset levels of PTS is not fully understood for marine mammal species, PTS onset acoustic thresholds have been extrapolated from marine mammal TTS measurements using growth rates from terrestrial and marine mammal data (Finneran et al. 2017).

The most severe physiological or physical effects caused by exposure to intense sound described in published literature are TTS and PTS, respectively, which were investigated in several bird species (Saunders and Dooling 1974, Ryals et al. 1999, Saunders and Dooling 2018). These studies also show that birds can regenerate the sensory cells in their inner ears, providing them with a mechanism to restore their hearing sensitivity even after a sound exposure that initially impacted their hearing negatively. During this restorative process, however, sound induced impairment of their hearing can have ecological consequences for these taxa as their ability to detect biologically important sounds is reduced.

As in other animal groups, hearing impairment in fishes can result from mutations, treatment with ototoxic chemicals, and exposure to excessive levels of underwater noise. Hearing impairment has been demonstrated in several fish species after exposure to different types of sounds (Popper and Clarke 1976, Scholik and Yan 2001, Amoser et al. 2004, Smith et al. 2004, Popper et al. 2005, Popper et al. 2007). Multiple exposures to very intense sounds (SPL over 190 dB re 1 μPa) or long-term exposure to lower-level sounds were necessary to cause hearing threshold shifts. The onset thresholds for hearing impairment, however, varied between individuals and species (Popper et al. 2005, Popper et al. 2007, Hastings et al. 2008, Hastings and Miksis-Olds 2012). Not all experiments involving exposure to intense sound, however, caused a hearing threshold shift in the exposed fishes; some species exhibited no or minimal hearing threshold shifts following intense sound exposure (Smith and Monroe 2016).

The biological significance of hearing impairment in fishes is mediated by the fact that perception of underwater sound for communication purposes is linked to regulating social and reproductive behaviours of fishes; fishes listen to other fishes (both conspecific and heterospecific) and other aquatic sound-producing organisms such as their predators (Lagardère et al. 2005, Vasconcelos et al. 2011, McIver et al. 2014). With sound playing such a vital role in a variety of behaviours, fishes of all life stages face a higher risk of mortality and decreased fitness if their hearing is impaired.

Noise induced effects on anatomical structures (statocysts), which were purportedly responsible for sound detection by marine invertebrates, have been shown, but results from a recent study on American lobster (Jézéquel et al. 2021) indicate that external cuticular hairs, which cover much of lobster bodies are the sensory organs for detecting particle motion. This implies that previous studies investigated the wrong organ, and their conclusions may be irrelevant. Despite this recent paradigm shift in scientific understanding of functional morphology of marine invertebrates, sound plays an ecologically important role for marine invertebrates, and it is justifiable to assume that impairing their perception of acoustic stimuli may lead to, however undefined and not quantified, ecological consequences.

4.4.5. Mortality

Exposure to excessive levels of impulsive sound or events characterised by rapid overpressure in water can kill and injure marine fauna (Carlson et al. 2011). Impulsive sounds, with rapid changes in pressure, are more damaging to tissues than gradual changes (Popper et al. 2014).

Mortality is either a direct effect of the exposure (in case of severe injury) or indirect if an animal is moderately injured. Data on sound-induced mortality have been documented for fishes (Caltrans 2001), but are scarce for marine mammals (Ketten 1995, Landsberg 2000) and only hypothesised for other taxa (Guerra et al. 2004).

Exposure to intense underwater sound may not directly result in death or injury; however, it may be one of the indirect causative factors in death or injury to marine mammals. Marine mammal strandings of beaked whales (D'Amico et al. 2009) and common dolphin (Jepson et al. 2013) are thought to be a result of the animals' behavioural responses to acoustic exposure to military mid-frequency sonar.

Investigating the mass stranding of approximately 100 melon-headed whales in the Loza Lagoon system in Madagascar lead to the conclusion that the use of a 12 kHz multibeam echosounder (with SPL of 236 to 246 dB re 1 µPa and per pulse SEL of 218 to 224 dB re 1 µPa^2·s) was "the most plausible and likely initial behavioural trigger of the stranding event, but that a variety of secondary factors contributed to or ultimately caused mortalities […]" (Southall et al. 2013).

Sound-induced mortality in birds and/or marine invertebrate species relevant for this assessment has not been documented. Fishes, however, have been shown to suffer non-acoustic traumata after exposure to intense impulsive sounds, e.g., near pile driving operations (Caltrans 2001). Popper et al. (2014) provide a review of existing information on non-acoustic injury to fishes and propose a comprehensive set of (qualitative and quantitative) noise exposure criteria.

4.5. Risk Screening Method

A risk-based screening approach has been used for the EES assessment in accordance with the requirements outlined in the 'Ministerial guidelines for assessment of Environmental Effects under the *Environment Effects Act 1978'* (page 14). The risk screening is undertaken to ensure that the level of investigation conducted in each technical study is adequate to inform an assessment of the significance and acceptability of the project's potential environmental impacts.

An environmental, social, and economic issues risk screening tool has been used to prioritise and focus the proposed investigations, assessments, and approaches to avoiding, minimising, or managing potential impacts. The issue screening process involved an evaluation of the potential environmental, social, and economic issues associated with the project based on the information collected through a series of initial assessments undertaken into the potential effects of the project.

A risk workshop convened by a qualified risk practitioner and comprising technical specialists from the proponent, project design team and EES team conducted the initial risk screening. The risk screening process utilised knowledge of the project infrastructure and design, existing environment and land use setting to assess potential risks based on the specialised knowledge of the technical experts.

The purpose of the issues screening approach was to assist in identifying:

- Significant issues, uncertainties and/or potential impacts that require more detailed characterisation and/or assessment within the EES, and
- Matters or potential impacts considered to be already well understood or less significant.

A high, medium, or low screening value was assigned to potential issues to determine the level of assessment required to identify and investigate impacts.

Each potential issue was given a score (1, 2 or 3) against the categories of:

- Community and stakeholder interest,
- Significance of assets, values and uses, and
- Potential impact (spatial, temporal and severity).

The scores were added together, or the highest score across the three contributing categories was used, to give a 'screening value' of high, medium, or low, which gives an indication of the level of impact assessment that is required. Issues that were assigned a screening value of high or medium required detailed assessment in the EES at a level commensurate with them being considered primary level issues.

Issues that were assigned a screening value of low were proposed to be documented and managed with some investigation and assessment in the EES at a level commensurate with them being considered secondary level issues.

4.5.1. Criteria and Consequence Ratings

Risks, issues, and potential impact pathways were identified for both construction and operation of the project. Table 8 defines the criteria and consequence ratings for each of the three categories that have been used to inform the issues screening. The sum of the scores against each of the three categories or the highest rating across any of the three contributing categories gives the 'screening value'.

Table 8. Issues screening criteria and consequence ratings.

Rating	Community and stakeholder interest	Significance of assets, values and uses	Potential impact (spatial, temporal and severity)
1	Low interest and perceived impact	Locally significant asset, value, or use	Potential for localised, temporary impact
2	Some interest and targeted perceived impacts	Regionally significant asset, value, or use	Potential for significant temporary, or localised permanent impact
3	Broad community and stakeholder interest or impacts	State or nationally significant asset, value, or use	Potential for significant permanent impact

Table 9 shows the screening values are then used to determine the level of assessment required.

Table 9. Issue investigation categories.

Screening score	Screening value	Potential consequences	Complexity of mitigation	Level of assessment
7, 8, or 9 or the highest rating across any one of the three contributing categories is 3	High	Potential for elevated, longer-term impacts, significant assets or values may be affected with enduring changes. Considers both impacts and benefits, or Issue may not be well defined and insufficient information is available for the impact assessment, or High level of community interest.	Stringent management measures may be required	Detailed assessment required
4, 5, or 6 or the highest rating across any one of the three contributing categories is 2	Medium	Potential for moderate level impacts, significant assets or values may be affected over an extended time frame with some resultant changes. Considers both impacts and benefits, or Issue may be moderately understood, and some information is available, however more is required for the impact assessment, or Medium level of community interest.	Standard management measures are available that can be adopted with some modification	Moderate assessment required
3 or the highest rating across any one of the three contributing categories is 1	Low	Potential for short term and localised impact. Asset or values may be temporarily affected but recovery expected, or Issue is well understood and there is enough information available for the impact assessment, or Low level of community interest.	Standard management measures are available.	Some assessment required

Further information about the risk screening process is detailed in Chapter 7 *Assessment framework.*

Outcomes from the risk screening process are outlined in Section 4.5.2.

4.5.2. Risk Screening Results

Table 10 provides the key potential issues related to changes in underwater noise identified as part of the risk screening process for the project and presents the screening value for each issue.

Table 10. Underwater noise issues screening result.

Aspect	Issue	Community & stakeholder perceived impacts	Significance of assets, values & uses	Potential impact (spatial, temporal & severity)	Screening score	Screening value
Construction						
Marine ecology	Potential impacts on marine fauna from underwater noise generated from piling and dredging activities	1	2	2	5	Medium
Operation						
Marine ecology	Underwater noise generated by operation of the FSRU and visiting LNG carriers impacts marine fauna	2	2	1	5	Medium

4.6. Impact Assessment Method

Underwater noise effects of the construction activities and operation of the facility are given a medium screening score (5) indicating the requirement for a detailed assessment in the EES at a level commensurate with them being considered primary level issues. There is no information about combined effects of underwater noise with the other environmental effects assessed for the project and, accordingly, underwater noise is assessed as a single impacting factor.

The impact assessment method includes a review of existing background information on the sensitivity of marine fauna species occurring in the area to underwater noise. In combination with the outcome of the underwater noise modelling study Green et al. (2021) this will provide the basis for assessing the likely impact severity, impact ranges and, ultimately, the ecological relevance of the impacts.

4.7. Stakeholder and Community Engagement

Stakeholders and the community were consulted to support the preparation of the project's EES and to inform the development of the project and understanding of its potential impacts.

An extensive engagement and consultation program was undertaken to ensure that the community and interested stakeholders were informed, involved and able to actively contribute to the development of the project and preparation of the EES. No specific issues related to underwater noise were raised by stakeholders and the community, however, concerns were raised about the potential impacts on the marine environment within and around Corio Bay and the Ramsar site

In accordance with the scoping requirements, a Technical Reference Group (TRG) was convened and chaired by DELWP on behalf of the Minister for Planning. The TRG has provided input throughout the EES process. Chapter 6 *Community and stakeholder engagement* provides a summary of the project's key engagement activities.

4.8. Assumptions and Limitations

4.8.1. Assumptions

The following conservative approaches/assumptions were made:

- The impact ranges are based on the maximum impact range (R_{max}) values calculated by Green et al. (2021), i.e., including the farthest extent at which the impact thresholds are exceeded. This can include outliers that are not representative of the main (95%) extent of the sound fields (which would be represented by the $R_{95\%}$ values, see Green et al. 2021 for details). These outliers were not found to lie irrationally beyond the main extent of the 95% impact range, so their inclusion makes the ranges precautionary but not unrealistic.
- It is assumed that animals will remain within the TTS impact zone to stay in their preferred habitat, thereby enduring TTS noise levels.
- The impact assessment is based on a static receiver approach. The predicted SEL levels (relevant for TTS and PTS thresholds) are calculated over a 24 h period, and animals are assumed to remain stationary, thus receiving and accumulating noise exposure over this period. This scenario, however, is unrealistic because marine mammals and birds are highly mobile species and are likely using the entire area dynamically, i.e., moving in and out of the area surrounding the project site; this includes pinnipeds that display vocal behaviour at or just under the water surface over extended periods.

4.8.2. Limitations

This assessment was made with the following limitations:

- This assessment considers the sound fields around the construction activities and use of new facilities as modelled by Green et al. (2021) for the following six scenarios:
    1. Pile driving:
        a. Dolphin pile, part of the construction of the pier extension for the gas terminal.
        b. Mooring piles at Lascelles Wharf.
    2. Dredging:
        a. Localised dredging at Refinery Pier to enable the FSRU and LNG carriers to berth at the pier extension.
        b. Installation of seawater transfer piping.
    3. Future operations:
        a. FSRU berthed .
        b. FSRU berthed and LNG carrier offloading.

    The assessment of potential impact to the different receiver groups (Sections 6–8) is based on calculated propagation ranges to the impact thresholds and accounts for the available information on their (auditory) sensitivity to sound into account.

- There are no intrinsic mitigation and management measures planned yet as part of the construction and operations plan to reduce the potential noise-induced effects of the planned activities.
- Scientific information on the importance of sound, sensitivity to underwater sound, and susceptibility to sound-induced effects on many of the marina fauna species considered in this assessment is scarce or does not exist. This restricts or precludes assessing the impact of noise-induced behavioural responses or physical impacts/hearing impairment for these animals. In the absence of sufficient site-specific or species-specific information, where available, studies at other locations, other sound sources or on phylogenetically related taxa were applied for assessing potential impacts of the planned activities at the project site.
- Scientific information is available indicating that invertebrates and fishes are sensitive to particle motion. There is, however, no information available on the importance of particle motion, and susceptibility to effects from exposure to particle motion. There are currently no thresholds for exposure to particle motion for any taxonomic group.

4.8.3. Linkages to Other EES Technical Studies

The findings of this study were used as inputs into Technical Report A: *Marine ecology and water quality impact assessment*.

5. Existing Conditions

5.1. Areas of Wildlife Conservation Value in the Project Area

In 1982, Port Phillip Bay (Western Shoreline) and Bellarine Peninsula were designated as Ramsar Site 266 under the Ramsar Convention (1971) as a wetland of international importance. The area is also part of the Swan Bay and Port Phillip Bay Islands Important Bird Area (Dutson et al. 2009), as it supports at least 1% of the flyway population of several waterbird (wader) species.

The site was designated mainly because of its value as waterbird habitat, and it was recognised as being of international importance for waders. Port Phillip Bay (Western Shoreline) and Bellarine Peninsula Ramsar Site is also significant for supporting breeding of at least 49 species of waterbird. (DEWLP 2018).

5.2. Marine Fauna occurring in the Project Area

Underwater noise can only affect receptor species that a) live permanently in the marine environment exposed to noise or enter it at least temporarily and b) are sensitive to sound or particle motion. Based on these considerations, species representing four major taxonomic groups were identified and are considered in this impact assessment (Table 11). No differentiation was made in the assessment regarding likelihood and duration of their occurrence in the project area.

The main bird species of concern in the EES are migratory waders and other waterbirds, particularly in the Ramsar wetland which is approximately 1.3 km from the FSRU and construction activity. However, these species are not considered in this assessment as they are not immersing their body partially or fully in/under the water and are therefore not likely to be impacted by underwater noise (their beaks or legs which are immersed in the water are not known to be sensitive to underwater sound); accordingly, the focus in the study being on diving birds.

Diving bird species expected to be present in the area include several pursuit diving species (penguins and cormorants), which spend a substantial amount of time underwater and dive to find food. Black swans (*Cygnus atratus*), while not a diving species per se, are equally dependent on finding food underwater, even though in the shallow inter-tidal areas where sound propagation is substantially reduced; moreover, they temporarily immerse only their head, neck, and potentially the upper part of their bodies.

Table 11. List of marine fauna species potentially occurring in the project area.

Taxonomic group	Common name	Scientific name	Status under EPBC Act/ FFG Act	Frequency range of vocalisations[1] and hearing	Sensitivity to underwater sound
Marine mammals					
Toothed whales	Bottlenose dolphin, subspecies: Burrunan dolphin[2]	*Tursiops aduncus australis*	Listed	Medium to high	High
	Short-beaked common dolphin	*Delphinus delphis*	Listed	Medium to high	High
Pinnipeds	Australian fur seal	*Arctocephalus pusillus dosiferus*	Listed	Low to medium	High
Fishes					
Finfish (Ray-finned fish, Teleost)	Australian anchovy	*Engraulis australis*	Not listed	Low	High
	Whiting	*Sillago spp.*	Not listed	Low	Moderate
	Silver sea bream	*Pagrus auratus*	Not listed	Low	Moderate
	Flathead	*Platycephalus spp.*	Not listed	Low	Moderate
	Australian grayling	*Prototroctes maraena*	Listed	Low	Moderate
Sharks, rays (Chondrynch-tyes)	Stingrays	Myliobatiformes	Not listed	Low	Low
Invertebrates					
Crustaceans	Crabs	Brachyura	Not listed	Low[3]	Unknown
Snapping shrimps	Snapping shrimp	*Alpheidae spp.*	Not listed	Low[3]	Unknown
Shellfishes/ Molluscs	Bivalves	Bivavlia	Some listed	Unknown	Unknown
Cephalopods	Squid	*Coleoidea*	Not listed	Low[2]	Moderate[3]
Avifauna[4]					
Penguins	Little (Fairy) penguin	*Eudyptula minor*	Listed	Low to medium[5]	Moderate
Cormorants	Australian pied cormorant	*Phalacrocorax varius*	Not listed	Low to medium[5]	Moderate
	Little black cormorant	*Phalacrocorax sulcirostris*	Not listed	Low to medium[5]	Moderate
	Black cormorant	*Phalacrocorax carbo*	Not listed	Low to medium[5]	Moderate
	Black-faced cormorant	*Phalacrocorax fuscescens*	Not listed	Low to medium[5]	Moderate
Swans	Black swan	*Cygnus atratus*	Not listed	Low to medium[5]	Unknown

[1] Including echolocation signals.
[2] Burrunan dolphin is considered a subspecies of the bottlenose dolphin; however, there remains controversy about its taxonomic status.
[3] Based on sensitivity to particle motion.
[4] Migratory waders and other waterbirds inhabiting the Port Phillip Bay and Bellarine Peninsula Ramsar site are not considered as they are not likely to be impacted by underwater noise.
[5] Based on in-air vocalisations.

6. Construction Impacts

Impacts were assessed based on information available on the occurrence and habitat use of the species/taxa in Corio Bay, information on their sensitivity to underwater sound, and the predicted ranges for sound levels to exceed impact thresholds around the project operations (Green et al. 2021). The impacts are described in terms of their expected magnitude, extent, and duration. The situation is assessed for the pre-mitigation and residual impacts are assessed for a post-mitigation scenario where mitigation measures are implemented to avoid, minimise, or manage impacts.

Stress

Detectable anthropogenic noise can cause stress in marine animals (e.g., Richardson et al. 1995, Nowacek et al. 2007, Erbe et al. 2019). While auditory perception of a sound per se does not automatically lead to an increased stress response and onset of stress can be considered as a gradual increase with increasing received levels, it is still impossible to quantify this impact. Moreover, it remains unclear what aspects of the noise (unfamiliarity, acoustic characteristics, behavioural context) are relevant in this context, to what extent stress is caused by noise, and what consequences an audible noise exposure would have for an individual. A conservative approach, however, would be to assume that any physical effect (e.g., hearing loss, hearing impairment) or significant behavioural response in reaction to exposure to construction noise is also associated with a stress response.

Due to the limited information about acoustically induced stress responses by marine fauna, this type of impact is not assessed in more detail for any species or activity-specific context in this impact assessment.

Acoustic masking

There is no quantitative information on the acoustic masking effect of construction activities for any marine fauna species. Based on the temporal pattern of the project-related construction and operational activities, it is likely that perception of acoustic signals will be partially or fully masked but that animals can use anti-masking strategies to release from masking (see Section 4.4.3) to compensate for the effects. A few disparate masking studies on different marine taxa provide insights into the presence of such impacts and their extent. Wherever these studies are available, the relevant results will be provided in this assessment. In general, the extent of masking effects and their ecological impact for the marine fauna cannot be fully assessed and only general qualitative statements can be made.

As for assessing stress impacts, a justifiable approach would be to assume that any physical effect (e.g., hearing loss, hearing impairment) or ecologically relevant behavioural response in response to exposure to construction noise is also associated with ecologically relevant level of auditory masking.

6.1. Noise Emissions of Construction Related Activities

6.1.1. Pile driving

The sound from impact pile driving is transient, repetitive, and discontinuous (Reinhall and Dahl 2011, McPherson et al. 2017). Sound levels produced depend on several interdependent factors such as pile size, hammer strike energy, and seabed geology. Field measurements of pile driving show that most acoustic energy is generated at frequencies <1 kHz (Robinson et al. 2007, Tougaard et al. 2009) (Figure 7), although it can extend (at greatly decreased sound levels) to much higher frequencies (MacGillivray 2018), including at least 100 kHz (Tougaard et al. 2009). The repetition rate for impact pile driving is usually in the order of 30–60 strikes per minute, depending on pile diameter and hammer type.

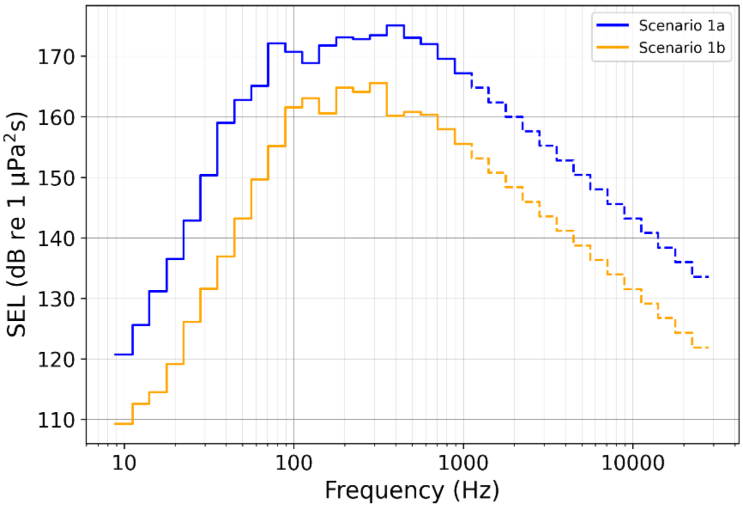


Figure 7. Maximum-over-depth decidecade band sound exposure level (SEL) at a receiver 10 m horizontally from the modelled pile driving sources. Dotted line indicates extrapolated portions of the spectra (taken from Green et al. 2021).

6.1.2. Dredging

Dredging generally produces continuous broadband sound with a peak level in the source spectrum between 100–1000 Hz (Thomsen et al. 2009, CEDA 2011, WODA 2013, Green et al. 2021) (Figure 8). Sound pressure levels can vary widely by dredger type and power, operational stage, and sediment type.

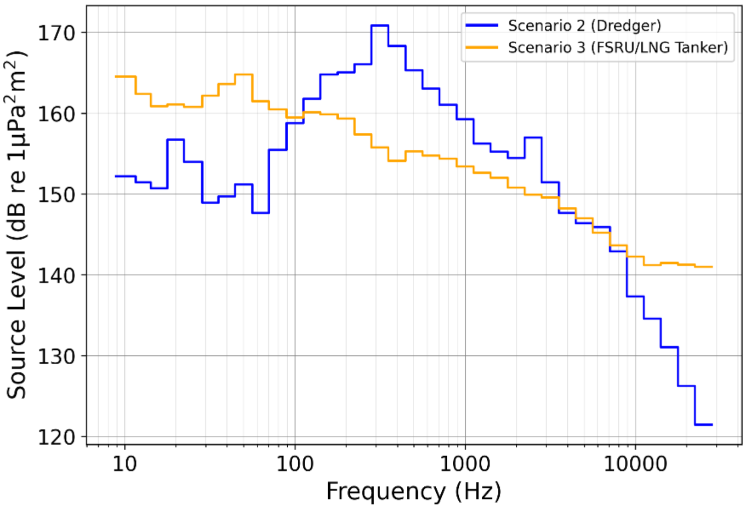


Figure 8. Decidecade band monopole source levels for dredging and vessel operations (FSRU/LNG carrier). Dredging noise spectrum derived from the backhoe dredger *New York* (Reine et al. 2014), and FSRU and LNG carrier noise spectrum derived by averaging the *Nganhurra* and *Ngujima Yin* (Erbe et al. 2013) (taken from Green et al. 2021).

6.2. Marine Mammals

6.2.1. Pile Driving

Behavioural Responses

Behavioural responses of the Burrunan dolphin and short-beaked common dolphin, which potentially occur in the project area, to impulsive noise such as emitted by impact pile driving have not been documented yet. A study on a closely related species, the Indo-Pacific bottlenose dolphin (*Tursiops aduncus*) in a busy harbour area, however, showed that impact pile driving reduced the number of animals detected in the study area (Paiva et al. 2015). Dähne et al. (2013) and Brandt et al. (2011) demonstrated avoidance of offshore pile driving activities by harbour porpoises (*Phocoena phocoena*), a smaller odontocete species over a distance of 20 km. While studies on captive animals are not necessarily representative of the behavioural responses of free-ranging animals, they provide useful information. Kastelein et al. (2013) conducted a study on a captive harbour porpoise and documented behavioural responses to playbacks of pile driving sounds. The results showed that above a received SPL of 136 dB re 1 µPa, the porpoise's respiration rate increased in response to pile driving sounds.

