REPORT

Review of Literature on Sound in the Ocean and Effects of Noise and Blast on Marine Fauna

Prepared for
Western Australian Water Corporation

URS Project No.: 42906896-1892 : R1340

8 July 2008

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1. INTRODUCTION

1.1 BACKGROUND

The Western Australian Water Corporation (WAWC) is proposing to develop a desalinisation plant at Binningup, Western Australia as part of the Southern Seawater Desalinisation Project (SSDP).

In accordance with Commonwealth and Western Australian environmental approvals requirements, the WAWC has undertaken a range of environmental studies and assessments in support of the SSDP proposal. These are summarised in the *Southern Seawater Desalination Project: Environmental Impact Assessment Public Environmental Review* (PER) (WAWC 2008).

The construction and operation of the SSDP will generate in-water noise, which has the potential to lead to adverse impacts upon marine fauna in the vicinity of the development site.

Potential sources of noise during construction include dredging activities, pile driving (e.g. during construction of the temporary jetty and the laying of the pipe), rock armour dumping, sand/sludge dumping and general vessel traffic. If explosives are used during construction of the pipeline then this too will be a source of noise as well as impulse. Potential noise sources during operations include the movement of water through the outfall as well as vessel traffic associated with periodic maintenance and inspection.

All of these activities may disturb marine fauna to varying degrees. As a result, it was deemed pertinent to undertake a review of literature focusing on the effects of noise and blast on marine fauna and assess potential impacts associated with this project.

1.2 OBJECTIVES AND SCOPE

This report provides information on important marine fauna in relation to noise generating activities and examines the potential risk associated with noise generated from activities attendant to this project. The report provides a literature review on sound in the ocean and the effects of noise on marine fauna, where the following topics are discussed:

- the characteristics of ambient noise;
- natural sources of noise in the ocean;
- anthropogenic sources of noise in the ocean;
- noise effects on marine fauna; and
- likely effects of noise from the construction and operation of the SSDP upon marine fauna of interest.

This review focuses principally on the known and potential physiological responses of fauna to noise in the offshore marine environment, with emphasis given to the area around Binningup. Although this review is not exhaustive, it does illustrate and place into a risk context the range of impacts that might be anticipated as a result of noise from this project.

The review's weighting towards cetaceans is a reflection of the relatively high research intensity afforded to this group of animals. Less is known about the effects of exposure to sounds on other marine fauna such as pinnipeds, turtles and sharks. In cases where data are available, they are often so few that one must be cautious in attempting to extrapolate between species, even for identical stimuli. Moreover, one must also be cautious with any attempts to extrapolate results between stimuli because the characteristics of sources (e.g., ship noise, pile driving) differ significantly from one another.

A description of the abundance and distribution of marine fauna in the area of the project is presented in the SSDP PER (WAWC 2008).

2. PROPOSED ACTIVITY IN RELATION TO UNDERWATER ACOUSTIC IMPACTS

2.1 NOISE GENERATING ACTIVITIES

The project to construct the SSDP, in particular the intake and outfall pipelines and a temporary jetty as well as associated activities, will result in a temporary increase in noise levels and a change in the characteristics of ambient background noise during construction. Operation of the SSDP may also generate noise from the flow of water in the pipelines, as well as periodic vessel activity undertaken for maintenance and inspection purposes. These alterations could conceivably affect transitory and resident marine fauna within the project area.

Activities associated with this project which will generate noise are:

i. dredging
ii. pile driving
iii. explosive blasting
iii. rock armour dumping and sand/sludge dumping
iv. general shipping/vessel traffic
v. pipeline laying and operation.

The key marine components of the SSDP are the seawater intakes and the brine outlets. The inlets will comprise up to three individual pipelines of up to 3 m diameter, extending 400 m to 600 m offshore. The brine discharge outlet pipelines, including diffuser, will comprise up to four pipes of up to 3 m diameter, extending no more than 1100 m offshore. The diffuser will have a total length of up to 450 m and will be located between 600 m and 1100 m offshore. The pipelines will be trenched and emerge from the seabed once beyond the 6 m depth contour and will extend into water no more than around 8 m deep.

At present there is no information available on actual noise levels likely to be generated from this project, or the frequency and duration of specific noise generating activities or the time of year these activities are likely to occur. The only information available is that the construction of the marine components of the project is likely to take up to 18 months and will mostly be undertaken in daylight hours only.

2.2 MARINE FAUNA OF INTEREST

Given their iconic and charismatic status, as well as their general level of protection under both Commonwealth and WA legislation, the marine fauna of particular interest in relation to underwater noise and the SSDP are cetaceans (i.e. whales and dolphins), Australian sea lions, marine turtles and sharks.

As denoted by WAWC (2008) and the Commonwealth Department of the Environment, Water, Heritage and the Arts (DEWHA), the principal marine species of interest in the context of acoustic noise effects are:

- humpback whale (*Megaptera novaeangliae*)
- southern right whale (*Eubalaena australis*)
- blue whale (*Balaenoptera musculus*)
- Bryde’s whale (*Balaenoptera edeni*)
- pygmy right whale (*Caperea marginata*)

- killer whale (or orca) (*Orcinus orca*)
- bottlenose dolphin (*Tursiops sp.*)
- Australian sea lion (*Neophoca cinerea*)
- grey nurse shark (*Carcharias taurus*)
- great white (or white pointer) shark (*Carcharodon carcharias*)
- whale shark (*Rhincodon typus*)
- leatherback turtle (*Dermochelys coriacea*)
- loggerhead turtle (*Caretta caretta*)

2.2.1 Cetaceans

Humpback whales migrate through WA's south west coastal waters. The species is mainly encountered within the area between the coast and the 200 m bathymetric contour. The northward migration is concentrated from June to August and southward from September to November. The southern migration usually occurs closer to the coast. A feature of the southern migration is the passage of cow/calf pairs, particularly in the latter stages. Humpbacks do not feed during the migration period and their presence in the waters around Binningup would normally be associated with migratory transit.

While most southern right whales venture no further north than WA's south coast, a small number migrate through the region around Binningup from around mid-May to late September. This number may be expected to increase over time as the population recovers from the decimation of earlier commercial whaling. This species is often encountered close to the coast in sheltered embayments, where whales may come to give birth and/or nurse their young. Based upon incidents with the closely related northern right whale, this species is considered especially vulnerable to ship strikes.

Blue whales prefer deeper waters of at least 500 m. From early November to mid-May both pygmy blue whale (*Balaenoptera musculus brevicauda*) and the true blue whale (*Balaenoptera musculus intermedia*) are known to congregate over the head of the Rottnest Trench (Perth Canyon), some 130 km or more from the project area. Blue whales are also infrequently observed, typically from October to December, over the continental shelf between Rottnest Island and Cape Naturaliste (i.e. about 100 km from Binningup), and have been periodically observed to come close in-shore in the Cape Naturaliste area, about 70 km from Binningup.

Other species noted of particular concern by regulatory authorities are Bryde's, pygmy right and killer whales. These are less frequently sighted in the waters around Binningup, but may nevertheless occur periodically in the area. Bryde's whales are known to venture as far as 35° South, but are more common in warmer sea areas between 30° North and 30° South (Carwardine 1995). Reeves et al. (2002) and Carwardine (1995) both note that the pygmy right whale is the least known and most rarely sighted of all the baleen whales. On this basis, if sighted in the Binningup area this would arguably generate greater scientific interest than subject the species to risk from the proposed SSDP.

Other whales, such as minkes (*Balaenoptera acutorostrata*), long-finned pilot whales (*Globicephala melas*), false killer whales (*Pseudorca crassidens*) and various species of beaked whales may be expected periodically in the waters around Binningup. The nearby Busselton/Geographe Bay area is a scene of regular strandings by many species, including beaked, false killer and pilot whales (URS 2003). Any of these species encountered in the Binningup area would most likely be itinerant specimens as the location presents no particular preferred habitat for these other species.

The waters around Binningup are known to be visited by a number of dolphin species, the two most frequently sighted being bottlenose and common dolphins (*Delphnius delphis*). The Leschenault Estuary and nearby Bunbury Harbour are noted as the scene of a population of dolphins which have become habituated to human interaction and support an active dolphin watching industry. The entrance to the Leschenault Estuary is around 18 km from the proposed SSDP site. The waters off Binningup are not known to be of any particular or distinct importance to any dolphins, but are most likely within the range of the nearby Bunbury/Leschenault population.

2.2.2 Pinnipeds

The Australian sea lion is an uncommon animal and populations are thought to have declined significantly since European settlement, although the population has stabilized in recent years. The Australian sea lion may migrate through or feed in the area around Binningup, but is not known to be resident in the region. It is a bottom foraging species which generally favours reef areas as sources of prey and has been observed to forage out as far as the 200 m bathymetric contour, although juveniles and lactating females remain in shallower waters (Costa & Gales 2003). Although within the range distribution of the species, neither Shaungnessey (1999) in the *Action Plan for Australian Seals*, nor the WA Department of Fisheries (Campbell 2005), as the responsible conservation management authority, identified any particular habitat area for the Australian sea lion in the vicinity of Binningup. The nearest breeding sites were located some 300 km north of the project area at Butler Island, near Cervantes, and the nearest haul-out sites (i.e. non-breeding resting sites) are at Penguin and Seal Islands, Shoalwater, some 90 km distant. It is possible that sea lions migrating between south coast and mid-west coast breeding sites may migrate through the Binningup area.

2.2.3 Sharks

The grey nurse shark is a coastal species found on the continental shelf from the surf zone down to at least 190 m. The shark is often seen hovering motionless near the bottom in or near deep sandy-bottomed gutters or in rocky caves around inshore rocky reefs and islands at depths between 15 m and 25 m. These sites may play an important role in pupping and/or mating activities as grey nurse sharks often form aggregations at these locations. Unlike the east coast population, there are no confirmed aggregation sites off WA. In an assessment for the WA Department of Fisheries, Chidlow et al. (2006) identified 34 potential areas of interest based on anecdotal observations by commercial fishers, divers and others. Of these 34 sites and following further habitat evaluation, 25 potential aggregation sites were considered to warrant further survey. Note that none of the sites identified by Chidlow et al. (2006) are confirmed aggregation sites. The potential grey nurse aggregation site nearest to the proposed SSDP was at Naturaliste Reef, around 70 km almost directly out to sea from the project area.

The great white shark is potentially present all year round in WA coastal waters. It is generally more common in south west coastal waters during the humpback whale migration period, particularly the latter part of the southern migration as it preys on humpback calves. DEWHA (2007) notes that juvenile great white sharks are commonly encountered in inshore areas, often in the vicinity of the open coast beaches. These are more usually associated, however, with great white shark pupping grounds. The Australian *White Shark (Carcharodon carcharias) Recovery Plan* (Environment Australia 2002) proposes the Great Australian Bight, Victor Harbour/Coorong region (SA), areas off Portland and Ninety Mile Beach (Victoria), Garie Beach – Wattamolla and Port Stephens – Newcastle (NSW) and some areas off southern Queensland as seasonally important for juvenile white sharks and as possible pupping grounds. No areas are identified in WA, although the Plan concedes that more research is required.

Whale sharks have a broad distribution in tropical and warm temperate seas, including shallow coastal waters, usually between latitudes 30° North and 35° South (DEWHA 2007). Although most common in tropical areas, confirmed sightings have been made further south than Kalbarri, WA and Eden, NSW. These sharks are thought to prefer sea surface temperatures of 21°C to 25°C, so if it is to occur near Binningup, this would most likely be during the warmer summer months.

2.2.4 Marine turtles

Four species of marine turtle are known to infrequently visit the waters south of Perth and juveniles may be encountered on or near local beaches after winter storms and the Leeuwin Current have driven them south. Leatherback turtles are occasionally seen in these waters although this species is usually a non-nesting migrant visitor to WA. Based on records of stranded dead turtles, it is probable that at least some green turtles (*Chelonia mydas*) and loggerhead turtles stray into the region seasonally, possibly brought southward by the warmer Leeuwin Current in winter. The hawksbill turtle (*Eretmochelys imbricata*) is also an infrequent visitor. There are no turtle breeding or nesting sites near Bimmngup and none in WA south of the area of Ningaloo Reef (Marsh et al. 1995).

3. AMBIENT NOISE IN THE OCEAN

This section describes the characteristics of ambient noise in the ocean and the natural components of that noise to identify the range of noise levels to which marine fauna are naturally exposed. Natural sources are described in more detail in Section 4 and anthropogenic sources in Section 5.

Ambient noise refers to the overall background noise from both natural and human sources such that the contribution of a specific source is not readily identifiable. The term ‘ocean noise’ has been used by the US National Research Council (NRC 2003) to encompass not only background noise but also sounds from distinguishable nearby sources such as individual ships or pods of whales.

Ambient noise levels are generally reported as ranges of sound pressure level recorded over various sampling periods. Any consideration of ambient noise levels needs to recognise that the indicated levels are actually averages over the selected sampling period. The averaging period used influences the indicated noise level. Short period, transient natural events can produce noise spikes far in excess of the assigned average level for any particular natural phenomenon.

The primary sources of mid-ocean ambient noise are weather effects, tectonic activity, ocean wave interactions (‘microseisms’) thermal agitation and distant shipping traffic (Figures 3.1 and 3.2). Examples of the differences in ambient noise levels, make-up and energy spectra, including deep sea versus coastal waters and regional differences are given in Urick (1983) and Cato (2000). The ambient noise level and frequency spectrum can be predicted for most deep water areas from known shipping traffic density and the wind speed, Beaufort force or sea state. Heavy rainfall can cause significant but localised increases (Section 4.2.5), since this surface source has significant vertical directionality (to 45^{o}) and therefore less range than omnidirectional and horizontal near-surface sources (e.g. Cato 2000).

Broadband ambient noise spectrum levels[1] range from 45-60 dB in quiet regions (light shipping and calm seas) to 80-100 dB for more typical conditions and over 120 dB re 1 µPa [2] during periods of high winds, rain or biological choruses. In the 100-500 Hz range, Urick (1983) estimated average deep water ambient noise spectra of 73-80 dB for areas of heavy shipping traffic and relatively high sea states and 46-58 dB for areas with light shipping and calms.

Background levels in the 20-500 Hz range are frequently dominated by distant shipping, particularly in heavy traffic regions. Vocalisations of the great whales also contribute to this low frequency band, with the duration and frequency of these choruses increasing in breeding, migrating and feeding areas as stocks recover from past whaling (Croll et al. 2001, McCauley & Cato 2003). Above 300-400 Hz the level of weather-related sounds exceeds shipping noise, with wind wave conditions and nearby rainfall dominating the 500-50,000 Hz range.

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[1] The level of a sound wave in a 1 Hz wide frequency band (Urick 1983; see also Figure 3.1). Reported spectrum levels are assumed to reflect mean square pressure unless otherwise stated.

[2] Measure of underwater noise, in terms of sound pressure. Because the dB is a relative measure, rather than an absolute measure, it must be referenced to a standard “reference intensity”, in this case 1 micro Pascal (1µPa), which is the standard reference that is used. The dB is also measured over a specified frequency, which is usually either a one Hertz bandwidth (expressed as dB re 1µPa^{2}/Hz), or over a broadband which has not been filtered. Where a frequency is not specified, it can be assumed that the measurement is a broadband measurement.

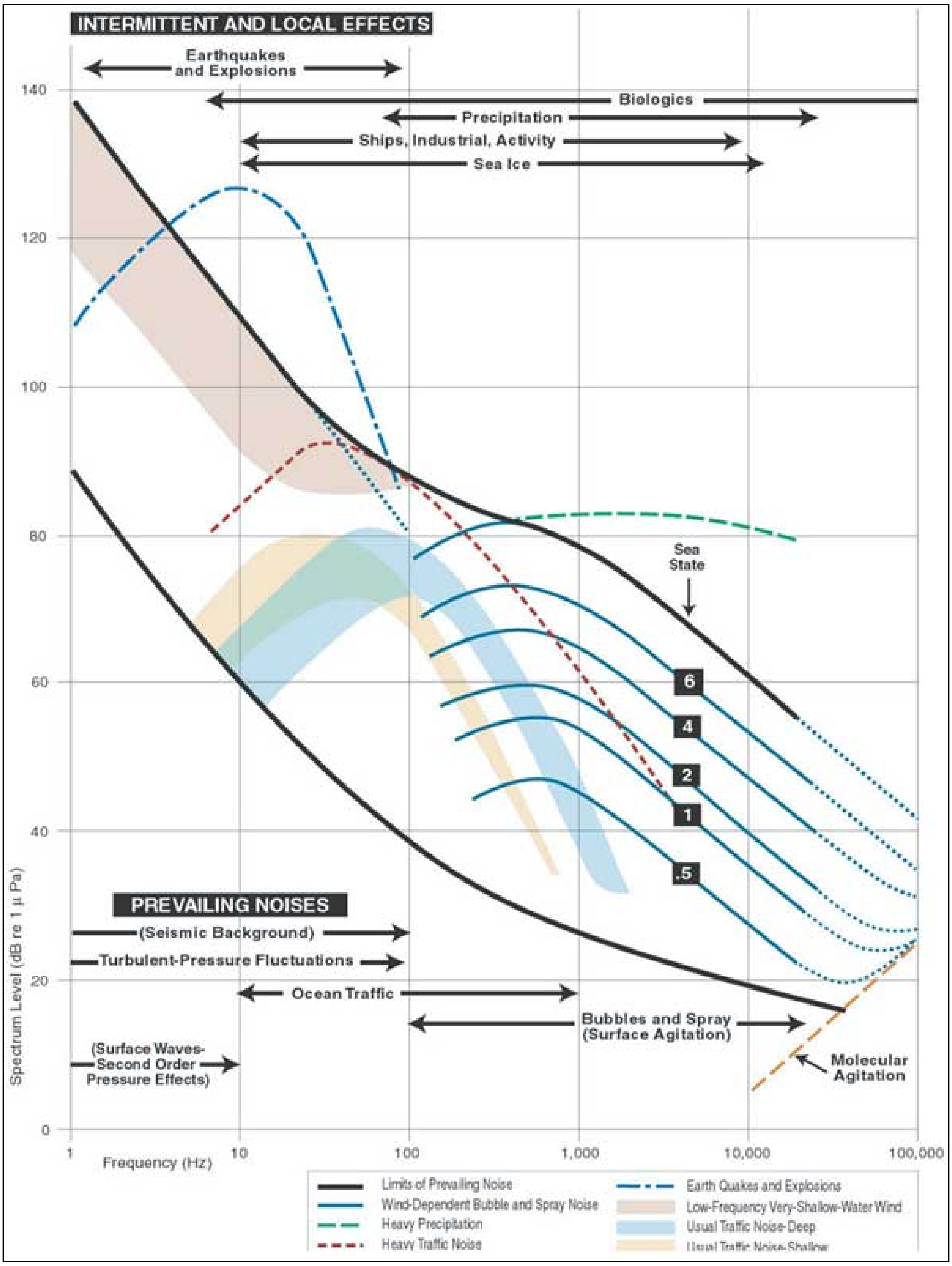

Figure 3-1 Generalised ambient noise spectra attributable to various sources

(compiled by Wenz 1962; reproduced from Richardson et al. 1995)

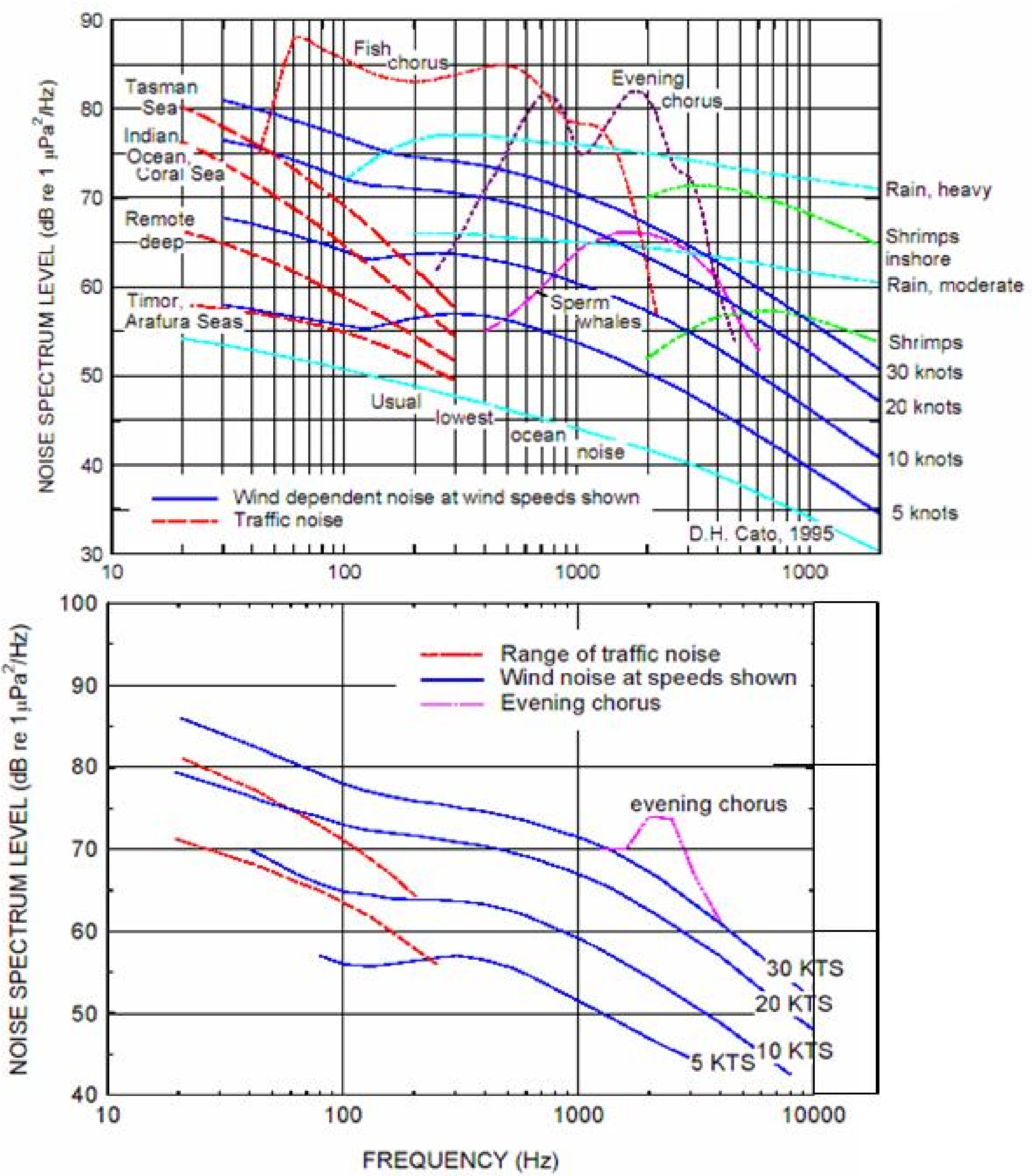

Figure 3-2 Pressure density curves of ambient noise components

Top: Australian waters (Cato 1995)
Bottom: From a Defence Science and Technology Organisation (DSTO) survey site off Perth

In contrast to deep sea regions, ambient noise levels and frequency components across shelfal and nearshore waters are far more variable with season, location and time of day and are less amenable to prediction without local measurements. While the key sources remain shipping and local weather patterns, contributions from marine biota as well as various fishing, boating and industrial noises near ports, harbours and marinas become significant, with the level and composition changing with time and place (Cato 2000; Urick 1983).

In regions with feeding or breeding great whales, whale vocalisations vary by season, week, day and hour and can boost background noise levels to over 120 dB re 1 μPa (e.g. 110-136 dB re 1 μPa [rms] at ⅓OB 300 Hz, with 123 dB re 1μPa peaks at 315 Hz[3]), as measured in March and April 1998 at four locations off Maui where humpback whales were not in the vicinity of the receivers (Au & Green 2000). The type, intensity and propagation of sources contributing to ambient noise in coastal waters are also more spatially variable as a consequence of finer scale changes in seafloor topography and seafloor substrate. Levels increase where more reflective rocky substrates are prevalent and decrease where thick absorptive layers of fine sediments and mud occur.

Turbulence and seafloor saltation noise induced by strong tidal streams can also become locally dominant, particularly in coastal parts of northern Australia with large tidal ranges, and where noise levels fluctuate widely according to local tidal flow rates and bottom types. Ambient noise in Kimberley embayments that contain coarse gravely sediments can exceed 110-120 dB on a diurnal basis, particularly during spring ebb and flood tides (C. Jenner, unpubl. data).

Published plots of low and high frequency ambient noise indicate that the waters surrounding Australia (Figure 3.2) are similar to those elsewhere except for the noisier areas of busy shipping traffic in south Asia, east Asia and NW Atlantic-European waters (see e.g. the colour global sound charts in NRC 2003).

