SWAN RIVER CROSSINGS PROJECT

Aquatic Noise Assessment

Prepared for:

Main Road Western Australia
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BASIS OF REPORT

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EXECUTIVE SUMMARY

Main Roads Western Australia (MRWA) is proposing to redesign and reconstruct the existing Fremantle Traffic Bridge (FTB) and the Fremantle Rail Bridge (FRB) and to develop an integrated solution incorporating four traffic lanes, three rail lines (two passenger, one freight) and pedestrian cyclist facilities, all forming part of the Swan River Crossings Project.

SLR Consulting Australia Pty Ltd (SLR) has been appointed by MRWA to undertake aquatic noise modelling and assessment of relevant impacts on marine fauna species and human divers/swimmers as a result of the construction activities of the project.

This report provides an aquatic noise modelling study and an assessment of impacts from the proposed construction activities associated with the development project. The assessment process involves characterisation of existing aquatic noise environment, identification of key aquatic sensitive receptors potentially to be impacted by the underwater noise emissions and their relevant assessment criteria based on a literature review, identification of major noise sources and their noise emission characteristics, detailed modelling prediction of underwater noise propagations and relevant zones of impact estimates, and development a management plan to implement relevant management and mitigation measures to minimise the impact.

Aquatic sensitive receptors of concern include marine mammals, particularly Swan River Dolphins (i.e. Indo-Pacific bottlenose dolphins), fish species and human divers/swimmers. The noise impact criteria in terms of physiological and behavioural impacts for these sensitive receptors, as outlined in **Section 4**, have also been established via a review of the most relevant guidelines or literature.

Detailed modelling predictions have been undertaken for noise emissions from the impact piling operations, the most dominant noise-generating activities during the bridge construction. Various zones of impact have been estimated for different marine sensitive receptors based on comparisons between predicted noise levels and impact assessment criteria with results presented in **Section 6.2**.

An aquatic noise management plan has been developed, as outlined in **Section 7**, with project specific management and monitoring procedure requirements provided in order to minimise the piling noise impact on assessed aquatic sensitive receptors.

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1 Introduction

1.1 Project background

Main Roads Western Australia (MRWA) is proposing to redesign and reconstruct the existing Fremantle Traffic Bridge (FTB) and the Fremantle Rail Bridge (FRB) and to develop an integrated solution incorporating four traffic lanes, three rail lines (two passenger, one freight) and pedestrian cyclist facilities, all forming part of the Swan River Crossings Project.

SLR Consulting Australia Pty Ltd (SLR) has been appointed by MRWA to undertake aquatic noise modelling and impact assessment on marine fauna species and human divers/swimmers as a result of the construction activities of the project.

1.2 Aquatic noise assessment – scope of works

This assessment has been undertaken with consideration of the current best practice in assessing aquatic noise impact on marine fauna and human divers/swimmers applied both nationally and internationally. The assessment methodology is detailed within the report structure below.

- **Section 2** gives an overview of the Swan River Crossings Project, as well as the possible major aquatic noise generating activities associated with the construction development.
- **Section 3** provides the characterisation of the existing aquatic noise environment, based on a review of general marine noise environment, as well as the aquatic soundscape studies undertaken for both the lower and middle reaches of the Swan River;
- **Section 4** conducts a review on potential aquatic noise impact on marine fauna and human divers/swimmers from identified major noise-generating activities associated with bridge construction, with particular focuses on piling activities and Swan River Dolphin (i.e. Indo-Pacific Bottlenose Dolphins). The assessment criteria will also be outlined for relevant general marine fauna species of concern (including marine mammals, fish species) and human divers/swimmers, based on relevant guidelines and criteria that represent the current industry best practice;
- **Section 5** covers detailed noise modelling prediction methodology and procedure, and provides relevant modelling environmental inputs and assumptions, modelling source locations and scenarios associated with the impact piling operations, and source levels of the piling noise emissions;
- **Sections 6** provides the detailed modelling results and the subsequent zones of impact estimated for general marine fauna species and human divers/swimmers based on criteria set out in **Section 4**;
- **Sections 7** outlines a aquatic noise management plan specific to the project, including recommended safety zones, monitoring and operation procedures, as well as potential for additional mitigation measures.

Acoustic terminologies used throughout the report are provided in **Appendix A**.

2 Project Description

2.1 Swan River Crossings Project – an overview

MRWA is proposing to build the Swan River Crossings that includes the construction of new road and rail bridges, the upgrading of the existing rail bridge and the demolition of the existing Fremantle Traffic Bridge in Fremantle, Western Australia. The purpose of the project is to ensure that the Swan River Crossing at this location provides appropriate levels of safety and transport capacity for motorists, pedestrians, cyclists, rail and river users.

Currently the Fremantle Traffic Bridge is a large wooden structure constructed in year 1938/9 in place of an older bridge, with an expected life of 40 years. The bridge was upgraded in 1974 to extend its life for another 30 years, and this extended life has now been reached. The bridge currently carries 23,000 vehicles a day and at peak times is congested. The existing rail bridge lies in close proximity to the traffic bridge, but on a slightly different alignment and with insufficient rail tracks to cater for freight and passenger rail. The pier alignment of the two existing bridges complicates river navigation.

The project includes the following major road and rail work components:

Road works

- Construction of a standalone four-lane bridge over the Swan River (to replace the existing Fremantle Traffic Bridge).
- Realignment and upgrade of Queen Victoria Street and Canning Highway to suit the new road bridge over the Swan River.
- Construction of a PSP from North Fremantle Station to Canning Highway including:
    - Construction of a bridge structure to take the PSP over Tydeman Road.
    - Crossing the Swan River via the new road bridge, which is to accommodate separated pedestrian and cycling traffic.
- Demolition of existing Fremantle Traffic Bridge with a minimum of 19m over water to be retained at the southern end.

Rail works

- Construction of new standalone passenger rail bridge over the Swan River carrying two narrow gauge mainlines.
- Realignment, modification, and upgrade of existing rail infrastructure to suit new and retained rail bridge structures.
- Retention and modification of the existing Fremantle Rail Bridge as a dedicated freight rail bridge.
- Modification of existing rail-over-road bridge on Tydeman Rd.

The indicative project site overview is presented as in **Figure 1** above. Road works are anticipated to extend from just north of Swan Street and will tie into the existing road network south of the river at Canning Highway and Queen Victoria Street, while rail works are anticipated to extend from the existing Tydeman Road grade separated crossings (north end), across the Swan River to Peter Hughes Drive Underpass railway bridge in the south.

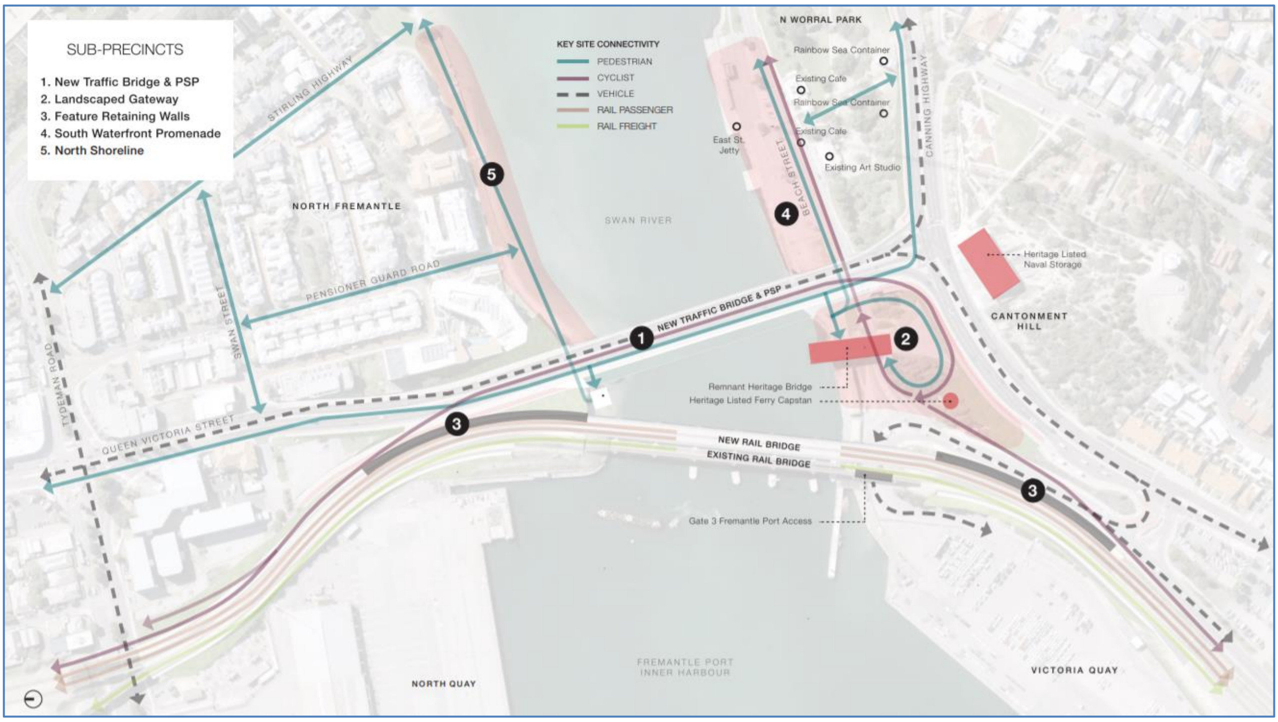


Figure 1 Swan River Crossings Project - concept design as at March 2021 - subject to change (Source: Swan River Crossings Project Update August 2020, MRWA)

2.2 Major aquatic noise generating activities and sensitive receptors

Major activities in regards to aquatic noise emissions during the bridge construction phase of the project include impact piling, sediment excavation and vessel movements. Impact piling is considered to have the highest impact on the aquatic noise environment, due to its very high noise emissions, as well as its impulsive noise characteristics. However, dredging and vessel movements are expected to have much lower impact as their noise emissions are lower in levels and continuous in nature, and are comparable to the existing shipping traffic from cargo ships and recreational vessels around the port area.

The sensitive aquatic receptors that are potentially to be adversely affected by the noise emissions from the construction activities include marine mammals particularly Swan River Dolphins (i.e. Indo-Pacific Bottlenose Dolphins), fish species and human divers/swimmers.

3 Existing Aquatic Noise Environment

3.1 General aquatic ambient noise

Aquatic 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 be detected (Richardson et al, 1995).

Aquatic 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. These sources are detailed as follows:

- Natural events: the major natural physical events contributing to aquatic 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 aquatic 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.

Figure 2 provides an overview of the indicative noise spectral levels produced by various natural and anthropogenic sources, 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.

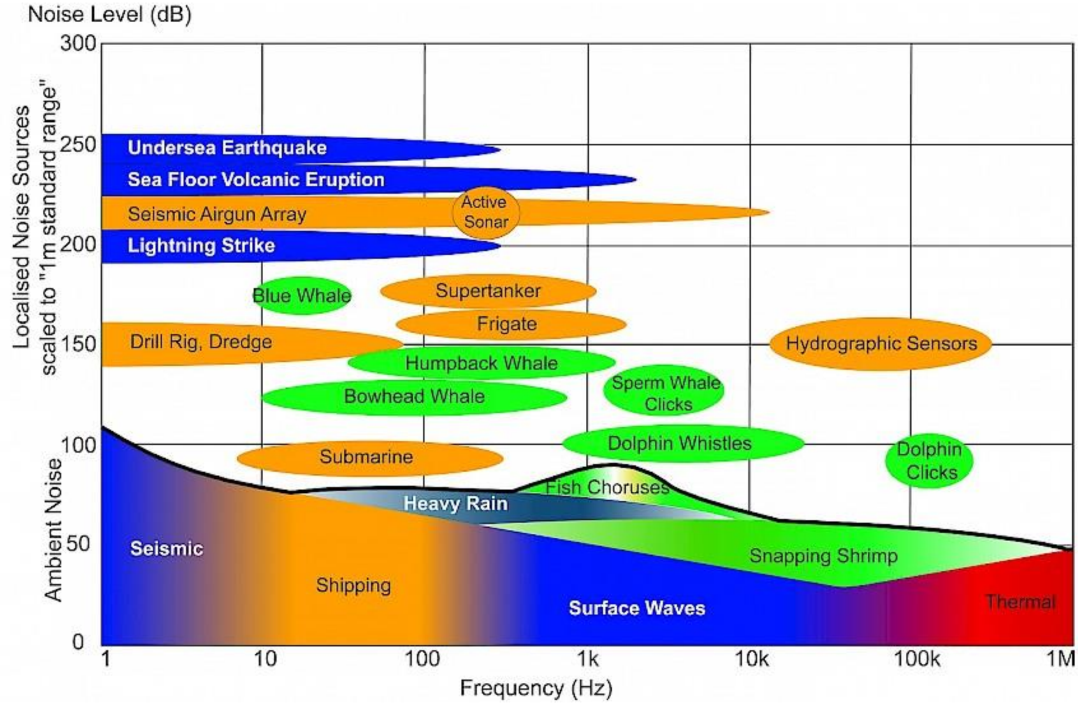


Figure 2 Levels and frequencies of anthropogenic and naturally occurring sound sources in the marine environment (from https://www.ospar.org/work-areas/eiha/noise). Natural physical noise sources represented in blue; marine fauna noise sources in green; human noise sources in orange

A summary of the spectra of various ambient noise sources based on a review study undertaken by Wenz (1962) is shown in **Figure 3**. It should be noted that although the spectral curves in the figure are based on average levels from reviewed references primarily for the North Atlantic Ocean region, they are regarded as representative in general for respective ocean ambient noise spectral components.

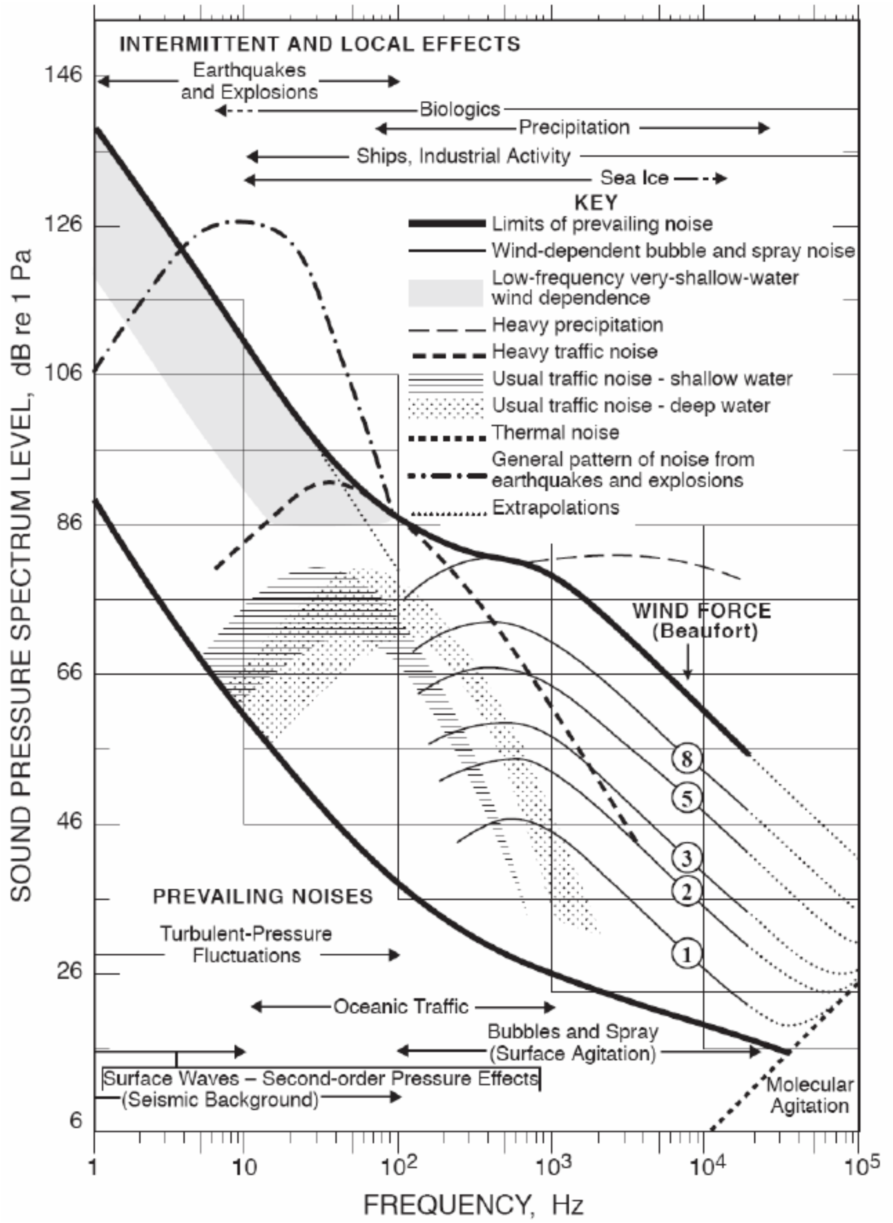


Figure 3 Composite of Ocean Ambient Noise Spectra (from Wenz (1962))

Studies in Australian waters have shown that there are some significant differences in the ambient noise compared to the colder Northern Hemisphere waters where most existing measurements have been recorded. **Figure 4** summarises the main components of sea ambient noise for the Australian waters, where the differences from Wenz's ambient noise spectra are due to the different environment of tropical waters, particularly in respect to noise from marine animals. Wind-generated noise and the traffic noise due to shipping activities are generally consistent in level range between the two studies (Wenz, 1962 and Cato, 1997).