There is also evidence suggesting that harbour porpoises can habituate and/or adapt to impulsive anthropogenic sound in their environment (Cox et al. 2001).

Behavioural reactions of pinnipeds, such as the Australian fur seal, to pile driving impulses or comparable signals have not been investigated. A study on the effects of pile driving on ringed seals (*Phoca hispida*) at Northstar Island, Alaska, however, did not show dramatic reactions to underwater pile driving impulses with received SPL of at least 150 dB re 1 µPa (Blackwell et al. 2004). A study conducted in the North Sea, in contrast, showed that offshore pile driving caused temporary localized displacement of harbour seals (*Phoca vitulina*) of up to 25 km from the centre of the pile driving site (Russell et al. 2016).

Hearing impairment

Sounds generated by impulsive sources such as pile driving have been tested directly and proven to cause noise-induced TTS[3] in marine mammals at high received levels. Finneran (2015) reviewed the current state of knowledge on TTS and PTS. TTS typically decreases in marine mammals relative to the logarithm of the increasing recovery time. There is, however, considerable individual difference in all TTS-related parameters between subjects and species tested to date.

Marine mammal TTS data from impulsive sources are limited to two studies with measured TTS of 6 dB or higher: Finneran et al. (2002) reported behaviourally-measured TTS of 6 and 7 dB in a beluga whale exposed to single impulses from a seismic water gun and Lucke et al. (2009) reported AEP-measured TTS of 7 to 20 dB in a harbour porpoise exposed to single impulses from a seismic airgun.

In addition to these data, Kastelein et al. (2015a) reported mean TTS of 4 dB at 8 kHz and 2 dB at 4 kHz after a harbour porpoise was exposed to a series of impulsive sounds produced by broadcasting underwater recordings of impact pile driving strikes through underwater sound projectors. The cumulative SEL was approximately 180 dB re 1 μPa^2·s. The pressure waveforms for the simulated pile strikes exhibited significant “ringing” not present in the original recordings, and most of the energy in the broadcasts was between 500 and 800 Hz. As a result, some questions exist regarding whether the fatiguing signals were representative of underwater pressure signatures from impact pile driving.

Several impulsive noise exposure studies have also been conducted without measurable TTS. Finneran et al. (2000) exposed dolphins and beluga whales to single impulses from an “explosion simulator,” and Finneran et al. (2015) exposed three dolphins to sequences of ten impulses from a seismic airgun (maximum cumulative SEL: 193 to 195 dB re 1 μPa^2·s, PK: 196 to 210 dB re 1 μPa) without measurable TTS.

Pinnipeds seem to be more resilient to exposure to impulsive noise compared to cetaceans. Finneran et al. (2003) exposed two sea lions to single impulses from an arc-gap transducer with no measurable TTS (maximum unweighted SEL: 163 dB re 1 μPa^2·s, PK: 183 dB re 1 μPa). Similarly, Reichmuth et al. (2016) exposed a spotted (*Phoca largha*) and a ringed (*Pusa hispida*) seal to seismic airgun impulses with received unweighted SEL from 165 to 181 dB re 1 μPa^2 s and peak-to-peak sound pressures from 190 to 207 dB re 1 μPa but did not measure any TTS.

Impact ranges

The impact ranges, i.e., the farthest extent at which the impact thresholds for marine mammals are exceeded by pile driving noise, were modelled by Green et al. (2021) and are reproduced in Table 12 for onset of behavioural responses and Table 13 for onset of hearing impairment (TTS and PTS).

The modelling results indicate that dolphin and pinniped behaviour is likely to be affected over a range of up to 800 m from the construction site during pile driving activities. TTS is only expected in the immediate vicinity of the construction site during these activities and PTS was not predicted within the limits of the modelling resolution (20 m).

[3] No PTS experiments have been performed on marine mammals.

Table 12. Behavioural impact ranges for pile driving; horizontal distances (m) from the dolphin pile (Scenario 1a) and mooring pile (dolphin pile (Scenario 1b) to maximum-over-depth per-strike SPL isopleths based on noise exposure criteria for non-impulsive sounds (NOAA 2019) (Green et al. 2021, Section 4.1.1).

SPL (L_p; dB re 1 µPa)	1a - Dolphin Pile		1b - Mooring Pile	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
180	0.03	0.03	–	–
170	0.26	0.24	0.05	0.05
160*	**0.80**	**0.71**	**0.26**	**0.23**
150	2.00	1.48	1.05	0.93

* Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019)

Table 13. TTS ranges for marine mammals for pile driving noise based on noise exposure criteria for impulsive sounds (Southall et al. 2019); maximum (R_{max}) horizontal distances (m) from the dolphin pile (Scenario 1a) and mooring pile (dolphin pile, Scenario 1b) to maximum-over-depth weighted SEL isopleths for marine mammals (Southall et al. 2019) (Green et al. 2021, Section 4.1.1).

Hearing group	PTS					TTS				
	SEL_{24h} threshold ($L_{E,\ weighted}$; dB re 1 µPa²s)	Single pile		3 piles		SEL_{24h} threshold ($L_{E,\ weighted}$; dB re 1 µPa²s)	Single pile		3 piles	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Dolphin pile										
HF cetaceans	185	–	–	–	–	170	0.03	0.03	0.07	0.07
Otariid pinnipeds (OCW)	203	–	–	–	–	188	0.04	0.04	0.10	0.09
Mooring pile										
HF cetaceans	185	–	–	–	–	170	–	–	–	–
Otariid pinnipeds (OCW)	203	–	–	–	–	188	–	–	–	–

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Conclusions

With several piles installed per day, pile driving activity could potentially lead to a temporary and spatially limited exclusion of marine mammals from the surrounding area of the construction site. It must be noted that the behavioural threshold value for impulsive sound sources promulgated by NOAA (2019) is based on extrapolation from other species and other sound sources; moreover, the threshold assumes and regulates each sound source in isolation, i.e., it does not account for the presence of other sounds, such as from vessel or industrial activities in adjacent areas. While representing the currently most applied regulatory threshold for onset of behavioural responses in marine mammals, the NOAA thresholds are single value thresholds that do not incorporate the context specificity and complexity of animal behaviour and do not account for the severity and duration of behavioural responses. It is most likely that severity and duration of the behavioural responses increase with increasing received sound levels, i.e., ranging from subtle and short-lived responses at the outer limits of the predicted impact ranges to more severe and longer lasting responses close to the sound source. As indicated by the information published in the scientific literature, dolphins are more likely to avoid the area surrounding the construction site while pinnipeds may still venture into the area if, e.g., a good food resource can be found in the area. The potential exclusion zone is comparatively small relative to the overall habitat of the marine mammals and being excluded from the area is not likely to have any ecologically significant consequences for the animals. It is likely that the animals would gradually return into the area after the noise emissions have ceased or abated.

As dolphins and seals are known to be highly mobile species, no marine mammal is likely to stay within the TTS range of 100 m around the construction site for the entire piling sequence of even a single pile; the likelihood of incurring TTS is therefore negligible.

6.2.2. Dredging

Unless an activity like dredging occurs in an otherwise acoustically undisturbed environment, it is difficult to assess distinct impacts of a on marine mammals specifically for this activity. As the soundscape in Corio Bay is dominated by continuous sounds such as vessel traffic (Wilson et al. 2021) dredging noise contributes to the cumulative sound field in the bay and its impact merges with the potential impact of other, existing sound sources. Nevertheless, potential impacts can be assessed based on the exceedance of noise exposure thresholds for marine mammals (Section 3.2.2).

Behavioural Responses

There are a few studies involving dredges, although these included very limited information about the sound levels during the exposures. Using fixed PAM (T-PODs, Chelonia Ltd., UK), Diederichs et al. (2010) found short-term avoidance in harbour porpoises at ranges of 600 m from a trailing suction hopper dredger operating to the west of Sylt (Germany, North Sea). Pirotta et al. (2013) also noted that presence of bottlenose dolphins in foraging areas in Aberdeen Harbour, Scotland, declined as dredging intensity increased. Aberdeen Harbour is subject to high shipping activity year-round, and thus dolphins are accustomed to high levels of vessel disturbance. In this case, it was possible for the authors to link avoidance to dredging activity noise and not vessel presence in general.

Hearing impairment

Noise-induced hearing impairment from exposure to non-impulsive sound such as vessel or dredging operations has not been directly observed or measured in free-ranging marine mammals. Many studies have been conducted on marine mammals in controlled conditions to investigate noise-induced threshold shift phenomena. The experiments have focused on measuring TTS exposed to intense tones and band-limited noise with various sound pressure levels, frequencies, durations, and temporal patterns. These studies have been performed with bottlenose dolphins and beluga whales (*Delphinapterus leucas*), and a harbour porpoise exposed to tones with durations ranging from 1 s to 1 h. Most of these studies employed non-impulsive exposures, though four studies used intermittent tones (Mooney et al. 2009, Finneran et al. 2010, Kastelein et al. 2014, Kastelein et al. 2015b). Tonal signals may be used to represent the effects of military sonars, fish finders, depth sounders, and other sources emitting narrowband signals but cannot be taken as proxy for exposure to vessel or dredging noise. The only generalisations that can be made from the results of these studies is that the temporal pattern of noise exposure affects the resulting threshold shift and for intermittent noise, the quiet periods between noise exposures allow some recovery of hearing thresholds compared to noise that is continuously present with the same total SEL (Ward 1997).

Impact ranges

The impact ranges, i.e., the farthest extent at which the impact thresholds for marine mammals are exceeded by dredging noise, were modelled by Green et al. (2021) and are reproduced in Table 14. for onset of behavioural responses and Table 15 for onset of hearing impairment (TTS and PTS). Dredging noise is classified as a continuous sound type and governed by substantially lower thresholds for onset of behavioural responses in marine mammals compared to impulsive noise. While the SPL levels are lower for dredging than for pile driving, the impact ranges are extending to a maximum of 1.84 km from the source.

Table 14. Behavioural impact ranges for marine mammals for dredging noise based on noise exposure criteria for non-impulsive sounds (NOAA 2019); horizontal distances (m) from the dredger (Scenario 2a Berth & swing basin dredging; Scenario 2b: Seawater pipe dredging) to maximum-over-depth per-strike SPL isopleths are given (Green et al. 2021, Section 4.2.1).

SPL (L_p; dB re 1 µPa)	2a – Berth & swing basin Dredging		2b – Seawater pipe Dredging	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
140	0.12	0.11	0.15	0.14
130	0.80	0.64	0.51	0.47
124.6[a]	1.11	1.01	1.16	1.00
119.6[b]	1.60	1.47	1.90	1.66
120[c]	**1.55**	**1.43**	**1.84**	**1.60**

[a] Median ambient level.
[b] 5th percentile ambient level
[c] Marine mammal behavioural threshold for non-impulsive sounds (NOAA 2019)

Table 15. TTS ranges for marine mammals for dredging noise based on noise exposure criteria for non-impulsive sounds (Southall et al. 2019); maximum horizontal distances (m) from the dredging scenarios (Scenarios 2a and b) to maximum-over-depth weighted SEL isopleths are given. PTS thresholds were not exceeded. (Green et al. 2021, Section 4.2.1).

Hearing group	SEL_{24h} threshold ($L_{E,\ weighted}$; dB re 1 µPa²s)	2a – Berth & swing basin Dredging		2b – Seawater pipe Dredging	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
HF cetaceans	178	0.01	0.01	0.01	0.01
Otariid pinnipeds (OCW)	199	<0.01	<0.01	0.01	0.01

Conclusions

Dredging during construction could potentially lead to a temporary and spatially limited exclusion of marine mammals from the surrounding area of the construction site. As pointed out for impulsive (pile driving) noise, it must be noted that the behavioural threshold value for non-impulsive sound sources promulgated by NOAA (2019) is also based on extrapolation from other species and other sound sources; moreover, the threshold assumes and regulates each sound source in isolation, i.e., it does not take the presence of other sounds such as from vessel or industrial activities in adjacent areas into account. While representing the currently most applied regulatory threshold for onset of behavioural responses in marine mammals, the NOAA thresholds are single value thresholds that do not incorporate the context specificity and complexity of animal behaviour and do not account for the severity and duration of behavioural responses. It is most likely that severity and duration of the behavioural responses increase with increasing received sound levels, i.e., ranging from subtle and short-lived responses at the outer limits of the predicted impact ranges to more severe and longer lasting responses close to the sound source. As indicated by the information published in the scientific literature dolphins are more likely to avoid the area surrounding the construction site while pinnipeds may still venture into the area if, e.g., a good food resource can be found in the area. The potential exclusion zone is comparatively small relative to the overall habitat of the marine mammals and being excluded from the area is not likely to have any ecologically significant consequences for the animals. It is likely that the animals would gradually return into the area after the noise emissions have ceased or abated.

With TTS ranges of 10 m or less, this impact is not expected to occur in marine mammals from exposure to dredging noise as they are highly mobile species and are unlikely to stay close to the area during dredging.

6.3. Fishes

6.3.1. Pile Driving

Behavioural responses

The published information on behavioural responses of fishes to pile driving sound is relatively scarce. Ruggerone et al. (2008) conducted a behavioural response study in juvenile Coho salmon (*Oncorhynchus kisutch*) that were held in cages next to a pile driving operation in a harbour. No apparent change in behaviour during the pile driving was reported, as less than 10% of the fishes exhibited a startle response during the first or subsequent hammer strikes of each pile.

In controlled exposure experiment, Mueller-Blenkle et al. (2010) exposed Atlantic cod and sole (*Solea solea*) held in two large (40 m) net pens located in a quiet bay to playbacks of pile driving noise. They tracked their movements visually and quantified both the received sound pressure level and particle motion. Sole showed an increase in swimming speed at received peak sound pressure levels (PK) of 144–156 dB re 1µPa, and cod exhibited significant freezing response at onset and cessation of playback at received peak sound pressure levels of 140–161 dB re 1 µPa (particle motion was determined to be between 6.51 × 10^{-3} $^{m}/s^2$ peak and 8.62 × 10^{-4} $^{m}/s^2$ peak). The authors report a high variability in behavioural reactions across individuals and a decrease of response with multiple exposures.

In a sound playback experiment in an enclosed, quiet, coastal sea lough, Hawkins et al. (2014) exposed free-living pelagic fishes to sound playback of synthetic, low-frequency, impulsive sounds, mimicking some of the features of sounds produced by pile drivers and seismic airguns. Behavioural responses of fishes were observed with a sonar/echo sounder. The fishes they encountered were predominantly sprat and Atlantic mackerel (*Scomber scombrus*) and were not accustomed to heavy disturbance from shipping and other intense sound sources. Following a short latency, sprat schools reacted to sound exposure with lateral dispersal, taking them outside the sonar beam. The fishes often then reappeared at a greater depth recombined into a school. Mackerels responded by dispersing and/or a rapid depth change. The lowest received sound pressure level (PK-PK) eliciting a response in free-living sprat was 140 dB re 1 µPa, while mackerel responded to a received sound pressure level of 143 dB re 1 µPa. There was an increase in the proportion of sprat and mackerel schools responding to sound playback with increasing sound levels. The 50% response level for sprat was at a received sound pressure level (peak-to-peak, PK-PK) of 163.2 dB re 1 µPa, for mackerel schools the 50% level was reached at a peak-to-peak sound pressure level (PK-PK) of 163.3 dB re 1 µPa.

Acoustic masking

There are no studies investigating the effect of dredging noise on fish; instead, results from studies on effects of another non-impulsive sounds source, vessel operations, is used as a proxy here.

Scholik and Yan (2001), Vasconcelos et al. (2007), and Codarin et al. (2009) demonstrated masking effects due to vessel noise in several marine fish families. They measured decreased hearing sensitivities between 10 dB and more than 30 dB in the presence of vessel noise.

Codarin et al. (2009) investigated the effects of ambient and ship noise on representatives of three vocal fish families with different hearing abilities. In their laboratory study, they found that the noise emanating from recreational shipping substantially masked the auditory perception in these fish species, with a pronounced effect on the frequencies used for communication.

Stanley et al. (2017) modelled the effective communication range in Atlantic cod and haddock at three spawning locations. These areas are characterised by elevated levels of anthropogenic underwater sound, particularly due to commercial shipping. They found near constant high levels of low-frequency sound and consequentially a reduction in the communication space during times of high vocalisation activity for these fish species.

TTS/PTS

Casper et al. (2013) used a specially designed wave tube to expose hybrid striped bass (white bass *Morone chrysops* and striped bass *Morone saxatilis*) and Mozambique tilapia (*Oreochromis mossambicus*) to pile driving sounds and investigated the effects on hair cells. Exposure to 960 pile driving strikes at SEL_{24h} levels of 210–216 dB re 1 µPa^2·s caused barotraumas in both species. Hair cells loss, in contrast, was only found at significant levels after exposure to the highest sound level in some striped bass and in a single tilapia.

Injury and Mortality

Casper et al. (2012b) showed that fishes can recover from less severe injuries under laboratory conditions, suggesting that minor injuries do not inevitably lead to mortality. Nevertheless, in open waters, minor injuries have the potential to reduce the animal's fitness to the extent that its ability to find food decreases and its risk of being predated increases (Halvorsen et al. 2011, 2012b).

Mortality is either a direct effect of barotrauma (in the case of severe injury) or indirect if an animal is moderately injured. Halvorsen et al. (2011, 2012a, 2012b) exposed different fish species in a well-controlled acoustic environment (using a wave tube) to signals replicated from actual pile driving operations and found that the extent of injury increased with sound exposure levels and number of pile driving strikes. Their results demonstrated that an appropriate metric for guidelines may be a combination of the single strike SEL (SEL_{ss}) and the number of strikes that are used to yield the SEL value, with the understanding that at the same SEL value, higher SEL_{ss} and fewer strikes can result in the same onset of effects as a lower SEL_{ss} and more strikes (Popper et al. 2014).

Data on sound-induced direct mortality in fishes are scarce and mainly related to underwater explosions (Popper and Hastings 2009). Observations conducted during pile driving activities showed that fishes within a few metres of driving a large pile were killed (Caltrans 2001, 2004), but no data from these studies document the sound levels to which the fishes were exposed or the extent of exposure before mortality occurred. At greater distances from pile driving activities, data from caged fishes show no mortality and no damage that can be clearly associated with pile driving activities (Abbott et al. 2005, Nedwell et al. 2006, Ruggerone et al. 2008, Caltrans 2010a, 2010b, Houghton et al. 2010).

Impact ranges

Pile driving noise is expected to exceed the noise exposure thresholds for recoverable injury at a distance of up to 60 m and the threshold for onset of TTS at a distance of up to 870 m from the sound source (Table 16).

Table 16. Impact ranges for fishes for pile driving noise; horizontal distances (m) from the pile driving site (Scenario 1a Dolphin pile; Scenario 1b: Mooring pile) to maximum-over-depth unweighted SEL isopleths for fish (Popper et al. 2014) (taken from Green et al. 2021, Section 4.1.1). A dash indicates the threshold was not reached within the limits of the modelling resolution.

Hearing group	SEL_{24h} threshold (L_E; dB re 1 µPa²s)	1a – Dolphin pile				1b – Mooring pile			
		Single pile		3 piles		Single pile		4 piles	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Mortal Injury									
Fish: No swim bladder	219	—	—	—	—	—	—	—	—
Fish: Swim bladder not involved in hearing; and eggs and larvae	210	—	—	0.02	0.02	—	—	—	—
Fish: Swim bladder involved in hearing	207	0.02	0.02	0.03	0.03	—	—	—	—
Recoverable Injury									
Fish: No swim bladder	216	—	—	—	—	—	—	—	—
Fish: Swim bladder not involved in hearing; and swim bladder involved in hearing	203	0.03	0.03	0.06	0.06	—	—	—	—
TTS									
Fish: No swim bladder; swim bladder not involved in hearing; and swim bladder involved in hearing	186	0.52	0.48	0.87	0.77	0.05	0.05	0.11	0.10

Conclusions

Behavioural effects in fishes caused by exposure to pile driving are likely limited to changes in their vertical position in the water column, their aggregation behaviour and spatial avoidance of the ensonified area. Based on the qualitative criteria developed by Popper et al. (2014), there is a moderate likelihood that Australian anchovy, the only fishes species in the project area with high sensitivity to underwater sound, would be exposed to noise levels exceeding their threshold for onset of behavioural responses at ranges exceeding 1 km; behavioural impact ranges for all other fish species are likely limited to ranges closer to the sound sources, i.e., more likely in the range of 10–100 m. It is likely that that the animals would gradually return into the area after the noise emissions have ceased or abated.

The ranges to recoverable injury and onset of TTS for all fish species range between are 60 m and 870 m, respectively for pile driving noise. However, given that the duration required to accumulate the acoustic energy to reach the threshold is 12 and 48 hours, respectively, it is unlikely that any fish species would experience such impacts.

6.3.2. Dredging

As specific information on impact of dredging noise on fishes is not available, knowledge about impact of another continuous noise source, vessel noise, must be used as a proxy.

Behavioural responses

Fishes can respond to approaching vessels by diving towards the seafloor or by moving horizontally out of the vessel's path, with reactions often initiated well before the vessel reaches the fishes (Ona et al. 2007, Berthe and Lecchini 2016). The avoidance of vessels by fishes has been linked to the high levels of infrasonic and low-frequency noise (>10 to 1000 Hz) emitted by the ships. Accordingly, it was suggested that silent ships have a higher chance of encountering more fishes than noisier ones (De Robertis et al. 2010). This assumption was initially contradicted when two research vessels were compared with regard to their effect on schooling herring (Ona et al. 2007). The authors found that the reaction initiated by the silent vessel was stronger and more prolonged than the one initiated by the conventional vessel. In a comment to this publication, Sand et al. (2008) pointed out that fishes are highly sensitive to particle acceleration and that the cue, in this case, may have been low-frequency particle acceleration caused by displacement of water by the moving hull in the near field of the vessel. This fact would explain the stronger response to the larger noise-reduced vessel in the study by Ona et al. (2007), which would have displaced more water as it approached.

Nedelec et al. (2016) investigated the response of reef-associated fishes by exposing them in their natural environment to playback of motorboat noise. They found that juvenile fishes increased hiding and ventilation rate after a short-term boat noise playback, but responses diminished after long-term playback thus indicating habituation to sound exposure over longer durations. These results were corroborated by Holmes et al. (2017) who also observed short-term behavioural changes in juvenile reef fishes after exposure to boat noise as well as desensitisation over longer exposure periods.

Hearing impairment

A single study reported temporary threshold shift caused by exposure to vessel noise: Scholik and Yan (2001) exposed fathead minnows (*Pimephales promelas*) for 2 h to sound playback recorded from small boats at a level of 142 dB re 1 µPa. They measured noise-induced threshold shift (NITS) of 7.8–13.5 dB at frequencies between 1–2 kHz, the most sensitive hearing range of this species.

Impact ranges

Dredging noise is expected to exceed the noise exposure thresholds for recoverable injury and TTS at a distance of 10 m from the sound source (Table 17).

Table 17. Impact ranges for fishes for dredging noise; horizontal distances (m) from the dredger (Scenario 2a Berth & swing basin dredging; Scenario 2b: Seawater pipe dredging) to maximum-over-depth per-strike SPL isopleths based on noise exposure criteria for vessel noise (Green et al. 2021, Section 4.2.1). A dash indicates the threshold was not reached within the limits of the modelling resolution.

SPL (L_p; dB re 1 µPa)	2a – Berth & Swing basin Dredging		2b – Seawater pipe Dredging	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
170*	**<0.01**	**<0.01**	–	–
160	0.01	0.01	0.01	0.01
158+	**0.01**	**0.01**	**0.01**	**0.01**
150	0.04	0.04	0.03	0.03

* Temporary threshold shift in fishes, 12 hours exposure (Popper et al. 2014)

+ Recoverable injury threshold for fishes, 48 hours exposure (Popper et al. 2014).