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[3] When evaluating the literature it is important to check the measure used when interpreting reported levels. Geophysical studies frequently record peak-to-peak values (dB re 1 μPa at 1 m), while the 'peak level' (zero-to-peak) for the same signal is typically some 6 dB less. Received sound levels of airgun pulses in biological reports are often given as the average level (root mean square; rms), which represents the mean sound pressure level over the duration of the pulse. These are typically some 10 dB lower than the zero-peak level and often 16 dB lower than the peak-peak value (e.g. Greene 1997, McCauley et al. 1998, 2000a). The energy level (dB re 1 μPa^2 per second) is less frequently used and is usually lower than rms pressure level because the peaks are less than 1 second.

4. NATURAL SOURCES OF NOISE IN THE OCEAN

4.1 CHARACTERISTICS OF NATURAL AMBIENT NOISE

The following section describes the naturally sourced sounds that contribute to the ambient background of ocean noise. In the absence of shipping, natural sources are the dominant sources of the long-term time-averaged ocean noise at all frequencies, including whale calling in many regions (e.g. McCauley & Cato 2003). Even in the presence of distant shipping, contributions from a range of natural sources dominate the ocean noise spectra below 5 Hz and from a few 100 Hz to 200 kHz.

The dominant source of natural noise across the 1 - 100,000 Hz range is associated with sea surface waves generated by wind acting on the sea surface. Non-linear interactions between ocean surface waves, previously called ‘microseisms’ (Section 4.2.2), are the dominant contributors below 500 Hz (referred to as ‘*Surface Waves—Second-Order Pressure Effects*’ in the classical Wenz curves of ambient noise; Figure 3.1). The dominant contributor above 50,000 Hz is thermal noise, which arises from pressure fluctuations associated with the molecular agitation of the ocean medium itself (Section 4.2.6).

Natural biological sound sources make significant contributions in certain regions, seasons and times of day. For example the natural noise from snapping shrimps (from ~5 kHz to 300 kHz) forms an important component close to reefs and in rocky bottom regions in shallow waters in <40° latitudes, reaching crescendo proportions in <60 m deep areas near tropical coasts. Fish choruses can significantly add to ocean noise in many locales, while groups of whistling and echo-locating dolphins can raise local noise levels in the frequency range of their signals. An almost infrasonic peak around 20 Hz created by calls of large baleen whales is often present in deep-ocean spectra, while choruses of humpback whales reach broad peaks near 300 Hz (e.g. Au & Green 2000).

4.2 COMPONENTS OF NATURAL AMBIENT NOISE

The frequency ranges of the following common natural physical and biological sources of relatively intense, persistent and/or frequent noise are shown in Figures 3.1 and 3.2, with their source levels listed in Table 4.1.

Physical: Subterranean vents, tremors, earthquakes, eruptions, sediment slumps and other tectonic activity, lightning strikes, microseisms, thermal noise, ice cracking, wind waves, surf, rainfall, tidal turbulence and seafloor saltation.

Biological: Sea urchins, snapping shrimp, Sciaenid croakers (jewfish, mulloway, etc), other fish choruses, high frequency whistles and echolocation clicks (dolphins and toothed whales), low frequency vocalisations (great whales, including near-infrasonic calls from rorqual species), unidentified ‘biotics’.

Table 4-1 Examples of intense natural sound sources

Source Type	Location and Timing	Perceived Direction	Periodicity	Frequency range (Hz)	Source Level*
Tectonic quakes, tremors, eruptions	Unpredictable	Seafloor or circumferential	Sudden irregular transients (2-20 mins)	LF (10-100)	220-250
Lightning	Unpredictable	Surface	Sudden short pulse	Broadband	~260
Breaching and fluke slapping	Variable (often close)	Surface	Sudden pulse	Broadband	170-190
Baleen whale songs and moans	Variable (often close)	Variable	Variable continuous or transients	LF-MF + harmonics	170-195
Delphinid whistles and squeals	Variable (often close)	Variable	Mostly anticipated transients	HF – VHF (>10 kHz)	180-195
Sperm whale click, codas and creaks	Variable	Variable	Mostly anticipated transients	HF	180-235
Toothed whale echolocation sonar	Variable (often close)	Variable	Mostly anticipated pulses or click bursts	HF-VHF (>10 kHz)	190-232
Sea ice noises	Surface	Multiple surface points	Variable transients	Broadband	120-190
Rough weather and rain	Surface	Background	Irregular, continuous	Broadband	80-120*
Tide turbulence and saltation	Seafloor	Background	Regular, continuous	Broadband	80-120*
Fish choruses	Variable	Stationary / background	Regular continuous	LF and MF/HF tonals	80-120*
Snapping shrimps	Seafloor	Stationary / background	Regular, continuous	LF-MF	80-120*

* dB re 1 µPa at 1 m (peak-peak)

(from University of Rhode Island [undated], NOAA 2002, Cato 2000, Simon et al. 2003.)

4.2.1 Eruptions, tremors and other tectonic events

Seismic events from tectonic activity produce one of the most intense sources of natural noise. Undersea earthquakes, seafloor venting and volcanic activity frequently provide sources of intense low frequency sound. Sounds from volcanic eruptions and resonance tremors in the Pacific Ocean are routinely detected and recorded across distances of thousands of kilometres.

Fox et al. (2002) noted that seismic monitoring since 1991 shows that natural seismic activity in the Pacific Basin produces nearly 10,000 acoustic events annually that involve source levels >200 dB re 1 µPa 1m. Arriving signals often have sudden, sharp onsets and can last from several seconds to several minutes, with frequencies extending from the infrasonic to over 100 Hz.

Earthquakes produce a triangular-shaped acoustic energy signal known as ‘T-waves’. The T-phase duration is related to the earthquake magnitude, and these produce the highest acoustic energy in the 5-35 Hz frequency range (e.g. Nishimura & Clark 2001). A T-wave showing the highest acoustic energy in the 5- 30 Hz range is shown in Figure 4.1 (the yellows and reds).

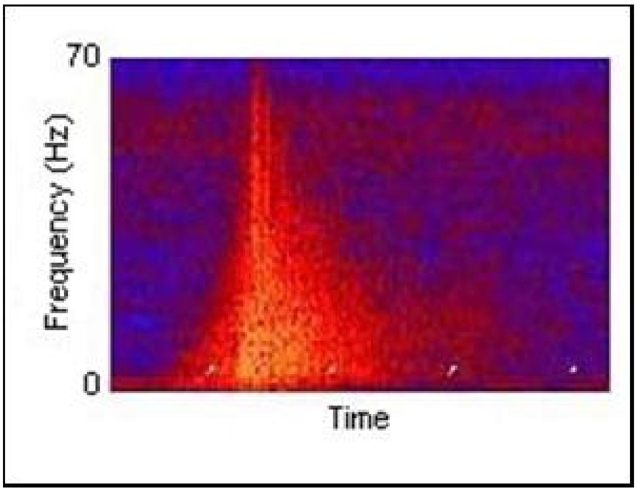

Figure 4-1 Triangular shaped low frequency signal from subsea earthquake.

Plots of T-waves recorded by both SOSUS[4] and the US National Oceanic and Atmosphere Administration's (NOAA) Eastern Equatorial Pacific autonomous hydrophone array[5] during the February 1996 Gorda eruption (near 42°40'N and 126 °48'W in the northeast Pacific), and the 1993 lateral magma injection and subsequent eruption at the 'CoAxial Segment' site (on the Juan de Fuca Ridge at 46°30'N) are shown in Figure 4.2(a,b). The latter event comprised a dike injection and eruption episode during June-July 1993, and intense T-waves were generated during the latter part of this event. The flow site was subsequently investigated by Canada's remotely operated vehicle ROPOS in mid-July 1993, where it found and mapped a fresh venting lava flow 2.5 km long plus extensive venting along a nearby 4 km tract.

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[4] The SOund SUrveillance System (SOSUS) is a fixed component of the US Navy's Integrated Undersea Surveillance Systems (IUSS) network that was deployed for deep ocean surveillance during the Cold War. Installation of SOSUS began in the mid 1950s for use in anti-submarine warfare. SOSUS consists of bottom mounted hydrophone arrays connected by undersea communication cables to facilities on shore. The individual arrays are installed primarily on continental slopes and seamounts at optimal locations for receiving undistorted long range acoustic propagation. The combination of location within the oceanic sound channel and the sensitivity of large-aperture arrays allows the system to detect radiated acoustic power of less than one watt at ranges of several hundred kilometres. A brief history of SOSUS and its current use is at **http://www.globalsecurity.org/intell/systems/sosus.htm.**

[5] In October 1990, NOAA was permitted to access the SOSUS arrays in the North Pacific for ocean environmental monitoring. The data collection systems developed by NOAA's VENTS Program were implemented in August 1991, with acoustic signals from the north Pacific Ocean recorded at NOAA's Pacific Marine Environmental Laboratory (PMEL) in Newport, Oregon. PMEL has subsequently deployed moored autonomous hydrophones for monitoring remote ocean areas not covered by fixed arrays such as SOSUS. PMEL is the primary centre for both continuous monitoring of low-level seismicity around the northeast Pacific Ocean and real-time detection of intense volcanic activity along the northeast Pacific spreading centres, in support of NOAA's VENTS research on ocean hydrothermal systems. Its first array was deployed in the eastern equatorial Pacific in May 1996 for long-term monitoring of the East Pacific Rise between 20N and 20S. Other arrays have since been deployed on the centre ridge of the Atlantic Ocean. Real time ridge crest monitoring permits timely on-site investigations of hydrothermal and magma emissions. Hydrophones were also deployed in the Gulf of Alaska for marine mammal monitoring in 2000. The sensitive PMEL arrays have recorded several airgun sources from around the Atlantic Basin, sometimes simultaneously. The most frequent originating locations are near Nova Scotia (Canada), northeast Brazil and northwest Africa. Airgun signals have occurred in approximately 75% of the annual data recordings of the Atlantic arrays. More information is at http://www.pmel.noaa.gov/vents/acoustics/haru_system.html.

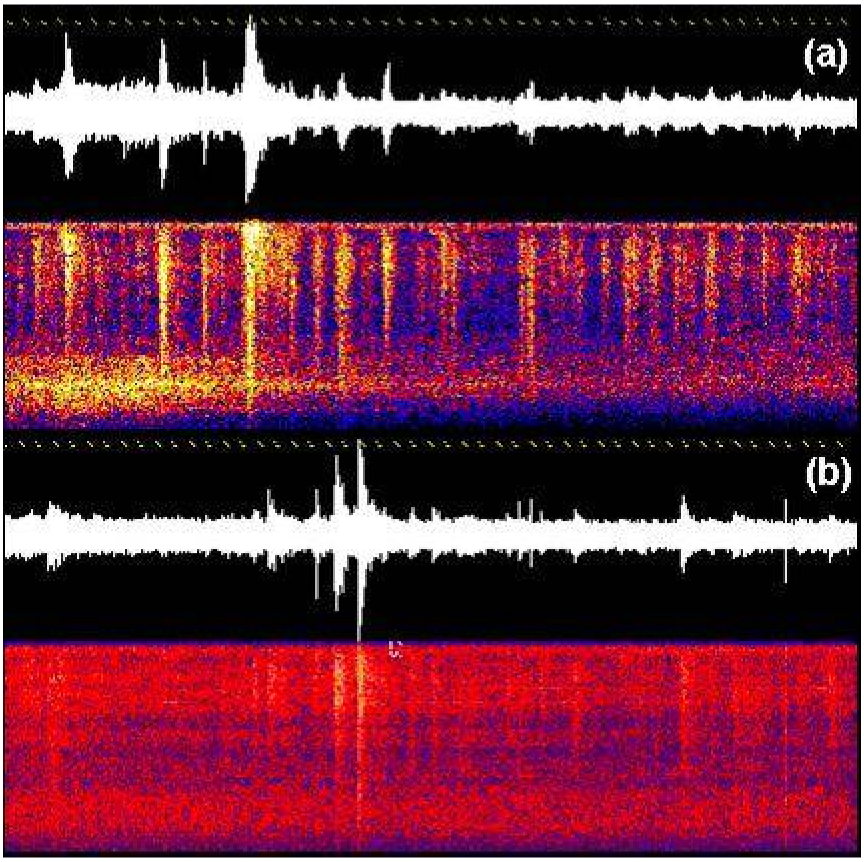
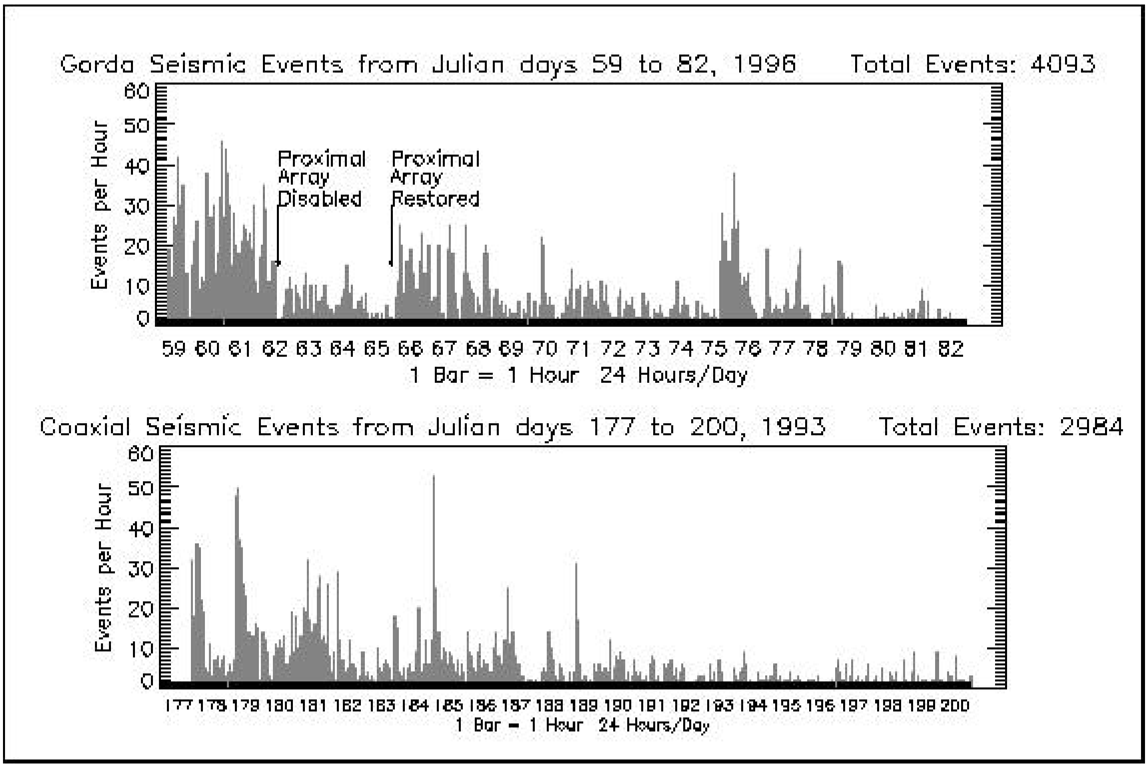


Figure 4-2 Colour spectrograms showing examples of T-waves

(a) Recorded during the 1996 Gorda eruption
(b) Recorded during the 1993 Coaxial segment magma injection
[one minute ticks along the x-axis, 0-75 Hertz along the y-axis; from PMEL (2006)].

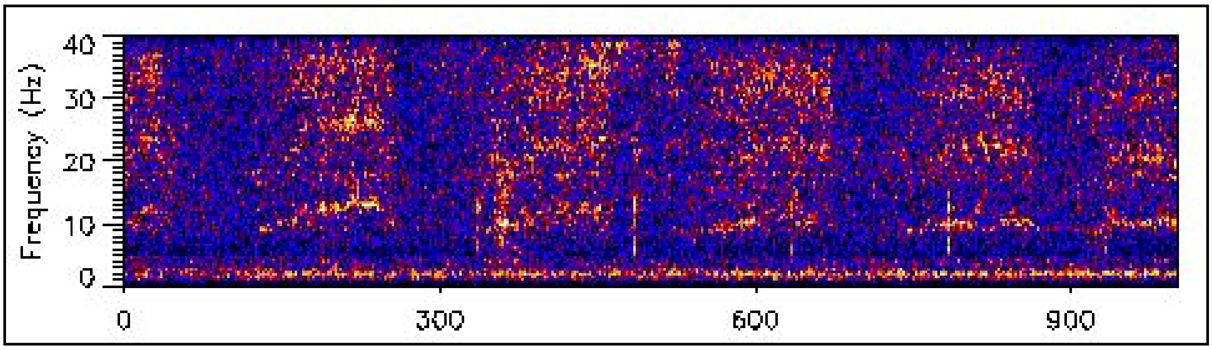
The seismicity of the Gorda and Coaxial segment events are very similar, in which a rapid series of earthquakes occurs without large ‘foreshocks’ (Figure 4.2(a,b)). The histogram in Figure 4.3 shows the number of events recorded per hour for each event. The apparent decline in activity of the Gorda seismic events from midday day 62 to late day 65 was probably due to loss of the closest array.

The various hydrophone arrays in the Pacific and Atlantic Oceans have been monitoring these types of seismic events for many years. A long-lasting example comprises the extremely loud tremor-like signals which emanated from the volcanically active island chain south of Japan. This is the so-called ‘Inferred Harmonic Tremor’ which developed on 30 separate occasions between May 1998 and December 1999 (PMEL 2006). The precise source was beyond the optimal array coverage but the best estimates place it between 22-27^{o}N and 138-141^{o}E. The signals were characterized by a high amplitude fundamental at ~10 Hz plus three harmonics at 20, 30, and 40 Hz. The signals typically appeared as discrete packets lasting 4-5 minutes, with brief quiescent periods of roughly 30 seconds followed by the beginning of the next packet of signals (Figure 4.4). During each signal packet, the spectral peaks typically rose by 5-10 Hz while maintaining their harmonic spacing. The largest peak amplitudes and longest durations occurred on four separate occasions during August 1998, on seven widely spaced occasions during 1999 and continued into 2000. The distinctive spectral characteristics have been previously seen in volcanic tremor signals recorded by seismic and airborne equipment from the Arenal and Pavlof volcanos in Costa Rica and Alaska (PMEL 2006).



(from PMEL [2006])

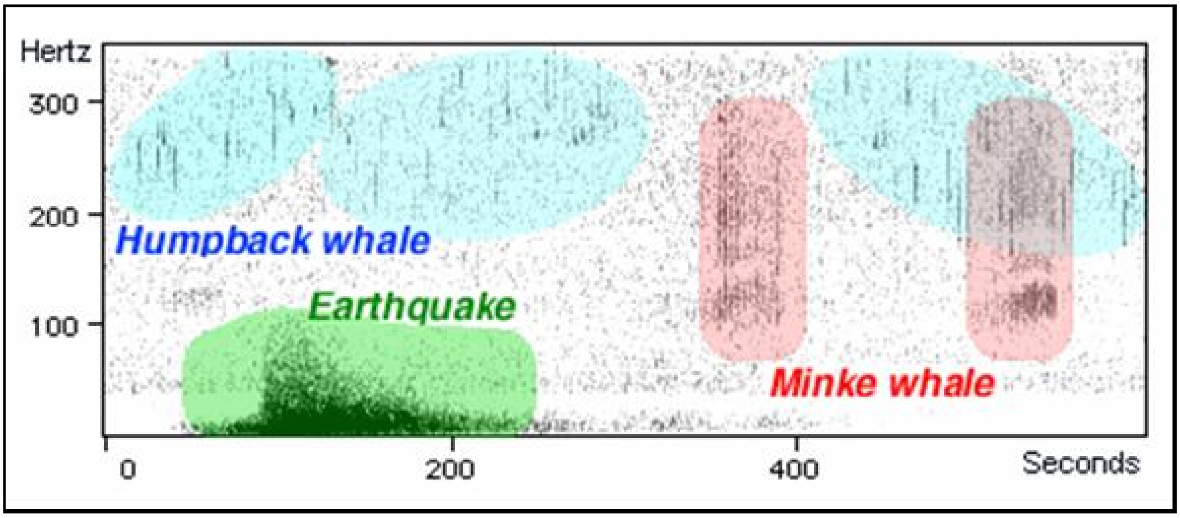
Figure 4-3 Frequency of events during the Gorda (top) and Coaxial segment (bottom) episodes.



(from PMEL [2006])

Figure 4-4 A 900 second portion of the 'Inferred Harmonic Tremor' that was detected south of Japan on many separate occasions in 1998-2000.

Figure 4.5 shows a 10-minute (600 second) spectrogram from SOSUS[2] autonomous deep water hydrophones in the western North Atlantic. The green-highlight shows a low frequency T-wave from an earthquake event in the mid-Atlantic, while the blue and pink-highlighted dark vertical streaks are vocalisations of humpback and minke whales in the vicinity of the array. The spectrogram and sound file show the earthquake produced a loud, low frequency rumble. This recording is on the Office of Marine Programs (OMP) sounds page as an example of how typical tectonic events do not apparently cause marked responses to baleen whale calling behaviour. Such statements would benefit from a longer spectrogram (i.e. showing the type and periodicity of calls recorded for at least the same period before the event of interest as that made after it). It is also unclear if the humpback auditory range is as sensitive to low frequency sounds as those considered likely for the minke and larger rorquals (i.e. the blue and fin whales).



(from OMP 2006)

Figure 4-5 600 second spectrogram showing whale calls recorded by the West Atlantic SOSUS array during and after a subsea earthquake

The northern waters of Australia are occasionally exposed to the intense low frequency sounds which emanate from major tectonic events along the Indonesian-Melanesian island chain, some of which also produce tidal waves that reach northwest Australian shorelines. Australian waters are not immune to local natural seismic sources, since smaller earthquakes (magnitude 4 or less) are not uncommon. On average 17 moderate-sized earthquakes occur annually on Australia's continental shelf, while seven seismic events were recorded in 21 days in the deep sound channel off Cape Leeuwin (southwest Australia) in June-July 1998 (Pidcock et al. 2003).

4.2.2 Ocean wave interactions ('Microseisms')

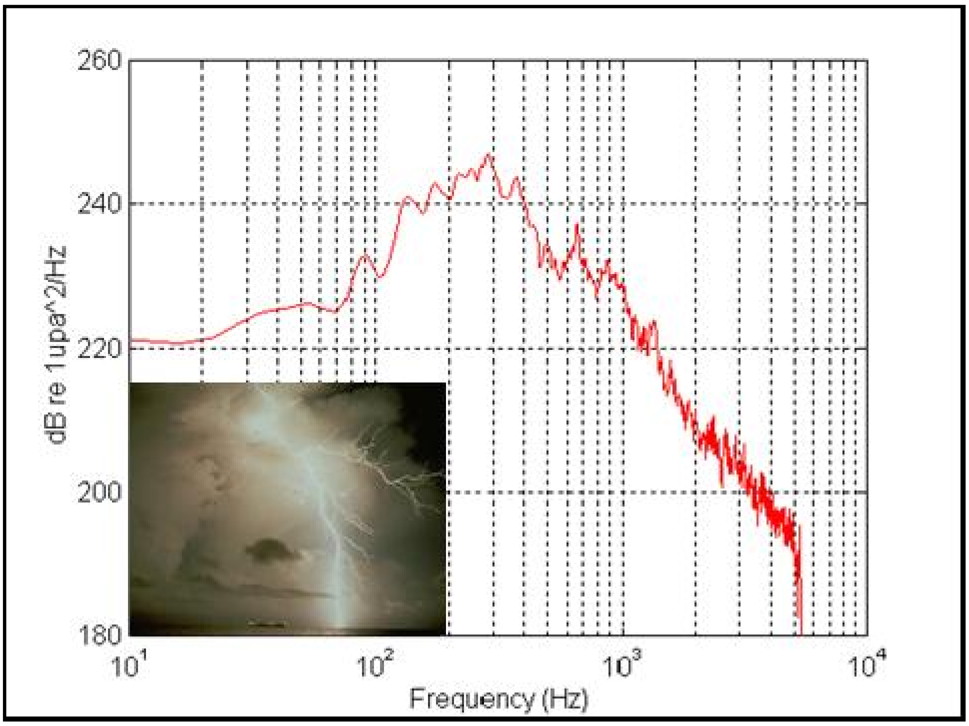
'Microseisms' are the dominant below 10 Hz natural noise source in the space and time averaged ocean noise spectra. This source is generated by non-linear interactions of ocean surface waves. Oppositely propagating waves produce a standing wave pattern that radiates sound with twice the frequency of that of the interacting surface waves. These waves are not related to tectonic processes but were termed 'microseisms' by seismologists because they are also the dominant source of noise in high quality, on-land seismometer measurements. The Wenz Curves include '*Seismic Background*' (Figure 3.1) but it is now known that earthquakes and other tectonic processes contribute only intermittently while the ocean wave interactions provide an almost continuous source of ocean noise in the low frequency range.

