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ENVIRONMENTAL IMPACTS OF UNDERWATER NOISE ASSOCIATED WITH HARBOUR WORKS, PORT HEDLAND

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1 Executive Summary

Overview and objectives

As part of the environmental assessment process for the proposed development of the Port Hedland Outer Harbour by BHP Billiton, the Centre of Marine Science and Technology (CMST) has been contracted to undertake an underwater noise impact study to estimate the potential impacts from the noise field produced by underwater construction and associated activities, to dugongs, cetaceans and fish (which include sharks). Some of this work has been sub-contracted to the Centre for Whale Research (WA Inc.).

To assess the impacts of underwater noise:

- key marine mammal species likely to be present in the region and their sensitive periods were identified. While the sensitivity of fish were described here, the species likely to be present in the area has been addressed in a separate report; Sinclair Knight Mertz. 2009b),
- the noise signature of the construction technologies were described,
- ambient sea noise was measured,
- sound propagation models were run to predict transmission of key underwater noise sources, and,
- an initial assessment was conducted for informing the final risk assessment tables presented by SKM (separate to this report).

Noise sources and potential impacts

In terms of underwater noise impacts, the noise sources related to the Outer Harbour Development in order of predicted severity of underwater noise impacts are:

- Pile drivers,
- Increased shipping and vessel traffic associated with harbour works, and
- Dredging including equipment such as the Cutter Suction Dredge (CSD) and Trailing Suction Hopper Dredge (TSHD).

Factors needing consideration to assess the impacts of these noise sources are; the impinging underwater noise characteristics (*i.e.* sound level, noise duration, frequency content); the sound propagation characteristics of the area; the sensitivity to sound of the species of concern; physical robustness, size and age of the species; life history and relative population sensitivity; timing of different stages of life history; animal distribution and abundance; migration patterns; and whether the species can or are likely to move away from the noise if distressed by it.

For this study very little information was available on the distribution, timing of occurrence, life history, and behavioural patterns of fauna for much of the region around Port Hedland. By drawing from the limited available information it can broadly be said that the following marine mammal species will either occur within the project area or within proximity to it, either as residents or migrating animals: humpback whales: Indo-Pacific humpback dolphins; snubfin dolphins; bottlenose dolphins; and dugongs. A large number of species of fish occur in the region, many of which may be ecologically or commercially significant, including sharks of various species (such as the whale shark that may pass Port Hedland during migration).

Auditory criteria for injury and disturbance caused by acoustic energy for these faunal groups have been a focus of much scientific work in recent years. The work, however, has resulted in criteria limited to mainly cetaceans, pinnipeds (seals and sea lions), and fish. Criteria are not yet available for dugongs.

Auditory criteria for potential noise impacts upon individual organisms have been categorised into the following order based on degree of severity, from highest to lowest:

- Organ damage: physiological damage which may lead to death.
- Permanent Threshold Shift (PTS): a permanent shift in hearing sensitivity.
- Temporary Threshold Shift (TTS): a temporary effect upon hearing (i.e. recoverable), and
- Behavioural responses: which may span short term startle responses to long term avoidance of areas by animals or a change to movement pathways or migration routes. These responses also include those resulting from masking of signals of interest.

Impacts for pile driving (the source with the greatest level of estimated direct impacts based on the high peak levels involved) within the severity classes described above are expected within the following radii:

- Injury/Death: within several to tens of metres from the source,
- PTS: within tens of metres from the source,
- TTS: within 200 m from the source, and
- Behavioural disturbance: within 2 km to tens of kilometres, depending upon the species, habituation or sensitisation and severity of the behavioural response considered

Generally, the underwater noise emissions produced by the three pile drivers, which are proposed to be used over a period of approximately 24 months, are likely to displace or disrupt the behaviour of most marine mammals within several kilometres of the operating pile drivers.

Some level of behavioural disturbance is likely for most species that occur within close proximity to continuous noise sources. Noise sources include dredging for construction of the jetty and wharf as well as shipping movements along the new channel (parallel to the existing channel). Less sensitive species, such as some fish, are likely to habituate to a certain extent.

Although there are no quantitative risk criteria available in the literature regarding population level responses, some qualitative assessments have been made. The greatest impacts are expected to occur to species that use the proposed development site as vital habitat (*i.e.* for migration, breeding, foraging, *etc.*), and whose population or community is particularly sensitive to impacts. The most sensitive populations include the dugongs and whale sharks, since these are declining Australia wide, and potentially snubfin dolphins since these appear to occur in smaller numbers and are endemic to northern Australia and Papua New Guinea. Other species such as the Indo-Pacific humpback dolphin and the spotted bottlenose dolphin occur in larger numbers around Australia, but these often occur in communities with high site fidelity. The Indo-Pacific humpback dolphin may in fact be a new species not occurring elsewhere in the world. The dolphin's overall behaviour, including spatial and temporal use of the study area is likely to be altered, although the level of impact to these dolphin communities cannot be determined without a greater understanding of their dependence on habitats in the development area and in the broader region.

Humpback whale ecology, in comparison, is much better understood. Humpback whales migrate past and may breed within the Port Hedland area, with northbound whales expected to occur between July and September and southbound whales passing between September to November. Southward migrating humpbacks may be more sensitive behaviourally to sound emissions than northbound since high numbers of mother-calf pairs occur during this period. This sensitive portion of the population (which includes the mother-calf pairs) is likely to be at a higher risk to impacts since calves will be weak from recent birth and since the mother-calf pairs tend to migrate close to the coast in shallow waters, hence may migrate within close proximity to the Port Hedland harbour works.

2 Introduction

This report has been prepared for the environmental approvals process required for BHP Billiton's proposed Port Hedland Outer Harbor development (Western Australia). Specifically, this report aims to assess the impact of the underwater noise that will be created during the Port Hedland Outer Harbor development on a number of sensitive marine faunal species. This impact assessment has been prepared to inform probability and risk tables prepared separately by SKM.

2.1 Objectives and report structure

The information presented throughout this report is diverse in the array of subjects addressed and the methods used to achieve the aims outlined above. To enhance the clarity for the reader of the work presented here, a set of specific objectives and associated methods are presented in Table 1.

Table 1: Objectives and their associated methods.

Objective	Description	Method
1	**Describe fauna likely to be present in the region of potential impact, their hearing sensitivities, and known impacts from underwater noise.**	**Literature review**
2	**Identify the type of noise expected to be produced during the Outer Harbour Development works.**	**Literature review**
3	**Describe known impacts from underwater noise to fauna**	**Literature review**
4	**Identify critical noise levels and noise risk criteria for the type of noise sources and faunal groups considered**	**Literature review**
5	**Identify baseline background noise levels**	**Field measurements**
6	**Predict the underwater noise expected to be produced during the Outer Harbour Development works (construction and operation)**	**Sound transmission modelling**
7	**Describe the impacts expected based on all information available from Obj 1-5.**	**Analysis and discussion based on Obj 1-6**

The structure of the report follows the order of the objectives above, but is split into sections that follow a general report format. These sections consist of the following:

1. Introduction (includes a description of the scope of the project)
2. Methods (describes the methods implemented to achieve the objectives outlined above)
3. Literature review (presents the results from the literature review; Objectives 1-4)
4. Underwater noise prediction (presents the results from the background noise measurements and the propagation modelling; Objectives 5-6)
5. Impact assessment (Objective 7)

Measures recommended for mitigating impacts due to underwater noise are presented in an accompanying, separate report by the authors.

2.2 Scope

2.2.1 Overview of the Outer Harbour Development

Port Hedland harbour currently has a large port facility, first developed in 1965 as a major hub for the export of iron ore from the Pilbara region. The aim of the Outer Harbour Development Project is to increase the harbour's current capacity to enable greater iron ore ship loading capability. The marine component of the planned port expansion includes construction of a conveyor crossing, a wharf, a loading jetty, associated infrastructure, and channel deepening (see Figure 1). The project area (the area in which construction, dredging, and shipping activity associated with the harbour works will take place) has been considered to be approximately 100 km x 40 km. This area includes 50 km on either side of the dredge footprint, and 40 km out to sea (which encompasses the area of work around the 34 km channel).

The main activities expected to have significant underwater noise source levels during construction and development of the Outer Harbour include dredging and pile driving. Hence, noise from these activities is addressed in this report. There is likely to be some piling associated with installation of navigation aids, although the number of these piles is small compared with the number associated with the jetty. Because of this, impacts from underwater noise produced by navigation aid piling have been considered here only briefly. Increased vessel movements due to construction activities and increased shipping activities during operations have also been considered here briefly.

Pile driving will be implemented mainly during the jetty and causeway construction, while dredging will be conducted to construct berth pockets and the new parallel shipping channel. Piling will occur over 2 years. The majority of the proposed piling will occur during the first year of works during the construction phase, with a more limited amount of piling occurring in the second year. High levels of dredging activity, however, will occur over an extended period of approximately 2 years initially (for stage 1), and then for ~2.5 years afterwards (stages 2 and 3). Periodic (maintenance) dredging thereafter will be required to maintain the shipping channel depth.

The pile driving activity is expected to involve over 1000 piles (with 892 within the first year) to establish the causeway and offshore jetty structures (details of which are presented in Table 2). Three jack-up pile driving rigs are planned to be used, with planned simultaneous use through much of the construction phase. The hammers are large, with a quoted hammer energy output in the range 30-48 tonne-m (294 – 470 kN-m).

Table 2: Number and types of piles to be driven in the first year.

	Number piles	**Pile types**
Jetty (3.6 km)	384	1200 mm OD x 25 mm wall thickness
Transfer Deck	136	900 mm OD x 25 mm wall thickness
Wharf	168	1500 mm OD x 25 mm wall thickness
Mouring Dolphins	204	1423 mm OD x 40 mm wall thickness

Figure 1: Conceptual overview of project footprint area of the Port Hedland Outer Harbor Development (Courtesy of BHP Billiton).

2.2.2 Environmental attributes of the site

The ‘Pilbara and 80 Mile Beach’ region (Figure 2) supports “significant mangroves, coral reefs, sponge gardens, seagrass beds, seaweed meadows, barrier and offshore islands, protected lagoons, deltas, rocky shores and sandy beaches” (WA DEC 2008). The region contains areas of particular significance to fauna, including habitat important to migratory sea and shore-birds, marine management areas, marine parks, and marine reserves (Figure 2). Whale sharks and humpback whales, for example, are known to migrate through the area, and a large number of endemic and commercially significant fish also occur within the region.

Figure 2: Map of the Pilbara and the 80 Mile Beach Planning Region.

The town and port of Port Hedland was established on a natural ‘lake’ or harbour, protected from the sea by a narrow channel. The location of the proposed development is known to be in the proximity of turtle feeding and breeding grounds, habitat critical for dugongs, and marine mammal migratory routes.

2.2.3 List of fauna considered

The species considered in this impact assessment include regional species of concern listed in the Commonwealth government *Environment Protection and Biodiversity Conservation (EPBC) Act 1999* as localised or migratory marine megafauna. Specifically, these include:

- *Balaenoptera musculus* (Blue Whale)
- *Megaptera novaeangliae* (Humpback Whale)
- *Dugong dugon* (Dugong)
- *Balaenoptera edeni* (Bryde’s Whale)
- *Orcinus orca* (Killer Whale)
- *Sousa chinensis* (Indo-Pacific Humpback Dolphin)
- *Tursiops aduncus* (Spotted Bottlenose Dolphin; Arafura Timor Seas populations)
- *Rhincodon typus* (Whale Shark)

There are several species and groups of animals not considered in this report, which are worth mentioning. Invertebrates and larval fishes have not been reviewed here although they are of significant importance ecologically and of potential commercial value (see Sinclair Knight Mertz, 2009b). There are also a large number of cetaceans not listed here which occur in the broader region, but are unlikely to occur in the Outer Harbour Development area (see Section 4.1), hence have not been listed above. Turtles are not included here, since noise impacts to turtles are considered in a separate report (Pendoley 2009).

It is also noteworthy to mention that while this report addresses a broad range of species that are covered through legislation, it does not cover potentially sensitive species not yet identified by science and/or legislation. For the majority of the recognised species, population dynamics and associated sensitivities have not been adequately described in the available literature.

3 Methodology

3.1 Acoustic metrics and units

As part of the background information, we present a description of relevant metrics referred to in underwater acoustics so that reference to units throughout this document may be clearly understood.

Underwater noise level units are confusing in the literature. The metric used in this report is underwater sound pressure level (SPL) given in decibels either at the source (source level or SL) or at the receiver (received level or RL). The levels here are generally expressed as SEL (sound exposure level in units of dB re 1μPa^2.s) or MSP (mean square pressure in units of dB re 1μPa). Previous studies have used the term RMS for mean squared pressure (MSP). The RMS level is the square root of the mean of the squared pressure over a defined period of a signal, expressed as a dB value (where it is squared again). The two measures, RMS and MSP, are derived identically and only the term MSP is used here as it better defines the way the value is derived.

For steady signals such as ship or dredge noise, the averaging time over which a mean squared pressure value is derived (a few seconds to 1 minute) does not matter, but for impulsive (short and sharp) signals the averaging time does matter significantly. While steady signals such as continuous noise can be described in terms of RMS, impulsive signals are better described by SEL. SEL is a measure proportional to the amount of energy which passes through time. McCauley *et al*. (2003) describes the SEL measurement technique, which is termed equivalent energy in that document. Later studies have re-phrased this as SEL. Both units (RMS and SEL) will be found throughout this document.

Other metrics that are important are peak SPLs given as dB re 1μPa (peak), and peak-to-peak SPLs given as dB re 1μPa (peak-to-peak). The peak SPL is related to the maximum absolute value of the instantaneous sound pressure during a specific time interval, and the peak-to-peak is related to the algebraic difference between the maximum positive and maximum negative instantaneous peak pressure.

When displaying frequency spectra in underwater acoustics the convention is to normalise the bandwidth of the measurement to 1 Hz, resulting in units of dB re 1μPa^2/Hz. These are termed spectral level units and can be readily compared between sources. When presenting noise levels one can present the frequency spectra in spectral level units, or the broadband noise which is the sum of energy across the frequency band of most energy in the signal.

3.2 Literature review

There are very few studies that have been conducted in the Port Hedland Region on the distribution of fauna, and none have investigated the response to and impacts on marine mammals from dredging and construction activities (McCauley *et al*. 2000). Therefore, in order to assess the potential impacts of human development related activities to fauna occurring in the region, it is critical to use the results of relevant published scientific studies from other parts of the world as a basis for predicting likely impacts.

Part of the literature review presented in this report was sub-contracted to the Centre for Whale Research (WA Inc.) whom advised on humpback whale movements through the area, and by Dr. Dave Holley (Department of Environment and Conservation, WA) whom advised on dugong in the area.

3.3 Field based background noise measurements at Port Hedland

The first phase of conducting a noise impact assessment is to establish and understand the ambient noise, and define the local underwater noise field. Underwater noise recordings were made at Port Hedland for this purpose between the 09-Oct-2008 and 23-Oct-2008. Two types of equipment were used: a CMST-DSTO noise logger and 'dip' recordings made by deploying a hydrophone from a small vessel.

The CMST-DSTO noise logger was deployed off of Port Hedland for a 14 day period (from the 09-23-Oct-2008) at the latitude of 20° 08.788' S and longitude of 118° 29.955' E (Figure 3, Figure 4) in a water depth of ~14 m (LAT). The location was approximately 560 m ENE of channel marker 14. The location of the logger with respect to the broad region of interest along the North West Shelf is shown on Figure 3, while a more detailed close-up showing the main shipping channel into Port Hedland, the proposed causeway and jetty locations, and the local bathymetry is presented on Figure 4.

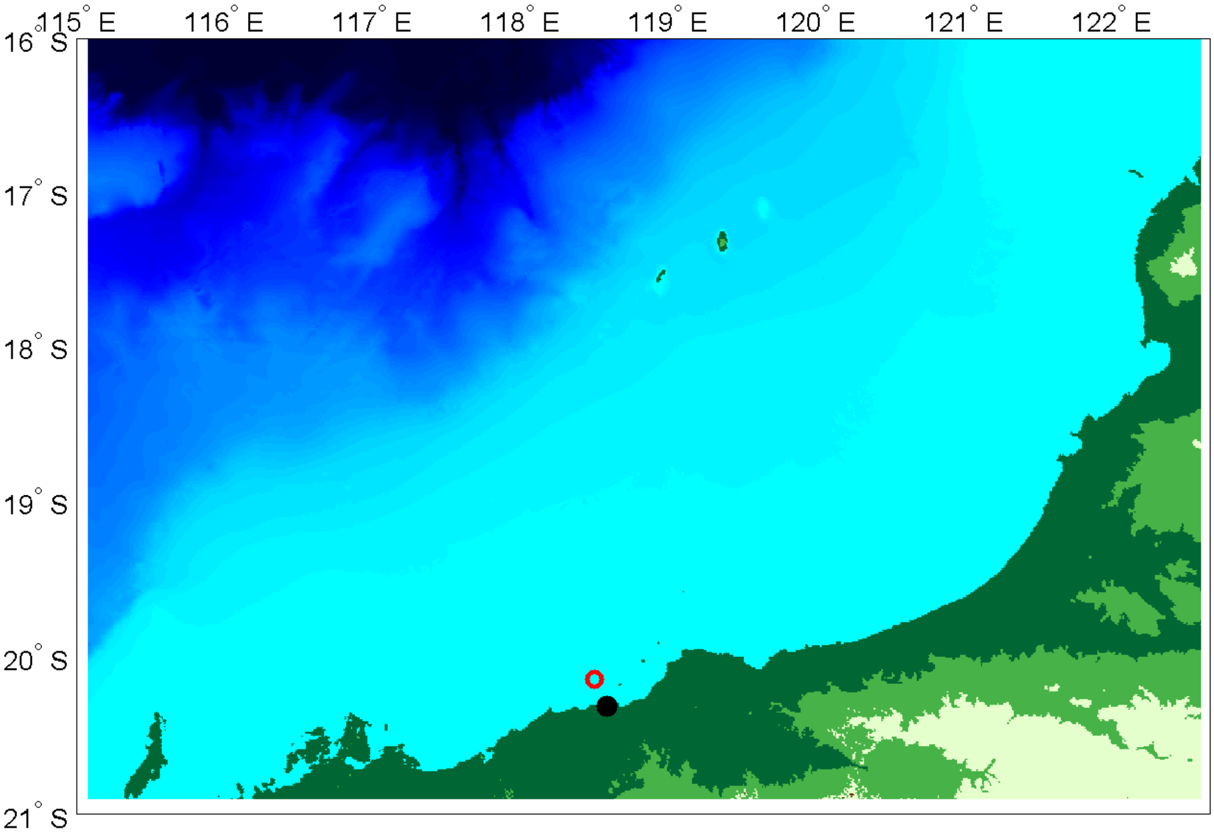

Figure 3: Location of Port Hedland along the northern WA coast (●) and of the sea noise logger (O).

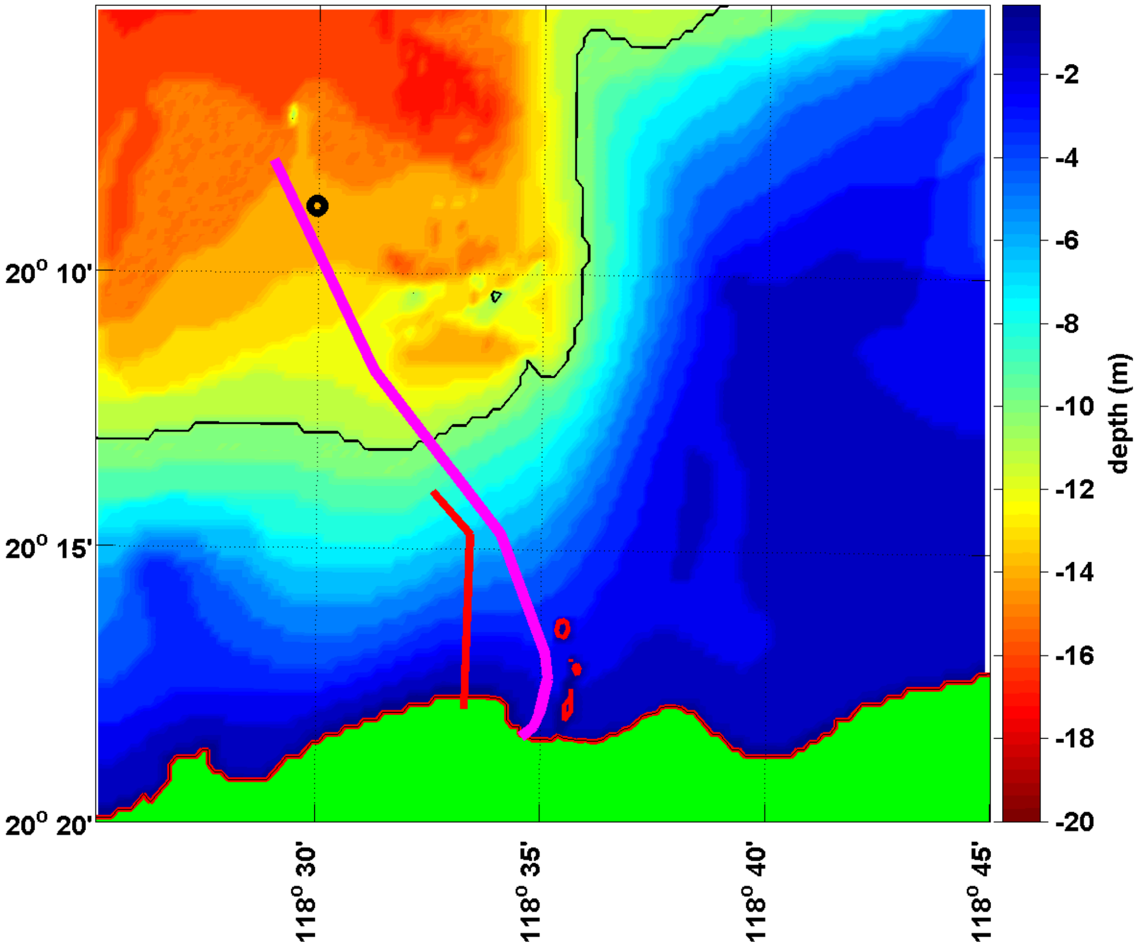

Figure 4: Location of sea noise logger (O), the current main shipping channel into Port Hedland (—), and the proposed causeway and loading jetty (—). The land is depicted in green, bordered by the heavy red line. The 10 m depth contour is shown (—).

The 'dip' recordings made by deploying a drifting hydrophone from a small vessel were conducted during the sea noise logger deployment and recovery days (09-Oct-2008 and 23-Oct-2008). These measurements were made as a backup to the sea noise logger records. Since the noise logger records resulted in an excellent data set, the drifted recordings were not analysed.

The noise logger was calibrated and programmed to collect samples 300 seconds long repeated at 10 minute intervals (see Appendix A for noise logger details). All analysis has been carried out in the Matlab environment using in-house CMST software. All times used in the sea noise logger analysis are presented in WST (Western Standard Time).

3.4 Underwater noise predictions for the Outer Harbour Development works

Underwater noise predictions were based on sound transmission modelling of source signals expected during the Outer Harbour Development works. Because pile driving is expected to represent the greatest impact, modelling was carried out at the proposed locations of pile driving sources. The signal source levels were derived from a library of information on hammer energies and associated source levels held by the consultants collected over the past ten years. Source level calculations are described in detail in Section 5.2.

To represent two pile driving hammers operating at the same time (the maximum number likely to be used at any one time), two reference sites were used for sound transmission; one at the northern end of the loading jetty (8.5 m depth LAT) and one at the southern end (6 m depth LAT).

The coordinates of these locations were:

- 662619 E, 7760595 N (southern end of the loading wharf)
- 661190 E, 7762024 N (northern end of the loading wharf)

Currently (previous to Outer Harbour Dredging works planned), maximum water depths in the vicinity of the jetty are 6-9 m (above LAT). However, dredging will occur during the pile driving construction phase, resulting in an increased water depth of around 14-15 m in the channel, in turning basins associated with the wharf, and alongside the wharf.

From each site eight lines were run out to 20 km from the source locations on 45° spokes. The location of sites and the lines are shown on Figure 5 out to 10 km. The bathymetry along each line out to 20 km was retrieved from the Geoscience Australia's 0.0025° digital bathymetry data set (280 m resolution; Figure 6 shows this bathymetry out to 10 km). The bathymetry profiles were gentle, with the maximum slope measured at 1.2 mm / m (or around 1m / km), and the mean of the absolute slope for all 16 tracks measured at 0.7 mm / m.

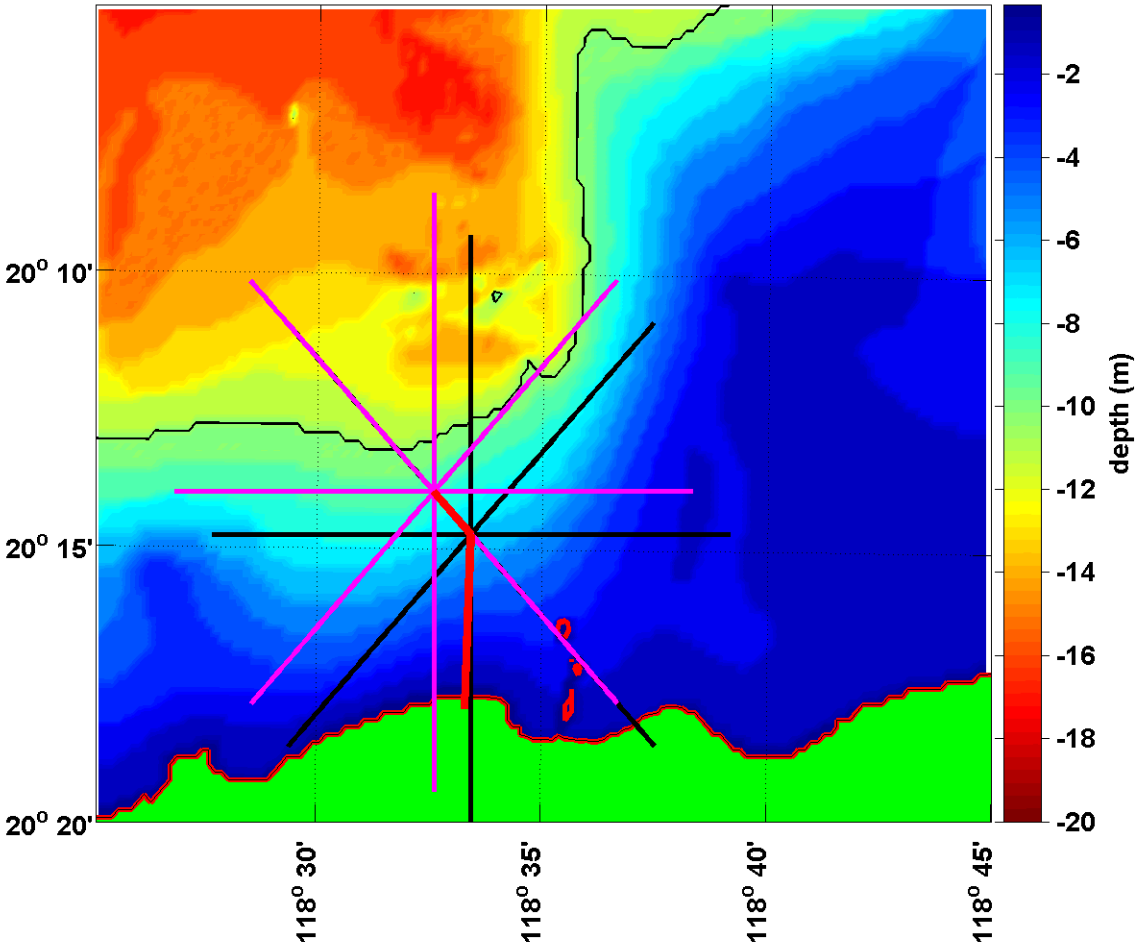

Figure 5: Location of the two sites from which transmission modelling was carried out, and the tracks from the two sites (shown out to 10 km). The heavy red line is the location of the causeway / wharf.

