Underwater Sound and Vibration from Offshore Petroleum Activities and their Potential Effects on Marine Fauna: An Australian Perspective

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Disclaimer: The authors have endeavoured to make the information in this report as accurate and comprehensive as possible. However the review depended upon the works made available to us and/or available on-line or published at the time.

Contents

Table of Figures

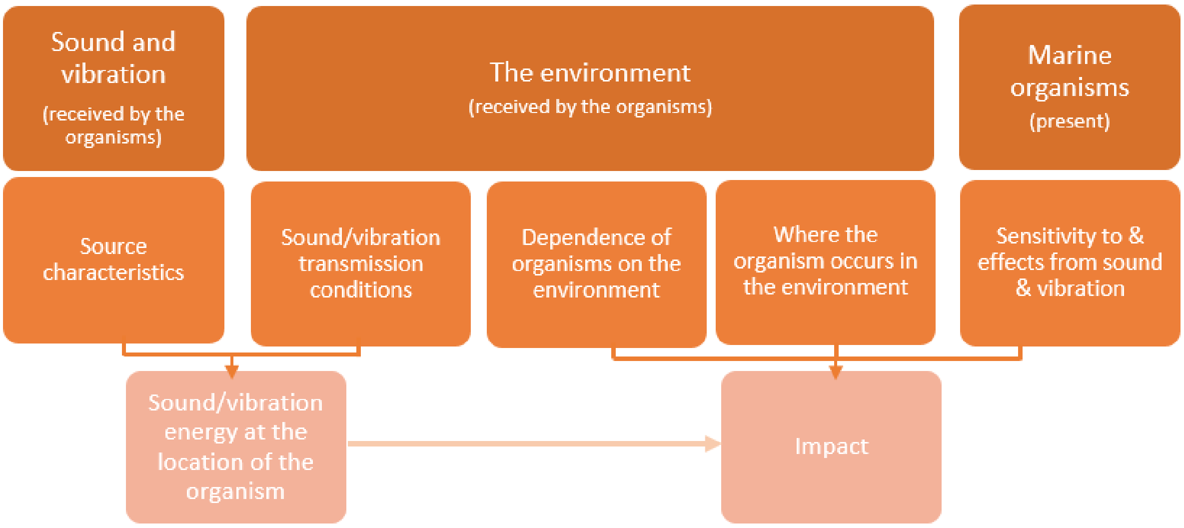
Table of Tables

1 Introduction

Over recent decades there has been heightened social and political awareness globally of the potential impacts of man-made underwater noise on the marine environment. While the effects of airborne noise on human occupational health and safety have been investigated to improve workplace conditions, research focusing on noise impacts on the marine environment is relatively recent. Consequently, we have limited knowledge on the impacts of noise on marine fauna, and even less on the impacts of underwater vibration.

1.1 Purpose of this report

Australia has abundant and diverse energy resources; a significant component is oil and gas located below the seafloor. We know that activities associated with the extraction of these resources contribute to man-made noise and vibration in the marine environment. Assessing their potential impacts on the environment is not trivial, however, and its accuracy depends upon knowledge available. Whether impacts will occur and how significant they may be depends on having knowledge and information about many factors (Figure 1). For example, the risk of an impact occurring depends directly on the marine fauna present and their physiological sensitivities to sound and vibration; how they use sound and vibration for survival and reproduction; the characteristics of the sound and vibration received from man-made sources; and what the impacts of it are to their biological functions. In addition, the characteristics of the sound and vibration depend on the source, and how they transmit through the environment. Ultimately, it is essential to have knowledge about the attributes of the natural environment (physical, chemical, and biological), and how fauna in the environment are affected by sound and vibration from human activities at that location.



Sound and vibration (received by the organisms)

The environment (received by the organisms)

Marine organisms (present)

Source characteristics

Sound/vibration transmission conditions

Dependence of organisms on the environment

Where the organism occurs in the environment

Sensitivity to & effects from sound & vibration

Sound/vibration energy at the location of the organism

Impact

Figure 1. Knowledge required to assess the impact of sound or vibration on an organism

The purpose of this report is review and synthesise the Australian research to date on impacts of underwater noise related to oil and gas industry activities on marine fauna. As in many jurisdictions around the world, Australia has gathered some momentum over the past decade in improving current knowledge on the effects of human activities on the marine environment.

1.2 Basis for synthesis and review

Progress to improve our current knowledge on the potential impacts of sound and vibration on marine fauna continues to be made through ongoing scientific research. The results from research are reported in a range of different formats and styles (often oriented specifically to a scientific audience), have varied and disparate accessibility, and vary in detail, breadth, and scientific rigor. Consequently, regular reviews of the work to date are required to synthesise and summarise our current knowledge on the topic. Reviews allow the information to be more readily accessible, improve the accuracy of environmental impact assessments, improve best practices, and focus research effort in areas where there are significant gaps in our current knowledge.