Conclusions

Behavioural effects in fishes caused by exposure to dredging noise are likely limited to changes in their vertical position in the water column, their aggregation behaviour and spatial avoidance of the ensonified area. Based on the qualitative criteria developed by Popper et al. (2014), there is a moderate likelihood that fish species in the project area would be exposed to noise levels exceeding their threshold for onset of behavioural responses at ranges up to 100 m. It is likely that the animals would gradually return into the area after the noise emissions have ceased or abated.

The ranges to onset of TTS and recoverable injury for fishes are 10 m or less for dredging noise; given that the duration required to accumulate the acoustic energy to reach the threshold is 12 and 48 hours, respectively, it is unlikely that any fishes would experience such impacts.

6.4. Invertebrates

It remains unclear what physical parameters of underwater sound marine invertebrates are sensing (see Section 4.3.3) and what role and ecological relevance sound has for these species. Accordingly, studies conducted on impacts of noise focus on different effects for these species as compared to marine mammals and fishes, i.e., morphological, and physiological studies and investigations of abundance and mortality replace studies of behavioural responses and auditory impairment. There are no noise exposure criteria for invertebrates and, accordingly, impact ranges were not calculated.

6.4.1. Pile Driving

Specific information about effects of sound from offshore pile driving activities on invertebrates is not available. Instead, information on effects of another impulsive sound source, marine seismic airguns, is used as proxy for assessing the potential effects of pile driving. It must be noted though that sound levels emitted by the two sources and other acoustic signal characteristics differ between the two signal types, and therefore results from seismic airguns can only be taken as indicative of potential effects of pile driving.

Moreover, pile driving impulses introduce a substantial amount of energy into the sediment which may be detected by bottom-living marine invertebrates as ground vibration and induce behavioural responses (Roberts et al. 2015, Roberts and Elliott 2017). Many marine invertebrates are permanently, or at least sporadically, in contact with bottom sediment. The sediment, however, does not follow exactly, or at all, the movement of the surrounding water. Therefore, exposure to underwater sound will result in a relative movement between the body of these animals and the oscillating water column. Accordingly, marine benthic invertebrates face a different situation and perception from free-swimming or neutrally buoyant animals such as demersal or pelagic fishes or marine mammals. In a discussion of the pressure-related as well as the particle motion-related sensitivity in marine invertebrates, it is therefore important to also consider the propagation of vibration through the ground. For benthic organisms, it is likely that this type of vibration is of similar if not greater importance than the water-borne vibration or even the compressional component of a sound (Roberts and Elliott 2017). The published scientific information on vibration sensitivity in marine invertebrates is extremely scarce (Roberts et al. 2015, Roberts et al. 2016). Most information on vibration sensitivity has been derived from semi-terrestrial species known to use vibration in mating behaviour (Aicher and Tautz 1990). Only a small number of studies have indicated reception of vibration and behavioural responses in bivalves, which include closing syphons and, in more active molluscs, moving away from the substrate (Mosher 1972, Ellers 1995, Kastelein 2008). Nevertheless, to date, there is no convincing evidence for any significant effects induced by non-impulsive noise in benthic invertebrates.

Due to the lack of quantitative information on the impacts of such exposure, however, it is impossible to specifically assess the effect of substrate-borne vibration on marine invertebrates. Moreover, given the rapid attenuation of vibrational signals beyond the near field of a sound source (Morley et al. 2014), it is unlikely that these stimuli are causing more than behavioural effects (such as flight or retraction) or physiological (e.g., stress) responses.

In the case of marine invertebrates living at least temporarily in the water column, several studies have investigated their susceptibility to noise-induced effects:
Aguilar de Soto et al. (2013) indicated that New Zealand scallop (*Pecten novaezelandiae*) larvae exposed to extended periods of airgun signals during their ontogeny may be negatively affected. The authors found an increase in abnormality and mortality rates in scallop larvae after continued exposure to playbacks of intense airgun signals in a laboratory experiment. These results indicated that there may be species-specific differences in sensitivity of early life stages to sound exposure.

In a field study, Przeslawski et al. (2016) focused on potential short-term impacts of marine seismic surveys on scallops in the Gippsland Basin. Commercial scallops (*Pecten fumatus*) were not abundant in the study area, and there was no evidence of mortality or change in the condition of scallops two months after a marine seismic survey ended. Analysis of images and samples revealed site-specific variance in scallop abundance, size, condition, and assemblages were higher than the observed effects from exposure. The analysis of the acoustic parameters, however, is likely compromised by unsuitable use of acoustic modelling methods and no close-range recordings.

Morris et al. (2018) assessed the effects of industry scale seismic exposure on catch rates of snow crab (*Chionoecetes opilio*) along the continental slope of the Grand Banks of Newfoundland. In a Before-After-Control-Impact study over two years they did not find evidence supporting the contention that seismic activity negatively affects catch rates in shorter term (i.e., within days) or longer time frames (weeks). However, significant differences in catches were observed across study areas and years. Their results suggest that if effects from exposure to seismic airgun impulses on snow crab harvests do exist, they are smaller than changes related to natural spatial and temporal variation.

Day et al. (2019) tested the impact of seismic surveys on the righting reflex and statocyst morphology of the rock lobster (*Jasus edwardsii*). Their results show that exposure to seismic airgun impulses with calculated received PK levels of up to 205 dB re 1 µPa and maximum SEL of 191 dB re 1 $\mu Pa^2 \cdot s$ can cause morphological damage to the sensory organ of rock lobster. Two reflex behaviours, tail tonicity or extension and righting behaviour, were assessed. These reflexes have been used in lobster fishery industries in grading animals for their likelihood of survival. While results for tail tonicity were inconclusive, there was a significant response to exposure in the righting response, which is a more complex reflex requiring neurological control and muscle coordination. The lobsters showed impaired righting and significant damage to the sensory hairs of the statocyst. Reflex impairment and statocyst damage persisted over the course of the experiments and did not improve following moulting.

Consistent with other studies of high-intensity, low-frequency sound exposure of crustaceans and molluscs (reviewed by Edmonds et al. 2016, Carroll et al. 2017), the study found no evidence of mass mortality directly following airgun exposure. Consequently, the authors rejected the hypothesis that exposure to seismic airguns causes immediate mass mortality.

Day et al. (2017) investigated the effect of exposure to airgun impulses on scallops (*Pecten fumatus*). The authors conclude that exposure to seismic signals significantly increases mortality, particularly over a chronic (months post-exposure) time scale, though not beyond naturally occurring rates of mortality. The calculated maximum PK levels at the position of the bivalves reached 213 dB re 1 µPa and maximum SEL of 198 dB re 1 $\mu Pa^2 \cdot s$.

Attention has also been given to potential impacts of underwater noise on cephalopods; Guerra et al. (2004) found statocyst and organ damage in seven stranded giant squids and considered these findings as circumstantial evidence for noise-induced effects caused by nearby seismic surveys. McCauley et al. (2000) and Fewtrell and McCauley (2012) conducted controlled exposure experiments with caged squid (*Sepioteuthis australis*) using a single seismic airgun as the sound source. They found that in one trial, where the received level of the first seismic air gun impulse was 162 dB re 1 μPa²·s, the squid inked (an alarm response). This response was not observed again within this trial, however the authors stated that it was unknown if this was due to depleted ink reserves or habituation. In two other trials, the initial received levels were lower (132 and 146 dB re 1 μPa²·s per-pulse SEL), and although the received levels did exceed 162 dB re 1 μPa²s, no inking behaviour was observed. Exposure to airgun impulses at sound levels greater than 147 dB re 1 μPa²·s induced the caged squid to start jetting away from the sound source (i.e., an avoidance behaviour). The authors hypothesised that the results also suggest that a gradual increase in received levels and prior exposure to seismic air gun impulses decreases the severity of the alarm responses in this species, i.e., the animals likely habituated to the sound exposure. This aligns with findings of general habituation in response to predators in squid (Long et al. 1989). While Fewtrell and McCauley (2012) stated that their results were preliminary, the level associated with inking (162 dB re 1 μPa²·s per-pulse SEL) has been considered as a startle response threshold for both squid and octopus (relevant particle motion levels were not reported by the authors).

6.4.2. Dredging

No specific information about effects of sound emitted by offshore drilling activities on bivalves and decapods is available. Instead, information on impacts from vessel noise and other non-impulsive sound sources is used as proxy information for assessing the potential impact of dredging noise on marine invertebrates.

Filiciotto et al. (2016) examined the effects of recorded boat noise on the behaviour and biochemistry of the common prawn (*Palaemon serratus*). The exposure elicited changes in locomotor patterns and caused physiological and behavioural effects that the authors identified as stress-related responses. Two tank-based experiments investigated the physiological and behavioural effects of sound exposure on marine invertebrates. The sound generated by tidal and wind turbines was found to delay the time to metamorphosis between larval stages in estuarine crabs (Pine et al. 2012). Celi et al. (2013) documented statistically significant variations in haemato-immunological parameters as well as a reduction in agonistic behaviour in red swamp crayfish (*Procambarus clarkii*) after constant exposure to frequency sweeps over a duration of 30 min. The signals covered a frequency range between 0.1–25 kHz and reached a peak amplitude 148 dB re 1 μPa at 12 kHz.

Mooney et al. (2016) tested unconditioned behavioural responses to tonal signals in squid (*Doryteuthis pealeii*). The reactions elicited by sound exposure from 80 Hz to 1 kHz ranged from inking and jetting to body pattern changes and fin movements. Animals responded to the lowest sound levels in the 200–400 Hz range.

Morphological impact

André et al. (2011) and Solé et al. (2013) provide evidence of acoustic trauma in different cephalopod species (*Sepia officinalis*, *Octopus vulgaris*, *Loligo vulgaris*, and *Illex condietii*) that they exposed (underwater) for 2 h to low-frequency sweeps between 50–400 Hz (1 s duration) generated by an in-air speaker. The received level at the animals' position was 157 dB re 1 μPa with peak levels (unspecified) up to 175 dB re 1 μPa. Both studies report permanent and substantial morphological and structural alterations of the sensory hair cells of the statocysts following noise exposure with no indication of recovery. In a more recent experiment, Solé et al. (2017) exposed common cuttlefish (*Sepia officinalis*) to tonal sweeps between 100–400 Hz in a controlled exposure experiments in open water. Their results show a clear statistical relationship between the cellular damage detected in the sensory cells of the individuals exposed to the sound sweeps and the distance to the sound source.

The authors measured the particle motion and pressure of the signals received by the animals. Due to the signal type (frequency sweep), they could only provide the maximum received levels or an estimate thereof, respectively; the maximal particle motion level was 0.7 ms^{-2} observed at 1 m depth, the pressure reached levels of 139–142 dB re $1 \mu Pa^2$. The sound pressure levels reported are only slightly higher than the hearing threshold determined for longfin squid (*Loligo pealeii*), another decapodiforme cephalopod, measured by Mooney et al. (2010). The maximum particle motion (reported in terms of particle acceleration) reported by Solé et al. (2017) is in the same order of magnitude as the behavioural thresholds measured at 100 Hz by (Packard et al. 1990) using a standing wave acoustic tube.

Conclusions

There are limited and inconclusive data available on the potential for behavioural responses and noise-induced physical effects on marine invertebrates. Theoretically, behavioural responses as well as significant sensory impairment or injury can have moderate to major consequences for an individual. In the absence of conclusive scientific information on important aspects such as the relevant physical parameters, sensory system responsible for detecting the noise, the scope of noise-induced effects and the animals' ability to compensate for the effects, however, it is impossible to assess the consequences of behavioural responses and noise-induced impairment or injury.

6.5. Avifauna

Given the small amount of information available on impacts of underwater noise on diving birds this section is assessing the potential impacts of pile driving and dredging together.

The limited scientific information on behavioural responses of flying seabirds to underwater sound indicates that the response can be species- and context-specific, i.e., responses depend on several factors (including but not limited to): life history characteristics of the species, characteristics of the noise source, sound source intensity, onset rate, distance from the noise source, presence or absence of associated visual stimuli, food and habitat availability, and previous exposure. Previous studies documented a range of bird behavioural responses to in-air noise, including no response, head turn, alert behaviour, startle response, flying or swimming away, diving into the water, and increased vocalisations (Larkin et al. 1996, Stalmaster and Kaiser 1997, Pytte et al. 2003, Plumpton et al. 2007).

To date, there have been few studies regarding behavioural responses by flying seabirds to impulsive underwater sound sources. Stemp (1985; as cited in Golde and Houtman (2012) conducted observations on the effects of impulsive sounds generated by a seismic exploration on seabirds and did not observe any negative effects.

Lacroix et al. (2003) investigated the effect of near shore seismic surveys on moulting long-tailed ducks in the Beaufort Sea, Alaska, and found no noticeable impacts on the movements or diving behaviour of ducks. During moult, the ducks' flight abilities are limited, and food requirements are high. The animals may have tolerated the seismic survey noise to stay in preferred feeding areas. Furthermore, Lacroix et al. (2003) noted that seismic (i.e., impulsive) activity did not appear to substantially change the ducks' diving intensity.

Melvin et al. (1999) examined the effect of acoustic deterrence devices (pingers) installed on fishing nets on two species of diving birds, the common murre and rhinoceros auklet (*Cerorhinca monocerata*). Fewer common murres were entangled in gillnets when the gillnets were outfitted with 1.5 kHz pingers with a source level of 120 dB re 1 µPa; however, there was no significant reduction in rhinoceros auklet bycatch in the same nets (Melvin et al. 1999, Melvin et al. 2011). Because the catchability of the nets was not reduced during the pinger trials (as compared to control trials), the murres' behavioural response was likely mediated through its acoustic perception of the signals.

Pichegru et al. (2017) investigated the behavioural response of breeding endangered African penguins to seismic surveys within 100 km of their colony in South Africa. Penguins showed a strong avoidance of their preferred foraging areas during seismic activities; foraging took place significantly farther from the survey vessel when in operation, while increasing their overall foraging effort and energy expenditure. The birds reverted to normal behaviour when the operation ceased.

In a controlled exposure experiment, Sørensen et al. (2020) exposed seven gentoo penguins (*Pygoscelis papua*) to underwater noise bursts (i.e., impulsive signals) and documented that the animals showed a graded reactions ranging from no reactions at 100 dB re 1 µPa SPL to strong reactions in more than 60% of the playbacks at 120 dB re 1 µPa SPL.

There is also insufficient information available to determine the onset thresholds of behavioural responses of diving birds from non-impulsive noise such as vessel or dredger noise; therefore, this assessment has not considered potential effects from non-impulsive noise on behaviour of diving birds.

Impact ranges

Pile driving impulses can be assumed to lead to birds avoiding the area up to a 5.76 km distance (Table 18).

Table 18. Behavioural impact ranges for diving birds for pile driving; horizontal distances (m) from the dolphin pile (Scenario 1a) and mooring pile (dolphin pile (Scenario 1b) to maximum-over-depth per-strike SPL isopleths (Green et al. 2021, Section 4.1.1)

SPL (L_p; dB re 1 µPa)	1a - Dolphin Pile		1b - Mooring Pile	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
140	4.04	2.69	2.20	1.91
130	5.12	4.23	3.70	3.23
124.6[a]	6.04	5.10	4.58	3.92
120[b]	**5.76**	**4.90**	**4.30**	**3.62**
119.6[c]	6.64	5.68	5.46	4.62

[a] Median ambient level
[b] Diving bird behavioural response threshold (OCW weighted) for impulsive noise (Sørensen et al. 2020).
[c] 5th percentile ambient level

The results documented by Sørensen et al. (2020) provide the only data set allowing to define an onset threshold for behavioural responses of birds to underwater noise; however, their results are only applicable to impulsive noise.

There is no criterion for hearing impairment (TTS) for birds; impact ranges for TTS (Table 19) were analysed based on noise exposure criteria for other carnivores in water (OCW) (see rationale in Section 3.2.5).

Table 19. TTS ranges for diving birds for dredging noise based on noise exposure criteria for non-impulsive sounds (Southall et al. 2019). PTS thresholds were not exceeded. Maximum (R_{max}) horizontal distances (m) from the dolphin pile (Scenario 1a) and mooring pile (Scenario 1b) to maximum-over-depth weighted SEL isopleths for marine mammals (Southall et al. 2019) (Green et al. 2021, Section 4.2.1). N/A = not applicable.

Hearing group	SEL_{24h} threshold ($L_{E,\ weighted}$; dB re 1 µPa²s)	1a – Dolphin Pile		1b – Mooring Pile		2a – Berth & swing basin Dredging		2b – Seawater pipe Dredging	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Pile driving									
Diving birds; proxy: Otariid pinnipeds (OCW)	188	0.04	0.04	0.10	0.09	N/A	N/A	N/A	N/A
Dredging									
Diving birds; proxy: Otariid pinnipeds (OCW)	199	N/A	N/A	N/A	N/A	<0.01	<0.01	0.01	0.01

Conclusions

It can be expected that pursuit-diving seabirds such as cormorants and penguins react to underwater sound emissions by altering or abandoning their foraging pursuits; penguins are likely to avoid ensonified areas for the duration of a sound-producing activity before returning to their habitat. It is unrealistic to assume a concrete risk for diving birds to be exposed to TTS-inducing sound levels from pile driving or dredging, as birds would have to dive constantly for 24 h (as per definition of the criterion) in a very small area (between 10 m and 100 m) around the sound sources to exceed the threshold.

6.6. Summary of Construction Impacts

Pile driving and dredging during construction would lead to a temporary and localised increase in underwater noise levels in the vicinity of the project area. Two important aspects must be considered when assessing the noise impacts related to the construction activities in Corio Bay:

1. The existing ambient noise level in the project area is high and may exceed some of the existing noise exposure criteria. Adding another noise source to the existing condition will only slightly increase the noise level in the bay but lead to an increase in levels in the vicinity of the activities.
2. The relevant information on cause-effect relationships between noise emitted by the construction activities and their impact on marine fauna are scarce or non-existent, often not specific to the type of activity (or noise emitted) or species occurring in the project area, or inconclusive. Consequently, some types of impact cannot be assessed, and/or information must be extrapolated from other species, sound sources, and even different sound types.

In an unmitigated ‘worst-case’ scenario, the most significant impacts to be expected are temporary behavioural responses over a range of several hundred metres for most species (fish and marine mammals) and for diving birds (when submerged) up to several kilometres from the project area. The impact ranges presented in this assessment indicate the onset of behavioural responses which are likely of little or no ecological relevance at their lowest level of severity and only become more severe and relevant the closer the animals are to the sound source(s). It can be expected that at received levels above the threshold, animals would react by subtly altering their behaviour. At higher received levels, i.e., closer to the sound source, where noise levels are generally higher, it is likely that animals

would abandon current behaviour. Ultimately, at the highest received levels animals would avoid the area for the duration of the sound-producing activity. The potential avoidance zones are comparatively small relative to the overall habitat of the marine mammals, birds and fishes and being excluded from these areas is not likely to have any ecologically significant consequences for the animals. It is likely that the animals would gradually return into the area after the noise emissions have ceased or abated.
.

With a reasonable (proportional) set of mitigation measures implemented, the underwater noise emitted by the construction activities is not likely to have unacceptable impacts on the marine fauna in Corio Bay. Recommended mitigation measures to avoid, minimise and manage potential impacts related to underwater noise are discussed in Section 9.

7. Operation Impacts

The operational scenarios assessed in this report for the new facility include the berthed FSRU (scenario 3a) and the FSRU berthed with an LNG carrier offloading simultaneously (scenario 3b), representing the operation of the new facility during regasification.

There is no empirical information on impacts specific to the activities for either of the two scenarios; instead, general information about the noise impacts of vessel operations is used to inform this assessment (thereby reusing some of the material presented for dredging noise in Sections 6.1.2, 6.2.2, 6.3.2, 6.4.2, and 6.5). That information is replicated in the sections below to provide a complete reference framework.

The results of the propagation modelling and the assessment of acoustic impacts, while similar to those for the dredging assessment, are specific to the noise emitted by the operational activities.

7.1. Marine Mammals

Behavioural reactions

While there is no information available on behavioural responses of marine mammals to FSRUs or LNG carriers, several scientific studies investigated the effect of vessel on marine mammal (mainly cetacean) behaviour. However, an important aspect to consider when trying to extrapolate from these studies to the project is that the FSRU and LNG carrier are stationary while all behavioural observations of marine mammals were conducted on moving vessels. Cetaceans have been shown to react to the received levels (Miller et al. 2012, Kuningas et al. 2013, Miller et al. 2014), proximity of the vessels (Kruse 1991, Williams et al. 2002a, Williams et al. 2002b, Bain et al. 2006, Williams et al. 2009) and its trajectory (Dunlop et al. 2017, Sprogis et al. 2020). In contrast to a moving vessel situation, the animals in Corio Bay determine their proximity and trajectory relative to the moored vessels. There is no empirical information on behavioural responses of marine mammals available for such situations; accordingly, the assessment of project-related behavioural impacts will be limited to a general consideration of published research results from vessel effect studies.

Killer whales (*Orcinus orca*) in British Columbia, Canada, and Washington State, USA, have recently received much attention with regards to impacts from ships, given the steady decline in their population size. Changes in behaviour (i.e., less foraging and increased surface-active behaviour), respiration, and swim speed and direction occurred at received SPL above 130 dB re 1 µPa (0.01–50 kHz), and the Lombard effect (i.e., increased source level and vocalization duration) has been reported in ship noise levels above 98 dB re 1 µPa (1–40 kHz) (Williams et al. 2002b, Foote et al. 2004, Holt et al. 2009, Lusseau et al. 2009, Noren et al. 2009, Holt et al. 2011, Williams et al. 2014). This geographic area has seen a lot of ship noise recording, quantification, and impact modelling studies (e.g. Erbe 2002, Erbe et al. 2012, Erbe et al. 2014, Williams et al. 2015, Cominelli et al. 2018, Joy et al. 2019).

Beluga whales lost pod integrity in response to icebreakers, commenced rapid movement, asynchronous and shallow dives, and changed their vocal behaviour (i.e., vocalisation types) at received SPL of 94–105 dB re 1 µPa (20–1000 Hz), while narwhals changed their locomotion (i.e., exhibited more directed and slower movement, became motionless, and sank) and fell silent at received SPL of about 124 dB re 1 µPa (20–1000 Hz) (Cosens and Dueck 1988, Finley et al. 1990). Since the 1990s, beluga whale responses to boats and ships have been studied more extensively in the St. Lawrence Estuary, Canada. Here, beluga whales have shown increasing avoidance (i.e., increased dive duration and swim speed) with the number of boats, as well as other changes in both physical and acoustic behaviour (Blane and Jaakson 1994, Lesage et al. 1999). The Lombard effect has been demonstrated as an increase in source level, vocalisation rate, and frequency (i.e., shift to higher frequencies; Lesage et al. 1999, Scheifele et al. 2005).

Dolphins were displaced or changed their site occupancy in response to vessel traffic (Lusseau 2005, Bejder et al. 2006, Rako et al. 2013, Pirotta et al. 2015, Pérez-Jorge et al. 2016). They altered their movement patterns within an area in response to vessel traffic, with animals changing their direction of travel, beginning to travel erratically, or significantly increasing traveling speeds when approached by vessels (Au and Perryman 1982, Nowacek et al. 2001, Mattson et al. 2005, Lemon et al. 2006, Lusseau 2006, Christiansen et al. 2010, Marley et al. 2017b).

Marley et al. (2017a) found that Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) in Fremantle Inner Harbour (WA) significantly increased their average movement speeds in high vessel densities but only for some activity states. Behavioural budgets also changed in the presence of vessels, with animals spending more time travelling and less time resting or socialising.

Hearing impairment

Acoustic emissions from (moving) vessel operations have not been tested for their potential for causing TTS in marine mammals. In the absence of information for these types of acoustic signatures, conclusions on potential effects and thresholds can only be drawn from research on TTS effects of other non-impulsive sounds such as (military) sonar signals, or from studies using tones or band-limited signals as acoustic stimuli (see Finneran 2015 for review). Tonal signals may be used to represent the effects of military sonars, fish finders, depth sounders, and other sources emitting narrowband signals but cannot be taken as proxy for exposure to vessel or dredging noise.

These studies have been performed with bottlenose dolphins and beluga whales, and a harbour porpoise exposed to tones with durations ranging from 1 second to 1 hour. Most of these studies employed non-impulsive exposures, though four studies used intermittent tones (Mooney et al. 2009, Finneran et al. 2010, Kastelein et al. 2014, Kastelein et al. 2015b).

The only generalisations that can be made from the results of these studies is that the temporal pattern of noise exposure affects the resulting threshold shift and for intermittent noise, the quiet periods between noise exposures allow some recovery of hearing thresholds compared to noise that is continuously present with the same total SEL (Ward 1997).