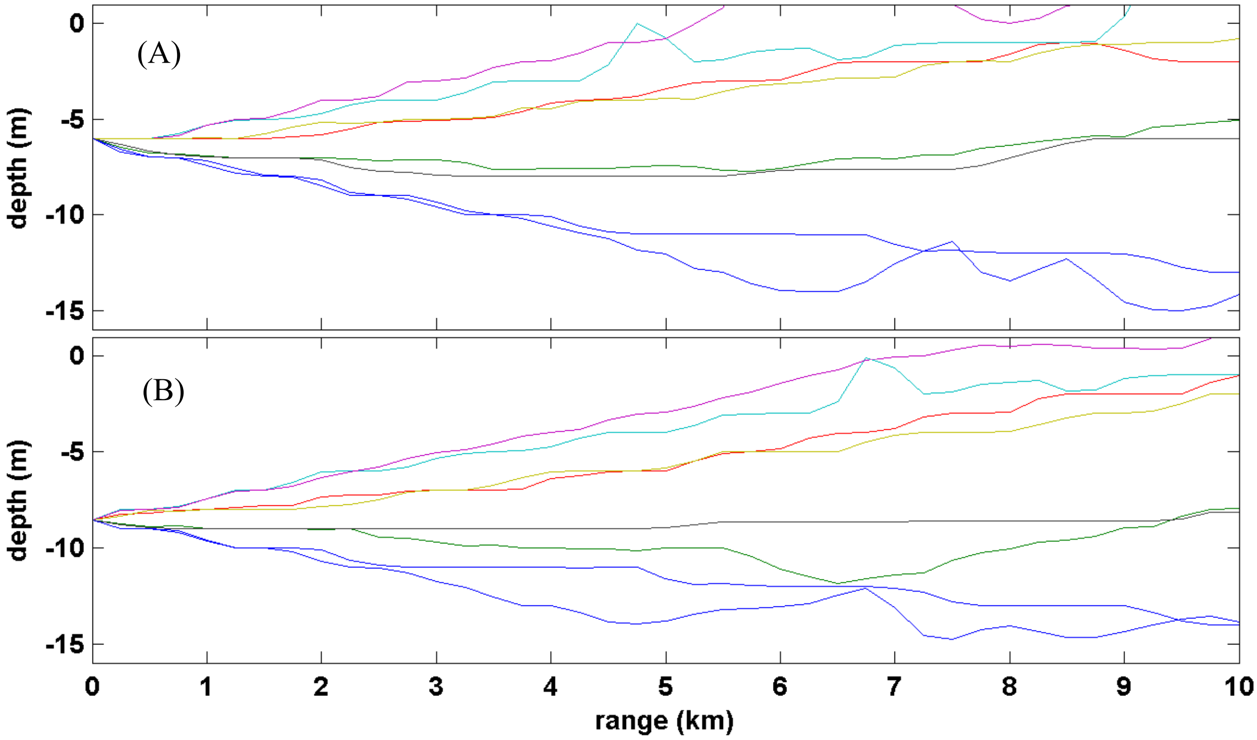

Figure 6: Bathymetry paths along (A) site 1 (southern), and (B) site 2 (northern) at chart datum.

Port Hedland has a maximum tidal range of just over 7 m, thus sound transmission was run at the tidal extremes of low and high spring tide (0 and 7 m). Given that, along each track, sound transmission loss models were run at two tidal regimes and 25 different frequencies (or 50 runs per track, with 8 tracks per site, and two sites), a total of 800 runs were necessary for each sound transmission loss model. Because the slopes were comparatively gentle, we have used constant depth during sound transmission runs. This allowed for a stable sound transmission model (Scooter) to be used. Scooter is fast, can accurately account for shear waves in the underlying limestone sediment, and is not prone to computational instabilities which plague sound transmission models.

For the model based on *zero tide*, the water depth was set as constant at the mean depth along each transect (over the first 5 km of the transects). For the model based on *high tide,* 7 m was added to all values. This averaging was a compromise for not being able to run range dependant sound transmission models, which would have been impossible given inherent model instabilities and the number of runs required. The model runs were made in 20 m steps out to twenty km using a 1 m depth increment over a 1-20 m water depth.

To produce accurate propagation models of sound at Port Hedland, it is necessary to have access to information on the physical characteristics of the environment. Generally, sound propagates more poorly in soft as compared to hard substrates, and transmission loss is greater in shallow areas than in deep areas (but actual transmission is highly dependent on the characteristics of the area). Complex bottom structures often result in complex bounce patterns of rays (from rays refracting off surfaces), which may result in focusing of noise at particular distances, producing enhanced sound levels. The planned site for the Port Hedland outer harbour lies in a semi enclosed embayment, with a gently sloping bathymetry, ranging from approximately 0 to 9 m. Seabed sediments of the inner shelf are believed to be sand dominated, with localised accumulations of mud, gravel and a large carbonate component occurring in the vicinity of Port Hedland. The specific information regarding the seabed properties and layering at the site was not available, but believed to be silty sand with underlying limestone and occasional limestone outcrops (based on observations of surficial sediments given in Mulhearn 1996).

For modelling purposes, the assumed seabed layering and seabed geoacoustic properties are given in Table 3. A uniform sound speed profile through the water column was assumed (well mixed). A silty / sand layer with geoacoustic properties midway between silt and sand was assumed, with underlying limestone with ranging geoacoustic properties as a function of depth. For the basement layer, limestone was used.

Table 3: Water column and seabed properties used in sound transmission modelling. For the limestone layer, appropriate values were interpolated with depth between the values in the square brackets.

layer	**Layer thickness (m)**	**Density (kgm^{-3})**	**Compressional sound speed (ms^{-1})**	**Compressional absorption (dB / λ)**	**Shear wave speed (ms^{-1})**	**Shear wave absorption (dB / λ)**
Water	Varied	1024	1541		0	0
Silty sand	4	1800	1600	0.9	100	2.5
Limestone	200	[2580 3000]	[2800 2900]	[0.1 0.1]	[1400 1400]	[0.2 0.2]
basement	> 200	3000	3000	0.1	1600	0.2

3.5 Impact assessment

Based on a review of literature available, and the estimated probability of presence of cetaceans, dugongs and fish of differing hearing sensitivities within the project area, an assessment was made on the level of impact (which was identified by modelling the areas of noise exposure away from the source). The assessment drew from known sensitivities to sound at various received energy levels and frequency spectra. Specifically, the following information was amalgamated and considered for the risk assessment.

1) Faunal occurrence in the designated project area where proposed works are to be conducted, the timing of their presence, and their hearing sensitivities (frequency and hearing thresholds, Section 4.2) of fauna;
2) Equipment to be used in the project area, their noise signatures (Section 4.3.1), underwater source propagation modelling (Section 5), and the timing of works (Section 2.2.1); and
3) Identification of any overlap between: a) the timing and presence of species and their sensitive periods *and* the timing of works in each area; and b) the frequency spectra and levels produced by the works in each area *and* the audiogram and critical levels for species at risk (presented in Section 6).

Fauna considered in this report were assessed for the risk of impacts by underwater noise generated at the following four levels of possible impacts:

- **Organ damage**: physiology damage such as organ damage that can lead to death.
- **Permanent Threshold Shift (PTS):** a permanent shift in hearing sensitivity.
- **Temporary Threshold Shift (TTS):** a temporary effect upon hearing (i.e. recoverable).
- **Behavioural response**: startle effect and/or avoidance or change to movement pathways/migration.

In this assessment, consideration is only given to those levels for which criteria have been developed, such as behavioural response, TTS and PTS/physiological damage (Southall *et al.* 2007). Criteria have not been developed for masking of signals of interest to animals nor for long term population effects, thus are not considered quantitatively in this assessment. However they are considered and presented as a qualitative discussion of potential affects.

4 Literature Review

4.1 Faunal distribution and periods of sensitivity

4.1.1 Cetaceans

There are few data on the distribution of cetaceans for much of this region and less information on their critical habitat (Sleeman *et al*. 2007). What is known is that a wide range of cetacean species are or are likely to be found, either permanently or on a transient basis in the surrounding waters. Of approximately 23 species of cetaceans which have a distribution overlapping the north-west Australian continental shelf edge, the shelf itself, and coastal waters, five species appear to spend most time offshore (although these may on rare occasions be seen inshore), four species often occur within the continental shelf and/or close to land, and three species are residents of coastal areas (Carwardine, 1995).

The four species that often occur within the continental shelf are the humpback whale (*Megaptera novaeangliae),* the blue whale (*Balaenoptera musculus),* the dwarf minke whale (*Balaenoptera acutorostrata*), and the killer whale (*Orcinus orca*). Of these, the humpback whale occurs closest to the coast, often within tens of metres to land in 10-20 metre water depth, and appears to be the most abundant. The north western region of Australia is known to be one of the largest (if not the largest) breeding and calving ground for humpback whales in the world (CWR unpublished data). A significant proportion (but not all) of the Western Australian population of humpback whales migrate into the Kimberley region, north of Port Hedland for calving and mating. Whales calve in the shallow warm tropical waters of the Kimberley, centred near Camden Sound (approximately 850 km northeast of Port Hedland). When calves are 1-2 weeks old the mothers begin the slow migration south. During the southern migration cow-calf pairs tend to migrate by following the coastline in shallow waters, typically within the 50 m contour and usually following the 20-30 m depth contour (depths relevant to the outer extent of the Project Area). Most of the breeding portion of the Western Australian humpback population which has made it as far north as the Kimberley (not all of the breeding population reaches the Kimberley) will pass south through or near the Project Area with some animals found closer to shore. Humpbacks off Port Hedland hence will be engaged either in migrating north or south, or engaged in breeding or calving related behaviours.

Blue whales (*Balaenoptera musculus),* and dwarf minke whales are sighted less often, and appear to occur in deeper waters preferentially near the shelf break (approximately 250 km north of Port Hedland). (Centre for Whale Research, WA Inc. unpublished data and noise logger data of McCauley). Killer whales are also known to be present, and occur both in deep and shallow waters.

Of the many dolphins occurring in the region, species that are residents of coastal areas and likely to be residents or utilize the Port Hedland region include the snubfin dolphin (*Orcaella heinsohnii*), the Indo-Pacific Humpback dolphin (*Sousa chinensis)*, and the spotted bottlenose dolphin (*Tursiops aduncus)*. The snubfin dolphin is endemic to Australian and Papuan New Guinea waters (Beasley *et al*. 2005) and the humpback dolphin form found in Australian waters is also highly likely to be a new species and endemic (Frere *et al*. 2008). All three cetacean species are listed as data deficient under the IUCN Red List and no publications exist for any formal surveys of cetaceans in Port Hedland. These three species have been documented as incidental sightings in the region (Centre for Whale Research, WA Inc. unpublished data), but no other thorough studies have been made to provide information on frequency of occurrence, proportion of total population present, and whether species are residents of migrants.

4.1.2 Dugongs

The dugong (*Dugong dugon*), a large marine vertebrate herbivore, occurs throughout Western

Australian waters from Shark Bay through the Kimberley and into the Northern Territory. The species is often found in water depths less than 5 m, in areas where there are extensive seagrass meadows. This species is regarded both as an important keystone species from an ecological perspective (Marsh *et al*. 1999) and an important cultural species for many indigenous communities. Given the extensive coastline of Western Australia (WA) and the historically limited threatening activity that dugongs have traditionally been exposed to, WA represents an important location for the species' conservation, on national and international levels. Globally, dugongs are classified as vulnerable to extinction (IUCN 2007) with Australia regarded as the last stronghold for the species (Marsh *et al*. 2002).

Knowledge on the distribution patterns, abundance estimates and habitat availability for dugongs (*Dugong dugon*) throughout the Pilbara region of WA is limited. Population abundance estimates of dugongs which have been determined in WA have been calculated from aerial surveys in Shark Bay, Exmouth Gulf and Ningaloo Reef (Marsh et al. 1994; Preen *et al*. 1997; Gales *et al*. 2004; Holley *et al*. 2006; Hodgson 2007). The only quantitative survey to have been conducted through the Pilbara region from Exmouth Gulf to the southern limit of the Kimberley region (Prince *et al.* 2001), was undertaken in April 2000. Prior to this survey, shoreline aerial surveys of the Pilbara region for dugong were undertaken during the late 1970's and identified both the Pilbara and Kimberley regions as regionally significant areas for dugong (Prince *et al*. 1981, Prince 1986).

Results from the Prince *et al.* (1981, 2001) surveys indicated dugongs occur within the Project Area. During the 2000 survey (Prince *et al.* 2001) no dugongs were observed north of Cape Thouin (Figure 2) along the predefined transects of the survey, with only one animal observed just outside of the Project Area. However, animals were identified off transect within the Port Hedland Harbour (Prince, pers. Comm.). Surveys conducted from the shoreline during February 1977 and July 1978 observed single animals within the survey Study Area during each survey. Due to the limited capacity of shoreline surveys to determine abundance estimates, none were made as a result of those surveys. The 2000 survey used methods as detailed in Marsh and Sinclair (1989) for estimating population abundance and returned an estimate for the Pilbara Survey Block of 2046 (± 376 standard error) dugongs at an average density of 1 dugong per 10 km². Recent advances in aerial survey calculation methodology to produce more robust estimates of dugong abundances (Pollock *et al*. 2006) have returned small differences in final estimates. This new methodology has not been applied to the most recent surveys undertaken. It has also been identified that there have been dugong mortalities around the Port Hedland region, although exact numbers, time period and cause of death are unknown (Prince pers. comm.).

Dugongs feed on and congregate near seagrass meadows of variable sizes. On a global scale dugongs are represented by relict populations separated by large areas where numbers have been greatly reduced or extirpated (IUCN, 2007). Little data exists on seagrass presence and composition within the study area, apart from a recent benthic survey in the proposed area (SKM 2009a). With respect to seagrass, the study concluded that none was observed along the transects surveyed, although it is not to say that seagrass does not occur in the study area. A broad scale seagrass survey of the region was undertaken (Walker and Prince 1987) however no detailed assessment was made of the Port Hedland region. Genera found within the Pilbara region include *Halodule, Halophila* and *Cymodocea* all of which are important forage seagrasses for dugongs (Sheppard *et al*. 2007). Along the west Australian coast dugongs generally calve in shallow (< 1 m deep waters), between August and September, although they may calve as late as December (Marsh *et al*. 1984).

4.1.3 Fish

A large number of fish species occur within the Pilbara region, including many species of sharks such as the whale shark (*Rhincodon typus*). The coastal areas are considered highly significant as they support nursery grounds and protective habitat for juvenile fish that migrate further off shore as they develop. It is outside of the scope of this document to present a comprehensive review of the fish species occurring in the region, including those that are ecologically or commercially significant or those that may be listed or protected species. This topic is addressed in a separate study by SKM (2009b). However, this study does address the potential effect of marine noise on fish species that may be present.

4.2 Hearing sensitivity

The use of sound for communication and detection in the marine environment is important for survival for marine animals. Marine animals depend on their hearing sensitivity for communication, for echolocation (among some marine mammals), to locate and capture food, for detection of predators, for sensing their physical and biological environment and for avoiding dangerous situations (including anthropogenic threats). There is great variation in hearing sensitivity among animals due to evolutionary diversification of anatomical structures involved in hearing and selection pressures on the way different animals utilise sound.

In terms of man made underwater noise, there is a large range of frequencies produced by different sources. The way in which a species is impacted by the sound will depend on the frequency range it can hear, the level of the sound (or its energy) and its frequency spectrum (Nedwell *et al.* 2004). Both the sensitivity of hearing and the frequency range over which sound can be heard varies from species to species, and can vary greatly even between species that are closely related. The hearing sensitivity of most of the species significant to the Port Hedland region have not been measured, so a review of thresholds of species (including both hearing generalists and hearing specialists for fish) with known sensitivity to sound has been collated and is discussed in this section. Hearing thresholds have been measured for the bottlenose dolphin and orcas which are discussed below. There is limited information available for the hearing sensitivity of dugongs. There is a paucity of information on the hearing of great whales. The review of hearing sensitivity and known impacts draws widely from published work, grey literature, and reviews conducted by Richardson *et. al.* (1995), Gorden *et al.* (2003), Nedwell *et al.* (2004) and Hastings and Popper (2005).

4.2.1 Cetaceans

Odontocetes (the group of mammals that includes toothed whales and dolphins) are known to communicate at frequencies from 1 kHz to greater than 20 kHz. Hearing in the bottlenose dolphin extends from at least 40-75 Hz to as high as 80-150 kHz with best sensitivity in the frequency range of ~15 kHz to 50 kHz, with several examples of dolphin audiograms shown on Figure 7.

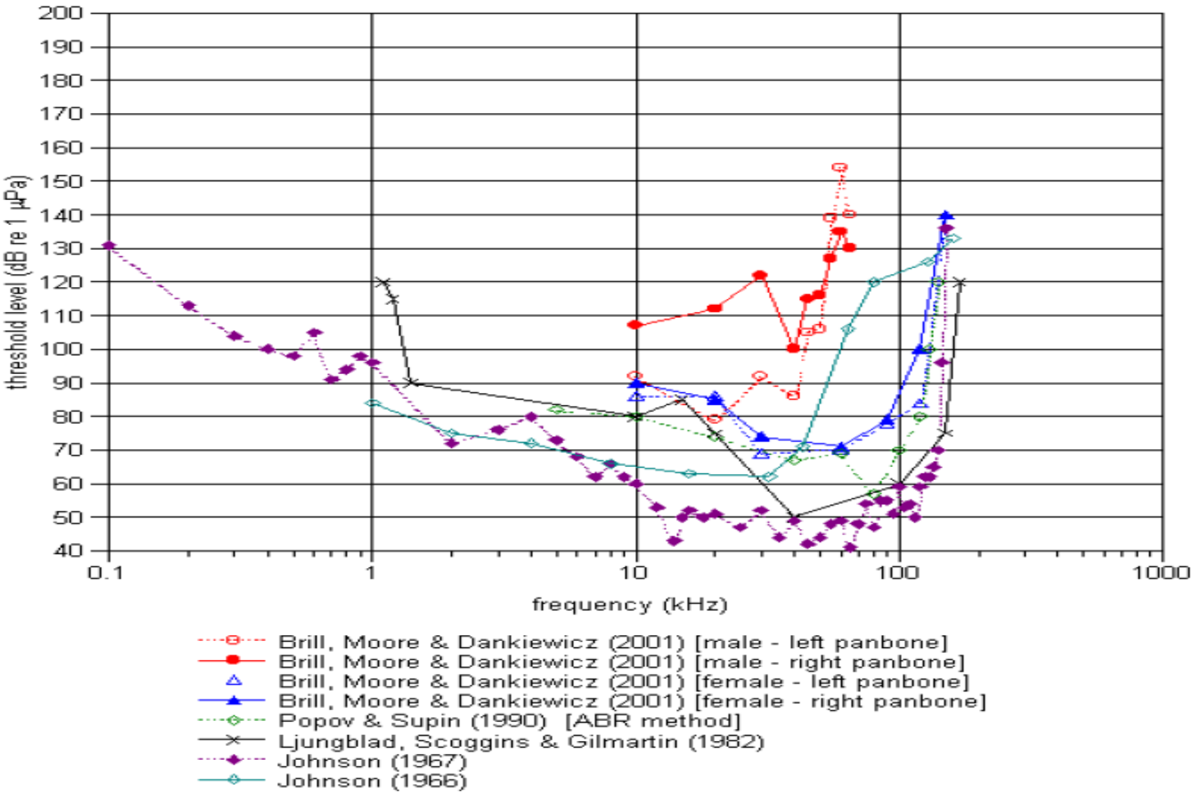

Figure 7: Underwater audiogram of the bottlenose dolphin (*Tursiops spp.*) (figure from Nedwell *et al.* 2004).

The Killer whale (*Orcinus orca*), like the other odontocetes has highest sensitivity at high frequencies, 10 kHz to 50 kHz, with example audiograms shown on Figure 8.

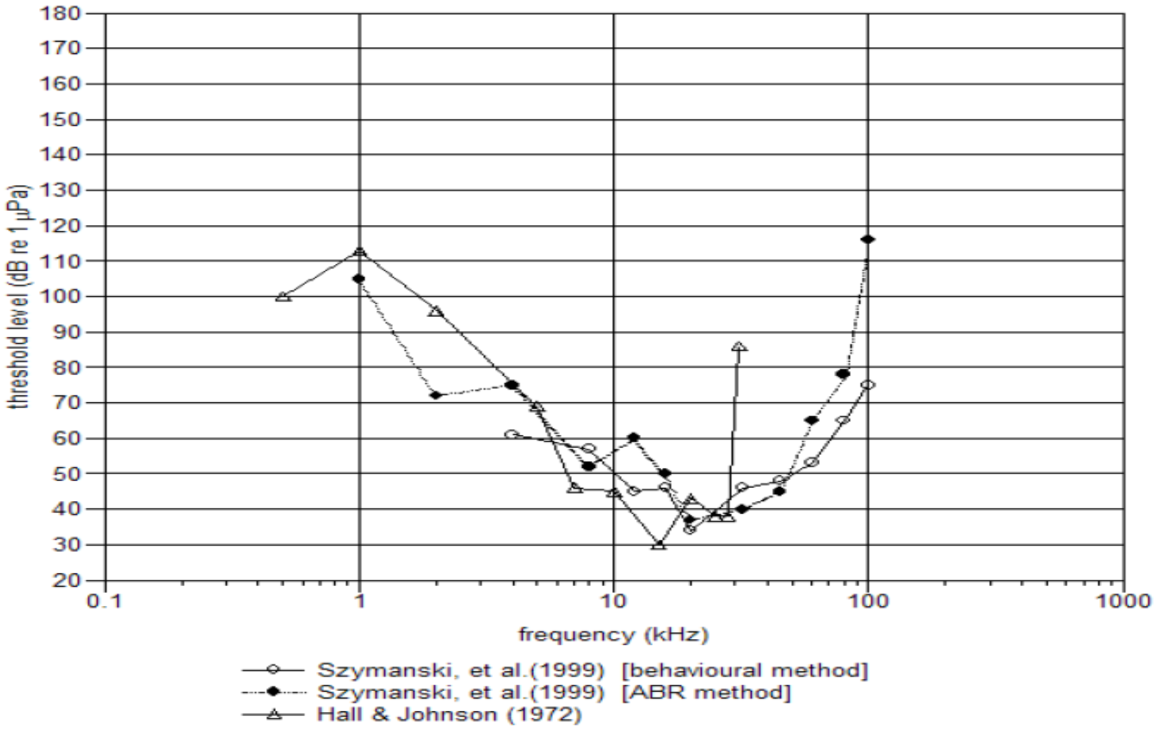

Figure 8: Underwater audiogram of killer whale (*Orcinus orca*) (figure from Nedwell *et al.* 2004).

There are no audiograms available for baleen whales. From behavioural observations it is apparent that baleen whales can localize sources of very low frequency sounds, in the range of tens to hundreds of Hz. Low frequencies dominate the frequency spectra of most baleen whale vocalizations. For example the blue whale, typically occurring along the Western Australia coast, produces calls with a fundamental tone at 18-26 Hz (McCauley *et al*. 2000, Salgado Kent and McCauley 2004).

4.2.2 Dugongs

Sirenians (manatees and dugongs) share common ancestry. Only one electrophysiological audiogram has been obtained for a dugong (Ketten, unpublished, referred to in Hodgson 2004), and indicates a hearing range of 4 to 32 kHz. There is more information available for manatees determined through the study of behavioural testing and auditory evoked potentials, which is summarised on Figure 9. A young Amazonian manatee *(Trichechus inunguis)* showed peak auditory sensitivity at about 3 kHz and averaged evoked potentials (AEP) from 200 Hz to 35 kHz but not at 40 kHz as measured by transcranial evoked Potentials (Bullock 1981 1982). A study based on behavioural responses showed that manatees had a range of hearing from 150 Hz to 46 kHz, which means the manatee can detect infrasonic and ultrasonic pulsed signals (Gerstein *et al.* 1994). The manatees greatest hearing sensitivity was found to be in the 6–20 kHz range.

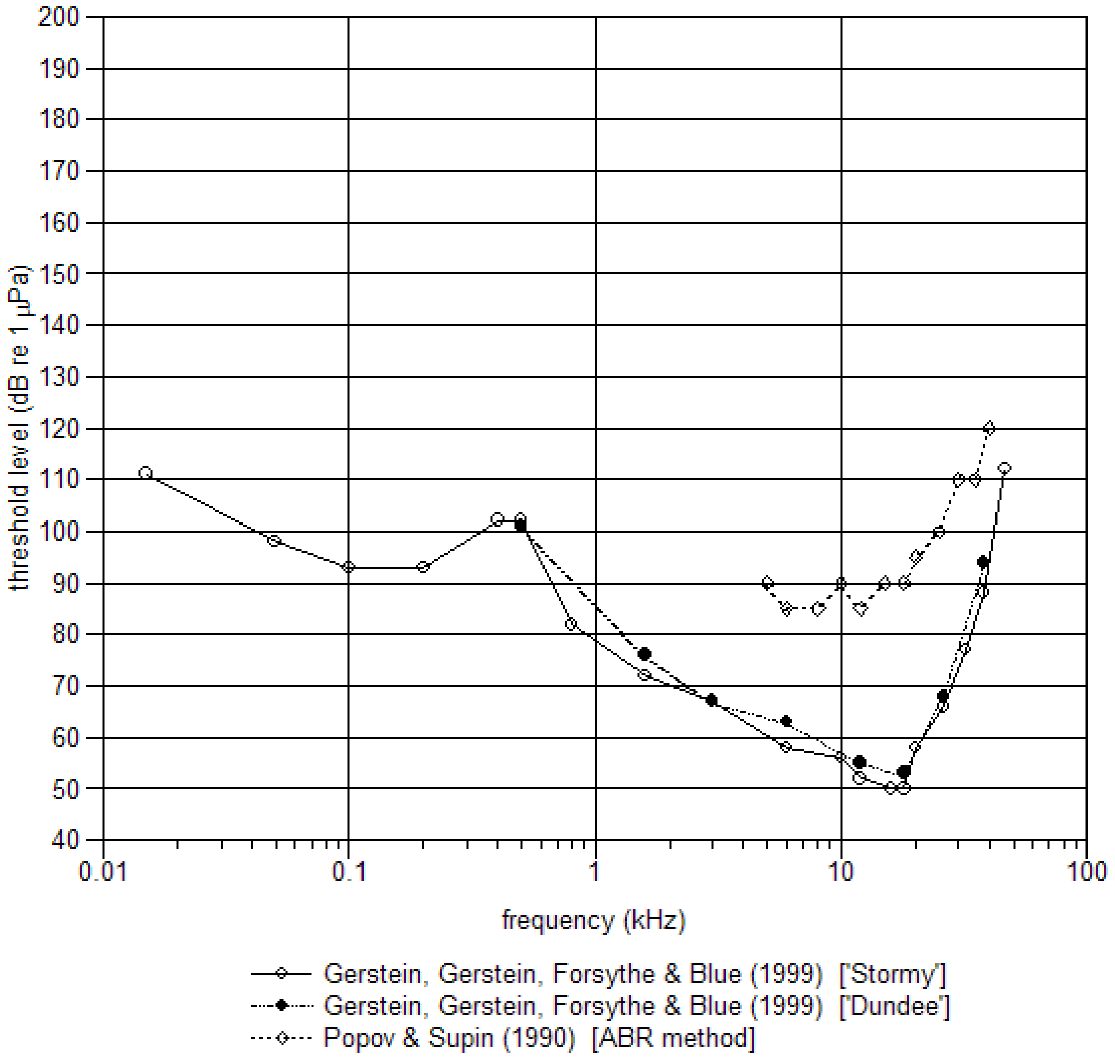

Figure 9: Underwater audiogram of manatees (*Trichechus manatus*) (figure from Nedwell *et al.* 2004).