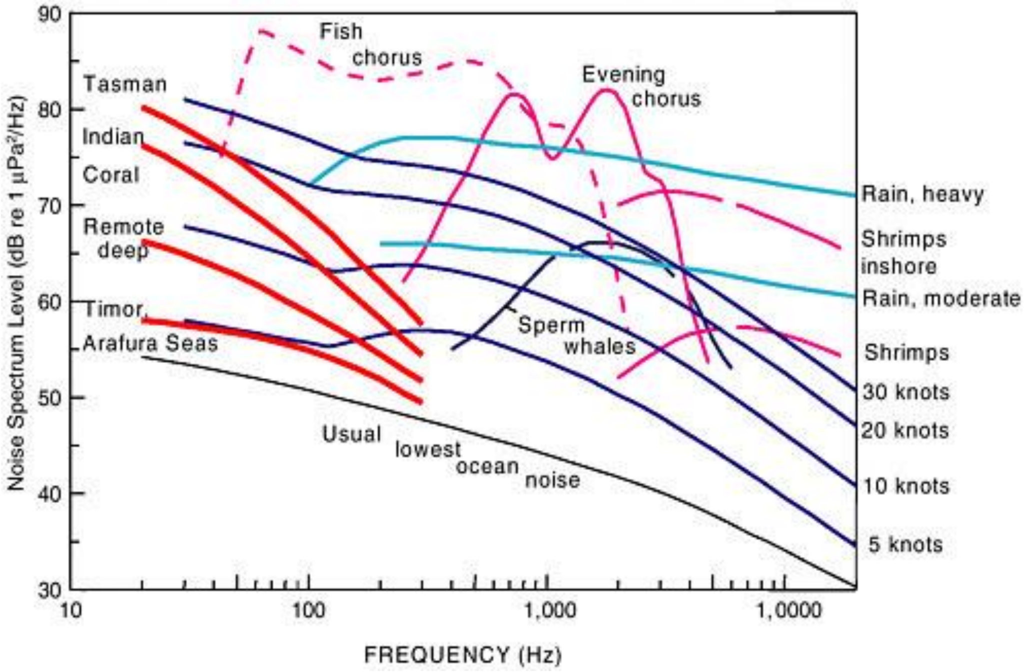


Figure 4 Summary of Aquatic Ambient Noise Spectra for the Australian Region (from Cato (1997))

3.2 Aquatic soundscape studies – Swan River

The aquatic noise environment for the lower and middle reaches of the Swan River estuary has been well investigated based on the two long-term noise monitoring studies at the following two monitoring locations (as shown in **Figure 5**):

- The lower reach - Fremantle Inner Harbour (Salgado et al, 2012)
- The middle reach – The Narrow Bridge (Marley et al, 2016)

The subsequent soundscape analysis undertaken for the noise recordings collected at the two monitoring locations demonstrate that the aquatic noise environments at both locations have similarities, i.e. both are predominantly from biological sources and anthropogenic noise sources. Biological sources are predominantly snapping shrimps which consistently contribute to wide broadband energy within high frequency range above 1 kHz. Anthropogenic noise sources are mainly from vessel operations and road/rail traffic across adjacent river bridges, with their sound energy contributions primarily at low frequency range.

Due to the differences in locality and surrounding anthropogenic activities, aquatic noise environment at the two locations are quite different. The soundscape at the monitoring location within Fremantle Inner Harbour is dominated by noise from vessel traffic and trains and vehicle traffics passing through nearby bridges. While at the monitoring location near the Narrow Bridge, broadband sound energy from snapping shrimp clicks is the dominant feature of the soundscape.

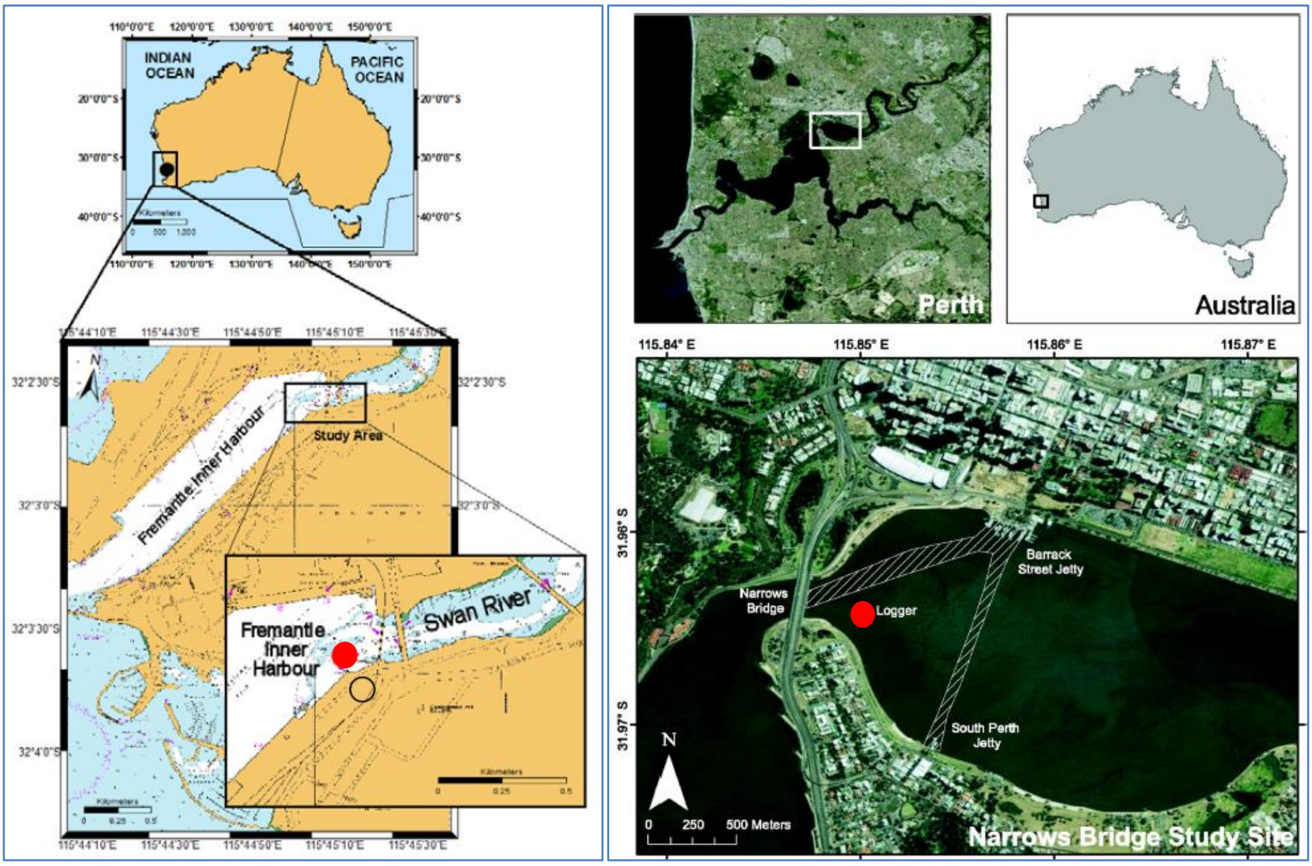


Figure 5 Long-term noise monitoring logger locations (red dots) within the Fremantle Inner Harbour (left) and near the Narrow Bridge (right).

3.2.1 Fremantle Inner Harbour

A long-term noise monitoring was conducted in 2010 over a total period of approximately 5 months (1st April – 2nd July, and 26th July – 20th August 2010) within the Fremantle Inner Harbour (Salgado et al, 2012). The monitoring noise logger location is just over 100 m from the adjacent Fremantle Rail Bridge as shown in the left panel in **Figure 5**.

Noise from a range of anthropogenic noise sources that are common to a busy and expanding port was recorded and dominated the marine noise environment over the entire monitoring period. The anthropogenic noise recorded include noise from vessel traffic, trains and vehicle traffics passing through nearby bridges, machinery noise from regular port operation, as well as vibratory and/or impact piling driving activities during wharf construction within the monitoring period. As an example, **Figure 6** demonstrates spectrogram of frequent train and vessel noise during the period from 31st March to 10th April 2010.

Noise from biological sources was also detected during the monitoring period, including snapping shrimp clicks as the dominant biological sources, fish chorus (particularly from mulloways) and fish grunts throughout the recordings, and whistles from Indo-Pacific bottlenose dolphins.

The average root-mean-square (RMS) broadband (10 – 4,500Hz) noise levels versus time of day over the monitoring period, excluding the noise recordings from piling operations, are presented in **Figure 7**. As can be seen, the broadband noise levels within the inner harbour were typically between 110 and 140 dB re 1µPa RMS, and with a clear diurnal cycle which is due to typical day-time port operation characteristics.

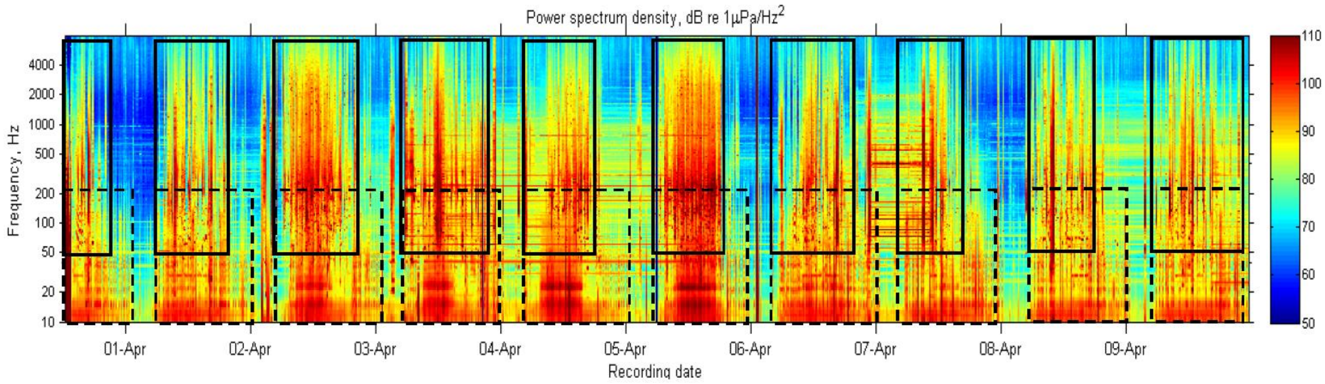


Figure 6 Spectrogram of frequent major noise sources (train noise – dash lines and vessel noise – solid lines) during the period from 31st March to 19th April 2010.

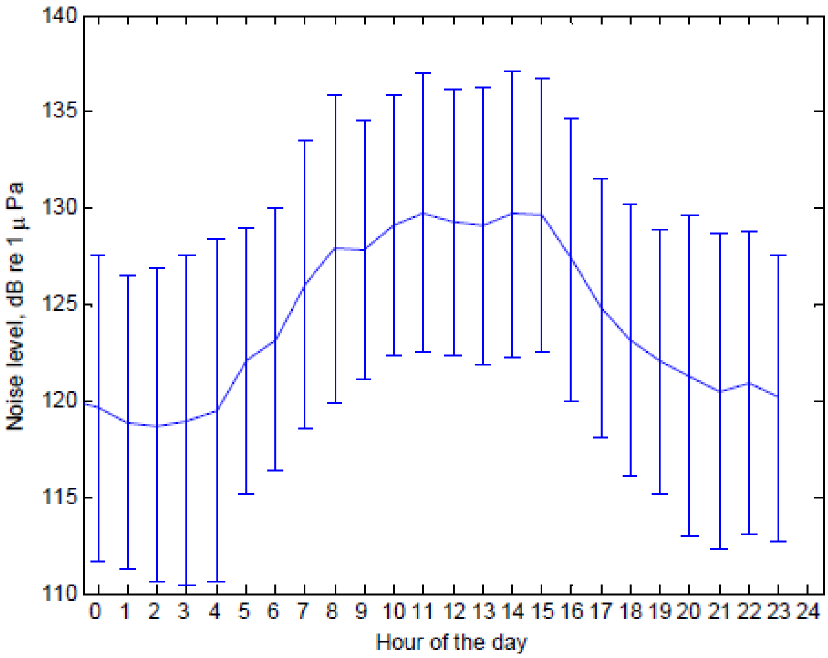


Figure 7 Average broadband (10 – 4,500 Hz) noise levels vs hour of the day. Error bars show one stand deviation.

3.2.2 The Narrow Bridge

Soundscape analysis for the middle reach of the Swan River estuarine was undertaken based on underwater noise monitoring data over a six-week period (27th November to 4th January 2014) (Marley et al, 2016). The noise monitoring logger was deployed near the Narrow Bridge and adjacent to the ferry channels as shown in the right panel in **Figure 5**.

The study found that the soundscape at the monitoring site comprised of natural events (waves, precipitation), anthropogenic noise (bridge traffic, machinery) and biological sources (fish, snapping shrimps and dolphins), and was strongly influenced by vessel traffic at relatively low frequency range (below 200 Hz) and particularly snapping shrimp clicks at very wide high frequency range (above 1 kHz). **Figure 8** presents an example spectrogram of the monitoring noise recording over a week period.

The noise level variation over the entire 6-week monitoring period, as shown in **Figure 9**, indicates that the over noise levels are quite consistent over time, with levels fluctuate slightly around 120 dB re 1µPa RMS. The is due to the dominant noise contribution from consistent snapping shrimp clicks over time at high frequency range.

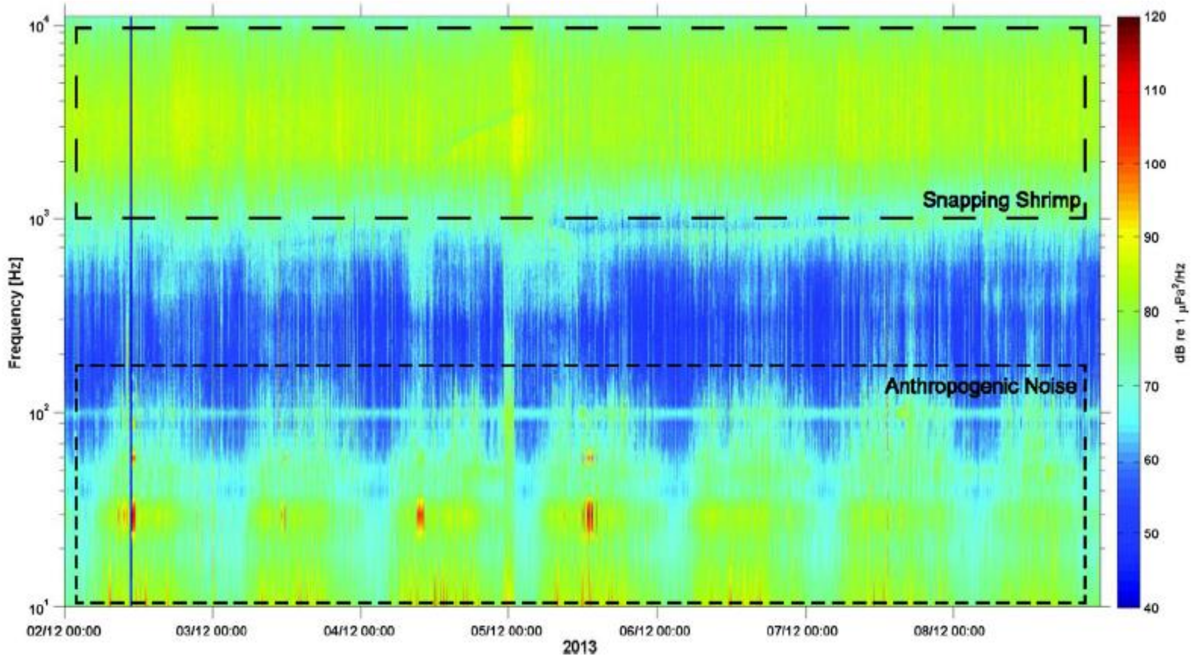


Figure 8 **Spectrogram of underwater noise recorded over a week in December 2013, showing prominent anthropogenic noise sources at low frequency range, as well as snapping shrimps over higher frequency range.**