In recent years, there have been several reviews summarising advances in the field of faunal responses to anthropogenic noise (e.g. Rabin et al. 2003; Patricelli and Blickley 2006; Warren et al. 2006; Popper and Hastings 2009a; Barber et al. 2010; Slabbekoorn et al. 2010, Knight and Swaddle 2011; Francis and Barber 2013). However, these papers mainly synthesise scientific work undertaken outside of Australia. A compilation specifically focused on potential impacts of noise and vibration from oil and gas industry activities on Australian marine fauna has not been produced in over a decade. The last synthesis produced was used extensively to guide legislation and mitigation strategies, and to help direct future scientific efforts (Blue Book II, Burns et al. 2003). This current document has been prepared for the purposes of updating the last review with current information so that it is broadly available to the community, researchers, stakeholders and regulators.

1.3 Approach

To achieve a scientifically rigorous synthesis of the research, a systematic process for searching available studies completed in Australian waters (reports and publications) was required. Here, we describe that process.

To access relevant works, we searched in two ways: 1) a search of published works, and 2) a search for commissioned reports in the grey literature. Published works were extracted from the *Web of Science* databases (http://ip-science.thomsonreuters.com/) over a 20-year period (1994–2014) using key words (with wildcard characters where relevant) and Boolean operators, including: seismic, underwater noise impacts, oil and gas, construction, wellhead, decommission, drill, extractions, petroleum, marine mammals, dolphins, whales, dugongs, seals, sea lions, pinnipeds, fish, hearing sensitivity, masking, hearing shift, hearing damage, physiological response, behaviour, physiological, plankton, Floating Production Storage and Offloading, petroleum, invertebrates, hearing damage, hearing threshold, marine mammals, penguins, sea turtles, sea snakes, crocodiles, eggs, larvae, and Australia, among others. *Web of Science* allows for a systematic approach to the search that allows conclusions to be based on a standardised procedure and the highest quality of evidence. However, because it is known that much of the important scientific work on the subject in Australia remains in technical reports and other grey literature, a search with the same approach described for *Web of Science* was conducted on *Google Scholar*. *Google Scholar* includes different types of sources, such as conference proceedings, books and technical reports, not all of which are included in *Web of Science*. *Google Scholar,* however, is not human-curated (unlike *Web of Science*) and has variable content meaning that the search results are not necessarily reproducible or systematic. In addition to these searches, all APPEA members, authors and stakeholders with known commissioned work in the area were contacted and invited to contribute grey literature reports on the subject to this review.

All documents were evaluated for relevance to the topic and scientific rigor, and included if they met the conditions in Table 1.

Table 1. Conditions for inclusion of published papers and grey literature in this synthesis

Conditions
The document was of scientific content (not personal perspectives).
The document consisted of research on underwater noise impacts on marine fauna.
The underwater noise in the research was from a source type used during oil & gas industry operations.
The fauna featured in the research work spend a significant amount of their lives underwater in marine environments.
The document was published in the English language.
The research was conducted in Australian state or commonwealth waters.

Works in the grey literature are not necessarily peer-reviewed and quality varies. These works may have not yet been published or may not be comprehensive enough to constitute a journal publication, but if the science is sound they can contribute information to current knowledge. For this reason an appraisal of each was made based on the following criteria:

- The experimental design was consistent with high-quality science.
- Appropriate measurements and metrics were used to answer the science questions.
- Conclusions were within the bounds of what the sample size could provide.
- Conclusions were qualified according to any unavoidable biases and limitations present in the experimental design.
- Conclusions were within the bounds of the expected measurement error.

Grey literature that met these criteria was included in this review. There are sources of grey literature presented in this review which have been prepared by the review authors. Where these data are presented, short descriptions of methods are included.

The reference list of each article was searched for relevant articles that may have been missed by the search engines. Using the results of the literature search and acquisition, a database with metadata was developed that included author, year produced, article/report title, and journal title or source.

The general approach for searching and reviewing published material and grey literature is illustrated in Figure 2.