4.2.3 Fish

Many more studies have been made on fish than on cetaceans or dugongs thus far, hence the review of hearing sensitivity and impacts presented here is more detailed.

The variability in hearing sensitivity in fish is related to the physiology of the hearing anatomy of different species (see section below; Yan *et al*. 2000). Fish have been divided into two broad groups based on hearing sensitivity, 'hearing specialists' and 'hearing generalists'. Distinctions between the groups are based on whether the species has specialised organs for improving sound reception. These two groups may serve as a general guideline for hearing sensitivity, but do not replace audiograms which accurately describe the hearing sensitivity of a species. Most fish have not yet been classified as hearing specialists or generalists.

The variation among fishes with respect to sensitivity to sound is immense, and is in part due to the diversity of anatomical structures involved in detection (Popper and Fay, 1999). Fish that have morphological adaptations to link the otolithic hearing end organs to their swimbladders or a gas filled bullae are considered 'hearing specialists'. Audiograms of 'hearing specialists' show high sensitivity to sounds with sound levels as low as 60 dB re 1µPa (MSP to tones) across a broad frequency range. Several examples of fish audiograms are shown on Figure 10.

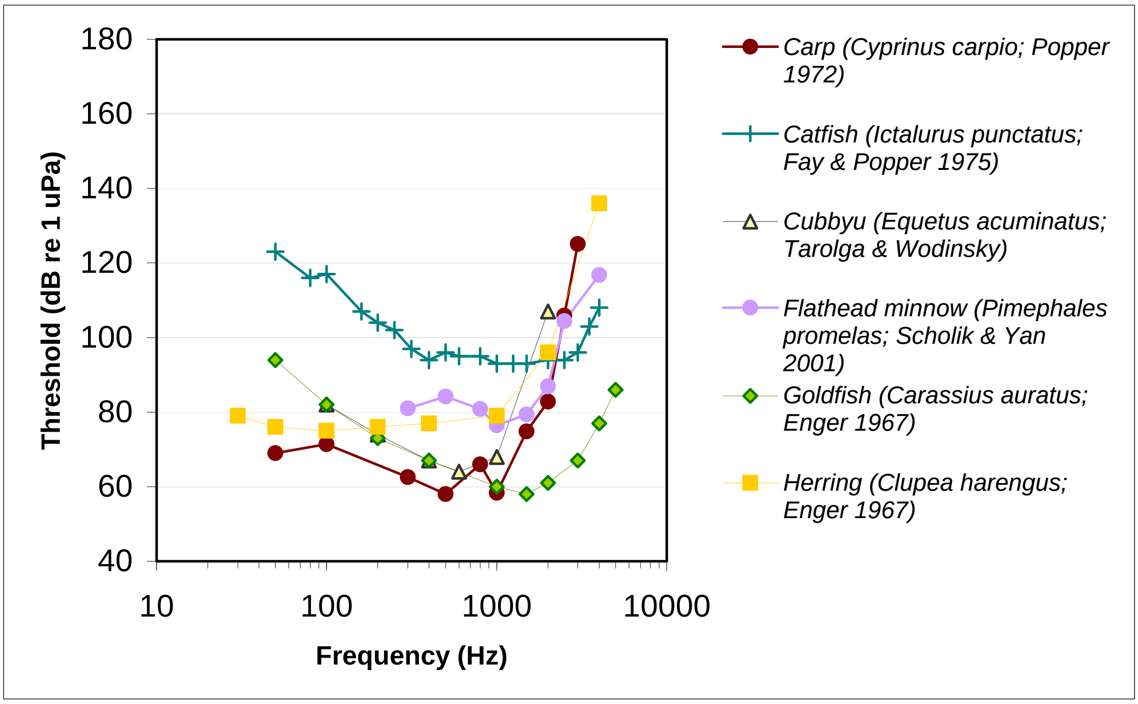

Figure 10: Underwater audiograms of some hearing specialists (from Nedwell *et al.* 2004).

Fish of the family Clupeoidea, which includes herring (*i.e. Clupea harengus,* Figure 10), anchovy (*Engraulis australis*), pilchard (*Sardinops sagax*) and sprat (*Sprattus sprattus*) are examples of hearing specialists having highly specialised auditory systems which include a structure called the prootic bulla (a gas-containing sphere evolved from the bones of the ear capsule; Blaxter, 1980; Nedwell *et al.* 2004). A membrane divides the bulla into an upper part containing fluid and a lower part containing gas. Movements of the bulla stimulate both the utricular macula and the lateral line improving sound receptivity.

Many fish have a swim bladder (rather than the prootic bulla of Clupeoidea) which is physically linked to the inner ear. The swim bladder is a gas-filled cavity that from a hearing point of view, can act to transfer an impinging sound waves pressure information, as driven by the swim bladder, to the fish ear end organs or otolith systems. Examples of fish having their swim bladder linked to the inner ear are the Otophysi (which include mostly freshwater species), including the order Cypriniformes (goldfish, carp, and minnows; Popper & Fay 1993).

Fish with the prootic bulla or coupling of the swim bladder to the fish ear end-organs, generally have higher sensitivity than those with a swim bladder only, and those with a swim bladder usually have greater sensitivity than non-hearing specialists with no swim bladder (Nedwell *et al.* 2004). Examples of species that have no direct coupling between the ear and the swim bladder and which fall into the group of 'hearing generalists' are the blue gourami (*Trichogaster trichopterus*) and the oyster toadfish (*Opsanus tau*).

Elasmobranchs rely on low frequency sound (as well as electro-chemical receptors) to locate distressed prey (Myrberg 1978). The hearing sensitivity of elasmobranches is thought to be low since they do not possess swim bladders, and are likely to fall into the hearing generalist group. Audiograms of some hearing generalist fishes are shown in Figure 11.

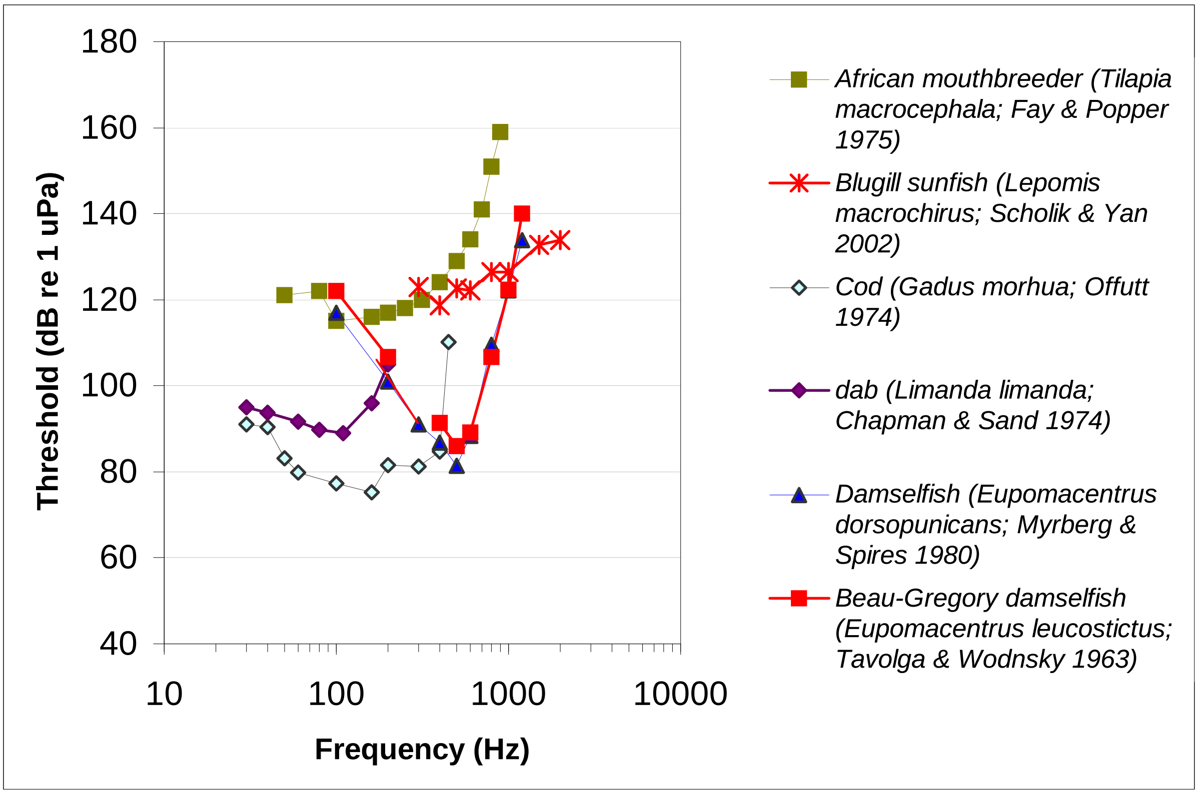

Figure 11: Underwater audiograms of some hearing generalists (from Nedwell *et al.* 2004).

4.3 Main underwater noise sources expected during the Outer Harbour Development works

To construct marine infrastructure for the Outer Harbour Development, several types of equipment will be used. There will be primarily two types of equipment for the proposed works – dredging and piling, with two pieces of equipment planned for dredging: a trailer suction hopper dredger (TSHD) and a cutter suction dredge (CSD). For dredging, the highest noise levels would be likely be emitted from a trailer suction hopper dredger (for the jetty/wharf structure). Pile driving (probably both vibratory and impact) will be needed to undertake construction work of berthing and navigation aids. Once the Outer Harbour has been developed, there will be increased noise generated from vessel movement and berthing in the Port.

4.3.1 Dredging

A trailer suction hopper dredger (TSHD) such as the one in Figure 12 is a self-propelled ship with a large internal hopper. A TSHD of a large size can be equipped with two suction pipes, one fitted to each side of the vessel, with a draghead at the end of each that is trailed along the seabed. Material is sucked through the draghead and up connecting pipes prior to discharge into the hopper.

Noise levels recorded in a trial dredge program using this piece of equipment (McCauley 2006, and Salgado Kent and McCauley 2006) indicated that broadband source levels for the TSHD could be as high as 180 dB re 1 µPa at 1 m, with a drop off of signal strength to 140-147 dB re 1 µPa MSP at 200 m in an area with a steep sloping canyon dropping from ~20-100 m deep (Mustoe 2006).

From recordings made at other sites, underwater noise level from hopper dredges appear to fluctuate depending on operating status (Richardson *et al*. 1995). Low frequencies, however, always characterize these dredges, and they can be a significant source of continuous noise. A hopper dredger under load in previous studies has higher broadband source levels than other dredging technologies (Richardson *et al*. 1995).

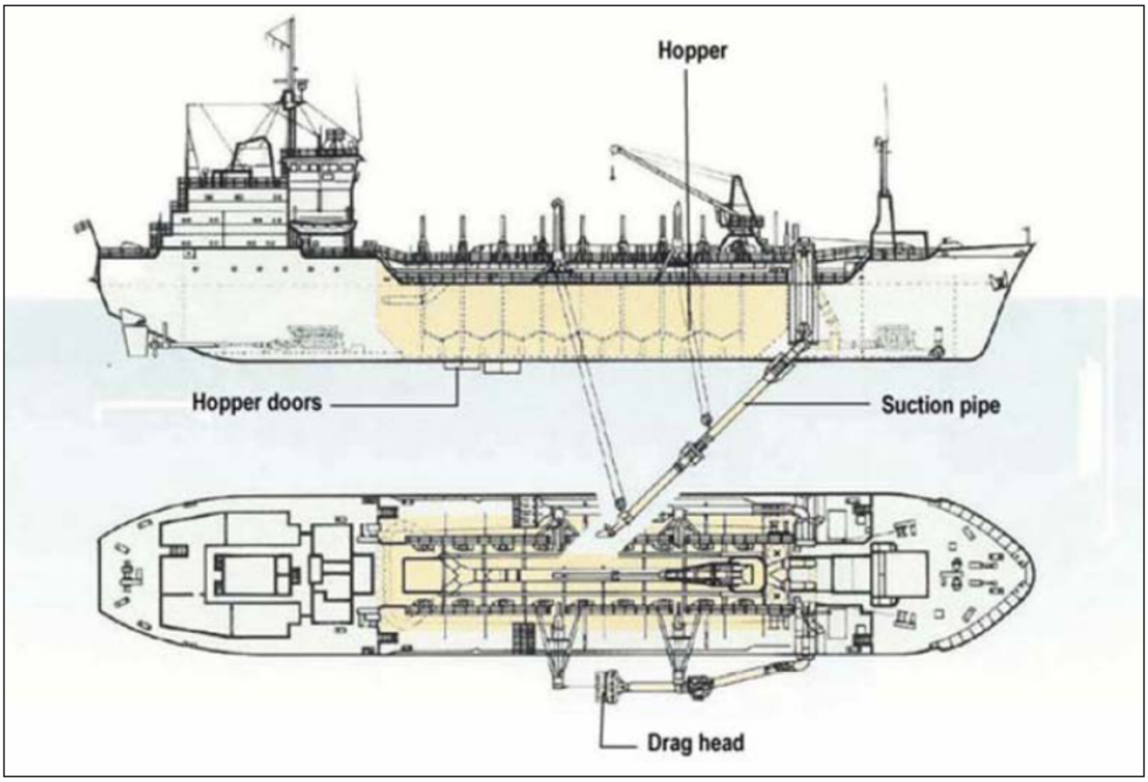

Figure 12: An example of a TSHD plan and sideviews (courtesy of PoM).

4.3.2 Pile Driving

Construction of the wharf as well as installation of navigation aids to outline the limits of the navigable channels for safe navigation by vessels through the shipping channels will require driving of approximately 1000 piles. Both hydraulic (Figure 13) and vibratory hammers will likely be used. Vibratory hammers vibrate the pile into the sediment by use of an oscillating hammer placed on top of the pile. The vibratory action causes the sediment surrounding the pile to liquefy and allows the pile to be driven into the sediment with less force. In most cases piles cannot be driven fully to the desired depth by vibratory hammers so an impact hammer (such as a hydraulic hammer) is used to finish driving the pile in.

Pile driving sounds are impulsive signals with example waveforms shown on Figure 14 and Figure 15. The frequency bandwidth for most of the energy in pile driving sounds is such that most energy occurs below 1,000 Hz (Figure 15 lower plot) although they have lower levels of higher frequency energy. The frequency content of pile driving signals matches well with the hearing capability of fish and great whales.

Figure 13: Open housing hydraulic hammer.

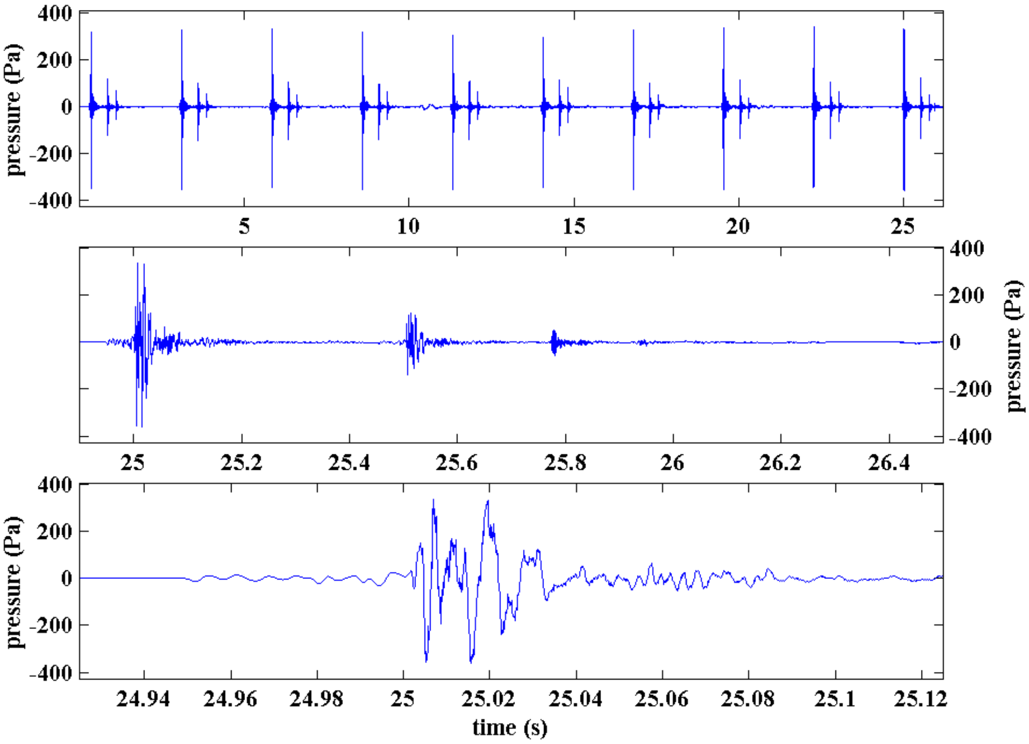

Figure 14: Waveform of blows and multiple bounces produced by pile driving at a range of 303 m at Twofolds Bay, NSW (from McCauley *et al.* 2002).

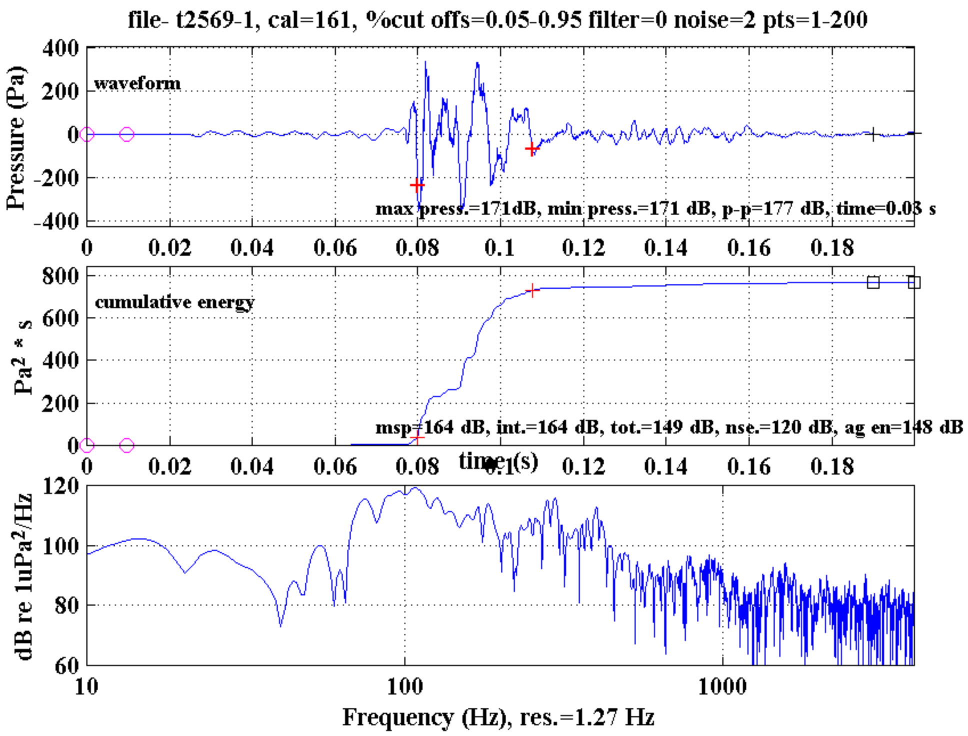

Figure 15: Signal waveform, the cumulative energy, and the power spectra of a pile driving signal from source at a distance of 303 m at Twofolds Bay, NSW (from McCauley *et al.* 2002).

Vagle (2003) reports differing sound characteristics produced by pile driving which depended upon bottom type, pile type (cedar *vs*. steel) and pile size. They suggested that with harder bottoms such as gravel or hard clay and larger piles, noise levels increased. Although this study was limited, it highlights the fact that there will be differing noise signatures resulting from different pile, pile driver, and environmental attributes. Sound levels from various projects are summarised by Hastings and Popper (2005) in Table 4, although the seafloor bottom type was not described.

For steel pipes of differing diameters driven into an area of mud/silt at two different sites in Canada, the sound energy levels below 10 kHz differed remarkably (Figure 16; Vagle, 2003). Vagle (2003) suggests that the excessive energy levels at the lower frequencies likely caused fish deaths observed in the study.

Table 4: Summary of Measured Underwater Sound Levels Near Marine Pile Driving, directly from Hastings and Popper (2005).

Pile Type	**Distance from Pile (m)**	**Peak (dB re 1µPa)**	**RMS (impulse) (dB re 1µPa)**	**SEL (dB re 1µPa^2-s)**
--Various Projects				
Timber (12-in) Drop	10	177	165	157
CISS (12-in) Drop	10	177	165	152
Concrete (24-in) Impact (diesel)	10	188	176	166
Steel H-Type Impact (diesel)	10	190	175	--
CISS (12-in) Impact (diesel)	10	190	180	165
CISS (24-in) Impact (diesel)	10	203	190	178
CISS (30-in) Impact (diesel)	10	208	192	180
--Richmond-San Rafael Bridge				
CISS (66-in) Impact (diesel)	4	219	202	--
CISS (66-in) Impact (diesel)	10	210	195	--
CISS (66-in) Impact (diesel)	20	204	189	--
--Benicia-Martinez Bridge				
CISS (96-in) Impact (Hydraulic)	5	227	215	201
CISS (96-in) Impact (Hydraulic)	10	220	205	194
CISS (96-in) Impact (Hydraulic)	20	214	203	190
--SFOBB East Span				
CISS (96-in) Impact (Hydraulic)	25	212	198	188
CISS (96-in) Impact (Hydraulic)	50	212	197	188
CISS (96-in) Impact (Hydraulic)	100	204	192	180

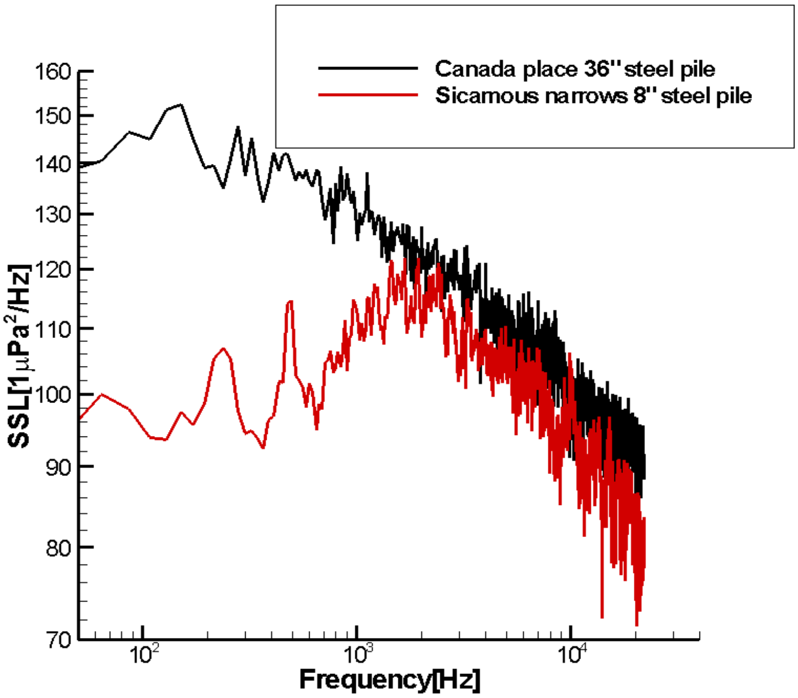

Figure 16: Spectra of a pile driving blow at Canada Place as compared to an equivalent blow in Sicamous Narrows (from Vagle, 2003).

4.3.3 Vessel movement and berthing

Vessel traffic is expected to increase as a result of the Outer Harbour Development. Hence the resulting traffic is expected to be around 960 ships per annum for Quantum, 960 ships for other BHP developments (RGP 1-6), many other ships of smaller sizes, and shipping associated with other companies.

4.4 Studies on impacts from underwater noise

4.4.1 Cetaceans

Many studies for marine mammals have recorded a response (behavioural impact) to a noise source without recording the received signal level at the animals. Therefore, availability of information on response to noise level is limited. However, the effects of elevated noise levels on marine mammals is known to include any of the following: avoidance of an area, tissue rupture, hearing loss, disruption of echolocation, masking, habitat abandonment, aggression, pup/calf abandonment, and annoyance.

Moving sources appear to often result in more acute responses. For example, there has been less response recorded by Belugas to a stationary dredger than a moving dredger (Richardson *et al*., 2005), although the sound levels have been similar. Other examples of impacts include a study where spinner dolphins were observed to reduce their use of a Hawaiian bay after noisy construction began (Shallenberger 1978). In a study on bowhead whales, observed avoidance occurred at 122-131 dB re 1µPa (MSP, or 21-30 dB above ambient, Richardson *et al.* 1990). The whales in this instance stopped feeding and moved > 2 km away. In this case, there was a start-up protocol, where noise levels were increased slowly over 10 min. In a study on grey whales, noise from dredging and shipping was prevalent for several years (Bryant *et al*. 1984). This was coincidental with grey whales being almost entirely absent from an area that they historically used. No sound levels are reported in this study.

In terms of noise impact on cetaceans, there are several levels to consider. Listed in increasing order of severity, impacts include:

- masking and interference (which can lead to behavioural responses);
- behavioural response;
- temporary threshold shift (TTS);
- permanent threshold shift (PTS);
- organ damage; and
- death.