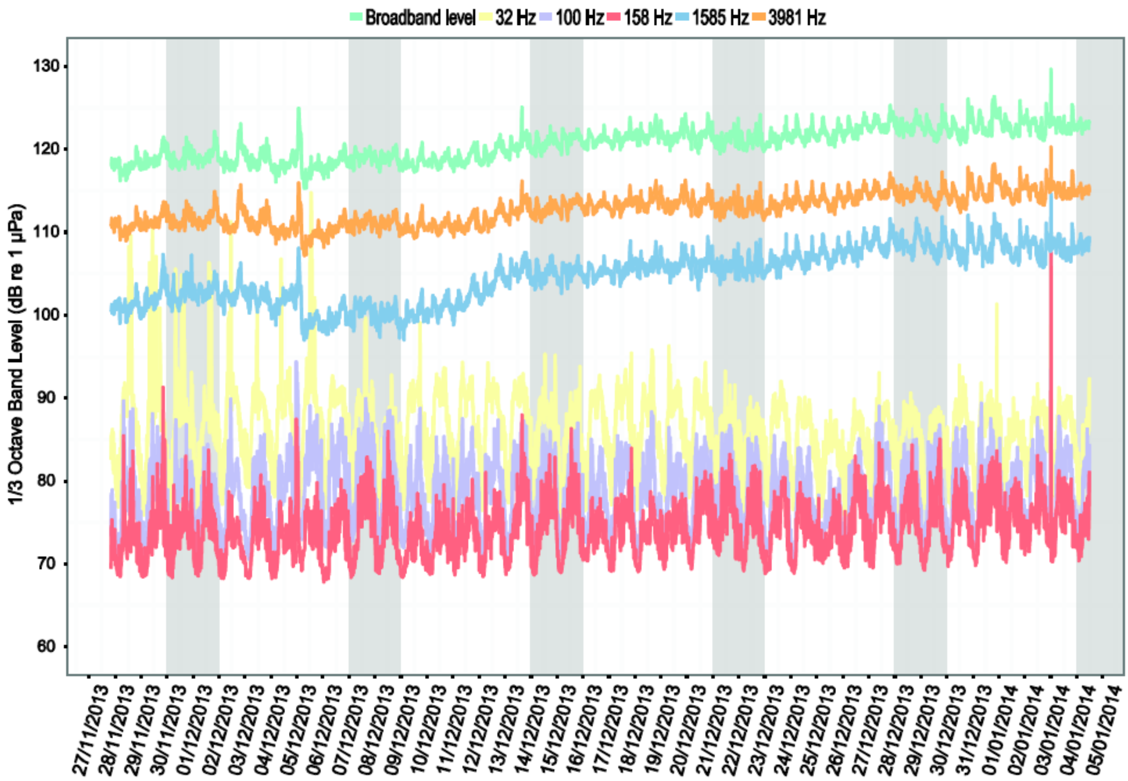


Figure 9 **Recorded noise level variation in broadband (9 Hz–9 kHz) and selected 1/3 octave band across the six-week monitoring period at Narrow Bridge.**

4 Aquatic Noise Impact Assessment Criteria

4.1 Impact of aquatic noise on marine fauna species

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 emitting 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 2004; Ladich et al, 2004 and 2006(a)&(b)), and potentially they also use acoustic environment for orientation (Montgomery et al, 2006). Some invertebrates such as decapod crustaceans are reported to be sensitive to low frequency underwater sound (Popper et al, 2001).

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 physical reaction of individual marine fauna species. The potential impacts of noise on marine fauna species include audibility, detection and masking of communication and other biological important sounds, behavioural responses and physiological impacts which generally include discomfort, hearing loss, physical injury and mortality (Richardson et al, 1995; Hasting and Popper, 2005).

The theoretical zones of noise influence based on the severity of noise impact is illustrated in **Figure 10** below.

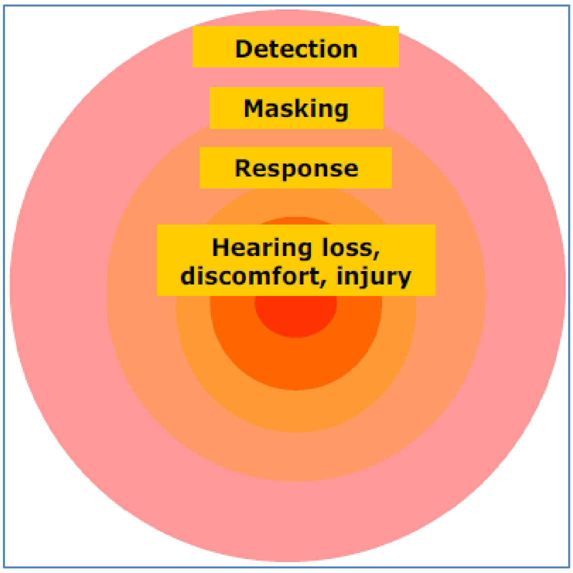


Figure 10 Theoretical zones of noise influence (Richardson et al. 1995)

[1] Impulsive noise is typically very short (with 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.

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).

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'[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, 2008).

Behavioural Responses

Behavioural responses to noise include changes in vocalisation, resting, diving and breathing patterns, changes in mother-infant relationships, and avoidance of the noise sources. For behavioural responses to occur, a sound would mostly have to be significantly above ambient levels and the animal's audiogram.

The behavioural response effects can be very difficult to measure and depend on a wide variety of factors such as the physical characteristics of the signal, the behavioural and motivational state of the receiver, its age, sex and social status and many others. 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).

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).

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

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 sea turtle species, as well as human divers and swimmers, based on a review of relevant guidelines and/or literature published.

4.2 Marine mammals

There have been extensive scientific studies and research efforts to develop quantitative links between marine noise and impacts on marine mammal species. For example, Southall et al (2007 & 2019) have proposed noise exposure criteria associated with various sound types, including impulsive noise (e.g. piling noise and seismic airgun noise) and non-impulsive noise (e.g. vessel and drilling noise)) for certain marine mammal species (i.e. cetaceans and sirenians and carnivores), based on review of expanding literature on marine mammal hearing and on physiological and behavioural responses to anthropogenic sounds.

The following two subsections provide the recommended frequency-weighting functions for use in assessing the effects of relatively intense sounds on hearing, as well as the noise exposure levels above which adverse effects on various groups of marine mammals, and they are derived based on all available relevant data and published literature (i.e. the state of current knowledge). For Indo-Pacific bottlenose dolphin species specifically, **Section 4.2.3** provides further details regarding its hearing sensitivity and responses to noise emissions from marine traffic and impact piling operations.

4.2.1 Marine mammal auditory weighting functions

Marine animals do not hear equally well at all frequencies within their functional hearing range. Based on the hearing range and sensitivities, Southall et al (2019) have categorised marine mammal species (i.e. cetaceans and pinnipeds) into six underwater hearing groups: low-frequency (LF), high-frequency (HF), very high-frequency (VHF) cetaceans, Sirenians (SI), Phocid carnivores in water (PCW) and Other marine carnivores in water (OCW). For each specific marine mammal species, refer to Appendix I – 6 within the reference document (Southall et al, 2019) for their corresponding hearing groups. A summary of these appendices is presented as **Appendix B** in this report.

The dolphin species that habit the Swan-Canning River System are the Indo-Pacific bottlenose dolphins (*Tursiops aduncus*), and they are categorised as the HF hearing groups, and are of particular concern for the adverse noise impacts.

The potential noise effects on animals depend on how well the animals can hear the noise. Frequency weighting is a method of quantitatively compensating for the differential frequency response of sensory systems (Southall et al, 2007 & 2019).

When developing updated scientific recommendations in marine mammal noise exposure criteria, Southall et al (2019) adopt the auditory weighting functions as expressed in the equation below, which are based on the quantitative method by Finneran (2015 & 2016) and are consistent with the U.S. National Oceanic and Atmospheric Administration (NOAA) technical guidance (NMFS, 2016 & 2018).

$$W(f) = C + 10log10\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a[1+(f/f_2)^2]^b}\right\} \quad (2.1)$$

Where:

- ***W(f)*** is the weighting function amplitude (in dB) at frequency f (in kHz).
- f_1 represents LF transition value (in kHz), i.e. the lower frequency at which the function amplitude begins to change from the flat, central portion of the curve.
- f_2 represents HF transition value (in kHz), i.e. the upper frequency at which the function amplitude begins to change from the flat, central portion of the curve.
- ***a*** represents the LF exponent value (dimensionless) which defines the rate of decline of the weighting function amplitude at low frequencies. The change in weighting function amplitude with frequency at low frequencies (the LF slope) is 20*a* dB/decade.
- ***b*** represents the HF exponent value (dimensionless) which defines the rate of decline of weighting function amplitude at high frequencies, becoming linear with the logarithm of frequency. The change in weighting function amplitude with frequency at high frequencies (the HF slope) is -20*b* dB/decade.
- ***C*** is the constant that defines the vertical position of the curve. It is defined so that the maximum amplitude of the weighting function equals 0 dB (with all other values being negative).

Table 1 lists the auditory weighting parameters for the six hearing groups. The corresponding auditory weighting functions for all hearing groups are presented in Error! Reference source not found.**.**

Table 1 Parameters for the auditory weighting functions

Marine mammal hearing group	*a*	*b*	f_1 (Hz)	f_2 (Hz)	*C* (dB)
Low-frequency cetaceans (LF)	1.0	2	200	19,000	0.13
High-frequency cetaceans (HF)	1.6	2	8,800	110,000	1.20
Very high-frequency cetaceans (VHF)	1.8	2	12,000	140,000	1.36
Sirenians (SI)	1.8	2	4,300	25,000	2.62
Phocid carnivores in water (PCW)	1.0	2	1,900	30,000	0.75
Other marine carnivores in water (OCW)	2.0	2	940	25,000	0.64

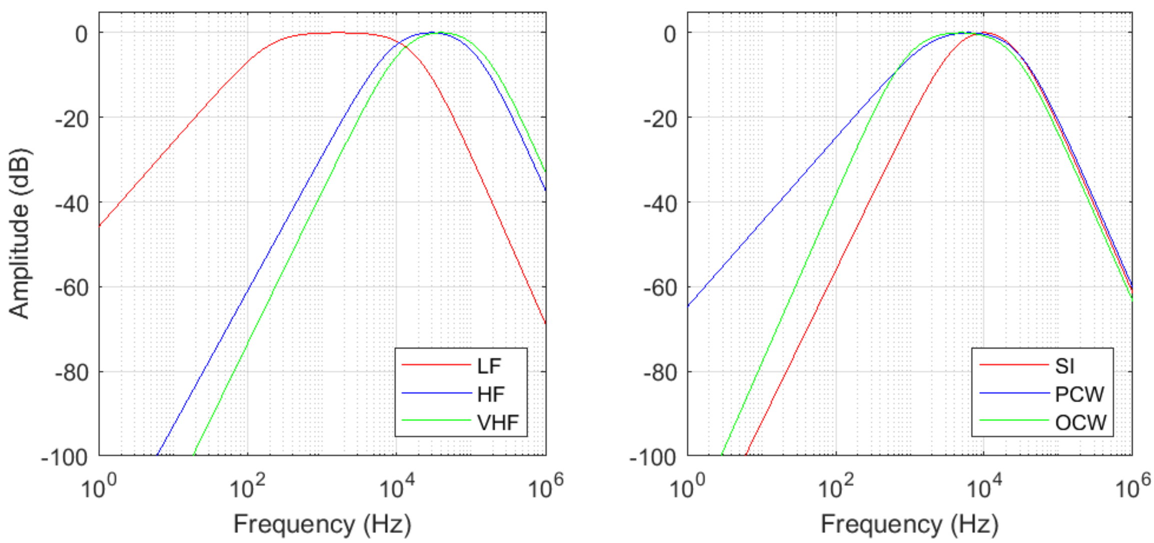


Figure 11 Auditory weighting functions - LF, HF, VHF, SI, PCW and OCW

4.2.2 Noise impact criteria for marine mammals

The newly updated scientific recommendations in marine mammal noise exposure criteria (Southall et al, 2019) propose PTS-onset and TTS-onset criteria for both impulsive noise and non-impulsive noise events. The PTS-onset and TTS-onset criteria for impulsive noise are outlined in **Table 2**, which incorporate a dual-criteria approach based on both peak sound pressure level (SPL) and cumulative sound exposure level (SEL) within a 24-hour period (SEL_{24hr}). The PTS-onset and TTS-onset criteria for non-impulsive noise as outlined in **Table 3** are based on cumulative SEL within a 24-hour period (SEL_{24hr}) only.

Table 2 PTS- and TTS-onset threshold levels for marine mammals exposed to impulsive noise

Marine mammal hearing group	PTS and TTS threshold levels – impulsive noise			
	Injury (PTS) onset		TTS onset	
	Pk SPL, dB re 1µPa (unweighted)	SEL_{24hr}, dB re 1µPa²·S (weighted)	Pk SPL, dB re 1µPa (unweighted)	SEL_{24hr}, dB re 1µPa²·S (weighted)
Low-frequency cetaceans (LF)	219	183	213	168
High-frequency cetaceans (HF)	**230**	**185**	**224**	**170**
Very high-frequency cetaceans (VHF)	202	155	196	140
Sirenians (SI)	226	190	220	175
Phocid carnivores in water (PCW)	218	185	212	170
Other marine carnivores in water (OCW)	232	203	226	188

Table 3 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 1µPa²·S (weighted)	SEL_{24hr}, dB re 1µPa²·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

For behavioural changes, the widely used assessment criterion for the onset of possible behavioural disruption in marine mammals is root-mean-square (RMS) SPL of 160 dB re 1µPa for impulsive noise and 120 dB re 1µPa or ambient level for non-impulsive noise (NMFS, 2013), as shown in **Table 4.**

Table 4 The behavioural disruption threshold level for marine mammals – impulsive and non-impulsive noise

Marine mammal hearing group	Behavioural disruption threshold levels, RMS SPL, dB re 1µPa	
	impulsive noise	non-impulsive noise
All hearing groups	160	120 / ambient level

4.2.3 Indo-Pacific bottlenose dolphin species

The Swan-Canning River system is home to a small resident community of Indo-Pacific bottlenose dolphins (*Tursiops aduncus*), plus juveniles and calves (Chabanne et al., 2012; SRT, 2015). The spatial and temporal patterns of dolphins occurrence within the river has shown that animals are distributed heterogeneously, with the Fremantle Inner Harbor area being identified as a seasonal 'hotspot' strongly lined with dolphin foraging behavior (Moiler, 2008; Marley et al, 2017).

The auditory sensitivities of bottlenose dolphins are greatest at very high frequencies (15 – 130 kHz), where the hearing threshold is in the range 40 – 80 dB, as demonstrated in **Figure 12** below. Hearing is progressively less sensitive as the frequency decreases, failing to approximately 130 dB for 100 Hz sounds (Johnson, 1967). In general, bottlenose dolphins' hearing threshold curve is aversely in line with the auditory weighting function for High-frequency (HF) cetacean hearing group as shown in **Figure 11**.

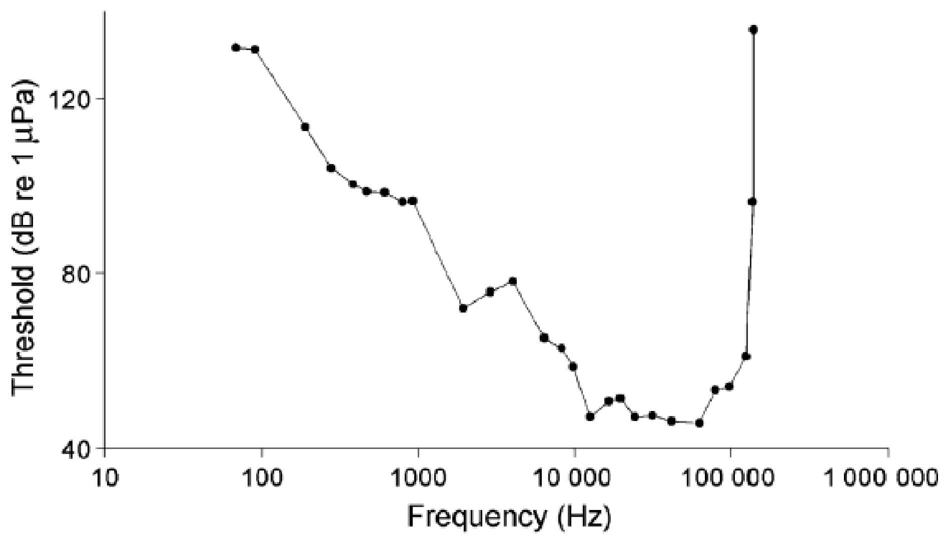


Figure 12 Hearing thresholds of a bottlenose dolphin (Johnson, 1967)

There have been limited research into detailed noise impact on Indo-Pacific bottlenose dolphin species (Southall et al, 2019). Their likely sensitivity to pile-driving and vessel traffic noise have been investigated previously (David, 2006; Marley et al, 2017), on the basis of potential noise effects on movements, behaviour and vocalizations of the species, rather than the more severe physiological effects. As such, the assessment criteria for Indo-Pacific bottlenose dolphin species are based on those criteria for HF cetaceans as outlined in **Section 4.2.2** above.

