Kimberley Supply Chain Cluster

Underwater noise impact assessment

Crestlink Pty Ltd

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→ **The Power of Commitment**

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Contents

Table index

Figure index

1. Introduction

1.1 Project description

In 2016, Crestlink Pty Ltd (Crestlink) proposed the construction and operation of the Kimberley Supply Chain Cluster (the ‘Project’) in Western Australia (WA) in the Buccaneer Archipelago. The project aimed to upgrade and develop infrastructure on Cockatoo Island, including an airfield, a wharf, an aftermarket subsea workshop, and other related support facilities.

The wharf area will sit atop reclaimed seabed on the leeward side of the Island. When the wharf is developed to its full extent, it has a land reclamation area of approximately 5.8 ha and will require approximately 700,000 m^3 of fill to raise the level of the platform to approximately 3m above high tide. The wharf, essentially a hardstand area built out into the ocean will require a rock armour sea wall to protect it from ocean activity. It is proposed to place a rock blanket layer over the reclamation area during low tide, via dump trucks and excavators. This will enable construction vehicles such as trucks to deliver and place armour rock along the edges of the reclaimed area. The hardstand will be progressively raised commensurate with the rise in the sea wall construction.

1.2 Purpose of this report

This underwater noise impact assess (UNIA) report aims to provide an environmental assessment for evaluating the effects of underwater noise from key construction activities in terms of physical injury, impairment to hearing, or behavioural disturbance it might cause to marine megafauna species in the proposed Project area and its immediate surrounds.

The potential marine megafauna species that may occur at the Project site and its surrounds include dolphins, whales, dugongs, whale sharks, sea turtles and fishes. Practical mitigation and management measures are provided, where required.

1.3 Scope of work

The following tasks were undertaken to complete the UNIA:

- Noise characteristics of rock dumping were estimated from literature and measurements from past rock dumping projects.
- Noise exposure assessment criteria was established for the identified marine fauna species in the project locale on the basis of applicable regulatory requirements and/or applicable guidelines/standards representing industry best practice.
- Underwater noise modelling was carried out for two (2) modelling scenarios with numerical underwater noise modelling algorithms (e.g. the range-dependent parabolic equation (PE) modelling algorithm RAMGeo for broadband low frequency noise modelling and/or ray tracing Bellhop algorithm for high frequency modelling).
- Post-processing of the modelling results was carried out to obtain other relevant assessment parameters such as root mean square (RMS) sound pressure levels (SPLs), based on predicted sound exposure levels (SELs). Cumulative effects from concurrent construction emission sources and any existing emission sources was considered in order to undertake cumulative sound exposure level (SELcum) predictions.
- The predictions were compared to the established assessment criteria to determine relevant zones of impact, taking into account the baseline ocean noise environment (likely estimates), the cumulative noise predictions, the schedules of the assessed activities, as well as the ecological characteristics of assessed marine fauna species.
- In-principle potential mitigation measures and resultant zones of impact have been provided.

1.4 Limitations

This report: has been prepared by GHD for Crestlink Pty Ltd and may only be used and relied on by Crestlink Pty Ltd for the purpose agreed between GHD and Crestlink Pty Ltd as set out in section 1.2 of this report.

GHD otherwise disclaims responsibility to any person other than Crestlink Pty Ltd arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer section(s) 1.5 of this report). GHD disclaims liability arising from any of the assumptions being incorrect.

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1.5 Assumptions

This report is subject to the following general assumptions at the time of writing this report:

– All information provided by Crestlink or by relevant third parties, including relevant project information and modelling data inputs are deemed as correct.
– The occurrence of marine fauna in the project area and adjacent region is based on information provided in the Marine Habitats and Fauna Report (GHD, 2025).
– Assessment criteria nominated for various sensitive species for the project are based on relevant available research (referenced throughout the report) and are deemed as compliant to relevant industry standards
– All parameters used in the modelling and assessment are based on best estimates using information provided by Crestlink and other relevant sources.

2. Policy context

2.1 Relevant legislation

Legislation governing the protection of marine fauna and their habitats in WA (and the study area) includes:

– *Environmental Protection Act 1986* (EP Act, WA)
– *Biodiversity Conservation Act 2016* (BC Act, WA)
– *Fish Resources Management Act 1994* (FRM Act, WA)
– State Environmental (Cockburn Sound) Policy 2015.

The EPBC Act and EP Act aim to support environmentally sustainable development while protecting environmental values, including biodiversity. Crestlink aims to comply with the intent of State legislation to the extent that these provisions are not inconsistent with Commonwealth requirements.

A referral for the Project is currently being prepared for assessment by the Commonwealth DCCEEW, as required under the EPBC Act. The findings of this Report will support the referral preparation.

2.2 Underwater noise guidelines

Currently, there are no national guidelines on acceptable exposure levels for fauna to underwater noise generated by construction works. However, the South Australian Department for Infrastructure and Transport and government departments from other countries have published guidelines on acceptable exposure levels for marine fauna on the basis of international research in the field.

These include:

– The South Australian Department for Infrastructure and Transport Underwater Piling and Dredging Noise Guidelines (SA DIT, 2023)
– The U.S. Department of Commerce NOAA Technical Memorandum NMFS-OPR-59 2018 Revision to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0) Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts (US National Marine Fisheries Service, 2018).

This assessment incorporates findings and guidance from the above references and as well as the latest research and recommendations found in the following documents:

– Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI (Popper A. H., 2014)
– Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects (Southall B. L., 2019)
– Great Barrier Reef Underwater Noise guidelines: Discussion and Options Paper (McPherson, 2017).

2.3 Impact of underwater noise

Underwater sound transmits effectively within the water column and is an important sensory modality for many marine organisms. A variety of marine fauna species, including marine mammals, fish species and invertebrates, have special mechanisms both for producing and detecting underwater sound (Richardson *et al*. (1995); Popper *et al*. (2001) and (2003)).

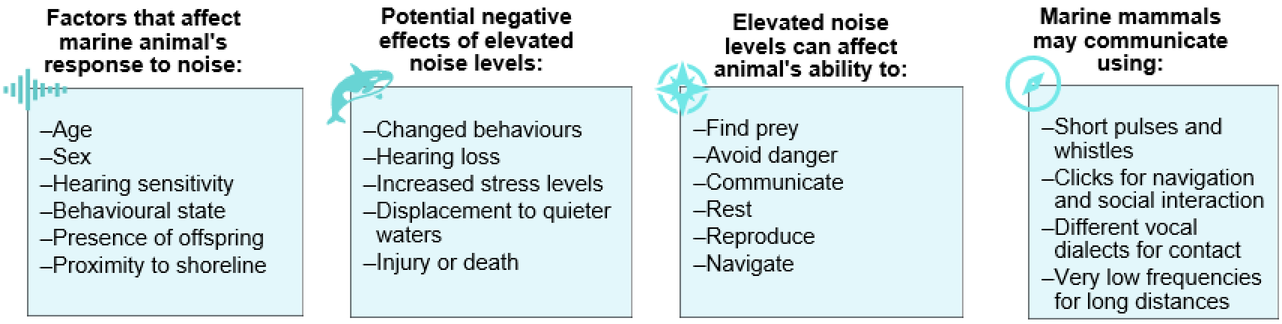
Marine mammals, including cetaceans and pinnipeds, use underwater sound in communication, orientation, predator avoidance and foraging (Tyack (1998); Tyack *et al.* (2000); Janik (2005)). Many marine fish species produce sounds for communication (Fay and Popper, (1999); Popper *et al.* (2003) and (2014); Ladich *et al*. (2004) , (2006(a)) and (2006(b))), and potentially they also use acoustic environment for orientation (Montgomery *et al.* (2006)). Marine invertebrates are known to respond mostly to sound particle motion rather than sound pressure (Salgado Kent *et al.* (2016)).

The introduction of underwater noise to their habitats can have both short-term and long-term effects on marine life. The effects of noise and the range over which these effects take place depend on the acoustic characteristics of the noise (e.g. source level, spectral content, temporal characteristics (e.g. impulsive[1] or non-impulsive/continuous[2]), directionality, etc.), the sound propagation environment as well as the hearing ability and responses of individual marine fauna species to sound. Impacts of noise on marine fauna can also depend on the ecological context, life history stage and behaviour of the fauna in question, such as individuals with calves are likely to be more sensitive to noise disturbance.

In general, the potential impacts of excessive levels of underwater noise on marine fauna can include:

- Significant behavioural disturbance that may affect important populations or species survival.
- Noise masking interference with acoustic communication and echo location.
- Temporary loss of auditory sensitivity.
- Permanent loss of auditory sensitivity.
- Other tissue damage (lethal and sub-lethal).

A summary of these factors and potential impacts is shown below.



It should be noted that the above impacts are potentially overlapping- i.e., where the marine fauna is close to a sound (highest intensity), the impact on an animal can include death, physiological effects, temporary hearing shift, masking and behavioural responses (Hawkins and Popper (2012)). These impacts are described in further detail below and are illustrated in Figure 2.1 below as impact zones from the source location.

[1] Impulsive noise is typically very short (seconds) and intermittent with rapid time and decay back to ambient levels. E.g. noise from pile driving, seismic airguns and seabed survey sonar signals.
[2] Non-impulsive or continuous noise refers to a noise event with pressure level remains above ambient levels during an extended period of time (minutes to hours), but varies in intensity with time. E.g., noise from marine vessels.

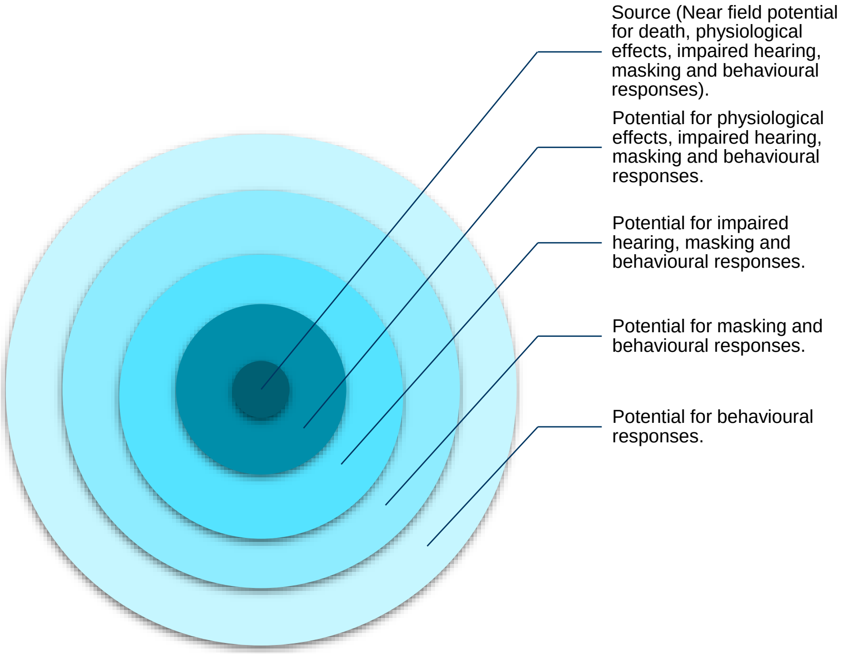


Figure 2.1 Theoretical zones of noise influence (Richardson et al. (1995))

2.3.1 Audibility/detection

A sound is audible when the receiver is able to perceive it over background noise. The audibility is also determined by the threshold of hearing that varies with frequency. The frequency dependant hearing sensitivity is expressed in the form of a hearing curve (i.e. audiogram). In general, marine mammals and fish species usually have ‘U-shaped’ audiograms, meaning that within their respective hearing ranges, they are more sensitive to the sound energy component in the mid frequency range, and less sensitive to the energy components in the lower and upper frequency ranges (Whitlow *et al.* (2008); Southall *et al.* (2007) ; Popper *et al.* (2014)).

For fish species, their sound detection is based on the response of the auditory portion of their ears (i.e. the otolithic organs) to particle motion of the surrounding fluid (Popper *et al.* (2014)). Some fish species have the ability to detect sound pressure via gas filled structures near the ear and/or extensions of the swim bladder that functionally affect the ear, in addition to purely the fluid particle motion, which as a result increase hearing sensitivity and broaden the hearing bandwidth (Popper *et al.* (2014)).

2.3.2 Masking

Masking occurs when the noise is high enough to impair detection of biologically relevant sound signals such as communication signals, echolocation clicks and passive detection cues that are used for navigation and finding prey. The zone of masking is defined by the range at which sound levels from the noise source are received above threshold within the 'critical band'[Note 3] centred on the signal (Richardson *et al.* (1995); NRC (2003)), and therefore strongly dependent on background noise environment.

The potential for masking can be reduced due to an animal’s frequency and temporal discrimination ability, directional hearing, co-modulation masking release (if noise is amplitude modulated over a number of frequency bands) and multiple looks (if the noise has gaps or the signal is repetitive), as well as anti-masking strategies (increasing call level, shifting frequency, repetition, etc.) (Erbe C. , 2008).

2.3.3 Behavioural responses

Behavioural responses to noise include changes in vocalisation, resting, diving and breathing patterns, changes in mother infant relationships, evasive responses and avoidance of the noise sources. For adverse behavioural

[3] **Note:** In biological hearing systems, noise is integrated over several frequency filters, called the critical bands.

responses to occur to a sound, the signal needs to be firstly detected over ambient noise and secondly needs to be perceived as a threat.

Behavioural responses to sound can be difficult to quantify and amongst other things depend on the ecological context and state of the individual exposed (e.g. age, sex, social status etc). Therefore, the extent of behavioural disturbance for any given signal can vary both within a population as well as within the same individual. Behavioural reactions can vary significantly, ranging from very subtle changes in behaviour to strong avoidance reactions (Richardson *et al.* (1995)).

2.3.4 Physiological impacts / hearing loss and physical injury

Physiological effects of underwater noise are primarily associated with the auditory system which is likely to be most sensitive to noise. The exposure of the auditory system to a high level of noise for a specific duration can cause a reduction in the animal's hearing sensitivity, or an increase in hearing threshold. If the noise exposure is below some critical sound energy level, the hearing loss is generally only temporary, and this effect is called temporary hearing threshold shift (TTS). If the noise exposure exceeds the critical sound energy level, the hearing loss can be permanent, and this effect is called permanent hearing threshold shift (PTS).