In this assessment (section 7), we only consider those levels for which criteria have been developed, which include behavioural response, TTS and PTS/physiological damage (Southall *et al.* 2007). Criteria have not been developed for masking, nor for long term population effects, and so are not considered quantitatively in this assessment, however they are considered in a qualitative discussion of possible affects.

Although data are limited on behavioural responses, these will generally indicate some level of disturbance (that may correlate with physiological impact) hence there have been attempts to set criteria for behavioural disturbance (Southall *et al*. 2007, see section 7). There are limited data on noise levels that cause TTS or PTS in marine mammals (Richardson *et al*. 1995). However, there are risk criteria that have been developed over a number of years by different authors in an attempt to mitigate impacts. Criteria from three authors are discussed here: 1) Richardson *et al*. 1995; 2) NMFS (2006); and 3) Southall *et al* (2007) being the most recent (see section 7 for a more detailed review of these). Richardson *et al*. (1995), extrapolated sound levels required to produce PTS in marine mammals from information on human threshold levels, which was based on levels 80 dB above hearing threshold causing PTS in humans (exposure of 8 hours a day over ~10 years).

Table 5: Measured and estimated impact levels for various cetaceans (estimates are based on levels causing human threshold shifts or damage risk criteria ◊Richardson *et al.* 1995).

Species	**Response**	**Source (dB re 1 µPa at 1 m)**	**Received Level** (dB re 1 µPa)	**Source**	**Reference**
Bottlenose dolphin*	PTS	120 dB		At most sensitive freq for continuous noise	Estimate based on human PTS
Bottlenose Dolphin*	TTS	1 s tones at 3 , 10, 20, and 75 kHz	192-201		Ridgway *et al.* 1997
Bottlenose Dolphin*	TTS	4-11 kHz	179 dB for 30-50 min		Nachtigall *et al*. 2003
Bottlenose dolphin*	TTS		161 - 171 dB over almost 50 min		Nachtigall *et al*., 2003
Bottlenose dolphin*	Auditory damage	178-208 dB for 100 long pulses		Impulsive hammering	Estimate based on human DRC◊
Killer whale*	PTS	135 dB		At most sensitive freq for continuous noise	Estimate based on human PTS◊
Killer whale*	Auditory damage	178-208 dB for 100 long pulses		Impulsive hammering	Estimate based on human DRC◊
Grey Whale	Behavioural response (avoidance)	100-500 Hz	170-178 dB		Moore and Clark 2002
Dolphin and Beluga	TTS		200 dB 1 s / day		Ridgeway *et al*., 1997; Finneran *et al*. 2000; Schlundt *et al*. 2000
Harbour Porpoise	Behaviour indicative of discomfort		97-111 dB re 1 µP		Karstelein *et al*. 2005
Harbour Porpoise and harbour seal	Behavioural response		128 dB re 1 µP	Wind turbine noise	Koschinski *et al*., 2003
Bowhead	avoidance	131 dB		Dredger	Richardson *et al*. 1990

Impulsive hammering sounds may present a greater risk than continual shipping sounds because of higher peak levels. There is no current information on levels of impulsive sounds which cause TTS or PTS in marine mammals. For humans the damage risk criteria (DRC) is 4 minutes of 164 dB re 20 µPa (in air) for brief pulses (25 µs), 152 minutes for pulses 1.5 ms long, 138 dB re 20 µPa for prolonged pulses (> 200 ms) with positive and negative peak pressures (Ward 1968).

The National Marine Fisheries Service in the US (NMFS) considered that underwater Sound Pressure Level (SPL) above MSP of 180 dB re 1µPa (impulse) could cause temporary hearing impairment in whales (Vagle 2003). Based on this, the NMFS has established a safety zone of 180 dB re 1µPa MSP (impulse) for grey whales near pile driving activities. If marine mammals are found within the safety zone, pile driving was to be delayed until the whales move out of the area (NMFS 2006).

NMFS states that cetaceans should not be exposed to underwater noise exceeding 180 dB re 1µPa MSP in order to avoid permanent physiological damage to hearing. The underwater disturbance threshold for cetaceans was considered 160 dB re 1µPa MSP for impulse noises and 120 dB re 1µPa MSP for non-impulse, continuous, industrial noises. These levels were set based on data on the effects of anthropogenic noise on grey whale migration from studies by Malme *et al.* (1984, as cited in NMFS 2006). Southall *et al*. (2007) updated the criteria so that they reflect RL in SEL rather than MSP, since this more accurately reflects the energy received from impulsive signals. They recommend that levels greater than 183 dB re 1µPa^2.s for impulsive sounds, and 195 dB re 1µPa^2.s for continuous noise sources will cause TTS; and 198 re 1µPa^2.s for impulsive signals and 215 re 1µPa^2.s for continuous noise sources will cause injury (PTS). These criteria are described in further detail in Section 7.

4.4.2 Dugongs

Studies on dugongs have shown that they are highly sensitive to sound, and often respond behaviourally even to low level sound (within their hearing range). Their response time is often slow, which increases the risk of collision (Hodgson and Marsh 2007, Gerstein 2002) and results in a greater number of boat strikes. In some locations, however, even slow moving vessels collide with sirenians. Recent studies on manatees in Florida have revealed that manatees cannot hear the dominant low frequency sounds of boats and that those sounds do not propagate well in shallow water. Slow moving boats result in quieter and lower frequency sounds which are inaudible or of limited audibility to manatees in many shallow water conditions (Gernstein 2002). Currently there is an ongoing effort to develop pingers (acoustic devices that emit “pings”) which do not have the same signal attenuation problem as many vessels appear to in these shallow water environments, so that manatees and other marine mammals can be warned of an approaching vessel.

4.4.3 Fish

The extent of potential noise impacts on fish is not comprehensively understood. It is known however, that intense impulsive signals such as those produced from pile drivers, can cause fish kills, and signals of a smaller magnitude can certainly cause behavioural changes (Nedwell *et al.* 2004). High-intensity sounds may temporarily or permanently damage fish audition. However, damage to hearing by intense sound depends on the auditory threshold of the receiving species and will therefore vary from species to species (Popper and Fay 1973, 1993). The highly variable auditory sensitivity of fish, means that it is impossible to generalise on the impact of impulse signals from one species to another.

While there are no studies yet conducted that have been dedicated to measuring mortality in relation to noise exposure levels, there are many observations from explosive and pile driving sources. Studies on explosives are relevant to pile driving in this report since the characteristics of the signals are similar. Nedwell *et al.* (2004) observed that fish kills occurred at a distance of 400 m from an explosive source, but did not occur where the estimated received peak level was only 134 dB re 1µPa, (however no other distances were assessed in this study). Greene and Moore (1995) found that the mechanical impact of a short duration pressure pulse such as an explosion was best correlated with organ damage. For fish, gas oscillations induced by high sound pressure levels can cause the swim bladder to tear or rupture, as has been shown in response to explosive stimuli in several reports (*i.e.* Alpin 1947; Coker and Hollis 1950; Yelverton *et al.* 1975).

Other structures within the body can also be affected by exposure to sound because of their small size or dynamic characteristics. There is some evidence to suggest that sound at sufficiently high-pressure levels can generate bubbles from micronuclei in the blood and other tissues such as fat. In fish, blood vessels are particularly small in diameter so bubble growth by rectified diffusion (Crum and Mao 1996) at low frequencies could create an embolism and burst small capillaries to cause superficial bleeding. This type of bubble growth may also occur in the eyes of fish where the tissue might have high levels of gas saturations. Impacts such as that mentioned above, have mainly been studied for impulse signals from explosions, but have also been observed in fish exposed to impact signals from pile driving (Hastings and Popper 2005).

Several studies have attempted to quantify non-mortality injuries that resulted from pile driving (mainly in the grey literature), but the degrees of damage in these studies are not readily quantifiable and comparable among studies. Other unpublished reports have attempted to observe the behaviour of fish during pile driving activities. For example, Feist *et al.* (1992) found that there were more fish schools in an area when there was no pile driving activity than when there was pile driving activity. None of these studies, however, reported any other notable effects on the fish or their behaviour. At the same time, these observations were opportunistic observations of free-swimming fish rather than on animals with known received sound exposures related to pile driving activity.

There are no studies that have focused on long-term effects of exposure to pile driving sounds that may lead to delayed death, or to other changes in behaviour that could affect the survival of individuals or of populations of fishes. Furthermore there are no studies examining responses of fishes outside of the pile driving / explosive “kill-zone”, effects that although may not be immediate, may have significant effects on fish populations. Non-mortality effects may include temporary injury that heals, injury that leads to a slow death (e.g., break down of tissues in some organ system), temporary or permanent hearing loss, movement of fish away from feeding grounds due to high signal levels, and many other possible impacts.

Finally, it is also important to consider the effects of cumulative exposures on mortality, physiology, and behaviour. For example consideration of the effects of exposure to multiple impacts from pile driving and the time between signals (one every few seconds for example) need to be made. Another aspect of cumulative exposure that needs investigation is a larger temporal length of exposure to repeated signals (repeated exposures several hours, days, or weeks later).

A study on hearing loss up to a few days after exposure from a seismic airgun has been conducted (Popper *et al.* 2005). This study involved exposing three species of fish to sounds from a seismic airgun (an impulse sound). Peak sound levels ranged between 205 and 209 dB re 1µPa peak pressure. They exposed a hearing generalist (broad whitefish), a hearing specialist (lake chub), and a species that is intermediate in hearing (northern pike). They found that the hearing generalist had no significant effects from air gun exposure, the lake chub indicated the most effect in temporary threshold shift, and the northern pike showed a significant hearing loss but less than that of the lake chub. Lake chub and northern pike returned to their respective normal thresholds after 18 to 24 hours. McCauley *et al*. (2003) exposed pink snapper to a regime of approaching and departing air gun pulses and observed strong behavioural changes (increase in startle responses, and changes in schooling patterns), and evidence of massive hearing damage which did not fully show until 60 days after the impulse exposure.

Table 6: Impacts for various fish species (TTS = temporary threshold shift).

Species	Level of Impact	Sound Source characteristics	Received Sound Level	Reference
Lake chub (fish)	TTS	200, 400, 1600 Hz	100 dB re 1µPa (RMS)	Popper *et al.* 2005
Fish	Alarm response		Multiple pulse signals 156-161 dB re 1µPa (RMS)	McCauley *et al.* 2000
Goldfish	TTS	500 and 800 kHz	149 dB re 1µPa (RMS) for 4 hrs	Popper and Clarke 1976
Flat fish and invertebrates	injury		217 dB re 1µPa (peak)	Cudahy *et al.*, 1998
Pink snapper	Hearing damage	Air gun	Ensemble of pulse signals up to 185 dB re 1µPa (RMS)	McCauley et al (2003)

It is difficult to extrapolate dredging noise from studies based on other types of signals (e.g., pure tones, air guns) since each sound source has particular signal characteristics in terms of duration, rise and fall times and frequency content (Yelverton *et al.* 1975; Hastings *et al.* 1996; McCauley *et al.* 2002). Specific signal components that affect marine animals may be different. Furthermore sound exposure levels are highly dependent on the characteristics of the environment which will affect propagation of the sound produced. Sound pressure levels do not necessarily decrease monotonically with increasing distance from the pile for example, since it depends upon the propagation characteristics of the water column and the seabed. When assessing impacts from noise it is advisable to measure noise levels within the proposed impact areas and / or to conduct sound propagation modelling exercises, in order to develop exposure metrics that may correlate with mortality and different types of impacts (including damage) observed in exposed animals.

Fish Kills

Key variables that appear to control the physical interaction of sound with fishes include the size of the fish relative to the wavelength of sound, mass of the fish, anatomical variation, and location of the fish in the water column relative to the sound source. Most studies on fish kills have been related to explosive blast pressure waves consisting of an extremely high peak pressure with very rapid rise times (< 1 ms). Yelverton *et al.* (1975) exposed eight different species of fish, five with ducted swim bladders and three with non-ducted swim bladders to blasts. Fish sizes ranged from 0.02 g to 744 g body mass and included small and large animals from each species. The fish were exposed to blasts having extremely high peak pressures with varying impulse lengths. Yelverton *et al.* (1975) found a direct correlation between body mass and the magnitude of the "impulse," (characterized by the product of peak overpressure and the time it took the overpressure to rise and fall back to zero), which caused 50% mortality. Trasky (1976) also reported significant differences between adult fishes, and salmon and herring fry in the lethal blast overpressure from buried seismic charges.

Additional studies using explosives suggest that there is far more damage to fishes with swim bladders than to species, such as flatfish, that do not have such air chambers (*e.g.*, Baxter *et al.* 1982, Hastings and Popper 2005). It has also been shown that the effects on fish decline rapidly with distance from the explosion as the peak overpressure decreases and the impulse duration increases. Similarly, a study by Kearns and Boyd (1965) suggested that the extent of fish kill decreases with increasing distance of the fish from an air gun source, and another unpublished study indicated no mortality from seismic air gun shots at considerable distance (4000 m) from the source.

There is evidence that the effects of explosions vary by species, even when all test fish have a swim bladder (Govoni *et al*. 2003). Based on these and other studies (*i.e.* Yelverton *et al.* 1975), it is clear that there is considerable variability in the effects of explosive blasts on fishes, and that the variables include received sound energy, presence or absence of gas bubbles (*i.e*., swim bladder), mass of fish and perhaps body shape, and biomechanical properties of the swim bladder wall.

Yelverton *et al.* (1975) suggested that a metric related to the amount of sound energy received, such as the sound exposure level rather than just peak pressure correlates with swim bladder and other tissue damage as well as mortality in fish. They concluded that peak pressure alone did not correlate with damage because peak pressure was kept constant and the impulse duration was varied or vice versa in their study. The injuries observed included swim bladder rupture, kidney damage, and liver damage.

Govani *et al.* (2003) also concluded that the total energy in the sound wave, regardless of pressure polarity, was responsible for observed effects of submarine detonations on juvenile pinfish (*Leiostomus xanthurus*). Moreover, Stuhmiller *et al.* (1996) suggested that incidence of blast injury to the lung and lethality correlated with total energy in the wave normalized by lung volume in terrestrial animals.

Other authors have suggested that the large negative overpressure characteristic of pile driving sounds may be more damaging to the swim bladder than the initial positive overpressure (Trasky 1976) because of the swim bladder expansion during the negative phase. Bailey *et al.* (1996), however, found that a sound pulse having a large positive peak overpressure was at least as damaging as one having a large negative peak overpressure of approximately the same level and duration, to the lungs of mice submerged in water. Damage increased with magnitude of pressure incident at the lung, but histology showed no differences between the effects of positive and negative pressures. Mouse lungs had increasing haemorrhage with increasing exposure levels regardless of the polarity of the peak overpressure. These findings indicate that injury would correlate with the work done on the lung tissue, which would be equivalent to the total energy in the sound wave.

Taking into consideration the limitations of any extrapolation when assessing level of fish kill, Hastings and Popper (2005) made a preliminary attempt at estimating levels of impact. Their reasoning was that if transient sounds, such as those produced by pile driving, could be characterized using a waveform similar to the ideal impulse sound, then effects of pile driving on aquatic animals could potentially be extrapolated from data based on effects observed from exposure to other transient signals (e.g. explosives, air guns, sonic booms) or other transient waveforms that could be described by the Friedlander wave model. These estimates could provide a basis for developing interim guidance for exposure to sound from pile driving until more research is completed. Hastings & Popper (2005) show an approximation of a pile driving sound using a Friedlander wave, and compare the temporal characteristics, sound exposure spectral density, and cumulative pressure squared over time, respectively, for the idealized and actual pile driving sound. This showed that pile driving waves are very close to explosives in exposure characteristics, at least at short range, which indicate that the key characteristics for pile driving may be the peak positive and negative pressures and their duration, which are combined to calculate the cumulative pressure squared and Sound Exposure Level (SEL). Thus Hastings & Popper (2005) suggest that a systematic approach to approximate pile-driving signals using Friedlander type waves could provide a way to determine how data, which have been obtained in effects studies using blasts or other transient sources, relate to different pile driving scenarios.

Based on the above methods and extrapolating from Yelveron *et al.* (1975), Hastings & Popper (2005) estimated impacts were predicted relative to Sound Exposure Level (SEL) as shown below on Figure 17. These estimates are based on a limited set of fish species.

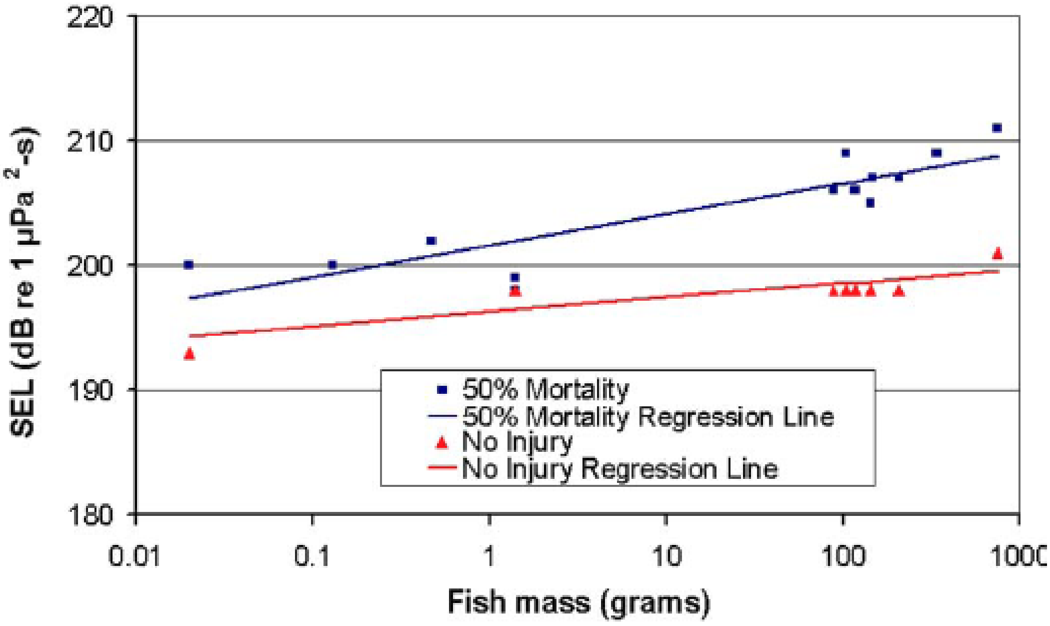

Figure 17: Estimated sound exposure level (SEL) that results in 50% mortality based on data for exposures to a single explosive sound as reported by Yelverton *et al.* (1975) and modelled as an ideal impulse wave. (Friedlander waveform as described by Hamernik and Hsueh 1991). Directly from Hastings and Popper (1995).

Based on the studies that have been made, Hastings (in 2002) recommended 150 dB re 1µPa (MSP) and 180 dB re 1µPa peak for impulsive sounds as the thresholds for protecting salmon against physiological damage (NOAA/USFWS 2005), and 150 dB re 1µPa (MSP) level as the threshold for disturbance to salmon, and bull trout. Based on their assessment, sound pressure levels in excess of 150 dB re 1µPa (MSP) were expected to cause temporary behavioural changes, such as elicitation of a startle response, disruption of feeding, or avoidance of an area. The USFWS (2004) has also identified underwater injury threshold sound levels for bull trout at 180 dB re 1µPa peak.

4.5 Critical sounds levels and noise risk criteria

4.5.1 Cetaceans

The most recent sound exposure criteria so far developed for underwater impacts on cetaceans have been recently published by Southall *et al.* (2007). Information presented by Richardson *et al.* (1995), however, is more comprehensive in describing underwater sound and studies on impacts of anthropogenic sound sources on marine mammals, but it does not include information that has become available during the last ~ 10 years.

The speculative Damage Risk Criteria (DRC, inferred from auditory Damage Risk Criteria for humans) for pulses for marine mammals presented by Richardson *et al.* (1995) are presented in Table 7.

Table 7: Inferred Auditory Damage Risk Criteria for marine mammals exposed to noise pulses underwater (from Richardson *et al.*, 1995).

Number of pulses	**Speculative DRC (in dB re 1µPa) for marine mammals listening in water**	
	Marine mammal with hearing threshold of 40 dB re 1uPa	Marine mammal with hearing threshold of 70 dB re 1uPa
100 long (>200 ms)	178	208
10 long (>200 ms)	183	213
1 long (>200 ms)	188	218
1 short (25 ms)	214	244

Southall *et al*. 2007 considered these criteria, historical work (such as that presented in section 4.4), and information that has recently become available, to create a new set of risk criteria based on three criteria (injury, TTS, and behavioural disturbance), three types of noise (single pulses, multiple pulses, and non-pulses), and five marine mammal groups based on hearing sensitivity (low frequency cetaceans, mid frequency cetaceans, high frequency cetaceans, pinnipeds in water, and pinnipeds in air, Table 8). The low frequency cetaceans include mainly the baleen whales (of estimated auditory bandwidth between 7 Hz-22 kHz such as the humpback and the blue whales), mid frequency cetaceans include many of the beaked whales, sperm whale, killer whales, and many inshore and offshore dolphins such as the bottlenose and the indo-pacific humpback dolphin (with estimated auditory bandwidth between 150 Hz - 160 kHz, the high frequency cetaceans include many of the river dolphins (200 Hz -180 kHz). Sirenidae (dugong), however, were not included within any of these groups based on the conclusion that there was too little information available to do an accurate risk assessment. Rather than detailing the risk criteria methodology, and qualifying assumptions made by the authors, the reader is referred to Southall *et al.* (2007) for a comprehensive description of the risk criteria methodology developed for cetaceans. Relevant matrices developed by Southall *et al*. (2007) are presented here in Table 9 and Table 10.

Table 8: Cetacean hearing sensitivity groups defined by Southall *et al.* (2007).

Marine mammal group name	Estimated auditory bandwidth
Low frequency cetaceans	**7 Hz – 22 kHz**
Mid frequency cetaceans	**150 Hz – 160 kHz**
High frequency cetaceans	**200 Hz – 180 kHz**

Based on published studies, Southall *et al*. (2007) considered behavioural responses to multiple pulses (mostly seismic survey signals) and non-pulsed noise (such as dredging) as highly variable, depending upon group, species and individual as well as context (*i.e.* source proximity, novelty, whether animals are migrating, foraging, resting or whether animals are residents or transients, *etc*.). For multiple pulses and migrating low frequency cetaceans, behavioural disturbance occurred at RL as low as 120 re 1 µPa (MSP) for bowhead whales (Richardson *et al*., 1986; 1999), whereas for all other low frequency cetaceans reviewed behavioural disturbance occurred at received levels around 160 dB re 1µPa (Malme *et al*., 1983; 1984; Ljungblad *et al*., 1988; McCauley *et al*., 1988; Todd *et al*., 1996).

In certain conditions relatively low RLs (80-90 dB re µPa) temporarily silenced the individual vocal behaviour of a sperm whale (Madsen & Møhl 2000; Madsen *et al.* 2002). In other conditions multiple pulses RL between 120- 180 dB re 1µPa did not elicit responses from a significant percentage of individual sperm whales (Akamatsu *et al*. 1993; Madsen & Møhl, 2000; Madsen *et al.* 2002; Miller *et al*. 2005).

For non-pulsed noise sources, low frequency cetaceans appear to respond at RL in the range of 120-160 dB re 1µPa. For mid-frequency cetaceans, results in the literature are highly variable, with some individuals responding with high severity to RL between 90-120 re 1µPa, and other individuals failing to respond to RL between 120-150 dB re 1µPa. There are no studies or criteria for repeated exposure of any of these sources (over month and years for example).

Table 9: Proposed injury criteria for individual marine mammals exposed to "discrete" noise events (either single or multiple exposures within a 24-h period (modified from Southall *et al.*, 2007).

Marine mammal group	**Sound type**		
	Single pulses	Multiple pulses	Non-pulses (includes continuous noise)
Low-frequency cetaceans			
Sound pressure level	230 dB re: 1 µPa (peak)(flat)	230 dB re: 1 µPa (peak)(flat)	230 dB re: 1 µPa (peak)(flat)
Sound exposure level	198 dB re: 1 μPa^2-s	198 dB re: 1 μPa^2-s	215 dB re: 1 μPa^2-s
Mid-frequency cetaceans			
Sound pressure level	230 dB re: 1 µPa (peak)(flat)	230 dB re: 1 µPa (peak)(flat)	230 dB re: 1 µPa (peak)(flat)
Sound exposure level	198 dB re: 1 μPa^2-s	198 dB re: 1 μPa^2-s	215 dB re: 1 μPa^2-s
High-frequency cetaceans			
Sound pressure level	230 dB re: 1 µPa (peak)(flat)	230 dB re: 1 µPa (peak)(flat)	230 dB re: 1 µPa (peak)(flat)
Sound exposure level	198 dB re: 1 μPa^2-s	198 dB re: 1 μPa^2-s	215 dB re: 1 μPa^2-s

Table 10: Proposed TTS criteria for individual marine mammals exposed to "discrete" noise events (either single or multiple exposures within a 24-h period (modified from Southall *et al.*, 2007).

Marine mammal group	**Sound type**		
	Single pulses	Multiple pulses	Non-pulses
Low-frequency cetaceans			
Sound pressure level	224 dB re: 1 µPa (peak)(flat)	224 dB re: 1 µPa (peak)(flat)	224 dB re: 1 µPa (peak)(flat)
Sound exposure level	183 dB re: 1 μPa^2-s	183 dB re: 1 μPa^2-s	195 dB re: 1 μPa^2-s
Mid-frequency cetaceans			
Sound pressure level	224 dB re: 1 µPa (peak)(flat)	224 dB re: 1 µPa (peak)(flat)	224 dB re: 1 µPa (peak)(flat)
Sound exposure level	183 dB re: 1 μPa^2-s	183 dB re: 1 μPa^2-s	195 dB re: 1 μPa^2-s
High-frequency cetaceans			
Sound pressure level	224 dB re: 1 µPa (peak)(flat)	224 dB re: 1 µPa (peak)(flat)	224 dB re: 1 µPa (peak)(flat)
Sound exposure level	183 dB re: 1 μPa^2-s	183 dB re: 1 μPa^2-s	195 dB re: 1 μPa^2-s

4.5.2 Dugongs

No auditory criteria based on injury, TTS, or behaviour exists for dugongs. Dugong sensitivity range may fall between the low-frequency and mid-frequency cetaceans. For the purposes of this assessment, the criteria for low-frequency and mid-frequency cetaceans for injury and TTS are proposed for application to dugongs, since sensitivity and hearing frequency range broadly overlap. The likelihood of behavioural disturbance is much more difficult to ascertain given the little information available, much of which is qualitative. A brief description of anecdotal evidence is given below for Sirenians in general.