Impact ranges

The behavioural impact ranges for operational FSRU and LNG carrier noise extend to 1.46 km (Table 20) and TTS ranges are limited to a maximum of 40 m (Table 21).

Table 20. Behavioural impact ranges for fishes for operational noise; horizontal distances (m) from the FSRU and LNG carrier (Scenario 3a: FSRU; Scenario 3b: FSRU + LNG carrier) to maximum-over-depth per-strike SPL isopleths based on noise exposure criteria for vessel noise. A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m) (Green et al. 2021, Section 4.2.1).

SPL (L_p; dB re 1 µPa)	3a – FSRU		3b – FSRU + LNG carrier	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
170	–	–	–	–
160	<0.01	<0.01	0.03	0.03
150	0.02	0.02	0.04	0.04
140	0.06	0.05	0.09	0.08
130	0.31	0.27	0.44	0.38
125*	0.63	0.54	0.85	0.72
120⁺	**1.10**	**0.98**	**1.46**	**1.26**

* Ambient noise floor.

⁺ Marine mammal behavioural threshold for non-impulsive sounds (NOAA 2019)

Table 21. TTS ranges for marine mammals for operational noise based on noise exposure criteria for non-impulsive sounds (Southall et al. 2019 horizontal distances (m) from the FSRU and LNG carrier (Scenario 3a: FSRU; Scenario 3b: FSRU + LNG carrier) to maximum-over-depth weighted SEL isopleths are given. PTS thresholds were not exceeded; a dash indicates the threshold was not reached within the limits of the modelling resolution (20 m) (Green et al. 2021, Section 4.2.1).

Hearing group	SEL_{24h} threshold ($L_{E,\text{ weighted}}$; dB re 1 µPa²s)	3a – FSRU		3b – FSRU + LNG carrier	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
HF cetaceans	178	0.01	0.01	0.04	0.04
Otariid pinnipeds (OCW)	199	–	–	0.03	0.03

Conclusions

Operational noise is expected to induce behavioural responses in marine mammals, most likely an avoidance of a relatively small area surrounding the sound source(s). The predicted ranges of exceedance of the behavioural threshold are however an overestimation of the true extent, given that the average ambient noise level (Wilson and McPherson 2021) already exceeds that threshold (animals in Corio Bay, in other words, are exposed daily to sustained noise levels supposed to elicit behavioural responses). Sound propagation modelling was performed for the operational scenarios in isolation; the impact assessment, however, must put the operational noise levels into context with the already existing acoustic environment. In this case, the ambient noise monitoring reveals that the behavioural impact from the FSRU and LNG carrier would not extend as far as modelled. While hearing related parameters (not elaborated on in this report) require a signal to be a few Decibels above ambient to be perceived, a precautionary estimate of potential behavioural effect range for this assessment would be the range to ambient level.

With TTS ranges of 40 m or below, this impact is not expected to occur in marine mammals because of exposure to operational noise as it is based on the extremely conservative and unrealistic assumption that animals remain stationary within this range around the sound source(s) over 24 h.

7.2. Fishes

Behavioural reactions

Like in the case of marine mammals, moving vessels provide additional sensory stimuli also to fishes and using results from a study involving moving vessel for assessing noise-induced impacts of a stationary vessel (FSRU / LNG carrier) can only be done with strong limitations. Most important in this context is the particle motion signature of a moving vessel, which is believed to cause behavioural responses in fishes (Ona et al. 2007, Sand et al. 2008)

Fishes can respond to approaching vessels by diving towards the seafloor or by moving horizontally out of the vessel's path, with reactions often initiated well before the vessel reaches the fishes (Ona et al. 2007, Berthe and Lecchini 2016). The avoidance of vessels by fishes has been linked to the high levels of infrasonic and low-frequency noise (>10 to 1000 Hz) emitted by the ships. Accordingly, it was suggested that silent ships have a higher chance of encountering more fishes than noisier ones (De Robertis et al. 2010). This assumption was initially contradicted when two research vessels were compared with regard to their effect on schooling herring (Ona et al. 2007). The authors found that the reaction initiated by the silent vessel was stronger and more prolonged than the one initiated by the conventional vessel. In a comment to this publication, Sand et al. (2008) pointed out that fishes are highly sensitive to particle acceleration and that the cue, in this case, may have been low-frequency particle acceleration caused by displacement of water by the moving hull in the near field of the vessel. This fact would explain the stronger response to the larger noise-reduced vessel in the study by Ona et al. (2007), which would have displaced more water as it approached.

Nedelec et al. (2016) investigated the response of reef-associated fishes by exposing them in their natural environment to playback of motorboat noise. They found that juvenile fishes increased hiding and ventilation rate after a short-term boat noise playback, but responses diminished after long-term playback thus indicating habituation to sound exposure over longer durations. These results were corroborated by Holmes et al. (2017) who also observed short-term behavioural changes in juvenile reef fishes after exposure to boat noise as well as desensitisation over longer exposure periods.

Acoustic masking

Scholik and Yan (2001), Vasconcelos et al. (2007), and Codarin et al. (2009) demonstrated masking effects due to vessel noise in several marine fish families. They measured decreased hearing sensitivities between 10 dB and more than 30 dB in the presence of vessel noise.

Codarin et al. (2009) investigated the effects of ambient and ship noise on representatives of three vocal fish families with different hearing abilities. In their laboratory study, they found that the noise emanating from recreational shipping substantially masked the auditory perception in these fish species, with a pronounced effect on the frequencies used for communication.

Stanley et al. (2017) modelled the effective communication range in Atlantic cod and haddock at three spawning locations. These areas are characterised by elevated levels of anthropogenic underwater sound, particularly due to commercial shipping. They found near constant high levels of low-frequency sound and consequentially a reduction in the communication space during times of high vocalisation activity for these fish species.

Hearing impairment

A single study reported temporary threshold shift caused by exposure to vessel noise: Scholik and Yan (2001) exposed fathead minnows (*Pimephales promelas*) for 2 hours to sound playback recorded from small boats at a level of 142 dB re 1 µPa. They measured noise-induced threshold shift of 7.8–13.5 dB at frequencies between 1–2 kHz, the most sensitive hearing range of this species.

Impact ranges

Operational noise, when assessed in isolation (i.e., not account for the existing ambient noise) can be assumed to lead to recoverable injury in fishes up to 30 m from the sound if the receiver is exposed to the noise over 48 hours (Table 22).

Table 22. Impact ranges for fishes for operational noise; horizontal distances (m) from the dredger (Scenario 3a: FSRU; Scenario 3b: FSRU + LNG carrier) to maximum-over-depth per-strike SPL isopleths based on noise exposure criteria for vessel noise (Green et al. 2021, Section 4.2.1)

SPL (L_p; dB re 1 µPa)	3a – FSRU		3b – FSRU + LNG carrier	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
170[1]	–	–	–	–
160	<0.01	<0.01	0.03	0.03
158[2]	**<0.01**	**<0.01**	**0.03**	**0.03**
150	0.02	0.02	0.04	0.04
124.6[3]	0.65	0.57	0.90	0.76
119.6[4]	1.14	1.03	1.52	1.30

[1] Temporary threshold shift in fishes, 12 hours exposure (Popper et al. 2014)
[2] Recoverable injury threshold for fishes, 48 hours exposure (Popper et al. 2014)
[3] Median ambient level
[4] 5th percentile ambient level.

Conclusions

The ambient noise floor in Corio Bay is dominated by continuous noise mostly emitted by vessels and reaches median levels of SPL 124.6 dB re 1 µPa, which indicates a substantial existing noise pollution. Even in the quietest situation (represented by the 5th percentile ranges in Figure 3), the ambient noise level is SPL 119.6 dB re 1 µPa. The additional operational noise from the FSRU and LNG carrier would increase the sound field only in the surrounding area; due to the pre-existing noise levels, however, it is less likely that fishes would show ecologically relevant behavioural responses over extended areas around the sound sources. Taking the qualitative criteria for onset of behavioural responses in fishes (Popper et al. 2014) as a baseline, the likelihood for responses should be lowered by one level to reflect this existing condition. For the acoustically most sensitive species in Corio Bay, the Australian anchovy, this would result in a moderate likelihood for behavioural responses within the nearfield (tens of meters) of the sound source(s) while there is a low likelihood for all other species showing behavioural responses.

TTS is unlikely to occur in any fish species from exposure to operational noise as the impact range extends only to 30 m and, moreover, this criterion is highly conservative as it is based on assuming a receiver being stationary in this sound field over 48 hours. More severe impacts such as non-lethal injuries, PTS or mortality are not expected to be caused by operational noise.

7.3. Invertebrates

It remains unclear what physical parameters of underwater sound marine invertebrates are sensing (see Section 4.3.3) and what role and ecological relevance sound has for these species.

Behavioural reactions

Like for other taxa, there is no information on behavioural responses of marine invertebrates to sound by a stationary FSRU and LNG carrier. Instead, information documented for exposures to other non-impulsive noise sources is used for assessing potential impacts of operational activities.

Filiciotto et al. (2016) examined the effects of recorded boat noise on the behaviour and biochemistry of the common prawn (*Palaemon serratus*). The exposure elicited changes in locomotor patterns and caused physiological and behavioural effects that the authors identified as stress-related responses.

Two tank-based experiments investigated the physiological and behavioural effects of sound exposure on marine invertebrates. The sound generated by tidal and wind turbines was found to delay the time to metamorphosis between larval stages in estuarine crabs (Pine et al. 2012). Celi et al. (2013) documented statistically significant variations in haemato-immunological parameters as well as a reduction in agonistic behaviour in red swamp crayfish (*Procambarus clarkii*) after constant exposure to frequency sweeps over a duration of 30 min. The signals covered a frequency range between 0.1–25 kHz and reached a peak amplitude 148 dB re 1 µPa at 12 kHz.

Mooney et al. (2016) tested unconditioned behavioural responses to tonal signals in squid (*Doryteuthis pealeii*). The reactions elicited by sound exposure from 80 Hz to 1 kHz ranged from inking and jetting to body pattern changes and fin movements. Animals responded to the lowest sound levels in the 200–400 Hz range.

Morphological impact

André et al. (2011) and Solé et al. (2013) provide evidence of acoustic trauma in different cephalopod species (*Sepia officinalis*, *Octopus vulgaris*, *Loligo vulgaris*, and *Illex condietii*) that they exposed (underwater) for 2 hours to low-frequency sweeps between 50–400 Hz (1 second duration) generated by an in-air speaker. The received level at the animals' position was 157 dB re 1 µPa with peak levels (unspecified) up to 175 dB re 1 µPa. Both studies report permanent and substantial morphological and structural alterations of the sensory hair cells of the statocysts following noise exposure with no indication of recovery. In a more recent experiment, Solé et al. (2017) exposed common cuttlefish (*Sepia officinalis*) to tonal sweeps between 100–400 Hz in a controlled exposure experiments in open water. Their results show a clear statistical relationship between the cellular damage detected in the sensory cells of the individuals exposed to the sound sweeps and the distance to the sound source. The authors measured the particle motion and pressure of the signals received by the animals. Due to the signal type (frequency sweep), they could only provide the maximum received levels or an estimate thereof, respectively; the maximal particle motion level was 0.7 ms^{-2} observed at 1 m depth, the pressure reached levels of 139–142 dB re $1µPa^2$. The sound pressure levels reported are only slightly higher than the hearing threshold determined for longfin squid (*Loligo pealeii*), another decapodiforme cephalopod, measured by Mooney et al. (2010). The maximum particle motion (reported in terms of particle acceleration) reported by Solé et al. (2017) is in the same order of magnitude as the behavioural thresholds measured at 100 Hz by (Packard et al. 1990) using a standing wave acoustic tube.

Impact ranges

There are no noise exposure criteria for invertebrates and, accordingly, impact ranges could not be calculated.

Conclusions

As already noted in the assessment of dredging noise impacts (Section 6.4.2), there are limited and inconclusive data available on the potential for behavioural responses and noise-induced physical effects on marine invertebrates. Theoretically, behavioural responses as well as significant sensory impairment or injury can have moderate to major consequences for an individual. In the absence of conclusive scientific information on important aspects such as the relevant physical parameters, sensory system responsible for detecting the noise, the scope of noise-induced effects and the animals' ability to compensate for the effects; however, it is impossible to assess the consequences of behavioural responses and noise-induced impairment or injury.

7.4. Avifauna

As remarked with regard to the potential impact of dredging noise (Section 6.5), the limited scientific information on behavioural responses of diving birds to underwater sound indicates that the response can be species- and context-specific, i.e., responses depend on several factors (including but not limited to): life history characteristics of the species, characteristics of the noise source, sound source intensity, onset rate, distance from the noise source, presence or absence of associated visual stimuli, food and habitat availability, and previous exposure. Previous studies document a range of bird behavioural responses to in-air noise, including no response, head turn, alert behaviour, startle response, flying or swimming away, diving into the water, and increased vocalisations (Larkin et al. 1996, Stalmaster and Kaiser 1997, Pytte et al. 2003, Plumpton et al. 2007). However, these studies cannot be used to inform the potential impact of operational noise on diving birds.

To date, there are no studies on behavioural effects of underwater noise emissions of vessels or any other non-impulsive sound source on diving birds. There is also no criterion for hearing impairment (TTS) for birds; impact ranges for TTS were analysed based on noise exposure criteria for other carnivores in water (OCW) (see Section 3.2.5 for rationale).

Impact ranges

The TTS impact ranges for diving birds are limited to 30 m, i.e., to the immediate vicinity of the FSRU and LNG carrier (Table 23).

Table 23. TTS ranges for diving birds for dredging noise based on noise exposure criteria for other carnivores in water for non-impulsive sounds (Southall et al. 2019). PTS thresholds were not exceeded. Maximum (R_{max}) horizontal distances (m) from the FSRU (Scenario 3a) and FSRU + LNG carrier (Scenario 3b) to maximum-over-depth weighted SEL isopleths for other carnivores in water (Southall et al. 2019) (Green et al. 2021, Section 4.2.1). A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Hearing group	SEL_{24h} threshold ($L_{E,\text{ weighted}}$; dB re 1 µPa²s)	3a – FSRU		3b – FSRU + LNG carrier	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Diving birds; proxy: Otariid pinnipeds (OCW)	199	—	—	0.03	0.03

Conclusions

It can be expected that pursuit-diving seabirds such as cormorants and penguins react to underwater sound emissions by altering or abandoning their foraging pursuits. Penguins likely avoid ensonified areas for the duration of a sound-producing activity before returning to their habitat. However, due to the existing high ambient noise levels in the project area (Wilson and McPherson 2021) it is unlikely that the operation of the new facility would lead to behavioural responses by birds on an ecologically relevant level. It is unrealistic to assume a concrete risk for diving birds to be exposed to TTS-inducing sound levels from the FSRU and LNGC operations, as birds would have to dive constantly for 24 h (as per definition of the criterion) to exceed the threshold; moreover, the animals would have to perform their dives within the immediate vicinity of (or between) the vessels.

7.5. Summary of Operation Impacts

Operating the FSRU including the offloading of LNG from a carrier during operation would lead to a localised increase in underwater noise levels in the vicinity of the project area. The noise would contribute to the existing soundscape and would raise the overall noise levels slightly. In assessing the potential noise related impacts of the operational activities, the same aspects must be considered as mentioned for the assessment of construction activities, i.e., the existing ambient noise level in the project area is high and already exceeds some of the existing noise exposure criteria and the relevant information on cause-effect relationships between noise and their impact on marine fauna are scarce or non-existent, often not specific to the type of activity or noise emitted or to the species occurring in the project area, or inconclusive. Consequently, some types of impact cannot be assessed and/or information must be extrapolated from other species, sound sources, and even different sound types.

In an unmitigated 'worst-case' scenario, the most significant impact to be expected are behavioural responses occurring over a range of several hundred metres for most species and only for birds up to several kilometres from the project area. However, these ranges indicate the onset of behavioural responses which are likely to be trivial responses of little or no ecological relevance at the and only become more severe the closer the animals are to the sound source(s). Also, they do not take into account the complexity and context-specific nature of behavioural responses and may under- or overestimate the true onset levels. More severe effects such as TTS or non-lethal injury (in fishes) are not likely to occur and stress and acoustic masking, while not quantifiable per se, can be assumed to occur at the same ranges as (ecologically relevant) behavioural responses.

With a reasonable (proportional) set of mitigation measures implemented, the underwater noise emitted by the operation of the FSRU, and the LNG carrier is not likely to have unacceptable impacts on the marine fauna in Corio Bay. Recommended mitigation measures to avoid, minimise and manage potential impacts related to underwater noise are discussed in Section 9.

8. Decommissioning Impacts

8.1. Summary of Residual Decommissioning Impacts

The FSRU, which continues to be an ocean-going vessel throughout the operation of the project, would leave Corio Bay on completion of the project life to be used elsewhere (see Section 1.4.3). Furthermore, it is anticipated that the Refinery Pier berth and facilities would be retained for other port related uses. While decommissioning activities may be subject to change, subject to legislative requirements at the time and potential repurposing of the infrastructure at the end of the project it is anticipated that decommissioning ancillary structures would, assuming the non-project related activities in Corio Bay have not changed, lead to a permanent reduction of emitted noise to levels similar to those measured prior to its construction (Green et al. 2021). Due to the lack of anticipated activities during the decommissioning phase that could lead to additional noise emissions, no mitigation measures are required and/or recommended at this point in time.

9. Recommended Mitigation Measures

The underwater noise generated by the planned construction and operation-related activities can impact marine fauna in several ways; there are, however, no intrinsic noise mitigation measures planned. To minimise or avoid noise-induced impacts a range of mitigation measures can be employed which differ in their effectiveness but also in their applicability and logistical and financial requirements to implement them. These aspects must be considered and assessed for proportionality as measures that come at a high cost but provide small noise reduction effects will not be sensible to use; similarly, high cost/effort measures would not be sensible to suggest if the impact ranges and/or the impact risk are small. These considerations are at the base of assigning the recommended mitigation measures to the project phases. However, no quantitative criteria exist or were developed in this context for this assessment; rather, assigning the mitigation measures to the project phases was conducted by expert judgement taking into account the likelihood of impacts to occur, the ecological relevance of noise-induced impacts and the predicted impact ranges (Green et al. 2021).

The most efficient methods to mitigate the noise exposure for marine mammals and diving birds is implementing and enforcing a safety zone around a sound source during noise-critical activities such as pile driving and constant visual monitoring of the surrounding area. Moreover, a soft start of the pile driving activities and the spatially and temporally limited use of acoustic deterrent devices prior to commencing the pile driving will reduce the likelihood of strong behavioural responses of listed species such as dolphins or penguins.

Mitigation measures recommended to avoid, minimise, and mitigate potential adverse effects on underwater noise are listed in Table 24.

Table 24. Recommended mitigation measures.

MM ID	Mitigation measure	Project phase
MM-UN01	**Minimising underwater noise impacts** • Isolating any piece of machinery from the ship (FSRU) structure can reduce structure-borne noise (Cruz et al. 2021). The level of noise reduction depends on the type of machinery; for medium- and high-speed diesel engines it can be up to 10 and 20 dB, respectively (Baudin and Mumm 2015). • Choosing the quietest operational technique possible and reduce the number and duration of sound exposure periods to the absolute minimum necessary to achieve the construction targets. • Consider use of noise dampening techniques such as air bubble curtains, Hydro Sound Dampers, etc. to reduce the noise propagated through the water column during noise-critical activities such as pile driving (e.g., Würsig et al. 2000, Stokes et al. 2010, Lucke et al. 2011, Saleem 2011, Koschinski and Lüdemann 2013, 2015, Dähne et al. 2017).	Construction + Operation
MM-UN02	**Acoustic Deterrence** • Using acoustic harassment devices (AHDs) during noise-critical activities such as the onset of impact pile driving; the use of AHDs should be temporally and spatially restricted as it introduces additional noise in the water column. • Increasing the power output of the sound source (e.g., increasing in the hammer energy for pile driving) gradually, that results in a gradual increase in the source level (SL) of the activity (Tougaard et al. 2003, JNCC 2004, Von Benda-Beckmann et al. 2014); this allows marine animals in the vicinity to move away to avoid the increasing noise to harmful levels.	Construction
MM-UN03	**Visual monitoring** • Monitoring the area surrounding the sound source visually prior to commencing loud activities (such as impact pile driving) to reducing the risk of exposing marine mammals to intense sound in the vicinity of the source. • Implement and enforcing a safety zone around loud sound sources such as pile driving and stop/delay the activity for 20 minutes based on a/ the last sighting of a listed species.	Construction
MM-UN05	**Awareness Building** Training construction workers and vessel/ machinery operators to understand noise impacts and endorse measures to reduce emissions (e.g., switching off machinery or equipment on a vessel while moored)	Construction + Operation
MM-UN06	**Performance Monitoring** Evaluating the proposed mitigation measures by continuous acoustic monitoring of the underwater sound field and visual monitoring of (noise-) critical activities during the construction- and operational phase of the project. This will provide the necessary information to inform decisions about compliance with keeping the noise exposure within acceptable levels and help in determining additional measures where necessary. The monitoring should be initiated prior to, and continued during, commencing the most critical activities and either routinely repeated throughout the project or conducted as a continuous effort.	Construction + Operation

10. Conclusion

10.1. Residual Impacts

Construction and operational activities would lead to localised increases in underwater noise levels in the vicinity of the project area. Applying the mitigation measures described in Section 9, however, has the potential of reducing the noise levels emitted by the construction activities and future operation and lead to a reduction in the severity and range of the potential noise-induced impacts.

The level or reduction is specific to each measure but not every measure can or should be applied to every activity; rather a differentiated approach is necessary, accounting for the proportionality of benefit (Section **Error! Reference source not found.**). As an example, some taxa such as bottom living invertebrates would not be able to be protected from exposure to ground vibration in the area surrounding the pile driving site; using a soft start during pile driving would allow mobile species to avoid the area before levels reach their maximum.

It is not possible to quantify the level of reduction for each of the mitigation measures and, accordingly, to determine the reduction of impact ranges and severity of impacts. It is likely though that a well-designed mitigation concept would reduce or even eliminate the risk of behavioural responses with the exception of the immediate vicinity of the activities. The potential noise-induced impacts for marine fauna arising from the planned project activities are not considered severe. Since TTS or other physical impacts are not likely and indeed unrealistic to assume, the impact type most expectable for the planned activities are behavioural responses of the exposed animals. Due to the existing acoustic condition, it is very probable that the animals are already accustomed (habituated) to living in a noisy environment and those individuals more sensitive to noise have long left the area.