In a broader sense, physiological impacts also include non-auditory physiological effects. Other physiological systems of marine animals potentially affected by noise include the vestibular system, reproductive system, nervous system, liver or organs with high levels of dissolved gas concentrations and gas filled spaces. Noise at high levels may cause concussive effects, physical damage to tissues and organs, cavitation or result in rapid formation of bubbles in venous system due to massive oscillations of pressure.

From an adverse impact assessment perspective, among the potential noise impacts above, physiological impacts are deemed as the primary adverse impact, and behavioural responses as the secondary adverse impact. The following sub-sections outline the corresponding impact assessment criteria for marine mammals and fish and marine turtle species, as well as marine invertebrates, based on a review of relevant guidelines and/or literature published.

3. Marine fauna hearing sensitivity and assessment thresholds

Different species of marine fauna have different hearing sensitivities, depending on the structure of hearing organs. In recognition of these differences, scientific research has focused on the creation of audiograms (measures of hearing sensitivity thresholds versus frequency) to better understand the hearing ranges of marine fauna.

These audiograms have been used to derive frequency-weighting functions for some marine fauna. The frequency weighting functions are similar to the weighting functions developed for the human ear and recognise the fact that the ear is not equally sensitive to noise at all frequencies.

The hearing sensitivities of individual species are discussed below.

3.1 Marine mammals

Southall *et al.* (2007) were the first to develop a comprehensive set of frequency-weighting functions for marine mammals. Citing previous scientific literature they used the following mammal hearing-groups: low frequency cetaceans (baleen whales), mid frequency cetaceans (toothed whales), high frequency cetaceans (porpoises, river dolphins, etc.), pinnipeds (seals, sea lions, walruses, in water) and pinnipeds (in air).

They proposed separate ‘M’ frequency-weighting functions for these groups, which were similar to the C-weighting function developed for human hearing at high sound levels. These functions were flat for a major part of the spectrum, symmetrical and assumed a logarithmic reduction in auditory sensitivity outside the range of best hearing. The ‘M’ frequency-weighting functions were a conservative representation of hearing sensitivities based on the scientific literature available at the time.

In the decade following that research, significant additional work has been undertaken in the field. Additional marine mammal groups have been added and modifications to the original groups and new weighting functions (based on audiograms) have been developed. This research has been incorporated into the guidance provided by the US NMFS (2018).

Southall et al. (2019) have also revisited their original recommendations and published amended scientific recommendations on the marine mammal noise exposure criteria, which further builds upon the guidance provided by the US NMFS (2018).

The currently recommended marine mammal hearing groups, relevant to this assessment, include the following:

– Low-frequency (LF) cetaceans: mysticetes (baleen whales). The generalised hearing frequency range for this group is estimated to be between 7 Hz and 35 kHz.
– High-frequency (HF) cetaceans: delphinid species (bottlenose dolphin, common dolphin, beaked whales, sperm whales and killer whales) and beaked whales. The generalised hearing frequency range for this group is estimated to be between 150 Hz and 160 kHz.
– Very high-frequency (VHF) cetaceans: porpoises, most river dolphin species, pygmy/dwarf sperm whales and some oceanic dolphins. The generalised hearing frequency range for this group is estimated to be between 275 Hz and 160 kHz.
– Sirenians (SI): manatees and dugongs. The generalised hearing frequency range for this group is between 250 Hz and 72 kHz.
– Phocid carnivores (in water) (PCW): true seals, including harbour, gray and freshwater seals, elephant and monk seals, and Antarctic and Arctic ice seals. The generalised hearing frequency range for this group is estimated to be between 50 Hz and 86 kHz.
– Other carnivores in water (OCW): otariid seals (sea lions and fur seals), walruses, sea otters and polar bears. The generalised hearing frequency range for this group is estimated to be between 39 Hz and 60 kHz

Revised frequency-weighting functions, analogous to the A-weighting function for human hearing, have been created based on a general band-pass filter equation for each marine mammal group. The band pass filter parameters were derived from audiogram data corresponding to each group.

These frequency-weighting functions are presented in Figure 3.1 and Figure 3.2. For phocid carnivores and other carnivores, the presented weighting functions have been limited to the 'in water' categories.

The functions are denoted by subscripts corresponding to the group names (LF, HF, VHF, SI, PCW, and OCW) as noted above.

The PTS onset and TTS onset criteria for non-impulsive noise have been sourced from Southall et al. (2019) and are outlined in Table 3.1.

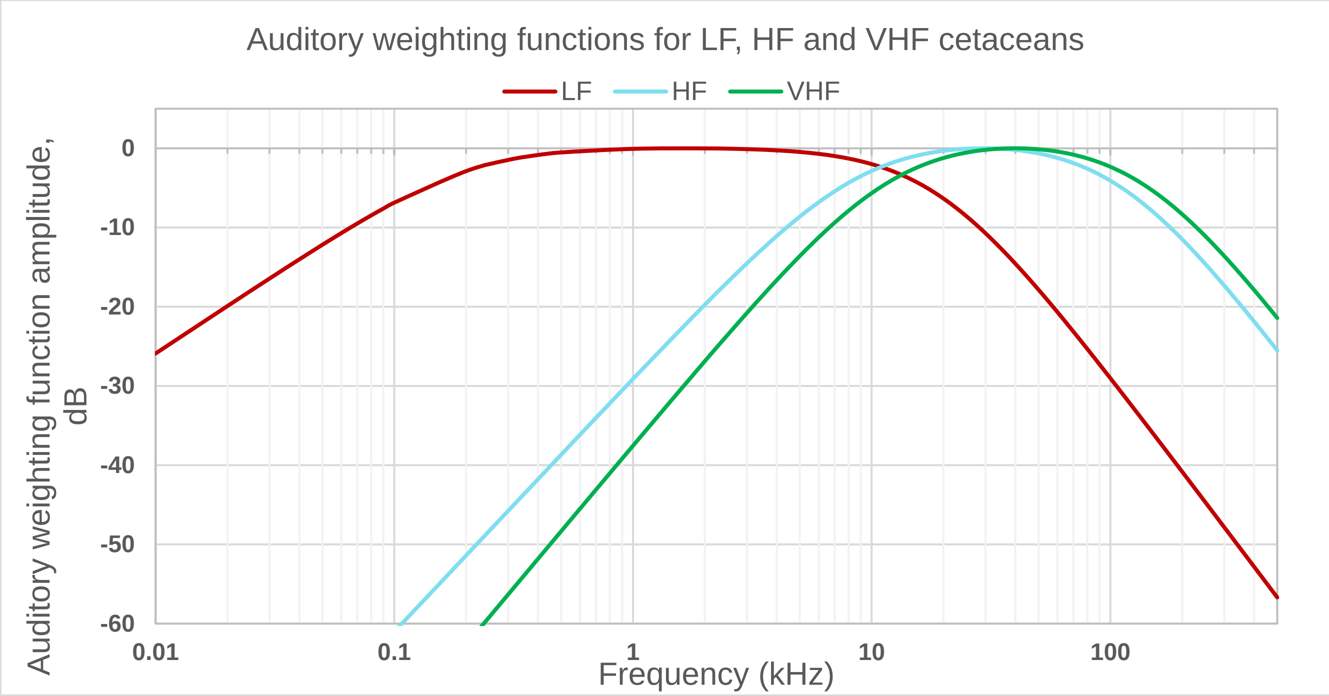


Figure 3.1 ***Auditory weighting functions for low frequency, high frequency and very high frequency hearing group cetaceans***

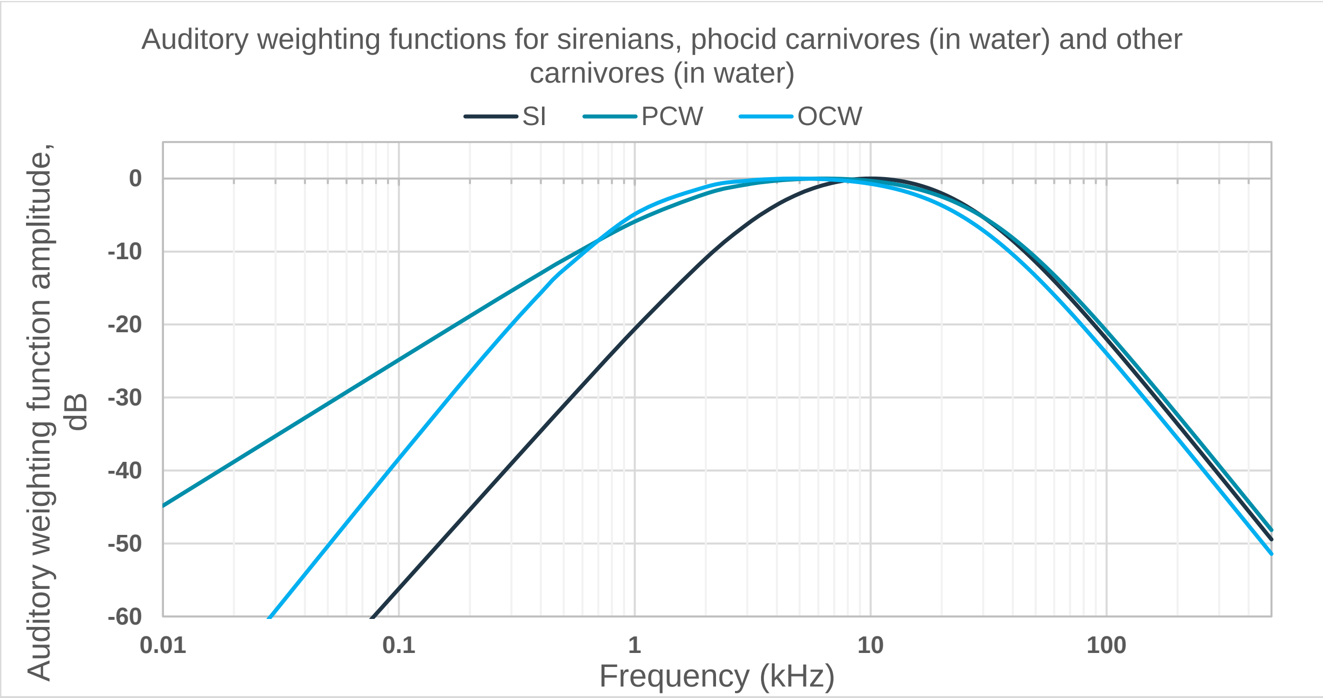


Figure 3.2 ***Auditory weighting functions for sirenians, phocid carnivores (in water) and other carnivores (in water)***

Table 3.1 PTS and TTS onset threshold levels for marine mammals exposed to non-impulsive noise

Marine mammal hearing group	PTS and TTS threshold levels – Non-impulsive noise	
	Injury (PTS) onset	TTS onset
	SEL_{24hr}, dB re 1µPa^2·s (weighted)	SEL_{24hr}, dB re 1µPa^2·s (weighted)
Low frequency cetaceans (LF)	199	179
High frequency cetaceans (HF)	198	178
Very high frequency cetaceans (VHF)	173	153
Sirenians (SI)	206	186
Phocid carnivores in water (PCW)	201	181
Other marine carnivores in water (OCW)	219	199

3.1.1 Relevant marine mammal species

Based on the *Marine Habitats and Fauna Report* (GHD, 2025), the following marine mammal species are known to or likely to occur within the study area:

– **Unlikely to occur**: Bryde's whale (LF), humpback whale (LF), killer whale (orca) (HF), Australian snubfin dolphin (HF), bottlenose dolphin (HF), common dolphin (HF), Risso's dolphin (HF), Pantropical spotted dolphin(HF)

– **Possible to occur:** Dugong (SI)

– **Likely to occur**: Australian humpback dolphin (HF), Indian ocean bottlenose dolphin (HF)

The marine mammal hearing groups are identified in brackets for each species. High-frequency cetacean (HF) marine mammal species have been identified likely to occur within the study area. Sirenians (SI) are identified as possible to occur and low frequency cetaceans (LF) are unlikely to occur within the study area.

3.2 Fish, fish eggs, fish larvae and sea turtles

Compared to cetaceans, comparatively little is known regarding the effects of sound for fishes and sea turtles. As such, assessment procedures and subsequent regulatory and mitigation measures are often severely limited in their relevance and efficacy. To reduce regulatory uncertainty for all stakeholders by replacing precaution with scientific facts, NOAA convened an international panel of experts to develop noise exposure criteria for fishes and sea turtles in 2004, primarily based on published scientific data in the peer-reviewed literature. The panel was organized as a Working Group (WG) under the ANSI-Accredited Standards Committee S3/SC 1, Animal Bioacoustics, which is sponsored by the Acoustical Society of America.

The outcomes of the WG are broadly applicable sound exposure guidelines for fishes and sea turtles (Popper *et al*. (2014)), considering the diversity of fish and sea turtle species, the different ways they detect sound, as well as various sound sources and their acoustic characteristics. The sound exposure criteria for non-impulsive noise are presented in Table 3.2.

Within the tables, where data exist that can be used to suggest provisional guidelines, received signal levels are reported in appropriate forms (e.g., peak, SEL). Where insufficient data exist to make a recommendation for guidelines, a subjective approach is adopted in which the relative risk of an effect is placed in order of rank at three distances from the source – near (N), intermediate (I), and far (F) (top to bottom within each cell of the table, respectively). In general, "near" might be in the tens of metres from the source, "intermediate" in the hundreds of metres, and "far" in the thousands of metres. The relative risk of an effect is then rated as being "high," "moderate," and "low" with respect to source distance and animal type. The rating for effects in these tables is highly subjective and represents consensus within the WG.

It should be noted that the period over which the cumulative sound exposure level (SEL_{cum}) is calculated must be carefully specified. For example, SEL_{cum} may be defined over a standard period (e.g. 12 hours) or for the duration of an activity (e.g. the full period of construction), or over the total period that the animal will be exposed. Whether an animal would be exposed to a full period of sound activity will depend on its behaviour, as well as the source movements.