4.3 Fish and sea turtles

In general, limited scientific data are available 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, the U.S. National Oceanic and Atmospheric Administration (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 sound sources relevant to the project including impulsive noise from pile driving and non-impulsive noise from marine vessels and other sources are presented in **Table 5** and **Table 6** respectively.

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 considered to be in the tens of meters from the source, "intermediate" in the hundreds of meters, and "far" in the thousands of meters. 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 general 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 of pile driving) 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.

Table 5 Sound exposure criteria applicable for pile driving – 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)	>219 dB SEL_{cum}, or >213 dB Pk SPL	>216 dB SEL_{cum} or >213 dB Pk SPL	>>186 dB SEL_{cum}	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing (particle motion detection)	210 dB SEL_{cum} or >207 dB Pk SPL	203 dB SEL_{cum} or >207 dB Pk SPL	>>186 dB SEL_{cum}	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing (primarily pressure detection)	207 dB SEL_{cum} or >207 dB Pk SPL	203 dB SEL_{cum} or >207 dB Pk SPL	186 dB SEL_{cum}	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate

Type of animal	Mortality and potential mortal injury	Impairment			Behaviour
		Recovery injury	**TTS**	**Masking**	
Sea turtles	210 dB SEL_{cum} or >207 dB Pk SPL	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	(N) High (I) Moderate	(N) High (I) Moderate (F) Low
Fish eggs and fish larvae	>210 dB SEL_{cum} or >207 dB Pk SPL	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low	(N) Moderate (I) Low (F) Low

Notes: peak sound pressure levels (Pk SPL) dB re 1 µPa; Cumulative sound exposure level (SEL_{cum}) dB re 1 µPa^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 6 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 rms for 48h	158 dB rms for 48h	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Sea turtles	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) High (I) Moderate (F) Low
Fish eggs and fish larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) High	(N) Moderate (I) Moderate (F) Low

Notes: rms sound pressure levels (RMS SPL) dB re 1 µPa. 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).

4.4 Human divers/swimmers

Hearing underwater differs from hearing in air as the acoustic properties of water and air are different. Human hearing underwater, with a 'wet' ear (i.e. where the external ear canal is filled with water, and water is in direct contact with the tympanic membrane), is less sensitive than it is in air, and so noise underwater is believed to produce less hearing damage than airborne noise. The comparison between hearing threshold levels for humans in the air and underwater (Parvin, 1998) is illustrated in **Figure 13**. As can be seen in the figure, the hood and face mask for recreational divers further increase the hearing threshold levels.

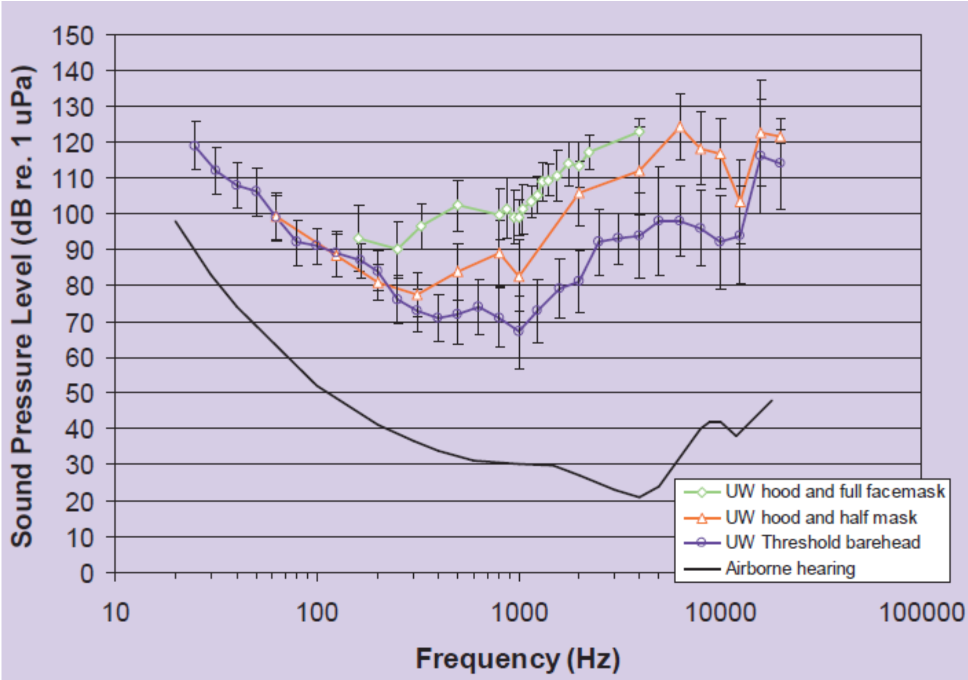


Figure 13 Hearing threshold levels for humans in the air and under water (Parvin, 1998).

A number of studies on the human diver exposure to underwater sound has been carried out, and relevant safety thresholds for both military and commercial/recreational divers under various frequency range have been proposed (Ainslie, 2008; Pestorius et al, 2009).

For low frequency range, a study with the Low Frequency Active (LFA) sonar as the nose source (Pestorius et al, 2009) shows that underwater noise with dominant energy component within frequency range 100 – 500 Hz would not have an adverse effect on human divers at levels less than 145 dB re 1 µPa rms over certain exposure settings (i.e. maximum continuous exposure of 100 seconds or with a maximum duty cycle of 20% and a maximum daily cumulative total of 3 hrs).

For relatively high frequency range, a joint UK-US research published by Parvin et al (2002) reports that for sound in the frequency range 500-2500 Hz, advised threshold 'exposure level' for human divers of 155 dB re µPa rms for use in environmental impact assessment.

As such, the threshold levels for human divers and swimmers under both frequency ranges are summarised in **Table 7**, with the lower level of 145 dB re µPa rms to be used for assessment purpose based on a conservative consideration.

Table 7 Threshold levels for human divers and swimmers (Pestorius et al, 2009; Parvin et al, 2002)

Frequency range	SPL RMS (dB re 1 µPa rms)
100 – 500 Hz	145
500 – 2500 Hz	155

4.5 Zones of bioacoustics impact

The received noise levels within and around the project area can be predicted using known source levels in combination with models of sound propagation transmission loss between the source and the receiver locations. Zones of impact can be determined by comparison of the predicted received levels to the noise exposure criteria.

Predicted zones of impact define the environmental footprint of the noise generating activities and indicate the locations within which the activities may have an adverse impact on a marine fauna species, either behaviourally or physiologically. This information can be used to assess the risk (likelihood) of potential adverse noise impacts, by combining the acoustic zones of impact with ecological information such as habitat significance in the affected area.

5 Underwater Noise Modelling Predictions

5.1 Underwater noise generating activities and source levels

Based on project information as provided in **Section 2**, major noise-generating construction activities and their relevant noise sources are summarised in **Table 8** below. Source levels of these activities have been sourced from relevant literature.

Table 8 Major noise-generating construction activities and their relevant noise sources

Activity / Scenario	Major Equipment / Noise Source
Pile installations	Piling with impact hammer
Sediment excavation and vessel movements	Dredgers and supporting vessels

5.1.1 Construction piling

Impact piling noise associated with the project using hydraulic impact hammer is impulsive in character. The pile driver is expected to be a IHC S-90 Hydrohammer, with the maximum hammer energy of 40 KN·m (Parnum et al, 2015).

The source spectral curve (one-third octave spectra) for the proposed piling activities are based on reference piling signals from a 59 kN·m impact hammer (Duncan et al, 2010) which were averaged to account for hammer energy variability, with the overall SEL source level as 205 dB re 1 $\mu Pa^2 \cdot S$ (201 dB re 1 $\mu Pa^2 \cdot S$ for frequency range above 100 Hz).

A conversion factor of 31 dB between the source peak sound pressure levels (Pk SPL) and source SEL levels is assumed within 20m from the source, based on the previous assessment prediction results for the piling noise created by a hammer of the same size for port facility constructions (Hall, 2013), and a conversion factor of 24.5 dB beyond 20m from the source location, based on previous piling noise measurements within the Fremantle Harbour (Parnum et al, 2015).

Conversion factors of 15 dB applied between the source RMS SPLs and SEL levels within 200m from the source location, 10 dB between 200m – 500m and 5 dB beyond 500m from the source location, are derived from the historical measurements described in relevant literature and study report (Hastings and Popper, 2005; Parnum et al, 2015).

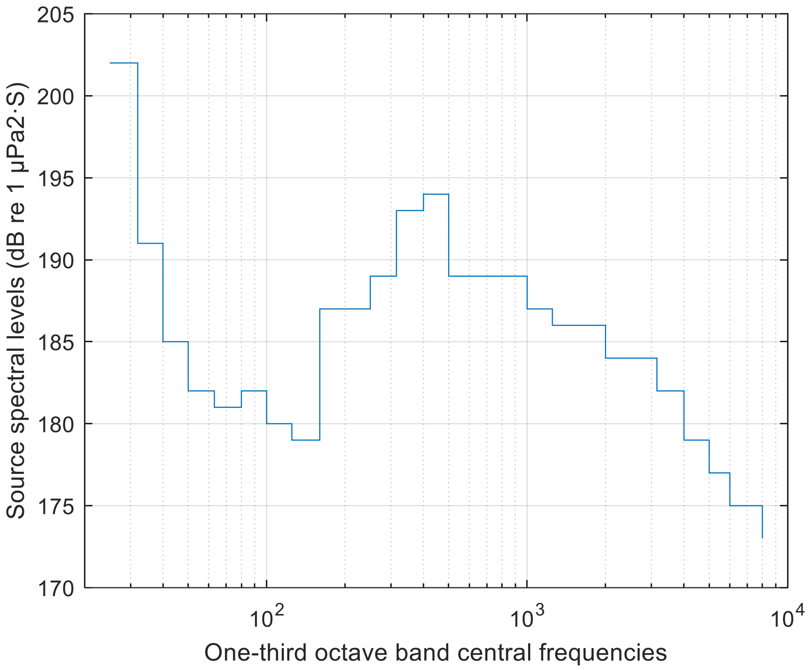


Figure 14 One-third octave SEL source spectral levels for the impact piling noise

5.1.2 Dredgers and supporting vessels

Both dredgers and supporting vessels have the source levels of up to 190 dB re 1µPa^2·S @ 1m under full-load conditions (Jones et al, 2016; Jimenez-Arranz et al, 2020). They generally have predominant low-frequency source energy components, and sporadic full-load operations which generally occur under full speed condition for vessels and hard sediment extraction for dredgers. Their noise emissions are much lower than the piling noise emissions and are comparable to the existing vessel traffic noise around the Fremantle Inner Harbour area. As such, their potential to cause significant adverse impact on the marine fauna species are expected to be low.

5.2 Modelling methodology and procedure

Underwater noise propagation models predict the sound transmission loss between the noise source and the receiver. When the source level (SL) of the assessed noise-generating activity is known, the predicted transmission loss (TL) is then used to predict the received level (RL) at the receiver location as:

$$RL = SL - TL \qquad (5.2.1)$$

The fluid parabolic equation (PE) modelling algorithm RAMGeo (Collins, 1993) is used to calculate the transmission loss between the source and the receiver. RAMGeo is an efficient and reliable PE algorithm for solving range-dependent acoustic problems with fluid seabed geoacoustic properties. The noise sources were assumed to be omnidirectional and modelled as point sources.

With the known noise source levels, either frequency weighted or unweighted, the received noise levels are calculated following the procedure outlined below.

- One-third octave source spectral levels are sourced via empirical reference data out of the historical measurements carried out on relevant noise sources in similar construction setting (as detailed in **Section 5.1**);

- Transmission loss is calculated using RAMGeo at one-third octave band central frequencies from 10 Hz to 8 kHz, based on appropriate source depths corresponding to relevant source scenarios. The acoustic energy of higher frequency range is significantly lower, and therefore is not included in the modelling calculation;
- Propagation paths for the TL calculation have a maximum range of up to 2.0 km and bearing angles with a 2-degree azimuth increment from 0 degrees to 358 degrees around the source locations. The bathymetry variation of the vertical plane along each modelling path is obtained via interpolation of the bathymetry dataset;
- The one-third octave source levels and transmission loss are combined to obtain the received levels as a function of range, depth and frequency; and
- The overall received levels are calculated by summing all frequency band spectral levels.

5.3 Modelling Input Parameters

5.3.1 Bathymetry

The bathymetry data used for the sound propagation modelling were based on publicly available bathymetric/hydrographic point survey datasets held within the Western Australian Department of Transport (DoT) Marine Bathymetry Data Portal for both Fremantle region and Swan Canning Estuary (DoT, 2021). The imagery of the combined datasets is displayed in **Figure 15**. The point survey datasets have been collected using a variety of methods (predominantly singlebeam acoustic point survey) and over a long historical period.

The two datasets were merged and reconstructed for the modelling inputs, with consideration of filling data gaps for the areas without survey data based on adjacent survey points of similar estuary conditions, as well as determining riverbank boundaries based on satellite images. The imagery of merged and reconstructed bathymetry dataset around the Swan River Crossing is shown in **Figure 16**.

Based on the Australian National Tide Tables (ANTT, 2021) and Admiralty Tide Tables Volume 4 (ATT, 2020), the Highest Astronomical Tide (HAT) for the area of Fremantle Port is around 1.40m, and the Mean Sea Level (MSL) is around 0.80m. As such, an adjustment of 0.60m is applied to the bathymetry dataset based on a conservative consideration.

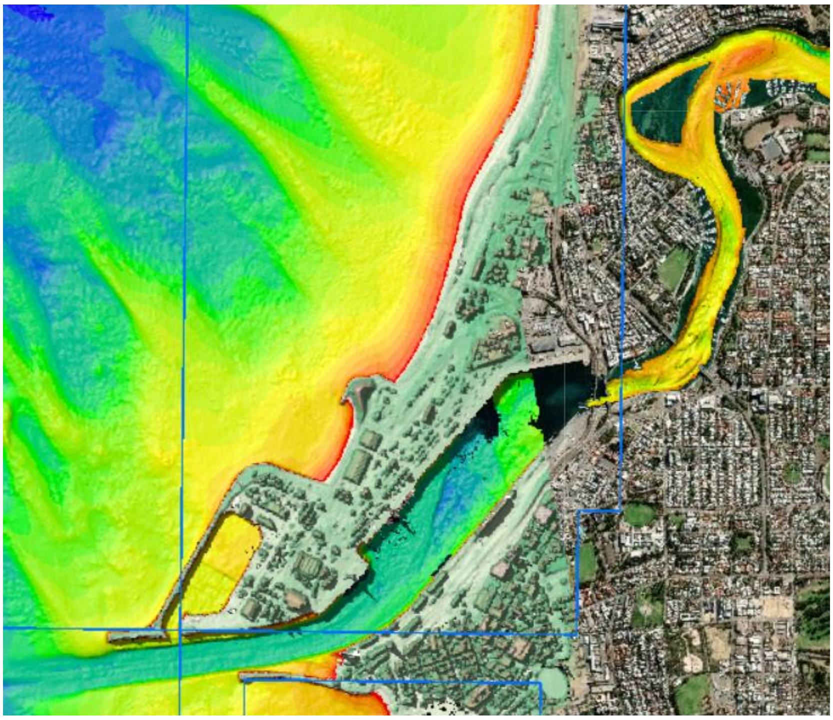


Figure 15 The imagery of the combined bathymetry datasets for both Fremantle Region and Swan Canning Estuary held by WA DoT Bathymetry Data Portal.