4.2.3 Surf

Breaking surf is a significant noise source in near coastal areas. Unlike open-ocean areas, wave noise in the surf zone is not predominantly dependent upon local winds, but is influenced by local as well as distant winds and ocean-derived swells. The NRC (2003) reported that breaking waves can increase ambient noise levels by more than 20 dB across the spectrum from 10 Hz to 10 kHz within several hundred metres of the surf zone. Heavy swells produced by storms many hundreds or thousands of kilometres away can arrive on exposed beaches to produce large plunging breakers which can raise local ambient levels over 20 dB for up to 1 km offshore from big surf beaches. In near shore areas, surf-induced noise is often the dominant character of the ambient acoustic environment.

4.2.4 Lightning strikes

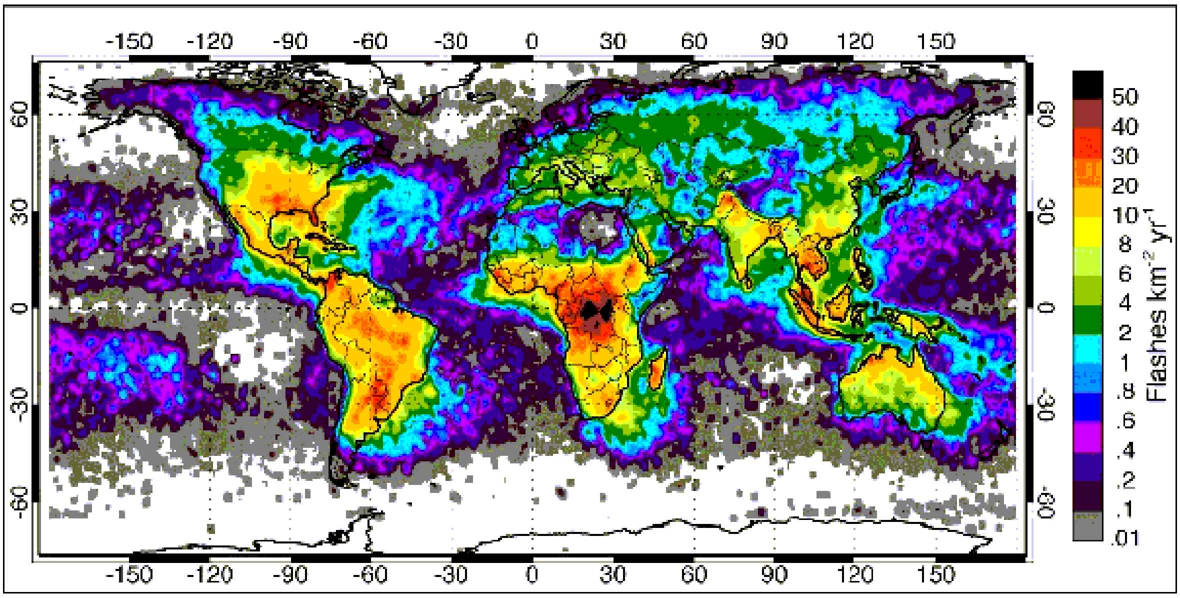
Underwater recordings of spectra of a received sound of thunder from a storm 5-10 km away show a peak between 50 and 250 Hz up to 15 dB above background levels, with detectable energy down to 10 Hz and up to 1 kHz (Dubrovsky & Kosterin 1993, in NRC 2003; Hill 1985). Lightning strikes produce one of the loudest natural sounds in the ocean, generating low tonal impulses with source levels close to the ocean surface of about 260 dB re 1 µPa at 1 m (Arnold, Bass & Atchley 1984; Hill 1985; OMP 2006). Analysis of underwater records indicates the sound has an inherent ability for substantial propagation as most of the energy is in the 10-1000 Hz range, with peaks between 100-300 Hz (Figure 4.6). Most lightning activity is recorded during thunderstorms which have lifetimes usually less than an hour and with fronts as small as 5-10 km. Sometimes thunderstorms are arranged in lines hundreds of kilometres long or form large circular clusters.



(recording from the DFO Institute of Ocean Sciences, British Columbia, Canada)

Figure 4-6 Spectrogram of an underwater recording of a lightning strike

As shown in Figure 4.7, lightning activity is generally less over the oceans than land, although the sea areas around Binningup receive around 2 to 4 flashes per km^2 per year. On this basis, the area out to sea for a radius of 10 km from the SSDP would be subject to the order of 300 or more lightning flashes per year, while the area within a 20 km radius would experience over 1200 lightning flashes per year.

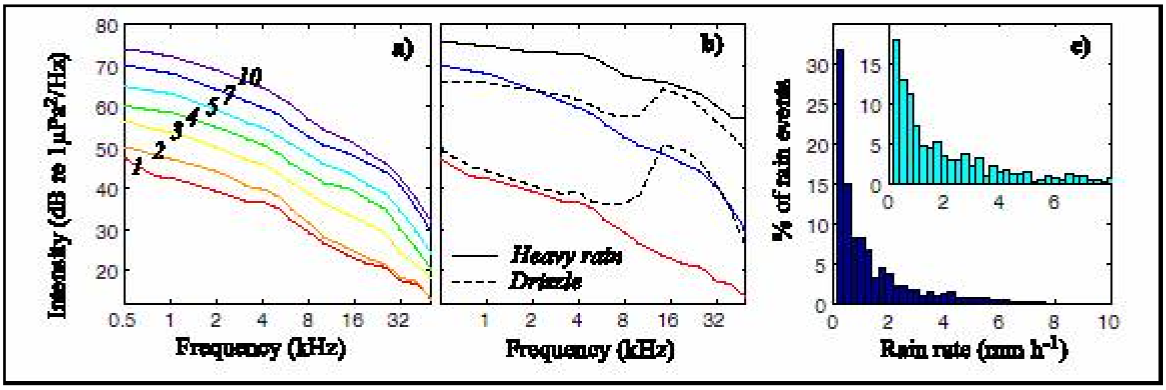


(from http://thunder.msfc.nasa.gov/otd/images/global_ltg_from_paper.JPG)

Figure 4-7 Global distribution of lightning flash density (km^2) per annum

4.2.5 Wind and rain sources

Wind is almost omni-present and its acoustic signature is discernible most of the time (e.g. Richardson et al. 1995, Quartly 2002, Figures 3.1 and 3.2). Wind generates subsurface sound via the production of breaking waves and generation of subsurface bubbles, with a frequency range from 200 to 50,000 Hz. Although the production of bubbles appears to visibly commence once wind speeds exceed ~5 ms^{-1} and breaking waves form 'white caps', bubbles are produced even under very light winds (Quartly 2002). The movement and breaking of these bubbles cause strong underwater sounds. The typical noise spectra due to wind-induced wave and bubble formation increase with wind speed and fall off with frequency (Figure 4.8(a)).



(All data for Loch Etive in Scotland, reproduced from Quartly 2002)

Figure 4-8 Underwater spectrograms for (a) different wind speeds (in m s^{-1}) and (b) rainfall, and (c) rainfall rate probability distributions when raining. (c) upper panel = Nov-Dec 1999; (c) lower panel = May-Jun 2000.

Recent meteorological events and shipping activity can have an effect, as both strong winds and heavy rain produce a sub-surface bubble layer that takes time to dissipate and attenuates the higher frequencies generated by any subsequent surface sources (Quartly 2002). Bubbles left in the wake of passing ships can be identified for almost an hour after the event.

Rain produces a loud, distinctive signal that can increase ambient noise by up to 35 dB across a wide band (100 Hz - 50 kHz; Figures 3.1, 3.2). Drizzle produces a characteristic ~14 kHz peak while the intensity of the frequency spectra of heavy rain often exceed that of wind (Figure 4.8(b,c)). Rain generates sound in several ways including the direct impact of droplets, although the bubbles produced by air entrainment during the splashes are the noisiest component. For most raindrop sizes and angles, the bubble sounds provide the loudest component. Small raindrops (0.8 -1.2 mm) generate frequencies between 10-25 kHz. Medium raindrops (1.2 - 2.0 mm) are quiet due to poor air entrainment while large (2.0 - 3.5 mm) and very large (>3.5 mm) raindrops trap large bubbles which generate frequencies as low as 1 kHz. Sound recordings of rainfall can be used to measure rainfall rate, raindrop size and other features, and are helping meteorologists, oceanographers and climatologists in climate change studies.

As different raindrop sizes produce distinctive sounds, the underwater sound can be inverted to quantitatively measure drop size distribution in the rain. Acoustical Rain Gauges (ARGs) are being deployed on oceanic moorings to make long-term measurements of rainfall using this acoustical technique.

4.2.6 Thermal noise

Thermal noise is generated by pressure fluctuations associated with the thermal molecular agitation of the ocean medium itself. It is what remains when all other noise sources are removed and so provides the lowest bound for noise levels in the ocean. Depending on sea state, thermal noise dictates the shape and level of ambient noise spectra above 50 kHz (Figures 3.1, 2.2; NRC 2003).

4.2.7 Biological sources

Before focusing on cetaceans, it is worth noting the sound levels and frequency ranges of some of the noises produced by other marine biota. These noises are dominated by sizzling and crackling sound of snapping shrimps, the croaks, grinding and grunting sounds of croaker fishes and fish choruses, which generate major peaks in the frequency ranges shown in Figures 3.1 and 3.2. The teeth grinding action of sea urchins resonates through their body shell and forms another significant biological sound in reef areas. Snapping shrimp are a dominant evening source in many sub-tropical and tropical shelfal waters, while loud fish choruses are common around Australia’s coasts, particularly after sunset and near dawn (Figure 3.2; see Cato 2000 for more details).

Whales, dolphins and porpoises produce a wide range of sound covering the frequencies between 10 and 20,000 Hz, and there are many web sites containing spectrograms and sound files of recorded vocalisations[6] covering a range of species. Some of these sites also provide

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[6] The term ‘vocalisation’ refers to any sound intentionally produced by a marine animal that may be used for communication, orientation, prey detection, feeding or breeding. It does not imply that marine mammals use vocal folds, i.e. by exhaling lung air to vibrate vocal cords in base of the throat.

audio file examples of various unidentified 'bloops' 'slow-downs' and other presumed biological sounds (some possibly cetacean) whose source is unknown.

The dolphins and other toothed species (odontocetes) typically produce all of the higher frequency (> 5000 Hz) calls, whistles and echolocation pulses (with the exception of the songs of male humpback whales), while the baleen whales (mysticetes) vocalise in the low to mid range, with the larger rorquals producing low to very low (infrasonic) frequencies (Figure 4.9).

It is not exactly understood how the various types of call and echolocation pulses are generated, although the melon is known to be critical for focussing the typically intense echolocation pulses and clicks in the odontocetes. Estimates of the source level of the 38 microsecond broadband clicks produced by orcas when searching and feeding on Norway herring are in the 187-213 dB (re 1µ Pa [(peak-peak] at 1 m) range, with centre frequencies of 26-57 kHz; Simon et al. 2003). These frequencies lie in the highest sensitivity zone of the orca audiogram. By contrast, an underwater tail slap used by orcas to stun herring produces a broadband multi-pulsed sound with an estimated source level of 187 dB (re 1µ Pa [(peak-peak] at 1 m) (Simon et al. 2003).

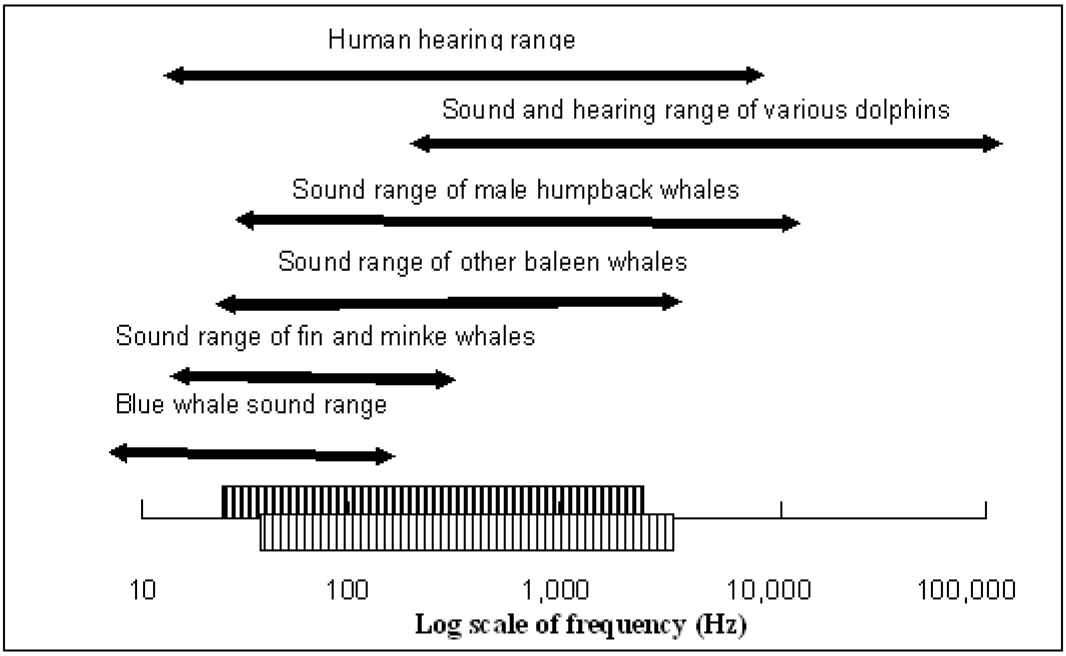

Figure 4-9 Frequency ranges for some baleen whales and dolphins
(Keyboard shows fundamental musical scale; adapted from McCauley [2003])

The following subsections describe the vocalisations of key species potentially occurring in the waters around Binningup.

4.2.7.1 Humpback whales

Humpback whales are probably the best known member of the rorqual group owing to the complex vocalisations of the mature males that cover many octaves. Sounds produced by the males are arranged in complex, repeating sequences that contain both tonal and pulsed components to form long 'songs', probably to help attract females. Some males will vocalise hundreds of times a day, sometimes for up to 20 hours without significant breaks. Large older males produce the longest and most complex songs, presumably to demonstrate fitness by maintaining a long song without interruption for surface breathing.

The loud songs directed in the breeding season by males towards females, other males or both, are now known to have estimated source intensities up to at least 189 dB (re 1 μPa 1 m) and frequencies in the 25 to 25000 Hz range (Payne 1970; Winn et al. 1970a; Thompson et al. 1986, in National Marine Fisheries Service [NMFS] 2002a; Mercado & Frazer 1999; NRC 2003). The songs differ among the regional populations and can change from year to year. Earlier estimates of their source levels (155-174 dB re 1 μPa 1 m) were considered to provide an effective 10-20 km range that could extend to 160 km depending on local conditions (Thompson et al. 1979, in NMFS 2002a).

Animals in mating groups produce a variety of sounds, and the sounds associated with apparent aggressive behaviour by males are different from the long songs. The shorter vocalisations extend from 50 Hz to at least 10 kHz, with most energy in the components below 3 kHz. The vocalisations appear to have audibly effective ranges of up to 9 km (Tyack 1981 1983; Silbert 1986; Tyack & Whitehead 1983; all in NMFS 2002a).

Songs from eight male humpback whales in a mating group were recorded by Mercado, Herman and Pack (2003) at very close ranges (20-40 m) by both single and vertical array hydrophones that had a uniform frequency response to 24 kHz. The equipment found many songs to comprise discrete bursts of sound. These bursts were organised into phrases, and phrases into themes. Most bursts had a mean duration between 1-2 seconds separated by similar intervals. Many of the recorded songs contained units that had high frequency harmonics extending to at least 22 kHz, implying that the broadband quality of the male songs is much wider than previously detected, providing further insight as to the possible high frequency limit in humpback hearing. The source levels of the different songs were estimated by considering the root mean square (rms) pressure level of the most intense units in each phrase of a song. Source levels varied between 171 and 189 dB (re 1 μPa 1m). The eight males were regularly observed within two whale lengths of females, indicating that male humpback whales exposed female whales to high sound intensity levels (Mercado, Herman & Pack 2003).

There is increasing evidence that similarly long, complex and intense humpback male calls are occurring in feeding areas, such as those sung daily in the summer feeding grounds in the North West Atlantic (Clark & Clapham 2004). Shorter sounds have also been recorded in the 75 m deep Soquel Canyon in Monterey Bay, California. These feeding-associated calls include low frequency grunts and higher frequency ‘eeeeees’ that may be used to coordinate group feeding, rally animals to feeding hotspots and/or concentrate the sardine schools that they target in this area. These distinctive sounds range from 20 Hz to 2 kHz, with median durations of 0.2-0.8 sec and estimated source levels of 175-192 dB (re 1 μPa 1 m) (Vincent et al. 1985, Thompson et al. 1986, Sharpe & Dill 1997, all in NMFS 2004).

In summary, humpback whales produce at least three types of sounds:

(1) Long complex songs with components ranging from 20 Hz to at least 4000 Hz (with some harmonics to 22 kHz) with estimated source levels in the 180-189 dB (re 1 μPa 1 m) range, as delivered by mature males in breeding areas.
(2) Male aggression sounds in the breeding areas, some extending from 50 Hz to over 10 kHz with most energy below 3 kHz.
(3) Less frequent but apparently increasing vocalisations in feeding areas, which are in the 20-2000 Hz range with estimated sources levels in the 175-192 dB (re 1 μPa 1m) range.

> Long complex songs from males form part of the apparently increasing repertoire in these areas.

The evidence of increasing vocalisations in humpback feeding grounds, as well as increasing call rates in winter breeding areas as humpback populations recover, lend further weight to the observation of McCauley and Cato (2003) that the ~40 year rise in low frequency oceanic background noise reported for some areas is not solely attributable to increased shipping.

4.2.7.2 Southern right whales

Right whale vocalisations are more concentrated in the lower frequencies, with their moans, groans, belches and pulses having most acoustic energy below 500 Hz. While moans are typically below 400 Hz some vocalizations have been reported to occasionally reach 2 kHz (in NMFS 2004). Right whales also produce a variety of low frequency sounds from noisy broadband blows and impulsive slaps, all with significant energies in the 50-1000 Hz range (Richardson et al. 1995). Source levels of southern right whales have been estimated as 172-187 dB (re 1 µPa at 1 m), although McCauley et al. (1998) found song components of southern right and humpback whales reaching an estimated 192 dB (re 1 µPa at 1 m).

Right whales use a variety of calls when socialising in a group, and recent studies indicate that the vocalising behaviour of the northern and southern right whale species are similar. However vocalisation rates are highly variable and individuals may remain silent for several hours. Vocalisation rates of North Atlantic right whales (*Eubalaena glacialis*) were measured using tagged and towed hydrophones by Matthews et al. (2001) in spring and summer 1999-2000 off Cape Cod (USA) and Bay of Fundy (Canada). Vocalisations were classed as either ‘moans’, 'low frequency calls' or 'gunshots'. Moan rates increased with size of whale aggregation. Individual whales produced 0 – 10 moans per hour. Small aggregations (2-10 individuals) produced 0-60 moans per hour, while larger aggregations (>10 individuals) typically generated 70-700 moans per hour. Higher moan rates were at night (as also noted for blue whales), and most moans were produced in clusters and within 10 m of the surface (Matthews et al. 2001).

Vocalisations made by North Pacific right whales (*Eubalaena japonica*) in the eastern Bering Sea in July 1999 were commonly detected to 20 km and once to 30 km via deployment of arrays of directional sonobuoys from a US Coast Guard vessel (McDonald & Moore 2002). Other cetaceans detected acoustically by these deployments included fin whales (19 times), killer whales (3 times) and sperm whales (once). From the deployments targeting the areas used by right whales, 26 acoustic detections were made while only five right whales were spotted, with only one making calls while under visual observation. Calls by the North Pacific right whales are similar in duration and frequency to those from South Atlantic right whales, *Eubalaena australis* (McDonald & Moore 2002). The predominant call (85% of 511 recorded calls) was the `up' call, a signal sweeping from 90 to 150 Hz in 0.7 seconds. Two other calls were termed `down' and `constant' calls based on the terms used for similar calls by other Southern right whales. Another call (`down-up') was considered unique to the North Pacific repertoire. As with the North Atlantic species (*E. glacialis*), the North Pacific right whales (*E. japonica*) typically produce a series of calls over several minutes then fall silent for an hour or more, with some animals not calling for four hours or more.

4.2.7.3 Blue whales

Blue whales are known to produce low-frequency moans which are lengthy, strong and often infrasonic by human standards. Recordings of blue whales off Chile noted the production of low-frequency moans at 12.5-200 Hz, lasting up to 36 seconds. Overall source levels were up to 188 dB (re 1 µPa-m). It was noted that a short pulse of 390 Hz was also produced during the moan (Richardson et al. 1995).

4.2.7.4 Bryde's whales

Data from recordings of Bryde's whales in the Gulf of California identified that this species produce short moans at a range of 70-245 Hz with a mean frequency of 124 Hz. Richardson et al. (1995) believe source levels could be ~152-174 dB (re 1 µPa-m), and have noted that Bryde's whales also produce short pulsed moans predominantly at 165-500 Hz. Calves may produce discrete pulses at 700-900 Hz (Richardson et al. 1995).

4.2.7.5 Dolphins

Bottlenose dolphins produce whistle sounds within a frequency range of 0.8-2.4 kHz, and between 3.5-14.5 kHz at maximum energy. Source levels for bottlenose dolphins are in the range of 125-173 dB (re 1 µPaat 1 m). The finless porpoise is known to produce click sounds within a frequency range of 1.6-2.2 kHz and at 2 kHz at maximum energy (Ketten 1998a).

4.2.7.6 Sea lions

While is there is some literature on the vocal behaviour and effects of noise on Californian sea lions, there are few published measurements of Australian sea lion vocalisations, and nothing on the effects of underwater or airborne noise on their behaviour (e.g. N. Gales, in Pidcock et al. 2003). California sea lions vocalise both in and out of water. Underwater sounds include barks, whinnies and buzzing, all below 4 kHz and associated with social interactions. Both males and females vocalise within the breeding colonies, with the loudest utterances in the 250 - 2000 Hz range (Richardson et al. 1995).

The Australian sea lion shares some life-style traits with Californian sea lions, including strong fidelity to seasonal breeding sites. Pidcock et al. (2003) considered that the Australian sea lion probably has a similar repertoire of sounds to the Californian species during both haul out and foraging periods.

4.2.7.7 Turtles

There is minimal information available regarding marine turtle generated noise, although Richardson et al. (1995) report that they have relatively weak vocalisation ability, mostly in the 100-700 Hz range.

5. ANTHROPOGENIC SOURCES OF NOISE IN THE OCEAN

5.1 COMPONENTS OF ANTHROPOGENIC NOISE

The main anthropogenic sources of noise in the marine environment include trading, working and recreational vessels, dredging activities, drilling and pile driving programmes, use of explosives, commercial sonar (depth sounders, fish finders and acoustic deterrents), geophysical sonar, and noise from low flying aircraft and helicopters. This section reviews what is known about these noise sources.

Table 5.1 shows the frequency range characteristics of a wide range of anthropogenic noise sources.

Table 5-1 Typical frequency ranges of anthropogenic noise sources

Frequency Band	Principal Contributors
<10 Hz	Ship propeller cavitation, seismic survey sources, explosives, aircraft sonic booms.
10 – 100 Hz	Distant ships, explosives, seismic survey sources, construction and industrial activities.
100 - 1,000 Hz	All sources of the 10-100 Hz band plus nearby ships, launches and other small craft and seismic air-gun arrays, low frequency active sonar.
1000 - 10,000 Hz	Shipping sources (close range), plus outboard powered boats, military tactical sonars, seafloor profilers and depth sounders.
10,000 - 100,000 Hz	Mine-hunting sonar, fish finders and some hydrographic survey systems.
>100,000 Hz	Mine-hunting sonar, fish finders, high-resolution seafloor mapping devices (side-scan sonar), some depth sounders, some oceanographic and research sonar for small-scale oceanic features and some hydrographic survey systems (e.g. Acoustic Doppler Current Profilers).

(from data in NRC 2003)

5.2 GENERAL SHIPPING

Surface shipping remains the most widespread source of low frequency (<1000 Hz) anthropogenic noise (e.g. Richardson et al. 1995, Simmonds & Hutchinson 1996, Popper et al. 1998). The US Navy (2001) has estimated that the +60,000 vessels of the world's merchant fleet annually emit low frequency sound into the world's oceans for the equivalent of 21.9 million days, on the basis that 80% of this fleet is at sea at any given time.