Regarding thresholds for sea turtles, NOA has released NMFS updated guidance, summary of endangered species acoustic thresholds (marine mammals, fishes, and sea turtles) (NOA, 2024) which provides updated thresholds based on available new information and includes thresholds for non-impulsive sources for sea turtles. These thresholds are included in Table 3.2.

Table 3.2 Noise exposure criteria for shipping and continuous sounds – fishes and sea turtles

Type of animal	Mortality and potential mortal injury	Impairment			Behaviour
		Recovery 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 is 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 RMS for 48h	158 dB SPL RMS for 48h	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Sea turtles	237 dB SEL_{cum}	220 dB SEL_{cum}	200 dB SEL_{cum}	(N) High (I) High (F) Moderate	175 dB SPL RMS
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) High	(N) Moderate (I) Moderate (F) Low

Notes: rms sound pressure levels (SPL RMS) dB re 1 μPa. All criteria are presented as sound pressure even for fish without swim bladders since thresholds, modelling and monitoring methods for peak particle motion sensitivity are still an active area of research. 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).

3.2.1 Relevant fish and marine turtle species

Based on the *Marine Habitats and Fauna Report* (GHD, 2025), the following listed fish and marine turtle species are known to or may occur within the study area:

– **Turtle species**: flatback turtle, green turtle, hawksbill turtle, leatherback turtle, loggerhead turtle, olive ridley turtle
– **Fish species without a swim bladder**: dwarf fish, freshwater sawfish, green sawfish, narrow sawfish, grey nurse shark, northern river shark, oceanic whitetip shark, scalloped hammerhead, whale shark, white shark
– **Fish species with a swim bladder not involved in hearing**: southern bluefin tuna
– **Fish species with a swim bladder involved in hearing**: pipefish and seahorses (Syngnathids)

3.3 Summary of noise criteria

3.3.1 Physiological impacts

The non-impulsive noise criteria for physiological impacts for species relevant to the area of interest are summarised in Table 3.3.

Table 3.3 Key physiological noise criteria for marine fauna identified within study area

Type of animal	Functional hearing groups[1]	Noise criteria (Non impulsive noise), PTS[2]	Noise criteria (Non-impulsive noise), TTS[3]
Marine mammals	Low-frequency cetaceans (LF)	199 SEL Weighted (LF)	179 SEL Weighted (LF)
	High-frequency cetaceans (HF)	198 SEL Weighted (HF)	178 SEL Weighted (HF)
	Sirenians (SI)	206 SEL Weighted (SI)	186 SEL Weighted (SI)
Sea turtles	Sea turtle	220 dB SEL_{cum}	200 dB SEL_{cum}
Fishes	Fish (no swim bladder)	Low risk	Low risk
	Fish (swim bladder not involved in hearing)	Low risk	Low risk
	Fish (swim bladder involved in hearing)	170 rms (48h)	158 rms (12h)

Note 1: The peak and rms noise criteria are in units dB re: 1 µPa. The Sound exposure level (SEL) noise criteria are in units dB re: 1 $\mu Pa^2 s$ and correspond to cumulative noise impacts, conservatively calculated over a 24-hour time period.
Note 2: Mortality or permanent injury.
Note 3: Temporary loss of hearing sensitivity.

3.3.2 Adverse behavioural response effects

For non-impulsive sounds, a widely used assessment criterion for the onset of possible behavioural disruption in marine mammals is root-mean-square sound pressure level (RMS SPL) of 120 dB re 1µPa or the ambient level (NMFS, 2013).

Behavioural thresholds are an active research area and behavioural responses to noise can vary significantly both within and between species. (Southall, et al., 2021). Recent evidence suggests that a single threshold for behavioural disruption can lead to significant errors in predicting a response, as such, this approach is deemed inconsistent with the probabilistic nature of behavioural responses.

In view of the above, the modelling and assessment is based on the potential for adverse physiological impacts to marine megafauna (i.e., PTS and TTS) that may occur in the project area and its surrounds.

4. Underwater noise modelling

Underwater noise models predict the sound transmission loss (TL) between the noise source and the receiver. When the source level (SL) of the noise generating activity is known, the modelled transmission loss (TL) is then used to predict the received level (RL) at a given receiver location by applying:

$$\mathrm{RL} = \mathrm{SL} - \mathrm{TL}$$

The straightforward expression is fundamental to the many approaches to modelling underwater noise, and its simplicity belies considerable complexity in the task of modelling the source level and propagation loss in order to predict received levels.

The basic modelling approach is to characterise the sound produced by the source, determine how the sound propagates within the surrounding water column, and then estimate species-specific exposure probabilities by combining the computed sound fields with the animal assessment criteria after post-processing and applying weighting functions to the results.

The sound propagation modelling incorporates site-specific environmental data including bathymetry, sound speed in the water column, and seabed geoacoustics in the proposed study area.

4.1 Source Level (SL)

Noise modelling has been considered for two primary underwater noise generating sources from this project:

– Dumping of rocks from truck into water
– Relocation of dumped material using land-based excavator

Source Levels (SLs) used as the basis of the noise modelling have been sourced from historical underwater noise measurements of similar activities. Details of the noise measurement reference, measurement conditions and Sound Exposure Levels (SEL) at 1 metre are summarised in Table 4.1

The following assumptions have been made regarding the operating period of each noise source:

– Assumed 1 truck would dump material every 5 minutes and it would take approximately 1 minute to unload material resulting in 12 minutes of dumping in every hour of operation
– Assumed relocation would occur during the periods when rock dumping is not occurring for up to 40 minutes of excavating activities in every hour of operation

Table 4.1 Noise modelling scenarios

Scenario	Activity	Operating period	Measurement details	Source level at 1 metre, dB re uPa	Reference
S1	Rock dumping from truck into water	12 min / hour	Rock-wall construction for Townsville Marine Precinct, depth 2-4m	179	(GHD, 2021)
S2	Relocation of dumped material using land-based excavator	40 min / hour	Dredge bottom impact and excavation noise from backhoe dredger, New York	179	(Reine & Dickerson, 2014)

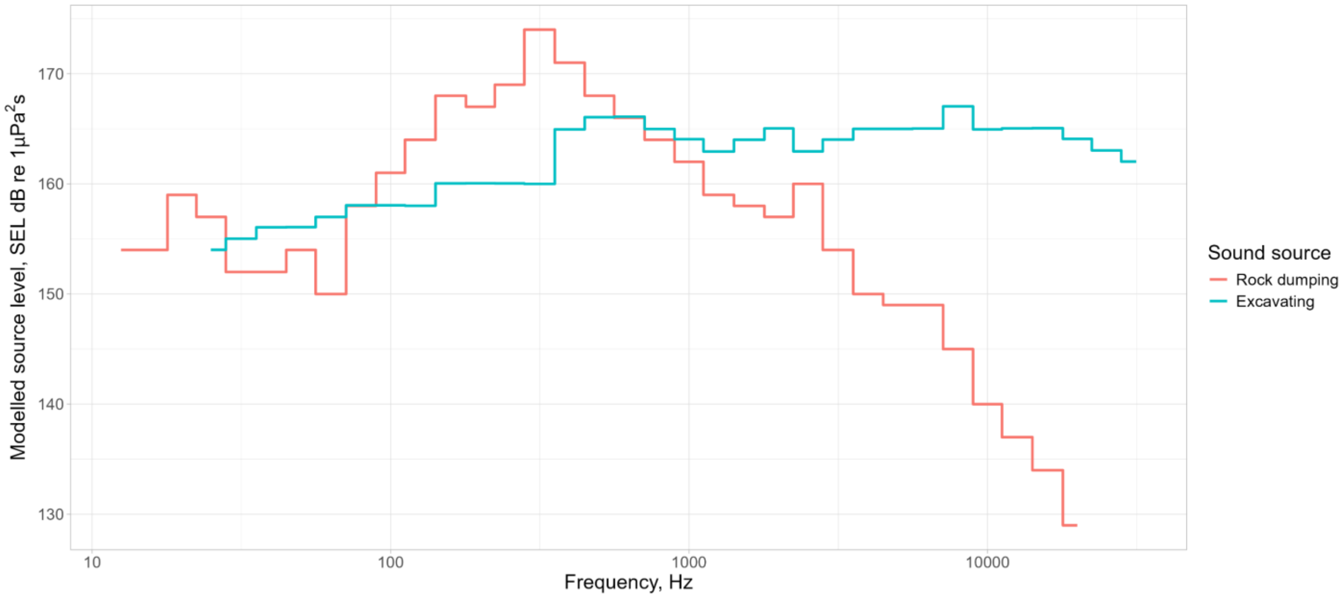


Figure 4.1 Modelled third-octave band spectra, SEL dB re 1µPa²s

4.2 Transmission Loss (TL)

4.2.1 Numerical solvers

The transmission loss (TL) is a complex interaction of multiple attenuation processes which generally differ across the acoustic frequency range (a detailed explanation is presented by Jensen *et al.* (2000)) and includes:

– Geometrical wave-front spreading
– Frequency dependent molecular sound absorption in the water column
– Frequency dependent scattering of surface and bottom reflected acoustic waves
– Frequency and depth dependent absorption of acoustic waves in thin bottom sediments (waterborne waves) and deeper strata
– Depth dependent cut off of lower-frequency wave-modes that are unsupportable in shallow water.

Various models can be used to calculate underwater acoustic propagation including ray theory, normal mode and the parabolic equation. However, each model can be limited in their applicability to shallow and deep water environments, their accuracy (and computational speed) for low frequencies and high-frequencies, and also their ability to model a range-dependent environment (Etter, P, 2011).

A hybrid modelling approach has been adopted and is considered appropriate to model a range dependent shallow water environment in the specified frequency range:

– RAMGeo: The fluid seabed parabolic equation (PE) modelling algorithm (Collins, M. D, 1993) has been used to model a range-dependent environment in the low frequency range 12.5 Hz to 2.5 kHz
– Bellhop: The ray and Gaussian beam tracing algorithm (Porter, M.B, 2011) has been used to model a range-dependent environment for the high frequency range 3.15 kHz to 31.5 kHz.

The accuracy of underwater noise propagation models also depends on the input parameters representing the local underwater environment, particularly the bathymetry, the seabed properties and the sound speed profile in the water column. The key inputs and parameters chosen to model the underwater acoustic field to predict the transmission loss (TL) from the noise source are detailed in Section 4.2.4.

4.2.2 Acoustic field modelling

Underwater noise models are typically two-dimensional (2D) solutions, calculating the TL along 'N' number of transects at a specified azimuth angle resolution (Δθ), and as such, do not include horizontal refraction, reflection or diffraction (i.e., each transect modelled is independent of the neighbouring transect).

TL is calculated as a function of depth (z) and range (r) and calculated separately for each modelled frequency (typically in third-octave bands, Hz). Such N x 2D models provide sufficient accuracy and can provide quasi-3D solutions by combining a number of two-dimensional (distance and depth) transects, and interpolating between the modelled transects.

This concept is illustrated in Figure 4.2 and Figure 4.3 showing how the depth of the water is sampled along 'N' transects from the source to model 2-Dimensional acoustic fields (i.e., vertical radial plots / cross-section).

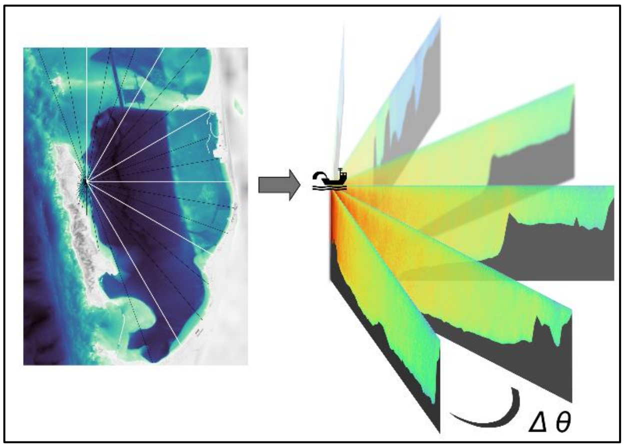


Figure 4.2 Bathymetry and propagation transects at Δθ

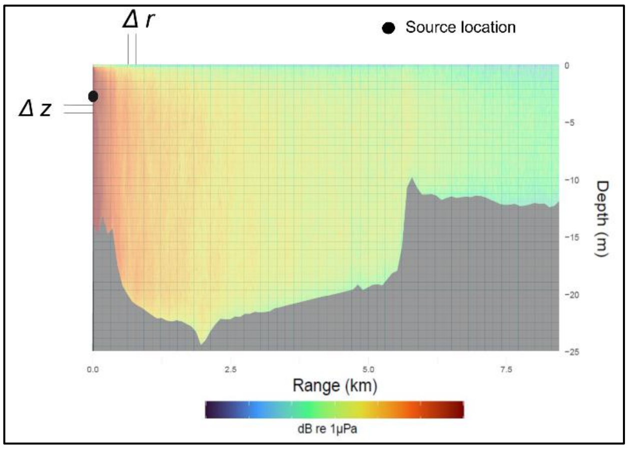


Figure 4.3 Example of cross-section (generic)

4.2.3 Model resolution

Defining the TL model resolution for each solver used requires balancing between the required accuracy to obtain representative results and optimising computational effort as increasing the resolution in any domain (i.e., frequency, range, depth, angular) can exponentially increase computational time.

The TL model was set based on the following key parameters from each noise source location:

– Azimuth angles 0° (North) to 355° with an angular resolution size (Δθ) of 5° (N = 72 radial planes)
– Domain maximum range (rmax) of 10 km at a range resolution (Δr) of 10 m
– Domain maximum depth (zmax) of 200 m at a depth resolution (Δz) 0.2 m.

4.2.4 Environment inputs and parameters

4.2.4.1 Local tidal planes

In very shallow water environments, tidal variations can represent a significant fraction of the actual water depth and thus significantly influence sound propagation. It was observed during the modelling process that higher water level cases (i.e. periods of high tide) have higher predictions of noise propagation than lower water level cases, particularly observed as better propagation in low-frequency bands. This effect is due to low frequency 'cut-off' in shallow water, which has a greater effect as water depth decreased (Jensen, B et al. , 2011).