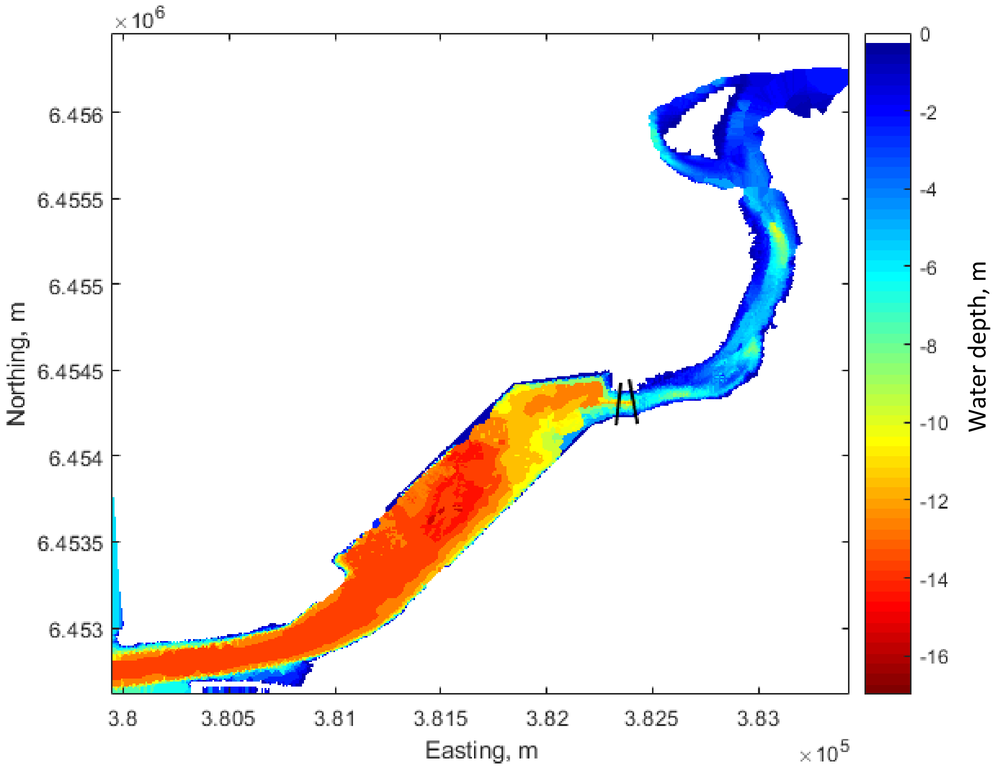


Figure 16 The imagery of merged and reconstructed bathymetry dataset around the project area.

5.3.2 Sound Speed Profiles

Temperature and salinity data required to derive the sound speed profiles were obtained from the Annual Swan Canning Estuarine Data Report (DWER, 2018). This data report is developed during the financial year 2017 – 2018 and presents data from June 2017 to May 2018 over background data generally from June 2012 to May 2017. The in-situ monitoring was conducted at multiple sites, and weekly sampling data were collected for the surface and bottom water at each monitoring site from June 2017 to May 2018, with monthly data values presented in **Figure 17** below.

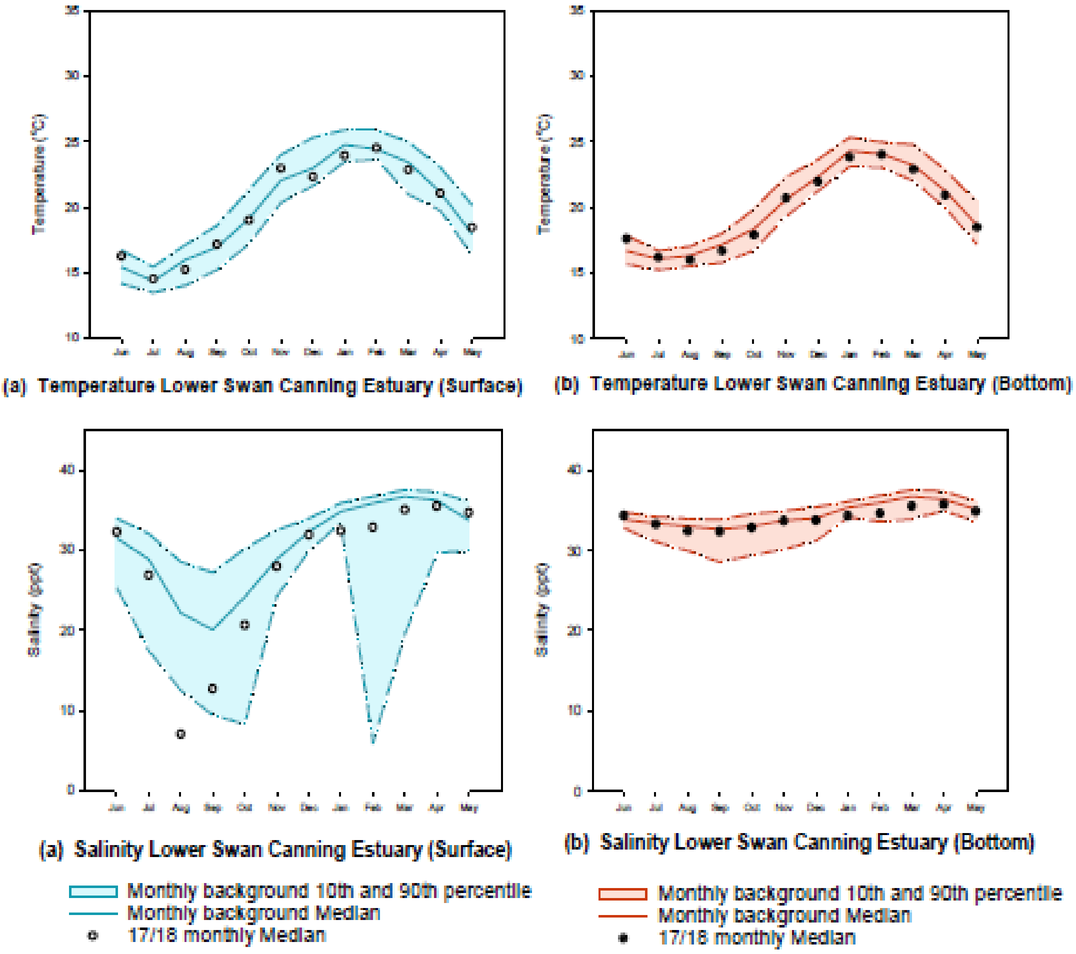


Figure 17 2017 – 2018 in situ temperature (*°C*) (top panels) and salinity (*ppt*) (bottom panels) in surface and bottom water, over background (June 2012 – May 2017) sampling data, in the Lower Swan Canning Estuary.

The sound speed profiles were derived based on an empirical function of the three independent variables (temperature (T) in degrees centigrade, salinity (S) in parts per thousand, and depth (z) in meters) (Medwin et al, 1997). Seasonal averages of the monthly median values of the sampling data collected over the monitoring sites within the Lower Swan Canning Estuary were used to derive the sound speed profiles.

Figure 18 presents the derived seasonal sound speed profiles within the Lower Swan Canning Estuary in close proximity to the project area. It can be seen that for Spring, Summer and Autumn seasons, the water column is relatively well mixed and sound speeds are relatively stable across the water depths. For Winter season, the surface water has low temperature and salinity compared with the bottom water, and the speed profile generally has relatively stronger upward refraction characteristics and is expected to be most favourable to propagation of sound from acoustic sources within the water column. As such, the winter season sound speed profile has been used for the sound propagation modelling in this study.

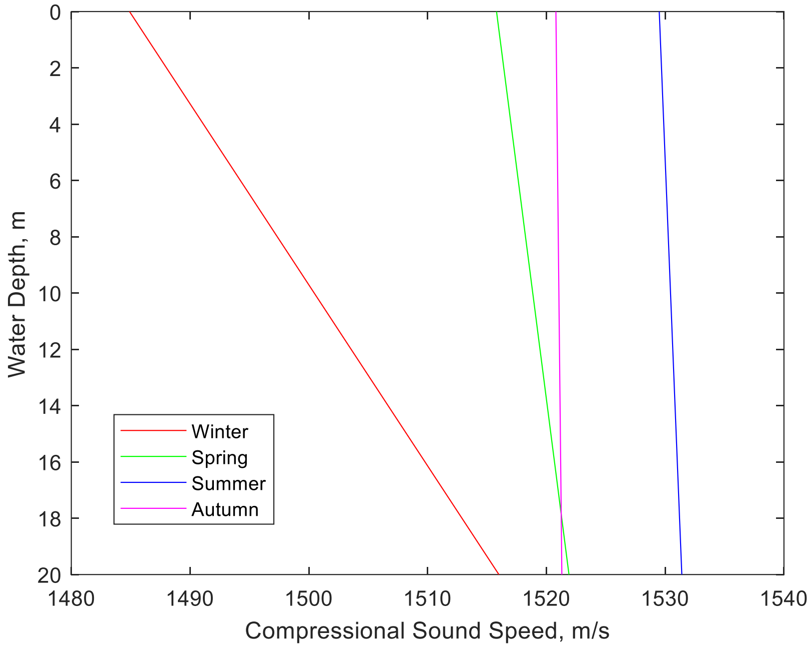


Figure 18 Sound speed profiles within the Lower Swan Canning Estuary for different southern atmosphere seasons

5.3.3 Seafloor Geoacoustic Model

The seafloor geoacoustic model for the modelling area is developed based on the sediment distribution assessment over the Swan River estuary (Quilty et al, 2006), as well as the regional geologic and geomorphic settings for the Perth region (McPerson et al, 2005; Davidson, 1995).

Sediment samples from 51 locations between the Narrow Bridge and Fremantle Harbour have been examined to assess the sediment distribution over the Swan River estuary (Quilty et al, 2006). The study revealed that the sediments over the estuary are dominantly clastic but include a significant biogenic content in certain areas. The distribution of the clastic component is controlled by water energy (and thus, secondarily, by depth). Fine-grained material (grey mud) is restricted to the basin and deeper, quieter channel setting. Sand is in the higher energy, shallow, floodplain and beach environments, including the estuary section between North Fremantle and Mosman Park.

A detailed review study on the geological settings and the geomorphic settings for the Perth region (Davidson, 1995) indicates that, along the coastal trip of the Perth region, the superficial formation is predominantly the Tamala Limestone as defined by Playford et al (1976). The Tamala Limestone contains various proportions of quartz sand, fine- to medium-grained shell fragments, and minor clayey lenses. Depending on the location, this formation has a maximum known thickness of 110 m in the Perth region. Its upper surface is exposed and leached to the extent that the upper part of the formation comprises unconsolidated limestone sand. This superficial formation is consistent with the site classification results based on the analysis of numerous geological borehole survey data within the central Perth region (Davidson, 1995).

Based on the above relevant studies on the top layer sediment distribution over the Swan River estuary, as well as the superficial geological formation over the Perth Basin, it is proposed that the seafloor geoacoustic model for the modelling area comprises of a 5.0-m sandy surface sediment layer, a 15-m slightly to semi-cemented sand/calcarenite layer, followed by a semi-cemented sand/calcarenite half space as detailed in **Table 9**. The geoacoustic properties for relevant sediments are as described in Hamilton (1980) and Jensen et al (2011).

Table 9 Geoacoustic parameters for the proposed seafloor model

Seafloor Materials	Thicknes s, m	Density, ρ, (kg.m^{-3})	Compressional Wave		Shear Wave	
			Speed, C_p, (m.s^{-1})	Attenuation, α_p, (dB/λ)	Speed, C_s, (m.s^{-1})	Attenuation, α_s, (dB/λ)
Unconsolidated sandy layer	5.0	1,800	1,750	0.80	0	0
Slightly to semi-cemented sand/calcarenite layer	15	1,900	2,100	0.12	550	0.25
Semi-cemented sand/calcarenite half space	∞	2,200	2,600	0.20	1,200	0.40

It is noted that the modelling algorithm (i.e. RAMGeo) proposed for this modelling study, as detailed in **Section 5.1.2**, is based on a fluid geo-acoustic model (all layers are modelled as fluid). Therefore, the geo-acoustic model inputs only consider the compressional wave parameters for the substrate layer materials as listed in **Table 9**, with the shear wave parameter values set as zeros.

The effect of representing a geo-acoustic model with elastic substrate layers as fluid substrates in the modelling has been investigated by examining the seafloor reflection coefficients for the two models (elastic and fluid). **Figure 19** shows the reflection coefficient variations with grazing angle and frequency for the two models, calculated using the plane-wave reflection coefficient program BOUNCE (Porter, 2020).

As can be seen from the figure, the sediment layer is thin compared with the incident wavelength at low frequencies (below 100Hz), resulting in the layer relatively more transparent to the incident wave. The reflection coefficient has an apparent critical angle slightly over 55 degrees. As frequency increases, the sediment layer gradually overtakes the substrate as being predominant in determining the reflection coefficient. The critical angle of the reflection coefficient is around 30 degrees for frequencies above 300Hz. The figure also reveals an evident angle-dependent resonance pattern, relating to the quarter and half-wavelength layer effects in the sediment layers. Apart from having similar features for the two panels within the figure, the left panel has more complex features at the low frequency range below 100Hz. The corresponding loss mechanisms relate to the presence of the shear characteristics in the substrate layers (Li and Hall, 2012).

As evident in **Figure 19**, the reflection coefficients of the two models are highly similar, with the fluid model has slightly higher reflection coefficients at low frequencies with low grazing angles. Therefore, it is considered to be slightly conservative to use the fluid seabed model with parameters described in **Table 9** for the modelling predictions.

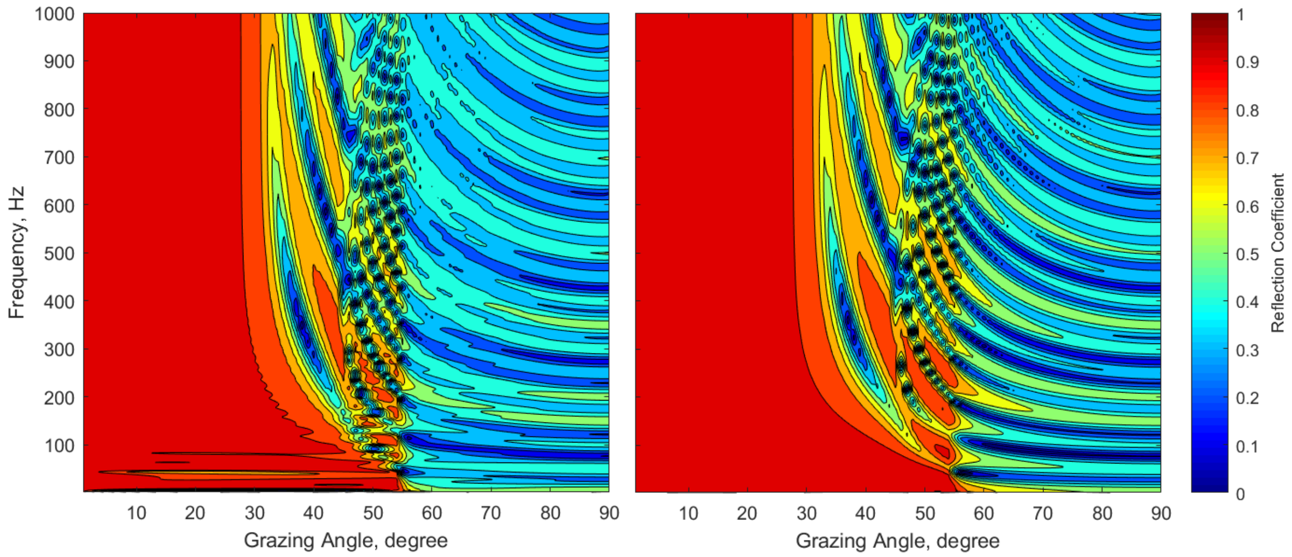


Figure 19 Reflection coefficient variations with grazing angle and frequency for the geo-acoustic model. Left panel - elastic substrate model; right panel - fluid substrate model

5.4 Modelling pling source locations

In order to understand the extent of underwater noise impacts from piling operations throughout the proposed project development, three source locations are nominated for the detailed noise modelling study. The three locations are selected to cover the spatial span of the bridge construction activities, as well as the propagation environment to the surrounding upstream and downstream river areas.

The three selected source locations are presented in **Figure 20**, and further detailed in **Table 10** below with their corresponding coordinates, water depths and localities.

Table 10 Details of the three selected piling source locations for noise modelling. The coordinate system is based on WGS84/UTM Zone 50S projection.

Piling Location	Water Depth, m	Coordinates, m [Easting, Northing]	Locality
L1	12.1	[3.82390 x 10^5, 6.45431 x 10^6]	North end of the construction site
L2	4.6	[3.82344 x 10^5, 6.45436 x 10^6]	Mid-point of the construction site
L3	5.6	[3.82420 x 10^5, 6.45427 x 10^6]	South end of the construction site

Figure 20 The selected three source locations (L1, L2 & L3) are indicated as yellow pins.

5.5 Modelling validation

The modelled outcomes have been compared with the previous piling noise measurement results (Parnum et al, 2015) for both upstream and downstream directions. It is found that the overall received noise levels for both modelling prediction and site measurements have similar attenuation trend against distances within 500 m from the source location. For distances beyond 500 m at the upstream direction, measured results have higher attenuation with distance, which could potentially attribute to stronger upslope water depth variation than the modelling bathymetric inputs.