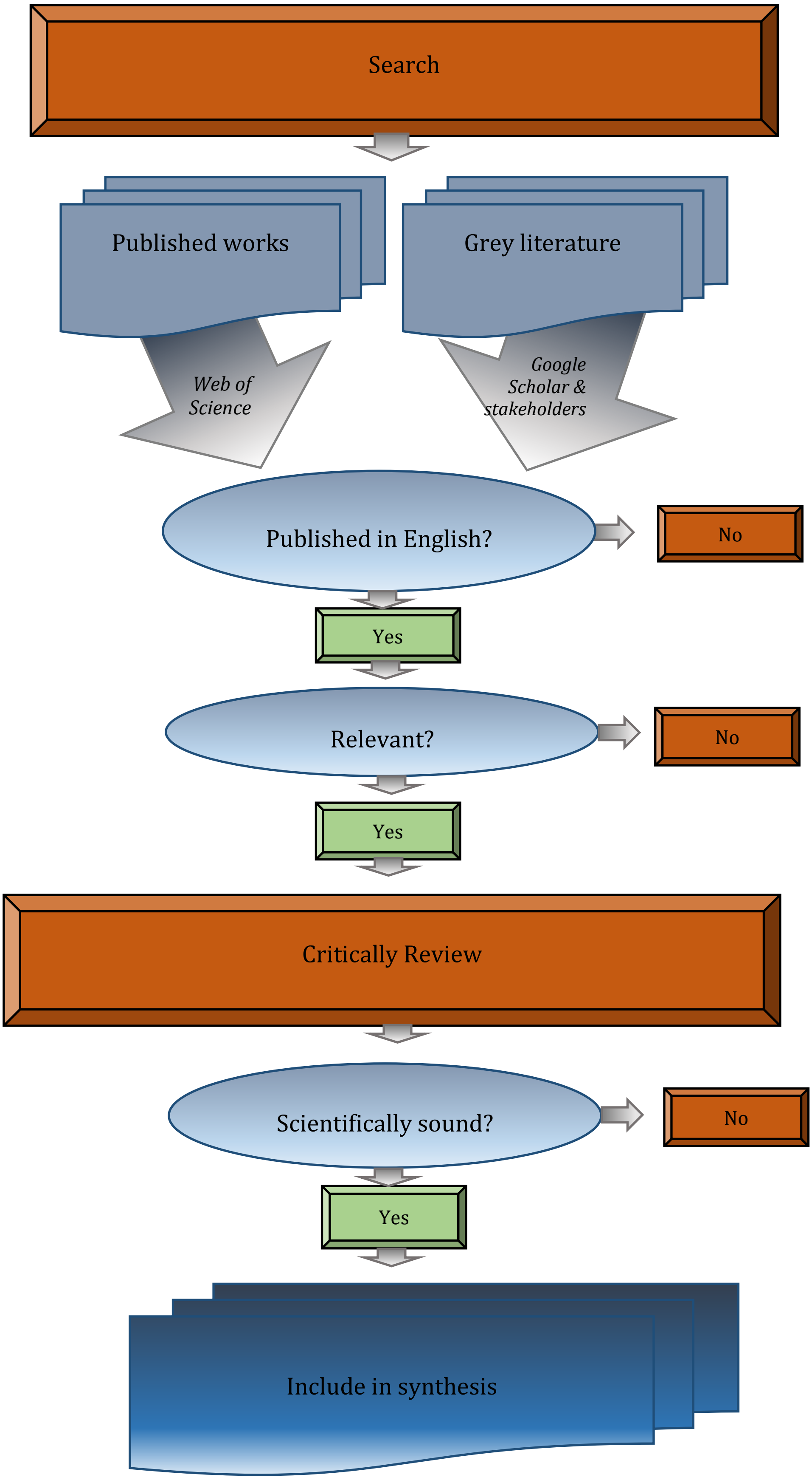


Figure 2. Approach used to select works for inclusion in this synthesis

Works reviewed were allocated a qualitative value from 1 to 4, to give an idea of the relevance to filling knowledge gaps on the effect of underwater noise produced by petroleum activities on marine fauna. The rank was a cumulative score, based on the criteria given in Table 2.

Table 2. Criteria for ranking the relative relevance of work in filling knowledge gaps on the effects of underwater noise produced by petroleum activities)

Criteria	Score
The work addressed a significant knowledge gap at the time it was undertaken relevant to petroleum activities	1
The metrics and exposure type were relevant to petroleum activities	1
The study conclusively identified the level of effects due to underwater noise on the subjects	1
The study can be generalised to the community/population/species targeted in the study	1
Total possible score	**4**

1.4 Report structure

To allow the reader to find relevant sections easily, we have prepared this report in the order described in the box and diagram (Figure 3) below.