There is no information available about abundance or densities of marine organisms in the project area which makes it unfeasible to assess the potential population level effects. Based on the relatively small acoustic and impact footprint of the activities it is justifiable to assume that, especially in a mitigated scenario, the ecological effects would be restricted to individuals and would not affect populations negatively. With a reasonable (proportional) set of mitigation measures implemented, the underwater noise emissions generated by the construction and operation of the FSRU are not expected to have unacceptable impacts on the marine fauna in Corio Bay

Abbreviations and Glossary of Terms

Abbreviation/ Term	Definition
ADD	Acoustic Deterrent Device
AEP	auditory evoked potentials
AHD	Acoustic Harassment Device
ANSI	American National Standards Institute
ASA	Acoustical Society of America
Caltrans	California Department of Transportation
CEDA	Central Dredging Association
DAWE	Department of Agriculture, Water and the Environment
DELWP	Department of Environment, Land, Water and Planning
DEWHA	Department of the Environment Water Heritage and the Arts
DOSITS	Discovery of Sound in the Sea
EES	Environment Effects Statement
EOL	End of life
EPBC Act	Commonwealth Environment Protection and Biodiversity Conservation Act 1999
FSRU	Floating storage and regasification unit
HF	High-frequency (cetacean)
HSD	Hydro Sound Damper
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
JNCC	Joint Nature Conservation Committee
LF	Low-frequency (cetacean)
LNG	Liquified natural gas
MHF	Major Hazard Facility
MLA	Marine loading arm

Abbreviation/ Term	Definition
MNES	Matters of national environmental significance
NIOSH	National Institute for Occupational Safety and Health
NITS	Noise-induced threshold shift
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
OCR	Office of the Conservation Regulator
OCW	Other Marine Carnivores (water)
PCW	Phocid Marine Carnivores (water)
PK	Peak sound pressure level
PTS	Permanent threshold shift
rms	Root mean square
ROW	Right of way
SEL	Sound exposure level
SL	Source Level
SPL	Sound pressure level
SWI	Seawater intake
SWP	South West Pipeline
TRG	Technical Reference Group
TTS	Temporary threshold shift
USA	United States of America
VHF	Very high-frequency
VTS	Victorian Transmission System
WODA	World Organisation of Dredging Associations

Term	Definition
ambient sound	Sound that would be present in the absence of a specified activity, 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
auditory frequency weighting	The process of applying an auditory frequency weighting function. In human audiometry, C-weighting is the most commonly used function, an example for marine mammals are the auditory frequency weighting functions published by Southall et al. (2019)
background noise	Combination of ambient sound, acoustic self-noise, and sonar reverberation. Ambient sound detected, measured, or recorded with a signal is part of the background noise
bandwidth	The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., seismic airguns, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI S1.13-2005 (R2010))
cetacean	Any animal in the order Cetacea. These are aquatic species and include whales, dolphins, and porpoises
continuous sound	A sound whose sound pressure level remains above ambient sound during the observation period. A sound that gradually varies in intensity with time, for example, sound from a marine vessel
decibel	Unit of level used to express the ratio of one value of a power quantity to another on a logarithmic scale. Unit: dB
ensonified	Exposed to sound
frequency	The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second

functional hearing group	Category of animal species when classified according to their hearing sensitivity and to the susceptibility to sound
Hertz (Hz)	A unit of frequency defined as one cycle per second
level	A measure of a quantity expressed as the logarithm of the ratio of the quantity to a specified reference value of that quantity. Examples include sound pressure level, sound exposure level, and peak sound pressure level.
non-impulsive sound	Sound that is not an impulsive sound. A non-impulsive sound is 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
otariid	A common term used to describe members of the Otariidae, eared seals, commonly called sea lions and fur seals. Otariids are adapted to a semi-aquatic life; they use their large fore flippers for propulsion. Their ears distinguish them from phocids. Otariids are one of the three main groups in the superfamily Pinnipedia; the other two groups are phocids and walrus
peak sound pressure level (zero-to-peak sound pressure level)	The level ($L_{p,pk}$ or L_{pk}) of the squared maximum magnitude of the sound pressure (p_{pk}^2). Unit: decibel (dB). Reference value (p_0^2) for sound in water: 1 μPa². $$L_{p,\mathrm{pk}} := 10\log_{10}\left(p_{\mathrm{pk}}^2/p_0^2\right)\,\mathrm{dB} \ = 20\log_{10}\left(p_{\mathrm{pk}}/p_0\right)\,\mathrm{dB}$$ The frequency band and time window should be specified. Abbreviation: PK or L_{pk}.
particle motion	Since sound is a mechanical wave, it can also be measured in terms of the vibratory motion of fluid particles. Sound particle motion is the magnitude and direction of movement of particles making up the media due to presence of a sound wave.
phocid	A common term used to describe all members of the family Phocidae. These true/earless seals are more adapted to in-water life than are otariids, which have more terrestrial adaptations. Phocids use their hind flippers to propel themselves. Phocids are one of the three main groups in the superfamily Pinnipedia; the other two groups are otariids and walrus
pressure, acoustic	The deviation from the ambient pressure caused by a sound wave. Also called sound pressure. Unit: pascal (Pa).
received level	The level measured (or that would be measured) at a defined location. The type of level should be specified.
sound	A time-varying disturbance in the pressure, stress, or material displacement of a medium propagated by local compression and expansion of the medium
sound exposure	Time integral of squared sound pressure over a stated time interval. 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: Pa²·s
sound exposure level	The level (L_E) of the sound exposure (E). Unit: decibel (dB). Reference value (E_0) for sound in water: 1 μPa² s. $$L_E := 10\log_{10}(E/E_0)\,\mathrm{dB} \ = 20\log_{10}\left(E^{1/2}/E_0^{1/2}\right)\,\mathrm{dB}$$ The frequency band and integration time should be specified. Abbreviation: SEL
sound field	Region containing sound waves
sound pressure level (rms sound pressure level)	The level ($L_{p,\mathrm{rms}}$) of the time-mean-square sound pressure (p_{rms}^2). Unit: decibel (dB). Reference value (p_0^2) for sound in water: 1 μPa². $$L_{p,\mathrm{rms}} := 10\log_{10}(p_{\mathrm{rms}}^2/p_0^2)\,\mathrm{dB} \ = 20\log_{10}(p_{\mathrm{rms}}/p_0)\,\mathrm{dB}$$ The frequency band and averaging time should be specified. Abbreviation: SPL or Lrms.
source level (SL)	A property of a sound source obtained by adding to the sound pressure level measured in the far field the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 μPa²m²
spectrum	An acoustic signal represented in terms of its power, energy, mean-square sound pressure, or sound

Literature Cited

[ANSI] American National Standards Institute and [ASA] Acoustical Society of America. S1.1-2013. *American National Standard: Acoustical Terminology*. NY, USA. https://webstore.ansi.org/Standards/ASA/ANSIASAS12013.

[ANSI] American National Standards Institute and [ASA] Acoustical Society of America. S1.13-2005 (R2010). *American National Standard: Measurement of Sound Pressure Levels in Air*. NY, USA. https://webstore.ansi.org/Standards/ASA/ANSIASAS1132005R2010.

[Caltrans] California Department of Transportation. 2001. *San Francisco – Oakland Bay Bridge East Span Seismic Safety Project. Pile Installation Demonstration Project. Fisheries Impact Assessment*. PIDP EA 012081. Caltrans Contract 04A0148. Task Order 205.10.90, San Francisco, CA, USA. 59 p. https://www.nrc.gov/docs/ML1434/ML14345A579.pdf.

[Caltrans] California Department of Transportation. 2004. *Fisheries and Hydroacoustic Monitoring Program Compliance Report*. San Francisco - Oakland Bay Bridge East Span Seismic Safety Project. Document EA 012023, 04-SF-80 KP 12.2/KP 14.3, 04-ALA-80 KP 0.0/KP 2.1 Technical report by Strategic Environmental and Illingworth & Rodkin, Inc. for Caltrans District 4. 148 p. http://ocr.org/pdfs/papers/2004_pile_driving_impacts.pdf.

[Caltrans] California Department of Transportation. 2010a. *Effects of pile driving sound on juvenile steelhead*. Prepared by ICF for Jones and Stokes.

[Caltrans] California Department of Transportation. 2010b. *Necropsy and histopathology of steelhead Trout Exposed to Steel Pile Driving at the Mad River Bridges, US Highway 101, July 2009*. Report by Gary D. Marty, Fish Pathology Services.

[CEDA] Central Dredging Association. 2011. *Underwater Sound in Relation to Dredging*. CEDA Position Paper, Delft, The Netherlands. 6 p. http://www.dredging.org/documents/ceda/html_page/2011-11_ceda_positionpaper_underwatersound_v2.pdf.

[DAWE] Department of Agriculture, Water and the Environment. 2021. *Guidance on key terms within the Blue Whale Conservation Management Plan*. https://www.awe.gov.au/environment/epbc/publications/guidance-key-terms-blue-whale-conservation-management-plan.

[DELWP] Department of Environment, Land, Water and Planning. 2020. Ecological character. (Chapter 1.1.1) *In Port Phillip Bay (Western Shoreline) and Bellarine Peninsula: Ramsar Site Management Plan Summary*.

[DEWLP] Department of Environment, Land, Water and Planning. 2018. *Port Phillip Bay (Western Shoreline) and Bellarine Peninsula Ramsar Site Management Plan*. East Melbourne, AU. 202 p.

[DOSITS] Discovery of Sound in the Sea. 2020. page). University of Rhode Island and Inner Space Center. http://www.dosits.org/. (Accessed 2 Jun 2020).

[IEC] International Electrotechnical Commission. 1994. *IEC 60050-801:1994 International Electrotechnical Vocabulary (IEV) - Part 801: Acoustics and electroacoustics*. https://webstore.iec.ch/publication/257.

[ISO] International Organization for Standardization. 2017. *ISO 18405:2017. Underwater acoustics – Terminology*. Geneva. https://www.iso.org/standard/62406.html.

[JNCC] Joint Nature Conservation Committee. 2010. *JNCC guidelines for minimising the risk of injury and disturbance to marine mammals from seismic surveys*. Aberdeen, UK.

[JNCC] Joint Nature Conservation Committee. 2017. *JNCC guidelines for minimising the risk of injury to marine mammals from geophysical surveys*. Aberdeen, UK. 26 p. http://data.jncc.gov.uk/data/e2a46de5-43d4-43f0-b296-c62134397ce4/jncc-guidelines-seismicsurvey-aug2017-web.pdf.

[NIOSH] National Institute for Occupational Safety and Health. 1998. *Criteria for a recommended standard: Occupational noise exposure. Revised Criteria*. Document 98-126. US Department of Health and Human Services, NIOSH, Cincinnati, OH, USA. 122 p. https://www.cdc.gov/niosh/docs/98-126/pdfs/98-126.pdf.

[NMFS] National Marine Fisheries Service (US). 2018. *2018 Revision to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts*. US Department of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-59. 167 p. https://media.fisheries.noaa.gov/dam-migration/tech_memo_acoustic_guidance_(20)_(pdf)_508.pdf.

[NOAA] National Oceanic and Atmospheric Administration (US). 2019. *ESA Section 7 Consultation Tools for Marine Mammals on the West Coast* (web page), 27 Sep 2019. https://www.fisheries.noaa.gov/west-coast/endangered-species-conservation/esa-section-7-consultation-tools-marine-mammals-west. (Accessed 10 Mar 2020).

[WODA] World Organisation of Dredging Associations. 2013. *Technical Guidance on: Underwater Sound in Relation to Dredging*. 8 p. https://dredging.org/documents/ceda/html_page/2013-06-woda-technicalguidance-underwatersoundlr.pdf.

Abbott, R., J. Reyff, and G. Marty. 2005. *Final report: monitoring the effects of conventional pile driving on three species of fish*. Manson Construction Company, Richmond, CA.

Aguilar de Soto, N., N. Delorme, J. Atkins, S. Howard, J. Williams, and M. Johnson. 2013. Anthropogenic noise causes body malformations and delays development in marine larvae. *Scientific Reports* 3(2831): 5. https://doi.org/10.1038/srep02831.

Aicher, B. and J. Tautz. 1990. Vibrational communication in the fiddler crab, *Uca pugilator*. *Journal of Comparative Physiology A* 166(3): 345-353. https://doi.org/10.1007/BF00204807.

Amoser, S. and F. Ladich. 2003. Diversity in noise-induced temporary hearing loss in otophysine fishes. *Journal of the Acoustical Society of America* 113(4): 2170-2179. https://doi.org/10.1121/1.1557212.

Amoser, S., L.E. Wysocki, and F. Ladich. 2004. Noise emission during the first powerboat race in an Alpine lake and potential impact on fish communities. *Journal of the Acoustical Society of America* 116(6): 3789. https://doi.org/10.1121/1.1808219.

Anderson-Hansen, K., A. Maxwell, U. Siebert, O.N. Larsen, and M. Wahlberg. 2017. Great cormorants (*Phalacrocorax carbo*) can detect auditory cues while diving. *The Science of Nature* 104(5): 45. https://doi.org/10.1007/s00114-017-1467-3.

André, M., M. Solé, M. Lenoir, M. Durfort, C. Quero, A. Mas, A. Lombarte, M. van der Schaar, M. López-Bejar, et al. 2011. Low-frequency sounds induce acoustic trauma in cephalopods. *Frontiers in Ecology and the Environment* 9(9): 489-493. https://doi.org/10.1890/100124.

Au, D.W.T. and W. Perryman. 1982. Movement and speed of dolphin schools responding to an approaching ship. *Fishery Bulletin* 80(2): 371-379. https://spo.nmfs.noaa.gov/sites/default/files/pdf-content/1982/802/au.pdf.

Au, W.W.L. and M.C. Hastings. 2008a. *Principles of Marine Bioacoustics*. Modern Acoustics and Signal Processing. Springer, New York. 510 p. https://doi.org/10.1007/978-0-387-78365-9.

Au, W.W.L. and M.C. Hastings. 2008b. Hearing in Marine Animals. *In Principles of Marine Bioacoustics*. New York, USA. pp. 337-400. https://doi.org/10.1007/978-0-387-78365-9_9.

Bain, D.E., J. Smith, R. Williams, and D. Lusseau. 2006. Effects of vessels on behavior of southern resident killer whales (Orcinus spp.). *NMFS Contract Report No. AB133F03SE0959 and AB133F04CN0040*.

Barth, F.A. 1980. *Campaniform sensilla*: Another vibration receptor in the crab leg. *Naturwissenschaften* 67: 201-202. https://doi.org/10.1007/BF01086310.

Basner, M., W. Babisch, A. Davis, M. Brink, C. Clark, S. Janssen, and S. Stansfeld. 2014. Auditory and non-auditory effects of noise on health. *The Lancet* 383(9925): 1325-1332.

Baudin, E. and H. Mumm. 2015. *Guidelines for Regulation on UW Noise from Commercial Shipping*. Prepared by Bureau Veritas, DNV GL for SONIC. Revision 4.3. http://www.aquo.eu/downloads/AQUO-SONIC%20Guidelines_v4.3.pdf.

Bejder, L., A. Samuels, H. Whitehead, and N. Gales. 2006. Interpreting short-term behavioural responses to disturbance within a longitudinal perspective. *Animal Behaviour* 72(5): 1149-1158. https://doi.org/10.1016/j.anbehav.2006.04.003.

Bejder, L., A. Samuels, H. Whitehead, H. Finn, and S. Allen. 2009. Impact assessment research: Use and misuse of habituation, sensitisation and tolerance in describing wildlife responses to anthropogenic stimuli. *Marine Ecology Progress Series* 395: 177-185. https://doi.org/10.3354/meps07979.

Bellmann, M.A., J. Schuckenbrock, S. Gündert, M. Müller, H. Holst, and P. Remmers. 2017. Is There a State-of-the-Art to Reduce Pile-Driving Noise? *In* Köppel, J. (ed.). *Wind Energy and Wildlife Interactions*. Springer, Cham, Switzerland. pp. 161-172. https://doi.org/10.1007/978-3-319-51272-3_9.

Berghahn, R., K. Wiese, and K. Lüdemann. 1995. Physical and physiological aspects of gear efficiency in North Sea brown shrimp fisheries. *Helgoländer Meeresuntersuchungen* 49(1): 507-518. https://doi.org/10.1007/BF02368378.

Berthe, C. and D. Lecchini. 2016. Influence of boat noises on escape behaviour of white-spotted eagle ray Aetobatus ocellatus at Moorea Island (French Polynesia). *Comptes Rendus Biologies* 339(2): 99-103. https://doi.org/10.1016/j.crvi.2016.01.001.

Bertrand, A. and E. Josse. 2000. Tuna target-strength related to fish length and swimbladder volume. *ICES Journal of Marine Science* 57(4): 1143-1146. https://doi.org/10.1006/jmsc.2000.0881.

Blackwell, S.B., J.W. Lawson, and M.T. Williams. 2004. Tolerance by ringed seals (*Phoca hispida*) to impact pipe-driving and construction sounds at an oil production island. *Journal of the Acoustical Society of America* 115(5): 2346-2357. https://doi.org/10.1121/1.1701899.

Blane, J.M. and R. Jaakson. 1994. The Impact of Ecotourism Boats on the St Lawrence Beluga Whales. *Environmental Conservation* 21(3): 267-269. https://doi.org/10.1017/S0376892900033282.

Bowles, A.E. 1995. Responses of wildlife to noise. (Chapter 8) *In* Knight, R.L. and K.J. Gutzwiller (eds.). *Wildlife Recreationists: Coexistence Through Management and Research*. Volume 57. Island Press, Washington, DC. pp. 109-156.

Brandt, M.J., A. Diederichs, K. Betke, and G. Nehls. 2011. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. *Marine Ecology Progress Series* 421: 205-216. https://doi.org/10.3354/meps08888.

Braun, C.B. and T. Grande. 2008. Evolution of Peripheral Mechanisms for the Enhancement of Sound Reception. *In* Webb, J.F., R.R. Fay, and A.N. Popper (eds.). *Fish Bioacoustics*. Springer, NY, USA. pp. 99-144. https://doi.org/10.1007/978-0-387-73029-5_4.

Bruintjes, R. and A.N. Radford. 2013. Context-dependent impacts of anthropogenic noise on individual and social behaviour in a cooperatively breeding fish. *Animal Behaviour* 85(6): 1343-1349. https://doi.org/10.1016/j.anbehav.2013.03.025.

Bruns, B., C. Kuhn, P. Stein, J. Gattermann, and K. Elmer. 2014. The new noise mitigation system 'Hydro Sound Dampers': History of development with several hydro sound and vibration measurements. *Inter-noise 2014*. Melbourne, Australia.

Buscaino, G., F. Filiciotto, G. Buffa, A. Bellante, V.D. Stefano, A. Assenza, F. Fazio, G. Caola, and S. Mazzola. 2010. Impact of an acoustic stimulus on the motility and blood parameters of European sea bass (*Dicentrarchus labrax* L.) and gilthead sea bream (*Sparus aurata* L.). *Marine Environmental Research* 69(3): 136-142. https://doi.org/10.1016/j.marenvres.2009.09.004.

Caiger, P.E., J.C. Montgomery, and C.A. Radford. 2012. Chronic low-intensity noise exposure affects the hearing thresholds of juvenile snapper. *Marine Ecology Progress Series* 466: 225–232. https://doi.org/10.3354/meps09933.

Carlson, T.J., G.E. Johnson, C.M. Woodley, J.R. Skalski, and A.G. Seaburg. 2011. *Compliance Monitoring of Underwater Blasting for Rock Removal at Warrior Point, Columbia River Channel Improvement Project, 2009/2010*. Report PNNL-20388. Report by Pacific Northwest National Laboratory for the US Army Corps of Engineers, Richland, WA. https://tethys.pnnl.gov/publications/compliance-monitoring-underwater-blasting-rock-removal-warrior-point-columbia-river.

Carroll, A.G., R. Przeslawski, A.J. Duncan, M. Gunning, and B.D. Bruce. 2017. A critical review of the potential impacts of marine seismic surveys on fish & invertebrates. *Marine Pollution Bulletin* 114(1): 9-24. https://doi.org/10.1016/j.marpolbul.2016.11.038.

Casper, B.M., M.B. Halvorsen, and A.N. Popper. 2012a. Are Sharks Even Bothered by a Noisy Environment? *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life*. Volume 730. Springer, New York. pp. 93-97. https://doi.org/10.1007/978-1-4419-7311-5_20.

Casper, B.M., A.N. Popper, F. Matthews, T.J. Carlson, and M.B. Halvorsen. 2012b. Recovery of barotrauma injuries in Chinook salmon, *Oncorhynchus tshawytscha* from exposure to pile driving sound. *PLOS ONE* 7(6): e39593. https://doi.org/10.1371/journal.pone.0039593.

Casper, B.M., M.E. Smith, M.B. Halvorsen, H. Sun, T.J. Carlson, and A.N. Popper. 2013. Effects of exposure to pile driving sounds on fish inner ear tissues. *Comparative Biochemistry and Physiology Part A* 166(2): 352-360. https://doi.org/10.1016/j.cbpa.2013.07.008.

Celi, M., F. Filiciotto, D. Parrinello, G. Buscaino, M.A. Damiano, A. Cuttitta, S. D'Angelo, S. Mazzola, and M. Vazzana. 2013. Physiological and agonistic behavioural response of *Procambarus clarkii* to an acoustic stimulus. *Journal of Experimental Biology* 216(4): 709-718. https://doi.org/10.1242/jeb.078865.

Cholewiak, D.M., C.W. Clark, D. Ponirakis, A.S. Frankel, L.T. Hatch, D. Risch, J.E. Stanistreet, M. Thompson, E.T. Vu, et al. 2018. Communicating amidst the noise: Modeling the aggregate influence of ambient and vessel noise on baleen whale communication space in a national marine sanctuary. *Endangered Species Research* 36: 59-75. https://doi.org/10.3354/esr00875.

Christiansen, F., D. Lusseau, E. Stensland, and P. Berggren. 2010. Effects of tourist boats on the behavior of Indo-Pacific bottlenose dolphins off the south coast of Zanzibar. *Endangered Species Research* 11(1): 91-99. https://doi.org/10.3354/esr00265.

Clark, C.W., W.T. Ellison, B.L. Southall, L.T. Hatch, S.M. Van Parijs, A.S. Frankel, and D.W. Ponirakis. 2009. Acoustic masking in marine ecosystems: Intuitions, analysis, and implication. *Marine Ecology Progress Series* 395: 201-222. https://doi.org/10.3354/meps08402.

Codarin, A., L.E. Wysocki, F. Ladich, and M. Picciulin. 2009. Effects of ambient and boat noise on hearing and communication in three fish species living in a marine protected area (Miramare, Italy). *Marine Pollution Bulletin* 58(12): 1880-1887. https://doi.org/10.1016/j.marpolbul.2009.07.011.

Cominelli, S., R. Devillers, H. Yurk, A.O. MacGillivray, L. McWhinnie, and R. Canessa. 2018. Noise exposure from commercial shipping for the southern resident killer whale population. *Marine Pollution Bulletin* 136: 177-200. https://doi.org/10.1016/j.marpolbul.2018.08.050.

Cosens, S.E. and L.P. Dueck. 1988. Responses of migrating narwhal and beluga to icebreaker traffic at the Admiralty Inlet ice-edge, NWT in 1986. *In* Sackinger, W.M. and M.O. Jeffries (eds.). *Port and ocean engineering under Arctic conditions*. Volume 2. Geophysical Institute, University of Alaska, Fairbanks, AK. pp. 39-54.

Cox, T.M., A.J. Read, A. Solow, and N. Tregenza. 2001. Will harbour porpoises (*Phocoena phocoena*) habituate to pingers? *Journal of Cetacean Research and Management* 3(1): 81-86.

Cranford, T.W. and P. Krysl. 2015. Fin whale sound reception mechanisms: Skull vibration enables low-frequency hearing. *PLOS ONE* 10(1). https://doi.org/10.1371/journal.pone.0116222.

Cruz, E., T. Lloyd, J. Bosschers, F.H. Lafeber, P. Vinagre, and G. Vaz. 2021. *Study on inventory of existing policy, research and impacts of continuous underwater noise in Europe.* WavEC Offshore Renewables and Maritime Research Institute Netherlands. EMSA report EMSA/NEG/21/2020. 104 p.

Cunningham, K.A. and D.C. Mountain. 2014. Simulated masking of right whale sounds by shipping noise: Incorporating a model of the auditory periphery. *Journal of the Acoustical Society of America* 135(3): 1632-1640. https://doi.org/10.1121/1.4864470.

D'Amico, A., R.C. Gisiner, D.R. Ketten, J.A. Hammock, C. Johnson, P.L. Tyack, and J.G. Mead. 2009. Beaked whale strandings and naval exercises. *Aquatic Mammals* 35(4): 452-472. https://doi.org/10.1578/AM.35.4.2009.452.

Dahlheim, M.E. and D.K. Ljungblad. 1990. Preliminary Hearing Study on Gray Whales (*Eschrichtius Robustus*) in the Field. *In* Thomas, J.A. and R.A. Kastelein (eds.). *Sensory abilities of Cetaceans*. Volume 196. Springer Science+Business Media, Boston. pp. 335-346. https://doi.org/10.1007/978-1-4899-0858-2_22.

Dähne, M., A. Gilles, K. Lucke, V. Peschko, S. Adler, K. Krügel, J. Sundermeyer, and U. Siebert. 2013. Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany. *Environmental Research Letters* 8(2). https://doi.org/10.1088/1748-9326/8/2/025002.

Dähne, M., J. Tougaard, J. Carstensen, A. Rose, and J. Nabe-Nielsen. 2017. Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbour porpoises. *Marine Ecology Progress Series* 580: 221-237. https://doi.org/10.3354/meps12257.

Dale, J.J., M.D. Gray, A.N. Popper, P.H. Rogers, and B.A. Block. 2015. Hearing thresholds of swimming Pacific bluefin tuna *Thunnus orientalis*. *Journal of Comparative Physiology A* 201(5): 441-454. https://doi.org/10.1007/s00359-015-0991-x.