Ships generate substantial broadband noise from their propellers, motors, auxiliary machinery, gear boxes and shafts, plus their hull wake and turbulence. Diesel motors produce more noise than steam or gas turbines, but most long distance (low frequency) noise is generated by the 'hissing' cavitation of the spinning propeller. The characteristics of the principal sources of ship noise are as follows:

Propeller noise: Originates from the propeller blade cavitation that forms gas-filled cavities whenever the pressure of the water accelerating over the face and any rough edges on each blade falls below critical values (propeller blades 'suck' ships forward by the very low pressures generated on their forward faces, and these rapid pressure falls cause the 'boiling' effect). Intense broadband sound is created when the bubbles subsequently collapse in either a turbulent stream or against the surface of the propeller. Cavitation noise is directly related to vessel speed (the faster the propeller rotates, the more cavitation plus the larger the wave wake, in which further air bubble generation and collapse occur).

For ships with constant pitch propellers, the intense ‘hissing’ noise begins above the cavitation inception speed (typically 7-14 knots for most merchant ships). For tugs, rig supply tenders and dynamically-positioned drilling ships equipped with variable pitch propellers, and/or thrusters, cavitation noise occurs at both low and high speeds, with cavitation-free speeds often restricted to the 7-10 knot range. Propeller blades also generate the distinct ‘blade-rate’ tones that are proportional to the rotation rate of the propeller, while ‘singing’ propellers are not uncommon but usually restricted to a narrow band of the vessel’s overall speed range[7].

Flow noise: While most collapsing bubble noise is generated by propeller blade cavitation, other bubble noises emanate from obstructions on the hull and in the wave wake produced by the ship. Flow noise is sourced mainly from the external flow of water around the hull but also includes the noise of any fluids flowing through internal pipework that becomes transmitted through the hull. External flow noise includes vibrations and rattles in the hull plating and other external structures, plus the noise of the continuously breaking bow and stern waves and turbulence produced by protruding structures such as bilge keels, rudders and corrosion protection sacrificial anodes.

Machinery noise: A range of mechanical vibrations that are generated by the main motors and auxiliary units and transmitted through the hull to the water, contributing to both broadband and narrowband noises.

Compared to merchant ships, fighting ships and submarines are designed, built, maintained and operated to be much quieter for two operationally critical reasons. Firstly to limit their potential to become acoustically detected by an adversary’s sensors and underwater weaponry, and secondly to reduce acoustic ‘self-masking’ and thus maximise their detection and range-finding capabilities.

The noise spectrum radiated from merchant ships is typically 20-500 Hz with tonal peaks at approximately 50-60 Hz. Their low frequency noise components significantly contribute to the amount of low-frequency ambient noise, particularly in regions with heavy ship traffic. Thus ship noise needs to be treated in two categories; noise from nearby ships and that from distant traffic. Noise from nearby shipping is usually readily discernible as coming from individual vessels, with each ship producing a specific noise signature. The sound level and frequency characteristics (‘signature’) of discernible ships depend on their size, number of propellers, number and type of propeller blades, blade biofouling condition and machinery/transmission maintenance condition. In general, the larger the ship the louder the source level and the lower its tonals.

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[7] Ship builders report that approximately four of every 100 of new or refurbished propellers which meet all industry design standards are discovered to be a ‘singing’ propeller when fitted (e.g. **http://www.henleyspropellers.com/faq.htm).** Singing occurs when the frequency of the vortices shed in the vicinity of the blade trailing edge match the blade’s structural natural frequency, exciting the blade in a twisting mode in the same way a wine glass can be made to sing when its rim is gently rubbed. A singing propeller will usually excite the hull via the shaft and brackets, causing an annoyingly loud audible tone at particular RPM bands. This can occur on all vessel types, from small recreational cruisers to large ships, and involve one or both of a matched pair on twin installations. The loud airborne tone inside the hull is produced via the blade resonation through the drive train, shaft bracket or other hull components. In most cases the resonance-producing RPM band is narrow (Δ50 rpm) but in severe cases the audible tone occupies the normal operating range and/or may extend for over 400 RPM.

Figure 5.1 illustrates the energy spectra measured from large bulk carriers sailing into and out of the Port of Dampier in Western Australia. Peak average noise was in excess of 180 dB at a frequency of 10 Hz, with 1000 Hz tones at levels of 140 - 150 dB. The sound source levels of trading ships are compared with non-trading vessel types in Table 5.2.

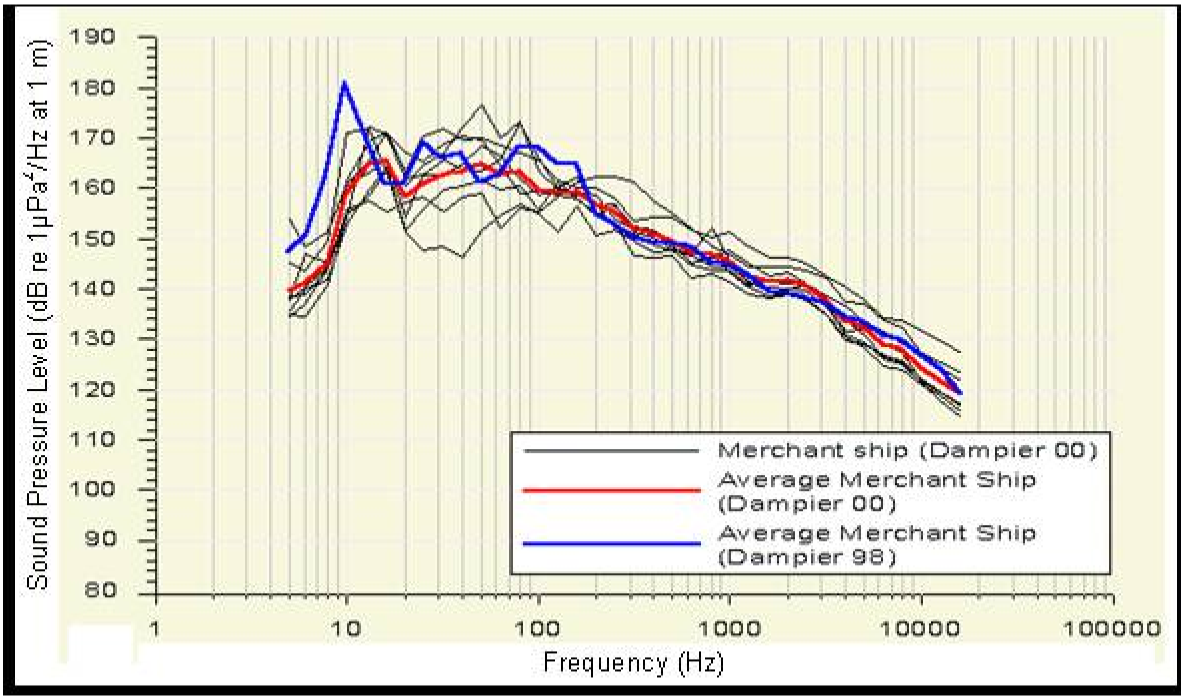


Figure 5-1 Merchant ship acoustic signatures measured in Dampier (WA) by DSTO

Table 5-2 Comparison of sound source levels from a range of anthropogenic sound sources

Source	Peak frequency or band	Peak source level/s (re 1 µPa 1 m)
Icebreaking ship (full power in ice)	10-1000 Hz	193 dB
Large tankers and bulk carriers* Container ship** 64 m Rig supply tender* Tug towing barge*	10-30 Hz 7-33 Hz *(broadband)* 1000-5000 Hz	180-186 dB 181 dB *177 dB* 145-171 dB
20 m Fishing vessel* Trawler# 25 m SWATH ferry with 2 x 950 hp inboard diesels**	*(broadband)* 100 Hz 315 Hz	*168 dB* 158 dB 166 dB
13 m catamaran with 2 x 200 hp inboard diesels* Bertram cabin cruiser with 2 x 165 hp inboard diesels*	315 / 1600 Hz 400 Hz	159 / 160 dB 156 dB
8 m RHIB with 2 x 250 hp outboards* Power boat with 2 x 80 hp outboards# 4.5 m inflatable with 1 x 25 hp outboard* Zodiac inflatable with 1 x 25 hp outboard#	315-5000 Hz 630 Hz 2500-5000 Hz 6300Hz	177-180 dB 156-175 dB 157-159 dB 152 dB
Cutter-suction dredge (working) Clamshell dredge (working) Pile driving operations	100 Hz tonal 250 Hz pulses Low tonal pulses	~180 dB 150-162 dB 170-180 dB
Seismic survey Drilling Supply vessel	0-1000 Hz 10-4000 Hz 1-500 Hz	200-232 dB 154-170 dB 182 dB

* recorded at 10-11 knots; ** recorded at ~15 knots; # unrecorded speed or speed range.

Data sourced from Richardson et al. 1995; Dames & Moore 1996; Au and Green 2000, McCauley et al. 2002; University of Rhode Island, undated; and DSTO data for the Port of Dampier.

Distant shipping elevates local ambient levels across the 5-100 Hz band and no single ship is discernible. For a typical deep ocean case where propagation conditions are good, a large tanker with a source spectrum of ~180 dB (re 1 $\mu Pa^2/Hz$ at 1 m) at 50 Hz may contribute 85 dB at 20 km, 75 dB at 200 km and 65 dB at 2000 km. Thus for a typical North Atlantic ambient noise spectrum level of 85 dB at 50 Hz, this may be dominated by the contribution from a single nearby ship (20 km) or ten large ships within 200 km, or 100 large ships within 2000 km (e.g. Popper et al. 1998). Thus the actual level of traffic-induced background noise depends on the number, size and distribution of trading ships underway within the particular sea or ocean basin, plus their source levels and propagation conditions.

NRC (1994) estimated that the background ocean noise level at 100 Hz may have increased by about 1.5 dB per decade since the advent of propeller-driven ships, while Ross (1976) estimated that the increased number, size and speed of the global shipping fleet between 1950 and 1975 caused overall average ambient ocean noise levels to rise by as much as 10 dB in this period. From a review of historical acoustic recording data, Andrew et al. (2002) concluded that the increased size of the world fleet was responsible for the 10-15 dB increase they detected in low frequency ambient noise records since the 1960s.

These trend estimations, however, are by nature speculative since their scientific basis is compromised by inadequate data in the historical records and confounded by the rise in other contributing sources, particular the intense low frequency calls of the recovering rorqual populations (McCauley & Cato 2003). In addition, McCarthy et al. (2002) examined a range of anthropogenic sources (including petroleum exploration, shipping, academic research and military activities) and concluded that although general levels of shipping activity have increased, regional noise levels do not necessarily rise in direct proportion, and in some cases might have fallen, owing to introduction of larger ships, new technologies and other improved efficiencies. Shipping activity around Australia is shown in Figure 5.2. One of the busier areas is around the lower west coast of WA, in the vicinity of the SSDP.

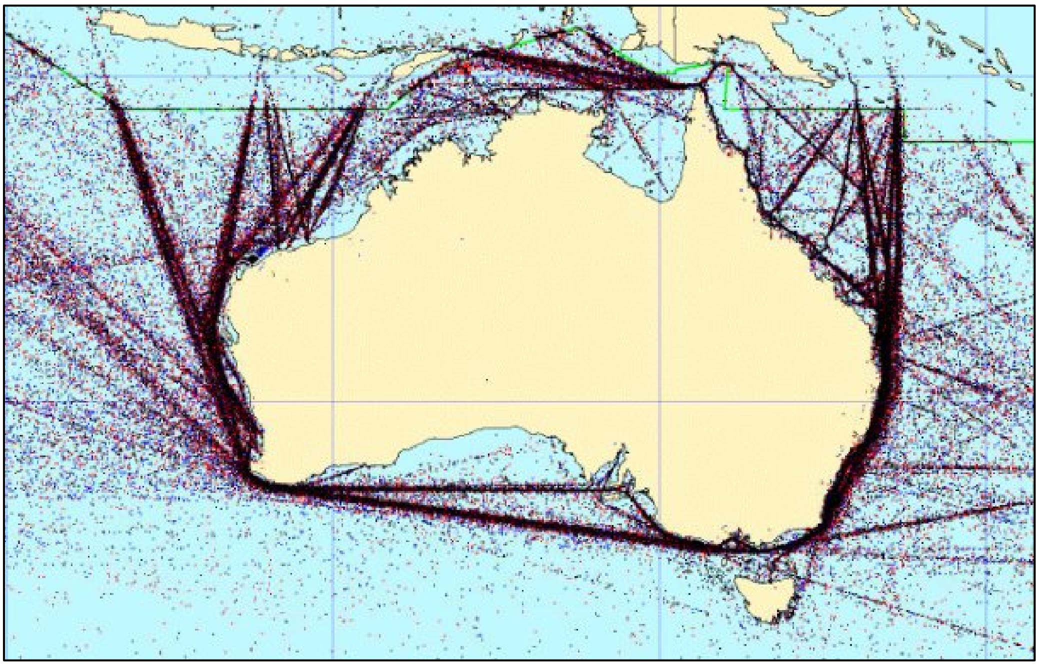


Figure 5-2 Vessel traffic density around Australia indicated via daily vessel movement reports (VMRs) to the Australian Maritime Safety Authority (AMSA)

5.3 TUGS

The propellers of most tugs are often heavily recessed and/or cowled to improve protection and thrust. These types of configurations reduce the forward and lateral transmission of the sound rays from propeller cavitation and blade rate tonals, but can also increase the directionality of sounds. Tugs towing barges produce less sound than larger or faster trading ships (Table 5.2).

5.4 DREDGES

Received sound levels from some large trailer suction hopper dredges operating in rocky areas have been recorded in excess of 150 dB re 1µPa at 1 km, while large cutter suction dredges can emit strong tones from the water pumps that are audible to 20-30 km ranges (Richardson et al. 1995, Dames & Moore 1996b). Underwater noise levels from the self-propelled hopper barges engaged in transferring dredge spoil are often higher than the noises from the dredge itself, particularly during the loading and dumping operation of rocky material.

Clamshell dredges emit varying sounds depending on the phase of the grab-retrieve-release operation, with strongest source levels (150-162 dB re 1µPa at 1 m) reported for the ⅓OB centred at 250 Hz. The highest level was from the bucket winch which generated a broadband source level of 167 dB re 1µPa 1 m (Miles et al. 1989 in Richardson et al. 1995).

5.5 LAUNCHES, FISHING VESSELS AND POWERBOATS

Underwater noise measurements of vessels of various designs and around 22 m length which carried whale-watchers in Hervey Bay, Queensland, showed that vessel speed was the primary factor which influences the amount of sound radiating from members of this 1-70 tonne fleet (McCauley et al. 1996). Small vessels produce significant directional noise patterns, with more noise radiating fore and aft than abeam. This has been attributed to the relative lack of hull noise shielding in the forward direction and only limited aft attenuation of propeller cavitation noise by the wake-induced bubble cloud. A number of vessels had ‘singing’ propellers (producing strong audible tones that significantly add to the noise signature at particular RPM ranges). The other key factor influencing vessel noise is size of vessel. In another example, McCauley (1998) noted the difference in broadband noise from a 20 m fishing vessel (168 dB re 1µPa) and a 64 m oil-rig tender (177 dB re 1µPa), as recorded when both were underway at 11-12 knots on different occasions in the Timor Sea. The difference of 9 dB represents a tripling of sound energy.

In the case of small power craft and patrol boats fitted with large outboard motors, these can produce relatively intense sound levels, particularly when travelling at planing speed. Single or twin outboard installations are the most common type of propulsion for <7 m long power boats in Australian coastal waters, i.e. inflatables, runabouts, small cabin cruisers, recreational fishing boats and rigid-hulled inflatable boats (RHIBs), and their fast rotating external machinery and small propellers produce intense and more complex sound spectra than those of launches fitted with inboard diesels (e.g. Gordon et al. 1992, Richardson et al. 1995, Au & Green 2000). Outboard motors produce broadband noise with many strong tonals and higher harmonics to 6000 Hz or more, with peak source levels in the 150-180 dB re 1 µPa 1 m range (Table 5.2). The development of four-stroke outboard motors, which are now becoming popular owing to their fuel efficiency, much quieter running and lack of oily exhaust pollution, may cause some reductions to outboard noise.

5.6 PIPELINES

5.6.1 Pipelaying

Noise of varying intensity and character is generated during all phases of marine pipelays. Noise sources may be continuous or impulsive and can be described as being transient or permanent, as shown in Table 5-3.

Table 5-3 Summary of noise sources and activities associated with pipelaying

	Activity	Source	Source Type	Duration (duty cycle)
Installation	Pile driving Pipe-laying Trenching Transport (equipment + personnel)	Pile driver +support vessel Pipe laying vessel + support Trenching vessel + support Helicopters + ships	Impulsive + Continuous Continuous Continuous	Transient (weeks) Transient (weeks) Transient (weeks) Transient (weeks)

There is likely to be some noise generated by movement and placement of the pipe, but this is of a transitory nature and of short duration, and is related to the size and type of pipe and method of placement. Most of the noise generated during pipelays is associated with the movement and operation of the dedicated pipelay and support vessels, as well as allied construction tasks such as trenching and rock armour dumping. This is the conclusion reached in the environmental impact assessment of a proposed underwater gas pipeline (Shapiro and Associates 2004).

5.6.2 Pipe operations

It may be speculated that movement of a fluid through an undersea pipe would generate noise that would be radiated into the water column beyond the pipe. Any such noise would be a function of several factors, such as: the fluid and its physical characteristics; its velocity through the pipe; the internal diameter of the pipe; the pipe length; the material from which the pipe was made, as this would influence both the transmission of vibration through the pipe and its acoustic coupling with the water; and any covering over the pipe, such as rock armour or bottom sediment.

This specific question was considered in the environmental assessment for an undersea gas pipeline across the Georgia Strait, in the north east Pacific. Data were obtained for an existing 250 mm epoxy-coated, high-pressure marine natural gas pipeline which identified radiated sound in the range of 60-72 dB (Birch et al. 2000). Further modelling and analysis concluded that the larger diameter gas pipeline proposed for the Georgia Strait would have a lower frequency for any given operating pressure than a smaller diameter line, with an estimated radiated noise equal to or lower than 30 dB at frequencies of 16 kHz and above (Shapiro and Associates 2004).

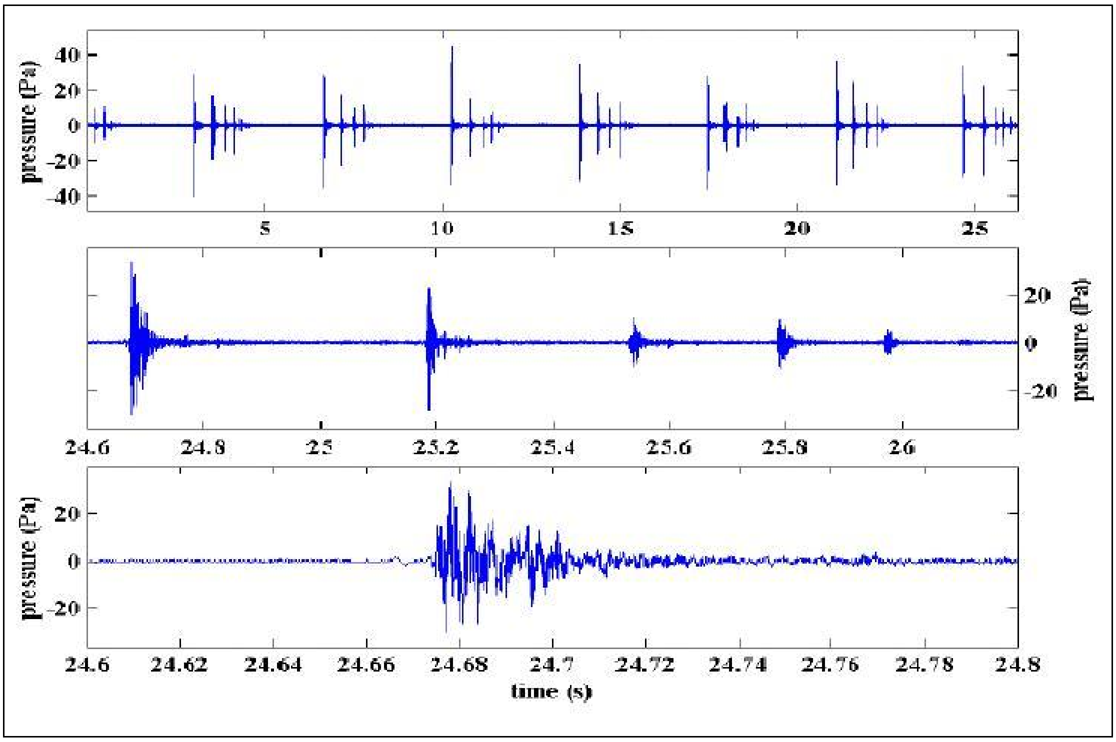
Marko (2003) considered sound propagation through bare and concrete-coated steel plates and longitudinal pipe sections. It was demonstrated that a concrete coating on a pipe acts as an acoustic insulator, and hence reduces radiated noise.

It is possible that the location of a pump near the marine portions of a pipeline, particularly if it exhibits a good acoustic couple with the pipeline, would cause an increase in the level of any radiated noise. The size, speed, power and other operational parameters of the pump be the principal determinants of any subsequent radiated noise, such as frequency and level.

5.7 PILE DRIVING

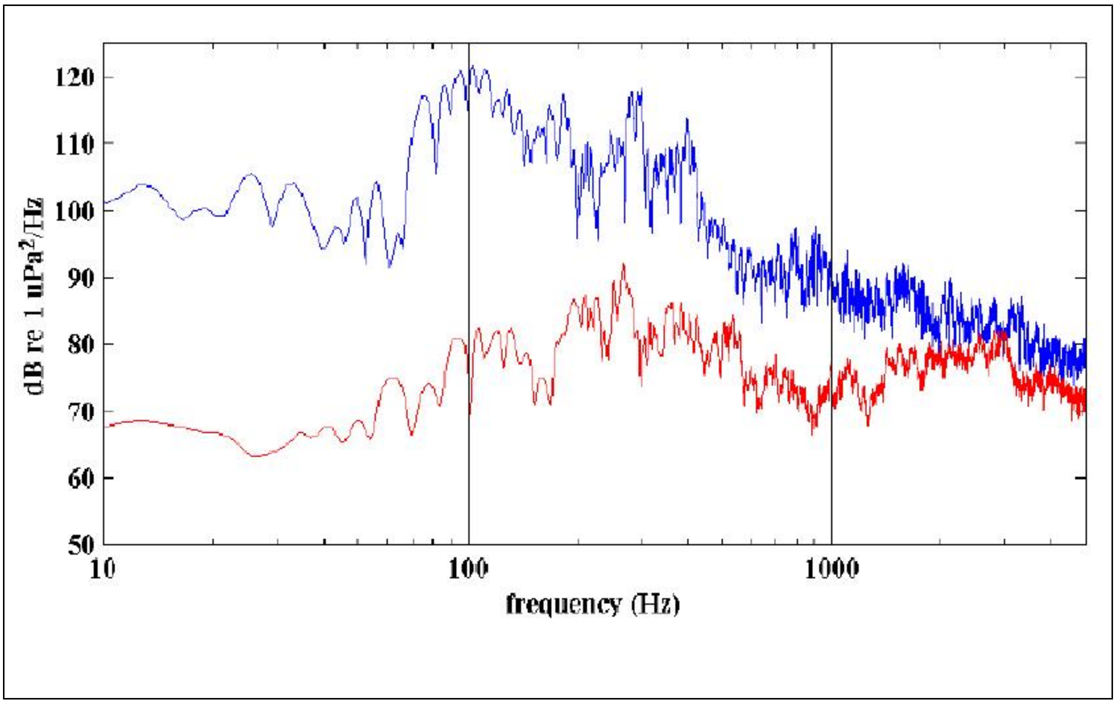
Noise from coastal construction and port activities includes hammering sounds from pile driving operations (e.g. 131 dB to 135 dB re 1 µPa at a range of 1 km, with audible ranges extending to 10-15 km from the source; Moore et al. in Dames & Moore 1996). A 2002 study of wharf pile driving operations to construct new Australian Defence Force (ADF) berths in Twofold Bay (Eden, NSW) by McCauley et al. (2002) provided sound level data that can be summarised as follows. Each pile driving event comprised a series of impulses associated with the weight being driven down. Power spectra showed peaks mostly between 100 Hz and 1 kHz. Individual signals typically fell by 20-30 dB between the initial drops and last bounces. Signal duration averaged 47 ± 0.5 milliseconds (range 10-200 milliseconds). The overall incidence of pile driving activities was low (only 2.5% of the samples recorded over a five day sequence contained pile driving signals). Average mean-squared-pressure of the signals was 167 dB (re 1 µPa) at 300 m from the operation, falling to 145 dB and 136 dB (re 1 µPa) at 1.8 and 4.6 km respectively. Curve-fitting of nine sets of measurements indicated average signal strengths fell from 150 dB to 140 dB (re 1 µPa) between 1 km and 3.1 km from the operation. The loudest recorded operation produced signals of which 6.5% at 4.8 km exceeded 140 dB (re 1 µPa) (McCauley et al. 2002).