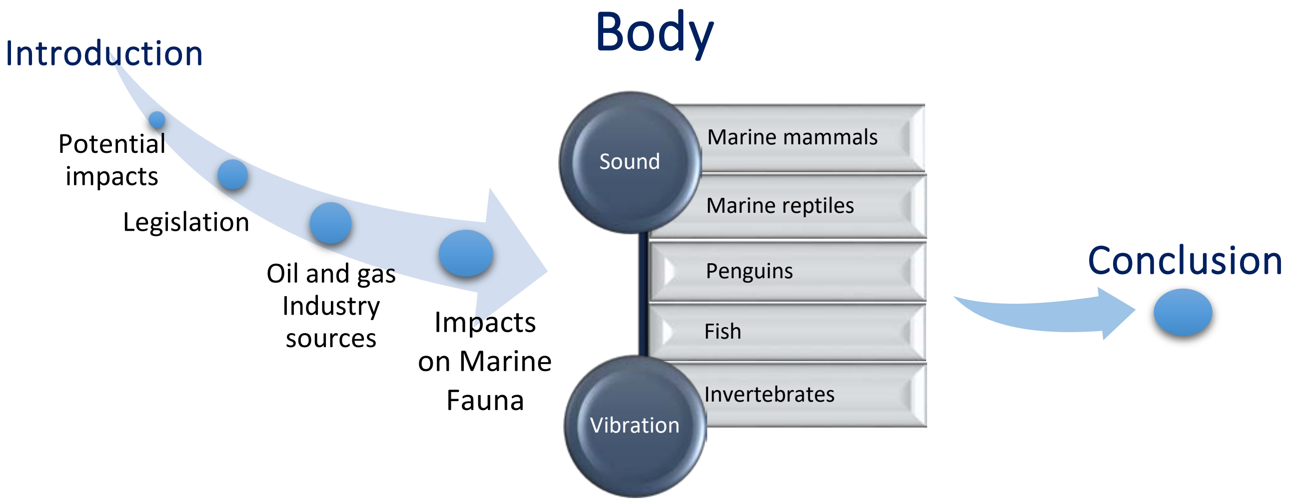


Figure 3. Lay-out and topics in this review

2 Sound and vibration in the marine environment

A review of underwater sound requires definition of the terms used. Before providing those definitions, it is necessary to explain the usage of the main terms used in this report – sound, noise and vibration.

Sound is often referred to as noise. Usually, it is referred to as noise when it is unwanted. For the purposes of this report, 'noise' is used to refer to sound from human activities as it is considered unwanted from the perspective of the marine fauna in the area. Vibration, in this report, refers to the oscillatory motion of particles. Sound, noise and vibration are explained more fully in the following sections.

2.1 Definition and measurement of sound and vibration

The nature, or characteristics, of sound and vibration produced by different sources varies widely. Further, sound and vibration – while closely related – are not the same. The term vibration is commonly used to refer to the oscillation of something (Figure 4) and is literally the mechanical oscillation of a particle from a neutral to a positive, then negative, and back to neutral position. When this oscillation repeats itself, the particles are said to be vibrating. For example, if you sing your vocal chords will vibrate. This vibration will be transmitted to the air molecules next to the vocal chords and cause them to vibrate, then they will push on nearby air molecules causing them to vibrate, and so on. From this vibration, there will be a pressure wave formed of alternating compression and rarefaction (Figure 5). This pressure wave is sound. The result of vibrating vocal chords is a sound wave travelling up your throat, out through your mouth, and spreading out through the room (Figure 5). If there is someone else in the room, these vibrating air molecules will cause their ear drums to vibrate and they will hear your song. Any vibrating object that is in contact with a fluid will generate a sound wave in the fluid in a similar way. The fluid in which the sound wave is travelling is the 'medium'.

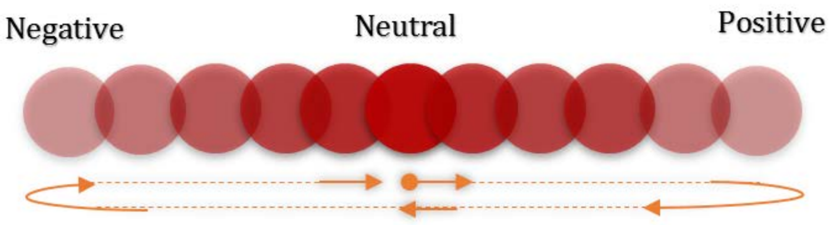


Figure 4. Vibration of a single particle shown as a mechanical oscillation from a neutral to a positive position, back to the neutral position, through to a negative position, and finally back to a neutral position

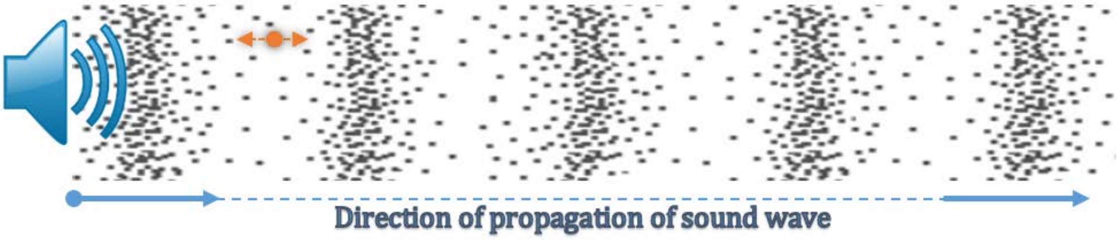


Figure 5. A sound wave produced by the oscillation of particles, with a single oscillating (vibrating) particle shown in orange

How sound and vibration travel through a medium depends on the medium's physical properties. Air and water, for example, are so different that the sound speed in water is about 4.4 times that in air. Sound speed can also vary within a medium if its physical properties vary spatially, resulting in bending of the sound through a process called refraction. This effect is often significant in the ocean because sound speed is a function of depth below the sea surface. For example, in the deep ocean there tends to be a minimum in the sound speed at a depth of about 1000 m at low latitudes (near the equator), rising in the water column towards high latitudes (polar regions). This gives rise to the formation of a duct, which can transmit sound energy over a limited frequency band across ocean-scale distances. In the deep ocean a near-horizontally travelling sound wave will be bent back towards the sound speed minimum after it passes through the duct axis, resulting in trapped waves that do not interact with the sea surface or seabed. Over a certain band of frequencies, <100 Hz, absorption of sound is minimal, thus these frequencies trapped in this duct can carry for ocean-scale distances, suffering loss only by two-dimensional spreading. The resulting sound channel is known as the Deep Sound Channel or SOFAR channel (Urick 1983). It must be noted that the deep sound channel only occurs in the deep ocean, and does not exist in Arctic or Antarctic waters. Thus, this type of long-range sound transmission does not occur in continental shelf waters (typically less than 200 m deep). Over the continental slopes that form the offshore edges of the continental shelves the situation is more complicated, with the downward sloping seabed often directing sound into the Deep Sound Channel further offshore.