6 Modelling Results and Zones of Impact Estimates

6.1 Modelling prediction results

The noise contour figures for all modelling scenarios are presented in **Appendix C**. The contour figures are the modelling results based on unweighted SEL source level inputs in dB re 1µPa^2·S as given in **Section 5.1**.

The weighted SEL modelling results for different marine mammal hearing groups are based on weighted SEL source level inputs which are derived by applying relevant auditory hearing functions as in **Figure 11** of **Section 4.2.1** to the unweighted SEL source levels.

For cumulative SEL estimates, the following cumulative factor (*CF*) is applied:

$$CF = 10 \times \log10 (N) \qquad (6.1)$$

Where *N* is the number of strikes for piling noise.

For non-impulsive noise, it is assumed the root-mean-square sound pressure levels (RMS SPLs) are equivalent to be the sound exposure levels (SELs) of 1-second duration.

Based on noise modelling prediction results and relevant post processing analysis as described above, the zones of impact for marine fauna species assessed from all modelling scenarios are detailed in the following section.

6.2 Estimated zones of impact

The predicted noise levels of considered piling modelling scenarios were compared with relevant threshold criteria as listed in **Section 4**. The zones of different levels of noise impact for marine mammals and fish and sea turtle species were calculated and all results are presented in **Table 11** to **Table 16**, including:

- Impact zones from impact piling as shown in **Table 11** to **Table 13** regarding immediate impact from single piling pulses;
- Impact zones from impact piling as shown in **Table 15** and **Table 16** regarding cumulative impact from multiple piling pulses exposure (i.e. under selected 100, 200, 1000, 1500, 3000 pulses exposure) within a 24-hour period.

In summary:

- For the mostly concerned Indo-Pacific bottlenose dolphins:
    - The immediate impact from the piling noise is unlikely to cause physiological effects and is predicted to have behavioural disturbance effects within 1.0 km from the piling locations.
    - The cumulative impacts from piling noise are predicted to have increasing zones of PTS and TTS effects with piling strikes. A cumulative exposure from up to 3,000 piling pulses within a 24-hour period is predicted to cause PTS effect within 100 m and TTS effect within 1.0 km from the piling locations.
- For fish species:
    - The immediate impact from the piling noise is predicted to have physiological effects within 20 m from the piling locations.

    - The cumulative impacts from piling noise are predicted to have increasing zones of PTS and TTS effects with piling strikes. A cumulative exposure from up to 3,000 piling pulses within a 24-hour period is predicted to cause recoverable injury up to 250 m and TTS effect beyond 1.5 km from the piling locations.
- For human divers and swimmers:
    - The immediate impact from the piling noise is predicted to have adverse hearing effects up to 1.5 km from the piling locations.

The following sub-sections detail the zones of impact estimated for all generic marine mammals, fish and sea turtle species, and human divers and swimmers.

6.2.1 Zones of impact from impact piling

Based on zones of impact estimated Pk-SPL metric criteria as in **Table 11**, marine mammals of all hearing groups except VHF cetaceans are predicted to experience PTS effect within 10 m from the piling locations. The maximum zones of PTS effect for VHF cetaceans are predicted to be within 40 m from the piling locations.

The zones of TTS effect due to a single pulse exposure for marine mammals of all hearing groups except VHF cetaceans are predicted to be within 10 m from the piling locations. The maximum zones of TTS effect for VHF cetaceans are predicted to within 100 m from the piling locations.

As presented in **Table 12**, the zones of potential injuries for fish species with swim bladders, turtles and fish eggs and fish larvae are predicted to be within 20 m from the piling locations. Fish species without swim bladders have slightly higher injury impact thresholds, and therefore have smaller zones of potential injuries within 10 m from the piling locations.

Table 11 Zones of immediate impact from single impact piling pulses for PTS and TTS – marine mammals

Marine mammal hearing group	Zones of impact – maximum horizontal distances from source to impact threshold levels			
	Injury (PTS) onset		TTS onset	
	Criteria - Pk SPL dB re 1µPa	Maximum threshold distance, m	Criteria - Pk SPL dB re 1µPa	Maximum threshold distance, m
Low-frequency cetaceans (LF)	219	< 10	213	10
High-frequency cetaceans (HF)	**230**	**< 10**	**224**	**< 10**
Very high-frequency cetaceans (VHF)	202	40	196	100
Sirenians (SI)	226	< 10	220	< 10
Phocid carnivores in water (PCW)	218	< 10	212	10
Other marine carnivores in water (OCW)	232	-	226	< 10

Table 12 Zones of immediate impact from single impact piling pulses for mortality and recovery injury– fish, turtles, fish eggs and fish larvae

Type of animal	Zones of impact – maximum horizontal distances from source to impact threshold levels			
	Mortality and potential mortal injury		**Recovery injury**	
	Criteria - Pk SPL dB re 1µPa	Maximum threshold distance, m	Criteria - Pk SPL dB re 1µPa	Maximum threshold distance, m
Fish: no swim bladder (particle motion detection)	213	10	213	10
Fish: swim bladder is not involved in hearing (particle motion detection)	207	20	207	20
Fish: swim bladder involved in hearing (primarily pressure detection)	207	20	207	20
Sea turtles	207	20	-	-
Fish eggs and fish larvae	207	20	-	-

Note: a dash indicates the threshold is not applicable.

The zones of behavioural disturbance for marine mammals of all hearing groups caused by the immediate exposure to individual pulses are predicted to be within 1.0 km from the piling locations, as presented in **Table 13**. The zones of adverse hearing impact for human divers and swimmers caused by the immediate exposure to individual pulses are predicted to be up to 1.5 km from the piling locations, as presented in **Table 14**.

Table 13 Zones of immediate impact from single impact piling pulses for behavioural changes – marine mammals

Type of animal	**Zones of impact – maximum horizontal distances from source to impact threshold levels**	
	Behavioural disturbance	
	Criteria - RMS SPL, dB re 1µPa	Maximum threshold distance, m
Marine mammals – all hearing groups	160	1,000

Table 14 Zones of immediate impact from single impact piling pulses for human divers and swimmers

Receivers	**Zones of impact – maximum horizontal distances from source to impact threshold levels**	
	Criteria - RMS SPL, dB re 1µPa	Maximum threshold distance, m
Human divers and swimmers	145	Upstream – 800 Downstream – 1, 500

Among marine mammals of all six hearing groups, LF and VHF cetaceans have the highest zones of PTS and TTS impact, as can be seen in **Table 15**. The zones of PTS impact are predicted to be within 400 m from piling locations with 100 piling pulses exposure and within 1.5 km from piling locations with 1,000 piling pulses exposure. Compared with LF and VHF cetaceans, the remaining hearing group cetaceans have much lower impact zones.

For cetaceans of all hearing groups, the zones of TTS impact are significantly higher than the corresponding PTS impact due to the much lower TTS threshold level (by at least 15 dB).

Table 15 Zones of cumulative impact from multiple impact piling pulses for PTS and TTS – marine mammals – 100, 200, 1000, 1500, 3000 pulses exposure

Marine mammal hearing group	Zones of impact – maximum horizontal distances from source to impact threshold levels			
	Injury (PTS) onset		TTS onset	
	Criteria - Weighted SEL_{24hr} dB re 1 $\mu Pa^2 \cdot s$	Maximum threshold distance, m	Criteria - Weighted SEL_{24hr} dB re 1 $\mu Pa^2 \cdot s$	Maximum threshold distance, m
Low-frequency cetaceans (LF)	183	100 pulses: 400 200 pulses: 800 1,000 pulses: 1,500 1,500 pulses: > 1,500 **3,000 pulses: > 1,500**	168	100 pulses: > 1,500 200 pulses: > 1,500 1,000 pulses: > 1,500 1,500 pulses: > 1,500 **3,000 pulses:** > 1,500
High-frequency cetaceans (HF)	**185**	**100 pulses: < 10** **200 pulses: 10** **1,000 pulses: 60** **1,500 pulses: 80** **3,000 pulses: 100**	**170**	**100 pulses: 100** **200 pulses: 150** **1,000 pulses: 500** **1,500 pulses: 800** **3,000 pulses: 1,000**
Very high-frequency cetaceans (VHF)	155	100 pulses: 400 200 pulses: 800 1,000 pulses: 1,500 1,500 pulses: > 1,500 3,000 pulses: > 1,500	140	100 pulses: > 1,500 200 pulses: > 1,500 1,000 pulses: > 1,500 1,500 pulses: > 1,500 3,000 pulses: > 1,500
Sirenians (SI)	203	100 pulses: < 10 200 pulses: < 10 1,000 pulses: < 10 1,500 pulses: < 10 **3,000 pulses: 10**	175	100 pulses: 100 200 pulses: 200 1,000 pulses: 800 1,500 pulses: 1,000 **3,000 pulses: 1,500**
Phocid carnivores in water (PCW)	185	100 pulses: 100 200 pulses: 150 1,000 pulses: 600 1,500 pulses: 800 **3,000 pulses: 1,500**	170	100 pulses: 1,500 200 pulses: > 1,500 1,000 pulses: > 1,500 1,500 pulses: > 1,500 **3,000 pulses: > 1,500**

Marine mammal hearing group	Zones of impact – maximum horizontal distances from source to impact threshold levels			
	Injury (PTS) onset		TTS onset	
	Criteria - Weighted SEL_{24hr} dB re 1 µPa²·s	Maximum threshold distance, m	Criteria - Weighted SEL_{24hr} dB re 1 µPa²·s	Maximum threshold distance, m
Other marine carnivores in water (OCW)	203	100 pulses: < 10 200 pulses: < 10 1,000 pulses: 20 1,500 pulses: 30 **3,000 pulses: 80**	188	100 pulses: 80 200 pulses: 100 1,000 pulses: 300 1,500 pulses: 500 **3,000 pulses: 800**

As presented in **Table 16**, within an example of 1,000 piling pulses exposure, the zones of potential mortal injury for fish species with swim bladder are predicted to be within 10 m from the piling locations, and within 40 m for fish without swim bladder, sea turtles and fish eggs and fish larvae. For recoverable injury, the zones of impact are predicted to be within 10 m from the piling locations for fish without swim bladder, and within 100 m for fish with swim bladder. The zones of TTS effect for fish species with and without swim bladders are predicted to be within 1.5 km from the piling locations for the exposure scenario considered.

Table 16 Zones of cumulative impact from multiple impact piling pulses for mortality and recovery injury– fish, turtles, fish eggs and fish larvae

<table>
<tr><th rowspan="3">Type of animal</th><th colspan="6">Zones of impact – maximum horizontal perpendicular distances
from source to cumulative impact threshold levels</th></tr>
<tr><th colspan="2">Mortality and
potential mortal injury</th><th colspan="2">Recoverable injury</th><th colspan="2">TTS</th></tr>
<tr><th>Criteria - SEL_{24hr}
dB re 1 µPa²·s</th><th>Maximum threshold distance, m</th><th>Criteria - SEL_{24hr}
dB re 1 µPa²·s</th><th>Maximum threshold distance, m</th><th>Criteria - SEL_{24hr}
dB re 1 µPa²·s</th><th>Maximum threshold distance, m</th></tr>
<tr><td>Fish: no swim bladder (particle motion detection)</td><td>219</td><td>100 pulses: < 10
200 pulses: < 10
1,000 pulses: < 10
1,500 pulses: < 10
3,000 pulses: 10</td><td>216</td><td>100 pulses: < 10
200 pulses: < 10
1,000 pulses: < 10
1,500 pulses: 10
3,000 pulses: 20</td><td>186</td><td rowspan="3">100 pulses: 300
200 pulses: 600
1,000 pulses: 1,000
1,500 pulses: 1,500
3,000 pulses: > 1,500</td></tr>
<tr><td>Fish: swim bladder is not involved in hearing (particle motion detection)</td><td>210</td><td>100 pulses: <10
200 pulses: <10
1,000 pulses: 20
1,500 pulses: 40
3,000 pulses: 80</td><td>203</td><td rowspan="2">100 pulses: 10
200 pulses: 20
1,000 pulses: 100
1,500 pulses: 150
3,000 pulses: 250</td><td>186</td></tr>
<tr><td>Fish: swim bladder involved in hearing (primarily pressure detection)</td><td>207</td><td>100 pulses: < 10
200 pulses: 10
1,000 pulses: 40
1,500 pulses: 80
3,000 pulses: 120</td><td>203</td><td>186</td></tr>
<tr><td>Sea turtles</td><td>210</td><td rowspan="2">100 pulses: < 10
200 pulses: < 10
1,000 pulses: 20
1,500 pulses: 40
3,000 pulses: 80</td><td>-</td><td rowspan="2">-</td><td>-</td><td rowspan="2">-</td></tr>
<tr><td>Fish eggs and fish larvae</td><td>210</td><td>-</td><td>-</td></tr>
</table>

Note: a dash indicates the threshold is not applicable.

7 Aquatic Noise Management Plan

7.1 Impact piling operation as the major noise source emissions

The impact piling operation during the new rail bridge construction has the highest noise emissions with impulsive characteristics, and therefore is predicted to have the highest potential for adverse impact on assessed marine fauna species and human divers and swimmers, in terms of both immediate impact and cumulative impact. As such, it is the major focus for this aquatic noise management plan.

Marine mammals, particularly the Indo-Pacific bottlenose dolphins, and human divers and swimmers are the major sensitive receptors to consider for this management plan. Biologically important areas within the Swan River region as part of the Swan Estuary Marine Park [4] are all not adjacent to the project area. Therefore, impact piling operations are no expected to result in significant impacts on key fish species that are biologically important for the Swan River region.

Other noise-generating construction activities, such as sediment excavation and supporting vessels, have much lower noise emissions and their characteristics are continuous in nature. Moreover, the noise emissions from supporting vessel activities under the full-load operation conditions generally occur under their full travel speeds which are not expected to take place curing construction. The emission levels from vessel operations are expected to be comparable to noise emissions from the existing vessel traffic along the project area. As such, the extent of potential impact from vessel operations are not significant compared with the impact piling operations.

7.2 Piling noise management framework

The Government of South Australia's *Underwater Piling Noise Guidelines* (2012) sets out guidance on procedures for piling noise mitigation as illustrated in **Figure 21** below.

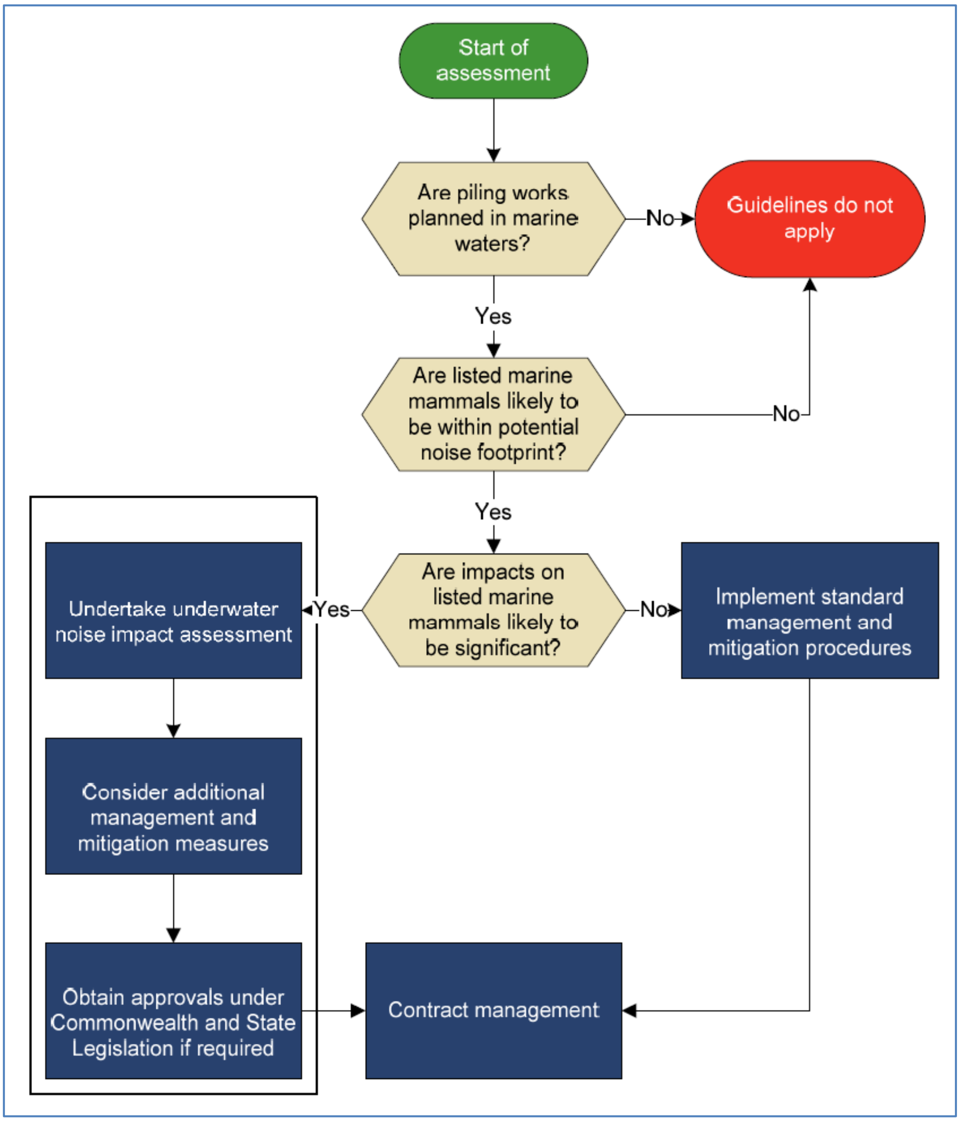
The guideline includes a framework for management and mitigation of underwater noise from piling, incorporating:

- **Safety zones** – these are observation and shut-down zones sized based on the likely noise levels produced by the piling activity.
- **Standard management and mitigation procedures** – these procedures are recommended for all piling activities, irrespective of location and time of year, when marine mammal species or human divers/swimmers may potentially be present within the noise footprint of the piling activity.
- **Additional management and mitigation procedures** – to be used when the impacts of the piling activity on concerned marine mammal species or human divers/swimmers are likely to be significant and standard management and mitigation procedures are not sufficient to minimise the impact.