Tidal variations at Cockatoo Island are semi-diurnal and macrotidal, meaning two high and two low tides are typically experienced within a 24-hour period and that the difference between low and high tides are in excess of 10 m. Tidal planes are detailed in Table 4.2 for different vertical datums (MRA 2011).

Table 4.2 Local tidal planes

Tidal Plane	m CID[1]	m CD[2]	m AHD
Highest Astronomical Tide	+10.1	+10.9	+6.2
Mean High Water Spring	+9.1	+9.9	+5.2
Mean High Water Neap	+6.0	+6.8	+2.1

Tidal Plane	m CID[1]	m CD[2]	m AHD
Mean Sea Level	+4.7	+5.5	+0.8
Mean Low Water Neap	+3.3	+4.1	-0.6
Mean Low Water Spring	+0.2	+1.0	-3.7
Lowest Astronomical Tide (LAT)	-0.8	0.0	-4.7

1. CID (Cockatoo Island Datum) is approximately 0.8m above CD (Chart Datum) and 3.9m below AHD (Australian Height Datum)
2. CD is approximately LAT

4.2.4.2 Bathymetry

The shape of the seabed and the depth of the water column define the boundary conditions of the TL model. On continental shelves, sloping seabeds, local seamounts and tidal variations affect the reflection, refraction and shielding effects of sound propagation in range dependent modelling, particularly in shallower waters.

The study area for the underwater noise model has been selected to be a 10-kilometre bounding box around the project location. Bathymetry data for the underwater noise model has been sourced from GHD's Marine Modelling of Coastal Processes and Construction Impacts Report (GHD, 2021) and has been adjusted to the Highest Astronomical Tide (HAT) to conservatively assess a high-tide scenario where sound propagation would propagate the furthest.

The water depth at the Project site is estimated to be approximately 12 m HAT. The bathymetry model used to calculate transmission loss is shown in Figure 4.4.

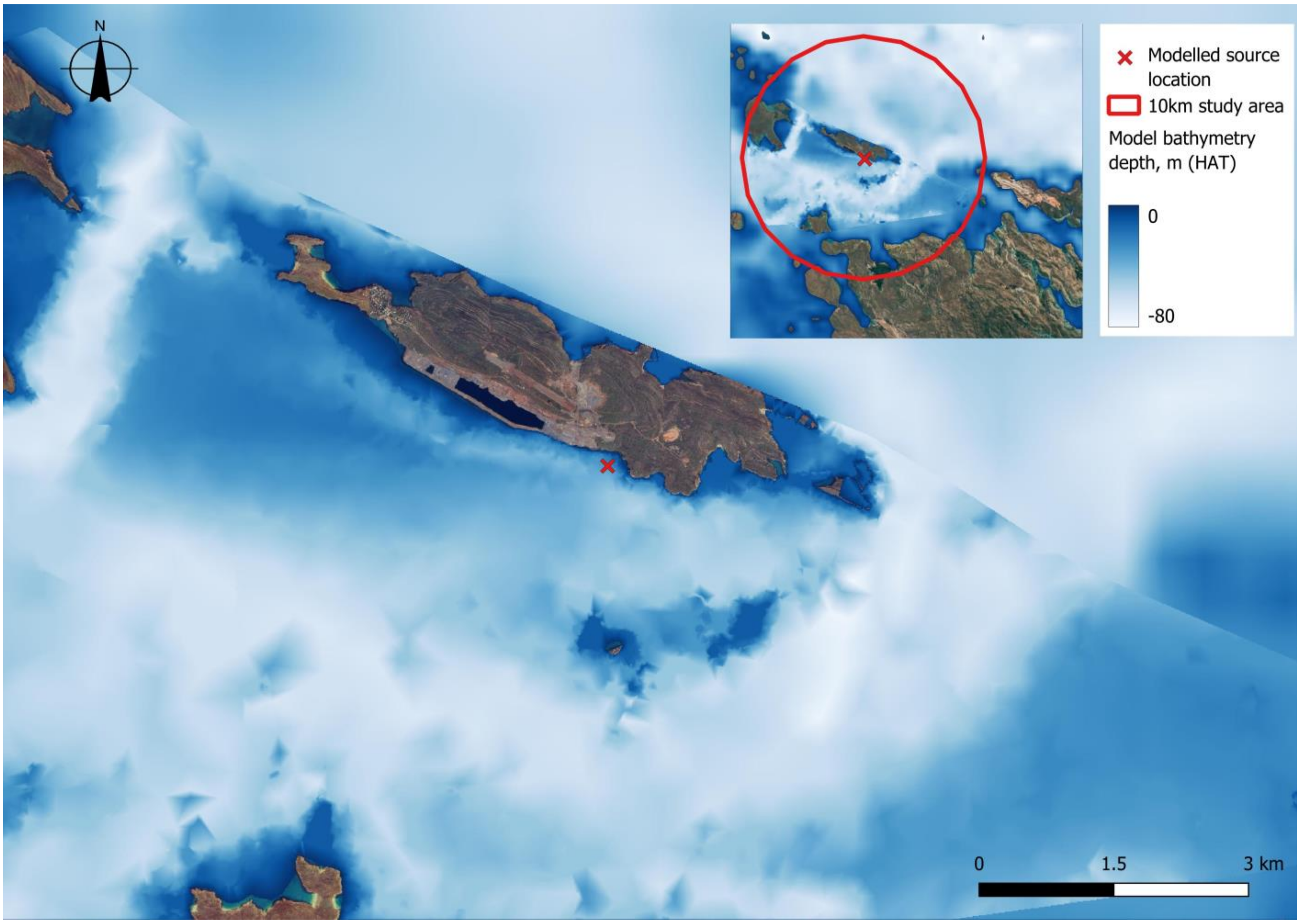


Figure 4.4 Transmission Loss (TL) bathymetry model

4.2.4.3 Sound speed profile

Temperature and salinity can vary as a function of depth and both affect the speed of sound in water, and thus the underwater sound speed profile. Temperature has a direct effect on the speed of sound in water- as water temperature increases, the speed of sound in water also increases, and vice versa. This is because at higher temperatures, water molecules move more rapidly and the speed of sound increases accordingly.

Salinity also affects the speed of sound in water, but in a more complex way. As the salinity of water increases, the speed of sound also increases, but not linearly. Instead, the speed of sound in water increases more rapidly with increasing salinity at lower salinities and then levels off at higher salinities.

The combined effect of temperature and salinity on sound speed profile underwater can be seen in the ocean's thermocline, which is the layer of water where temperature changes rapidly with depth. As temperature and salinity both vary with depth in the ocean, the speed of sound also varies with depth, resulting in a sound speed profile that can have multiple layers or gradients.

To gain an understanding of the speed of sound profiles (SSPs) in the study area across the year, salinity and temperature data has been sourced from World Ocean Atlas 2023 (WOA23) dataset at Station 292802 as shown in Figure 4.5.

The data indicates that the sound speed during summer months (i.e., January to March) is higher than during winter months (i.e., July to September) at depths until 40m. The winter sound speed profile has been modelled to conservatively reflect the conditions during the project.

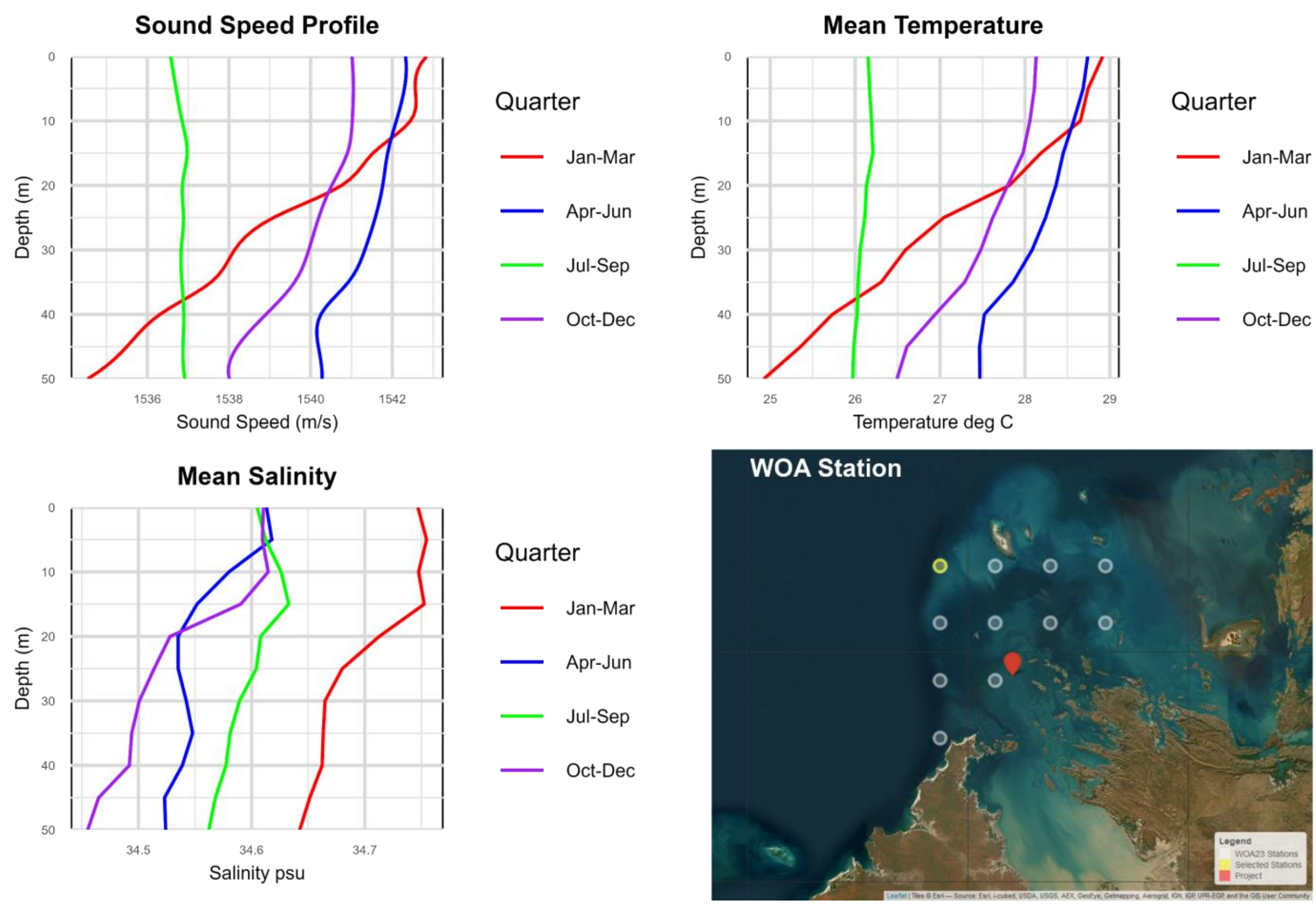


Figure 4.5 Hydrographic features and speed of sound profiles

4.2.4.4 Seabed

Geoacoustic properties of the seabed influence sound reflection and transmission. Loosely consolidated sediment particles act like a fluid medium and attenuates sound, stratified seabeds can bend sound waves, while stiff seabed layers like rock can reflect sound, affecting energy transmission back into the water column.

Accurately representing seabed properties can be limited by the availability of the geotechnical data and the computational effort required to model the geotechnical data at a resolution representative of the actual environment. As a result, seafloor models are often simplified in underwater acoustic modelling to represent the key sea substrate characteristics such as the loose sediment layer, the intermediate layer and the underlying consolidated sedimentary rock layer.

The seabed model used to represent the Project study area is presented Table 4.3 including the geoacoustic parameters for each substrate layer sourced from Computational Ocean Acoustics (Jensen, B et al. , 2011), Geoacoustic Modelling of the Sea Floor (Hamilton, 1980) and Marine Acoustic Zones of Australia (Erbe, Peel, Smith, & Schoeman, 2021).

Table 4.3 Geoacoustic parameters for the TL seafloor model

Seafloor Materials	Depth	Density, ρ, (kg·m^{-3})	Compressional wave		Shear wave	
			Speed, C_p, (m·s^{-1})	Attenuation, α_p, (dB/λ)	Speed, C_p, (m·s^{-1})[1]	Attenuation, α_p, (dB/λ)
Silty-sand (unconsolidated)	0 – 50 m	1861	1655	0.78	115	2.07
Limestone/siltstone (consolidated)	>50 m	2400	3000	0.1	1500	0.2

The low-frequency solver RAMGeo considers the seafloor as a layered fluid seabed (i.e., uses the compressional wave components of each layer) and does not account for the elastic properties of the seabed (i.e., the shear wave component). Given this, the reflection coefficient model BOUNCE (Porter, M.B) was used and the RAMGeo fluid layer parameters were adjusted until a representative equivalent to the elastic reflection coefficient results were achieved using the approach described by Erbe (Erbe et al, 2021).

4.3 Received Level (RL)

4.3.1 Methodology

The predictions from the RAMGeo and Bellhop models were combined to produce broadband results for the descriptor $SEL_{(1\ sec)}$ using SL – TL = RL for each modelled transect. Where applicable, the marine mammal weightings were applied to the unweighted SEL levels such that they can be compared against the weighted SEL criteria.

An example of the vertical plane sound field for a given transect is shown in Section 5.3.1. The maximum noise level over depth at all azimuth angles is then taken to reduce the noise predictions from a quasi-3D domain to a 2D domain. An example transmission loss profile from the source is shown in Section 4.3.3.

The maximum sound level over depth was then taken to:

1. Develop noise level contours using interpolation between each modelled horizontal azimuth transect;
2. Estimate the distances from the source to nominal noise levels based on the $R_{95\%}$ distance (i.e., the 95th percentile of distances at which that level is met. i.e., excluding 5% of the furthest noise levels); and
3. Estimate the distance to the noise exposure threshold criteria in Section 3.3 based on the $R_{95\%}$ distance.