Sirenians appear to be highly sensitive to disturbance when not habituated. Dugongs have been recorded to respond to outboard boats running at moderate-speed in Shark Bay at a distance of at least 150 m with avoidance (Anderson, 1982). A fast outboard powered boat resulted in aggregation and vertical surfacing by a distinguishable component of a dugong group (Anderson, 1982). Bengston and Fitzgerald (1985) noted manatee's react to shuffling feet in a boat 15 m distant, human voices at 5 m, and an aircraft engine 300 m from the animal (Bengston and Fitzgerald 1985). Manatees have been observed to dive to the bottom in deep water as a response to an outboard motorboat approach, when in shallow water head to deeper water, and to "panic" when surprised (Hartman, 1971). Sirenians, however, appear to be much less sensitive if habituated to non-detrimental sounds. Anderson (1982) indicated that tradition suggests dugongs flee in response to faint unfamiliar sounds, however when researchers failed to induce flight it was suggested that reactions are learned where dugongs are hunted. Sound responses tested on two captive manatees where the source intensity increased from 75 to 197 re 1µPa at 12 kHz, resulted in no significant response from the animals (Kinnaird 1983). Reynolds (1981) suggested that manatees may habituate to the sound of boat engines, however they may become confused when surrounded by numerous boats (Tiedemann 1980). Finally, Hodgson (2004) found that dugongs habituated to high boat traffic in Moreton Bay (Queensland, Australia) responding only when vessels were within 50 m of the animal, even when the vessels' heading intersected the dugong's position.

4.5.3 Fish

Based on the studies reviewed in this report regarding fish, recommendations for auditory criteria based on physiological damage, TTS, and behaviour responses have been presented. These are RLs of 180 dB re 1µPa (peak) for impulsive sounds as the thresholds for injury, 170 dB re 1µPa (peak) for TTS, and 150 dB re 1µPa (MSP) level as the threshold for disturbance. Behavioural responses to RL of 150 dB re 1µPa (MSP) are expected to cause temporary behavioural changes, such as elicitation of a startle response if the noise onset is sudden, disruption of feeding, or avoidance of an area. No auditory criteria have been developed for non-pulse noise. Also, there are no studies or criteria for repeated exposure of any of these sources over long time periods.

4.6 Summary

Impacts to a large number of species which occur in the Project Area may be of significance because of their listing as species protected under legislation, or because of their economic or recreational importance. For cetaceans, three species are likely to occur year round within the immediate area. These three species include the snubfin dolphin, Indo-Pacific humpback dolphin, and the spotted bottlenose dolphin. Although little is known about the occurrence of dugongs in the Port Hedland area, they have been sighted in the area. In 12 months of fortnightly water quality monitoring surveys two individuals have been spotted on the landward side of Weerdee Island. Also a turtle spotting aerial survey conducted in December 2008 observed 3 individuals and a group of 6-8 dugongs near Little Turtle Island (Pendoley 2009). Breeding and migrating humpback whales move close to the coast seasonally. A large number of other species of megafauna including whale sharks, blue whales, killer whales and minke whales also occur within the broader region although can be expected to be rare visitors to the Port Hedland works area. Finally the coastal area including the Project Area is considered to be significant nursery areas for regional and commercially important fish (and invertebrates).

Information on the specific sensitivity to sound energy for the majority of these species is not available, however, it can be said that the sensitivity to sound of differing groups is:

- Dugongs: this species may have a hearing range somewhere between 150 Hz and 40 kHz (inferred from manatees), with greatest sensitivity in the low kHz range;
- Odontocetes, including the dolphins and killer whale, have sensitive hearing which is centred at high frequencies (10-100 kHz);
- Baleen whales: Many baleen whales hear at low frequencies (10 Hz to 1 kHz) although a high frequency hearing capability cannot be ruled out.
- Fish (Hearing Generalists and Specialists): highly variable sensitivity to sound energy, with highest sensitivity at mid frequency ranges (typically 20-100 Hz to 1 kHz, although some species can hear into the kHz range). Hearing generalists may have a narrower frequency range of sensitivity than hearing specialists.

A summary of hearing sensitivity from measured audiograms of the fish and marine mammals discussed earlier in this section is presented below in Figure 18. The arrows within the figure indicate a general frequency range of sensitivity for these animals.

In terms of noise sources related to the Outer Harbour Development works, the following equipment is expected to create noise above background noise levels:

- Pile drivers,
- Cutter suction dredges and Trailer Suction Hopper Dredge (TSHD),
- Increased shipping and vessel traffic associated with harbour works, and

The potential noise impacts upon individual organisms from the above listed noise sources can be categorised into the following order based on degree of severity at the level of the individual organism, from highest to lowest:

- Organ damage: physiological damage which may lead to death.
- Permanent Threshold Shift (PTS): a permanent shift in hearing sensitivity.
- Temporary Threshold Shift (TTS): a temporary effect upon hearing (i.e. recoverable), and
- Behavioural responses: which may span short term startle responses to long term avoidance of areas by animals or a change to movement pathways or migration routes. These responses also include those resulting from masking.

Damage risk criteria from Southall *et al.* (2007) are the main criteria that will be used here to assess the level of impact, since these are deemed to be the most comprehensive and recent. Other criteria (Richardson *et al*. 1995 and NMFS 2006) have been used where there has been a lack of information in Southall *et al*. (2007). The impact assessment for fish (including sharks) is based on damage risk criteria developed by NOAA/USFWS 2005.

Finally, the impact assessment has focused on the species of cetaceans that are highly likely to occur within close proximity of the port development project; and the assessment on fish is inclusive of sharks (including the whale shark).

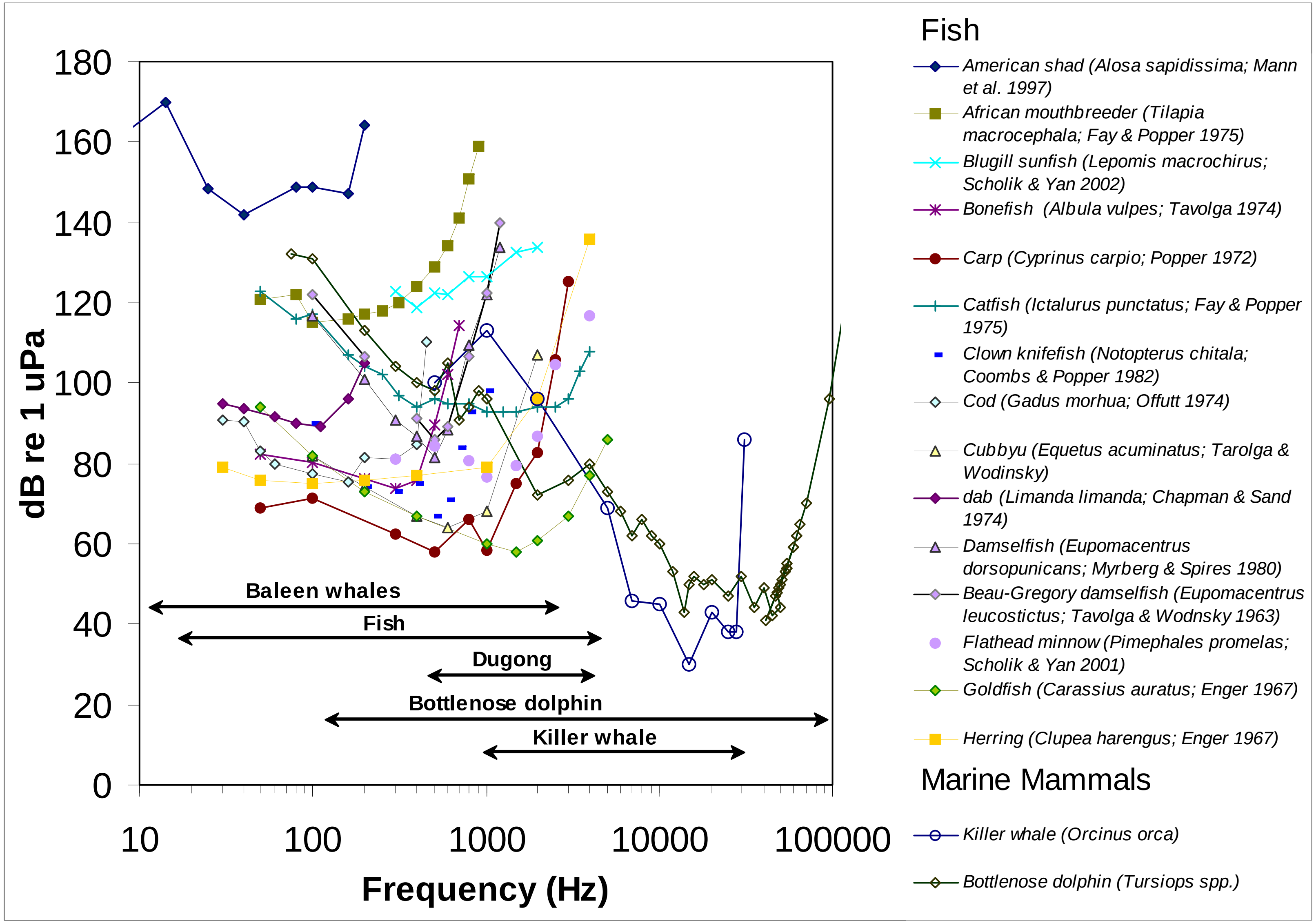

Figure 18: Summary of estimated hearing range based on audiograms of fifteen fish species and two marine mammals (from Nedwell *et al.* 2004). Estimated hearing range of dugongs in the figure are based on manatee audiograms (Gerstein *et al.* 1994), and for baleen whales are based on vocal frequencies used and observed behavioural responses to sounds (Southall *et al.* 2007)

5 Underwater noise prediction for the Outer Harbour Development works

5.1 Background noise at Port Hedland

The major noise sources evident in the recordings from deployed sea noise loggers were vessel noise, distant airgun signals, humpback whale signals, fish noise, and snapping shrimp. It should be noted that many ambient noise sources, particularly those of biological origin, display marked seasonality in their calling behaviour. Thus the 14 day period sampled here, while significant in itself, must be considered a snapshot only. Many biological sources which may be present at some time of the year will not necessarily be represented, and physical sea noise will only reflect the sea conditions over the recording period.

To visually display long term trends in the noise sources evident in the data, stacked sea noise spectra have been calculated and graphed (Figure 19 shows sea noise from the 09-Oct to 17-Oct-2008, and Figure 20 from 17-Oct to 23-Oct-2008). These plots are made by taking the time averaged power spectra of each sample at four frequency resolutions and stacking a combination of the averaged spectra through time as a colour plot. The figures are displayed with a logarithmic frequency scale from 10 Hz to 4800 Hz (the upper calibrated limit of the recording system) and a fixed colour scale with bounds from 60 to 110 dB re 1 $\mu Pa^2/Hz$. While high frequency dolphin clicks were not recorded by the sampling equipment since their frequency will be above that sampled at, any lower frequency dolphin whistles and dugong calls with energy up to 4.8 kHz will have been detected. The colour scale bounds have been fixed to standardise the plots and optimise the colour dynamic range (highlighting the natural animal chorus levels which tend to be lost if the full recording dynamic range is used). These figures are designed to detect broad scale temporal patterns only, and because of the averaging involved (within a sample) can miss or not display well signals which are short relative to the sample length (such as dolphin signals).

A description of the major noise sources seen in the stacked spectra is given below.

- Vessel noise – several types of vessel noise were present in the recordings, including: 1) small vessel traffic; 2) ship passages (*i.e.* the short wide band burst of energy on the top panel of Figure 19 on the evening of the 9-Oct-2008, near sample 100); 3) the noise from moored ships (illustrated as wavy lines over 100-1000 Hz on all days except the 23-Oct); and 4) bursts of cavitation noise from ships manoeuvring nearby, presumably for anchoring. The moored ship noise was dominated by a series of tones which varied as the vessel producing the noise swung around on its anchor. This swinging had the effect of changing the range to the noise logger, and the multipath structure and tonal frequencies received by the logger.
- Distant air gun signals – Signals similar to distant air gun energy was transmitted to the sea noise logger via ground borne paths (suggesting shallow sand over limestone) with energy arriving at < 50 Hz. The signals had a regular 8-10 second repetition (shot spacing) occurring in batches of a few hours (representing a survey line) which is typical of seismic operations. This energy can be seen from the 14-Oct-2008 to the morning of the 18-Oct-2008.
- Humpback whale signals – there was almost continual humpback whale singing in the two week recording. Examples of nearby humpback whale singing can be seen in several places in the data set, with a 12 hour burst shown on Figure 20 (top panel) centred around midday on the 20-Oct-2008.
- Fish noise – Several types of fish noise were present and common in the recording set.
- Snapping shrimp noise – While not evident on Figure 19 and Figure 20, low level snapping shrimp noise was present throughout the full recording period.

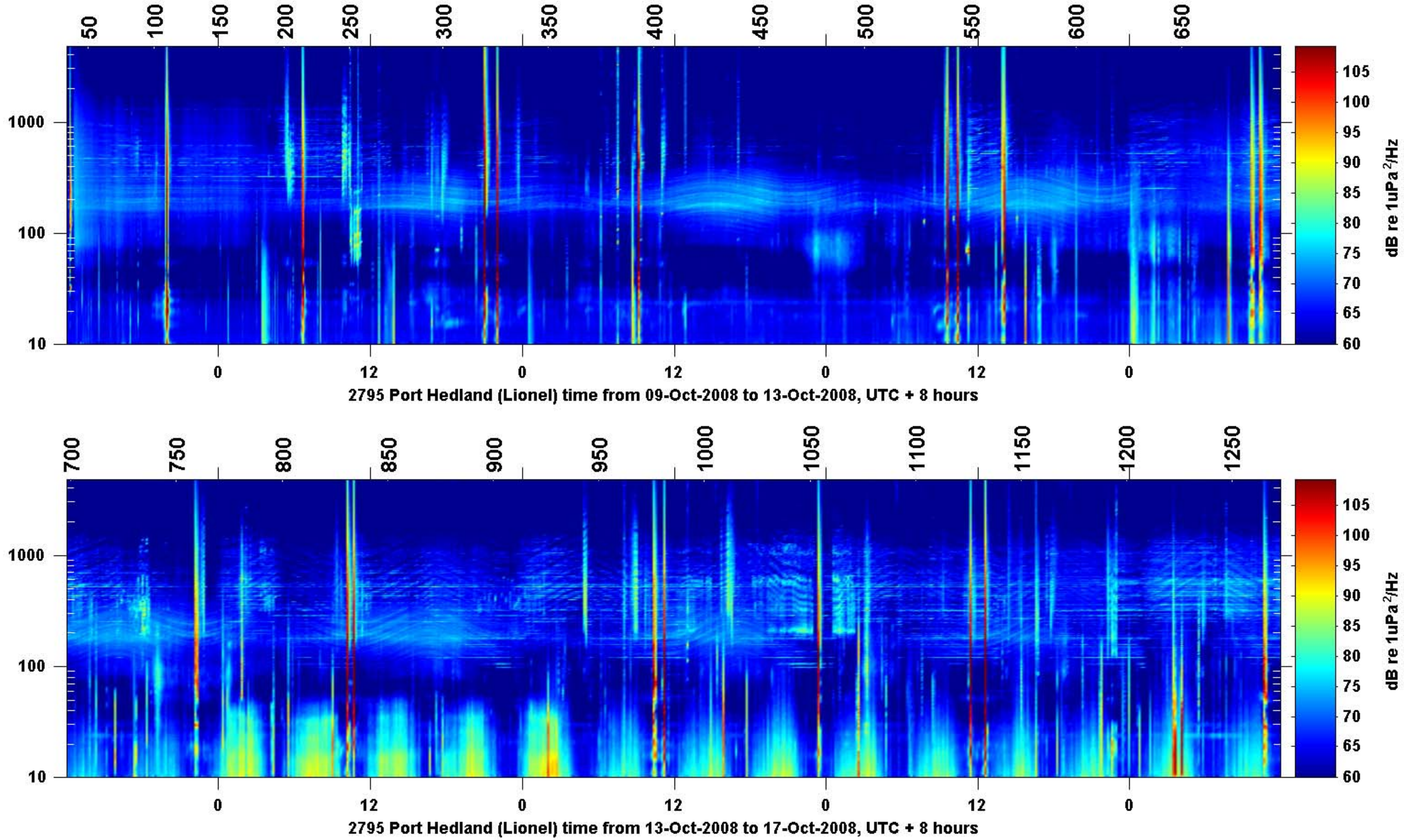

Figure 19: Stacked sea noise spectra from the noise logger set off Port Hedland over 9-17 Oct-2008. A logarithmic frequency scale has been used, the received spectra level colour scale fixed and the upper values refer to sample numbers.

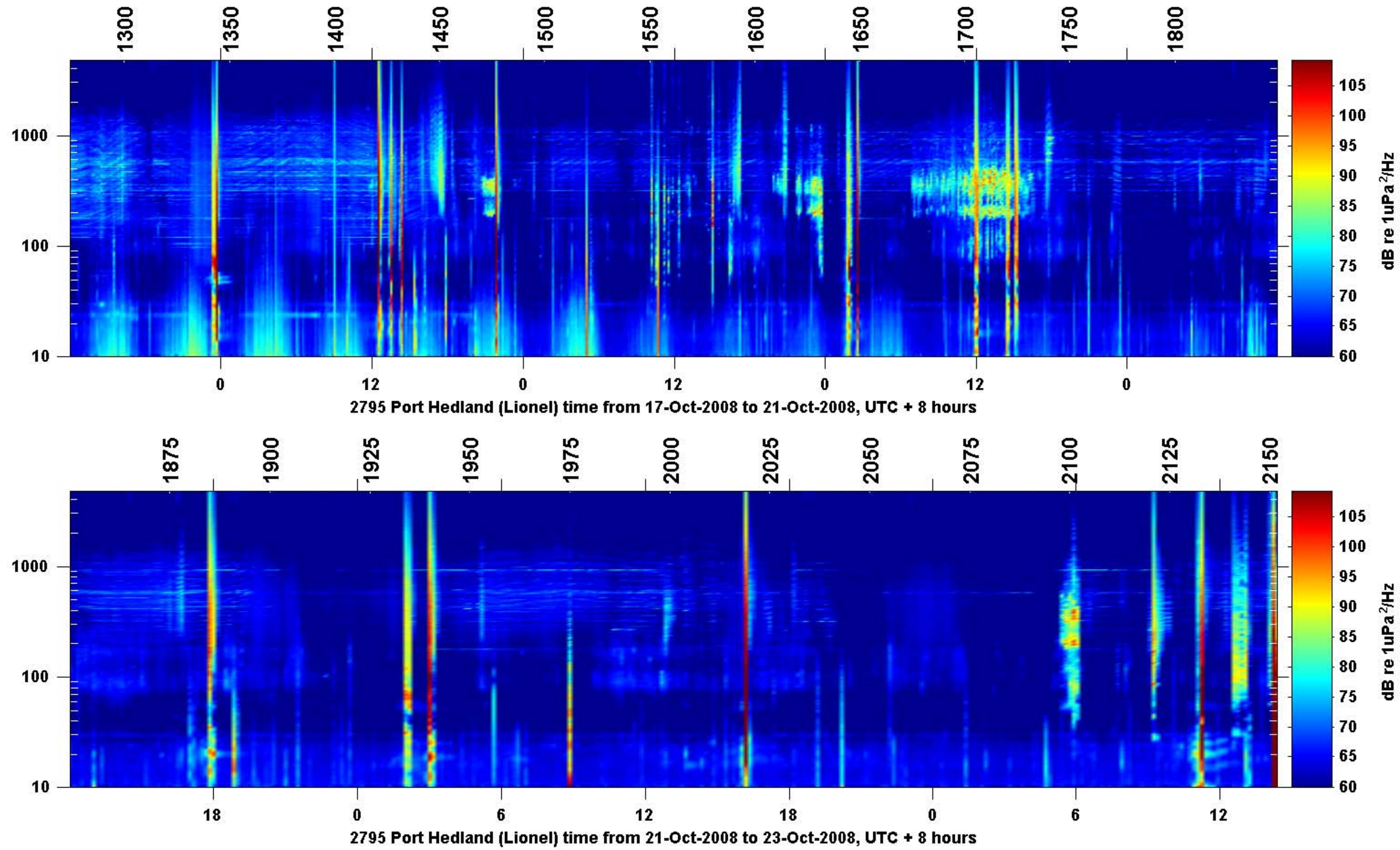

Figure 20: Stacked sea noise spectra from the noise logger set off Port Hedland over 17-23 Oct-2008. A logarithmic frequency scale has been used, the received spectra level colour scale fixed and the upper values refer to sample numbers.

5.1.1 Ambient noise

Quantifying ambient noise is a vexed problem since this requires a definition of what noises are considered natural sources and what are considered as ‘noise’. For a busy harbour, for example, shipping noise is constant and could be considered to be normal ambient conditions for the area. For the purposes here, ‘ambient’ noise is considered to be the background noise without any anthropogenic sounds. This still leaves several biological sources which will contribute to the baseline noise levels; including snapping shrimp, fish and humpback whales. In the recordings made for this study, there was always snapping shrimp noise present, almost always some level of fish noise, and sporadic humpback whales – at times distant and at times close. Thus, baseline noise conditions here have been defined as natural noise, which include snapping shrimp noise and a degree of fish noise.

Snapping shrimp noise varied across the recording period by up to around 8 dB (in long term time averaged trends), but not in any easily discernible cycle. The total input into sea noise by snapping shrimp was low. In fact, the levels were low enough that they would not have contributed to the total broadband ambient noise level, thus this variation in shrimp noise has been largely ignored.

To assess ambient noise levels in the absence of vessel noise, a ‘quiet’ vessel noise period was selected from the recordings. There was only one period in the two week recording with comparatively low vessel noise levels. This period was over the last two days of the set, on the 22 and 23-Oct (evident on the lower panel of Figure 20). This ‘quiet’ period is shown in eight frequency spectra with averaged levels across a respective 300 second noise logger sample (shown on Figure 21). Also shown on Figure 21 are the mean of the eight spectra, and predicted sea noise for 5 knot wind speed (based on predictions of Cato 1997, which predict wind noise levels only – *i.e.* no vessel traffic noise).

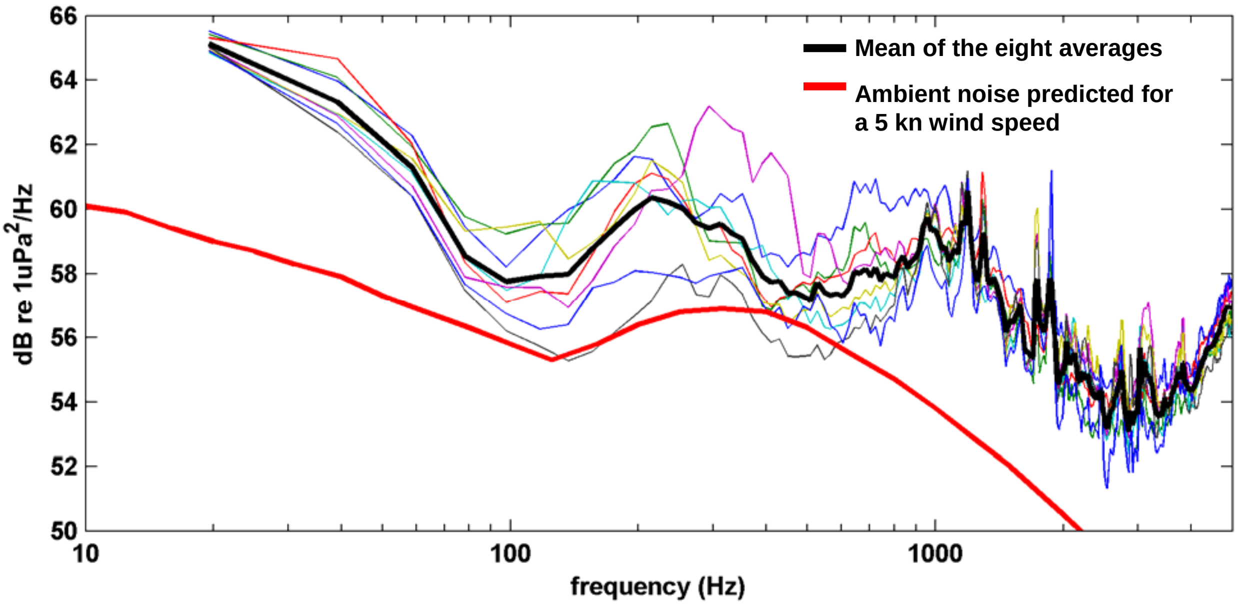

Figure 21: ‘Ambient’ noise spectral levels of eight 300 s averages, during periods when vessel noise was low on the 22-Oct and 23-Oct-2008 (spectra have a 19.53 Hz resolution).

While the eight ambient noise spectra were chosen at the quietest conditions found across the recording period they still contained distant humpback whale calling, fish, snapping shrimp and some tones associated with distant moored vessels. The tones take the form of spikes in the spectra, the distant humpback and fish noise over 100-500 Hz and the shrimp noise contribute to the noise energy typically above 1.8 kHz but here noticeably above 2.3 kHz. The broadband level of the mean of the eight ambient noise spectra (shown on Figure 21 as the heavy solid black line) was 93 dB re 1µPa.

To compare the ambient noise expected with 5 kn wind speed predicted by Cato (1997) with the wind speed conditions and ambient noise at Port Hedland, the average daily wind speed for Port Hedland at 09:00 and 15:00 each day was retrieved from the Bureau of Meteorology website. Over the 22 to 23-Oct, the mean wind speed was around 6 km/hr or 3.2 kn (Figure 22). Thus the 5 kn wind sea noise prediction curve of Cato (1997) with no extraneous sources, shown on Figure 21, is appropriate for use as a comparison. The higher noise spectral levels from the Port Hedland recordings compared with the Cato predictions indicate that even in the quietest conditions off of Port Hedland, there was some background sources inputting into sea noise.

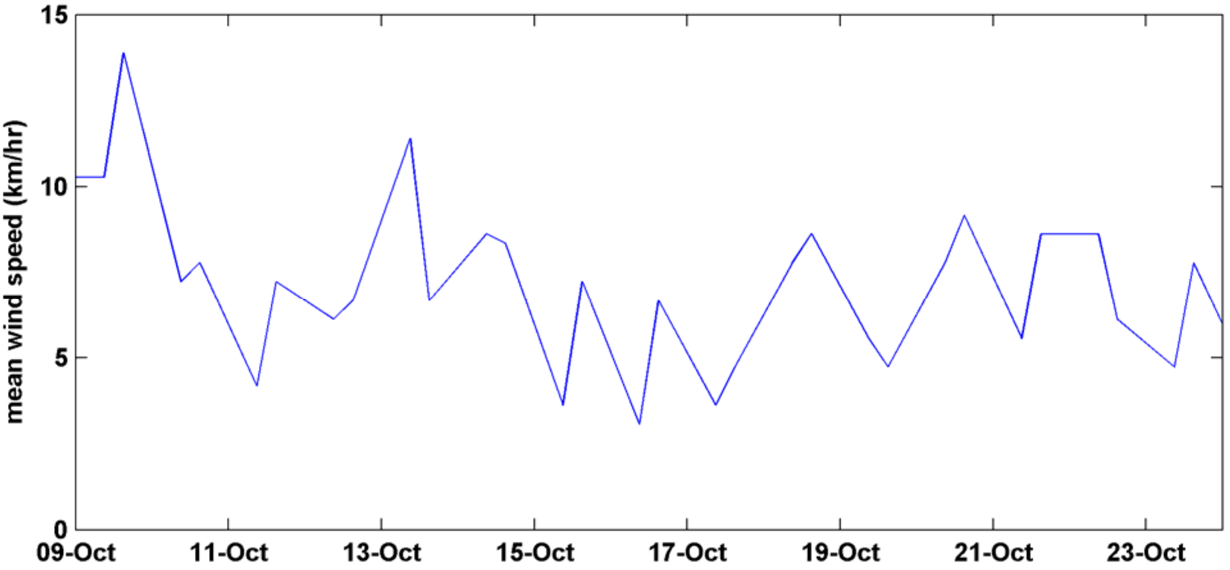

Figure 22: Mean 3 hour average wind speed from Port Hedland over the sea noise logger set.