Each pile driving impulse event comprises a primary pulse, which is immediately followed by 2-6 lower level ‘bounce’ signals if the drop-weight method is being used (Figure 5.3). The pile driving data were sourced from spectra plots (Figure 5.4) and other data reported by McCauley et al. (2002).



(from McCauley et al. 2002).

Figure 5-3 Example of seven pile drops and associated bounces (top), with the last set (middle) and its primary pulse (bottom) time-expanded



(from McCauley et al. 2002).

Figure 5-4 Frequency spectra plots of averaged primary pulses from 10-20 pile drops at ranges of 303 m (blue) and 590 m (red)

As a result of pile driving operations in British Columbian estuaries and waterways being linked with salmon mortalities, the impacts of pile driving projects, plus the mitigating value of using simple noise-reducing bubble curtain rings for each pile, have been examined by the

Canadian Department of Fisheries and Oceans (Vagle 2003). Their preliminary studies of four pile driving projects in the Vancouver region have shown that:

- the intensity and frequency spectra generated from each project site, pile and hammer strike vary markedly according to the pile driving equipment used (e.g. diesel hammering versus 1 tonne or 3.5 tonne drop-weight hammers), the hammer drop height (1-7 m), the use of a wood block shock-absorber, the material, diameter and design of the pile (e.g. cedar versus 36" and 8" diameter steel piles, with closed-end steel piles causing more salmonid deaths), the driven depth, and the type and density of the seabed strata;
- impulses need to exceed 30 kPa to induce observable changes to fish movements and density; with fatal swim-bladder injuries to chum, chinook salmon and herring associated with 120-150 kPa impulses;
- small bubble/low supply volume curtains can attenuate source levels by between 8-20 dB re 1 $\mu Pa^2/Hz$ in the 50-1000 Hz range, and by 18-30 dB in the 10-20 kHz range, while large bubble/ high supply volume designs produce little effect;
- bubble curtain attenuation efficiency decreases with increased bubble ring depth and larger bubble size (becoming agglomerated 'blobs' of air separated by large gaps);
- bubble curtain rings and apertures require careful maintenance to prevent gaps and 'holes' in the bubble screen from uneven bubble distribution, while tidal currents readily cause asymmetric distortions to the curtain.

5.8 BLAST AND CAVITATION

5.8.1 Explosive effects

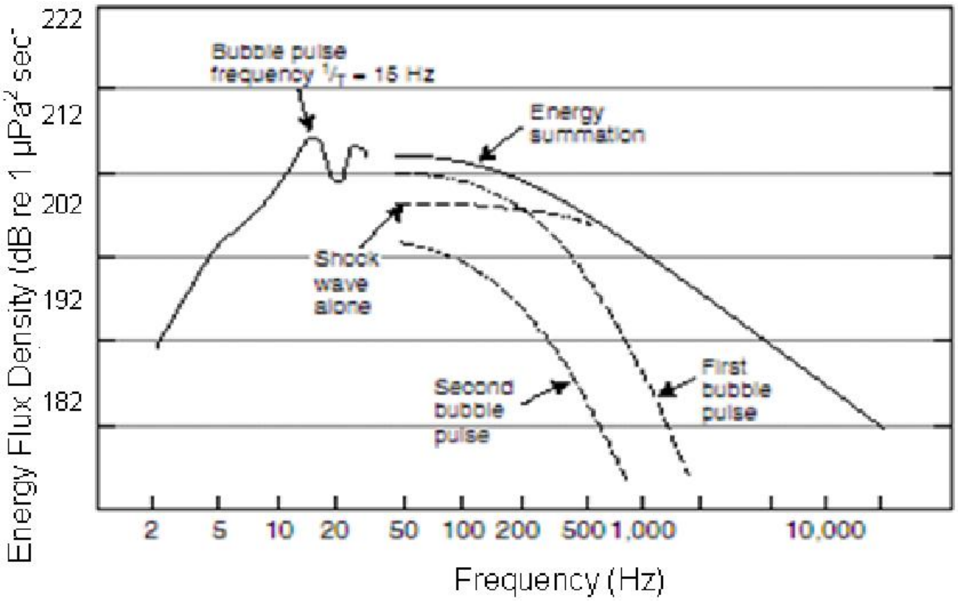
Blast refers to any shock wave generated in water (e.g. by detonation of a high explosive charge) or air (e.g. a sonic boom from a supersonic aircraft). A shockwave is an acoustic wave where the amplitude of the field is so large and non-linear that portions of the medium become torn and bodily shifted, with discontinuities in pressure and particle velocity invalidating the physics behind normal sound equations. Both an explosive blast and sonic boom start as a non-linear shock wave which, through dissipation and absorption, eventually evolves into a linear acoustic wave some distance from the source.

Explosive sources produce broadband signals with a very high zero-to-peak source level and a relatively flat spectral structure, in which the largest-amplitude component in the detonation time series comprises the initial shock wave (Figure 5.5). The zero-to-peak source pressure level produced by an explosive device can be predicted using its charge weight and detonation depth with the following equation from Urick (in NRC 2003):

$$\text{SL(0–pk) dB re 1 } \mu\text{Pa at 1 m} = 271.8 \text{ dB} + 7.533 * \log(w)$$

where w is the charge weight in pounds. Thus a ~0.45 kg (1 lb) detonation of high explosive at 37 m depth yields a maximum zero-to-peak pressure of 272 dB re µPa at 1 m, while ~45 kg (100 lb) produces an initial zero-to-peak pressure of 287 dB re 1 Pa at 1 m (Urick, in NRC 2003).

Cavitation is the tearing apart of water when the negative component of a pressure wave exceeds the surrounding hydrostatic pressure and becomes sufficiently large to cause bubble formation. Water becomes readily 'torn' into many bubbles as it cannot support much tension. 'Bulk' cavitation is the process where the water is torn apart by the surface-reflected shock wave of an underwater explosion. As discussed by Lewis (1996a), when a shock wave hits the water-air interface its outgoing (positive) pressure wave is reflected back down into the water as a negative pressure (tension) wave, which is an inverted image of the outgoing wave. As a result, the pressure wave at a particular point in the water column is a combination of the outgoing compression wave and the reflected tension wave that arrives soon after. Figure 5.5 shows how the shock-wave and bubble pulse energies combine at frequencies greater than 1/T (T = time (seconds) between the shock wave and first bubble pulse).



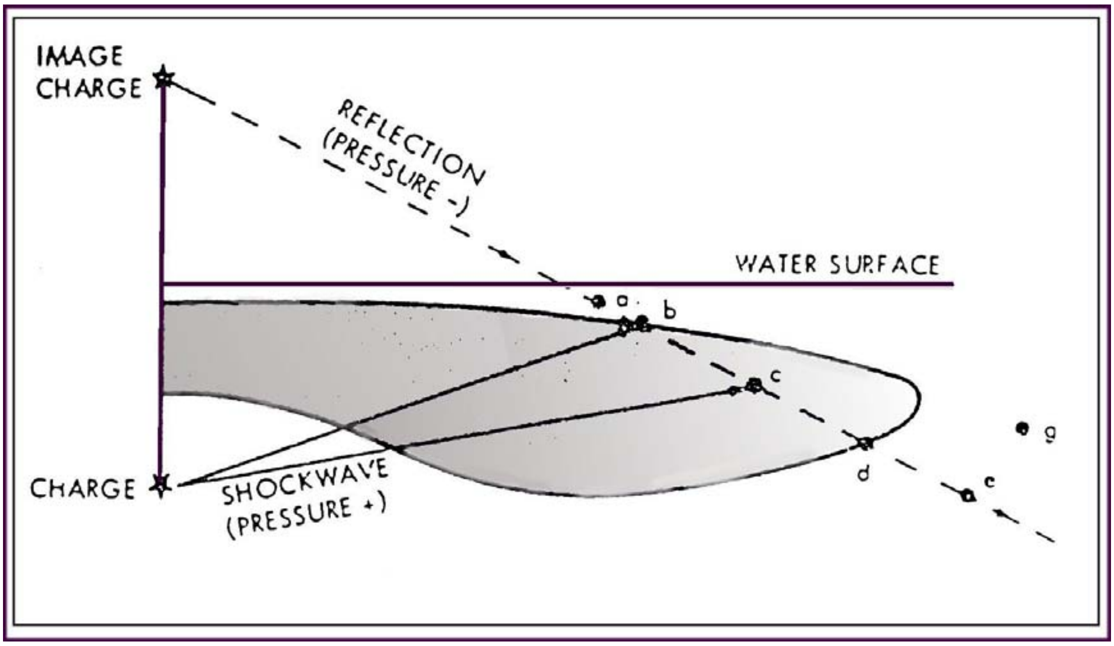
(modified from Urick, in NRC 2003)

Figure 5-5 Spectrum showing the broadband source from detonating ~0.45 kg (1 lb) of high explosive at 37 m depth

[N.B. Energy flux density = the squared instantaneous pressure amplitude summed over the duration of one second]

A schematic of the zone of bulk cavitation around an underwater explosion is shown in Figure 5.6. Below this zone no cavitation occurs since the tension never exceeds the hydrostatic pressure (which increases relatively rapidly with depth). While charge size influences the maximum depth (thickness) of the cavitation zone, the zone's horizontal limit (radial distance from the detonation point) is far more influenced by the depth of the detonated charge than its size. For example, increasing the charge size by ten times (a magnitude increase) roughly doubles the maximum depth of the cavitation zone but its horizontal distance is increased by only about 20% (for further detail see Lewis 1996a).

Interpretation of pressure time records recorded for underwater detonations normally includes determining the impulse of the pressure pulse (Pa.seconds; as calculated from the area under the curve of the first positive pressure pulse), its maximum zero-to-peak pressure and arrival time, the time constant of the decaying pressure-time signal, and the 'bubble' period. Impulsive sounds can be defined as the generation of an acoustic energy field in which the overall sound pressure level measured for 0.5 - 1 seconds via F time-weighting is more than 12 dB above the average maximum sound level.



[from Christian, in Lewis 1996a]

Figure 5-6 Diagrammatic representation of the zone of bulk cavitation

In a classic pressure pulse signal, the first positive peak usually provides the highest zero-to-peak pressure. However detonations in shallow water (<5 m) focus the shock wave towards the surface and markedly reduce the amount of lateral blast propagating into the surrounding water column. This feature can lead to unusually complex pressure-time histories in nearshore environments where the second peak may have a greater value (e.g. Box et al. 2000). In complex cases, measuring the impulse may require calculating both the positive and negative areas for several oscillations after the initial peak to ensure all significant pressure excursions are included.

Cavitation imposes an upper limit to the maximum acoustic power output of sound sources. For example, for a 3 kHz source in shallow water, the cavitation threshold is slightly more than 1.013 bar (= 220 dB [re 1 µPa]; Urick, in NRC 2003). Since some cavitation can be tolerated the effective sound level can be 2-3 times larger than this threshold (i.e. close to 230 dB [re 1 µPa]; NRC 2003).

The most damaging component of an underwater shock wave is the initial fast rise in pressure. The area over which this has a significant effect is limited however due to the rapid loss of the component frequencies which form the sharp leading edge of the pulse. After propagating through the water column these higher frequency components diminish such that the initial shockwave rapidly attenuates into a broad spectrum of frequencies with most energy in the sub-1 kHz range.

5.8.2 Use of explosive charges in the marine environment

Various explosive devices are occasionally used for research, removal of navigational hazards, removal of rocky outcrops during capital dredging programs, deconstruction of abandoned structures, scuttling hulks for artificial reefs, military exercises and (rarely) for hull-shock trials. They are also sometimes used for geophysical seismic surveys in shallow nearshore and transitional (littoral) areas. For example, 0.2-0.3 kg charges of Geoflex primacord and similar charge types have provided seismic sources in intertidal and shallow sublittoral sites where vibrators or airguns cannot be deployed due to rapid depth changes, navigational hazards and environmental constraints (e.g. LeProvost Environmental Consultants 1992).

Charges used for ship scuttling or underwater rock blasting are typically small (0.1 - 5 kg TNT). Use of explosive discharges by the research community has declined in recent decades, partly because of environmental and safety concerns but also because of the lack of control and the non-reproducible nature of the source waveform and the precise detonation depth.

The range of explosive ordnance and special purpose items containing high explosives (HE) which may be detonated at or beneath the surface during ADF live-fire practices and other maritime activities were reviewed by URS (2003). The HE content of these items ranged from 0.02 kg up to 428 kg.

6. BEHAVIOURAL AND PHYSIOLOGICAL EFFECTS OF NOISE

The purpose of this section is to summarise what is known about the behavioural and physiological effects of various levels of noise on marine fauna. However, prior to describing the range of sound impact categories and zones of sound influence, a summary description of the auditory system of the marine fauna of interest is presented.

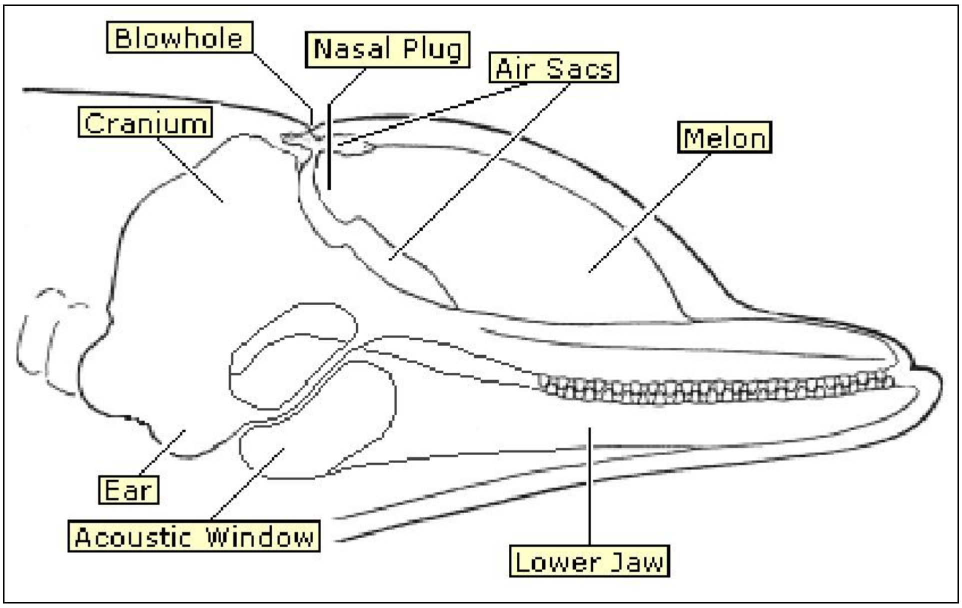
6.1 AUDITORY SYSTEMS OF MARINE FAUNA

6.1.1 Cetaceans

6.1.1.1 Overview

With some key modifications to meet the demands of underwater hearing, cetaceans have an auditory anatomy that follows the basic mammalian pattern, i.e. outer, middle and inner ear components are present. The outer ear is separated from the middle and inner ear by the tympanic membrane (eardrum), and the inner ear is where sound energy is converted into neural signals which are transmitted to the brain via the auditory nerve.

However, while the air-filled external canal and middle ear of terrestrial mammals transmit airborne sound to the fluid-borne hair cells lining the inner ear (cochlea), this matching is not required underwater and cetaceans have no air-filled ear cavities. Thus the ear canal of cetaceans is filled with debris and wax, and external sounds are channelled to the middle ear through the lower jaw. The core of the lower jaw is filled with fats that conduct sound to the tympanic membrane of the middle ear via a thin bony area called the pan bone or ‘acoustic window’. While toothed whales and dolphins receive sound through their lower jaw, they produce sounds by passing air through sacs in their head (Figure 6.1).



(adapted from Scheifele [1991])

Figure 6-1 Hearing and sound production structures in the dolphin

Another difference between cetaceans and terrestrial mammals is that the middle and inner ear complex of all whales and dolphins is located <u>outside</u> their skull. While the complex is suspended by ligaments in a cavity outside the skull, it is encased by other bones, and the precise functioning of the cetacean middle ear continues to be investigated. Much more is understood about the inner ear as the cochlea is very similar to that of land mammals.

Thus acoustic energy transmitted to the inner ear causes the basilar membrane in the cochlea to vibrate. Sensory hair cells are excited by different sound frequencies according to their position along this membrane.

6.1.1.2 Determining cetacean hearing ranges

When assessing the potential effects of a particular sound source, it is important to compare its frequency spectrum with the known or estimated auditory range of the marine mammal of interest. For example, Swift et al. (2003) used a speculative baleen whale audiogram from Clark and Ellison to help assess the potential of vessels engaged in petroleum field development operations west of the Shetland Islands to be detected by fin whales in the region. Vessel noise levels recorded for two of the fin whale vocalising bands (18-22 Hz and 22-28 Hz) varied between 120 and 49 dB re 1 $\mu Pa^2/Hz$ at recording sites between 8.5 - 40 km from the source. Without a model for fin whale hearing it would not be possible to estimate that the levels in ⅓rd octave bands had exceeded the predicted lower limit of the threshold of fin whale hearing in 50% of cases (ambient +16 dB; Urick 1983), and exceeded the predicted upper limit of the hearing threshold in 25% of cases (ambient +24 dB; Urick 1983).

The anatomical components of the ears of any mammal, particularly that of its cochlea, dictates the frequency range it can perceive. Hearing sensitivity in particular low or high frequency ranges is dependent on the stiffness and mass along the inner-ear membrane and how the membrane is organized mechanically.

For dolphins, porpoises and seals that can fit inside computed topography (CT) scanners (Figure 6.2), suction electrodes are placed on the surface of an animal's head, tones are played and the brainwaves are recorded using a fixed or portable acoustic brainwave recorder (ABR). The scans allow precise anatomical measurements of the cochlea plus a 'gold standard' audiogram with respect to obtaining reliable narrowband frequency sensitivity. However CT scanners cannot accommodate larger heads and ABRs are unable to detect baleen whale brainwaves because of the interference caused by the huge mass of intervening bone, muscle and fat versus the relative small size of the brain[8].

The middle/inner ear complex in baleen whales is two to three times bigger than that of toothed whales, and all mysticetes studied to date have inner ears that appear well specialised for low-frequency hearing. For example, Ketten (1997) deduced from comparative morphological studies of the blue whale auditory apparatus that these rorquals have good infrasonic hearing (10-20 Hz). Because there are no other humane methods for obtaining direct measurement audiograms for baleen whales, comparative anatomical modelling studies using mathematical functions have been devised (Ketten 2000).

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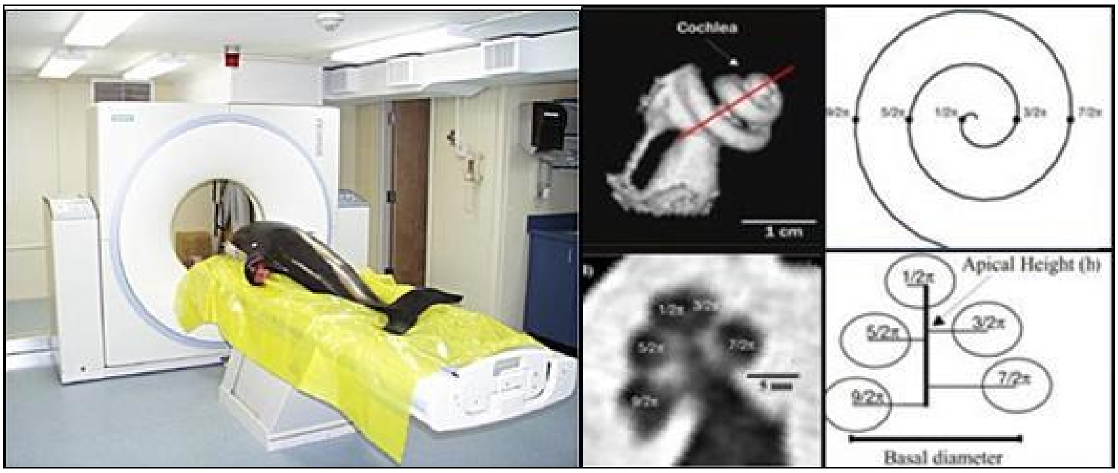
[8] When compared to body weight, the brain of baleen whales is more than an order of magnitude smaller than that of humans and dolphins.



(Ketten 2003)

Figure 6-2 Measuring inner anatomy and determining an audiogram using a CT scanner

The mathematical functions used to estimate frequency sensitivity of the humpback whale were obtained by relating the relative length of the basilar membrane with known data for cats and humans. The predicted audiogram was the typical mammalian U-shape that suggested 200-10,000 Hz auditory range with maximum sensitivity between 2000-6000 Hz (e.g. Houser et al. 2001). A model of humpback hearing was subsequently created as a series of pseudo-Gaussian bandpass filters. Model sensitivity optimised to the predicted audiogram by using programs to evolve the number, frequency distribution and shape of the model filters, and the sensitivity of the model was evaluated through a simulated hearing test. Maximum deviations between model sensitivity and predicted humpback whale sensitivity remained below 10%. This integrated approach provided the first predicted audiogram for humpback whales and was used to develop the first bandpass model of the humpback ear (Houser et al. 2001).

Similar comparative auditory analysis work has been undertaken to examine the capacity of right whales to hear oncoming ships (Ketten 2003), as appears to be the case by recent field studies using ship-source surrogate devices (Tyack 2003). This study included checking for the presence of pathogens in ears from stranded right whales, particularly animals showing evidence of a ship-strike. Since noise from shipping, seismic surveys and long distance sonar have all or most energies in 5 Hz to 500 Hz range, these sources overlap the current estimates for the sensitive parts of the auditory range of baleen whales.

6.1.2 Sea Lions

Compared to the cetaceans and sirenia, all other marine mammals, including pinnipeds, spend periods of time on land. Consequently their ears have not evolved major differences from those of land mammals (the external ear flaps [pinnae] in the pinnipeds are reduced or absent, but their external ear canals remain open). Eared seals (otariids), such as the Australian sea lion, have small ear flaps and broad ear canals. Muscles around the ear canal close it to water during dives, and the middle and inner ear are still attached to the skull. The middle and inner ears of pinnipeds are more similar to those of land mammals and do not display any specialisations for detecting either very high or low frequency sounds.

The functional hearing range of Australian sea lions in water is around 1 kHz to 30 kHz, with best hearing from 2 kHz to 16 kHz. Sensitivity in the lower range (below 1 kHz) deteriorates rapidly in both air and water and their hearing sensitivity is better underwater than in air, although the latter is very adequate and on a par with humans above 10 kHz.

Australian sea lions have no echolocation ability but are understood to vocalise while in the water. Their underwater repertoire includes barks, whimpers, buzzes and clicking sounds, all below 4 kHz. Based on research concerning Californian sea lions (Richardson et al. 1995) it is surmised that these vocalisations are associated with social interactions rather than feeding.

6.1.3 Marine Turtles

The auditory sensitivity of sea turtles is reported to be centred in 400 – 1000 Hz range, with a rapid drop-off in noise perception on either side of this range. This auditory range matches their weak vocalisation abilities which are also in the low frequency range (100-700 Hz). This is supported by electro-physical studies which have shown that the hearing range for marine turtles is approximately 100–700 Hz (McCauley 1994). No information, however, is available regarding the threshold level necessary for behavioural effects.

6.1.4 Sharks

The range of hearing sensitivities in the bony fishes is better known than in the sharks and rays (about 80 fish species audiograms have been determined versus four for sharks and rays - the bull shark [*Carcharhinus leucas*], the lemon shark [*Negaprion brevirostris*], the horn shark [*Heterodontus francisi*] and the little skate [*Raja erinacea*]; e.g. Casper et al. 2003, Mann et al. 2006). However all fishes tested to date appear capable of performing the same basic hearing tasks as terrestrial and marine vertebrates, such as discriminating between sounds, determining sound direction and filtering biologically relevant signals in the presence of ambient noise (Popper et al. 2003).

The best hearing sensitivity of the sharks is within the 20 Hz to 800 Hz low frequency range. In addition, sharks also have at least some ability to perceive infrasounds (0.1 Hz to 10 Hz) at particle acceleration levels from <10~6 to >10~4 ms-^{2} (sufficient to detect 120-180 dB re. 1 µPa at 0.1 Hz). Sharks appear to use infrasound to detect potential prey such as struggling fish.

6.2 CATEGORIES OF SOUND IMPACTS

Reviews such as Richardson et al. (1995), Gisiner (1998), McCauley and Cato (2003) and URS (2003) note how sound waves from nearby, discernible sound sources affect marine fauna, and mammals in particular, differently to those from distant, undiscernible ships and other low frequency sources which add to background ambient noise.