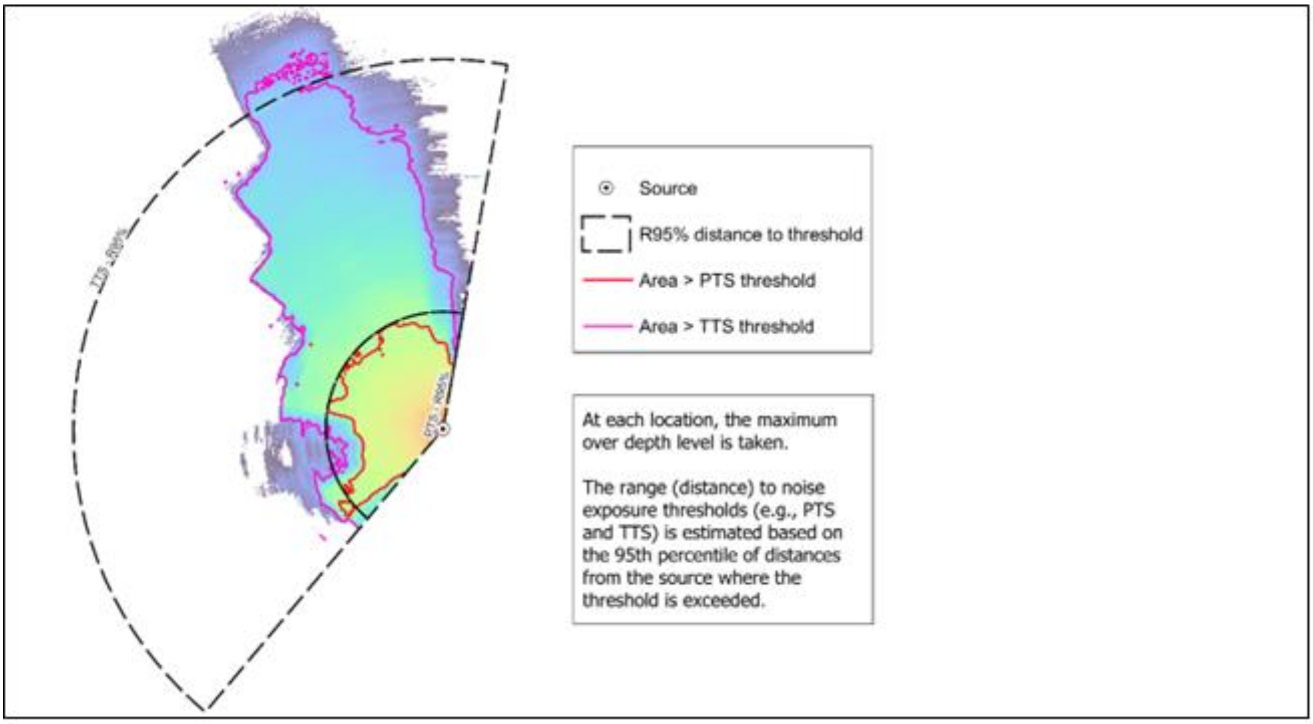


Figure 4.6 ***TTS and PTS isopleths and $R_{95\%}$ range to the TTS and PTS noise exposure thresholds***

4.3.2 Vertical plane sound field

The vertical plane sound field for the 255° (south-west) azimuth angle is shown in Figure 4.7 and Figure 4.8 for rock dumping and rock placement, respectively.

From these results the maximum $SEL_{(1\ sec)}$ over all modelled depths was found and is shown in red. These figures show that noise levels reduce with distance from the source and are relatively consistent over the modelled depths of the water column. The maximum over depth noise level tends to occur within the mid to lower half of the water column. These figures demonstrate the difference in propagation for the two modelled source levels.

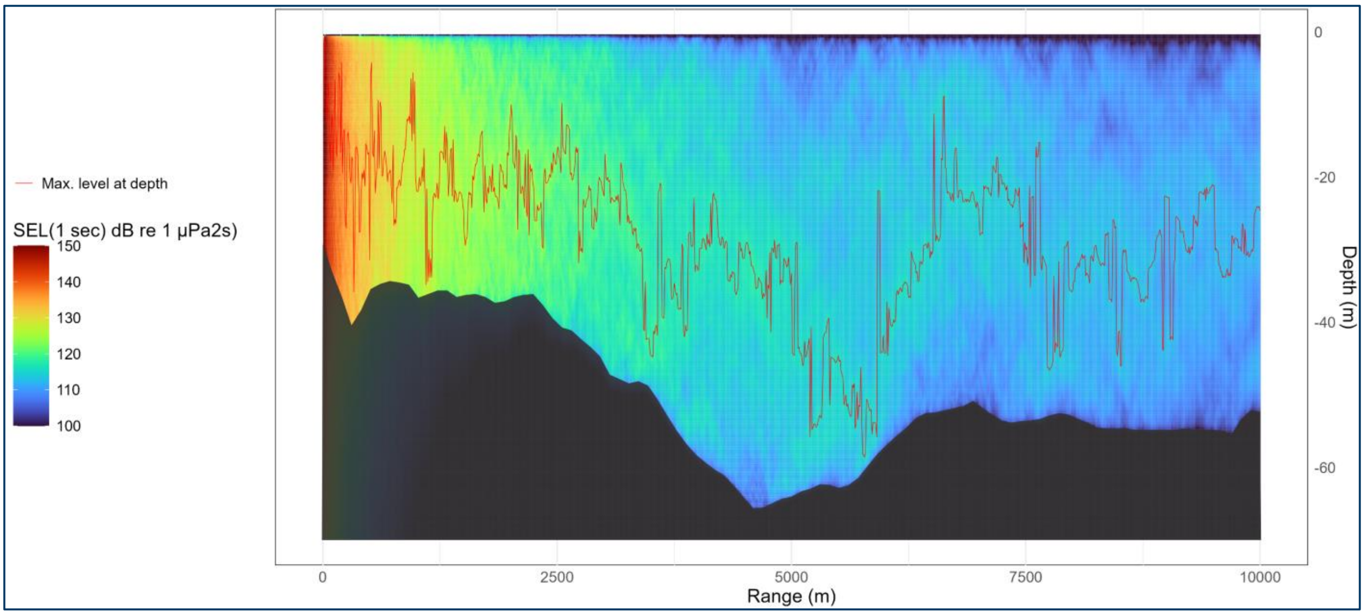


Figure 4.7 Rock dumping 255° azimuth angle vertical plane sound field and maximum level over depth, SEL dB re 1 μPa²s (1 sec)

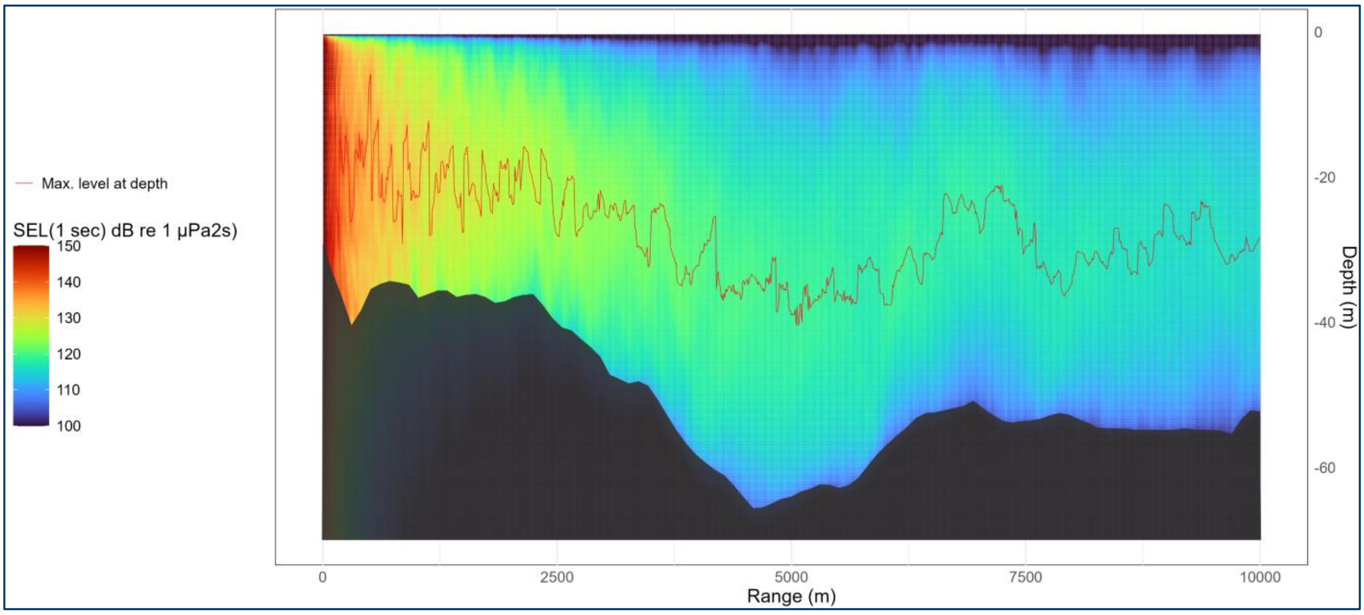


Figure 4.8 Rock placement 255° azimuth angle vertical plane sound field and maximum level over depth, SEL dB re 1 μPa²s (1 sec)

4.3.3 Transmissions loss (TL) vs range

An example of the modelled transmission loss (TL) versus range results for rock dumping are shown in Figure 4.9 and Figure 4.10 rock dumping and rock placement, respectively.

The plot shows the TL versus range results for the 10 azimuth angles most favourable to sound propagation. Underwater sound propagates the furthest to the southwest and southeast, and the transmission loss decay is relatively consistent in these directions from the source. The plots also show the decay curves for both spherical and practical spreading. The transmission loss can be approximated as a 16*log(R) to 17*log(R) model, where R is the distance from the source for these directions.

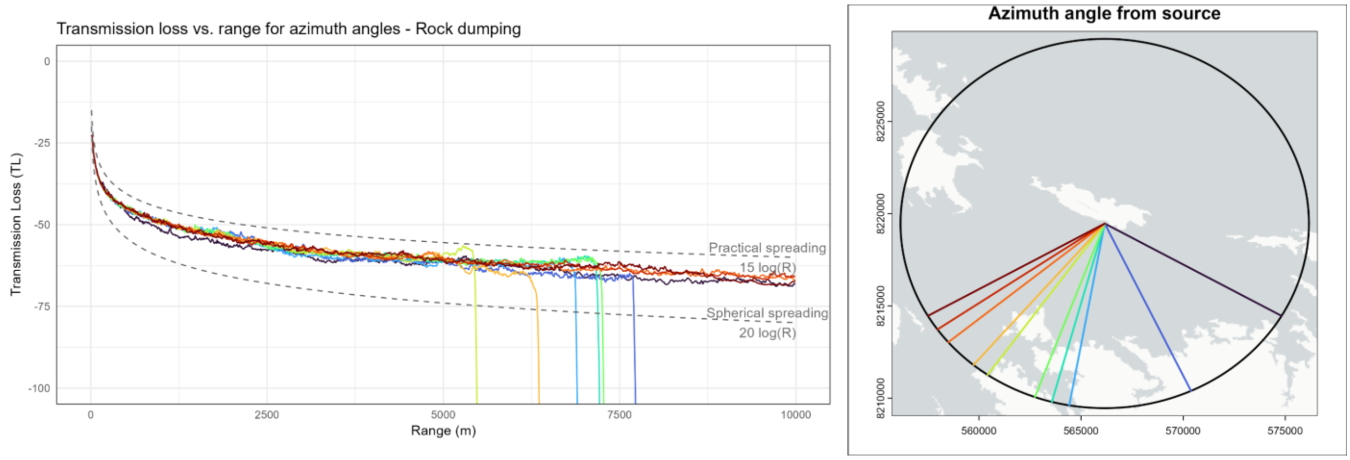


Figure 4.9 Transmission Loss (TL) vs range (R) for 10 azimuth angles with the best propagation – Rock dumping

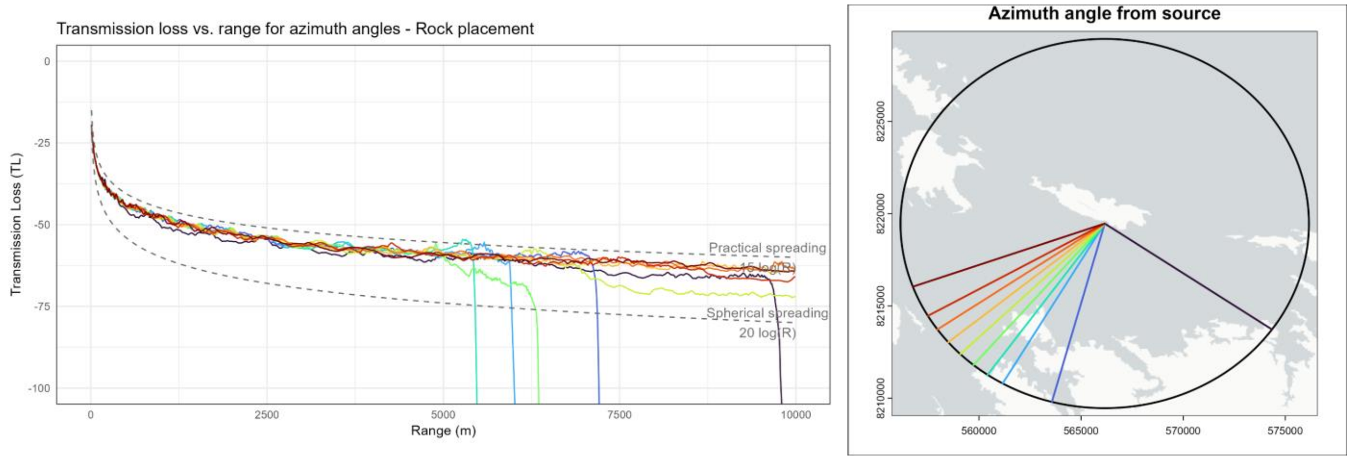


Figure 4.10 Transmission Loss (TL) vs range (R) for 10 azimuth angles with the best propagation – Rock placement

4.3.4 Range to maximum over depth noise levels

The $R_{95\%}$ range to nominal unweighted (maximum over depth) SEL_{1sec} noise levels (equal to the RMS SPL) and the SEL_{24hr} noise level (cumulative exposure to noise over a 24-hour period), are shown in Table 4.4 for each modelled scenario. To calculate the SEL_{24hr} noise level, the following formula is used with the operating times specified in Table 4.1:

$$\mathrm{SEL}_{1sec} + 10\log_{10}(N)\ where\ N = \ no.of\ seconds\ within\ a\ 24\ hour\ period\ of\ acitivity\ operation$$

The ranges to nominal noise levels presented in Table 4.4 demonstrate that sound propagation is slightly more favourable for rock placement and cumulative noise levels reach greater distances due to a longer activity time per hour.