This management plan follows the management framework as outlined above, with project specific requirements for each framework element being detailed in the following subsections.

[4] http://www.fish.wa.gov.au/Sustainability-and-Environment/Aquatic-Biodiversity/Marine-Protected-Areas/Pages/Recreational-fishing-in-Swan-Estuary-Marine-Park.aspx

Figure 21 Piling noise management and mitigation framework (Government of South Australia, 2012)



7.2.1 Safety Zones

Two safety zones would be applied around each piling location:

- **An observation zone**, within which the movement of marine mammals or human divers/swimmers would be monitored to identify any approach to the shut-down zone.
- **A shut-down zone**, within which the sighting of a marine mammal or human divers/swimmers would trigger piling activities to be ceased as soon as reasonably practical.

The proposed observation zones and shut-down zones are outlined in **Table 17** below. It should be particularly noted that the shut-down zones for Indo-Pacific bottlenose dolphins are based on potential cumulative TTS impact, which is dependent on number of piling strikes and animal movements over the assessment period. Based on a precautionary measure, it is recommended to implement a shut-down zone of 500 m, which is equivalent to a cumulative TTS impact zone under 1,000 piling strikes within 24 hours period.

Table 17 Proposed observation zones and shutdown zones

Sensitive Receptor	Observation Zone **radius, m**	Shutdown Zone **radius, m**	Rationales and Actions
Indo-Pacific bottlenose dolphins	1,000 – downstream 800 - upstream	100 m - 500 m	• Observation zones to be consistent with behavioural response zone estimate. • Shutdown zones upon cumulative TTS impact which depends on number of piling strikes within 24 hours period and animal movements.
Human divers / swimmers	1,500 – downstream 800 - upstream		• Zones cover the reaches of sight upstream and downstream. • Areas within the zones to be cleared for diving and swimming during the piling operation.

7.2.2 Standard management and mitigation measures

In addition to the proposed safety zones, the following management and mitigation measures are to be implemented:

- Contract documentation – include these requirements for piling noise management and mitigation measures in the contract documentation.
- Trained crew – ensure a suitably qualified person is available during piling to conduct the recommended standard operational procedures to manage noise impacts.
- Standard operational procedures – standard operating procedures undertaken by contractors during piling activities include pre-start, soft start, normal operation, stand-by operation, and shut-down procedures, as follows and as shown in **Figure 22**.
    - Pre-start monitoring – the presence of marine mammals or human divers/swimmers will be visually monitored by a suitably trained crew member (i.e. qualified marine mammal observer (MMO)) for at least 30 minutes before piling commences using a soft start procedure.
    - Soft start – if marine mammals or human divers/swimmers have not been observed inside the shut-down zone during the pre-start observations, soft start (6 strikes/min at low impact energy) may commence with piling impact energy gradually increased over a 10-minute time period. A soft start will also be used after long breaks of more than 30 minutes in piling activity.
    - Normal piling – if marine mammals or human divers/swimmers have not been observed inside the shut-down or observation zones during the soft start, piling at full impact energy may commence. Visual observations will continue throughout piling activities.
    - Stand-by – if marine mammals or human divers/swimmers are sighted within the observation zone during the soft start or normal operation piling, the operator of the piling rig will be placed on stand-by to shut down the piling rig, while visual monitoring of the animal or divers/swimmers continues.
    - Shut-down – if a marine mammal or human divers/swimmers is sighted within or are about to enter the shut-down zone, piling activity should be stopped immediately. If the animal is observed to move outside the zone again, or 30 minutes have elapsed with no further sightings, piling activities will recommence with the soft start procedure. If a marine mammal or human divers/swimmers is detected in the shut-down zone during a period of poor visibility, operations will stop until visibility improves.

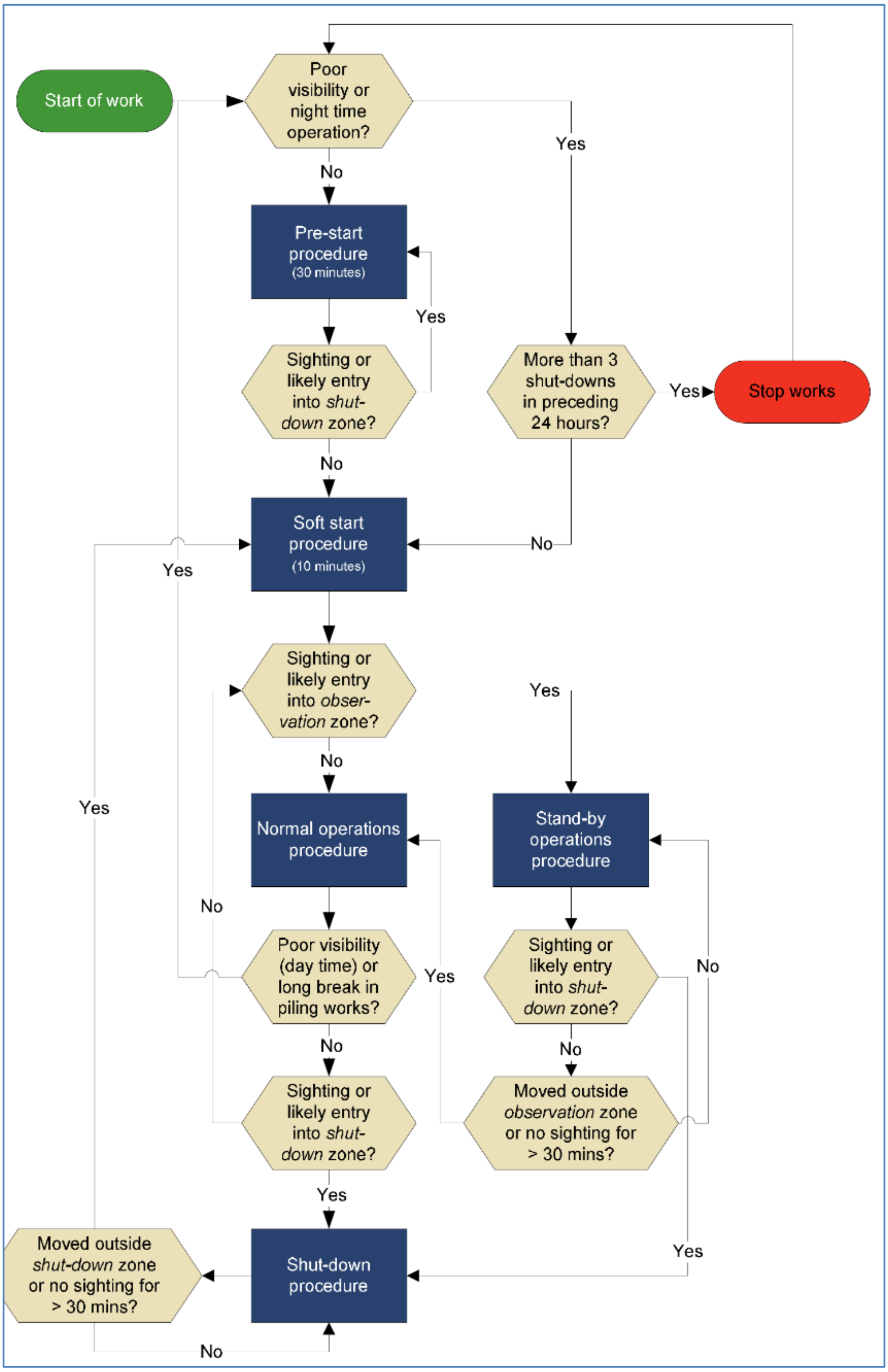
- Compliance and sighting report – maintenance of a record of procedures employed during piling, including information on any marine mammals or human divers/swimmers sighted, and their reaction to the piling activity. A report will include the location, date, start and completion time, information on the piling rig (hammer weight and drop height), pile size, number of piles, number of impacts per pile, details of the trained crew members (i.e. MMOs) conducting the visual observations, times when observations were hampered by poor visibility or high winds, times when start-up delays or shut-down procedures occurred, and the time and distance of any marine mammal or human divers/swimmers sightings.

7.2.3 Additional mitigation measures

The following additional mitigation measures could be considered to further minimise noise impact on marine mammals. However, the practicality of implementing these measures needs to be investigated, and the actual effectiveness to be validated via site acoustic testing.

- Lower piling duration/piling strike number per day. Lower number of piling strikes for impact piling within a 24-hour period results in lower cumulative SELs, and therefore has smaller impact extent.
- Use of piling noise attenuation measures. Various attenuation measures have been developed to attenuate underwater piling noise to minimise exposure of marine mammals during piling activities (Caltrans, 2009; Jimenez-Arranz et al, 2020). These measures include but not limited to the following:
    - **Isolation casings/pile sleeves**. Isolation casings are hollow casing slightly larger in diameter than the pile to be driven. The casing is inserted into the water column and bottom substrate, and then dewatered so that the work area could be isolated from the surrounding water column in order to attenuate the sound propagation. Dewatered isolation casings generally can be expected to provide attenuation 10 dB or above. However, it could be challenging to integrate the placement and removal of the pile sleeve into the piling driving operation.
    - **Cushion blocks/pile cap**. Cushion blocks consist of blocks of material atop a pile during piling to minimise the noise generated during impact hammering. Materials typically used for cushion blocks include wood, nylon and micarta blocks. The resulted noise reduction could be from close to 10 dB to over 20 dB. The cushion blocks will results in loss of peak force during the piling operation, and this may strongly affect the piling effectiveness (or the piling may even fail) at this location with hard geological conditions.
    - **Air bubble curtains**. Air bubble curtains are designed to infuse the water column surrounding the pile with air bubbles, generating a bubble screen that attenuate the sound propagation from the pile. The previous experiment data indicates that an air bubble curtain will provide up to 10 dB of noise reduction for a mid-sized steel pile. It should be noted however, due to the strong tidal conditions at the project location, the effectiveness of the bubble curtain could be significantly compromised.

Figure 22 Impact piling noise management procedures (Government of South Australia, 2012)



8 Conclusions

SLR has been appointed by MRWA to undertake aquatic noise modelling and assessment of relevant potential impacts on marine fauna species and human divers/swimmers as a result of the construction activities of the proposed Swan River Crossings Project.

Detailed modelling predictions have been undertaken for noise emissions from the impact piling operations, the most dominant noise-generating activities during the bridge construction. Various zones of impact have been estimated for marine fauna species and human divers/swimmers based on comparisons between predicted noise levels and impact assessment criteria with results.

An aquatic noise management plan has been developed, with project specific management and monitoring procedure requirements provided in order to minimise the piling noise impact on assessed aquatic sensitive receptors.

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APPENDIX A

Acoustic Terminology

Sound Pressure	A deviation from the ambient hydrostatic pressure caused by a sound wave
Sound Pressure Level (SPL)	The logarithmic ratio of sound pressure to the reference pressure. The reference pressure underwater is P_{ref} = 1 µPa
Root-Mean-Square Sound Pressure Level (RMS SPL)	The mean-square sound pressure is the average of the squared pressure over the pulse duration. The root-mean-square sound pressure level is the logarithmic ratio of the root of the mean-square pressure to the reference pressure. Pulse duration is taken as the duration between the 5% and the 95% points on the cumulative energy curve
Peak Sound Pressure Level (Pk SPL)	The peak sound pressure level is the logarithmic ratio of the peak pressure over the impulsive signal event to the reference pressure
Peak-to-Peak Sound Pressure Level (Pk-Pk SPL)	The peak-to-peak sound pressure level is the logarithmic ratio of the difference between the maximum and minimum pressure over the impulsive signal event to the reference pressure
Sound Exposure Level (SEL)	SEL is a measure of energy. Specifically, it is the dB level of the time integral of the squared instantaneous sound pressure normalised to a 1-s period
Power Spectral Density (PSD)	PSD describes how the power of a signal is distributed with frequency
Source Level (SL)	The acoustic source level is the level referenced to a distance of 1m from a point source
1/3 Octave Band Levels	The energy of a sound split into a series of adjacent frequency bands, each being 1/3 of an octave wide
Sound Speed Profile	A graph of the speed of sound in the water column as a function of depth

APPENDIX B

Marine Mammal Hearing Group Classification

The following table gives a summary of marine mammal hearing group classification.

Table B.1 Summary of marine mammal classification

Classification	Common Name	Scientific Name
Low frequency cetaceans (extracted from Appendix 1 Southall *et al.* (2019))	Bowhead whale	*Balaena mysticetus*
	Southern right whale	*Eubalaena australias*
	North Atlantic right whale	*Eubalaena glacialis*
	North Pacific right whale	*Eubalaena japonica*
	Common minke whale	*Balaenoptera acutorostrata*
	Antarctic minke whale	*Balaenoptera bonaerensis*
	Sei whale	*Balaenoptera borealis*
	Bryde's whale	*Balaenoptera edeni*
	Omura's whale	*Balaenoptera omurai*
	Fin whale	*Balaenoptera physalus*
	Humpback whale	*Megaptera novaeangliae*
	Pygmy right whale	*Caperea marginate*
	Gray whale	*Eschrichtius robustus*
High frequency cetaceans (extracted from Appendix 2 Southall *et al.* (2019))	Sperm whale	*Physeter macrocephalus*
	Arnoux' beaked whale	*Berardius arnuxii*
	Baird's beaked whale	*Berardius bairdii*
	Northern bottlenose whale	*Hyperoodon ampullatus*
	Southern bottlenose whale	*Hyperoodon planifrons*
	Tropical bottlenose whale	*Indopacetus pacificus*
	Sowerby's beaked whale	*Mesoplodon bidens*
	Andrews' beaked whale	*Mesoplodon bowdoini*
	Hubb's beaked whale	*Mesoplodon carlbubbsi*
	Blainville's beaked whale	*Mesoplodon densirostris*
	Gervais' beaked whale	*Mesoplodon europaeus*
	Ginkgo-toothed beaked whale	*Mesoplodon ginkgodens*
	Gray's beaked whale	*Mesoplodon grayi*
	Hector's beaked whale	*Mesoplodon hectori*
	Deraniyagala's beaked whale	*Mesoplodon hotaula*
	Layard's beaked whale	*Mesoplodon layardii*
	True's beaked whale	*Mesoplodon mirus*
	Perrin's beaked whale	*Mesoplodon perrini*