There is evidence that the development of harbour facilities serviced by heavy vessel traffic will elevate local background levels, and may cause some species to avoid former nearby breeding or feeding areas owing to the amount of vessel movement disturbances as well as the noise. For example, gray whales temporarily abandoned a breeding lagoon in Baja California during a period of extensive coastal industrial activity involving heavy vessel traffic. The whales did not return to the lagoon until the vessel activity had decreased (Gard 1974).While some marine mammals can appear more capable of habituating to such activities than others (such as dolphins in noisy urbanised estuaries and embayments, and sperm whales feeding in busy shipping lanes), their calving or pupping areas are almost invariably restricted to less disturbed locations.

The above effects are due to essentially permanent vessel traffic and other noise generating activities. These are not addressed in the following sub-sections, which focus on the effects of noise from discernible sources generated by relatively short-term human activities (as summarised in Table 6.1).

Table 6-1 Summary characteristics of some common human sound sources

Source	Perceived location/s	Perceived speed and direction of source	Sound periodicity	Frequency range (Hz)	Source Level[1]
Seismic airgun array	Moving	Slow (4-6 knts) and steady direction	Very regular short pulses	LF (8-1000) Most <500	215-240[3] (ramped)
Well drilling	Fixed	Fixed	Steady continuous	Tonals	130-150
Field development support vessels	Almost fixed	Slow with variable direction	Irregular periods of continuous or transients	LF + tonals	170-190
Trading ships	Moving	Fast (12-22 knots) and steady	Steady continuous	LF (10-500) + tonals (1 kHz)	160-186
Whale watching vessels[2]	Multiple, moving	Variable speeds and directions	Variable (continuous and transients)	LF-MF + HF tonals	140-190
Pile driving	Fixed	Stationary	Irregular periods of regular pulses	LF-MF tonals	170-180
Detonations[4]	Unpredicted	N/A	Unpredictable sudden short pulse	Wideband	240-260
Dredging	Fixed	Stationary	Variable continuous sounds	LF-MF + tonals	150-195
Sea dumping	Unpredicted	Stationary, or slow with variable direction	Unpredictable sudden transients (2-10 mins)	LF-MF	140-190
MF tactical sonar	Multiple and moving	Erratic	Unpredictable sudden short pulses	MF (2-4 kHz)	180-225
LF surveillance sonar	Moving	Slow and steady	Regular long pulses	LF (100-400)	230-250 (ramped)
NPAL research sonar	Fixed	Stationary	Regular 20 minute pulses	LF (40-300)	195 (ramped)

(1) dB re 1 µPa @ 1m / dB re 1 µPa ^{2} @ 1m msp.
(2) small ferries, launches, outboard RHIBS, various recreational.
(3) for 2,000-2,800 cubic inch arrays in Aus. waters.
(4) e.g. rock blasting, hulk scuttling, removals, bay cable survey.

Different types of noise can be broadly categorised as follows:

- Continuous or near-continuous sources that may prevent marine mammals or turtles from hearing social communications or other acoustic cues (= temporary masking effects).
- Noise that induces behavioural changes and responses in marine mammals and turtles.
- Noise that induces behavioural responses by the prey of toothed whales (fish, cephalopods).
- Very intense noise that may cause temporary or possibly permanent loss of hearing sensitivity to marine mammals via damage to the auditory hair cells (or other tissue trauma via possible excitatory and organ resonance mechanisms).

To assess the potential scale and likelihood of these effects, ‘safety ranges’ or zones of influence have been developed for predicting, measuring and managing noise-generating activities, in the same way that zones of lethality[9] have been used for assessing the spatial extent of possible marine animal injuries from the non-acoustic blast impulses of underwater explosions**.**

6.2.1 Zones of Influence

Depending on the type of source, the species of interest, its known or assumed habits and acoustic behaviours, one or several of the following zones can help determine an appropriate safety range. For a given source, these zones can be roughly ordered from likely largest to smallest as follows:

- Zone of audibility (pertinent for sudden sounds with designed or inadvertent capacity to scare off individuals, such as acoustic deterrent devices or the pulsed tone of a research sonar).
- Zone that induces behavioural avoidance or other undue stress (e.g. for calving and resting areas, turtle nesting areas, commercial fish grounds).
- Zone that masks distant (LF) or nearby (HF) communication calls, echolocation pulses and possible navigation cues (e.g. for social calls, prey detection and/or local orientation by groups of toothed whales or dolphins).
- Zone eliciting discomfort, flight and possible temporary hearing shift (for marine mammals or turtles).
- Zone of pain, possible permanent hearing shift or other tissue injury (for marine mammals, turtles, fish or cephalopods).

Further detail on each of these zones is provided below.

6.2.2 Zone of Audibility

The zone of discernible audibility represents the maximum possible radius of influence by a particular source. This range can vary markedly according to the species and individuals of interest, plus their specific location, source-receiver-seabed geometry, season and time of day. Factors which can cause the boundary of these zones to expand and contract on an almost moment by moment basis include:

- the frequency, temporal characteristics, directionality, depth and orientation of the source
- the host of physical factors dictating the transmission loss rate and propagation of the peak frequency band/s towards the receiver
- the particular depth of the receiving individuals of interest and their hearing thresholds with respect to the peak frequency components of the source’s bandwidth
- the levels of the various physical, biological and other human sources that form the ambient noise intensity spectrum at the receiver’s location
- the level of attention and habituation (previous signal experience) of the receivers, which will influence their ability and motivation to perceive and interpret the signal.

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[9] The maximum amplitudes of acoustic waves that do not contain sufficient energy to kill, maim or stun marine mammals or turtles outright (e.g. Lewis 1996, Richardson et al. 1995, URS 2003).

Many of the above factors can vary minute by minute as well as differ substantially between regions and locations, and thus limit the significance and value of determining this zone for most sources and species. Nevertheless estimates of maximum audibility of specific noise sources are occasionally reported for marine mammals with known or estimated spectral audiograms and hearing thresholds. For example, the absolute auditory threshold to a 1000 Hz tone for a captive beluga whale has been measured as 104 dB re 1 µPa. The critical signal to noise ratio (SNR) at this frequency (i.e. the amount by which the signal must exceed background noise to become audible) was determined to be 17 dB.

Such measurements imply that beluga whales experiencing typical arctic ocean ambient noise conditions cannot detect icebreaker noise at ranges beyond 20 km, even at full power (Table 6.2). This example contrasts with earlier findings by Finley et al. (1990), who had previously attributed a substantial movement of beluga whales to avoid icebreaker noise. In this case, the beluga whales were reported to stop feeding and swim away from approaching icebreakers, travelling up to 80 km from feeding areas before returning after 1-2 days (Finley et al. 1990). The apparent contradictory evidence highlights the problem of attributing cause/effects in field conditions where the auditory sensitivity is unclear and where control examples are unavailable or involve different conditions.

For cases involving the maximum audibility of continuous or regular periods of low broadband noise (such as the sound of distant shipping traffic, a slow-moving icebreaker or a stationary drilling operation), there is little in the weakly discernible signals to invoke a particular behavioural effect, learned or otherwise, and the issue turns toward masking effects. In the case of repetitive short pulses of low frequency sound from distant airgun or pile driving sources, their pulsed nature would make them more readily perceivable at long distance, but the separation of the weak and distant pulses by intervals of many seconds (typically >10) lessens their ability to mask out any long distance calling sequences of the larger rorquals (which last >20 seconds or, in the case of humpbacks, many minutes; Section 4.2.7.1). Sources that propagate near-continuous and essentially non-discernible broadband sound contribute to ambient noise, and it is more useful to assess their capacity to mask incoming sounds and cues of import to local receivers.

The audible zone has more relevance for acoustic deterrent or harassment devices which emit aperiodic pulsed signals as these have the capacity to startle marine fauna, as could the sudden appearance of a research or military sonar tone. Thus the value of assessing a source’s audible range increases (a) the more its signal is readily distinguishable from ambient background and (b) the more likely the characteristics of this signal will invoke interpretation and potentially adverse responses by individuals of the species of interest. This switches our attention to zones which induce behavioural reactions to noise such as the startle response and avoidance. These ranges are also more amenable to monitoring and mitigation.

6.2.3 Zone of Behavioural Responses

The zone of behavioural response is logically smaller than the zone of audibility, and is based on the received sound level which evokes changes in behaviour that may result in adverse effects on the well-being of individuals and populations of protected species.

The capacity of an unmanaged sound source to cause startle responses, or other types of undue interference and stress that may lead to biologically significant consequences to a protected marine species, varies markedly according to the source characteristics. Not all human sounds cause undue behaviour responses, and some are more amenable to habituation than others. Sound source features which increase a source’s capacity to receive attention from and interfere with marine mammals or turtles engaged in feeding, breeding or resting activity are summarised in Table 6.2.

Table 6-2 Features of an audible source likely to increase level of attention and invoke behavioural responses in marine fauna

Source characteristic	Increased biological significance	Response
Frequency range	Within sensitive part of receiver's auditory range	↓ Increasing attention / curiosity
Narrowband signal	Easier to detect (>SNR*); imparts potential meaning	
Pulsed signal	Easier to perceive, potentially disruptive	
Moving	Invokes more attention (e.g. vectoring to discern direction)	
Sudden / aperiodic	Increases likelihood of causing a startle response	↓ Increasing stress/alarm
Moving fast (>10 knots)	Increases chance of alarm and flight unless the source is common with steady direction (habituation effect)	
Position or heading	Between receiver and its intuitive pathway to safety	
Erratic direction and speed	Unpredictable movements invoke continual vectoring, sense of alarm, disengagement of previous activities, avoidance/defensive reactions.	

* = Signal to (ambient) Noise Ratio

The types of observable reaction have depended on the nature and affordability of the particular physiological or behavioural responses that can be measured in research aquaria (i.e. for captive dolphins or the occasional small toothed whale) or observed visually and/or acoustically in natural open waters for the larger whales. Field methods are constrained by the availability, amenability and 'repertoire' of measurable behaviours of the species of interest, while both field and laboratory studies are constrained by ethical considerations regarding the effect of deliberate sound exposures to the welfare of tested subjects[10].

Behavioural reactions to sound vary with the species and individuals of interest, including their state of attention and activity, maturity, experience and parental duty, all of which will alter with season, location and times of day, etc. Reactions involving relatively small avoidance responses by individuals are clearly not biologically significant, whereas those produced in scenarios involving a near permanent sound source displaces animals from key feeding or breeding grounds over month or seasonal time scales have obvious import to growth, stress levels, breeding success, survivorship and hence population recovery rates.

A range of surface-visible and acoustic behaviour features of whales have been monitored as direct or surrogate measures of potentially adverse responses to the onset or approach of a sound source (or its surrogate device), with the level of success highly dependent on weather

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[10] There has been development of increasingly sophisticated and affordable digital telemetry acoustic tags (DTAGs) which can be temporarily attached to large whales in open waters by suction cap (some with depth and inertial motion detectors for diving studies or positioning systems for satellite monitoring). This is widening the number of observable responses that previously were constrained to captive dolphins or small odontocete whales within the confines of research aquaria.

conditions, whale abundance and activity, and/or the appearance of unanticipated confounding factors, versus the amount of available study time, observation platform/s, reliable hydrophone systems and field personnel.

Behavioural changes monitored during open water studies of specific sound sources typically include one or more of the following (depending on the particular source, species and the level of activity of the individuals[11] at the location of interest):

- course alterations to directions away from or towards the source and speed changes
- cessation or change to previous activity
- altered local/regional distribution patterns of individuals/groups (typically by aerial survey)
- close up (bunching) of group members or pairs
- alterations to cow-calf interactions
- alterations to surfacing interval and/or number of breaths between dives
- absence of 'fluke-ups' (marking feeding dives in some species)
- alterations to dive patterns and durations
- alteration of call type, rate, duration, depth and timing
- alteration of echolocation rate, type, duration, depth and timing
- changes to spy-hopping, breaching or fin slap rates (interpreted as evidence of curiosity, defensive or annoyance behaviours respectively).

For any given location and propagation conditions, the range at which the received sound of a source invokes a behavioural response will depend on the auditory sensitivity of the species of interest, while the biological significance of this response will vary according to the type of activity being undertaken. Not all behaviour responses increase risk of harm to individuals, breeding success or population recovery rates. Some responses may be momentary inconsequential reactions such as the turn of a head, or have limited duration and lie within the bounds of natural behaviour variations. Table 6.3 summaries the potential significance of possible diverted attention, avoidance and alarm responses by large whales as a result of a human noise source, in the context of feeding, migrating, resting, calving or mating activities.

Early studies had pointed to the baleen whales and possibly sperm whales as the most sensitive to seismic surveys (a source of intense, low frequency broadband noise) of marine mammals in terms of behavioural responses and the eared seals and sea lions (otariids) as the least sensitive (Richardson et al. 1995). Work during and since the 1990s has shown this generalisation is not uniform and is untrue for sperm whales (e.g. Madsen et al. 2003; Richardson et al. 1999; Stone 2003).

Seals and sea lions have been known to rapidly habituate to various acoustic scaring devices, especially if attracted due to the feeding opportunities being protected, such as occurs with aquaculture facilities. Off California, observations from a seismic vessel found California sea lions ignored the array, with some individuals occasionally attracted to it, even when operating (URS 2004). Monitoring was conducted in the Alaskan Beaufort Sea over the period 1996 to 2001 on the behaviour of seals exposed to seismic pulses from 6–16 airgun arrays with total volumes of 560 -1500 cubic inches (Harris et al. 2001, Moulton & Lawson 2002). Results found some seals will avoid the immediate area of seismic vessels, with small avoidance movements of one to several hundred metres. Many other seals, however, remained within 100 - 200 m of the track line of the passing array.

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[11] Whales engaged in an intensive activity such as feeding are generally more preoccupied and less responsive to external stimuli and cues than when inactive, resting or migrating (Richardson et al. 1995).

Marine turtles have been recorded as demonstrating a startle response to sudden noises (Lenhardt et al. 1983; McCauley et al. 2000b). Although turtles are often observed approaching offshore oil and gas facilities, it is possible that anthropogenic noise may cause some turtles to avoid certain areas.

Based on caged turtle trials and extrapolated response levels for a large air-gun array operating in 100 m of water, McCauley et al. (2000) predicted that sea turtles would, in general, commence displaying behavioural responses at 2 km and avoidance behaviour at 1 km (Table 6.3). However, McCauley et al. (2000) also noted that such rules of thumb for intensive acoustic sources with peak frequencies in their range of hearing (i.e. below 1 kHz) cannot be reliably applied to turtles in shallower coastal waters (i.e. less than 20 m where propagation conditions differ and transmission losses are usually higher than in open ocean deep water areas). It is also worth noting that the response predictions were derived from two caged trials with the same two animals (a green and a loggerhead turtle) held in relatively cold water (i.e. at the lower end of the turtles' sea temperature distribution range). It remains to be seen if these predicted range responses to sound pressure levels would be shown by free-swimming individuals engaged in feeding.

Table 6-3 Effects reported for airgun pulses on two turtle species

Species	Received Level (dB re 1 µPa rms)	Effect	Source
Loggerhead turtle	175-176	Avoidance response	O'Hara and Wilcox 1990
One Green and one Loggerhead turtle	166	Noticeable increase in swimming behaviour, presumed avoidance response	McCauley et al. 2000
One green and one Loggerhead turtle	175	Behaviour becomes increasingly erratic, presumed alarm response	McCauley et al. 2000

(modified from table in McCauley et al. 2000)

In the case of pulsed low frequency sound effects on turtle nesting behaviour, nest numbers monitored on beaches near the Port of Hay Point (Queensland) before, during and after a pile driving program lasting several months in 1996-97 were compared. Results showed no significant trend in nest numbers, indicating that the female turtles had not been particularly sensitive to this pulsed source (Dames & Moore 2000), but nest numbers were too few to provide a conclusive result.

6.2.4 Zone of Potential Masking

Zones of masking depend on the amount of overlap between received source peak frequencies and the communication band/s of the species in question, plus the proximity of habitat deemed critical to the conservation and well-being of its local population or regional stock. As noted in Section 6.2.2, examining the potential of a near-continuous low frequency broadband source to mask long distance communications is more useful than estimating its maximum discernible audible range, particularly for a whale frequented locality already experiencing elevated background noise levels from other human sources.

Table 6-4 Type and possible consequences of behaviour changes from exposure to human noise source

Activity	Possible Effect / Response	Potential Consequence	Significance*
Intense feeding on important but possibly ephemeral or seasonally restricted prey	Influences normal diving and recovery sequences, group working, use of echolocation, or causes other behaviour change that reduces feeding	Reduced feeding efficiency causes reduced net energy intake (size of reduction depends on number and duration of encounters)	Low if encounters are brief and few. If prey is limiting, increases with percent of feeding time affected. May stabilise if habituation occurs.
Long distance migration to/from feeding ground	Alter course to avoid source	Course deviations involving +10 km add a fraction of time and energy loss to the overall journey budget of >2000 km	Low (equivalent to detouring around the approaches to a busy port)
Resting	Increased sensitivity to novel or unexpected noise reduces sound level tolerance. Forced to move away from source.	Unplanned exertion and use of energy	Increases with number of disturbances before or after calving
Calving	Increased stress, avoidance or defensive behaviour increases risk of injury to calf and cow	Disrupted birthing or suckling increases risk of cow/calf injury, calf oxygen debt, reduced milk intake, exposure to predators.	Risk of mortality increases with number of interactions (risk of reduced population recovery rate).
Social interactions and mating in winter breeding grounds	Diverted attention, disrupted vocalisations, and/or avoidance behaviour disrupts mate selection, courtship and mating.	Reduction in factors facilitating adequate insemination, conception and embryo implantation.	As above, with respect to reduced pregnancy rate.

* Assumes exposure to a novel noise source. May stabilise/reverse if the characteristics and commonality of the particular source facilitate habituation.

Both toothed and baleen whales have been observed to respond to increased background noise by producing more calls, louder calls, longer calls and/or shifting call frequencies. In the case of dolphins and toothed whales, these tend to remain in large family groups, specialise in high frequency (short-distance) vocalisations and do not generate low frequency sounds capable of long distance communication. In noisy localities and embayments bottlenose dolphins have been shown to echolocate louder (Au & Penner 1981) and change the frequency characteristics of their whistles and echolocation clicks (Au et al. 1974, plus recent Hervey/ Moreton/Port Philip Bay comparative studies).

6.2.5 Zone-inducing Possible Temporary Threshold Shifts in Hearing

When exposed to a sufficiently intense sound source, the inner ear hair cells of marine mammals can receive excessive excitation and subsequently cause a temporary decline in hearing sensitivity, in the same way as land mammals and humans. This is called a ‘temporary threshold shift’ (TTS), and its appearance due to the ‘tiring out’ of the hair cells is a function of the strength of the sound and duration of exposure. In the case of human health and safety regulations, the typical workplace regulations to prevent TTS via 8 hour shift exposures are 80 or 90 dB re 20 μPa, which are equivalent to underwater levels of roughly 142 to 152 dB re 1 μPa**.**

The TTS threshold is a time versus energy exposure function of the received sound, with the measured loss in hearing sensitivity (3-6 dB at or just above the frequency of the received sound) related to the total received energy (e.g. Finneran et al. 2002). When a TTS is present, the hearing threshold rises and a sound must be stronger in order to be heard. A TTS typically lasts for minutes, but may extend to hours or even days in cases of a strong TTS. The affected region remains at and just above the frequency range of the offending TTS-causing sound.

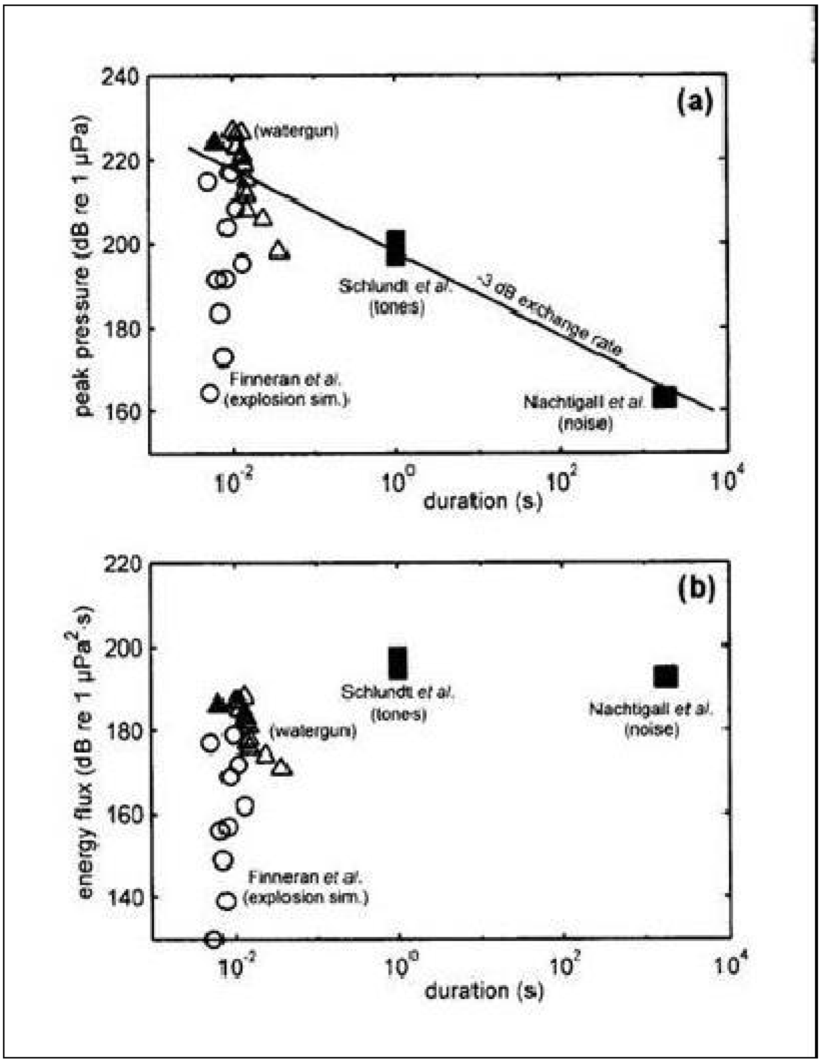
Repeated TTS events without sufficient intervening recovery periods can lead to irreparable damage to the hair cells, thereby leading to a Permanent Threshold Shift (PTS). The potential significance of TTS to long lived mammals such as the larger whales is therefore twofold: a temporary period when the ability to perceive a social signal, echolocation image or orientation cue may be impaired, plus an increase in the long term risk of accelerated hearing loss in old age. However, as with humans and terrestrial mammals, the auditory system is resilient and can experience the occasional TTS without undue risk of PTS developing. Thus some workers maintain that mild TTS is not injury *per se*, as it is a natural phenomenon experienced by humans and terrestrial mammals and has also been shown in marine fauna. In this context, there are a range of natural sources that can emit intense LF, MF and/or HF sounds that, during the lifespan of a larger whale, could be capable of producing a mild TTS (Table 4.1).

Since the capacity of neonates and young juveniles to receive several TTS with the same likelihood of avoiding an early onset of PTS is unclear, the biological significance of TTS-inducing levels is arguably higher in calving areas and for cow-calf pairs on their first migration to feeding grounds.

While the potential for TTS to occur in marine mammal ears has been recognised for several decades, reliable data regarding the sound levels inducing TTS did not begin to emerge until the late 1990s. Before these results, expert opinion sought by the US NMFS (e.g. HESS 1999, US Marine Mammal Commission 2004**)** had indicated that, for precautionary reasons including possible TTS, cetaceans and pinnipeds should not be exposed to pulsed underwater noise at received levels exceeding 180 dB and 190 dB re 1 μPa (rms) respectively. The more recent studies have since identified that pulsed sounds which cause mild TTS in dolphins and small toothed whales need to exceed >200 dB re 1 μPa (rms) (e.g. Kastak et al. 1999, Schlundt et al. 2000, Finneran et al. 2002; refer Figure 6.3).

Recent laboratory results of TTS testing in delphinid species indicate the received level of a single seismic pulse needs to be ~210 dB re 1 μPa rms (approx. 221–226 dB re 1 μPa peak–peak) to induce brief TTS (i.e. minutes of reduced hearing sensitivity). Exposure to several seismic pulses over a 30-60 minute period may require received levels of 200–205 dB (rms) to cause the same level of TTS in a dolphin or small toothed whale. Exposure levels inducing a mild TTS by typical seismic survey sounds (i.e. a series of very short pulsed sounds each separated by 8-15 second intervals) have not been determined, but can be assumed to be the roughly the same as the values inducing TTS reported for short (1 second) pulses (e.g. Finneran et al. 2002) versus the long exposure periods (>20 minutes) (e.g. Nachtigall et al. 2003).

The ability of the 5-15 second inter-pulse intervals to provide an ameliorative ‘mini’ recovery phase may be low. Nevertheless, the zone of potential temporary hearing loss and discomfort near an airgun array is relatively small, with geometrical spherical spreading causing a decline in sound levels to <200 dB re 1 μPa within 500 m of the largest commercial arrays.