Abrupt changes in medium properties can result in sound being reflected in the same way light reflects from a mirror. At the sea surface, where the air meets the water, the acoustic mismatch is large and the sea surface behaves as a highly effective reflector of sound (Urick 1983), with very little sound transmission across the air-water boundary. For airborne sound, transmission is limited to incidence angles of <13 degrees from the vertical. At greater angles, total reflection occurs. At high frequencies (>1 kHz), scattering of sound by a rough sea surface occurs.

In the ocean, it is common for the acoustic properties of the upper (often unconsolidated) seabed to be quite similar to those of the water, resulting in some sound being transmitted into the seabed, and some being reflected back into the ocean. The relative amounts of transmission and reflection can strongly influence how far sound travels in shallow water, especially at low frequencies. As such, knowledge of seabed properties in the area of interest is essential for accurately predicting sound propagation and received sound levels. Because of the complexity of sound transmission in the ocean, sound propagation in a given environment cannot be applied to different environments, unless the two can be considered equivalent. For example, the transmission of sound from surveys for oil and gas reserves (using airguns, see Section 5.2) will vastly differ when operated in Bass Strait (between Tasmania and mainland Australia) along the shelf slope than in shelf waters of Western Australia or in the Joseph Bonaparte Gulf (in north-western Australia). For low-frequency sound sources such as from oil and gas reserve surveys, it is usually necessary to use numerical models that take into account the full complexity of acoustic wave propagation. However, simpler methods analogous to ray tracing methods often used for light can deal adequately with high-frequency sources such as sonars.

Sound in water is most easily detected and measured by the pressure fluctuations resulting from the vibration of the water molecules, which take the form of alternating compressions and rarefactions. These compressions and rarefactions are detected by a receiver, such as a hydrophone (underwater microphone), that converts them to an electrical signal. Marine animals have evolved a variety of sensing organs for sound and vibration, some responding to pressure and others directly sensing the motion of water molecules (Raven and Johnson 2001). Almost all sensory organs used by marine fauna rely on structures that effectively function as transducers, converting mechanical energy from sound waves to electrical signals interpreted by the central nervous system.

To describe sound pressure in a meaningful way that corresponds to how humans and animals perceive sound, some measure of the pressure fluctuations is usually converted to a logarithmic scale called the decibel (dB). These logarithmic quantities are called 'sound levels'. The logarithmic scale is chosen to reduce the scale of measured pressure values detectable by animal hearing systems to a smaller range. The decibel unit requires a reference value as it is a ratio of a measured value to the reference value. The choice of the particular reference pressure measure determines what the corresponding sound level is called and its units. It is very important that the units be stated explicitly to avoid confusion. Table 3 provides a summary of some common choices.

Table 3. Common sound pressure measures and their corresponding sound level quantities and units

Pressure measure	**Logarithmic (sound level) quantity**	**Units of sound level**
Peak (maximum)	Peak sound pressure level (SPL_{Pk})	dB re 1 μPa peak
Peak-to-peak (maximum minus minimum)	Peak-to-peak sound pressure level (SPL_{p-p})	dB re 1 μPa p-p
Root mean square	Rms sound pressure level (SPL)	dB re 1 μPa rms
Integrated squared pressure (sound exposure)	Sound exposure level (SEL)	dB re 1 $\mu Pa^2.s$

Sound pressure quantities are useful for different purposes. For example, continuous sources of sound are best described by the rms sound pressure level, whereas pulsed sounds are better described by their sound exposure level, peak sound pressure level and/or peak-to-peak sound pressure level. Pulsed sounds are broadband, brief, transient sounds that have a rapid rise time in pressure (Harris 1991). These include seismic airgun signals and pile driving (Figure 6). Non-pulsed sounds such as continuous or intermittent sounds can be broadband and/or tonal, and do not have the rapid rise time in pressure that pulsed sounds have. Examples of non-pulsed sounds are those produced by dredging and vessels (Figure 6). Further information can be found in Appendix A.