Classification	Common Name	Scientific Name
	Pygmy beaked whale	*Mesoplodon peruvianus*
	Stejneger's beaked whale	*Mesoplodon stejnegeri*
	Spade-toothed whale	*Mesoplodon traversii*
	Tasman beaked whale	*Tasmacetus shepherdi*
	Cuvier's beaked whale	*Ziphius cavirostris*
	Killer whale	*Orcinus orca*
	Beluga	*Delphinapterus leucas*
	Narwhal	*Monodon monoceros*
	Short- and long-beaked common dolphins	*Delphinus delphis*
	Pygmy killer whale	*Feresa attenuata*
	Short-finned pilot whale	*Globicephala macrorhynchus*
	Long-finned pilot whale	*Globicephala melas*
	Risso's dolphin	*Grampus griseus*
	Fraser's dolphin	*Lagenodelphis hosei*
	Atlantic white-sided dolphin	*Lagenorhynchus acutus*
	White-beaked dolphin	*Lagenorhynchus albirostris*
	Pacific white-sided dolphin	*Lagenorhynchus obliquidens*
	Dusky dolphin	*Lagenorhynchus obscurus*
	Northern right whale dolphin	*Lissodelphis borealis*
	Southern right whale dolphin	*Lissodelphis peronii*
	Irrawaddy dolphin	*Orcaella brevirostris*
	Australian snubfin dolphin	*Orcaella heinsohni*
	Melon-headed whale	*Peponocephala electra*
	False killer whale	*Pseudorca crassidens*
	Indo-Pacific humpback dolphin	*Sousa chinensis*
	Indian Ocean humpback dolphin	*Sousa plumbea*
	Australian humpback dolphin	*Sousa sahulensis*
	Atlantic humpback dolphin	*Sousa teuszii*
	Tucuxi	*Sotalia fluviatilis*
	Guiana dolphin	*Sotalia guianensis*
	Pantropical spotted dolphin	*Stenella attenuata*
	Clymene dolphin	*Stenella clymene*
	Striped dolphin	*Stenella coeruleoalba*
	Atlantic spotted dolphin	*Stenella frontalis*
	Spinner dolphin	*Stenella longirostris*
	Rough-toothed dolphin	*Steno bredanensis*
	Indo-Pacific bottlenose dolphin	*Tursiops aduncus*

Classification	Common Name	Scientific Name
	Common bottlenose dolphin	*Tursiops truncatus*
	South Asian river dolphin	*Platanista gangetica*
Very high frequency cetaceans (extracted from Appendix 3 Southall *et al.* (2019))	Peale's dolphin	*Lagenorhynchus australis*
	Hourglass dolphin	*Lagenorhynchus cruciger*
	Commerson's dolphin	*Cephalorhynchus commersonii*
	Chilean dolphin	*Cephalorhynchus eutropia*
	Heaviside's dolphin	*Cephalorhynchus heavisidii*
	Hector's dolphin	*Cephalorhynchus hectori*
	Narrow-ridged finless porpoise	*Neophocaena asiaeorientalis*
	Indo-Pacific finless porpoise	*Neophocaena phocaenoides*
	Spectacled porpoise	*Phocoena dioptrica*
	Harbor porpoise	*Phocoena phocoena*
	Vaquita	*Phocoena sinus*
	Burmeister's porpoise	*Phocoena spinipinnis*
	Dall's porpoise	*Phocoenoides dalli*
	Amazon river dolphin	*Inia geoffrensis*
	Yangtze river dolphin	*Lipotes vexillifer*
	Franciscana	*Pontoporia blainvillei*
	Pygmy sperm whale	*Kogia breviceps*
	Dwarf sperm whale	*Kogia sima*
Sirenians (extracted from Appendix 4 Southall *et al.* (2019))	Amazonian manatee	*Trichechus inunguis*
	West Indian manatee	*Trichechus manatus*
	West African manatee	*Trichechus senegalensis*
	Dugong	*Dugong dugon*
Phocid carnivores (extracted from Appendix 5 Southall *et al.* (2019))	Hooded seal	*Cystophora cristata*
	Bearded seal	*Erignathus barbatus*
	Gray seal	*Halichoerus grypus*
	Ribbon seal	*Histriophoca fasciata*
	Leopard seal	*Hydrurga leptonyx*
	Weddell seal	*Leptonychotes weddellii*
	Crabeater seal	*Lobodon carcinophaga*
	Northern elephant seal	*Mirounga angustirostris*
	Southern elephant seal	*Mirounga leonina*
	Mediterranean monk seal	*Monachus monachus*
	Hawaiian monk seal	*Neomonachus schauinslandi*
	Ross seal	*Ommatophoca rossii*
	Harp seal	*Pagophilus groenlandicus*
	Spotted seal	*Phoca largha*

Classification	Common Name	Scientific Name
	Harbor seal	*Phoca vitulina*
	Caspian seal	*Pusa caspica*
	Ringed seal	*Pusa hispida*
	Baikal seal	*Pusa sibirica*
Other marine carnivores (extracted from Appendix 6 Southall *et al.* (2019))	Walrus	*Odobenus rosmarus*
	South American fur seal	*Arctocephalus australis*
	New Zealand fur seal	*Arctocephalus forsteri*
	Galapagos fur seal	*Arctocephalus galapagoensis*
	Antarctic fur seal	*Arctocephalus gazella*
	Juan Fernandez fur seal	*Arctocephalus philippii*
	Cape fur seal	*Arctocephalus pusillus*
	Subantarctic fur seal	*Arctocephalus tropicalis*
	Northern fur seal	*Callorhinus ursinus*
	Steller sea lion	*Eumetopias jubatus*
	Australian sea lion	*Neophoca cinerea*
	South American sea lion	*Otaria byronia*
	Hooker's sea lion	*Phocarctos hookeri*
	California sea lion	*Zalophus californianus*
	Galapagos sea lion	*Zalophus wollebaeki*
	Polar bear	*Ursus maritimus*
	Sea otter	*Enhydra lutris*
	Marine otter	*Lontra feline*

APPENDIX C

Modelled Underwater Noise Contours

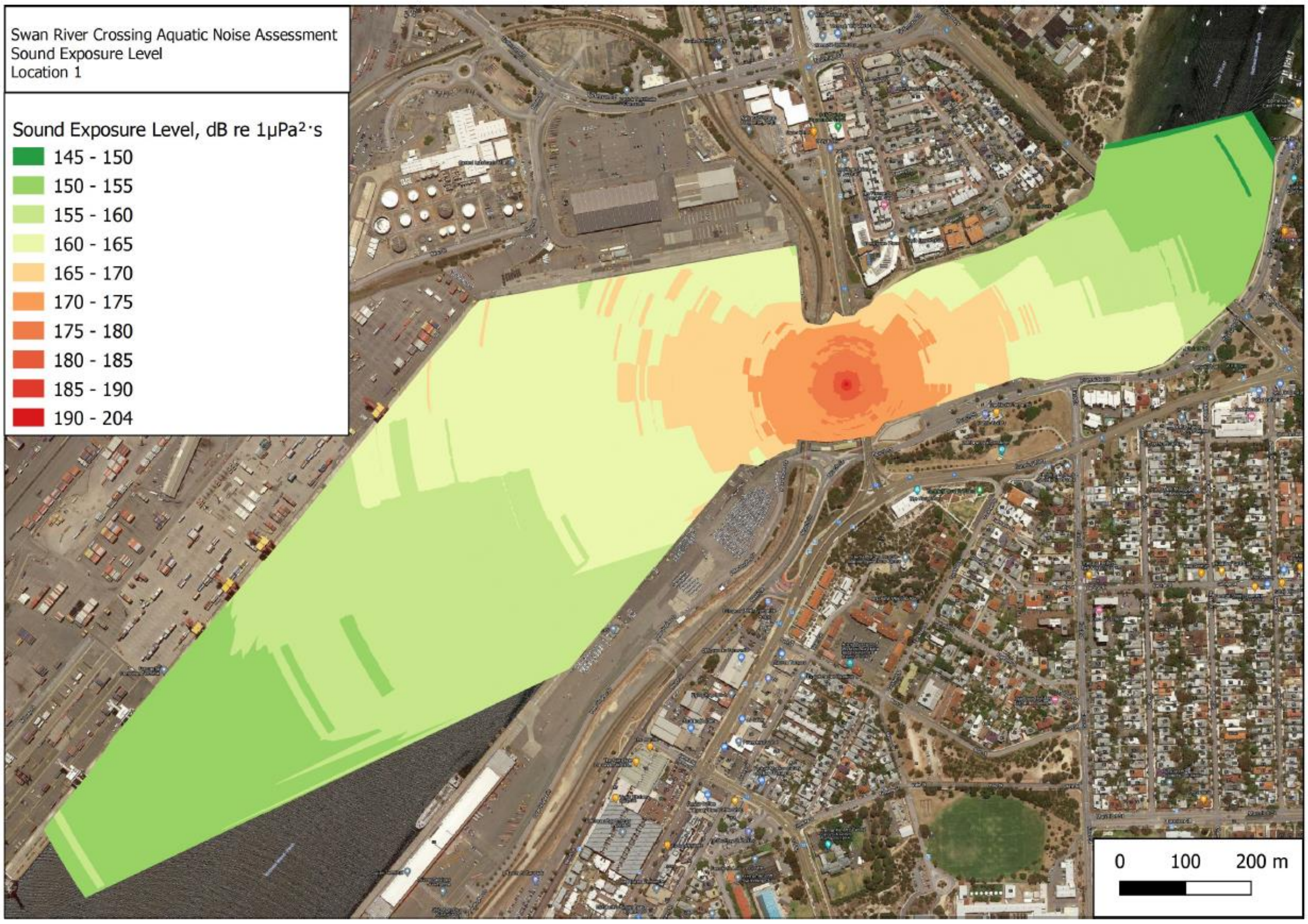

Figure C.1 Modelled noise contour plot for piling location L1

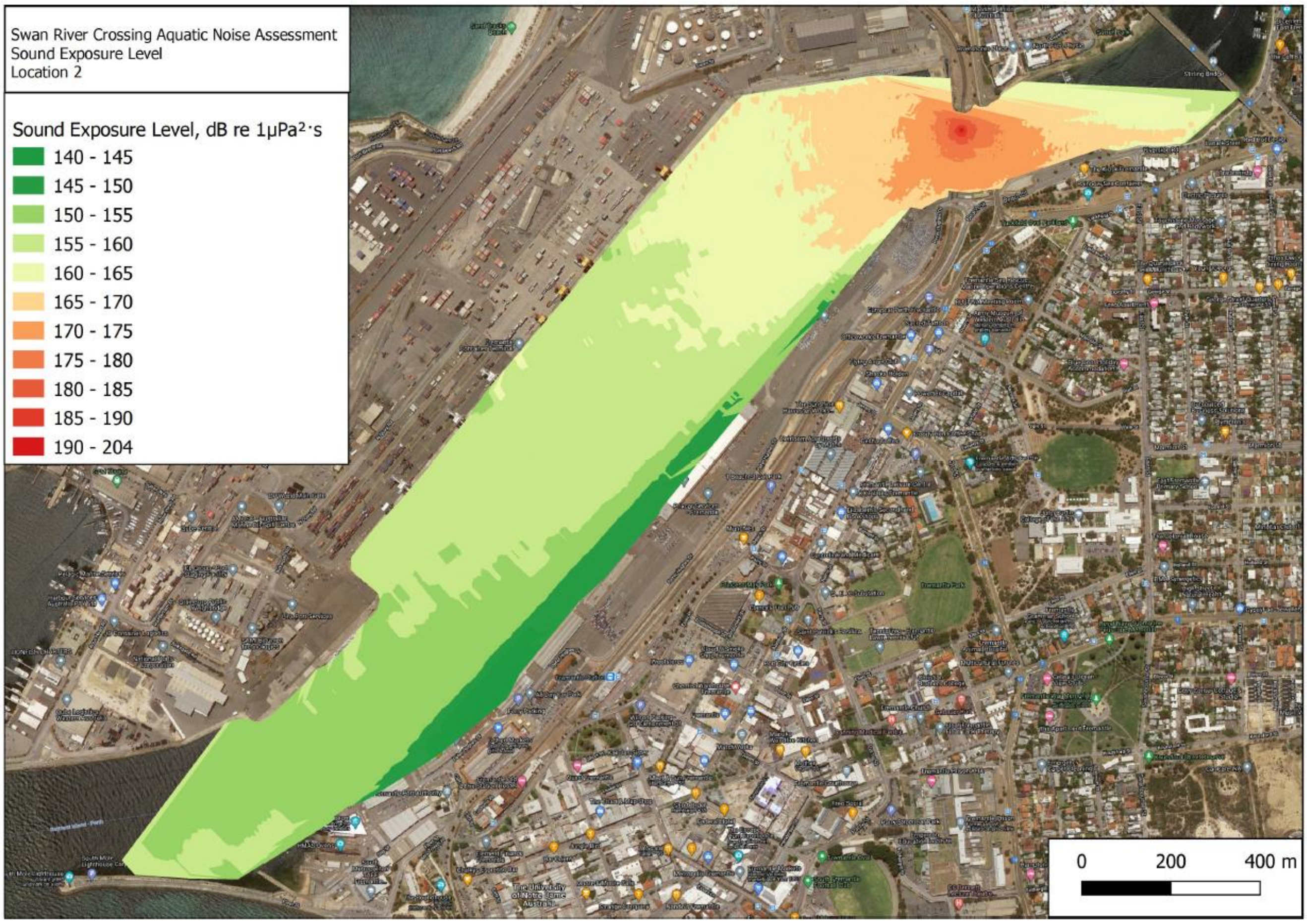

Figure C.2 Modelled noise contour plot for piling location L2

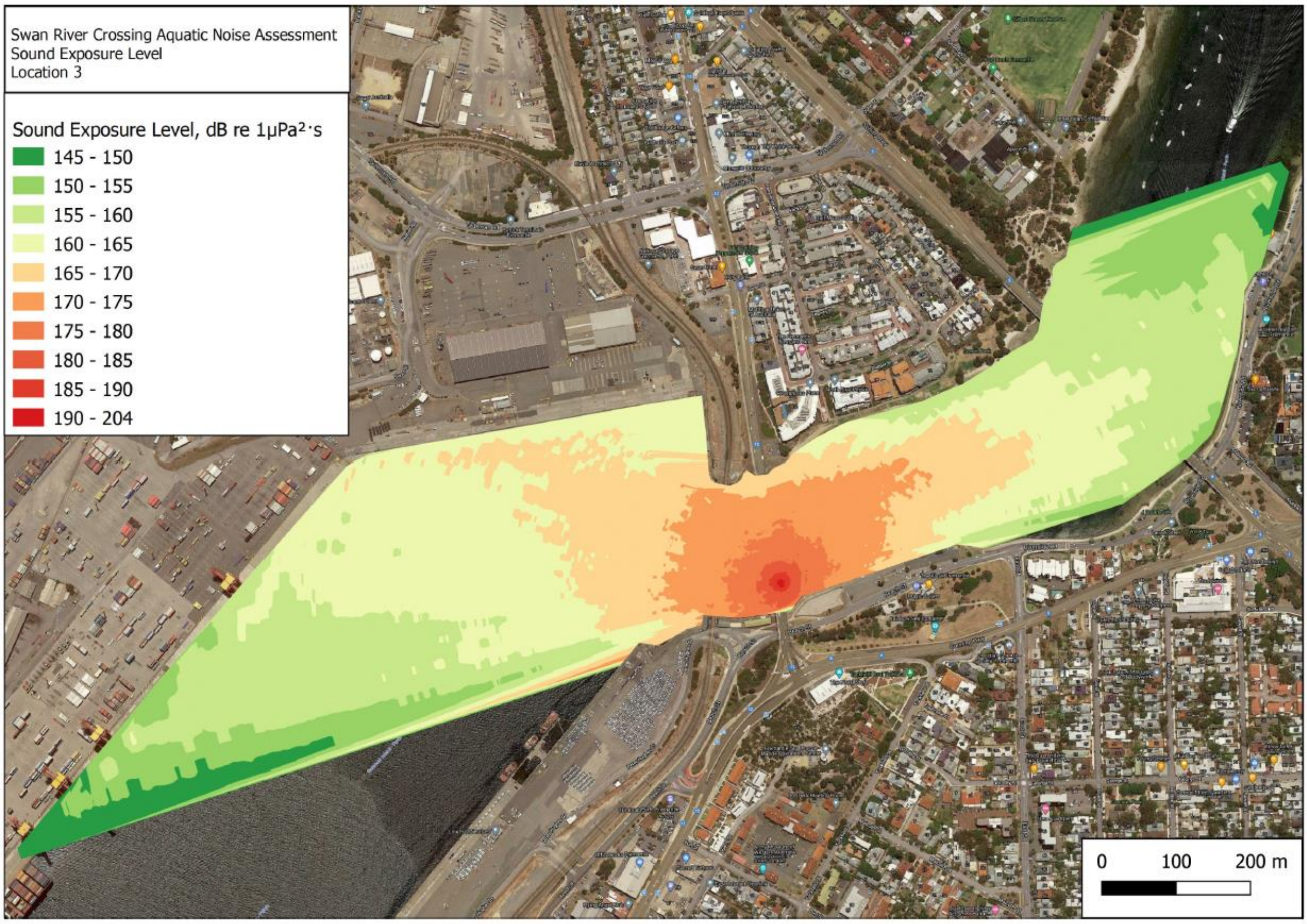

Figure C.3 Modelled noise contour plot for piling location L3

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