Results are presented for operating periods of 12 hours (preferred case), 10 hours and 8 hours within a 24-hour day and give an indication of how the range to the SEL_{24hr} thresholds would decrease by reducing the activity duration within each 24 hour period.

Table 4.4 R95% distance to nominal SEL_{1sec} and $SEL_{24\ hr}$ levels, metres

Maximum level over depth, dB re 1 µPa²·s	Rock dumping				Rock placement			
	$SEL_{1\ sec}$	$SEL_{24hr,}$ operating period			$SEL_{1\ sec}$	$SEL_{24hr,}$ operating period		
		12hr	10hr	8hr		12hr	10hr	8hr
190	-	30	30	30	-	90	90	80
185	-	70	60	50	-	210	180	160
180	-	140	130	110	-	440	400	350
175	-	310	280	240	-	1040	960	830
170	-	740	660	560	-	2160	2010	1840
165	-	1730	1510	1210	-	4350	3830	3200
160	-	2720	2490	2300	-	7790	7150	6670
155	20	5890	5400	4570	20	8770	8770	8660
150	40	8590	8370	7810	50	>10000	>10000	8840
145	80	8800	8760	8745	100	>10000	>10000	8870
140	150	>10000	>10000	8870	230	>10000	>10000	>10000

5. Range to noise exposure thresholds

5.1 Marine mammals

Distances to the physiological noise exposure onset criteria ($SEL_{24hr,}$ dB re 1 μPa^2·s) were calculated for the following functional hearing groups:

– Low-frequency cetaceans (LF),
– High-frequency cetaceans (HF),
– Sirenians (SI)

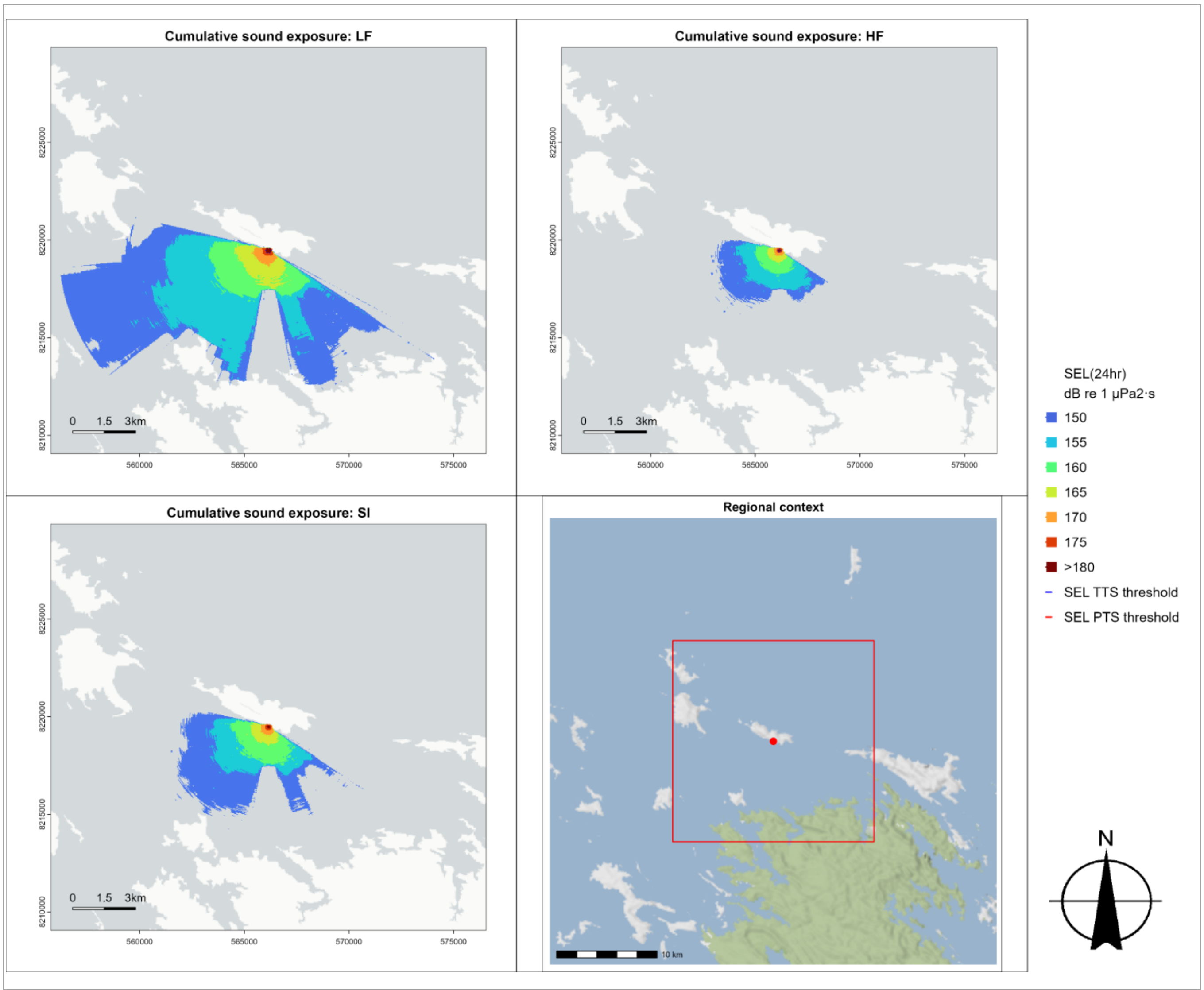
SEL_{24hr} is a cumulative metric that represents the effect of noise within the operational period based on the assumption that an animal is continuously exposed to operational noise at a stationary position. This is considered an unlikely worst-case scenario since, more realistically, marine animals would not stay in the same location or at the same distance from a sound source for an extended period of time. Given this, the estimated range to an exceedance of the SEL_{24h} criteria does not mean that any animal travelling within this radius from the source *will* be injured, but rather that it *could* be injured if it remained within that range for the entire duration of the construction activity.

The results are based on an animal's noise exposure to rock dumping and rock placement activities assuming three activity durations (12hr, 10hr and 8hr) within that 24-hour period. The estimated range at which a permanent threshold shift (PTS) and temporary threshold shift (TTS) could occur is based on the 95^{th} percentile distance from the source at which the criteria is exceeded.

The R95% distances to the physiological noise exposure onset criteria (PTS and TTS) are shown in Table 5.1. The PTS thresholds for low frequency cetaceans are predicted to be met up to 10 meters from the source for any operating period and are not met for other mammals. The distance to the TTS thresholds are greatest for low frequency cetaceans during a 12 hour working period and are met up to 430 metres from the source.

Table 5.1 R95% distance to PTS and TTS threshold levels, metres

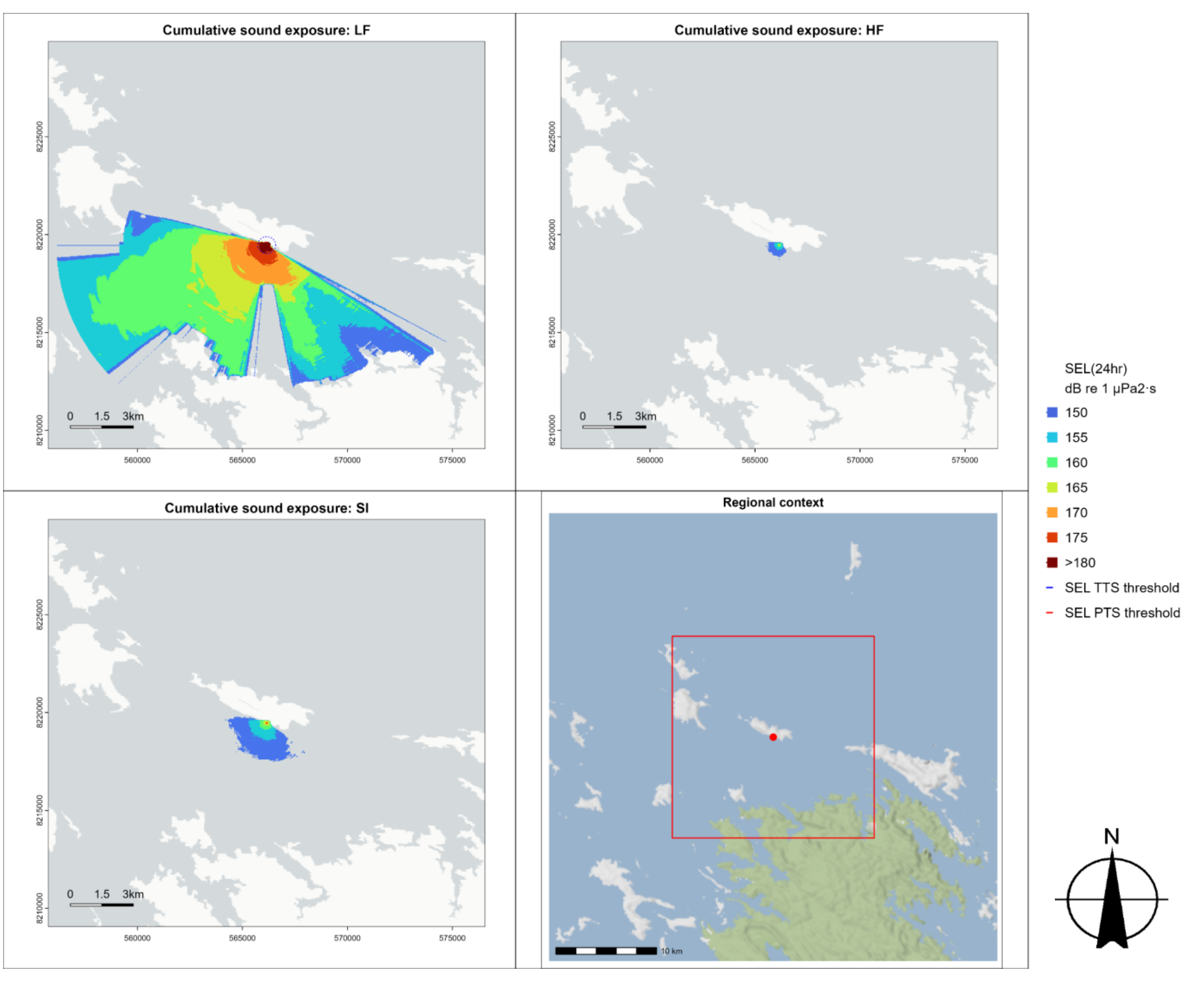
Scenario	SEL_{24hr} Threshold, dB re 1 μPa^2·s	Rock dumping, SEL_{24hr}			Rock placement, SEL_{24hr}		
Operating period		12hr	10hr	8hr	12hr	10hr	8hr
Permanent Threshold Shift (PTS)							
LF	**199**	-	-	-	10	10	10
HF	**198**	-	-	-	-	-	-
SI	**206**	-	-	-	-	-	-
Temporary Threshold Shift (TTS)							
LF	**179**	140	120	110	430	380	330
HF	**178**	90	80	70	-	-	-
SI	**186**	40	30	30	-	-	-



Map projection: Transverse Mercator
Horizontal Datum: MGA20
Grid: MGA20 Zone 51

Data source: StadiaMaps
Date: 13/03/2025
Creator: R Browell

Figure 5.1 ***SEL_{24hr} azimuth isopleths and R95% range to PTS/TTS thresholds: Rock dumping (activity duration: 12 hours operation in 24 hours)***



Map projection: Transverse Mercator
Horizontal Datum: WGS 84
Grid: MGA20 Zone 51

Data source: StadiaMaps
Date: 13/03/2025
Creator: R Browell

Figure 5.2 *SEL_{24hr} azimuth isopleths and R95% range to PTS/TTS thresholds: Rock placement (activity duration: 12 hours operation in 24 hours)*

5.2 Fish species and sea turtles

5.2.1 Fish species

For the purposes of the risk assessment to fish species, the risk ratings in Section 3.2 have been used to determine the potential for adverse impacts. The risk ratings are based on the following relative distance categories:

– **‘Near’ the source**: tens of metres from the noise source (e.g. up to <100 metres)
– ‘**Intermediate’ distance from the source**: hundreds of metres from source (e.g. up to <1,000 metres)
– ‘**Far’ from the source**: thousands of metres from the source (e.g. up to 10,000 metres)

For fish species without swim bladders and those with swim bladders not involved in hearing, due to lack of quantitative assessment criteria as indicated in Section 3.2, it is not possible to draw clear zones of impact. However, the following impact assessment conclusions can be made based on generic qualitative assessment criteria for fish and sea turtle species due to non-impulsive noise exposures:

– For fish species with no swim bladder (e.g. whale sharks) or with a swim bladder not involved in hearing (e.g. yellowfin tuna):
    - the risk of mortality, potential mortality and recovery injury is ‘**low’** at all distances from the source
    - the risk of TTS onset is ‘**moderate’** near the source, and ‘**low’** at all other distances
– For fish eggs and fish larvae:
    - the risk of mortality, potential mortality and recovery injury is ‘**low’** at all distances from the source
    - the risk of TTS onset is injury is ‘**low’** at all distances from the source
– For sea turtles (e.g. green turtle or loggerhead turtle):
    - the risk of mortality, potential mortality and recovery injury is ‘**low’** at all distances from the source
    - the risk of TTS onset is ‘**moderate’** near the source, and ‘**low’** at all other distances

The thresholds set for fish with a swim bladder that is involved in hearing, for example pipefish and seahorse species, are not met within the study area and therefore no risk is expected for injury or hearing impairment to these species.