Day, R.D., R.D. McCauley, Q.P. Fitzgibbon, K. Hartmann, and J.M. Semmens. 2017. Exposure to seismic air gun signals causes physiological harm and alters behavior in the scallop *Pecten fumatus*. *Proceedings of the National Academy of Sciences of the United States of America* 114(40): E8537-E8546. https://doi.org/10.1073/pnas.1700564114.

Day, R.D., R.D. McCauley, Q.P. Fitzgibbon, K. Hartmann, and J.M. Semmens. 2019. Seismic air guns damage rock lobster mechanosensory organs and impair righting reflex. *Proceedings of the Royal Society B* 286(1907). https://doi.org/10.1098/rspb.2019.1424.

De Robertis, A., C.D. Wilson, N.J. Williamson, M.A. Guttormsen, and S. Stienessen. 2010. Silent ships sometimes do encounter more fish. 1. Vessel comparisons during winter pollock surveys. *ICES Journal of Marine Science* 67(5): 985-995. https://doi.org/10.1093/icesjms/fsp299.

Diederichs, A., M. Brandt, and G. Nehls. 2010. Does sand extraction near Sylt affect harbour porpoises? *Wadden Sea Ecosystem* 26: 199-203.

Dooling, R.J. 2010. *Animal hearing [abstract]*. *Joint 159th Meeting of the Acoustical Society of America/NOISE-CON 2010*. Volume 127, 19-23 Apr 2010. Journal of the Acoustical Society of America, Baltimore, MD. https://doi.org/10.1121/1.3383951.

Dunlop, R.A., M.J. Noad, R.D. McCauley, L. Scott-Hayward, E. Kniest, R. Slade, D. Paton, and D.H. Cato. 2017. Determining the behavioural dose–response relationship of marine mammals to air gun noise and source proximity. *Journal of Experimental Biology* 220(16): 2878-2886. https://doi.org/10.1242/jeb.160192.

Dunlop, R.A. 2018. The communication space of humpback whale social sounds in wind-dominated noise. *Journal of the Acoustical Society of America* 144: 540-551. https://doi.org/10.1121/1.5047744.

Dunlop, R.A. 2019. The effects of vessel noise on the communication network of humpback whales. *Royal Society Open Science* 6(11). https://doi.org/10.1098/rsos.190967.

Dutson, G., S. Garnett, and C. Gole. 2009. *Australia's Important Bird Areas: Key sites for bird conservation.* . Report by Birds Australia, BirdLife International, and Rio Tinto. Conservation Statement No. 15. 40 p.

Edmonds, N.J., C.J. Firmin, D. Goldsmith, R.C. Faulkner, and D.T. Wood. 2016. A review of crustacean sensitivity to high amplitude underwater noise: Data needs for effective risk assessment in relation to UK commercial species. *Marine Pollution Bulletin* 108(1–2): 5-11. https://doi.org/10.1016/j.marpolbul.2016.05.006.

Ellers, O. 1995. Discrimination Among Wave-Generated Sounds by a Swash-Riding Clam. *The Biological Bulletin* 189(2): 128-137. https://doi.org/10.2307/1542463.

Ellison, W.T., B.L. Southall, C.W. Clark, and A.S. Frankel. 2012. A New Context-Based Approach to Assess Marine Mammal Behavioral Responses to Anthropogenic Sounds. *Conservation Biology* 26(1): 21-28. https://doi.org/10.1111/j.1523-1739.2011.01803.x.

Engås, A., S. Løkkeborg, E. Ona, and A.V. Soldal. 1996. Effects of seismic shooting on local abundance and catch rates of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*). *Canadian Journal of Fisheries and Aquatic Sciences* 53(10): 2238-2249. https://doi.org/10.1139/f96-177.

Engineering-Environmental Management, Inc. 2008. *United States Coast Guard and Maritime Administration draft environmental impact statement for Port Dolphin LLC Deepwater Port licence application*. USCG Deepwater Ports Standards Division, Washington, DC.

Erbe, C. and D.M. Farmer. 1998. Masked hearing thresholds of a beluga whale (*Delphinapterus leucas*) in icebreaker noise. *Deep Sea Research Part II* 45(7): 1373-1388. https://doi.org/10.1016/S0967-0645(98)00027-7.

Erbe, C. 2002. Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca*), based on an acoustic impact model. *Marine Mammal Science* 18(2): 394-418. https://doi.org/10.1111/j.1748-7692.2002.tb01045.x.

Erbe, C. 2008. Critical ratios of beluga whales (*Delphinapterus leucas*) and masked signal duration. *Journal of the Acoustical Society of America* 124(4): 2216-2223. https://doi.org/10.1121/1.2970094.

Erbe, C., A.O. MacGillivray, and R. Williams. 2012. Mapping cumulative noise from shipping to inform marine spatial planning. *Journal of the Acoustical Society of America* 132(5): EL423-EL428. https://doi.org/10.1121/1.4758779

Erbe, C., R.D. McCauley, C.R. McPherson, and A. Gavrilov. 2013. Underwater noise from offshore oil production vessels. *Journal of the Acoustical Society of America* 133(6): EL465-EL470. https://doi.org/10.1121/1.4802183.

Erbe, C., R. Williams, D. Sandilands, and E. Ashe. 2014. Identifying modeled ship noise hotspots for marine mammals of Canada's Pacific Region. *PLOS ONE* 9(3): 1-10. https://doi.org/10.1371/journal.pone.0114362.

Erbe, C., C. Reichmuth, K. Cunningham, K. Lucke, and R.J. Dooling. 2016. Communication masking in marine mammals: A review and research strategy. *Marine Pollution Bulletin* 103(1): 15-38. https://doi.org/10.1016/j.marpolbul.2015.12.007.

Erbe, C., S.A. Marley, R.P. Schoeman, J.N. Smith, L.E. Trigg, and C.B. Embling. 2019. The Effects of Ship Noise on Marine Mammals—A Review. *Frontiers in Marine Science* 6. https://doi.org/10.3389/fmars.2019.00606.

Fewtrell, J.L. and R.D. McCauley. 2012. Impact of air gun noise on the behaviour of marine fish and squid. *Marine Pollution Bulletin* 64(5): 984-993. https://doi.org/10.1016/j.marpolbul.2012.02.009.

Filiciotto, F., M. Vazzana, M. Celi, V. Maccarrone, M. Ceraulo, G. Buffa, V. Arizza, G. de Vincenzi, R. Grammauta, et al. 2016. Underwater noise from boats: Measurement of its influence on the behaviour and biochemistry of the common prawn (*Palaemon serratus*, Pennant 1777). *Journal of Experimental Marine Biology and Ecology* 478: 24-33. https://doi.org/10.1016/j.jembe.2016.01.014.

Finley, K.J., G.W. Miller, R.A. Davis, and C.R. Greene, Jr. 1990. Reactions of belugas, *Delphinapterus leucas*, and narwhals, *Monodon monoceros*, to ice-breaking ships in the Canadian high arctic. *Canadian Bulletin of Fisheries and Aquatic Sciences*.

Finneran, J.J., C.E. Schlundt, D.A. Carder, J.A. Clark, J.A. Young, J.B. Gaspin, and S.H. Ridgway. 2000. Auditory and behavioral responses of bottlenose dolphins (*Tursiops truncatus*) and a beluga whale (*Delphinapterus leucas*) to impulsive sounds resembling distant signatures of underwater explosions. *Journal of the Acoustical Society of America* 108(1): 417-431. https://doi.org/10.1121/1.429475.

Finneran, J.J., C.E. Schlundt, R.L. Dear, D.A. Carder, and S.H. Ridgway. 2002. Temporary shift in masked hearing thresholds in odontocetes after exposure to single underwater impulses from a seismic watergun. *Journal of the Acoustical Society of America* 111(6): 2929-2940. https://doi.org/10.1121/1.1479150.

Finneran, J.J., R. Dear, D.A. Carder, and S.H. Ridgway. 2003. Auditory and behavioral responses of California sea lions (*Zalophus californianus*) to single underwater impulses from an arc-gap transducer. *Journal of the Acoustical Society of America* 114(3): 1667. https://doi.org/10.1121/1.1598194.

Finneran, J.J., D.A. Carder, C.E. Schlundt, and R.L. Dear. 2010. Temporary threshold shift in a bottlenose dolphin (*Tursiops truncatus*) exposed to intermittent tones. *Journal of the Acoustical Society of America* 127(5): 3267-3272. https://doi.org/10.1121/1.3377052.

Finneran, J.J. 2015. Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. *Journal of the Acoustical Society of America* 138(3): 1702-1726. https://doi.org/10.1121/1.4927418.

Finneran, J.J., C.E. Schlundt, B.K. Branstetter, J.S. Trickey, V. Bowman, and K. Jenkins. 2015. Effects of multiple impulses from a seismic air gun on bottlenose dolphin hearing and behavior. *Journal of the Acoustical Society of America* 137(4): 1634-1646. https://doi.org/10.1121/1.4916591.

Finneran, J.J. 2016. *Auditory weighting functions and TTS/PTS exposure functions for marine mammals exposed to underwater noise*. Technical Report for Space and Naval Warfare Systems Center Pacific, San Diego, CA, USA. 49 p. https://apps.dtic.mil/dtic/tr/fulltext/u2/1026445.pdf.

Finneran, J.J., E.E. Henderson, D.S. Houser, K. Jenkins, S. Kotecki, and J. Mulsow. 2017. *Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase III)*. Technical report by Space and Naval Warfare Systems Center Pacific (SSC Pacific). 183 p. https://nwtteis.com/portals/nwtteis/files/technical_reports/Criteria_and_Thresholds_for_U.S._Navy_Acoustic_and_Explosive_Effects_Analysis_June2017.pdf.

Foote, A.D., R.W. Osborne, and A.R. Hoelzel. 2004. Whale-call response to masking boat noise. *Nature* 428(6986): 910. https://doi.org/10.1038/428910a.

Francis, C.D., C.P. Ortega, and A. Cruz. 2009. Noise Pollution Changes Avian Communities and Species Interactions. *Current Biology* 19(16): 1415-14199. https://doi.org/10.1016/j.cub.2009.06.052.

Gabriele, C.M., D.W. Ponirakis, C.W. Clark, J.N. Womble, and P.B.S. Vanselow. 2018. Underwater acoustic ecology metrics in an alaska marine protected area reveal marine mammal communication masking and management alternatives. *Frontiers in Marine Science* 5: 270. https://doi.org/10.3389/fmars.2018.00270.

Golde, H.M. and B. Houtman. 2012. *Environmental assessment of marine geophysical surveys by the R/V Marcus G. Langseth in the Northeastern Pacific Ocean, June-July 2012*. Report by LGL. Ltd.; National Science Foundation (US), Division of Ocean Sciences; Lamont-Doherty Earth Observatory; and National Oceanic and Atmospheric Administration., Office of Program Planning and Integration. https://repository.library.noaa.gov/view/noaa/19732.

Graves, M. 1968. Air-bubble curtain in sub-aqueous blasting at Muddy Run. *Civil Engineering* June: 59-61.

Green, M.C., M. Wood, and C. McPherson. 2021. *Viva Energy Gas Terminal: Underwater Acoustic Modelling*. Technical report by JASCO Applied Sciences for AECOM. Document 02534, Version 1.0.

Guerra, A., A.F. González, E.G. Dawe, and F. Rocha. 2004. Records of giant squid in the north-eastern Atlantic, and two records of male Architeuthis sp. off the Iberian Peninsula. *Journal of the Marine Biological Association of the United Kingdom* 84(2): 427-431. https://doi.org/10.1017/S0025315404009397h.

Halvorsen, M.B., B.M. Casper, C.M. Woodley, T.J. Carlson, and A.N. Popper. 2011. Predicting and mitigating hydroacoustic impacts on fish from pile installations. Project 25–28. *National Cooperative Highway Research Program Research Results Digest* 363: 2011. https://doi.org/10.17226/14596.

Halvorsen, M.B., B.M. Casper, F. Matthews, T.J. Carlson, and A.N. Popper. 2012a. Effects of exposure to pile-driving sounds on the lake sturgeon, Nile tilapia and hogchoker. *Proceedings of the Royal Society B* 279(1748): 4705-4714. https://doi.org/10.1098/rspb.2012.1544.

Halvorsen, M.B., B.M. Casper, C.M. Woodley, T.J. Carlson, and A.N. Popper. 2012b. Threshold for onset of injury in Chinook salmon from exposure to impulsive pile driving sounds. *PLOS ONE* 7(6): e38968. https://doi.org/10.1371/journal.pone.0038968.

Hastings, M.C., C.A. Reid, C.C. Grebe, R.L. Hearn, and J.G. Colman. 2008. The effects of seismic airgun noise on the hearing sensitivity of tropical reef fishes at Scott Reef, Western Australia. *Underwater Noise Measurement, Impact and Mitigation, Proceedings of the Institute of Acoustics* 30(5).

Hastings, M.C. and J.L. Miksis-Olds. 2012. Shipboard Assessment of Hearing Sensitivity of Tropical Fishes Immediately After Exposure to Seismic Air Gun Emissions at Scott Reef. *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life*. Volume 730. Springer, New York. pp. 239-243. https://doi.org/10.1007/978-1-4419-7311-5_53.

Hawkins, A.D., L. Roberts, and S. Cheesman. 2014. Responses of free-living coastal pelagic fish to impulsive sounds. *Journal of the Acoustical Society of America* 135(5): 3101-3116. https://doi.org/10.1121/1.4870697.

Hawkins, A.D., A.E. Pembroke, and A.N. Popper. 2015. Information gaps in understanding the effects of noise on fishes and invertebrates. *Reviews in Fish Biology and Fisheries* 25(1): 39-64. https://doi.org/10.1007/s11160-014-9369-3.

Heinisch, P. and K. Wiese. 1987. Sensitivity to Movement and Vibration of Water in the North Sea Shrimp *Crangon Crangon* L. *Journal of Crustacean Biology* 7(3): 401-413. https://doi.org/10.2307/1548290.

Holmes, L.J., J. McWilliam, M.C.O. Ferrari, and M.I. McCormick. 2017. Juvenile damselfish are affected but desensitize to small motor boat noise. *Journal of Experimental Marine Biology and Ecology* 494: 63-68. https://doi.org/10.1016/j.jembe.2017.05.009.

Holt, M.M., D.P. Noren, V. Veirs, C.K. Emmons, and S. Veirs. 2009. Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. *Journal of the Acoustical Society of America* 125(1): EL27-EL32. https://doi.org/10.1121/1.3040028.

Holt, M.M., D.P. Noren, and C.K. Emmons. 2011. Effects of noise levels and call types on the source levels of killer whale calls. *Journal of the Acoustical Society of America* 130(5): 3100-3106. https://doi.org/10.1121/1.3641446.

Houghton, J., J. Starkes, J. Stutes, M. Havey, J.A. Reyff, and D. Erikson. 2010. Acoustic monitoring of in situ exposures of juvenile coho salmon to pile driving noise at the port of Anchorage Marine Terminal redevelopment project, Knik Arm, Alaska. *Alaska Marine Sciences Symposium, Anchorage*.

Houser, D.S., D.A. Helweg, and P.W.B. Moore. 2001. A bandpass filter-bank model of auditory sensitivity in the humpback whale. *Aquatic Mammals* 27(2): 82-91. https://www.aquaticmammalsjournal.org/share/AquaticMammalsIssueArchives/2001/AquaticMammals_27-02/27-02_Houser.PDF.

Houser, D.S., W. Yost, R. Burkard, J.J. Finneran, C. Reichmuth, and J. Mulsow. 2017. A review of the history, development and application of auditory weighting functions in humans and marine mammals. *Journal of the Acoustical Society of America* 141(3): 1371-1413. https://doi.org/10.1121/1.4976086.

Houser, D.S., S. Martin, D.E. Crocker, and J.J. Finneran. 2020. Endocrine response to simulated U.S. Navy mid-frequency sonar exposures in the bottlenose dolphin (*Tursiops truncatus*). *Journal of the Acoustical Society of America* 147(3): 1681-1687. https://doi.org/10.1121/10.0000924.

Hu, M.Y., H.Y. Yan, W.-S. Chung, J.-C. Shiao, and P.-P. Hwang. 2009. Acoustically evoked potentials in two cephalopods inferred using the auditory brainstem response (ABR) approach. *Comparative Biochemistry and Physiology Part A* 153(3): 278-283. https://doi.org/10.1016/j.cbpa.2009.02.040.

Hughes, A.R., D.A. Mann, and D.L. Kimbro. 2014. Predatory fish sounds can alter crab foraging behaviour and influence bivalve abundance. *Proceedings of the Royal Society B* 281(1788). https://doi.org/10.1098/rspb.2014.0715.

Hwang, P.A. and W.J. Teague. 1999. Low-frequency resonant scattering of bubble clouds. *Journal of Atmospheric and Oceanic Technology* 17: 847-853.

Jacobsen, R.C. 1972. Air-bubble curtain to cushion blasting. *Ontario Hydro Research News* 1: 17-23.

Jepson, P.D., R. Deaville, K. Acevedo-Whitehouse, J. Barnett, A. Brownlow, R.L. Brownell, Jr., F.C. Clare, N. Davison, R.J. Law, et al. 2013. What caused the UK's largest common dolphin (*Delphinus delphis*) mass stranding event? *PLOS ONE* 8(4): e60953. https://doi.org/10.1371/journal.pone.0060953.

Jézéquel, Y., I.T. Jones, J. Bonnel, L. Chauvaud, J. Atema, and T.A. Mooney. 2021. Sound detection by the American lobster (Homarus americanus). *Journal of Experimental Biology* 224(6): jeb240747.

JNCC. 2004. *Guidelines for minimising acoustic disturbance to marine mammals from seismic surveys*. Joint Nature Conservation Committee, Aberdeen.

Johansen, S., O.N. Larsen, J. Christensen-Dalsgaard, L. Seidelin, T. Huulvej, K. Jensen, S.-G. Lunneryd, M. Boström, and M. Wahlberg. 2016. In-air and underwater hearing in the great cormorant (*Phalacrocorax carbo sinensis*). *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life II*. Volume 875. Springer, New York. pp. 505-512. https://doi.org/10.1007/978-1-4939-2981-8_61.

Joy, R., D.J. Tollit, J.D. Wood, A.O. MacGillivray, Z. Li, K. Trounce, and O. Robinson. 2019. Potential Benefits of Vessel Slowdowns on Endangered Southern Resident Killer Whales. *Frontiers in Marine Science* 6: 344. https://doi.org/10.3389/fmars.2019.00344.

Kaplan, M.B. and T.A. Mooney. 2016. Coral reef soundscapes may not be detectable far from the reef. *Scientific Reports* 6(1): 31862. https://doi.org/10.1038/srep31862.

Kastelein, R.A. 2008. Effects of vibrations on the behaviour of cockles (bivalve molluscs). *Bioacoustics* 17(1-3): 74-75. https://doi.org/10.1080/09524622.2008.9753770.

Kastelein, R.A., D. van Heerden, R. Gransier, and L. Hoek. 2013. Behavioral responses of a harbor porpoise (*Phocoena phocoena*) to playbacks of broadband pile driving sounds. *Marine Environmental Research* 92: 206-214. https://doi.org/10.1016/j.marenvres.2013.09.020.

Kastelein, R.A., L. Hoek, R. Gransier, M. Rambags, and N. Claeys. 2014. Effect of level, duration, and inter-pulse interval of 1–2 kHz sonar signal exposures on harbor porpoise hearing. *Journal of the Acoustical Society of America* 136(1): 412-422. https://doi.org/10.1121/1.4883596.

Kastelein, R.A., R. Gransier, M.A.T. Marijt, and L. Hoek. 2015a. Hearing frequency thresholds of harbor porpoises (*Phocoena phocoena*) temporarily affected by played back offshore pile driving sounds. *Journal of the Acoustical Society of America* 137(2): 556-564. https://doi.org/10.1121/1.4906261.

Kastelein, R.A., R. Gransier, J. Schop, and L. Hoek. 2015b. Effects of exposure to intermittent and continuous 6–7 kHz sonar sweeps on harbor porpoise (*Phocoena phocoena*) hearing. *Journal of the Acoustical Society of America* 137(4): 1623-1633. https://doi.org/10.1121/1.4916590.

Ketten, D.R. 1995. Estimates of blast injury and acoustic trauma zones for marine mammals from underwater explosions. *In* Kastelein, R.A., J.A. Thomas, and P.E. Nachtigall (eds.). *Sensory Systems of Aquatic Mammals*. De Spil Publishers, Woerden, The Netherlands. pp. 391-407.

Kight, C.R. and J.P. Swaddle. 2011. How and why environmental noise impacts animals: An integrative, mechanistic review. *Ecology Letters* 14(10): 1052-1061. https://doi.org/10.1111/j.1461-0248.2011.01664.x.

Klages, M., S. Muyakshin, T. Soltwedel, and W.E. Arntz. 2002. Mechanoreception, a possible mechanism for food fall detection in deep-sea scavengers. *Deep Sea Research Part I* 49(1): 143-155. https://doi.org/10.1016/S0967-0637(01)00047-4.

Knight, R.L. and D.N. Temple. 1995. Origin of Wildlife Responses to Recreationists. *In* Knight, R.L. and K.J. Gutzwiller (eds.). *Wildlife and recreationists: Coexistence through mangement and research*. Island Press. Washington DC 372s, Washington, DC. pp. 81–91.

Koschinski, S. and K. Lüdemann. 2013. *Development of Noise Mitigation Measures in Offshore Wind Farm Construction*. Commissioned by the Federal Agency for Nature Conservation (Bundesamt für Naturschutz, BfN). Original report (in German) published Jul 2011, updated Feb 2013, Nehmten and Hamburg, Germany. 97 p. https://www.bfn.de/fileadmin/MDB/documents/themen/meeresundkuestenschutz/downloads/Berichte-und-Positionspapiere/Mitigation-Measures-Underwater-Noise_2013-08-27_final.pdf.

Koschinski, S. and K. Lüdemann. 2015. Quieting technologies for offshore pile driving. *4th International Conference on Progress in Marine Conservation in Europe*. 14-18 Sep 2015, Stralsund, Germany. pp. 217-220.

Kruse, S. 1991. The interactions between killer whales and boats in Johnstone Strait, B.C. *In* Pryor, K. and K.S. Norris (eds.). *Dolphin societies: Discoveries and puzzles*. University of California Press, Berkeley. pp. 149-159.

Kuhn, C., B. Bruns, J. Fischer, J. Gattermann, and K.-H. Elmer. 2012. Development of a new underwater piling noise mitigation system using Hydro Sound Dampers (HSD). *International Conference on Ocean, Offshore and Arctic Engineering*. 1–6 Jul 2012, Rio de Janeiro, Brazil. p. 8.

Kuningas, S., P.H. Kvadsheim, F.-P.A. Lam, and P.J. Miller. 2013. Killer whale presence in relation to naval sonar activity and prey abundance in northern Norway. *ICES Journal of Marine Science* 70(7): 1287-1293.

Lacroix, D.L., R.B. Lanctot, J.A. Reed, and T.L. Mcdonald. 2003. Effect of underwater seismic surveys on molting male Long-tailed Ducks in the Beaufort Sea, Alaska. *Canadian Journal of Zoology* 81(11): 1862-1875. https://doi.org/10.1139/z03-185.

Ladich, F. and A.N. Popper. 2004. Parallel evolution in fish hearing organs. *In* Manley, G.A., A.N. Popper, and R.R. Fay (eds.). *Evolution of the Vertebrate Auditory System* Springer-Verlag, NY, USA. pp. 98-127.

Ladich, F. 2013. Effects of Noise on Sound Detection and Acoustic Communication in Fishes. *In* Brumm, H. (ed.). *Animal Communication and Noise*. Springer Berlin Heidelberg, Berlin, Heidelberg. pp. 65-90. https://doi.org/10.1007/978-3-642-41494-7_4.

Ladich, F. and R.R. Fay. 2013. Auditory evoked potential audiometry in fish. *Reviews in Fish Biology and Fisheries* 23(3): 317-364. https://doi.org/10.1007/s11160-012-9297-z.

Lagardère, J.P., S. Millot, and E. Parmentier. 2005. Aspects of sound communication in the pearlfish *Carapus boraborensis* and *Carapus homei* (Carapidae). *Journal of Experimental Zoology Part A* 303A(12): 1066-1074. https://doi.org/10.1002/jez.a.230.

Landsberg, P.G. 2000. Underwater blast injuries. *Trauma & Energy Medicine* 17(2).