5.1.2 Shipping noise

Both moving and moored ship noise was detected in the noise recordings. Noise from a number of small vessels passing was also detected, in addition to manoeuvring noise probably from large ships anchoring or coming off anchor.

For moving ships, at least 19 ships were detected over the 14 days, which constituted a steady stream of ships passing the noise logger (the logger was approximately 540 m east of the main ship channel into and out of Port Hedland harbour). Energy from the ships was present up to the logger sampling limit of 4.5 kHz, although most energy was below a few hundred Hz (see Figure 23 for the frequency spectra of two ships passing). Radiating ‘spokes’ of energy were evident in the frequency spectra (Figure 23) which is due to the sound transmission environment. These radiating ‘spokes’ are always seen from moving nearby sources, and was also evident from the noise of nearby anchored ships oscillating over long time periods (Figure 19 and Figure 20). This type of effect is prominent in some fish and whale calls also.

To describe broadband ship noise levels, the spectra across the passage of the 19 ships (made consecutively at 1.22 Hz resolutions or 0.8192 s per spectra) were converted to broadband levels (> 8 Hz), then the time base zeroed to the time of maximum level (see Figure 24). There was a consistent trend in that broadband ship noise increasing approximately ten minutes before the closest range to the noise logger at ~3.5 dB / minute until a maximum ship noise level in the range 130-148 dB re 1µPa was reached. The ship noise then decreased as the ship’s distance from the noise logger grew, until the ship noise approached ambient levels. This period was generally around 15 minutes. While the average ship speed in the channel was not known, if we assume a ten kn transit speed then the ships were detected from around 3 km from the closest range to the logger, and fell to background noise levels at a distance of 4.5 km. However, tonal signals would have been detected at much greater ranges (since these tend to be averaged down in the broadband noise calculations).

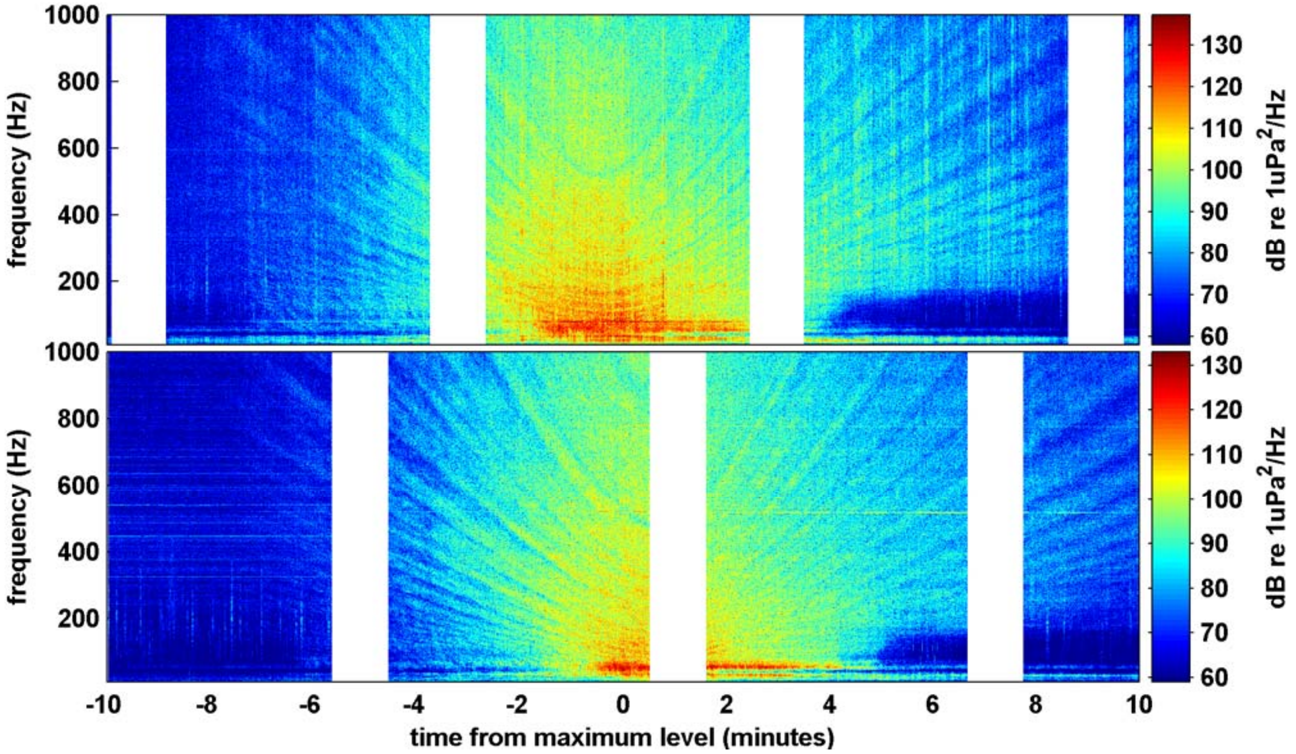

Figure 23: Frequency content of the passage of two ships. The gaps in the spectrogram are periods between noise logger samples (the logger was free running at this time, and had not begun its correct sampling schedule).

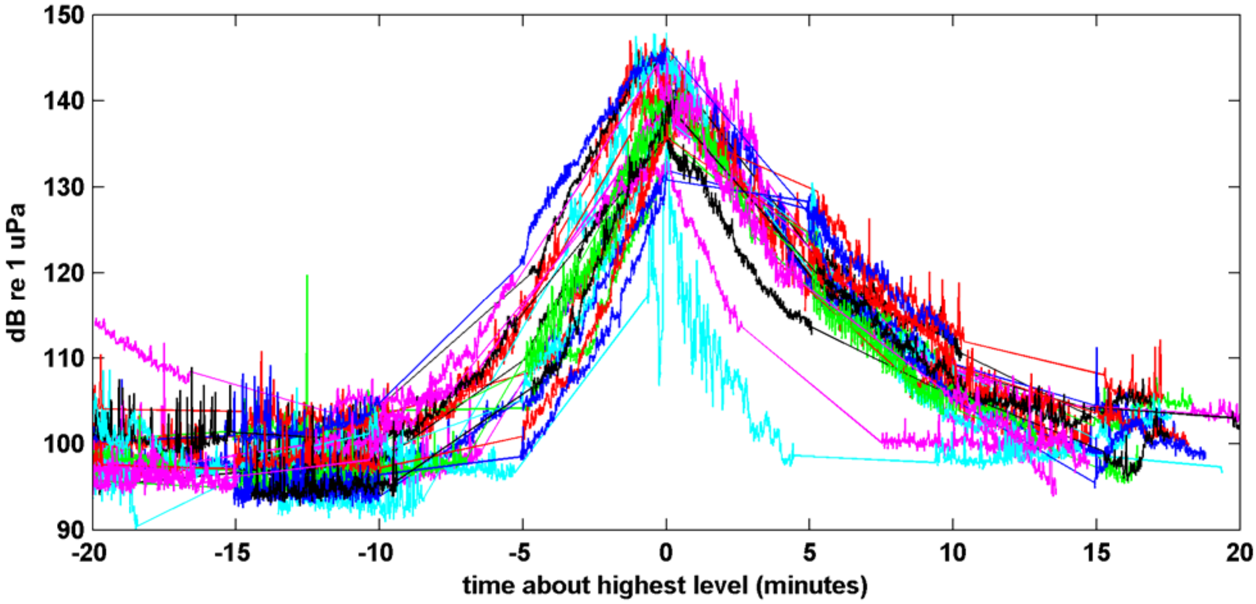

Figure 24: Broadband noise level of 19 ships passing the noise logger over the two week deployment (the sampling schedule of the sea noise logger was 5 minutes of every 15 minutes, hence non-sampling periods are represented by connecting straight lines above). The noise logger was 540 m north of the shipping channel.

For moored ships, there was consistent low level noise present in all but the last few days of the sea noise logger recordings. The noise was often tonal in nature (see Figure 19 and Figure 20). To assess the contribution of moored ship noise to ambient noise, several steps were taken:

- First, four sections of moored shipping noise were selected (listed in Table 11), which had no intense overlapping signals;
- For each section the time averaged spectra across each sample was used to obtain the broadband sea noise level for frequencies > 8 Hz (this was independent of frequency down to at least 5 Hz);
- The broadband level as a function of time was then used to calculate the proportion of time that the noise was greater than a series of thresholds (98 to 130 dB re 1μPa in 2 dB steps). This was done by calculating crossing points of the broadband level-with-time, curve above the chosen threshold and summing all the times the curve exceeded the threshold;
- The mean of the lowest 15 broadband values (a value is an average across a sample) was taken as the lowest ambient sea noise level under these conditions.

Table 11: Four sections for which the noise from anchored ships has been analysed.

Section	Blocks	Start	End	Ship Noise
1	**400-500**	**11-Oct-2008 10:20:01**	**12-Oct-2008 03:00:01**	**Moored Ship noise**
2	**750-1875**	**20-Oct-2008 19:20:01**	**21-Oct-2008 16:10:21**	**Moored Ship noise**
3	**1978-2010**	**22-Oct-2008 09:20:01**	**22-Oct-2008 14:40:01**	**Moored Ship noise**
4	**2025-2080**	**22-Oct-2008 17:10:02**	**23-Oct-2008 02:20:01**	**Weak Moored Ship noise with some quiet periods**

The lowest noise levels recorded in each curve (mean of lowest 15 values) ranged from 94-96 dB re 1μPa at an average of 95 dB re 1μPa (see Figure 25 for broadband sea noise over time, zeroed at 00:00 hours of the first day of recording). This is only 3 dB above the lowest ambient sea noise level recorded (with almost no ship noise present). So, while the noise from moored shipping was consistent (Figure 19 and Figure 20), it was mostly low level (< 100 dB re 1μPa; Figure 25). The spikes on the curves (shown on Figure 25) are possibly due to regular fish calling cycles (since they repeat over the different days).

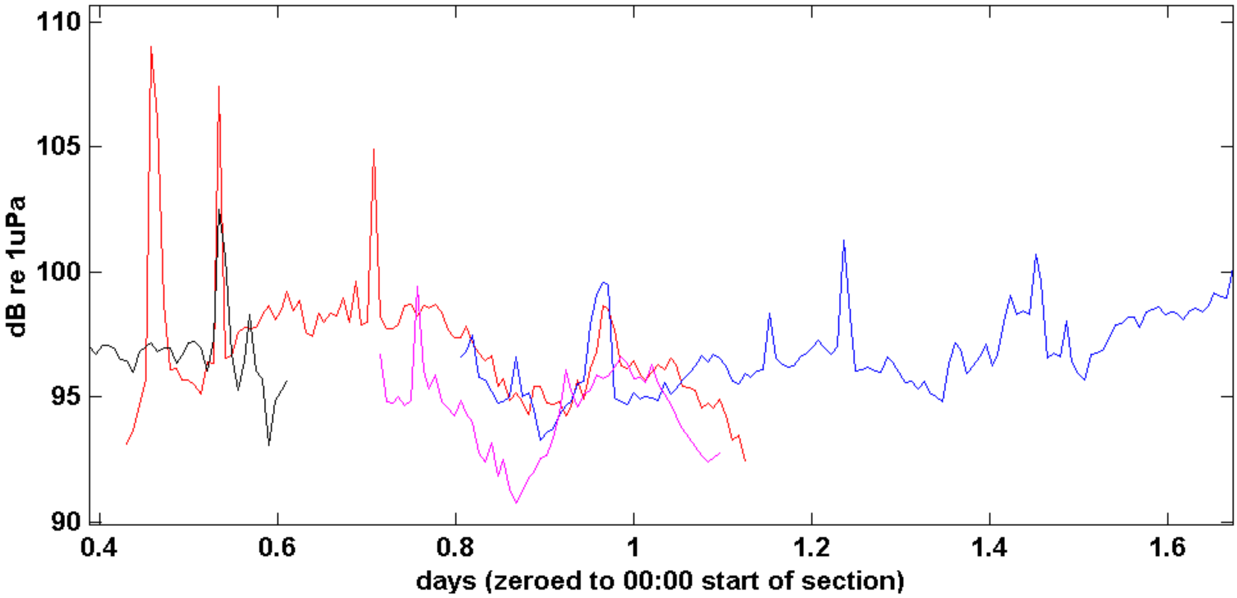

Figure 25: Broadband sea noise levels over time for four periods, with only moored shipping noise and some fish calling present.

As a comparison to periods of moored ship noise, the proportion of time broadband sea noise exceeded the same series of thresholds (98-130 dB re 1µPa in 2 dB steps) was also calculated for the full sea noise logger deployment period. The results, including curves of the proportion of time the moored ship noise exceeded the threshold for the four sections (listed in Table 11), and the full sea noise recording period, are shown on Figure 26. Across the full recording period, the passage of ships, nearby humpback whales, and distant air guns all contributed to the sea noise. The moored shipping noise was mostly low level, and typically raised sea noise above 98 dB re 1µPa between 10-30 % of the time, with the proportion of time rapidly dropping for thresholds > 98 dB re 1µPa.

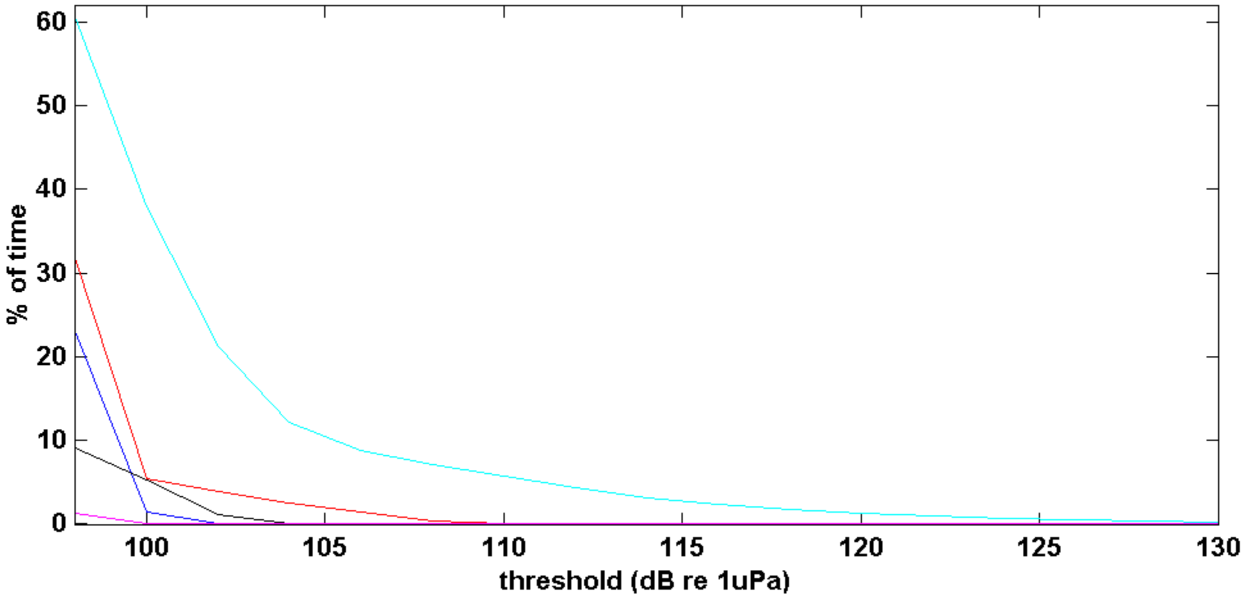

Figure 26: Proportion of time sea noise exceeded thresholds for: the full recording set (upper cyan curve), and for the four periods of noise from anchored ships and fish only.

5.1.3 Biological noise

Two dominant fish call types were recorded, one of which can be described as a series of knocks and the other a popping sound. The series of knocks (illustrated in Figure 27) was present in most of the recordings at some level. McCauley (2001) has studied this call in north eastern and northern Australian waters. In eastern Australia the call: consisted of 6-13 knocks with each knock 20-15 ms long; had a dominant spectral frequency between 240-420 Hz; was present in water depths up to 50 m, but was most prevalent in depths of 10-30 m; had a source level of 125-128 dB re 1µPa^2.s (sound exposure level) or 144-147 dB re 1µPa (mean squared pressure); displayed daily and seasonal calling patterns most prevalent in the afternoons of spring and summer; and was believed to be produced as part of the fishes reproductive strategy. McCauley (2001) was unable to attribute the call to a species. Fish calls of this sophistication nearly always involve specialised muscles attached to the fishes swimbladder, with these muscles oscillating the swimbladder at various rates.

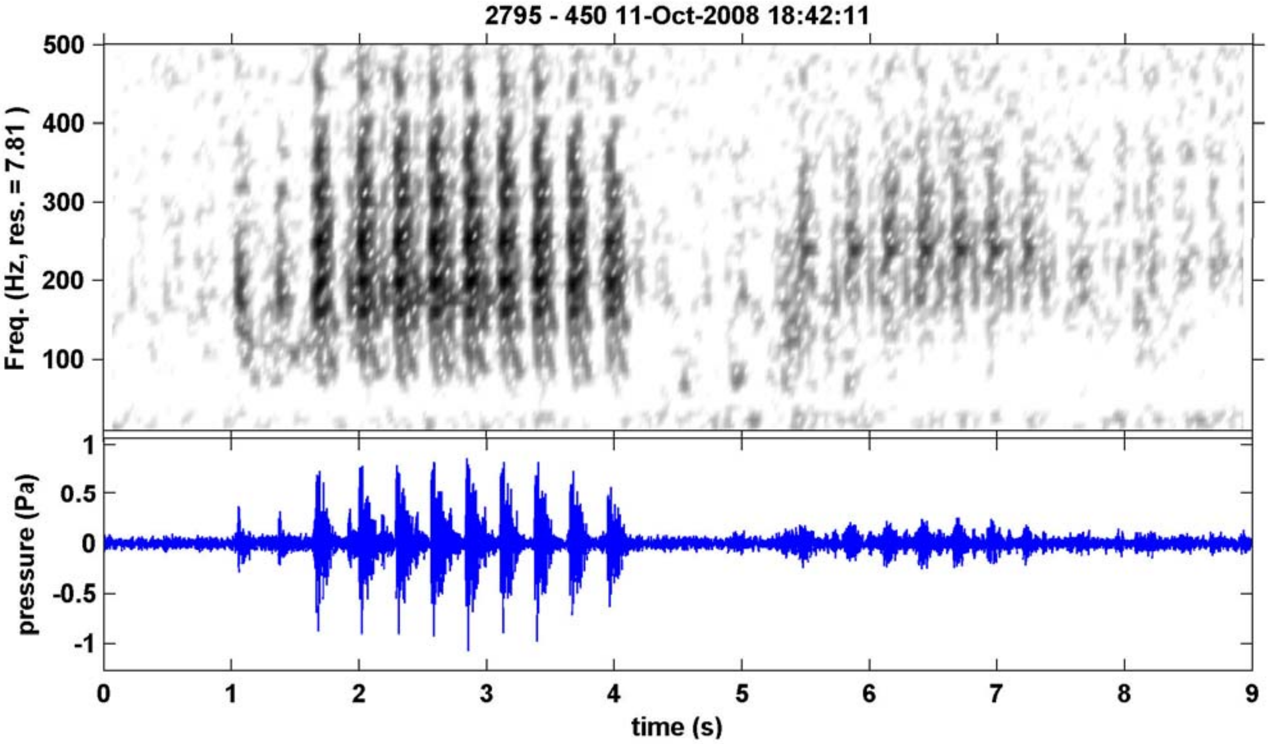

Figure 27: Fish knocking signal common in the sea noise logger recordings (top = spectrogram, bottom = waveform) . Two calls are present, the stronger of which is evident over 1-4 s.

The fact that the call was consistently heard amongst the vessel noise from passing and moored ships implies that the level of anthropogenic noise in the area had not displaced the fish.

The second common fish call type, the popping sound, was comprised of a single swimbladder knock. This call was consistently heard repeated frequently at intervals of a few seconds, and probably was produced by multiple sources. The species producing this call was unknown and its call and habits are not elucidated further here.

Humpback whale calling, like the two fish call types, was more or less continual across the two week recording period. A humpback song is typically 8-15 minutes long although this is variable, with an individual animal maintaining singing bouts for anything from 8 min to 12 hours. At any given point in time most to all individuals of the Western Australian humpback whale population all sing the same song type, although the song structure can evolve across seasons. The humpback song typically has a wide frequency spread from as low as 20 Hz to as high as several kHz, although usually most energy is focused in the 300-400 Hz band. The song seems to have some components designed to be heard only at short ranges (weaker high kHz components); some of which seem optimised for on-shelf transmission, and some components which transmit better in deeper water (< 100 Hz intense signals). Thus the humpback song signals detected normally vary depending on the whales' proximity and the local environment. An example of singing close to the receiver is evident from strong energy bands centred between 200-400 Hz in Figure 20, although weaker song from animals at greater ranges was consistent in the 14 day recording period. Examples of humpback song are shown on Figure 28 where the repetition of song components can be easily seen.

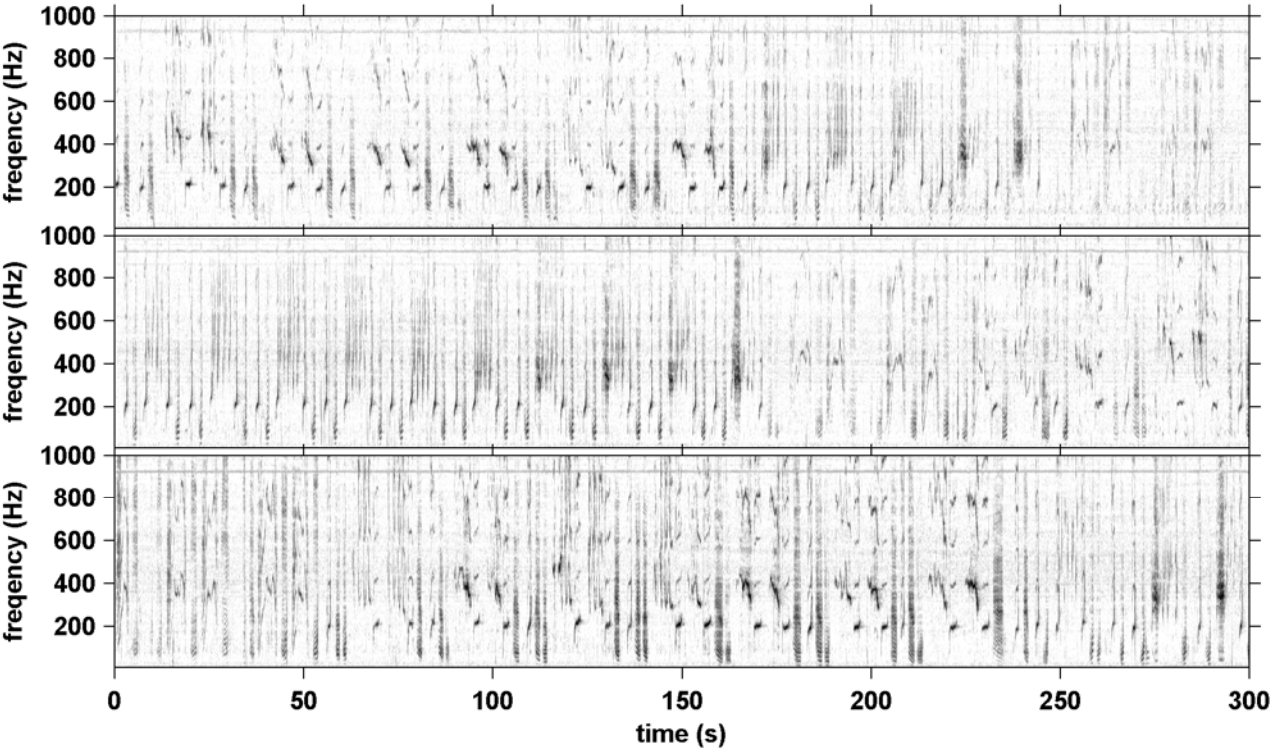

Figure 28: Humpback whale calling from three successive samples taken by the sea noise logger (samples 2099-2101 recorded at 05:30 – 05:50 on the 23-Oct-2008).

Relative humpback whale abundance can be estimated by quantifying the singing rates over long time periods. Curtin uses a count of the number of individual singers per sample as the relative abundance index. Obtaining this count is a time consuming task for humpbacks given the variability of received signals due to the high song complexity, variability in song within and among individual whales, and the effects of the environment on signal transmission. Counting the number of individual singing whales has not been attempted here.

5.2 Underwater noise predictions

Underwater noise predictions for pile driving during the Port Hedland Outer Harbour Development were based on reference signals available to the authors. The signals were averaged to account for variability, then scaled according to hammer energy so that it would correspond to the signal expected from the hammer energies proposed to be used during construction. The signals to be scaled were from a 49 kN-m hammer recorded with a mid-water receiver at a depth of 13 m and distance from the source of 21 m. The estimated source level of the 49 kN-m strike and the source spectra are shown in Figure 29 (in units of dB re 1µPa^2.s/Hz; the power spectra has been multiplied by the FFT length in the linear domain).