5.2.2 Sea turtles

Cumulative exposure thresholds have been set for physiological and hearing loss impacts for sea turtles, outlined in Section 3.2. These thresholds are not exceeded for either rock dumping or rock placement for up to 12 hours of operation within a 24hr period. As such hearing impairment (PTS or TTS) is unlikely for sea turtles from the proposed works.

6. Recommendations

It is recommended that the Construction Environmental Management Plan (CEMP) for the Project includes management and mitigation measures that would be implemented to reduce the risk of noise impacts to marine mammals as far as reasonably practicable. The key mitigation and management measures to be included in the marine fauna management plan are:

- Safety zones for marine mammals – these are observation zones sized based on the likely noise levels produced by worst-case noise-generating activities associated with the Project
- Planning of activities – these are management measures these recommended for all construction activities, irrespective of location and time of year, when marine mammals species may potentially be present within the noise footprint.

6.1 Safety zones

The following safety zone should be applied around the construction location:

- **An observation zone of 450 metres**, within which the movement of marine mammals would be monitored to identify any approach to the project site, where practicable. This has been based on the estimated range to the TTS noise exposure threshold.

6.2 Planning of activities

The following measures pertaining to the planning of activities should be incorporated into the CEMP:

Timing and duration: Where possible, construction and associated activities should avoid periods when marine mammals are likely to be breeding, calving, feeding, or resting within biologically important habitats in the potential noise impact area. Operations should also avoid calving or nursing habitats, migratory corridors or important feeding grounds.

Marine fauna observer (MFO): Ensure a suitably qualified MFO is present during construction activities to oversee and enforce standard operational procedures.

Educational materials: Provide all staff with briefings on environmental regulations, marine mammals identification, and specific environmental obligations. Information about marine mammal concentration areas, migration patterns, and key feeding sites should be identified during planning and used to enhance the effectiveness of marine fauna observation.

Compliance and sighting observation report: maintenance of a record of procedures employed during construction activities, including information on any marine mammal species of concern observed, and their reaction to the construction activity. A report will include the location, date, start and completion time, information on the construction activities (e.g. number of rock dumping loads, excavation/placement duration, presence of support vessels etc.), details of the trained crew members conducting the observations, times when observations were hampered by poor visibility or high winds, and details of any marine fauna species of concern observed including time, distance, species, number of individuals, presence of calves, and observed behaviour.

Contract documentation: Standard operational procedures and any additional protective measures should be included in the contract documentation for all contractors/operators.

7. Conclusion

An underwater noise impact assessment (UNIA) has been undertaken of the two noise-generating activities associated with land reclamation project, specifically:

– S1 – rock dumping
– S2 – rock placement

The aim of the UNIA was to assess the potential adverse physiological impacts on marine fauna likely to occur in the study area. The potential for adverse behavioural response effects on marine megafauna was also qualitatively assessed.

The Buccaneer Archipelago is home to a number of key species of concern which were categorised into the following functional hearing groups:

– Low-frequency cetaceans (e.g., Bryde’s whale)
– High-frequency cetaceans (e.g, killer whale and humpback whale)
– Sirenians (e.g., Dugong)
– Sea turtles (e.g., Green turtle and Hawksbill turtle)
– Fishes with no swim bladders (e.g., Whale shark and hammerhead)
– Fishes with swim bladders not involved in hearing (e.g., tuna).
– Fishes with swim bladders involved in hearing (e.g., pipefish and seahorse)

Noise-exposure thresholds for physiological impacts (i.e. mortality, permanent threshold shift and temporary threshold shifts) for each functional hearing group were determined from current literature and guidelines.

Detailed underwater noise modelling was undertaken using RAMGeo (parabolic equation solver used for low-frequencies) and Bellhop (ray tracing solver used for high-frequencies). The modelling was used to calculate the estimated range to the relevant physiological impact noise exposure thresholds for each of the two modelled activities. The results of the modelling can be summarised as follows:

– The range to the noise exposure threshold for permanent threshold shift (PTS) onset from construction activities is 10 metres or less (based on the worst-case low frequency cetacean hearing group).
– The range to the noise exposure threshold for temporary threshold shift (TTS) onset from construction activities is approximately 430 metres or less (based on the worst-case low frequency cetacean hearing group).

Given the non-impulsive nature of the construction activities proposed, the risk of physiological impacts to fishes and sea turtles are considered to be ‘low’ at distances greater than 100 m from the source. No impacts are expected to fish with swim bladders involved in hearing or sea turtles.

Recommendations have been provided to reduce the potential for physiological impacts to marine mammals. These include safety zones for marine mammals and management measures (planning of activities). The recommended safety zone as follows:

– **An observation zone of 450 metres**, within which the movement of marine mammals would be monitored to identify any approach to the project site, where practicable.

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Appendices

Appendix A

Fundamentals to underwater sound

A-1 Terms and definitions

A-1-1 Comparison of sound in air vs in water

Factor	Air	Water
Speed of sound	– 343 m/s in gas (1 atm, 20 deg C, 1.205 Kg/m^3) – Time to travel 1 km = 2900 ms	– 1482 m/s in water (1 atmosphere, 20 deg C, 0.9982 Kg/m3) – Time to travel 1 km = 675 ms
Factors that affect the density of the medium (air / water) and therefore the speed of sound	– Temperature – Humidity – Pressure	– Temperature – Salinity – Pressure
Factors that affect environmental noise propagation	– Topographical profile (ground elevation) – Absorptive ground cover – Shielding and reflection from buildings structures – Weather – Wind effects and temperature inversions – Source noise geometry and levels	– Hydrodynamic profile (bathymetry) – Geoacoustic seabed characteristics – Shielding and reflection from the seabed and air/water interface – Hydrology (temperature, salinity, pressure) – Surface wind effects (sea roughness) – Source noise geometry and levels
Sensitive receivers	– Generally fixed sensitive receiver locations (humans)	– Fixed and mobile sensitive receiver locations (habitats/migratory patterns)
Reference level	0 Decibels 20 micropascals (ref 20 µPa)	0 Decibels 1 micropascals (ref 1 µPa)
Common weightings	– dB Linear (unweighted) – dB A-weighted (human response) – dB C-weighted (entertainment noise/low frequency noise)	– dB Linear (unweighted) – dB-M-Weighted (Southall et. al marine mammal weightings LF, HF, VHF, SI, PCW, OCW)
Human hearing comparison in (Kinsler & Frey: Fundamentals of Acoustics, 2nd edition, John Wiley & Sons, 1962, page 392)	Reference pressure re 20 µPa	Reference pressure in water re 1 µPa
	0 - Lower limit of hearing	62 - Lower limit of hearing
	60 - Comfortable hearing	122 - Comfortable hearing
	120 - Threshold of hearing	182 - Threshold of hearing
	140 - Threshold of pain	202 - Threshold of pain
	160 - Threshold of damage	222 - Threshold of damage
Typical measurement equipment	Microphone + recorder	Hydrophone + recorder

A-1-2 Underwater sound descriptors

Term	Definition
Peak Sound Pressure Level SPL(pk)	The maximum absolute pressure deviation (the difference from zero to peak level) in a given time interval or simply the amplitude of a signal, and is sometimes also termed peak sound pressure level.
Peak-to-peak level	Difference between the maximum and minimum noise level recorded during the measurement period, expressed in dB re 1 μPa. The peak-to-peak level is used as a descriptor for impulsive sources.
Sound Pressure Level (rms SPL)	The decibel representation of the RMS acoustic pressure. The sound pressure level uses a logarithmic factor of 20 and a reference RMS pressure of 1 μPa, calculated as follows: $$SPL_{rms} = 20\log_{10}\left(\frac{p_{rms}}{1\ \mu\text{Pa}}\right)$$
Sound Exposure Level (SEL)	A measurement of sound energy, taking into account received sound pressure level and duration of exposure. SEL is useful for comparing total received sound energy from sources with different durations and is calculated as follows: $$SEL = 10\log_{10}\left(\frac{p_{rms}^2 \cdot r}{1\ \mu Pa^2 s}\right) = SPL_{rms} + 10\log_{10}(r)$$ For continuous noise sources, the SPL and SEL descriptors for a given time period (e.g., 1 second), are generally consistent. As such, the SEL(1s) descriptor can generally be used to define continuous noise sources. For impulsive noise sources, the SPL and SEL descriptors for a given time period (e.g., 1 second) may vary significantly depending on amplitude variations over the time period. SEL can be computed for a single pulse or signal, which in studies of pile driving is often referred to as single-strike SEL or SEL(ss).
Sound Exposure Level (SEL(cum) or SEL(24hr)	Various guidelines for assessing the effects of anthropogenic noise on marine mammals in use a 24-hour period to account for accumulated sound exposure expressed as SEL(cum). For impulsive sounds such as pile-driving, if the individual pulses or signals are approximately the same, then the SEL(cum) can be estimated as: $$\text{SEL(cum)} = \text{SEL(ss)} + 10\log_{10}\text{N}$$ Where N is the number of pulses and should be specified, as should the total duration over which sound energy is being accumulated. For continuous noise sources, such as shipping noise or drilling, the SEL(cum) can be estimated as: $$\text{SEL(cum)} = \text{SEL(1s)} + 10\log_{10}\text{N}$$ Where N is the total number of seconds over a 24 hour period considering the source's duty cycle.

A-1-3 Units

Term	Description
ºC	Degrees celsius
dB	Decibels
Hz	Hertz
μ	Micro
μPa	Micropascal
Pa	Pascal
ppt	Parts per thousand
s	Seconds
t	Tonnes
W	Watts

A-1-4 Underwater sound terms

Term	Description
Ambient sound	Environmental background noise not of direct interest during a measurement or observation. Can include prevailing noise from: – weather, – waves, – seismic events, – marine fauna, – distant shipping movements, and – other anthropogenic sources.
Broadband level	The total level measured over a specified frequency range.
Continuous sound	A sound whose sound pressure level remains above ambient sound during the observation period. A sound that gradually, rather than impulisicely, varies in intensity over 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 (ddec)	One tenth of a decade. Note: An alternative name for decidecade 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 / third-octave band	A frequency band whose bandwidth is one decidecade (or approximately one-third octave). The bandwidth of a decidecade band increases with increasing centre frequency.
Decibel (dB)	Unit of measurement used to express the ratio of one value of a power quantity to another on a logarithmic scale.
Duty cycle	The proportion of time that an intermittent noise source is operational and producing sound during a measurement or assessment period For example, a source transmitting for 1 hour per day has a duty cycle of 1/24 = ~0.04 (4%)
Flat weighting	A term indicating that no frequency weighting function is applied. Often also referred to as unweighted.
Frequency	The rate of oscillation of a periodic function measured in cycles-per-unit-time and is the reciprocal of the period.
Frequency weighting	The process of applying a frequency weighting function or ‘filter’.
Frequency-weighting function	The ratio of output power to input power of a specified filter for sound of a given frequency, sometimes expressed in decibels. It is the squared magnitude of the sound pressure transfer function. 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.
Hertz (Hz)	The unit use to denote frequency, defined as one cycle per second.
Impulsive Sound	Sound characterised by high pressure and short rise time and whose sound pressure level may drop below the ambient sound periodically during the observation period.
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. A value of sound exposure level with reference to 1 μPa^2 s can be written in the form: e.g., 120 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.
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
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, measured in pascals (Pa).
Reference values	The value used for calculating sound levels and/or expressing in decibels. For example, the reference value for expressing sound pressure level in decibels is 1 µPa.
Sound	A time-varying disturbance in the pressure, stress, or material displacement of a medium propagated by local compression and expansion of the medium.

Term	Description
Sound exposure	Time integral of squared sound pressure over a stated time interval measured in Pa^2 s. 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).
Sound pressure	The contribution to total pressure caused by the action of sound
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. The source level is generally provided as a measured or calculated level at 1 m from the source. Unit: decibel (dB re 1 $\mu Pa^2 m^2$)
Spectrum	An acoustic signal represented in terms of its power, energy, mean-square sound pressure, or sound exposure distribution with frequency.
Unweighted	Term indicating that no frequency weighting function is applied. See also flat-weighting.
Wavelength	Distance of a cycle in a propagating periodic or harmonic wave, the wavelength is inversely proportional to the frequency, i.e., wavelength increases as frequency deceases. Wavelength is denoted by the Greek letter lambda (λ) and is measured in metres (m).