Larkin, R.P., L.L. Pater, and D.J. Tazik. 1996. *Effects of Military Noise on Wildlife: A Literature Review*. Report TR 96/21. Report by Construction Engineering Research Laboratories of the US Army Corps of Engineers Champaign, IL, USA. https://apps.dtic.mil/sti/pdfs/ADA305234.pdf.

Lemon, M., T.P. Lynch, D.H. Cato, and R.G. Harcourt. 2006. Response of travelling bottlenose dolphins (*Tursiops aduncus*) to experimental approaches by a powerboat in Jervis Bay, New South Wales, Australia. *Biological Conservation* 127(4): 363-372. https://doi.org/10.1016/j.biocon.2005.08.016.

Lesage, V., C. Barrette, M.C.S. Kingsley, and B. Sjare. 1999. The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence River estuary, Canada. *Marine Mammal Science* 15(1): 65-84. https://doi.org/10.1111/j.1748-7692.1999.tb00782.x.

Long, T.M., R.T. Hanlon, A. Ter Maat, and H.M. Pinsker. 1989. Non-associative learning in the squid *Lolliguncula brevis* (Mollusca, Cephalopoda). *Marine Behaviour and Physiology* 16(1): 1-9. https://doi.org/10.1080/10236248909378736.

Lovell, J.M., M.M. Findlay, R.M. Moate, and H.Y. Yan. 2005. The hearing abilities of the prawn *Palaemon serratus*. *Comparative Biochemistry and Physiology Part A* 140(1): 89-100. https://doi.org/10.1016/j.cbpb.2004.11.003.

Lucke, K., U. Siebert, P.A. Lepper, and M.-A. Blanchet. 2009. Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. *Journal of the Acoustical Society of America* 125(6): 4060-4070. https://doi.org/10.1121/1.3117443.

Lucke, K., P.A. Lepper, M.-A. Blanchet, and U. Siebert. 2011. The use of an air bubble curtain to reduce the received sound levels for harbor porpoises (*Phocoena phocoena*). *Journal of the Acoustical Society of America* 130(5): 3406-3412. https://doi.org/10.1121/1.3626123.

Lusseau, D. 2005. Residency pattern of bottlenose dolphins *Tursiops spp*. in Milford Sound, New Zealand, is related to boat traffic. *Marine Ecology Progress Series* 295: 265-272. https://www.int-res.com/abstracts/meps/v295/p265-272/.

Lusseau, D. 2006. The short-term behavioural reactions of bottlenose dolphins to interactions with boats in Doubtful Sound, New Zealand. *Marine Mammal Science* 22(4): 802-818. https://doi.org/10.1111/j.1748-7692.2006.00052.x.

Lusseau, D., D.E. Bain, R. Williams, and J.C. Smith. 2009. Vessel traffic disrupts the foraging behavior of southern resident killer whales *Orcinus orca*. *Endangered Species Research* 6(3): 211-221. https://doi.org/10.3354/esr00154.

MacGillivray, A.O. 2018. Underwater noise from pile driving of conductor casing at a deep-water oil platform. *Journal of the Acoustical Society of America* 143(1): 450-459. https://doi.org/10.1121/1.5021554.

Markov, V.I. 1977. Underwater sounds in Macaroni Penguins. *In Adaptations of Penguins*. Moscow, Nauka. pp. 111-121.

Marley, S.A., C.P. Salgado Kent, C. Erbe, and I.M. Parnum. 2017a. Effects of vessel traffic and underwater noise on the movement, behaviour and vocalisations of bottlenose dolphins in an urbanised estuary. *Scientific Reports* 7: 13437. https://doi.org/10.1038/s41598-017-13252-z.

Marley, S.A., C.P. Salgado Kent, C. Erbe, and D. Thiele. 2017b. A Tale of Two Soundscapes: Comparing the Acoustic Characteristics of Urban Versus Pristine Coastal Dolphin Habitats in Western Australia. *Acoustics Australia* 45(2): 159-178. https://doi.org/10.1007/s40857-017-0106-7.

Mattson, M.C., J.A. Thomas, and D. St Aubin. 2005. Effects of boat activity on the behavior of bottlenose dolphins (*Tursiops truncatus*) in waters surrounding Hilton Head Island, South Carolina. *Aquatic Mammals* 31(1): 133-140. https://doi.org/10.1578/AM.31.1.2005.133.

McCauley, R.D., J. Fewtrell, A.J. Duncan, C. Jenner, M.-N. Jenner, J.D. Penrose, R.I.T. Prince, A. Adhitya, J. Murdoch, et al. 2000. *Marine seismic surveys: Analysis and propagation of air-gun signals; and effects of air-gun exposure on humpback whales, sea turtles, fishes and squid*. Report R99-15. Prepared for Australian Petroleum Production Exploration Association by Centre for Maine Science and Technology, Western Australia. 198 p. https://cmst.curtin.edu.au/wp-content/uploads/sites/4/2016/05/McCauley-et-al-Seismic-effects-2000.pdf.

McIver, E.L., M.A. Marchaterre, A.N. Rice, and A.H. Bass. 2014. Novel underwater soundscape: Acoustic repertoire of plainfin midshipman fish. *Journal of Experimental Biology* 217(13): 2377-2389. https://doi.org/10.1242/jeb.102772.

McPherson, C.R., H. Yurk, G.R. McPherson, R. Racca, and P. Wulf. 2017. *Great Barrier Reef Underwater Noise Guidelines: Discussion and Options Paper*. Document 01130. Technical report by JASCO Applied Sciences for Great Barrier Reef Marine Park Authority. http://hdl.handle.net/11017/3245.

Melvin, E.F., J.K. Parrish, and L.L. Conquest. 1999. Novel Tools to Reduce Seabird Bycatch in Coastal Gillnet Fisheries. *Conservation Biology* 13(6): 1386-1397. https://doi.org/10.1046/j.1523-1739.1999.98426.x.

Melvin, E.F., K.S. Dietrich, S. Fitzgerald, and T. Cardoso. 2011. Reducing seabird strikes with trawl cables in the pollock catcher-processor fleet in the eastern Bering Sea. *Polar Biology* 34(2): 215-226. https://doi.org/10.1007/s00300-010-0873-1.

Miller, P.J.O., P.H. Kvadsheim, F.-P.A. Lam, P.J. Wensveen, R. Antunes, A.C. Alves, F. Visser, L. Kleivane, P.L. Tyack, et al. 2012. The severity of behavioral changes observed during experimental exposures of killer

(*Orcinus orca*), long-finned pilot (*Globicephala melas*), and sperm (*Physeter macrocephalus*) whales to naval sonar. *Aquatic Mammals* 38(4). https://doi.org/10.1578/AM.38.4.2012.362.

Miller, P.J.O., R.N. Antunes, P.J. Wensveen, F.I.P. Samarra, A. Catarina Alves, P.L. Tyack, P.H. Kvadsheim, L. Kleivane, F.-P.A. Lam, et al. 2014. Dose-response relationships for the onset of avoidance of sonar by free-ranging killer whales. *Journal of the Acoustical Society of America* 135(2): 975-993. https://doi.org/10.1121/1.4861346.

Mooney, T.A., P.E. Nachtigall, and S.A. Vlachos. 2009. Sonar-induced temporary hearing loss in dolphins. *Biology Letters* 5(4): 565-567. https://doi.org/10.1098/rsbl.2009.0099.

Mooney, T.A., R.T. Hanlon, J. Christensen-Dalsgaard, P.T. Madsen, D.R. Ketten, and P.E. Nachtigall. 2010. Sound detection by the longfin squid (*Loligo pealeii*) studied with auditory evoked potentials: Sensitivity to low-frequency particle motion and not pressure. *Journal of Experimental Biology* 213(21): 3748-3759. https://doi.org/10.1242/jeb.048348.

Mooney, T.A., J.E. Samson, A.D. Schlunk, and S. Zacarias. 2016. Loudness-dependent behavioral responses and habituation to sound by the longfin squid (*Doryteuthis pealeii*). *Journal of Comparative Physiology A* 202(7): 489-501. https://doi.org/10.1007/s00359-016-1092-1.

Mooney, T.A., A.B. Smith, O.N. Larsen, K. Anderson Hansen, M. Wahlberg, and M.H. Rasmussen. 2019. Field-based hearing measurements of two seabird species. *Journal of Experimental Biology* 222(4). https://doi.org/10.1242/jeb.190710.

Morley, E.L., G. Jones, and A.N. Radford. 2014. The importance of invertebrates when considering the impacts of anthropogenic noise. *Proceedings of the Royal Society B* 281(1776). https://doi.org/10.1098/rspb.2013.2683.

Morris, C.J., D. Cote, S.B. Martin, and D.G. Kehler. 2018. Effects of 2D seismic on the snow crab fishery. *Fisheries Research* 197: 67–77. https://doi.org/10.1016/j.fishres.2017.09.012.

Mosher, J.I. 1972. The responses of *Macoma balthica* (bivalvia) to vibrations. *Journal of Molluscan Studies* 40(2): 125-131. https://doi.org/10.1093/oxfordjournals.mollus.a065209.

Mueller-Blenkle, C., P.K. McGregor, A.B. Gill, M.H. Andersson, J. Metcalfe, V. Bendall, P. Sigray, D.T. Wood, and F. Thomsen. 2010. *Effects of Pile-driving Noise on the Behaviour of Marine Fish*. COWRIE Ref: Fish 06-08; Cefas Ref: C3371. 62 p. https://dspace.lib.cranfield.ac.uk/handle/1826/8235.

Mulsow, J., C. Reichmuth, F.M.D. Gulland, D.A.S. Rosen, and J.J. Finneran. 2011. Aerial audiograms of several California sea lions (*Zalophus californianus*) and Steller sea lions (*Eumetopias jubatus*) measured using single and multiple simultaneous auditory steady-state response methods. *Journal of Experimental Biology* 214: 1138-1147. https://doi.org/10.1242/jeb.052837.

Nedelec, S.L., J. Campbell, A.N. Radford, S.D. Simpson, and N.D. Merchant. 2016. Particle motion: The missing link in underwater acoustic ecology. *Methods in Ecology and Evolution* 7: 1-7. https://doi.org/10.1111/2041-210X.12544.

Nedwell, J.R. and A.W. Turnpenny. 1998. The use of a generic frequency weighting scale in estimating environmental effect. *Workshop on Seismics and Marine Mammals*. 23–25 Jun 1998, London, UK.

Nedwell, J.R., A.W.H. Turnpenny, J. Langworthy, and B. Edwards. 2003. *Measurements of underwater noise during piling at the Red Funnel Terminal, Southampton, and observations of its effect on caged fish*. Document 558 R 0207 Report 558 R 0207. Report by Subacoustech Ltd for Red Funnel. https://tethys.pnnl.gov/sites/default/files/publications/Nedwell-2003.pdf.

Nedwell, J.R., B. Edwards, A.W.H. Turnpenny, and J. Gordon. 2004. *Fish and Marine Mammal Audiograms: A summary of available information*. *In*: Subacoustech (ed.). Document 534R0214. 278 pp. p.

Nedwell, J.R., A.W.H. Turnpenny, J.M. Lovell, and B. Edwards. 2006. An investigation into the effects of underwater piling noise on salmonids. *Journal of the Acoustical Society of America* 120(5): 2550-2554. https://doi.org/10.1121/1.2335573.

Nedwell, J.R., A.W. Turnpenny, J. Lovell, S.J. Parvin, R. Workman, J.A.L. Spinks, and D. Howell. 2007. *A validation of the dB$_{ht}$ as a measure of the behavioural and auditory effects of underwater noise*. Document 534R1231 Report prepared by Subacoustech Ltd. for Chevron Ltd, TotalFinaElf Exploration UK PLC, Department of Business, Enterprise and Regulatory Reform, Shell UK Exploration and Production Ltd, The Industry Technology Facilitator, Joint Nature Conservation Committee, and The UK Ministry of Defence. 74 p. https://tethys.pnnl.gov/sites/default/files/publications/Nedwell-et-al-2007.pdf.

Nehls, G., A. Rose, A. Diederichs, M.A. Bellmann, and H. Pehlke. 2016. Noise Mitigation During Pile Driving Efficiently Reduces Disturbance of Marine Mammals. (Chapter 92) *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life II*. Volume 875. Springer, NY, USA. pp. 755-762. https://doi.org/10.1007/978-1-4939-2981-8_92.

Nisbet, I.C.T. 2000. Disturbance, Habituation, and Management of Waterbird Colonies. *Waterbirds* 23(2): 312-332. www.jstor.org/stable/4641163.

Noren, D.P., A.H. Johnson, D. Rehder, and A. Larson. 2009. Close approaches by vessels elicit surface active behaviors by southern resident killer whales. *Endangered Species Research* 8: 179-192. https://doi.org/10.3354/esr00205

Nowacek, D.P., L.H. Thorne, D.W. Johnston, and P.L. Tyack. 2007. Responses of cetaceans to anthropogenic noise. *Mammal Review* 37(2): 81-115. https://doi.org/10.1111/j.1365-2907.2007.00104.x.

Nowacek, S.M., R.S. Wells, and A.R. Solow. 2001. Short-term effects of boat traffic on bottlenose dolphins, *Tursiops truncatus*, in Sarasota Bay, Florida. *Marine Mammal Science* 17(4): 673-688.

Ona, E., O.R. Godø, N.O. Handegard, V. Hjellvik, R. Patel, and G. Pedersen. 2007. Silent research vessels are not quiet. *Journal of the Acoustical Society of America* 121(4): EL145-EL150. https://doi.org/10.1121/1.2710741.

Packard, A., H.E. Karlsen, and O. Sand. 1990. Low frequency hearing in cephalopods. *Journal of Comparative Physiology A* 166(4): 501-505. https://doi.org/10.1007/BF00192020.

Paiva, E.G., C.P.S. Kent, M.M. Gagnon, R.D. McCauley, and H. Finn. 2015. Reduced detection of indo-pacific bottlenose dolphins (*Tursiops aduncus*) in an inner harbour channel during pile driving activities. *Aquatic Mammals* 41(4): 455-468. https://doi.org/10.1578/AM.41.4.2015.455.

Parks, S.E., D.R. Ketten, J.T. O'Malley, and J. Arruda. 2007. Anatomical predictions of hearing in the North Atlantic right whale. *The Anatomical Record* 290(6): 734-744. https://doi.org/10.1002/ar.20527.

Pérez-Jorge, S., I. Gomes, K. Hayes, G. Corti, M. Louzao, M. Genovart, and D. Oro. 2016. Effects of nature-based tourism and environmental drivers on the demography of a small dolphin population. *Biological Conservation* 197: 200-208. https://doi.org/10.1016/j.biocon.2016.03.006.

Picciulin, M., L. Sebastianutto, A. Codarin, A. Farina, and E.A. Ferrero. 2010. In situ behavioural responses to boat noise exposure of *Gobius cruentatus* (Gmelin, 1789; fam. Gobiidae) and *Chromis chromis* (Linnaeus, 1758; fam. Pomacentridae) living in a marine protected area. *Journal of Experimental Marine Biology and Ecology* 386(1-2): 125-132. https://doi.org/10.1016/j.jembe.2013.05.012.

Pichegru, L., R. Nyengera, A.M. McInnes, and P. Pistorius. 2017. Avoidance of seismic survey activities by penguins. *Scientific Reports* 7: 16305. https://doi.org/10.1038/s41598-017-16569-x.

Pine, M., D.E. Hannay, S.J. Insely, W.D. Halliday, and F. Juanes. 2018a. Assessing vessel slowdown as an option for reducing acoustic masking for Arctic cod in the western Canadian Arctic. *Journal of the Acoustical Society of America* 144(3). https://doi.org/10.1121/1.5067412.

Pine, M.K., A.G. Jeffs, and C.A. Radford. 2012. Turbine sound may influence the metamorphosis behaviour of estuarine crab Megalopae. *PLOS ONE* 7(12). https://doi.org/10.1371/journal.pone.0051790.

Pine, M.K., D.E. Hannay, S.J. Insley, W.D. Halliday, and F. Juanes. 2018b. Assessing vessel slowdown for reducing auditory masking for marine mammals and fish of the western Canadian Arctic. *Marine Pollution Bulletin* 135: 290-302. https://doi.org/10.1016/j.marpolbul.2018.07.031.

Pirotta, E., B.E. Laesser, A. Hardaker, N. Riddoch, M. Marcoux, and D. Lusseau. 2013. Dredging displaces bottlenose dolphins from an urbanised foraging patch. *Marine Pollution Bulletin* 74(1): 396-402. https://doi.org/10.1016/j.marpolbul.2013.06.020.

Pirotta, E., N.D. Merchant, P.M. Thompson, T.R. Barton, and D. Lusseau. 2015. Quantifying the effect of boat disturbance on bottlenose dolphin foraging activity. *Biological Conservation* 181: 82-89. https://doi.org/10.1016/j.biocon.2014.11.003.

Plumpton, D.L., S.E. Sheaffer, D. Hunsaker, and S.A. Petrie. 2007. *Review of Studies Related to Aircraft Noise Disturbance of Waterfowl: A Technical Report in Support of the Supplemental Environmental Impact Statement (SEIS) for Introduction of F/A-18 E/F (Super Hornet) Aircraft to the East Coast of the United States*. US Department of the Navy, Naval Facilities Engineering Command Atlantic, Norfolk, VA, USA.

Popov, V.V., A.Y. Supin, A.P. Gvozdeva, D.I. Nechaev, M.B. Tarakanov, and E.V. Sysueva. 2020. Spatial release from masking in a bottlenose dolphin Tursiops truncatus. *Journal of the Acoustical Society of America* 147(3): 1719-1726. https://doi.org/10.1121/10.0000909.

Popper, A.N. and N.L. Clarke. 1976. The auditory system of the goldfish (*Carassius auratus*): Effects of intense acoustic stimulation. *Comparative Biochemistry and Physiology Part A* 53(1): 11-18. https://doi.org/10.1016/S0300-9629(76)80003-5.

Popper, A.N., J. Fewtrell, M.E. Smith, and R.D. McCauley. 2003. Anthropogenic sound: Effects on the behavior and physiology of fishes. *Marine Technology Society Journal* 37(4): 35-40. https://doi.org/10.4031/002533203787537050.

Popper, A.N., M.E. Smith, P.A. Cott, B.W. Hanna, A.O. MacGillivray, M.E. Austin, and D.A. Mann. 2005. Effects of exposure to seismic airgun use on hearing of three fish species. *Journal of the Acoustical Society of America* 117(6): 3958-3971. https://doi.org/10.1121/1.1904386.

Popper, A.N., M.B. Halvorsen, A. Kane, D.L. Miller, M.E. Smith, J. Song, P. Stein, and L.E. Wysocki. 2007. The effects of high-intensity, low-frequency active sonar on rainbow trout. *Journal of the Acoustical Society of America* 122(1): 623-635. https://doi.org/10.1121/1.2735115.

Popper, A.N. and M.C. Hastings. 2009. The effects of anthropogenic sources of sound on fishes. *Journal of Fish Biology* 75(3): 455-489. https://doi.org/10.1111/j.1095-8649.2009.02319.x.

Popper, A.N. and R.R. Fay. 2011. Rethinking sound detection by fishes. *Hearing Research* 273(1): 25-36. https://doi.org/10.1016/j.heares.2009.12.023.

Popper, A.N., A.D. Hawkins, R.R. Fay, D.A. Mann, S. Bartol, T.J. Carlson, S. Coombs, W.T. Ellison, R.L. Gentry, et al. 2014. *Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI*. ASA S3/SC1.4 TR-2014. SpringerBriefs in Oceanography. ASA Press and Springer. https://doi.org/10.1007/978-3-319-06659-2.

Popper, A.N., A.D. Hawkins, and M.B. Halvorsen. 2019. *Anthropogenic Sound and Fishes*. Document WA-RD 891.1. Report by ICF for Washington State Department of Transportation, Research Office. 170 p.

Przeslawski, R., L. Hurt, A. Forrest, A. Carroll, and Geoscience Australia. 2016. *Potential short-term impacts of marine seismic surveys on scallops in the Gippsland Basin*. Report 2014-041. CC BY 3.0, Canberra. http://frdc.com.au/research/Final_Reports/2014-041-DLD.pdf.

Putland, R.L., N.D. Merchant, A. Farcas, and C.A. Radford. 2018. Vessel noise cuts down communication space for vocalizing fish and marine mammals. *Global Change Biology* 24(4): 1708-1721. https://doi.org/10.1111/gcb.13996.

Pye, H.J. and W.H. Watson, III. 2004. Sound detection and production in the American lobster, *Homarus americanus*: Sensitivity range and behavioral implications. *Journal of the Acoustical Society of America* 115(5): 2486-2486. https://doi.org/10.1121/1.4782805.

Pytte, C.L., K.M. Rusch, and M.S. Ficken. 2003. Regulation of vocal amplitude by the blue-throated hummingbird, *Lampornis clemenciae*. *Animal Behaviour* 66(4): 703-710. https://doi.org/10.1006/anbe.2003.2257.

Rako, N., C.M. Fortuna, D. Holcer, P. Mackelworth, M. Nimak-Wood, G. Pleslić, L. Sebastianutto, I. Vilibić, A. Wiemann, et al. 2013. Leisure boating noise as a trigger for the displacement of the bottlenose dolphins of the Cres-Lošinj archipelago (northern Adriatic Sea, Croatia). *Marine Pollution Bulletin* 68(1-2): 77-84. https://doi.org/10.1016/j.marpolbul.2012.12.019.

Ramcharitar, J., D.P. Gannon, and A.N. Popper. 2006. Bioacoustics of fishes of the family Sciaenidae (croakers and drums). *Transactions of the American Fisheries Society* 135(5): 1409-1431. https://doi.org/10.1577/T05-207.1.

Reichmuth, C.J., A. Ghoul, J.M. Sills, A. Rouse, and B.L. Southall. 2016. Low-frequency temporary threshold shift not observed in spotted or ringed seals exposed to single air gun impulses. *Journal of the Acoustical Society of America* 140(4): 2646-2658. https://doi.org/10.1121/1.4964470.

Reine, K.J., D. Clarke, and C. Dickerson. 2014. Characterization of underwater sounds produced by hydraulic and mechanical dredging operations. *Journal of the Acoustical Society of America* 135(6): 3280-3294. https://doi.org/10.1121/1.4875712.

Reinhall, P.G. and P.H. Dahl. 2011. Underwater Mach wave radiation from impact pile driving: Theory and observation. *Journal of the Acoustical Society of America* 130(3): 1209-1216. https://doi.org/10.1121/1.3075600.

Remmers, P. and M.A. Bellmann. 2013. *Untersuchung und Erprobung von Hydroschalldämpfern (HSD) zur Minderung von Unterwasserschall bei Rammarbeiten für Gründungen von OffshoreWindenergieanlagen*. Auswertung der Hydroschallmessungen im OWP London Array. Project number1918-c-bel version 3. Report by Itap GmbH, Oldenburg, Germany.

Richardson, W.J., C.R. Greene, Jr., C.I. Malme, and D.H. Thomson. 1995. *Marine Mammals and Noise*. Academic Press, San Diego, CA, USA. 576 p. https://doi.org/10.1016/C2009-0-02253-3.

Ridgway, S.H. and D. Carder. 1997. Hearing deficits measured in some *Tursiops truncatus*, and discovery of a deaf/mute dolphin. *Journal of the Acoustical Society of America* 101(1): 590-594. https://doi.org/10.1121/1.418122.

Roberts, L., S. Cheesman, T. Breithaupt, and M. Elliott. 2015. Sensitivity of the mussel *Mytilus edulis* to substrate-borne vibration in relation to anthropogenically generated noise. *Marine Ecology Progress Series* 538: 185-195. https://doi.org/10.3354/meps11468.

Roberts, L., S. Cheesman, M. Elliott, and T. Breithaupt. 2016. Sensitivity of *Pagurus bernhardus* (L.) to substrate-borne vibration and anthropogenic noise. *Journal of Experimental Marine Biology and Ecology* 474: 185-194. https://doi.org/10.1016/j.jembe.2015.09.014.

Roberts, L. and M. Elliott. 2017. Good or bad vibrations? Impacts of anthropogenic vibration on the marine epibenthos. *Science of The Total Environment* 595: 255-268. https://doi.org/10.1016/j.scitotenv.2017.03.117.

Robinson, S.P., P.A. Lepper, and J. Ablitt. 2007. The measurement of the underwater radiated noise from marine piling including characterisation of a" soft start" period. *OCEANS 2007*. 18-21 Jun 2007. IEEE, Aberdeen, UK. pp. 732-737. https://doi.org/10.1109/OCEANSE.2007.4302326.