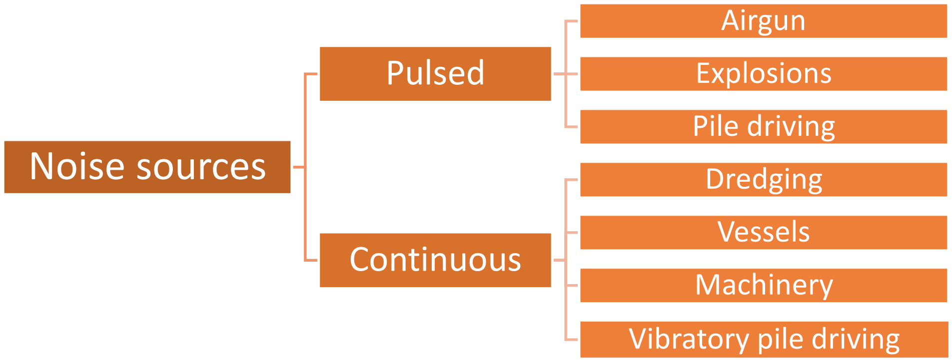


Figure 6. Examples of sources of pulsed and continuous noise from human activities

Unlike sound, vibration is generally measured in terms of particle motion. Quantities measured typically include velocity in metres per second, and acceleration in metres per second squared. Common equipment includes ‘geophones’, which convert particle velocity into an electrical signal, and accelerometers, which measure particle acceleration.

2.2 Sources of sound and vibration

The ocean is a naturally noisy environment. This is because there are a wide variety of sources of sound and vibration in marine systems (Figure 7), the transmission of sound is generally good in the ocean, and the range at which sound can be detected is often large. However, the range sound travels depends upon the environment. The Southern Ocean, for example, has relatively little sound from human activity, but has markedly high noise levels from high natural background noise transmitted over long distances. In contrast, on the continental shelf of Australia adjacent to the Southern Ocean, distances at which sounds from particular sources transmit are shorter than in the Southern Ocean itself, hence the ocean there is relatively quiet (McCauley et al. 2015). Natural sounds can be broken down into physical sources such as wave activity, rain and earthquakes, and biological sources such as fauna that produce sound. Animals in the ocean that produce sound include many invertebrates, fish and marine mammals.

There are many sources of sound and vibration produced during human activities. Man-made sources of sound and vibration in the ocean include those produced during human activities in the water, on the land, or in the air, which transmit into the ocean (Figure 7). Sometimes, sound generation during the activities is deliberate and is a necessary part of these activities. Examples include imaging sound sources (as used in seismic surveys), sonars (e.g. for pipeline route surveys) and communication and positioning systems. In other cases, sound and vibration are unwanted byproducts of the activity. Noise and vibration from pile driving, support ships and drilling are examples of such cases.

The combination of sound from all of these sources – physical, biological, and man-made – is what makes up the underwater sound environment (or 'soundscape'; Figure 7).

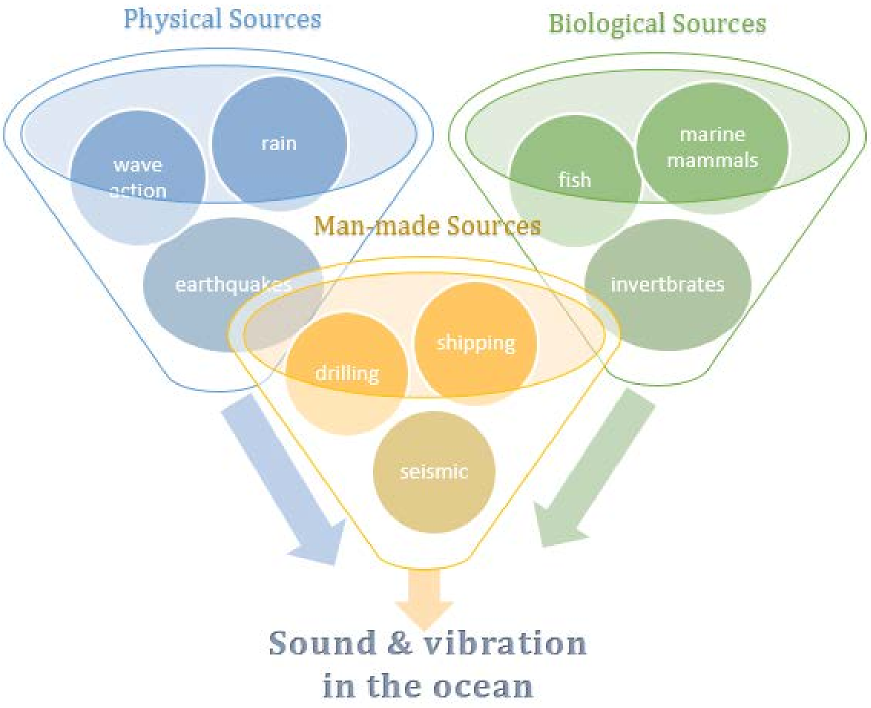


Figure 7. Examples of physical, biological and man-made sources of sound and vibration in the ocean

2.3 Marine faunal sensory systems

Sound and vibration play a significant role in marine animal sensory processes. In fact, they largely replace visual cues, which are greatly limited in the ocean. Sound is routinely used by most marine animals for communication and sensing the environment. For example, many marine mammals use biosonar (echolocation) to navigate and capture prey, or may vocalise to communicate with others of the same species (conspecifics). Many species of fish aggregate for reproduction and broadcast their locations by creating choruses where large numbers of individuals vocalise simultaneously. Fish choruses can be heard many kilometres to many tens of kilometres away, and can be orders of magnitude greater than the range of an individual fish call (McCauley 2001). Some baleen whale species produce complex songs thought to have a reproductive role (Clapham 1996). Given the right conditions, whale song can be transmitted distances of tens to hundreds of kilometres or more. Marine animals able to hear or sense sounds that their predators produce use detection of these sounds to avoid predation. While some invertebrates (such as cephalopods) may detect waterborne sound, benthic invertebrates such as many crustaceans may be 'coupled' to the bottom of the ocean and detect vibrations and sound transmitted through the seabed. Marine animals potentially also use the overall soundscape to gather relevant environmental information. For instance by sensing ambient noise, a marine animal could conceivably gather information on wind conditions, sea state, nearby biota, the local bathymetry or even long-range events such as ice calving in polar regions.