A-1-5 Underwater sound propagation

Term	Description
Absorption	The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium
Attenuation	The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium.
Azimuth	A horizontal angle relative to a reference direction, which is often magnetic north or the direction of travel. In navigation it is also known as bearing.
Cylindrical spreading	Received level diminishes by 3 dB per doubling of distance from the source. This is also referred to a 10·log relationship when calculating transmission loss at a distance from the source
Directivity	The directional signature of a sound source. Most commonly a source has a directivity that is an *omnidirectional pattern* or a perfect sphere, a source is more *directive* when its directivity pattern diverts from this default. At wavelengths that are comparable to or lower than the dimensions of a source, the directional behaviour is more pronounced
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.
Geoacoustic	Relating to the acoustic properties of the seabed
Isopleth	A line drawn on a map through all points having the same value of some quantity
Lloyd Mirror	The acoustic phenomenon produced by the combination of the direct sound wave and the sea surface reflection or *ghost*. The Lloyd mirror is characterised by a pattern of constructive and destructive interferences, followed by a rapid decay of sound pressure with distance.
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 oceanacoustic propagation problems
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
received level	The level measured (or that would be measured) at a defined location. The type of level should be specified.
sound field	Region containing sound waves
Sound Propagation Model:	mathematical algorithm that uses a numerical approximation to predict the transmission loss experienced by the sound emitted by an acoustic source as it propagates in a given underwater environment. Some of the most widely used propagation modelling theories and examples of algorithms are raytracing (Bellhop),parabolic equation (RAMGeo) and normal modes (Kraken).
Sound speed profile (SSP)	The speed of sound in the water column as a function of depth below the water surface. The SSP is generally dependent on temperature and salinity.
Spreading Loss Factor	Level of attenuation per ten-times distance increase. A factor of 20 indicates spherical propagation of sound, associated with free-field (i.e. unbounded) conditions, and a factor of 10 indicates cylindrical propagation, associated with long-range propagation in-between two parallel, perfectly rigid, semi-infinite planes i.e. waveguide). The spreading loss factor can be lower than 10 or higher than 20, specially at ranges where the direct sound or early reflections dominate
Spherical spreading	Received level diminishes by 6 dB per doubling of distance from the source. This is also referred to a 20·log relationship when calculating transmission loss at a distance from the source.
Transmission loss (TL)	The difference between a specified level at one location and that at a different location, $$\mathrm{TL}(x_1, x_2) = \mathrm{L}(x_1) - \mathrm{L}(x_2)$$

A-2 Ambient underwater noise

A-2-1 Underwater noise sources

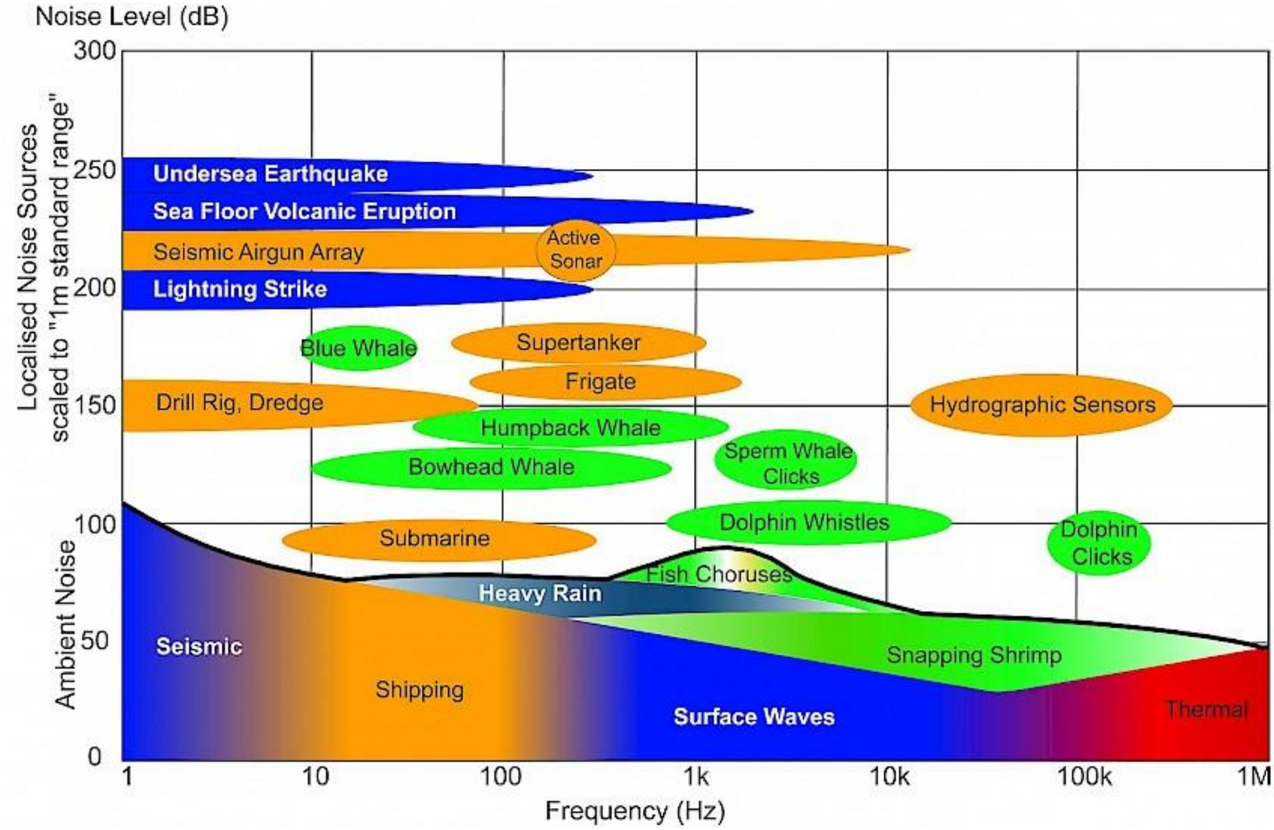
Marine ambient noise poses a baseline limitation on the use of sound by marine animals as signals of interest that must be detected against noise background. The level and frequency characteristics of the ambient noise environment are the two major factors that control how far away a given sound signal can potentially be detected (Richardson *et al*., 1995).

Marine ambient noise is comprised of a variety of sounds of different origin at different frequency ranges, having both temporal and spatial variations. It primarily consists of noise from natural physical events, noise produced by marine biological species and anthropogenic noise (Carey and Evans, 2011). These sources are detailed below.

Source	Summary	Description
Natural events	The major natural physical events contributing to marine ambient noise include, but are not limited to, wave/turbulence interactions, wind, precipitation (rain and hail), breaking waves and seismic events (e.g. earthquakes / tremors):	– The interactions between waves/turbulence can cause very low frequency noise in the infrasonic range (below 20 Hz). Seismic events such as earthquakes/tremors and underwater volcanos also generate noise predominantly at low frequencies from a few Hz to a few hundred Hz. – Wind and breaking waves, as the prevailing noise sources in much of the world's oceans, generate noise across a very wide frequency range, typically dominating the ambient environment from 100 Hz to 20 kHz in the absence of biological noise sources. The wind dependent noise spectral levels also strongly depend on sea states which are essentially correlated with wind force, and – Precipitation, particularly heavy rainfall, can produce much higher noise levels over a wider frequency range of approximately 500 Hz to 20 kHz.
Bioacoustic production	Some marine animals produce various sounds (e.g. whistles, clicks) for different purposes (e.g. communication, navigation or detection):	– Baleen whales (e.g. great whales like humpback whales) regularly produce intense low frequency sound (whale songs) that can be detected at long range in the open water. Odontocete whales, including dolphins, can produce rapid burst of high frequency clicks (up to 150 kHz) that are primarily for echolocation purposes. – Some fish species produce sounds individually, and some species also make noise in choruses. Typically, fish chorusing sounds depend on species, time of day and time of season, and – Snapping shrimps are important contributors among marine biological species to the marine ambient noise environment, particularly in shallow coastal waters. The noise from snapping shrimps is extremely broadband in nature, covering a frequency range from below 100 Hz to above 100 kHz. Snapping shrimp noise can interfere with other measurement and recording exercises, for example it can adversely affect sonar performance.
Anthropogenic sources	Anthropogenic noise primarily consists of noise from shipping activities, offshore seismic explorations, marine industrial developments and operations, as well as equipment such as sonar and echo sounders:	– Shipping traffic from various sizes of ships is the prevailing man-made noise source around nearshore port areas. Shipping noise is typically due to cavitation from propellers and thrusters, with energy predominantly below 1 kHz. – Pile driving and offshore seismic exploration generate repetitive pulse signals with intense energy at relatively low frequencies (hundreds of Hz) that can potentially cause physical injuries to marine species close to the noise source. The full frequency range for these impulsive signals could be up to 10k Hz, and – Dredging activities and other marine industry operations are additional man-made sources, generating broadband noise over relatively long durations.

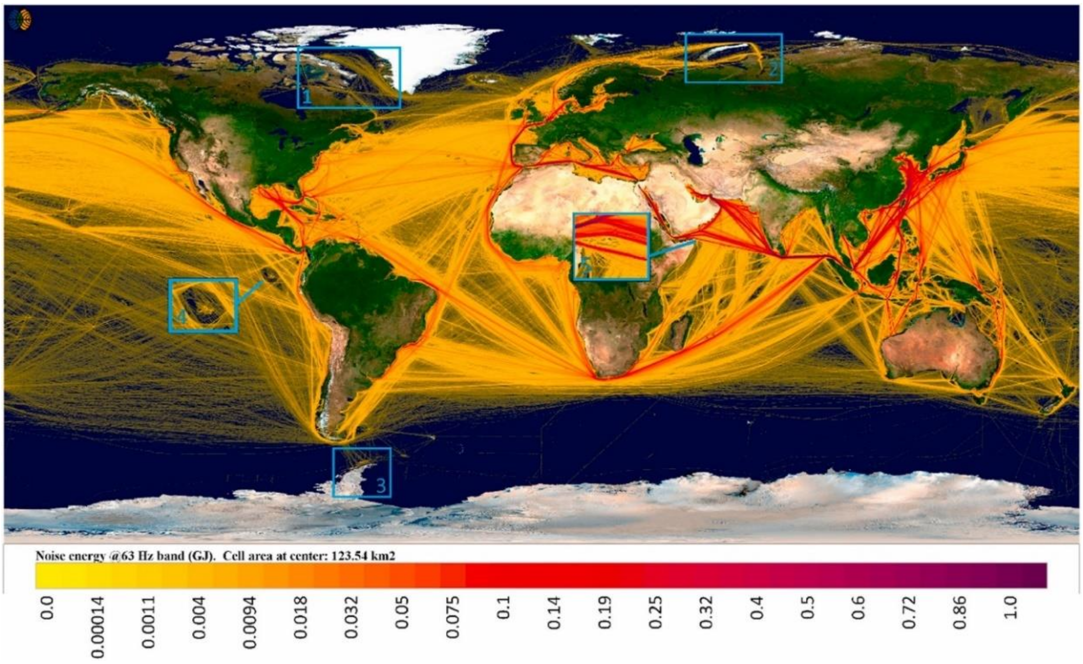
A-2-2 Spectral range of underwater noise sources

The figure below provides an overview of the indicative noise spectral levels produced by various natural (shown in blue), bioacoustics (shown in green) and anthropogenic sources (shown in orange), relative to typical background or ambient noise levels in the ocean. Human contributions to ambient noise are often significant at low frequencies, between about 20 Hz and 500 Hz, with ambient noise in this frequency range being predominantly from distant shipping (Hildebrand, 2009). In areas located away from anthropogenic sources, background noise at higher frequencies tends to be dominated by natural physical or bioacoustics sources such as rainfall, surface waves and spray, as well as fish choruses and snapping shrimp for coastal waters.



A-2-3 Global noise energy from shipping movements (63 Hz)

Commercial shipping is the primary contributor to elevated underwater noise levels from anthropogenic sources. Noise levels from cargo vessels are in the range of 180 – 200 dB at 1 metre and noise levels can travel great distances across oceans (Jalkenen et al., 2022). The map below (Jalkenen et al., 2022) shows the underwater noise emissions from ships during 2019, with the following areas highlighted: 1) Baffin Sea, 2) Kara Sea, 3) Palmer Basin, 4) Galapagos Islands and 5) Socotra



A-3 Marine fauna response to underwater sound

A-3-1 Common terms

Term	Description
Auditory frequency weighting	The process of applying an auditory frequency weighting function to account for a species' physiological sensitivity to sound. An example for marine mammals are the auditory frequency weighting functions published by Southall et al. (2019)
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.
Behavioural response	Behavioural responses to noise include changes in vocalisation, resting, diving and breathing patterns, changes in mother-infant spatial relationships, and avoidance of the noise source (NRC 2005). Masking of biologically important sounds may interfere with communication and social interaction, and cause changes in behaviour as well.
Cetacean	Any animal in the order Cetacea. These are aquatic species and include whales, dolphins, and porpoises
Ensonified	Exposed to 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 hearing threshold represents the lowest signal level an animal can detect at a particular frequency, usually referred (and measured) as the threshold at which an animal will indicate detection 50% of the time.
Mortality or injury	Most severe consequence of underwater noise on marine animals can be permanent injury other than hearing loss and in some cases death.
M-weighting	See auditory frequency weighting function (as proposed by Southall et al. 2019)
Physiological response	Most discussions of physiological effects of underwater noise have centred on the auditory system, as this system is likely to be most sensitive to noise. When the auditory system is exposed to a high level of sound for a specific duration, the sensory hair cells begin to fatigue and do not immediately return to their normal shape. This causes a reduction in the animal's hearing sensitivity, or an increase in hearing threshold. If the noise exposure is below some critical sound energy level, the hair cells will eventually return to their normal shape. This effect is called a temporary threshold shift (TTS) as the hearing loss is temporary. If the noise exposure exceeds the critical sound energy level, the hair cells become permanently damaged and the effect is called permanent threshold shift (PTS).
Permanent threshold shift (PTS)	An irreversible loss of hearing sensitivity caused by excessive noise exposure. PTS is considered auditory injury.
Pinniped	Commonly known as seals and are a widely distributed and diverse clade of carnivorous, fin-footed, semiaquatic, mostly marine mammals. They comprise the extant families Odobenidae (whose only living member is the walrus), Otariidae (the eared seals: sea lions and fur seals), and Phocidae (the earless seals, or true seals)
Sirenians	Commonly referred to as sea cows or sirenians, are an order of fully aquatic, herbivorous mammals that inhabit swamps, rivers, estuaries, marine wetlands, and coastal marine waters. The extant Sirenia comprise two distinct families: Dugongidae (the dugong and the now extinct Steller's sea cow) and Trichechidae (manatees).
Temporary threshold shift (TTS)	Reversible loss of hearing sensitivity. TTS can be caused by noise exposure
Zones of impact	The following zones of impact can be defined (Richardson et al. 1995): • *Zone of audibility* – Area within which marine mammal might hear the source noise but not show any significant behavioural response. The size of the zone of audibility is highly dependent on the ambient noise environment. • *Zone of responsiveness* – Area within which the considered marine mammal might react behaviourally to the noise source. This zone can be smaller than the zone of audibility as marine mammals usually do not show significant behavioural responses to noises that are faint but audible. • *Zone of hearing injury* – Area closest to the noise source where the noise levels may be high enough to cause a physiological impact such as TTS or PTS.

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