Ruggerone, G.T., S.E. Goodman, and R. Miner. 2008. *Behavioral response and survival of juvenile coho salmon to pile driving sounds*. Report by Natural Resources Consultants, Inc. for Port of Washington, Seattle, WA, USA.

Russell, D.J.F., G.D. Hastie, D. Thompson, V.M. Janik, P.S. Hammond, L.A.S. Scott-Hayward, J. Matthiopoulos, E.L. Jones, and B.J. McConnell. 2016. Avoidance of wind farms by harbour seals is limited to pile driving activities. *Journal of Applied Ecology* 53(6): 1642-1652. https://doi.org/10.1111/1365-2664.12678.

Ryals, B.M., R.J. Dooling, E. Westbrook, M.L. Dent, A. MacKenzie, and O.N. Larsen. 1999. Avian species differences in susceptibility to noise exposure. *Hearing Research* 131(1-2): 71-88. https://doi.org/10.1016/S0378-5955(99)00022-2.

Saleem, Z. 2011. *Alternatives and modifications of Monopile foundation or its installation technique for noise mitigation*. Report by Delft Univeristy of Technology and Stichting De Noordzee for the North Sea Foundation. http://www.vliz.be/imisdocs/publications/223688.pdf.

Salgado Kent, C.P., R.D. McCauley, I.M. Parnum, and A.N. Gavrilov. 2012. Underwater noise sources in Fremantle inner harbour: Dolphins, pile driving and traffic. *Acoustics 2012*. 21-23 Nov 2012, Fremantle, Australia.

Sand, O., H.E. Karlsen, and F.R. Knudsen. 2008. Comment on "Silent research vessels are not quiet" [J. Acoust. Soc. Am. 121, EL145–EL150]. *Journal of the Acoustical Society of America* 123(4): 1831-1833. https://doi.org/10.1121/1.2839134.

Saunders, J. and R.J. Dooling. 1974. Noise-induced threshold shift in the parakeet (*Melopsittacus undulatus*). *Proceedings of the National Academy of Sciences of the United States of America* 71(5): 1962-1965. https://doi.org/10.1073/pnas.71.5.1962.

Saunders, J.C. and R.J. Dooling. 2018. Characteristics of Temporary and Permanent Threshold Shifts in Vertebrates. (Chapter 4) *In* Slabbekoorn, H., R.J. Dooling, A.N. Popper, and R.R. Fay (eds.). *Effects of Anthropogenic Noise on Animals*. Volume 66. Springer, New York. pp. 83-108. https://doi.org/10.1007/978-1-4939-8574-6_4.

Scheifele, P.M., S. Andrew, R.A. Cooper, M. Darre, F.E. Musiek, and L. Max. 2005. Indication of a Lombard vocal response in the St. Lawrence River beluga. *Journal of the Acoustical Society of America* 117(3): 1486-1492. https://doi.org/10.1121/1.1835508.

Scholik, A.R. and H.Y. Yan. 2001. Effects of underwater noise on auditory sensitivity of a cyprinid fish. *Hearing Research* 152(1-2): 17-24. https://doi.org/10.1016/S0378-5955(00)00213-6.

Scholik, A.R. and H.Y. Yan. 2002. Effects of boat engine noise on the auditory sensitivity of the fathead minnow, *Pimephales promelas*. *Environmental Biology of Fishes* 63(2): 203-209. https://doi.org/10.1023/A:1014266531390.

Sierra-Flores, R., T. Atack, H. Migaud, and A. Davie. 2015. Stress response to anthropogenic noise in Atlantic cod *Gadus morhua* L. *Aquacultural Engineering* 67: 67-76. https://doi.org/10.1016/j.aquaeng.2015.06.003.

Simpson, S.D., J. Purser, and A.N. Radford. 2015. Anthropogenic noise compromises antipredator behaviour in European eels. *Global Change Biology* 21(2): 586-593. https://doi.org/10.1111/gcb.12685.

Sisneros, J.A., A.N. Popper, A.D. Hawkins, and R.R. Fay. 2016. Auditory Evoked Potential Audiograms Compared with Behavioral Audiograms in Aquatic Animals. *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life II*. Volume 875. Springer, New York. pp. 1049-1056. https://doi.org/10.1007/978-1-4939-2981-8_130.

Slabbekoorn, H., N. Bouton, I. van Opzeeland, A. Coers, C. ten Cate, and A.N. Popper. 2010. A noisy spring: The impact of globally rising underwater sound levels on fish. *Trends in Ecology & Evolution* 25(7): 419-427. https://doi.org/10.1016/j.tree.2010.04.005.

Slabbekoorn, H., J. Dalen, D. de Haan, H.V. Winter, C. Radford, M.A. Ainslie, K.D. Heaney, T. van Kooten, L. Thomas, et al. 2019. Population-level consequences of seismic surveys on fishes: An interdisciplinary challenge. *Fish and Fisheries* 20(4). https://doi.org/10.1111/faf.12367.

Smith, M.E., A.S. Kane, and A.N. Popper. 2004. Noise-induced stress response and hearing loss in goldfish (*Carassius auratus*). *Journal of Experimental Biology* 207(3): 427-435. https://doi.org/10.1242/jeb.00755.

Smith, M.E., A.B. Coffin, D.L. Miller, and A.N. Popper. 2006. Anatomical and functional recovery of the goldfish (*Carassius auratus*) ear following noise exposure. *Journal of Experimental Biology* 209(21): 4193-4202. https://doi.org/10.1242/jeb.02490.

Smith, M.E. and J.D. Monroe. 2016. Causes and Consequences of Sensory Hair Cell Damage and Recovery in Fishes. *In* Sisneros, J.A. (ed.). *Fish Hearing and Bioacoustics*. Volume 877. pp. 393-417. https://doi.org/10.1007/978-3-319-21059-9_17.

Solan, M., C. Hauton, J.A. Godbold, C.L. Wood, T.G. Leighton, and P. White. 2016. Anthropogenic sources of underwater sound can modify how sediment-dwelling invertebrates mediate ecosystem properties. *Scientific Reports* 6: 20540. https://doi.org/10.1038/srep20540.

Solé, M., M. Lenoir, M. Durfort, M. López-Bejar, A. Lombarte, and M. André. 2013. Ultrastructural Damage of *Loligo vulgaris* and *Illex coindetii* statocysts after Low Frequency Sound Exposure. *PLOS ONE* 8(10): e78825. https://doi.org/10.1371/journal.pone.0078825.

Solé, M., P. Sigray, M. Lenoir, M. Van Der Schaar, E. Lalander, and M. André. 2017. Offshore exposure experiments on cuttlefish indicate received sound pressure and particle motion levels associated with acoustic trauma. *Scientific Reports* 7: 45899. https://doi.org/10.1038/srep45899.

Song, J., D.A. Mann, P.A. Cott, B.W. Hanna, and A.N. Popper. 2008. The inner ears of northern Canadian freshwater fishes following exposure to seismic air gun sounds. *Journal of the Acoustical Society of America* 124(2): 1360-1366. https://doi.org/10.1121/1.2946702.

Sørensen, K., C. Neumann, M. Dähne, K.A. Hansen, and M. Wahlberg. 2020. Gentoo penguins (*Pygoscelis papua*) react to underwater sounds. *Royal Society Open Science* 7(2): 191988. https://doi.org/10.1098/rsos.191988.

Southall, B.L., A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Greene, Jr., D. Kastak, D.R. Ketten, J.H. Miller, et al. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. *Aquatic Mammals* 33(4): 411-521. https://doi.org/10.1578/AM.33.4.2007.411.

Southall, B.L., T. Rowles, F. Gulland, R.W. Baird, and P.D. Jepson. 2013. *Final report of the Independent Scientific Review Panel investigating potential contributing factors to a 2008 mass stranding of melon-headed whales (Peponocephala electra) in Antsohihy, Madagascar*.

Southall, B.L., D.P. Nowaceck, P.J.O. Miller, and P.L. Tyack. 2016. Experimental field studies to measure behavioral responses of cetaceans to sonar. *Endangered Species Research* 31: 293-315. https://doi.org/10.3354/esr00764.

Southall, B.L., J.J. Finneran, C.J. Reichmuth, P.E. Nachtigall, D.R. Ketten, A.E. Bowles, W.T. Ellison, D.P. Nowacek, and P.L. Tyack. 2019. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. *Aquatic Mammals* 45(2): 125-232. https://doi.org/10.1578/AM.45.2.2019.125.

Sprogis, K.R., S. Videsen, and P.T. Madsen. 2020. Vessel noise levels drive behavioural responses of humpback whales with implications for whale-watching. *eLife* 9: e56760. https://doi.org/10.7554/eLife.56760.

Stalmaster, M.V. and J.L. Kaiser. 1997. Flushing responses of wintering bald eagles to military activity. *Journal of Wildlife Management* 61(4): 1307-1313. https://doi.org/10.2307/3802130.

Stanley, J.A., S.M. Van Parijs, and L.T. Hatch. 2017. Underwater sound from vessel traffic reduces the effective communication range in Atlantic cod and haddock. *Scientific Reports* 7(1): 14633. https://doi.org/10.1038/s41598-017-14743-9.

Stein, P., H. Sychla, J. Gattermann, and J. Degenhardt. 2015. Hydro sound emissions during impact driving of monopiles using Hydro Sound Dampers and Big Bubble Curtain. *RAVE Offshore Wind R&D Conference*. 13-15 Oct 2015, Bremerhaven, Germany.

Stokes, A., K. Cockrell, J. Wilson, D. Dwight, and D. Warwick. 2010. *Mitigation of underwater pile driving noise during offshore construction: Final report*. Report M09PC00019-8. Report by Applied Physical Sciences Corp. for Department of the Interior, Minerals Management Service. http://users.ece.utexas.edu/~ling/4A_US5.pdf.

Tavolga, W.N. and J. Wodinsky. 1963. Auditory capacities in fishes: Pure tone thresholds in nine species of marine teleosts. *Bulletin of the American Museum of Natural History* 126: 177-240.

Tennessen, J.B. and S.E. Parks. 2016. Acoustic propagation modeling indicates vocal compensation in noise improves communication range for North Atlantic right whales. *Endangered Species Research* 30: 225-237. https://doi.org/10.3354/esr00738.

Terhune, J.M., R.E.A. Stewart, and K. Ronald. 1979. Influence of vessel noises on underwater vocal activity of harp seals. *Canadian Journal of Zoology* 57(6): 1337-1338. https://doi.org/10.1139/z79-170.

Thomsen, F., S. McCully, D. Wood, F. Pace, and P. White. 2009. *A generic investigation into noise profiles of marine dredging in relation to the acoustic sensitivity of the marine fauna in UK waters with particular emphasis on aggregate dredging: PHASE 1 Scoping and review of key issues*. . Document MEPF/08/P21. Technical report by Marine Aggregate Levy Sustainability Fund (MALSF).

Thorpe, W.H. 1963. *Learning and instinct in animals*. Methuen & Co., London.

Tougaard, J., J. Carstensen, O.D. Henriksen, H. Skov, and J. Teilmann. 2003. *Short-term effects of the construction of wind turbines on harbour porpoises at Horns Reef*. Report by Danish Hydraulic Institute (DHI), National Environmental Research Institute (NERI), and TechWise A/S, Røskilde, Denmark. 72 p. https://tethys.pnnl.gov/publications/short-term-effects-construction-wind-turbines-harbour-porpoises-horns-reef.

Tougaard, J., J. Carstensen, J. Teilmann, H. Skov, and P. Rasmussen. 2009. Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (*Phocoena phocoena* (L.)). *Journal of the Acoustical Society of America* 126(1): 11-14. https://doi.org/10.1121/1.3132523.

Tubelli, A.A., A. Zosuls, D.R. Ketten, and D.C. Mountain. 2012. Prediction of a mysticete audiogram via finite element analysis of the middle ear. *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life*. Volume 730. Springer, New York. pp. 57-59. https://doi.org/10.1007/978-1-4419-7311-5_12.

Vasconcelos, R.O., M.C.P. Amorim, and F. Ladich. 2007. Effects of ship noise on the detectability of communication signals in the Lusitanian toadfish. *Journal of Experimental Biology* 210(12): 2104-2112. https://doi.org/10.1242/jeb.004317.

Vasconcelos, R.O., P.J. Fonseca, M.C.P. Amorim, and F. Ladich. 2011. Representation of complex vocalizations in the Lusitanian toadfish auditory system: Evidence of fine temporal, frequency and amplitude discrimination. *Proceedings of the Royal Society B* 278(1707): 826-834. https://doi.org/10.1098/rspb.2010.1376.

Vinh, P.C. 2013. Scholte-wave velocity formulae. *Wave Motion* 50(2): 180-190. https://doi.org/10.1016/j.wavemoti.2012.08.006.

Voellmy, I.K., J. Purser, D. Flynn, P. Kennedy, S.D. Simpson, and A.N. Radford. 2014. Acoustic noise reduces foraging success in two sympatric fish species via different mechanisms. *Animal Behaviour* 89: 191-198. https://doi.org/10.1016/j.anbehav.2013.12.029.

Voellmy, I.K., J. Purser, S.D. Simpson, and A.N. Radford. 2016. Effects of Previous Acoustic Experience on Behavioral Responses to Experimental Sound Stimuli and Implications for Research. *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life II*. Springer New York. pp. 1191-1196. https://doi.org/10.1007/978-1-4939-2981-8_149.

Von Benda-Beckmann, A.M., P.J. Wensveen, P.H. Kvadsheim, F.-P.A. Lam, P.J.O. Miller, P.L. Tyack, and M.A. Ainslie. 2014. Modeling effectiveness of gradual increases in source level to mitigate effects of sonar on marine mammals. *Conservation Biology* 28(1): 119-128. http://dx.doi.org/10.1111/cobi.12162.

Ward, W.D. 1997. Effects of high-intensity sound. (Chapter 119) *In* Crocker, M.J. (ed.). *Encyclopedia of acoustics*. Volume III. John Wiley and Sons, New York. pp. 1497-1507. https://doi.org/10.1002/9780470172537.ch119.

Wartzok, D. and D.R. Ketten. 1999. Marine Mammal Sensory Systems. (Chapter 4) *In* Reynolds, J. and S. Rommel (eds.). *Biology of Marine Mammals*. Smithsonian Institution Press, Washington, DC. pp. 117-175.

Wever, E.G., P.N. Herman, J.A. Simmons, and D.R. Hertzler. 1969. Hearing in the blackfooted penguin, Pheniscus demersus, as represented by cochlear potentials. *Proceedings of the National Academy of Sciences of the United States of America* 63(3): 676-680. https://doi.org/10.1073/pnas.63.3.676.

Williams, R., D.E. Bain, J.K.B. Ford, and A.W. Trites. 2002a. Behavioral responses of male killer whales to a "leapfrogging" vessel. *Journal of Cetacean Research and Management* 4(3): 305-310.

Williams, R., A.W. Trites, and D.E. Bain. 2002b. Behavioural reponses of killer whales (*Orcinus orca*) to whale-watching boats: Opportunistics observations and experimental approaches. *Journal of Zoology* 256(2): 255-270. https://doi.org/10.1017/S0952836902000298.

Williams, R., D.E. Bain, J.C. Smith, and D. Lusseau. 2009. Effects of vessels on behaviour patterns of individual southern resident killer whales *Orcinus orca*. *Endangered Species Research* 6(3): 199-209. https://doi.org/10.3354/esr00150.

Williams, R., C. Erbe, E. Ashe, A. Beerman, and J. Smith. 2014. Severity of killer whale behavioral responses to ship noise: A dose–response study. *Marine Pollution Bulletin* 79(1-2): 254-260. https://doi.org/10.1016/j.marpolbul.2013.12.004.

Williams, R., C. Erbe, E. Ashe, and C.W. Clark. 2015. Quiet(er) marine protected areas. *Marine Pollution Bulletin* 100(1): 154-161. https://doi.org/10.1016/j.marpolbul.2015.09.012.

Wilson, C.C. and C. McPherson. 2021. *Viva Energy Gas Terminal Project: Baseline Monitoring of Ambient Environment*. Document 02580, Version 1.0 DRAFT. Technical report by JASCO Applied Sciences for AECOM.

Würsig, B., C.R. Greene, Jr., and T.A. Jefferson. 2000. Development of an air bubble curtain to reduce underwater noise of percussive piling. *Marine Environmental Research* 49(1): 79-93. https://doi.org/10.1016/S0141-1136(99)00050-1.

Supplement A. Physical Characteristics of Underwater Sound

The following subsections provide a brief overview of the most important aspects of underwater sound and introduce the most relevant terms and metrics.

A.1. Sound Characteristics

Sound is a physical phenomenon consisting of minute vibrations that travel through a supporting medium, such as air or water. When the surface of a vibrating object (sound source) moves forward into the medium, it compresses the surrounding molecules, thereby creating a region of higher pressure. As the surface then moves back toward and past its neutral position, the molecules of the surrounding medium expand back and a region of lower pressure results. These cycles are called compressions and rarefactions, respectively (see Figure A-1).

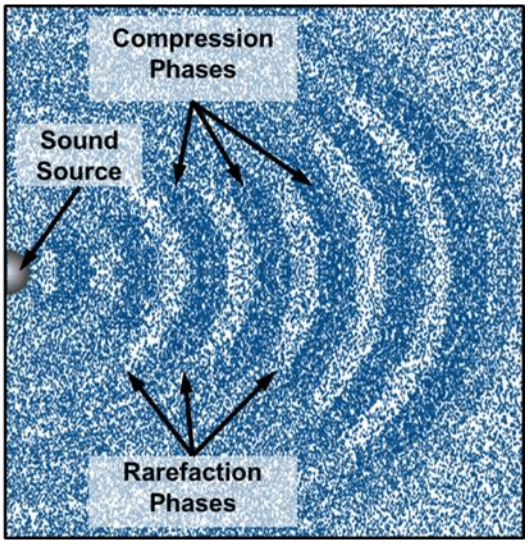


Figure A-1. Cession and rarefaction phases of a travelling sound wave.

The successive compressions and rarefactions result in sound waves. The speed at which these compressions and rarefactions travel away from the source depends on the compressibility and density of the medium and defines the speed of sound in that medium. Sound waves travel much faster in water than in air.

Sound is generally described in terms of frequency (or pitch), intensity, and temporal properties (e.g., short or long in duration, impulsive and non-impulsive). The following text provides a general description of these terms. For more details, there are several publications and books that provide detailed overviews of underwater acoustics, such as Richardson et al. (1995) and Au and Hastings (2008a), and some internet sources such as the Discovery of Sound in the Sea (DOSITS 2020), which is a highly recommended source of information on the subject.

Frequency is a measure of how many times the crest of a sound pressure wave passes a fixed point over the duration of a second; it is measured in Hertz (Hz). Some mysticetes (baleen whales) produce and may hear sounds below 20 Hz, while odontocetes (toothed whales) produce and hear sounds at frequencies much higher (up to 180 kHz for some species).

Sound intensity is defined as the acoustic power per unit area. The intensity, power, and energy of a sound wave are proportional to the average of the squared pressure. Measurement instruments and most receivers (humans, animals) sense changes in pressure, which is measured in Pascals (Pa). While pressure changes due to sound waves can be measured in Pascals, they are more commonly expressed in decibels (dB). The decibel is a logarithmic scale that is based on the ratio of the sound pressure relative to a standard reference pressure. The logarithmic decibel scale is used to allow comparison of extremely large sound pressure differences between sources.

Different standard reference pressures are used for airborne sounds and underwater sounds. The airborne standard pressure reference is $p_{ref(air)}$ = 20 micropascals (μPa), while the underwater standard reference pressure is $p_{ref(water)}$ = 1 μPa. The formula used to convert a pressure p measured in micropascals to sound pressure level P measured in dB is $P = 20 \log 10\ [p/p_{ref}]$. Because of the logarithmic nature of the decibel scale, sound levels cannot be added or subtracted directly. (If a sound's pressure is doubled, its sound level increases by 6 dB, regardless of the initial sound level.)

Impulsive Sounds versus Non-impulsive Sounds

Impulsive and non-impulsive sounds are primarily distinguished by their temporal pattern: Impulsive or 'pulsed' sounds can be described as discrete (single pulses) and sometimes intermittent sounds (multiple pulses) produced by sources such as airguns and pile driving. These sounds, sometimes also termed transients, are typically brief signals consisting of high peak sound pressure with a rapid rise time and a rapid decay (NIOSH 1998).

Non-impulsive sounds, which can be intermittent or continuous, produced by sound sources such as ships and pumps. Non-impulsive sounds are longer than impulsive ones and usually do not have the high peak sound pressure and rapid rise/decay time that impulsive sounds do (NIOSH 1998). However, especially in respect to their auditory effects, the term non-impulsive does not imply long duration signals.

Particle Motion

Since sound is a mechanical wave, it can also be measured in terms of the vibratory motion of fluid particles. Particle motion can be measured in terms of three different (but related) quantities: displacement, velocity, or acceleration. Acoustic particle velocity is the time derivative of particle displacement, and likewise acceleration is the time derivative of velocity. The most relevant particle motion metrics regarding potential effects on marine fauna are acceleration and velocity.

Acoustic Metrics

Three metrics are commonly used for analysing underwater sound propagation and evaluating underwater sound impacts on marine wildlife: peak pressure (PK), sound pressure level (SPL), and sound exposure level (SEL). Terminology in this field should refer to the ISO standard International Organization for Standardization (2017). For impulsive sources, SPL is gradually being supplemented or replaced by fast time-weighted average SPL.

Figure A-2 shows a representation of a sinusoidal (single frequency) pressure wave to illustrate the various metrics. The amplitude of the pressure is shown along the vertical axis, and time is shown along the horizontal axis. The pressure of the wave fluctuates around the neutral point. The peak pressure is the absolute value of the maximum variation from the neutral position of a wave oscillation; therefore, it can result from either a compression or a rarefaction. The peak-to-peak sound pressure is the difference between the maximum and minimum pressures. The average amplitude is the average of absolute value of pressure over the period of interest.

The rms amplitude is a type of average determined by squaring all the amplitudes over the period of interest, determining the mean of the squared values, and then taking the square root of this mean. The rms amplitude of an impulsive signal will vary significantly depending on the length of the period of interest.

SEL is a metric related to the sound energy per area received over time, though it does not have energy units; it is proportional to the square of the sound pressure and the time over which a sound is received.

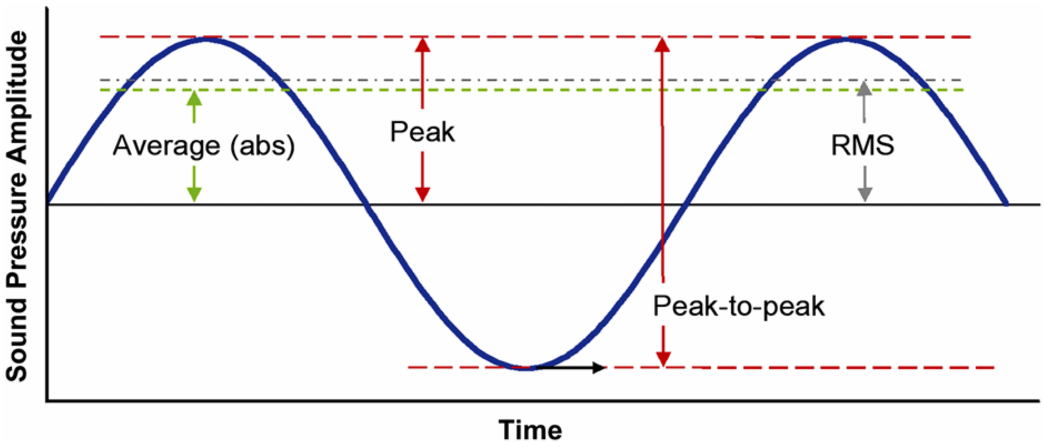


Figure A-2. Sound level metrics.

Sources of underwater noise, such as ship propellers or marine mammal vocalisations, generate radiating sound waves whose intensity generally decays with distance from the source. The reduction in sound level measured in decibels that results from propagation of sound away from an acoustic source is called propagation loss (PL) or transmission loss (TL). The loudness or sound volume of a noise source is quantified in terms of the source level (SL), which is the sound level referenced to some fixed distance from a noise source. The standard reference distance for underwater sound is 1 m. By convention, transmission loss is quoted in units of dB and underwater acoustic source levels are specified in units of dB re 1 µPa.