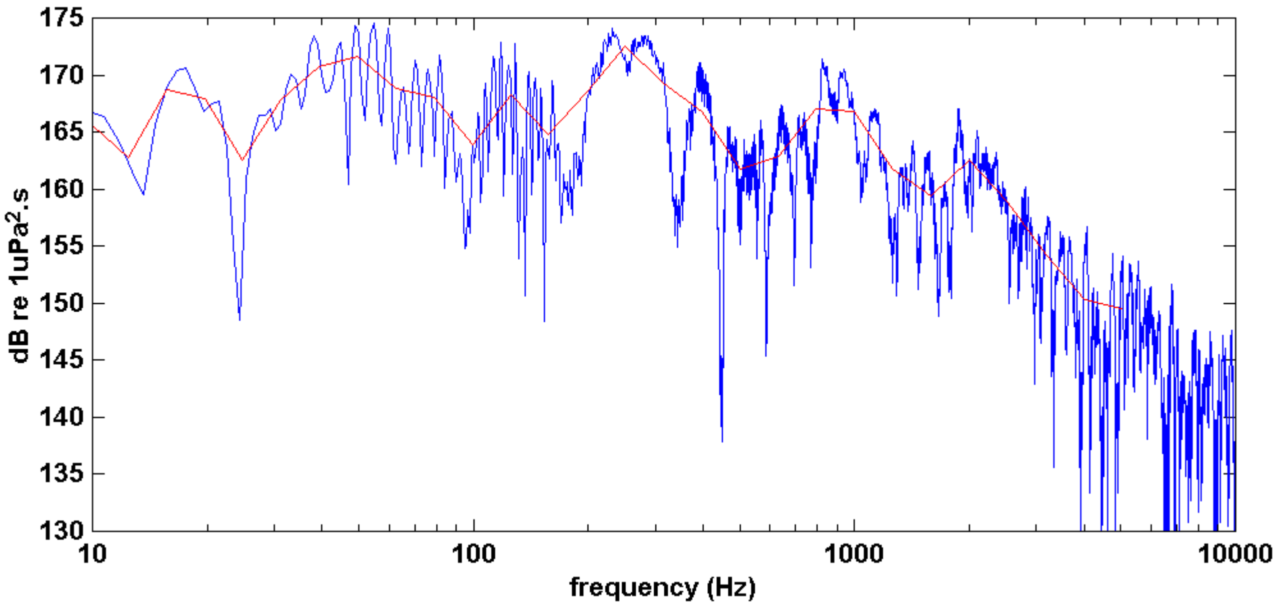

Figure 29: Frequency spectra of the estimated source level of a pile driving signal from a 49 kN-m hammer (blue curve, 0.98 Hz resolution), and the 1/3 octave spectra over 8 Hz to 2 kHz (1/3 octave centre frequencies: red curve).

To scale the 49 kN-m hammer signal to a signal that would correspond to the large hammers proposed for the Outer Harbour Development, the assumption has been made that the underwater noise output of a pile strike is proportional to the energy delivered to the pile, according to the following relationship:

$$dB_o = 10 * \log_{10}\left(\frac{E_1}{E_2}\right)$$

where dB_o is the offset from pile-2 to pile-1 in dB, E_1 is the energy delivered to pile-1 and E_2 is the energy delivered to pile-2 (kN-m). Using this equation the 30 tonne-m (294 kN-m) pile driver would have a 7.8 dB increase over the 49 kN-m pile signal, and the 48 tonne-m (470 kN-m) signal a 9.8 dB increase.

The broadband level of the 49 kN-m pile driving signal within each 1/3 octave was thus increased by 7.8 or 9.8 dB to emulate the respective larger hammer source levels. This was done based on the energy of the source spectra found within each 1/3 octave frequency band from 1/3 octave centre frequencies of 8 Hz to 2 kHz (25, 1/3 octaves). The reference source level (from the 49 kN-m piling signal) along with the calculated source levels (representing the proposed larger hammer signals) are listed in below in Table 12.

Table 12: Source levels (at 1 meter) and length (in seconds) of pile driving signals for different hammer energies.

Hammer energy	**SEL (dB re 1μPa^2.s)**	**RMS (dB re 1μPa)**	**length (s)**
49 kN-m	199	213	0.039
294 kN-m	207	221	0.039
470 kN-m	209	223	0.039

The transmission modelling was done with the source origin set to the seabed depth corresponding to the respective run. It is probable that in reality underwater noise radiates from the pile along its full length in the water column and from below the seabed, depending on the seabed type. However, all of the sound transmission models require the source to be placed at a single point within the water column. Typically, increasing the source depth (placing the source deeper in the water column) increases the lateral transmission of energy. Thus as a conservative approach the source depth was chosen as at the seabed.

The source energy units used were sound exposure level (SEL expressed in dB re 1μPa^2.s). SEL is considered as the metric which best defines impulsive signals such as from pile driving or air guns (McCauley *et al.* 2003). To derive SEL, the pile driving power spectra have been multiplied by the length of time the associated FFT was calculated over (or the dB correction, 10*log$_{10}$(FFTlength), added to the dB values of the source spectra). The source 1/3 octave broadband levels are derived from the power spectra in dB re 1μPa^2.s after accounting for the power spectra bandwidth. Sound transmission models return a phase and amplitude correction at each spatial point in the receiving grid chosen. The absolute value of these corrections gives the transmission loss which best defines the loss of energy from the source to that point. Since sound exposure level units are directly proportional to noise energy, then for impulsive signals these units are considered to give a better estimate of received signal energy after subtracting transmission loss. For continuous signals, such as vessel noise, which are longer than 1 s, the mean squared pressure would be used to estimate received level from transmission loss. The loss of SEL to the background noise level has been derived using background noise level in mean squared pressure. This is valid since background noise is an average of a long period noise hence the averaging time is of low significance and for an averaging time of one second then SEL and mean squared pressure are equivalent.

Thus sound transmission runs have been made along eight tracks at 25 frequencies, from two sites using low tide and high tide conditions. The resulting outputs were then matched with the different source spectra to give estimated received levels along each track. This process involved:

- subtracting the estimated transmission loss from the source level to give received level (RL) at each frequency, range and depth location along each track at which sound transmission modelling was run,
- Adding broadband ambient noise levels at a specified sea state, at each frequency to the RL in the linear domain and converting this back to dB, and
- At each spatial point summing the energy across frequencies in the linear domain and converting this back to dB.

This gave the estimated received level of the pile driving signal plus the ambient noise contribution, on a spatial grid of depth and range along each track. The natural ambient noise at the Port Hedland site was measured to be very low (92 dB re 1uPa, broadband), effectively increasing the range to which the pile driving signals can transmit before they fell into the ambient noise.

An example of pile driving signal transmission for the two hammer energies along what would be considered the best and worst tracks for sound transmission, to the north and south of each site respectively, are shown on Figure 30. These tracks were modelled along constant depth profiles, although tracks running inshore will attenuate the signal much more rapidly than this as the water shallows.

The results show that there is little difference in transmission of the pile driving signals, except for periods at low tide running up into shallow water. The differing transmission for low tide is most marked on the southward tracks at site 1, which show a rapid drop with range beyond 200 m from the pile driving source (Figure 30). At 8 km ranges along the deeper tracks, the pile driving signals are still well above ambient noise conditions (which can typically range from 90-110 dB re 1μPa), although the loss rate increases rapidly with range at this point. Although not shown here, the estimated pile driving levels shown on Figure 30 are in agreement with data collected by the authors in southern Australia from smaller pile driving hammers (with energies up to 60 kN-m).

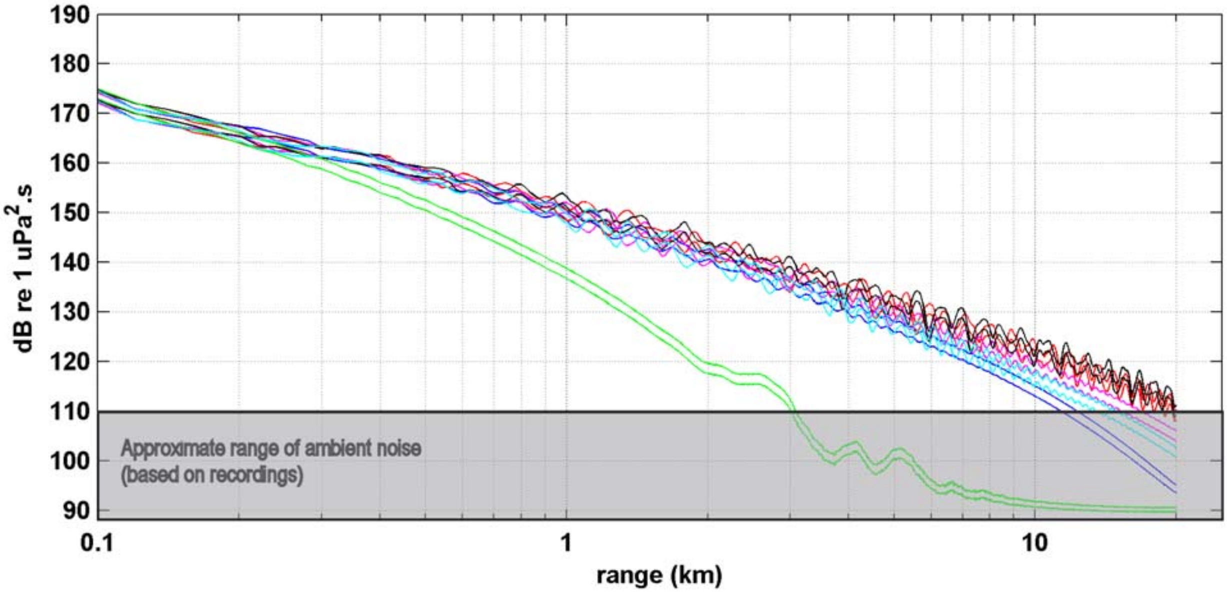

Figure 30: Estimated transmission of the pile driving signals north and south of sites 1 and 2 (see Figure 5) for the two pile driving hammer energies (30 and 48 tonne-m) at high and low tides. The lower curve is the southward track from site 1 at low tide.

In order to picture the larger scale implications of pile driving noise in the Port Hedland area, the sound transmission modelling output was linked to a spatial model which could plot the sound field of any underwater source within the Port Hedland area for a specified receiver depth. This model was constructed by following a number of steps:

- First, the output of modelling at a site was used to build a 2D sound field grid around the selected site location. This step first retrieved the estimated broadband received pile driving level along each heading about the site location (eight headings at 45° increments) for the specified receiver depth, without an ambient noise correction.
- The level between headings was interpolated to give received levels along 16 spokes radiating from the selected locations.
- A 2D grid of uniform x-y spatial points encompassing the ensonified area was set up and this gridded to the estimated received levels. Spatial points in the 2D grid not within the radius for which sound transmission was run were set to a low dB value.
- The site central point was located in the Port Hedland region (*i.e.* the site from which the 2D grid of estimated received levels was calculated could be moved around within the general area) and the bathymetry paths along each spoke retrieved. Where the bathymetry was shallower than a specified depth (2 m used) the 2D grid was trimmed to suit by setting the received level to a low value.
- The above steps were repeated for however many sources were to be used, using the same x-y co-ordinate system.
- The broadband level of all sources used were summed in the linear domain at each respective spatial point where they overlapped into a single larger grid encompassing the full region of interest.
- The broadband ambient noise was added in (linear domain) to give received underwater noise levels in the region specified with a set background sea state.
- The sound field was plotted with bathymetry overlain. An example of the output assuming different source and tidal scenarios are given in Figure 31 and Figure 32.

The different scenarios include:

- Two simultaneous pile driving signals, one from a 470 kN-m pile strike at the northern wharf end and one from a 294 kN-m pile strike at the southern jetty end, for 5 and 25 kn wind ambient noise conditions and LOW tide conditions (Figure 31).

- Two simultaneous pile driving signals, one from a 470 kN-m pile strike at the northern wharf end and one from a 294 kN-m pile strike at the southern jetty end, for 5 and 25 kn wind ambient noise conditions and HIGH tide conditions (Figure 32).

5.3 Summary

The equipment proposed for use in the construction activities of the Port Hedland Outer Harbour Development has most of its energy below 1 kHz, but the nature of the signals (impulsive *vs*. continuous) and the source levels are different. Cumulative sound levels are important to consider given that various activities using different technologies will be conducted simultaneously and over a lengthy period of time. Source levels for pile driving will range from an SEL of 207-209 dB re 1µPa^2.s @ 1 m, while from the dredging with a TSHD source levels are expected to be below an MSP of 180 dB re 1µPa @ 1 m. Pile driving is planned to occur initially over at least 12 months, and with up to three hammers working concurrently, but it is expected that two hammers will be used simultaneously during the majority of the works. Dredging is expected to occur for approximately 50 months during the construction activities, with channel upkeep dredging necessary at later times.

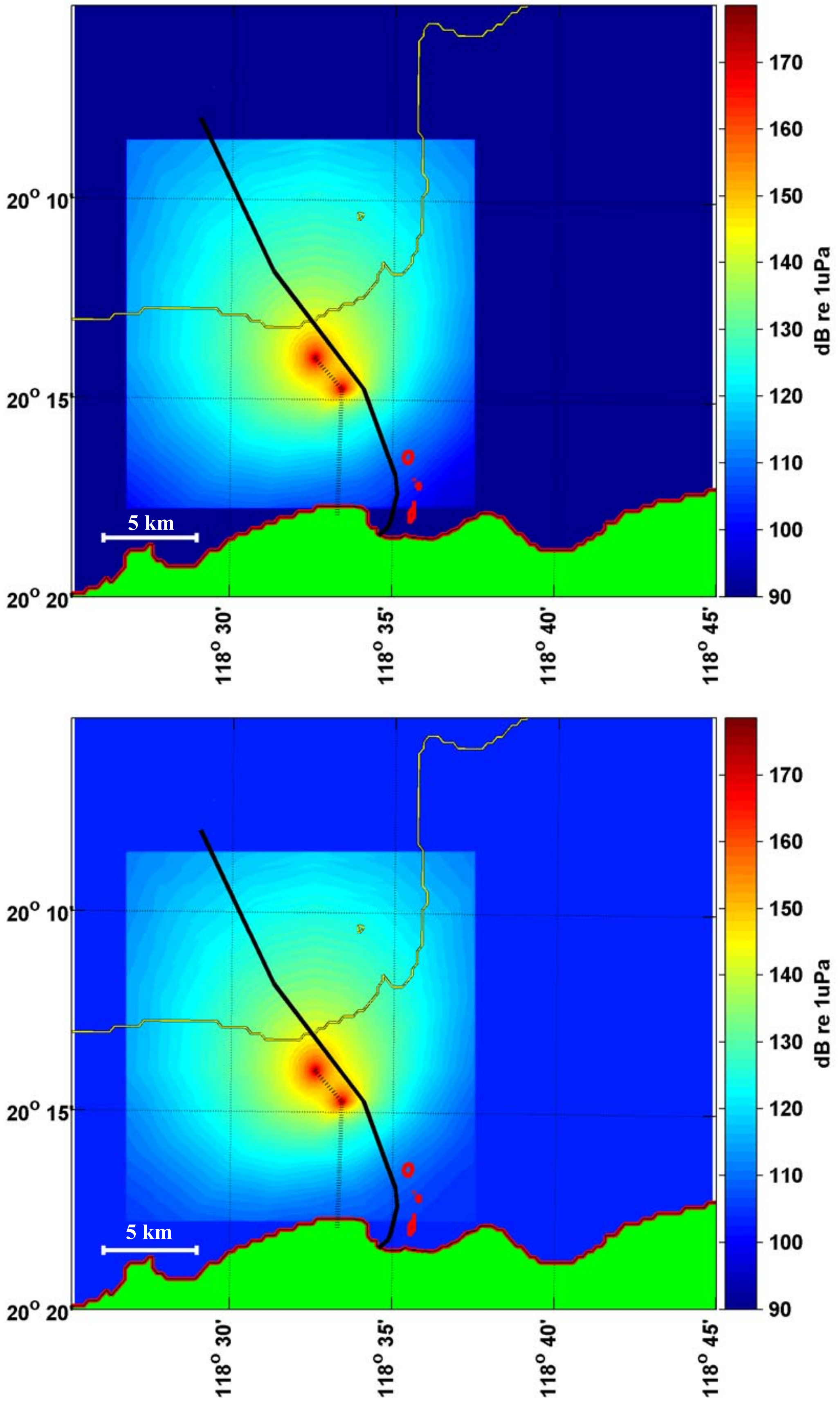

Figure 31: Predicted underwater noise field at LOW tide for a receiver at a depth of 4 m, and a two simultaneous pile driving signal sources; one at the northern end of the jetty of 470 kN-m and the other at the southern end of the jetty of 294 kN-m. Wind speed scenarios include a 5 kn (top), and a 25 kn (bottom). The 10 m depth contour is shown.

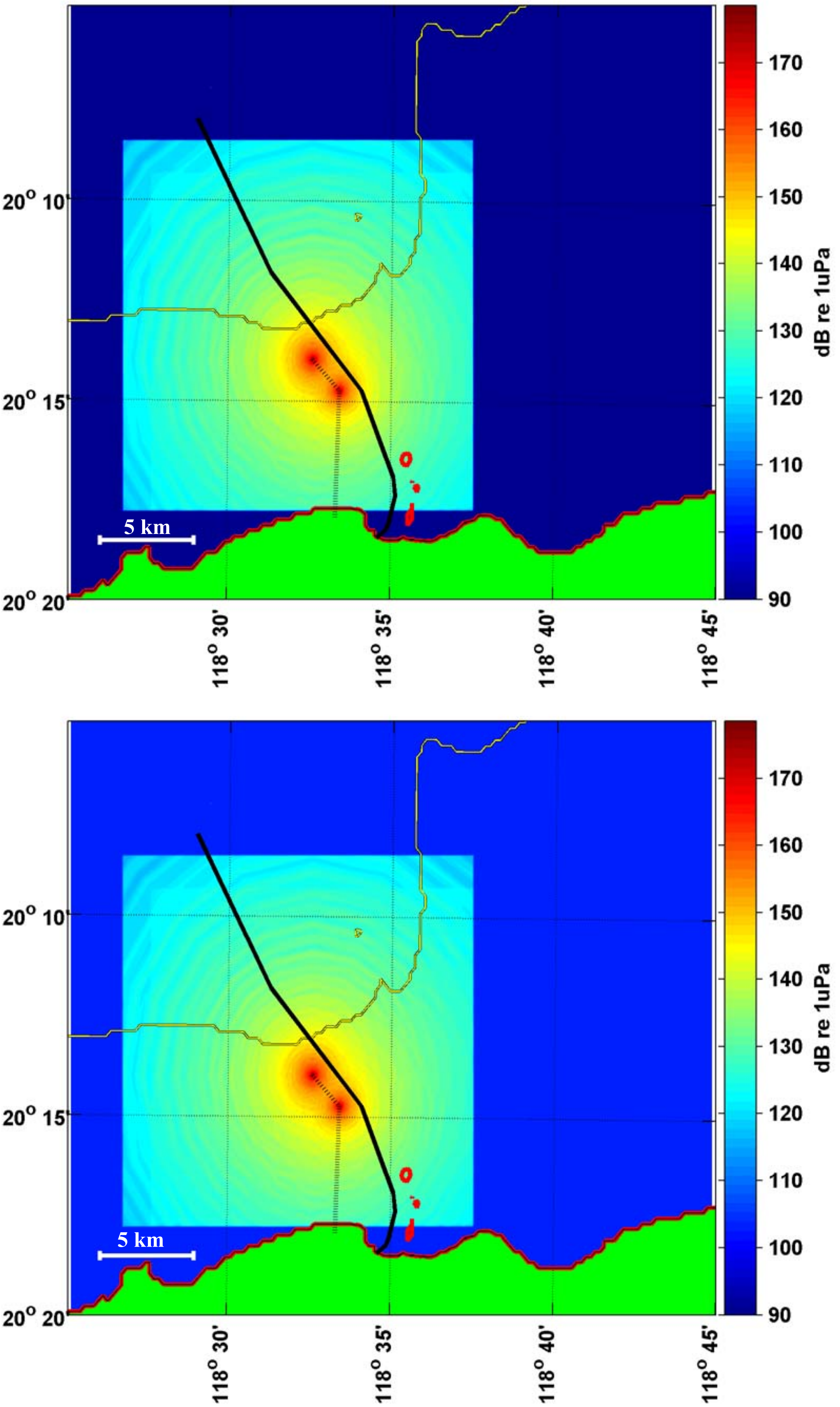

Figure 32: Predicted underwater noise field at HIGH tide for a receiver at a depth of 4 m, and a two simultaneous pile driving signal sources; one at the northern end of the jetty of 470 kN-m and the other at the southern end of the jetty of 294 kN-m. Wind speed scenarios include a 5 kn (top), and a 25 kn (bottom). The 10 m depth contour is shown.

6 Impact Assessments

6.1 Timing considerations

The effects of the timing of scheduled dredging and construction activities upon potentially impacted species are summarised as follows:

- The proposed timing of the 24 hours a day, 7 days per week construction activities in the region is year round, with initial pile driving to occur for approximately 1-2 years, and dredging over two years to extend to up to 4 years;
- Spawning, migration and other sensitive behaviours willoccur sometime during this period for fish (although defining these periods and exact locations for the respective species of fish is outside the scope of this report and for the relevant fisheries study to address);
- Humpback whales migrate and breed calve seasonally between July and November in this region, migrating north and south through the Port Hedland region,
- Three species of dolphins are likely to be residents or transients in this area, utilising it for foraging, calving, resting, or travelling through. Certain time periods may be more sensitive that others, such as when calves are newly born or young.
- Dugongs may migrate through the area, possibly reside within the region and may feed locally. Their calving period will overlap with works being scheduled.

6.2 Assessment of overlap in expected noise spectra and faunal hearing sensitivity

As part of an evaluation of the impacts, it is important to assess overlap of audiograms (hearing sensitivity) of animals that may occur in the areas where dredging or construction are proposed, with the noise spectra from the sound sources. This is addressed below.

6.2.1 Dredging

By overlaying the audiograms of relevant groups of animals over noise level data, the frequencies of most sensitivity to the noise source can be identified. As an example of fish that may have hearing ranges similar to those that occur within the project area, Figure 33 shows audiograms from a catfish and cod, overlayed with noise level data from the TSHD recorded at 318 m from the source.

The frequencies of most sensitivity for a species is where the audiogram line ‘dips’ (e.g. the frequencies where an animal is able to hear a sound at the lowest sound levels). The cod has highest sensitivity at 50-500 Hz, while the catfish has highest sensitivity at 200 Hz-5 kHz.

The TSHD produces broadband noise, with the highest sound levels between 50 Hz and 9 kHz. These frequencies overlap the range of highest sensitivity of both species, but noise levels produced by the TSHD are lower within the range of most sensitivity for the catfish. Considering only these levels of highest sensitivities, the impact of noise from the TSHD on cod is expected to be greater than for the catfish (although both have hearing sensitivity in the frequency range of the TSHD and therefore both are susceptible to impacts).

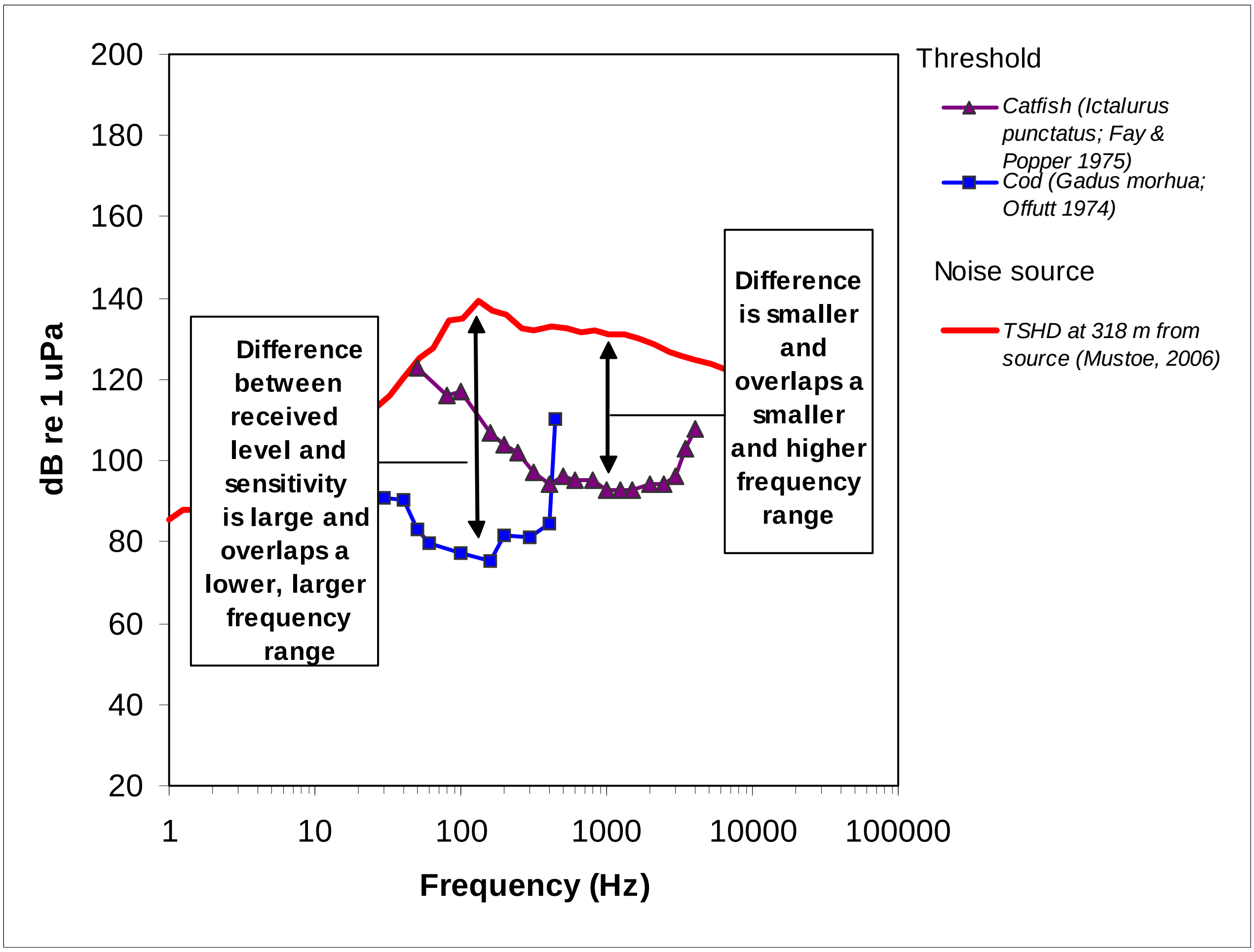

Figure 33: Example (for interpretative purposes) of information extracted from overlapping audiogram (hearing threshold measured for the catfish and cod (from Nedwell *et al.* 2004) with noise spectra of a TSHD (recorded from a distance of 318 m; Mustoe, 2006).

Frequencies with the highest source levels (80 Hz – 10 kHz) recorded at 318 m from the TSHD (during a trial dredge program, Mustoe 2006) overlap directly with the peak hearing sensitivity range of many fish species described in the literature (see Figure 34). Because high frequencies attenuate more quickly than do low frequencies, higher frequency sound levels are expected to be greater close to the source than levels at 318 m from the source.

However, the actual sensitivity at any one frequency, depends highly on the receiving species. Many species (for example *Lepomis macrochirus* and *Tilapia macrocephala*, Figure 35) appear to be sensitive to sound levels 20 dB below the highest received level of noise from the TSHD at that distance. Other species however, have a far greater sensitivity 65-70 dB below the highest received level, *i.e. Carassius auatus* in Figure 34.