(from Finneran et al. 2002)

Figure 6-3 Plot indicating sound exposure regimes (a) and energy flux densities (b) that can induce measurable TTS in odontocetes

Most experiments on TTS have been undertaken on bottlenose dolphins and beluga whales. The test tones were in the range of 40 to 7500 Hz with levels up to 202 dB re 1 μPa (Schlundt et al. 2000). Evidence of TTS was obtained, disappearing within a few days. The following account summarises the methods and findings of TTS experiments reported by Finneran et al. (2002). A behavioural response paradigm was used to measure masked underwater hearing thresholds in a bottlenose dolphin (*Tursiops truncatus*) and a beluga whale (*Delphinapterus leucas*) before and after exposure to single underwater impulsive sounds produced by a seismic watergun[12].

Pre- and post-exposure thresholds were compared to determine if a temporary shift in masked hearing thresholds (MTTS), defined as a 6-dB or larger increase in the post-exposure threshold, had occurred. Hearing thresholds were measured at 400 Hz, 4000 Hz and 30 kHz. MTTSs of 7 and 6 dB were observed in the beluga at 400 Hz and 30 kHz respectively, for approximately 2 minutes after exposure to single impulses with peak pressures of 160 kPa, peak-to-peak pressures of 226 dB re 1 μPa and total energy fluxes of 186 dB re 1 μPa^2·s.

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[12] Watergun impulses probably contain proportionally more energy at higher frequencies because there is no significant gas-filled bubble (Hutchinson & Detrick 1984).

Thresholds returned to within 2 dB of the pre-exposure value approximately 4 min after exposure. No MTTS was observed in the dolphin at the highest exposure conditions: 207 kPa peak pressure, 228 dB re 1 μPa peak-to-peak pressure, and 188 dB re 1 $\mu Pa^2 \cdot s$ total energy flux.

Finneran et al. (2002) also compared their findings with results from other TTS studies using different sound exposure regimes (Figure 6.3). The plots show that inducing TTS in cetaceans involves a sound dosage function in which the critical energy flux density for species tested to date is above 185 dB re 1 μPa^2 sec^{-1}. There are no measured data on sound levels that induce TTS in baleen species.

6.2.6 Zone-inducing Possible Permanent Threshold Shift or Other Tissue Damage

PTS results from irreparable injury to the hair cell receptors that line the basement membrane of the inner ear (unlike birds and reptiles, these are not replaced during adult mammal life). If relationships between TTS and PTS thresholds in marine mammals are similar to those studied in humans and other terrestrial mammals, PTS requires an exposure to ~20 dB higher peak-to-peak sound pressure levels than TTS.

Extreme PTS cases involve partial or total deafness that occurs by exposure to non-acoustic blast pressures, i.e. via proximity to detonations of high explosives. Exposure to explosive energies causes PTS owing to the more rapid rise time of the blast pressure wave (i.e. microseconds versus the milliseconds of airgun pulses). Humans and mammals with a PTS have continually impaired ability to hear sounds over various frequency ranges, which widen and worsen in older life, particularly for the higher frequencies.

If marine mammals have an inherently high behavioural tolerance to intense levels of pulsed noise (~200 dB re 1 μPa rms), this does not necessarily mean their hearing sensitivity may not become impaired over the long-term. For example, McCauley and Duncan (2001) have noted that while humans can tolerate short, repetitive explosive signals such as gunfire (because <200 millisecond sounds are not interpreted by the auditory brain stem or consciously perceived as excessively loud), such energies can still over-drive the inner ear and result in TTS and PTS.

Other effects as a result of sudden, very intense underwater sounds include stress, startle and ‘panic-flight’ responses, plus possible neurological effects. In the case of a severe startle reaction, this would be more likely to occur if there is no previous experience of the sound type (no learning or habituation), and the sound is both sudden and unanticipated by the receiving animal (no accommodation). Anticipation of a loud sound causes automatic tensing of ocular structures and head musculature, in part as an adaptation to increase head shadowing and reduce middle-ear gain to prevent ‘self-deafening’ when mammals vocalise loudly (e.g. Gisiner 1998).

Incidents involving beaked whale strandings have led some workers to suggest the possibility that intense tonal sounds might have the capacity to injure non-auditory tissue via resonance, such as to gas-filled sacs/sinuses (but only if the latter have an inherent fundamental frequency capable of excitement by the action of continuous sound waves at that frequency, with the ensuing vibrations sufficiently strong to be capable of damaging delicate membranes and capillary walls). In the case of the very short pulse lengths and long inter-pulse intervals of airgun seismic, this source would not provide sufficient energy to induce or maintain a tissue resonance.

While there is no known mechanism for the low frequency broadband pulses of airgun arrays to induce resonance in marine mammals, some workers have raised the possibility that relatively intense mid-frequency sonar tones could induce resonance, or cause gas bubble formation in the blood of deep-diving mammals. These conjectures arose following the March 2000 beaked whale stranding event in the Bahamas which had coincided with a US Navy exercise involving tactical mid-frequency sonar. It was speculated that if newly formed or coalesced micro-bubbles enter the blood system of marine mammals, these in turn might induce a pulmonary or cerebral artery gas embolism, as can occur in severe forms of decompression sickness (DCS; ‘bends’) experienced by human divers (e.g. Gisiner 1998, Houser et al. 2001).

Subsequent workshops convened to examine the Bahamas and more recent Canary Island beaked whale stranding incidents have concluded that resonance in air-filled structures was unlikely to be the cause as the air spaces in marine mammals are too large to resonate with both the frequencies and short pulse lengths emitted by mid- and low-frequency sonar (Gentry et al. 2002, cf. Finneran 2003). Following the September 2002 beaked whale stranding incident, Jepson et al. (2003) undertook biopsies and suggested that mid-frequency sonar might have caused *in vivo* formation of gas bubbles in some of the 14 stranded beaked whales which showed possible evidence of such tissue damage, but their results and conclusions were refuted by several commentators, such as Piantadosi and Thalmann (2004).

It also appears that the received levels of sonar (estimated at ~160 dB re 1 μPa rms) are too weak to cause the possibility of sonar-induced nitrogen gas bubble formation/coalescence, and that a ‘panic-flight’ response which caused the beaked whales to surface too rapidly may have been the cause of the possible DCS. Little is known about acoustic tissue damage and DCS signs in the poorly studied beaked whales because this can be reliably measured and assessed only very soon after death. All workers have agreed that more work is needed to resolve both the potential mechanisms and clinical signs of possible sonar-induced DCS in beaked whales.

In summary, the biological assessment of underwater acoustic impacts is an emerging science that promises to fill knowledge gaps which may allow previous ‘rule of thumb’ sound level criteria and safety range regulations to be adjusted or customised. When reliable estimates for TTS and PTS become available for the baleen whales, current use of the precautionary 182 dB US NMFS criterion as an acceptable exposure level to pulsed sounds[13] for all marine mammals may therefore become refined.

6.3 EXPLOSIVE BLAST IMPACTS

In the case of explosives, Lewis (1996a) described three zones of effect which have commonly been used for humans or marine fauna, as follow:

- one involving the likelihood of discomfort, temporary hearing loss or minor injury;
- one involving serious injury and high risk of permanent hearing loss; and
- the third comprising the innermost lethal zone.

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[13] US regulatory standards for endangered species ‘take’ permits refer to received levels of 120 dB re 1 μPa for continuous sound, 160 dB for intermittent sound, and 180 dB re 1 μPa for sounds of all frequencies and durations.

As well as the magnitude of the blast and the character of its associated pressure wave, the size of these zones is related to the morphology and anatomy and size of the subject receptor organism. The tissues and organs of fish, turtles and marine mammals most susceptible to pressure wave injury are the hair cells of the auditory system, and the blood vessels and organs that lie beside flexible gas-filled spaces. For a pressure wave to induce immediate physical damage, the animal must be located inside the range where sufficient attenuation has occurred to reduce and ameliorate the steep rise time, peak amplitude and shape of the impulse. The ‘blow-out’ effect of the sudden rarefraction (negative pressure pulse) on any gas-filled or spongy chamber associated with buoyancy control or hearing explains why swim bladder fish, as well as turtles and marine mammals, are killed or injured over larger ranges than other types of marine fauna. Lethal injuries typically include organ rupturing and blood vessel haemorrhaging around the swim bladder and hearing organs (Ketten 1995, 1998; Lewis 1996a). As with the bulk cavitation zone, the fish kill zone around a large explosion is often asymmetric, with swim bladder fish near the surface typically more vulnerable than fish deep in the water column (Lewis 1996a). Fish very close to the surface tend to have little or no injury owing to the attenuating influence of the ‘Lloyd mirror effect’ on the size and shape of the pressure pulse.

While the large body mass of larger fauna, such as marine mammals, means that pressure induced injuries are almost always sublethal, they are capable of causing subsequent mortality. For example, damage to the auditory tissues may lead to secondary infection, or produce sufficient pain, hearing loss and disorientation to prevent adequate navigation, communication or hunting.

Based on the use of 100 kg charges, an environmental assessment of Australian navy mine warfare activities using submerged explosives in shallow water (as reported in URS 2003) estimated that:

- fish with swim bladders would be affected for distances up to 200 m;
- fish without swim bladders, molluscs and crustaceans would be affected to distances of substantially less than 100 m;
- marine mammals and turtles could be exposed to pressure at levels sufficient to cause sub-lethal damage at distances varying between 750 m to 1,500 m, dependent upon their size (e.g. 750 m for a whale, 1,000 m for a dolphin, 900 m for a turtle, and that marine mammals may suffer acoustic-induced sub-lethal damage at distances less than 1,500 m (based on a 90 kg charge).

PTS is typically taken as the (conservative) threshold indicator of sub-lethal injuries. PTS results from irreparable injury to the hair cell receptors that line the basement membrane of the inner ear (unlike birds and reptiles, these are not replaced during adult mammal life). If relationships between TTS and PTS thresholds in marine mammals are similar to those studied in humans and other terrestrial mammals, PTS requires an exposure to ~20 dB higher peak-to-peak sound pressure levels than TTS.

Extreme PTS cases involve partial or total deafness that occurs by exposure to non-acoustic blast pressures, i.e. via proximity to detonations of high explosives. Exposure to explosive energies causes PTS owing to the more rapid rise time of the blast pressure wave (i.e. microseconds versus the milliseconds of airgun pulses). Humans and mammals with a PTS have continually impaired ability to hear sounds over various frequency ranges, which widen and worsen in older life, particularly for the higher frequencies. However there is no evidence that airgun array pulses can or have caused PTS in marine mammals, as this would require frequent multiple exposure to TTS events with short intervening periods.

On the other hand, if marine mammals have an inherently high behavioural tolerance to intense levels of pulsed noise (~200 dB re 1 µPa rms), this does not necessarily mean their hearing sensitivity may not become impaired over the long-term. For example, McCauley and Duncan (2001) have noted that while humans can tolerate short, repetitive explosive signals such as gunfire (because < 200 millisecond sounds are not interpreted by the auditory brain stem or consciously perceived as excessively loud), such energies can still over-drive the inner ear and result in TTS and PTS.

Other effects as a result of sudden, very intense underwater sounds include stress, startle and 'panic-flight' responses, plus possible neurological effects. In the case of a severe startle reaction, this would be more likely to occur if there is no previous experience of the sound type (no learning or habituation), and the sound is both sudden and unanticipated by the receiving animal (no accommodation). Anticipation of a loud sound causes automatic tensing of ocular structures and head musculature, in part as an adaptation to increase head shadowing and reduce middle-ear gain to prevent 'self-deafening' when mammals vocalise loudly (e.g. Gisiner et al.1998).

It is recognised that the impulsive effect from even small explosive charges generates a detectable impulse and acoustic perturbation over a wide field, with charge size being the principal determinant of the extent of the field of potential influence. Many other factors influence the rate of attenuation of the impulse, as well as the extent and shape of its potential field of influence upon sensitive marine fauna. These factors include:

- depth of water
- depth of charge in water column/depth of detonation
- water turbidity
- bottom composition
- bathymetry
- background noise

As previously noted, the most damaging frequency components of an underwater shock wave are rapidly depleted. Thus the area within which the blast and shock effect plays a dominate role constrained before the blast effect deteriorates to an expression of a broadband noise impulse, with most energy in the sub-1 kHz range.

7. EFFECTS OF NOISE ON MARINE FAUNA

This section reviews the known effects on marine mammals, turtles and sharks of noise sources, including exploration drilling, shipping, whale-watching vessels and pile driving operations.

It is difficult to predict which species will be most vulnerable to man-made noise because of the wide range of individual and population sensitivities as well as differences in wariness or motivation. Currently, it may only be possible to make generalisations about the vulnerability of species groups based on behavioural observations of responses to man made sounds, habits and what is known about a species' auditory sensitivity or vocal range.

When evaluating likely impacts, consideration should also be given to differences in local conditions that may affect sound propagation, e.g. depth, bottom type, size and type of source. A majority of man-made sounds have significant amounts of energy at low frequencies, thereby leading to potential disturbance, damage or interference to the mysticete whales. There is evidence of low frequency hearing in sperm whales (Ketten 1992, 1997) and this species appears to be extremely sensitive to disturbance from a variety of sound sources. Deep diving odontocetes may also be at risk as their behaviour puts them in the deep sound channel or Sound Fixing and Ranging (SOFAR) channel, along which sound is believed to travel efficiently for distances of hundreds to thousands of kilometres.

7.1 DREDGING

Reported source levels for general marine dredging operations range from 160 to 180 dB re 1 µPa @ 1 m for 1/3 octave bands with peak intensity between 50 and 500 Hz (Greene & Moore 1995). One of the most comprehensive studies of underwater noise emissions from dredging was carried out by the United States Army Corps of Engineers in Cook Inlet, Alaska (Dickerson et al. 2001). The research provides detailed records of the underwater noise generated by a bucket (grab) dredging operation. Measurements of the dredging in Cook Inlet, showed that the bucket striking coarse gravels on the seabed generated the most noise with a recorded peak of 124 dB (re 1 µPa) at 150m from the dredge site which attenuated by 30 dB (re 1 µPa) over a distance of 5 km. The digging operation was characterised by a grinding noise with a recorded peak of 113.2 dB (re 1 µPa) at 150 m from the dredging site to 94.97 dB (re 1 µPa) 5 km away.

Recorded noise levels for large cutter suction dredgers are higher than those associated with grab dredgers. Recorded broadband noise data for the large cutter suction dredger *JFJ de Nul* are given as 183 dB (re 1 µPa at 1 m) at Sakhalin Island, 2004. Measurements of two suction dredgers, *Aquarius* and *Beaver Mackenzie*, are reported in Nedwell and Howell (2004). Their octave band spectra peak between 80 and 200 Hz, with the Aquarius having the higher of the two spectra peaking at approximately 177 dB (re 1 µPa at 1 m). In the 20-1000 Hz band, *Beaver Mackenzie* and the *Aquarius* were measured to have a 133 dB (re 1 µPa) level at 0.19 km and a 140 dB (re 1 µPa) level at 0.2 km respectively.

Information from a number of studies indicates that acute damage to fish caused by sound does not occur below about 160 dB (re 1 µPa). During grab dredging activities, this noise level is unlikely to be generated, even when dredging through partially consolidated rock. However, noise levels as high as, or higher than, 160 dB (re 1 µPa) could have been generated in close proximity to the cutter suction dredger. Available data indicates that in shallow coastal waters, underwater noise transmission loss is typically of the spherical spreading type (Nedwell & Howell 2004). This means that for each tenfold increase in distance from the source the sound level will reduce by 20 dB. For the source measurements for the cutter suction dredgers provided above, this means that a noise level of approximately 160 dB/1 Pa would occur at a distance of 10 m from the cutter head and 140 dB (re 1 µPa) at 100 m. This calculation, although broad brush, demonstrates that potential acute damage to fish would only be likely to occur up to 100 m of the cutter head and probably at a distance significantly less than this.

Thus, at distances greater than a 100 m, acute damage would not have been likely to occur. Fish would have avoided moving close to the working dredger head as the sound would have caused an avoidance response, and therefore acute damage would only occur if fish were present in the vicinity when dredging operations started. This in itself would be highly unlikely given the physical disturbance that this activity would have caused.

It has also been calculated that the majority of fish would not be able to detect the noise made by dredging activity at a distance greater than 1km from the activity. Henderson (2003), assuming spherical spreading of sound, calculated that the predicted sound level from a suction cutter dredger would be 100 dB/1 µPa at 1km. On this basis it is considered that the noise generated during dredging would not lead to fish mortality and at worse would lead to temporary avoidance of nearshore waters immediately adjacent to the dredging activity.

Dredging noise varies through time and periodically dredging ceases whilst the dredged material is taken away for disposal. This creates periods of calm and quiet, during which fish can move through the area undisturbed.

Table 7.1 lists the sound source levels and estimated sound levels at different distances from dredging activities/techniques and it shows that the activities typically produce noise levels less than 160 dB and therefore, auditory damage to fish would not be expected.

Table 7-1 Sound sources from dredging activities

Dredging Technique	**Frequency Range**	**Average Source Level**	**Estimated Received Level at Different Distances (km) by Spherical Spreading**			
	(kHz)	dB	0.1	1.0	10.0	100
Mechanical dredge	-	130	90	70	49	28
Suction dredge	0.38	160	120	100	79	58

7.2 PILE DRIVING

The intense pulses of pile driving can injure swim bladders and kill salmonid fishes, and they have the potential to elicit a startle response to cetaceans if the hammering operation is commenced without any form of soft-start procedure. A ‘worst-case’ scenario in terms of invoking undue stress to whales would involve start-up of a three month operation at a site located in a shallow embayment that is being used for calving or resting, or as a temporary stop-over by humpback cow-calf pairs migrating slowly southward. There is no evidence of any piling operation having caused a panic-flight response to pilot whales or other small toothed whales which can enter these areas.

Nedwell et. al. (2003) reports on monitoring measurements of the waterborne noise resulting from impact piling and vibropiling at Town Quay, Southampton, UK, during construction of a ferry terminal. Underwater noise levels were monitored during the vibropiling operation at a location 417 m from the actual site of piling. The recorded levels showed that there was no discernible increase in the background noise signal at this point during the vibropiling operation (with recorded background levels periodically reaching 150 dB, but typically in the region of 110-120 dB). However, it should be noted that background noise levels in Southampton Water, as a result of the high level of shipping traffic and other water-based activities, are likely to be significantly greater than those for Aniva Bay. Caged brown trout (*Salmo trutta*) placed at 25 m from vibropiling locations reportedly showed no discernible behavioural reaction to the works (Nedwell et. al. 2003).

Nedwell and Edwards (2002) report on underwater noise measurements obtained during vibropiling operations for a wharf extension at Littlehampton in the UK. The recorded noise levels from a number of points showed a considerable degree of scatter indicating that the level of sound generated by the source varied. They attributed this variation to differing propagation conditions caused by variations in soil density near to the piles. The average (root mean square RMS) noise level for each measurement location varied between 132-152 dB/1 µPa at distances of 20-80 m from the piling works.

Noise spectra obtained for the piling shows that there was a strong signal in the region of 27 Hz but with most of the signal being concentrated in the midfrequencies (200 Hz – 2 kHz). Nedwell et. al. (2003) measured underwater noise levels associated with seabed drilling operations (from a jack-up rig) into sandstone for the installation of piles for offshore wind turbines. Although a source noise level for the drilling could not be obtained, all of the measurements from 100 m to 9 km from the drilling location were below a level at which significant behavioural effects in marine mammals and fish might be expected to occur (Nedwell et. al. 2003).

Much higher noise levels are generated during pile driving operations using the impact piling technique. An assessment of the effect of impact pile driving noise on fish species predominant near Rødsand, Denmark has been made by Engell-Sørensen (2000). This work assessed the potential behavioural and physical effects of the noise levels of pile driving associated with construction of offshore wind turbines. Sound exposure levels for four measurement positions between 30 m to 720 m from the activity gave levels ranging from 166 dB to 188 dB (re 1 µPa), with a calculated source level of 210 dB (re 1 µPa at 1 m). Engell-Sørensen (2000) concluded that: avoidance reactions would be likely to occur up to 30 m from the source, especially for species with swim bladders; the measured noise levels could harm the hearing ability of clupeids such as herring (*Clupea harengus*) and sprat (*Sprattus sprattus*), but this may regenerate over time; and, other than those already mentioned, the noise from pile driving is unlikely to cause any other physical effect.

The data from this and other studies demonstrate that the noise generated by impact pile driving works in the marine environment has the potential to cause acute damage and in cases of extreme exposure, mortality to fish. For pelagic fish and sharks, the most likely behavioural response during piling would be avoidance of the area in which the noise signals reach a threshold at which discomfort or annoyance is reached.

Nedwell and Edwards (2000), processed recorded noise levels from vibropiling works into levels that are indicative of how much a species would be affected by sound. These figures indicated that the noise levels generated by vibropiling were considered to be unlikely to induce any significant behavioural response in fish species such as salmon or flatfish. Recorded source noise levels for vibropiling are below levels at which mortality and acute harm to fish would be likely to occur and data also suggests that significant behavioural responses in species such as salmon would also be unlikely. Even so, if disturbance threshold levels were exceeded there would be extensive acoustically undisturbed areas available for fish to move into without detriment to their survival.

7.3 SHIPPING NOISE

It is widely considered that the baleen whales have evolved their low frequency vocalisations as a result of the selective advantages of achieving long distance communications, with the largest species most capable of exploiting the ocean's natural sound ducts. The apparent ‘male-only’ intense calling behaviour now known for the three blue whales plus the fin and humpback whales implies a reproductive strategy. If only the males make the loudest, longest and most complex calls among the range of vocalisations emitted by both sexes, these may help females select fit males to help ensure successful calving and genetic quality of their progeny. In this context, Croll et al. (2002) speculated that if breeding is “*limited by the encounter rate of receptive females with singing males, the recovery of fin and blue whale populations from past exploitation could be impeded by low-frequency sounds generated by human activity*”. If it is accepted that the two sexes possess no other mechanisms for (a) navigating to their usual breeding area during the same season, and (b) undertaking relatively simple random-search strategies to yield audible range encounters (e.g. 50-100 km wide cross-tracks), this concept increases the impact significance of potential call-masking sound sources (i.e. a breeding area where low frequency background noise is continuously elevated by heavy shipping traffic).

In the case of the potential for shipping or other low frequency sources to mask the long distance calls of baleen whales in Australian waters, there are few locations where ambient noise is significantly elevated by heavy shipping traffic (see Section 5.2) and there are no concentrated offshore petroleum developments where supply vessels, rig tenders and oil tankers are sufficiently numerous to contribute markedly to regional ambient noise, as can occasionally occur in parts of the North Sea, north-east Atlantic and Gulf of Mexico[14].

In this context, McCauley and Cato (2003) have criticised Andrew et al. (2002) who claimed, from a comparison of records from an established deep sound channel acoustic monitoring system off Point Sur (north California), that current ambient noise levels in the North Pacific had increased in selected low frequency bands (20–80 Hz and 200–300 Hz) compared to levels measured from the same equipment in the 1960s, offering support to the concept that rising vessel traffic noise is significantly limiting communications between baleen species which produce sounds at the same frequencies (Payne & Webb 1971). McCauley and Cato (2003) considered that the records comparison by Andrew et al. (2002) was marred by a recent calibration of the Point Sur equipment, by the dismissal in their calculations of the contribution of distant great whale calling, and that traffic noise reference levels were based on limited knowledge from 30–35 year old samples. Great whale numbers in the Pacific during the 1960s were historically at their lowest levels due to commercial whaling and hence would have contributed little to the low frequency components of ambient noise. Recoveries in their numbers over the recent decades mean that great whales calling from thousands of kilometres away could well be adding to the ambient noise in the deep sound channel where the Point Sur measurements are made.

Arguments that shipping traffic noise is significantly masking great whale communications in all regions also assume that the northern hemisphere, with its high density of busy shipping

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[14] The north-west Atlantic, west Shetland area and parts of the Mediterranean represent regions where limited rorqual stocks and such activities overlap, and the potential for excessive background noise in these areas to affect the recovery of northern fin and blue whale stocks has been raised by some workers such as Croll et al. (2001).

lanes, is typical of all oceans and seas including those in the southern hemisphere (McCauley & Cato 2003). Yet even in the high traffic areas of the Tasman Sea, wind-induced sea surface noise drowns out shipping noise whenever wind speeds attain 20 knots or more (see Figure 3.2). McCauley and Cato (2003) have also noted that whales have always had to contend with noise levels that are as high as, or higher than, ship traffic noise, and that in some areas their own calls are producing greater ambient noise levels than traffic noise when averaged over time.