If an animal can sense sound or vibration it is said to be ‘sensitive’ to it. In regard to the effects of noise and vibration on fauna, sensitivity can have one of two meanings. Sensitivity in the context of sensory organs – such as the ears in mammals – describes the physiological ability to perceive sound and vibration. Alternatively, sensitivity can be used to describe an animal’s tendency to react to sound. For the purposes of this report, sensitivity is used to refer to an animal’s physiological ability to perceive sound and vibration.

Most (if not all) marine fauna are sensitive at some level to sound and/or vibration, and have evolved a diverse range of sensory organs to perceive them (Figure 8). Some animals have evolved systems that are sensitive to particle motion, others to sound pressure, and others to both. Sensory organs for detecting sound and vibration range in complexity, depending upon the required functionality for survival and reproduction of the animal. Some of these sense organs may have additional functions, such as angular detection and body orientation.

The simplest of these structures are mechanoreceptors, evolved to detect mechanical energy associated with vibration, sound pressure, gravity, touch, hydrodynamic flow and/or movement. A diversity of mechanoreceptors exist in marine invertebrates. For instance, crustaceans have cuticular mechanoreceptors called sensory hairs covering much of their bodies. When exposed to vibrations, these cells stimulate the underlying nerve cells and, ultimately, the nervous system (Ehrlich 2010). Many crustaceans and cephalopods also have mechanoreceptors called statocysts. Statocysts are another type of sensory cell known to function in maintaining an animal’s position in the water column, and are thought to detect the particle motion component of sound. Mechanoreceptors known as chordotonal organs tend to be associated with animals with jointed legs or antennae, such as those of crustaceans. When located on appendages that are coupled to the seabed (e.g. legs), vibrations through the seabed can be detected (Meurant 1982). The mechanoreceptors described above are only a few of the diverse structures invertebrates have evolved.

Fish have a range of sensory mechanisms that can detect sound and vibration, including free-standing neuromasts, lateral line systems, and otoliths (or ‘ears’; Popper and Platt 1993). Free-standing neuromasts are found along the length of the body and contain sensory cells that operate as mechanoreceptors. In many fish, neuromasts also occur below the skin of their heads and in lateral lines running along their sides. Lateral lines are systems of fluid-filled canals designed for water to be channelled through, and are open to the surrounding environment through a series of pores. These systems and associated free-standing neuromasts mainly function to sense vibration, hydrodynamic flow, direction and nearby movement. They do this by forming maps within the brain based on the amplitude and direction of water flow signals at different locations along the body.

Fish also have ears consisting of dense calcareous masses (otoliths) and associated sensory tissue. Three otoliths are laterally paired on each side of the head, with one on each side often much larger than the other two. The otoliths have a groove along their length, which are coupled to sensory epithelia containing hair cells by a gelatinous material. The sensory hair cells sit within the groove of the otolith. Sound pressure travels almost unchanged through the soft tissue of fish – which has very similar acoustic density as water – to the otoliths. When a sound wave reaches the sensory epithelia and the otolith, these move with different phases and at different rates, since the stone is much denser than the epithelia, which has a similar density to water. The sound wave causes the hair cells to deflect resulting in nervous signals sent to the brain that are interpreted as sound. Through this complex system, fish are able to obtain considerable information about sound, including the direction it originates from. Some fish species have swim bladders that are physically coupled to the ears, allowing them greater hearing sensitivity and frequency range. When pressure on the swimbladder fluctuates, the energy is transferred the otolith and sensory epithelia arrangement.

Marine reptiles' main sensory systems are their ears. They do not have outer ears (pinnae). In sea turtles, sound and vibration is thought to be mainly conducted through a fatty tissue located between the skin and bone on the sides of the head (Thewissen and Nummela 2008). This fatty, fibrous tissue extends also to a structure surrounded by bone located at the middle ear called the extracolumella, which serves as a kind of eardrum (Ridgway et al. 1969). Sound and vibration are conducted through this fatty tissue, causing the extracolumella to vibrate (Ketten et al. 1999). The vibration is transmitted further inward through a connected shaft composed of a longitudinally, free-moving thin rod of bone (called the columella or stapes). The columella transmits the energy to an opening covered by a membrane which leads to the inner ear called the oval window. The energy is transferred through the oval window into the inner ear, and into a cavity called the cochlea. Within the cochlea (which is not elongated and coiled as in mammals), sensory hair cells transform the mechanical energy of sound waves into electrical signals that stimulate the auditory nerve (Ridgway et al. 1969).