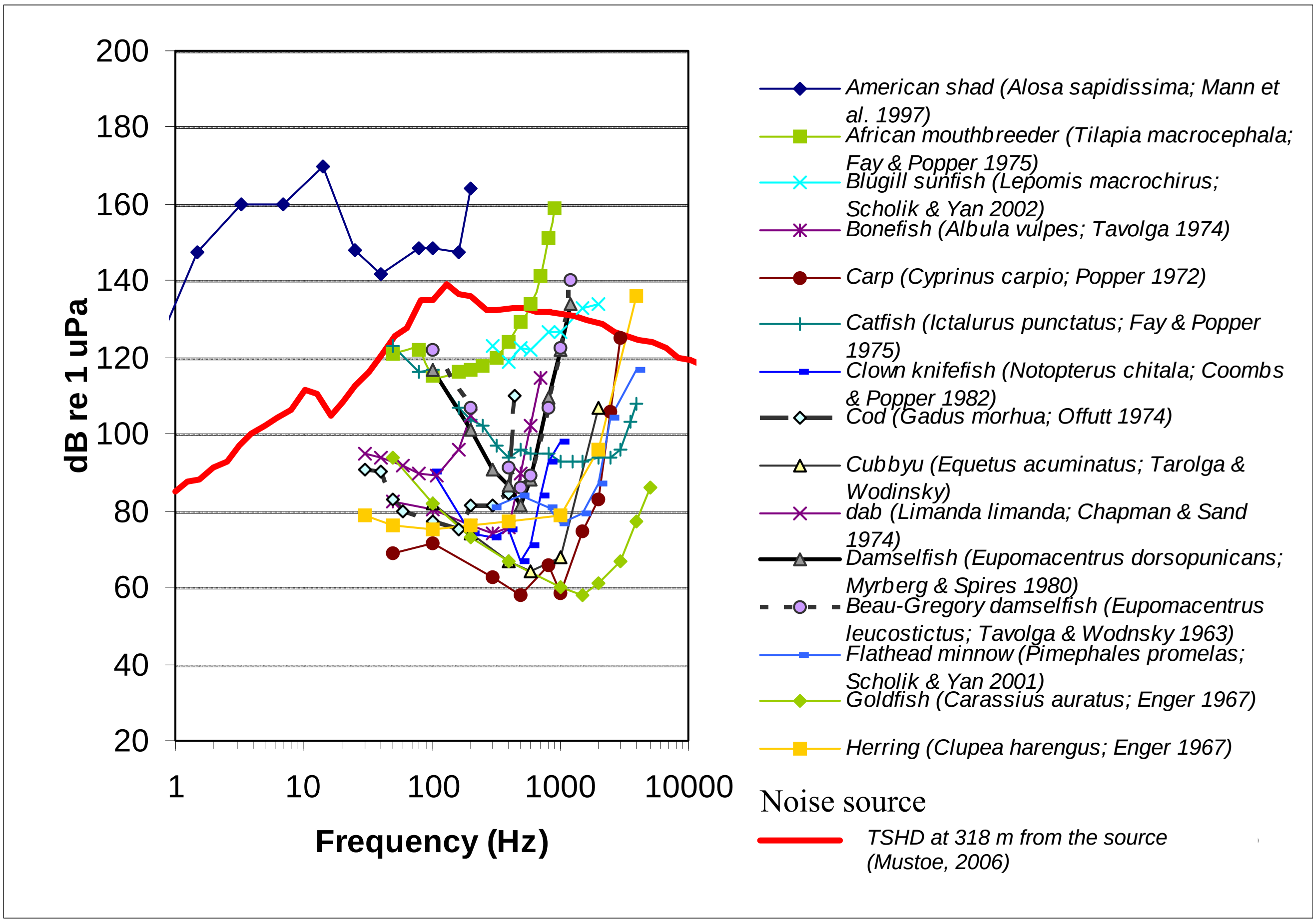

Figure 34: Underwater audiogram of various fish (from Nedwell *et al.* 2004) overlaid with noise spectra of the *TSHD* recorded from a distance of 318 m (Mustoe, 2006). The shaded area is the frequency range of most sensitivity for most fish (whose audiogram have been measured).

Highest hearing sensitivity measured for the odontocetes (including the bottlenose dolphin, the common dolphin and killer whale) during previous studies show that highest sensitivity is in the mid frequencies (~8 kHz – 20 kHz). The greatest noise levels produced by the TSHD overlap the lower frequency range of highest sensitivity for these animals (Figure 35).

For both baleen whales and dugongs (based on estimated sensitivity range) the higher levels of noise produced by the TSHD overlaps directly with the frequencies of most sensitivity (10 Hz to 5 kHz).

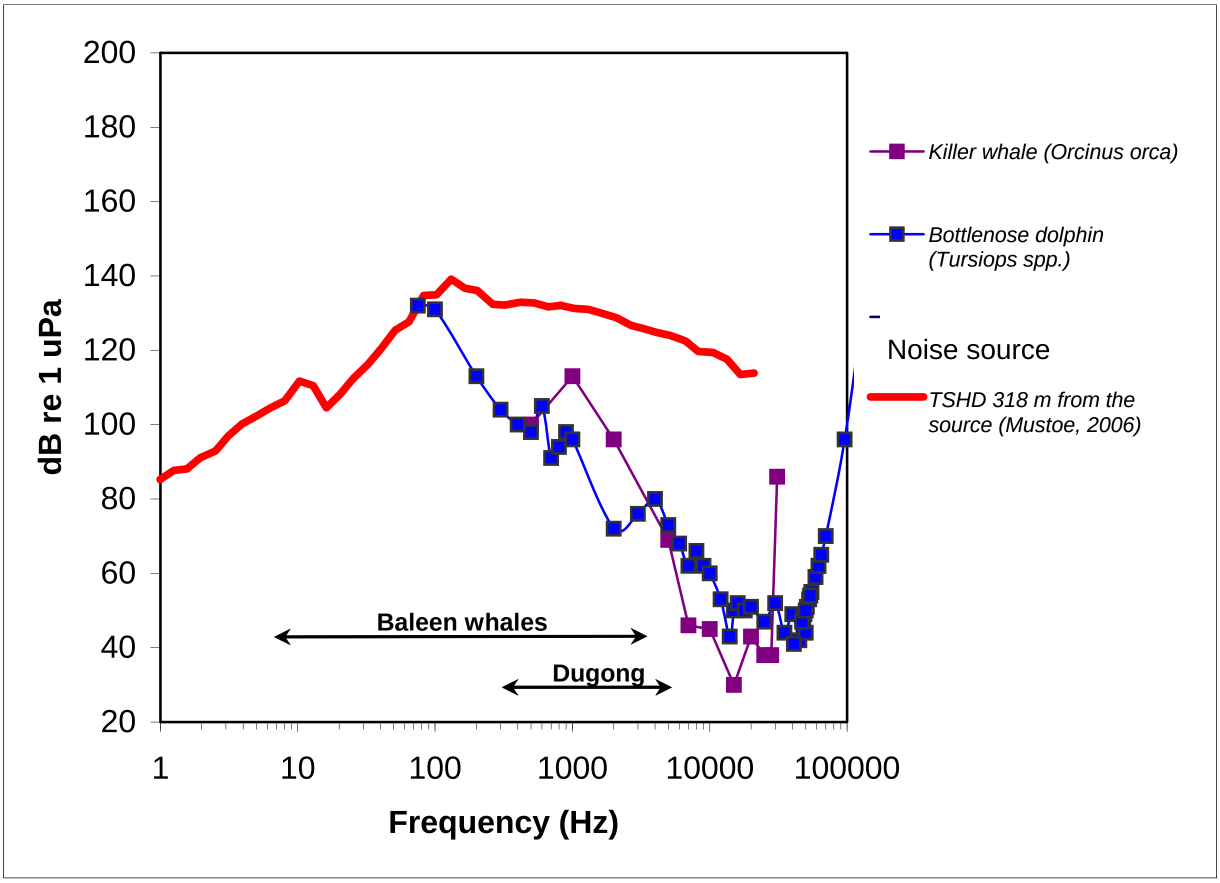

Figure 35: Underwater audiogram of marine mammals (from Nedwell *et a*l. 2004) overlaid with noise spectra of a TSHD recorded at a distance of 318 m (Mustoe, 2006).

6.2.2 Pile driving

The frequency spectra from the pile driving example 257 m from the source at Twofolds Bay (NSW) shows highest sound levels between 100 Hz and 300 Hz (smaller range compared to the TSHD), although a significant level of noise (above ambient) occurs to frequencies above 1 kHz (Figure 36). Noise levels from pile driving overlap the frequencies of greatest sensitivity of many fish species of known sensitivity including hearing generalists and specialists (~60 Hz – 4 kHz; similar to the overlap described above for the TSHD, Figure 36).

Also, much of the overlap of sensitivities for the marine mammals to pile driving noise, is similar to that observed for the TSHD. The frequencies of high sensitivity of the animals overlap with the higher frequencies of pile driving noise levels (10 Hz to 5 kHz, Figure 37).

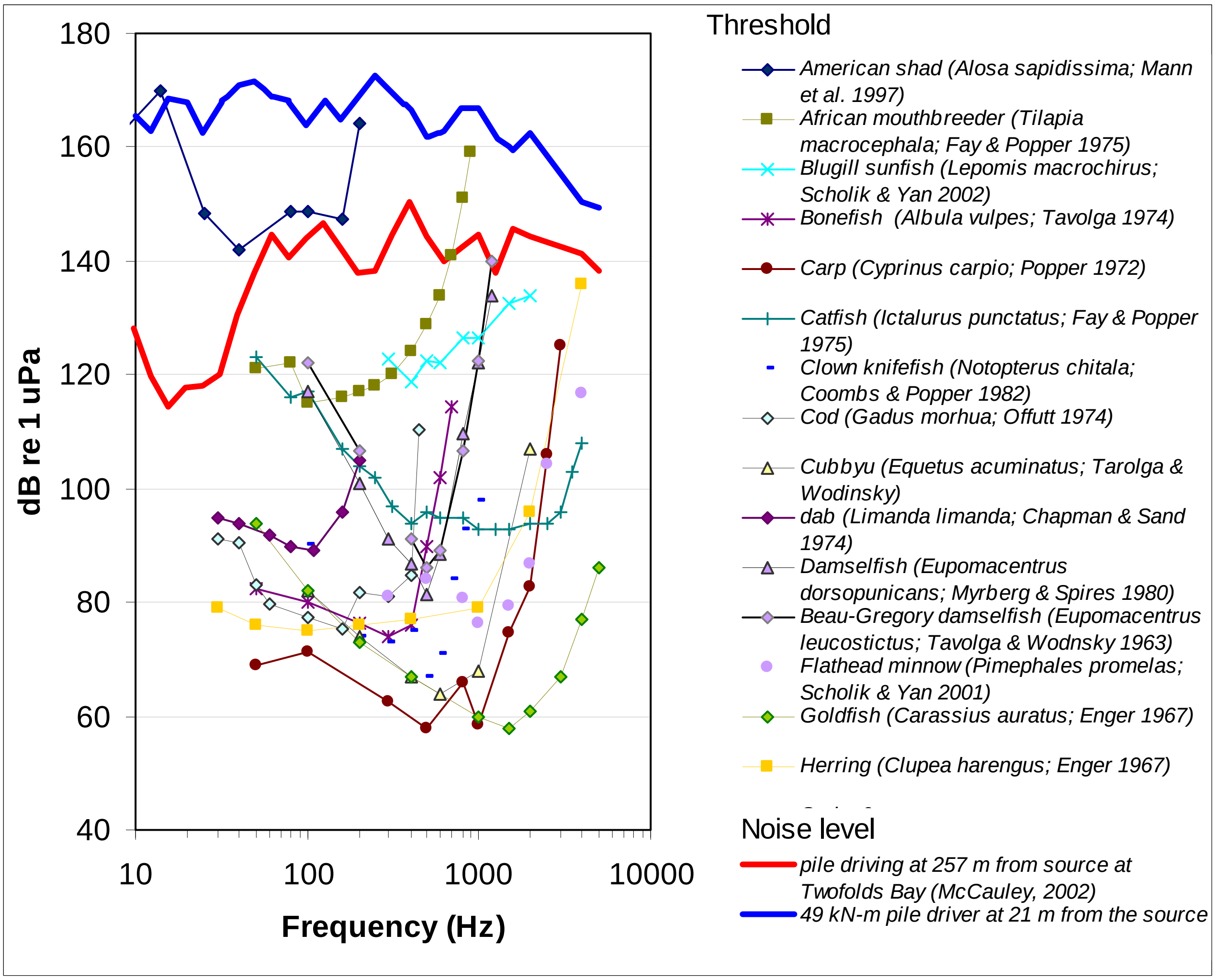

Figure 36: Underwater audiogram of various fish species (from Nedwell *et a*l. 2004) overlaid with 1/3 octave noise spectra of a pile driver recorded at the Twofolds Bay (NSW) from a distance of 257 m (McCauley 2002), and of a 49 kN-m hammer recorded at 21 m from the source (from Figure 29).

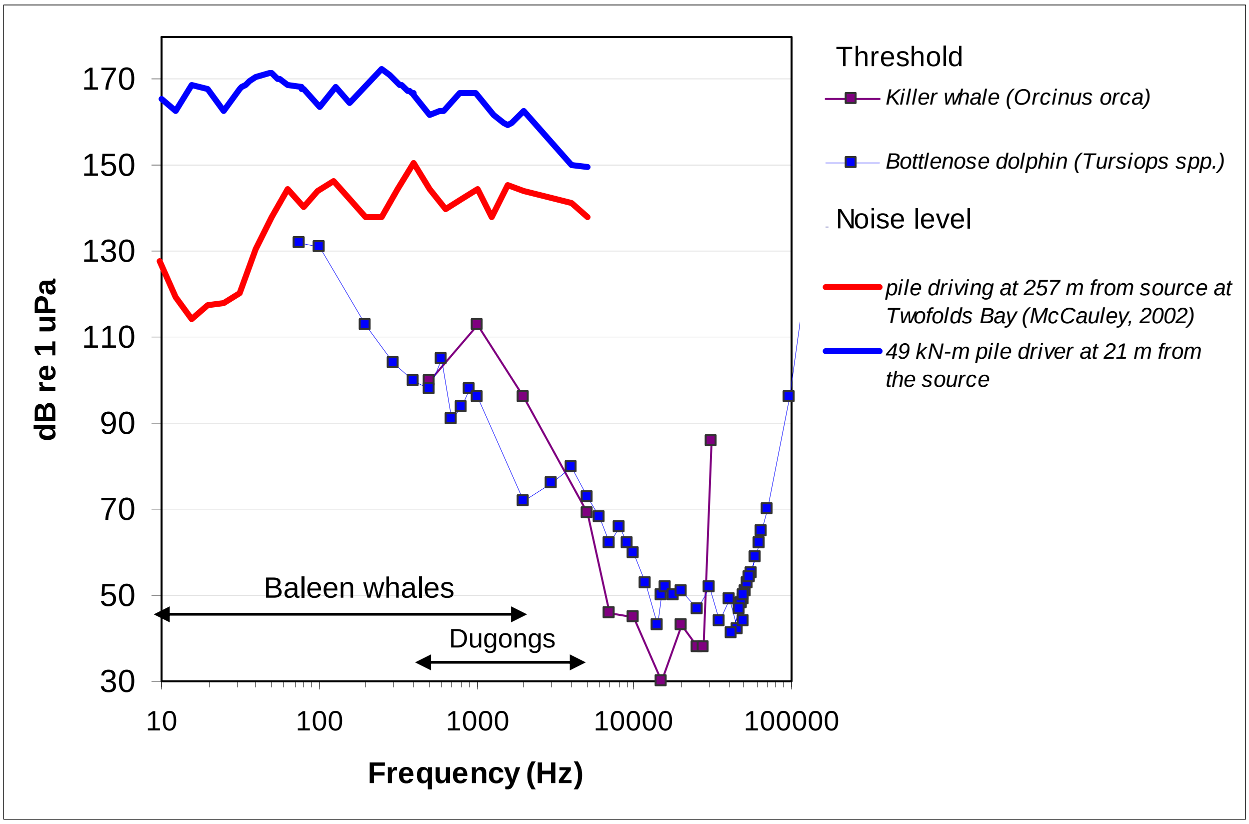

Figure 37: Underwater audiogram of marine mammals (from Nedwell *et al.* 2004) overlaid with 1/3 octave noise spectra of a pile driver recorded at the Twofolds Bay (NSW) from a distance of 257 m (McCauley 2002), and of a 49 kN-m hammer recorded at 21 m from the source (from Figure 29).

6.3 Assessment by faunal group

Received sound levels (RL) that are expected to cause impacts (PTS, TTS, behavioural, etc.) are first described for pulsed signals such as those from pile driving, and then for continuous noise from sources such as dredging and shipping activities.

Any underwater noise impacts from the Port Hedland Outer Harbour Development are expected to be mainly on fauna that are residents, or occur in the area during a sensitive period of their life history.

6.3.1 Cetaceans

Impulsive signals are expected to cause the most impact, given their sharp rise in energy, sound energy level, and the 12 month duration of the pile driving operations. Disturbance to humpback whales is expected for multiple pulses such as pile driving at RL between 120-160 re 1µPa (MSP), if carried out frequently over a short time frame. Whales not engaged in resting are likely to respond to RL around 140-160 dB re 1µPa (MSP), while resting whales may be disturbed at RL as low as 120 dB re 1µPa (MSP). These levels are expected at distances up to several to tens of km (for pile driving). Disturbances will range from increased stress to avoidance. TTS is expected for single and multiple pile driving pulses at 183 dB re 1µPa^2.s (SEL) or 224 dB re 1µPa (peak). TTS is likely for animals within a few hundred meters of the pile driving source and at larger distances if the animals remain within the vicinity while continual piling occurs. Injury (PTS or other) is expected to occur for multiple or single pulses at RL of ≥ 198 dB re 1µPa^2.s. The danger in pile driving start-up is that animals nearby have no warning, and if close enough to the source may experience injury (auditory, and otherwise).

For non-pulsed noise sources such as dredging and boat traffic, humpback whales or any other low-frequency hearing sensitive marine mammal, are likely to become disturbed at RL in the range of 120-160 dB re 1µPa (MSP). Humpbacks are not likely to experience TTS or injury during dredging activities, unless the animals are in the immediate vicinity (< 50 m) of the dredger. If, however, an animal remained for some period within the general vicinity of the area (a few hundred meters), there is a possibility of onset of TTS. Injury (PTS) caused by noise from dredging or shipping activities is not expected for humpback whales.

For the smaller cetaceans (*e.g.* dolphins), PTS and TTS from construction noise (pulsed and continuous) are expected to be similar to that described above for humpback whales. Although smaller cetaceans are perhaps at higher risk to TTS or PTS since many habituate to noise and so may receive higher cumulative sound loadings than if they were exposed on a transitory basis. Bottlenose dolphins are particularly known for habituating to noise sources. The Indo-pacific humpback dolphin and the snubfin dolphin perhaps will experience greater observable behavioural disturbance since the available literature suggests these species appear to shy away from human activity. In general, it is difficult to predict the behavioural response of the smaller cetaceans to the proposed Outer Harbour Development construction activities and operation (dredging, pile driving, and shipping), although responses are likely to be highly variable ranging from responding to low RL to not responding at all to higher RL (120-180 dB re 1µPa). It is possible that bottlenose dolphins may habituate to a greater degree to dredging and shipping for example, than the other two dolphin species, but it is equally possible that some or all of the three species occurring in the region may avoid the area altogether. To further confound the issue, dolphins will respond to the abundance, distribution and behaviour of their prey. If the dolphin prey field in the area of port construction work is altered adversely then dolphins may be found less frequently in the area, even though they may tolerate relatively high levels of the construction noise and activity. For any dolphin population (or indeed any marine mammal population) for which the Port Hedland area is critical for their viability, long term noise exposure from the construction activity may have significant impacts.

6.3.2 Dugongs

Dugongs migrating through the area are likely to experience behavioural disturbance from all development operations at the lowest exposure levels, although individuals exposed over multiple events may habituate to the noise if they are not associated with any negative or deleterious events. If the proposed site is vital for dugong migration, calving, foraging or other critical uses, then impacts could be significant because of the highly sensitive nature of the population. According to the Department of the Environment, Water, Heritage and the Arts (2008a), the Pilbara coast, in general, is an important area for dugongs An aerial survey in 2000 estimated the population of dugongs in the whole Pilbara coastal and offshore region to be approximately 2000 animals (1 dugong per 10km^2; Marsh *et al*. 2002).

PTS (injury) and TTS can be expected to be similar to levels suggested for dolphins. This is considered a conservative measure, however, since hearing sensitivity appears to be 10 dB lower and more limited in frequency range than the bottlenose dolphins. Finally, increased shipping will likely result in increased boat strikes when dugongs are present. Dugongs habituated to high levels of boat traffic appear to have a highly delayed response time to oncoming vessels (Hodgson 2004). The high levels of boat strikes on the east coast of Australia have been attributed, at least in part, to these delayed responses (Hodgson 2004).

6.3.3 Fish

The more severe impacts from noise are likely to occur to hearing specialist fish since they are more sensitive to sound than hearing generalist fish. For multiple pulses such as pile driving, fish will likely become disturbed at RL of around 150 re 1µPa (MSP). These disturbances will range from increased stress to avoidance. TTS is expected to occur above 180 dB re 1µPa (MSP). Injury (PTS, physiological or mortality) is expected to occur within close proximity of a single pile driving pulse or multiple pulses. Mortality is expected to occur at 190-200 dB re 1µPa^2.s (SEL) for small fish or 200-210 dB re 1µPa^2.s for larger fish. Fish can experience TTS (or even PTS) during dredging activities if the fish are highly territorial and continue to reside within close proximity to the operating equipment. Injury caused by noise from dredging or shipping activities is not expected for fish, unless indirectly due to hearing impairment or masking of predatory or other critical signals.

6.4 Summary

A summary of estimated impacts (RL and distance) for all groups of animals is presented in Table 13. These are considered estimates since there are a large number of unknown variables.

Table 13: **Estimated impacts thresholds for the Port Hedland Outer Harbour Development based on impact criteria described in this report for multiple pulses (units of received level are variable depending upon the units used in the impact criteria; Distance is in m). Ranges of RLs have been given in many cases since values depend upon exposure period.**

Species	**Death**		**PTS**		**TTS**		**Behavioural response**	
	Received Level	**Distance**	**Received Level**	**Distance**	**Received Level**	**Distance**	**Received Level**	**Distance**
Fish – Hearing Specialists	Unknown, expected to be > 200 dB (RMS)	Within several m	Unknown, expected to be > 190 dB (RMS)	Within tens of m	Unknown, expected to be > 180 dB (RMS)	Within 200 m	Unknown, expected to be > 120-150 dB (RMS)	kms to tens of km
Fish –hearing generalists	Unknown, expected to be > 200 dB (RMS)	Within several m	Unknown, expected to be > 190 dB (RMS)	Within tens of m	Unknown, expected to be > 190 dB (RMS)	Within 100 m	Unknown, expected to be > 150 dB (RMS)	several kms
Dugongs	Unknown, expected to be > 200 dB (RMS)	Within several m	Unknown, expected to be > 178-198 dB (SEL)	Within tens of m	Unknown, expected to be > 183 dB (SEL)	Within 200 m	Unknown, expected to be > 120-150 dB (SEL)	~2 kms to tens of km
Dolphins	Unknown, expected to be > 200 dB (RMS)	Within several m	Unknown, expected to be > 178-198 dB (SEL)	Within tens of m	expected to be > 183 dB (SEL)	Within 200 m	Unknown, expected to be > 120-180 dB (SEL)	~2 kms to tens of km
Whales	Unknown, expected to be > 200 dB (RMS)	Within several m	Unknown, expected to be > 178-198 dB (SEL)	Within tens of m	expected to be > 183 dB (SEL)	Within 200 m	Unknown, expected to be > 120-150 dB (SEL)	~2 kms to tens of km

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Appendix A

The CMST-DSTO sea noise logger deployed was designed and built at Curtin. The noise logger was set on the seabed. The hydrophone signal was amplified using an impedance matching pre-amplifier (20 dB gain), filtered with a low frequency roll off starting at 8 Hz and with the loss increasing with decreasing frequency so as to flatten the naturally high levels of low frequency ocean noise and increase the system dynamic range. An anti-aliasing filter was applied and the signal then fed to an analogue to digital converter. The digital signal then had further gain applied (20 dB) and was sampled according to a pre-programmed sampling schedule. Samples were written to flash card (power cheap) then when the flash card was near full transferred to a hard disk (power hungry).

The noise logger (named Lionel), sampled at 10 kHz using a 4.8 kHz anti-aliasing filter. Samples were 300 s long repeated at 10 minute intervals. The logger sampled in the water from:

09-Oct-2008 12:00 (sample 32) to 23-Oct-2008 12:30 (sample 2141) or for 14 days. The sampling set was given the Curtin number of 2795.

The noise logger was calibrated with white noise of known level and the system frequency response calculated, as shown by the system gain curve on Figure 38. A HiTec HTIU90 hydrophone was used with sensitivity of -196.8 dB re µPa/V and capacitance of 13.78 nF. With this hydrophone the system was calibrated from1 Hz to the anti-aliasing filter setting of 4.8 kHz.

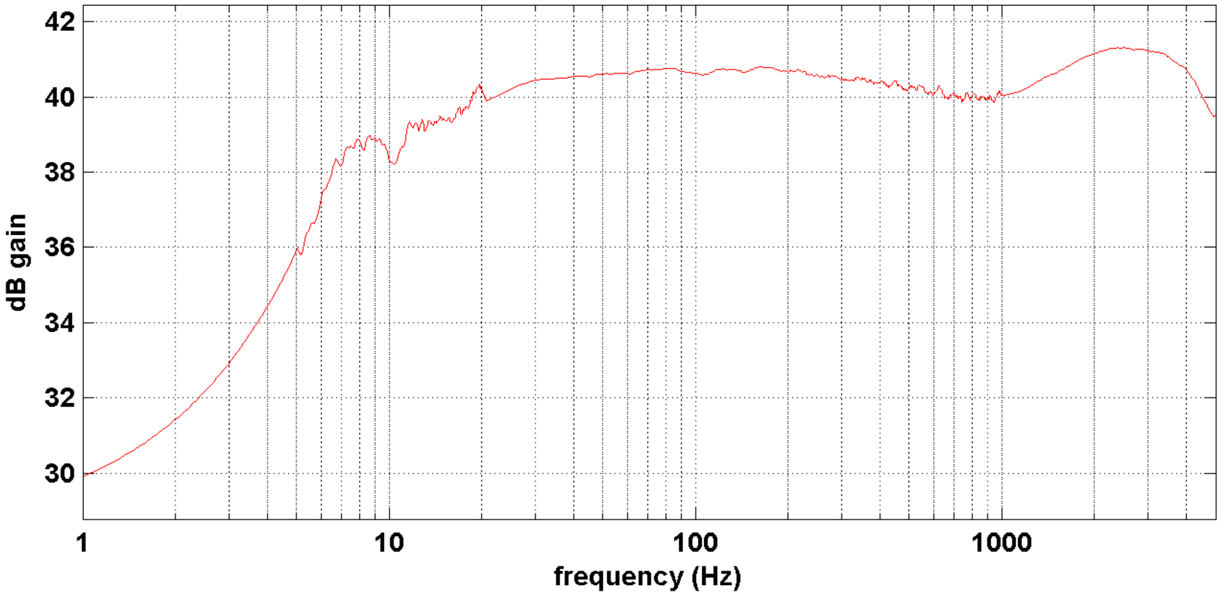

Figure 38: System calibration curve for the Port Hedland noise logger.