In another study, shipping noise levels were examined with respect to resident sperm whales feeding in the Canary Islands (André & Degollada 2003). This study was undertaken following fears that the sperm whales, which are exposed to heavy ferry and merchant ship traffic, were suffering increased collision rates due to adverse effects from the local acoustic budget. However controlled exposure experiments to test the ability of underwater sound system to repel sperm whales from ferry routes and thus reduce collision risks found that none of the low frequency sounds tested altered their behaviour or location. This is perhaps unsurprising given the apparent disdain displayed to merchant ships by sperm whale groups when feeding and surface resting in the busy shipping lane off Sri Lanka. In a recent (May 2003) example of this behaviour, a family group of 40-50 sperm whales were monitored for some 12 hours while feeding and socialising in the busy shipping lane 50 miles south of Dondra Head (south Sri Lanka). “Numerous tankers” were passing during this period since the whales were inside the very busy oil tanker and container ship lane between Asia and the Gulf and Suez Canal, and it was speculated that the whales had been attracted to an area containing abundant prey (Madsen 2003). During the observations, a subgroup of 10 were observed to show no apparent change in their surface resting behaviour and slow swimming speed as a large, fast-moving container ship passed just behind their own surface wake.

Erbe (2002) modelled the potential effects of underwater noise from whale-watching vessels on orcas off southern Canada. Results indicated that faster boats made more noise, being audible to killer whales over 16 km away, to mask killer whale calls over 14 km, to elicit behavioural response over 200 m and to cause changes in hearing of 5 dB after 30 minutes within 450 m. For slower vessel speeds the predicted ranges were 1 km for audibility and masking, 50 m for behavioural responses, and 20 m for hearing changes. The effects of combined vessel noise around a group were close to a level considered likely to cause a permanent hearing loss if there was prolonged exposure.

Concerns about long distance masking would require a major rise in shipping traffic, discovery of offshore oil reservoirs on a par with the size of those off Scotland or Norway, or a major new industrial port complex proposed near a recognised significant baleen whale locality. In this context, experience from the right, humpback and sperm whale stocks in the North Atlantic and Mediterranean indicates that increased rates of ship strikes rather than call masking would be a more plausible concern regarding the ability of vessel traffic to influence population recovery rates.

A considerable body of fisheries literature exists on the behavioural response of fish to the noise of approaching vessels (e.g. Olsen 1990). These studies have shown that fish avoid approaching vessels when the radiated noise levels exceed their threshold of hearing by 30 dB or more, usually by swimming down or horizontally away from the vessel path. Environmental and physiological factors play a part in determining the noise levels that will trigger an avoidance reaction in fish. For many vessels fish avoidance reaction distances are 100 - 200m but for the noisiest 400 m is more likely. The degree of observed effect weakens with depth, with fish below about 200 m depth being only mildly affected and the effect is only temporary with normally schooling patterns resuming shortly after the noise source has passed. Surface and mid-water dwelling fish may theoretically be adversely affected by noise generated during vessel movement, however the clear and abundant presence of fish that accumulate adjacent to operating industrial infrastructure (oil/gas production platforms, wharves, shiploaders, etc.) indicates that they are able to habituate to some noise with no apparent detriment.

7.4 VESSEL PRESENCE

Many pinniped and cetacean species display considerable tolerance of shipping and boating traffic, and several delphinids (and occasionally other toothed whales such as humpback and pilot whales) are often attracted to vessels both large and small, most commonly for bow wave or wake riding in the case of dolphins and porpoises. However the responses to ships and boats by many cetaceans comprise a vast, heavily anecdotal and often self-contradicting 'database' that hinders systematic robust analysis. Why individuals of a certain species appear attracted to vessels on some occasions and actively avoid them on others requires detailed background information if patterns and common factors are to be identified for that species. Clearly there is a wide range of external, internal and intrinsic factors which can influence any cetacean's perception as to where, when and what particular vessel represents an acoustic irritant, a physical intrusion, an object of interest or merely part of the general seascape, and thus whether an avoidance action is initiated or not.

Humpback whales have been reported to show various responses to moving sources such as whale-watching vessels, fishing boats and recreational craft (Beach & Weinrich 1989, Clapham et al. 1993, Atkins & Swartz 1989). The types of approach, avoidance and apparent non-responses in behaviour to vessels have been related to the type, number and activity of the whales at the time of the observed interactions (Herman et al. 1980, Watkins. 1981, Krieger & Wing 1986). In early research, some investigators suggested that vessel traffic would cause humpback whales to avoid or leave both winter feeding and summer calving areas (Jurasz & Jurasz 1979b), while subsequent researchers have noted evidence suggesting that humpback whales can habituate to vessel traffic but may become more vulnerable to ship strikes once habituated (Swingle et al. 1993; Wiley et al. 1995).

Humpback whales are occasionally killed by ship strikes along both US coasts. On the Pacific side a humpback whale is killed about every other year, while six out of 20 humpback whales stranded along the mid-Atlantic coast had evidence of a major ship strike. In Alaska, the number of cruise ships entering Glacier Bay has been limited to reduce their possible disturbance to feeding humpback whales. In Hawaii, regulations prohibit vessels including whale-watching boats from approaching within 91 m (100 yards) of humpback whales and within 274 m (300 yards) in areas designated additional protection to cow-calf pairs.

In a long-term study over 25 years of whale responses to vessel approaches (Watkins 1986), the most vigorous responses by whales came from vessel noise sources that changed suddenly, rapidly, increased or were unexpected. Watkins was one of the first to recognise that preoccupied whales were typically less responsive than inactive whales. Later workers have found similar results where rapidly changing vessel noise often evokes a strong avoidance response, while a slow non-aggressive vessel approach results in little response from the whales, noting that feeding whales may be less responsive to vessel traffic as they are involved in a biologically important, directed activity (Richardson et al. 1995; McCauley et al. 1996).

Vessel activity has been implicated in long-term and short term changes in distribution of humpback whales in Hawaiian waters (Norris & Reeves 1978, Jurasz & Palmer 1981, Baker & Herman 1989). Results from a long-term study (27+ years) of southern right whales in

Argentina imply flexibility in several aspects of their habitat use (Rowntree et al. 2001). This included the apparent abandonment of one calving/resting ground and establishment of a new 'nursery' beside the centre of a growing whale-watching industry, plus some small-scale shifts in distribution possibly in response to natural and human disturbances. Southern right whales are increasingly observed in Albany's harbours, suggesting at least a tolerance of local ship and boat traffic.

While family groups of sperm whales can exhibit apparent *en masse* indifference to the relatively intense emissions of nearby large and fast-moving ships that maintain steady courses (e.g. Sri Lanka, Canary Islands), individual sperm whales in New Zealand's famous nearshore feeding area off Kaikoura displayed individualistic, contrasting reactions to outboard-powered RHIBs used for commercial whale-watching, as studied in the early 1990s (Gordon et al. 1992). 'Resident' whales appeared more tolerant of these vessels but spent shorter surface intervals and a more erratic and overall lower number of ventilations when RHIBs were present. 'Non-resident' sperm whales were much less tolerant of RHIB approaches and also reduced their surface intervals and ventilations when one or more of these vessels was present in the area. Evidence for slightly slower rates of initial descent were apparent in the rates of change of the bouts of clicks following the start of a feeding dive (marked by a fluke-up). No change to vocalisation or fluke-up could be related to RHIB presence/absence (Gordon et al. 1992).

7.5 ROCK AND SLUDGE DUMPING

Minimal information is available regarding noise generated from rock dumping activities, however, it is reasonable to expect that any noise will be dominated by the splash, tumble and grinding of rocks, possibly associated with mechanical transients generated by the operating gear. Given the normal pattern of rock dumping activities, it may be anticipated that any noise will be intermittent.

It is reasonable to assume that noises associated with the dumping, movement and settling of the rocks themselves would be low frequency broadband. Intensity and period of the noise event would be influenced by factors such as the amount, size and mass of rocks dumped, the depth of water in which they were dumped and the type of surface upon which they landed and settled. In any event, it is unlikely that the noise levels attained would be of any great significance.

The dumping of sludge itself and its movement through the water column and settlement or dispersion upon the bottom is unlikely to generate any tangible noise. This is due to the usually viscous, semi-fluid nature of the sludge or slurry.

Depending upon the method of rock or sludge dumping employed, the operation may also be the source of mechanical transients. These would be due to the operation of bottom hopper doors, if employed. Although no data are available, it is illustrative to consider the noise associated with the operation of a clamshell dredge as a useful surrogate. Richardson et al. (1995) described noise from a clamshell dredge as variable depending on the operating status. It was noted that the strongest sounds are usually from the winch motor pulling a loaded clamshell back to the surface. This noise had a broadband source level of ~167 dB (re 1 μPa at 1 m) and included a fundamental tone of 125 Hz with many harmonics. Richardson et al. (1995) also noted that noise from the tug and barge used to transfer dredged material was greater than that produced by the dredge itself.

7.6 EXPLOSIVES

7.6.1 Marine Mammals

Richardson et al. (1995) reported on observed effects of explosives upon the behaviour of marine mammals. Humpback whales in the vicinity of explosives being detonated near Bermuda displayed no interruption to their vocalisations. Similarly, humpbacks within 2 km of explosions in sub-bottom rocks off Newfoundland displayed no obvious reactions when 200 to 2,000 kg charges were detonated. Gray whales within a ‘few’ kilometres of detonations of 9 to 36 kg charges used during seismic survey have been observed to alter swimming behaviour, while other observers (Fitch and Young 1948, in Richardson et al. 1995) report the whales “were seemingly unaffected and in fact were not even frightened from the area”.

Toothed whales show a tolerance for impulsive acoustic disturbances, although the initial reaction may be one of avoidance. Captive false killer whales showed no obvious reaction to small charges, and other odontocetes have been found to be attracted to the location of detonations (Richardson et al. 1995), presumably in search of dead, injured or disoriented fish as prey.

Pinnipeds have also been widely observed to develop habituation to explosive detonations, as ‘seal bombs’, used to keep seals and sea lions away from fishing vessels and aquaculture pens, have been found to have limited long-term effect (Lewis 1996a).

Risk of physical injury or mortality does exist for large fauna, but these are only realistic probabilities in the immediate zone around the point of detonation and only for charges substantially larger than those likely to be used for the SSDP; these risks are ameliorated by standard marine fauna observation and clearance procedures.

Although any use of explosives during construction of the SSDP will be detectable over a wide area by potentially sensitive fauna, this risk is considered minimal when it is noted that use of explosives will be irregular, dispersed over time and intermittent. This conclusion is supported by Richardson et al. (1995), who summarised that while some pinnipeds and odontocetes, in particular, display short-term avoidance reactions to explosive impulses, overall, marine mammals show considerable tolerance of noise pulses from explosions. This conclusion is supported by observed reactions to explosives used singly or repetitively. The observed tolerance of marine mammals may be linked to their experience of the intense, impulsive nature of many acoustic events of natural origin, such as lightning strikes and whale breaching and tail slapping.

7.6.2 Sharks

Sharks may be less susceptible to blast and impulse effects than are many fish. This is due to the absence of a swim bladder, their physical size and arguably also due to their general morphology. While fish without swim bladders are much less sensitive to blast pressure damage than swim bladder fish, it is worthy of note that fish with a cylindrical body shape (e.g. barracuda, queenfish, kingfish) have been found less vulnerable than laterally compressed fish with thin-walled bladders (Lewis 1996a).

7.6.3 Marine Turtles

In the case of shockwave effects, there are very little hard data available on the types and extent of turtle tissue damage due to underwater detonations, and most workers assume that turtle lungs, ear drums and other gas-containing organs would be affected to the same degree as their counterparts in marine mammals (Lewis 1996a).

Due to the lack of specific injury response curves for turtles, Young (1991) followed US National Marine Fisheries Service criteria for sea turtles in the Gulf of Mexico and provided safe-distance ranges plots for sea turtles based on cube-root scaling, where:

$$\text{Turtle Safe Range (feet)} = 560 \times \text{NEQ TNT (lbs)}^{1/3}$$

Three specific predictions listed by Lewis (1996a) support Young's (1991) prediction plot; namely that organ tissue damage in sea turtles may occur at range distances less than 750 m from a 100 kg HE charge, with hearing damage at range distances less than 1500 m from charge weights exceeding 90 NEQ kg TNT (Lewis 1996a).

These predictions match limited aerial monitoring observations obtained during a training exercise in the Shoalwater Bay Training Area (SWBTA), where an apparently healthy green turtle was spotted in shallow water seagrass beds within 800 m from a site where, less than 40 minutes previously, a large detonation of ~100 kg NEQ TNT ordnance had been conducted. No drifting or disoriented turtles were seen by the low-level aerial survey crew nor by the on-site observers (URS 2002).

Lewis (1996a) also describes an incident involving three sea turtles in the vicinity of an underwater shock trial involving detonation of a 545 kg TNT charge at 37 m depth off Florida in 1981. A large adult turtle (182 kg) that was between 153-214 metres from the detonation was killed, a ~120 kg turtle that was 366 m away was slightly injured, while the third turtle (~120 kg) that was at a range of 908 m was uninjured. From these data it was considered that a conservative safety range for turtles could be predicted by the formula of 80 m per $\text{kg}^{1/3}$ of HE (O'Keefe and Young, in Lewis 1996a).

The results of the Florida test are in agreement with the aerial observations in Shoalwater Bay in 2001 (i.e. uninjured adult green turtle at 700-800 m from a shallow water (~3 m) detonation of 100 kg TNT; URS 2002). While there are no observations or data on the range thresholds for either acoustic injury or behavioural responses for the five other marine turtle species found in Australian waters, there is no anatomical evidence to suggest these species should be any more sensitive than either green or loggerhead turtles.

7.7 PIPELINE LAYING AND OPERATION

In their review of marine mammals and noise, Richardson et al. (1995) did not specifically note piplelaying as a distinct source of marine anthropogenic noise, although they did address a range of other marine construction activities. It is reasonable to conclude that the pipelay itself is unlikely to be a source of any noise of environmental significance; more tangible sources of noise during pipelay will be as a result of vessel movements and associated construction activities, such as trenching, pile driving and rock dumping.

There is a general paucity of information in the literature about the noise effects of the operation of undersea pipelines, possibly as a reflection of either a direct lack of research, or indirectly because this is not considered to be a likely source of significant environmental disturbance. In recent reviews of offshore petroleum activities (ENTRIX, Incorporated 2004; Minerals Management Service 2001 & 2006; NMFS 2002b), marine noise in general (Richardson et al. 1995) and the construction and operation of a seawater desalination plant in New South Wales (The Ecology Lab 2005), no specific consideration or assessment was made of the noise of operation of undersea pipelines.

As previously noted, Shaipro and Associates (2004) estimated that a high velocity gas pipeline proposed for the Georgia Strait would exhibit radiated noise equal to or lower than 30 dB at frequencies of 16 kHz and above. A larger diameter pipeline as planned for the SSDP, with a slower moving fluid (around 0.5 ms^{-1} for the SSDP outfall[15] and 0.15 ms^{-1} for the intake [WAWC 2008]), would reasonably be expected to radiate noise at a lower level and lower frequency than for a smaller diameter, high pressure gas pipeline, where velocities are typically in the order of 15 ms^{-1}.

The conclusions of the regulatory authority, the US Minerals Management Service (2001 & 2006) are illustrative. For the cited assessments, the whale species of greatest concern was the California gray whale (*Eschrichtius robustus*), which has similar acoustic acuity and an analogous migration habit to the humpback. Thus, it may be considered that the California gray whale and its apparent indifference to the operation of undersea pipelines represents a useful surrogate for the SSDP pipelines and their effect or otherwise upon migratory baleen whales, particularly humpbacks. In the case of an Alaskan offshore oil development including pipelines, the NMFS (2002b) came to a similar conclusion with regard to bowhead whales (*Balaena mysticetus*), which typically exhibit perhaps the greatest sensitivity to anthropogenic noise of any of the baleen whales (Richardson et al. 1995).

Any radiated noise from the operation of the SSDP outfall would be further ameliorated by the intended trenching and rock armouring of some sections. Furthermore, any outer coating of concrete or similar would further attenuate radiated noise.

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[15] This estimate is based on data for the existing Kwinana Seawater Desalination Plant, as presented in Olkely et al. (2007).

8. ASSESSMENT OF RISK FROM THE PROPOSED ACTIVITIES

8.1 CHARACTERISTICS OF NOISE GENERATING ACTIVITIES

As described previously, it is likely that the following activities will generate noise, and may therefore pose a risk to marine fauna in the area:

i. dredging;
ii. pile driving;
iii. rock armour dumping and sand/sludge dumping;
iv. general shipping/vessel traffic;
v. explosive blasting; and
vi. pipeline installation and operation

8.1.1 Dredging

The noise generated from dredging activities will vary depending on the dredging method used, details of which will be determined during later stages of the project development. Research shows that noise levels are higher from cutter suction dredgers compared to grab dredgers (Richardson et. al. 1995). Nevertheless, source levels from dredges are relatively modest, at around 160 – 170 dB (re 1 µPa).

8.1.2 Pile Driving

Pile driving is only likely to be undertaken over a period of a few weeks and noise generated will be periodically persistent and confined to daylight working hours. Noise levels will also vary depending on the substrate and the pile driving method used, with the impact piling technique likely to create greater noise. Pile driving is arguably the most noise intensive activity in the proposed package of works, with its inherent repetitive, impulsive nature possibly accentuating its ability to startle or lead to avoidance behaviour by marine fauna. Any effects arising from pile driving would most likely be more acute during the initial start-up phase.

8.1.3 Rock Armour Dumping and Sand/Sludge Dumping

These activities are likely to be intermittent during the construction phase. Noise from rock dumping is likely to be broadband low frequency, although at relatively modest source levels. Sand/sludge dumping is not expected to generate noise to any appreciable extent, except for that generated by the vessels themselves.

8.1.4 General Shipping/Vessel Traffic

Noise generated from vessel traffic associated with this project will mainly occur during the construction phase. Most information available is in regard to whales where it has been identified that noise from shipping can occasion disturbance to some degree, but they are generally tolerant of such activities.

Noise from vessels associated with this activity is unlikely to be of any significance in the broader field, particularly noting the close proximity of the project site to the commercial port of

Bunbury and standard shipping routes and level of shipping activity around the south west of WA.

8.1.5 Explosives Blasting

If used during SSDP marine construction activities, explosive charges do pose a risk to marine fauna. In a relatively small area around the point of detonation, there is a risk of mortality, with a wider, albeit relatively small, zone where injury is possible. Beyond the immediate vicinity of detonation there is a wider area where minor injury, in the form of PTS, is also possible. The greatest likely effect from the use of explosives, however, is as a result of noise disturbance, rather than blast or impulse. The zone of influence of noise-related potential impacts as a result of underwater detonations is substantially larger than that for lethality or injury, but still relatively confined.

Risks to marine fauna from the use of explosives will be inherently limited due to the modest number and small size of charges likely to be used, if at all. This risk can be further mitigated by the establishment of marine fauna safety zones around the detonation site/s in the period leading up to and at the time of detonation. It is suggested that an exclusion zone of 2 km radius be established around detonation sites. From 30 minutes before the planned time of detonation this zone should be checked to be clear of large marine fauna such as whales, dolphins, sharks and turtles. If any are observed to be within the zone then detonation should be delayed until such time as the observed fauna are outside the zone. To enhance the effectiveness of surveillance, detonation should only be conducted in daylight conditions and with benign sea conditions (e.g. sea state 3 or below) so that boat and land-based observers have a reasonable probability of sighting any marine fauna incursion into the safety zone.

Although not considered critical, residual risks could be further reduced by conducting underwater blasting outside of the recognised migration periods in that area for southern right whales (May to October) and humpback whales (May to November).

8.1.6 Pipeline Installation and Operation

Installation of the pipeline itself is unlikely to be a source of any distinct acoustic disturbance. As previously noted, however, the pipelay operation will generate noise as a result of associated activities, such as vessel movements, dredging/trenching, pile driving and rock dumping. Some noise arising from vessel movements will also arise from periodic inspection and maintenance of the pipe.

The actual operation of the pipeline is unlikely to generate any noise of any biological significance. Any noise that is generated would be minimal and inconsequential in comparison with the ambient noise environment of the near-surf zone where the pipelines will be located.

8.2 ASSESSMENT OF RISK TO MARINE FAUNA

8.2.1 Cetaceans

Baleen Whales

It is likely that noise generated from this project will be within the hearing ranges of baleen whales. However, as these whales have, with the periodic exception of southern right whales, minimal presence in the nearshore coastal area in which the pipeline will be located, and recognising that the construction activities will be short-term, there is likely to be no significant risk. Any audibility of the pipeline and the associated construction activities is likely to be significantly masked by the persistent, ambient noise emanating from the nearby surf zone.

Toothed Whales

Noise generated from this project may be audible to toothed whales (including dolphins), although at frequencies below their optimal hearing ranges. Effects upon dolphins, if any, are likely to be behavioural and most likely confined to the immediate area and most likely only during any period of pile driving.

8.2.2 Sea Lions

As summarised by McCauley (1994), seals and sea lions have poor hearing at low frequency and, therefore, can approach low frequency noise sources, such as seismic survey vessels, without suffering adverse effects. On this basis, it may be concluded that the construction and operation of the SSDP, and the associated noise sources, is unlikely to have any deleterious impacts upon the Australian sea lion.

Pinnipeds have also been widely observed to develop habituation to explosive detonations, as ‘seal bombs’, used to keep seals and sea lions away from fishing vessels and aquaculture pens, have been found to have limited long-term effect (Lewis 1996a). On this basis, it is conceivable that sea lions may be attracted to explosions causing fish kills and may then be caught in the next explosion if these were to be conducted with any regularity and repetition. This risk can be mitigated by application of an exclusion zone around blast sites and the employment of a suitable interval between detonations.

8.2.3 Marine Turtles

Turtles have been known to demonstrate a startle response to sudden noise, such as occurs with pile driving or the detonation of explosives. Thus, any turtles in the project area may experience short-term behavioural effects, including some avoidance of the site. Any such effect may impact on feeding but is likely to only occur during the limited pile driving activities which will occur at the site. Dredging, rock dumping, vessel movements and pipe operation are less likely to elicit any significant response.

There is no risk of adverse effect upon turtle nesting or hatching as the project area is not anywhere near turtle breeding areas.

8.2.4 Sharks

Sharks within the area will be able to detect the low frequency noises generated by the construction activities, particularly the pile driving. However, no critical habitat or aggregation areas are known to occur within the vicinity of the project site, so any acoustic-induced impact is likely to be short-term and non-persistent.

Any potential effects from the use explosives can be mitigated by application of an exclusion zone around blast sites.

8.3 CONCLUSIONS

Some noise, generally low frequency broadband, will be generated from the proposed activity, particularly during the construction phase. It may be concluded that this should be considered as unlikely to trigger any long-term, persistent, deleterious impact upon marine fauna in the area. This conclusion is founded upon several key points, namely:

- the relatively low levels of noise expected to be generated;
- the temporary nature of the predicted acoustic disturbance;
- the high levels of persistent, broadband noise expected in the project area emanating from the nearby surf zone; and
- the absence of any identified critical or important habitat in the project area for sharks, turtles or cetaceans, and the availability of nearby alternative areas for temporary refuge.

It is possible that the proposed activities, particularly the pile driving, will elicit some short-term behavioural changes. These are likely to be confined to startle responses, changes to feeding patterns and temporary avoidance of the project area. None of these are considered likely to result in long-term harm to either individuals or populations of any of the marine fauna considered.

Explosive blasting could potentially cause mortality or sub-lethal injury, but the areal extent of the zones in which these types of impact may be experienced are exceedingly small. More likely, the impact of explosives would be limited to acoustic-induced startles. The limited risks presented by any use of explosives can be significantly ameliorated by the establishment and surveillance of effective marine fauna exclusion zones around the blasting sites.

The intermittent presence and lack of any specific residency of the nominated species of concern in the project area suggests minimal risk of exposure to any noise or shock effects from the proposed SSDP. Furthermore, potential noise and shock effects are intrinsically low and will be further attenuated by the intended risk mitigation measures. Taking these factors into account, it is unlikely that the construction and operation of the proposed SSDP would occasion any significant noise or shock-related impact upon any individual of the nominated species of concern, with population level effects a significantly less remote possibility.

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10. LIMITATIONS OF REPORT

URS Australia Pty Ltd (URS) has prepared this report in accordance with the usual care and thoroughness of the consulting profession for the use of Western Australian Water Corporation and only those third parties who have been authorised in writing by URS to rely on the report. It is based on generally accepted practices and standards at the time it was prepared. No other warranty, expressed or implied, is made as to the professional advice included in this report. It is prepared in accordance with the scope of work and for the purpose outlined in the Proposal dated 23 June 2008.

The methodology adopted and sources of information used by URS are outlined in this report. URS has made no independent verification of this information beyond the agreed scope of works, and URS assumes no responsibility for any inaccuracies or omissions. No indications were found during our investigations that information contained in this report as provided to URS was false.

This report was prepared in July 2008, and is based on the conditions encountered and information reviewed at the time of preparation. URS disclaims responsibility for any changes that may have occurred after this time.

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