In contrast to sea turtles, sea snakes do not have fatty tissue that conducts energy to the middle ear, rather the middle ear bone is connected to the jaw bones. This allows vibration and sound energy to be transmitted through the jaw to the inner ear. As in sea turtles, sea snakes also have cochleae with sensory cells to covert mechanical energy to electrical signals.

Of the Australian marine reptiles, only crocodiles have slits and canals leading to the inner ears. The canals are protected by flaps of skin that close when they are underwater. Crocodiles are the only marine reptile in Australia that is structurally adapted for detecting sound in air, based on the similarities to avian (bird) ear morphology and the structure responsible for transmitting the information to the brain (auditory brainstem structures; Gleich and Manley 2000).

As for reptiles, birds do not have outer ears but do have ear canals to channel sound waves. Penguins are no different to other birds. They have middle ears composed of a tympanic membrane (the eardrum) that conducts sound and vibration to the columella and through to the inner ear. The inner ear has a cochlea that functions as it does in reptiles; and like in reptiles, the cochlea is not coiled as it is in marine mammals.

Marine mammals have some of the most highly developed systems for detecting underwater sound. These animals have external ears that sometimes have outer flaps (e.g. in sea lions), adapted for both airborne and waterborne hearing. Some marine mammals, such as cetaceans (dolphins and whales), have small redundant ear holes located just behind the eyes. While the ear holes are not functional, the physiology and morphology of the ears are adapted for underwater hearing. Baleen whales have a wax ear plug with a density similar to water that transmits waterborne sound to the inner ears, but sound also transmits through the body to the inner ear. In toothed whales, sound is conducted through the bones of the skull and fatty tissue running along the lower jaw to the inner ear. The middle and inner ear is fused into the tympano-periotic complex, and is the densest bone in a whale's body. The middle ear is composed of the malleus, incus, and stapes (Perrin *et al.* 2009). The middle ear surrounds the cochlea in the inner ear, which has the same overall function as it has in terrestrial mammals and humans.

The sensory organs involved in conducting and transmitting sound and vibration described for the taxonomic groups above vary widely. Furthermore, the characteristics of the structures and tissues, such as the thickness, elasticity, rigidity, shape, density and length differ among species. These characteristics ultimately determine the sensitivity of the animals to sound and vibration. Sensitivities vary not only in how high the sound level or force of particle motion needs to be for animals to detect them, but also in the frequencies animals can detect. For example, humans can hear sound between 20 Hz and 20 kHz with greatest sensitivity between 2 and 5 kHz, while some species of fish may hear between 20 Hz and 3 kHz with greatest sensitivity between 200 Hz and 1 kHz. Species that are taxonomically similar often are sensitive to similar frequency ranges, but each species is unique in its hearing sensitivity. In fact, even individuals of the same species vary in their hearing sensitivity. Older animals may have poorer hearing or lower sensitivities at certain frequencies than younger animals due to a longer history of exposure to noise and general senescence.

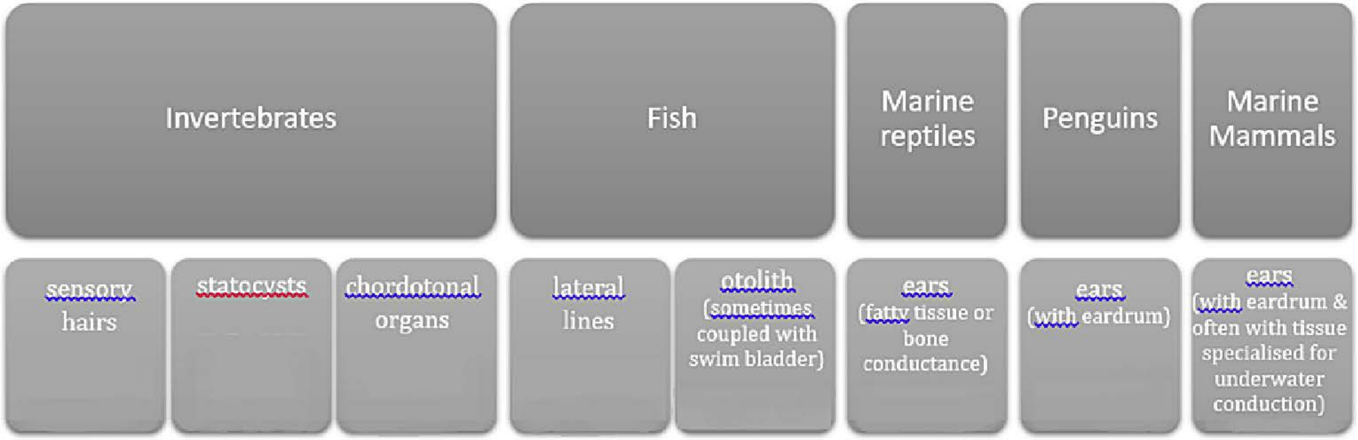
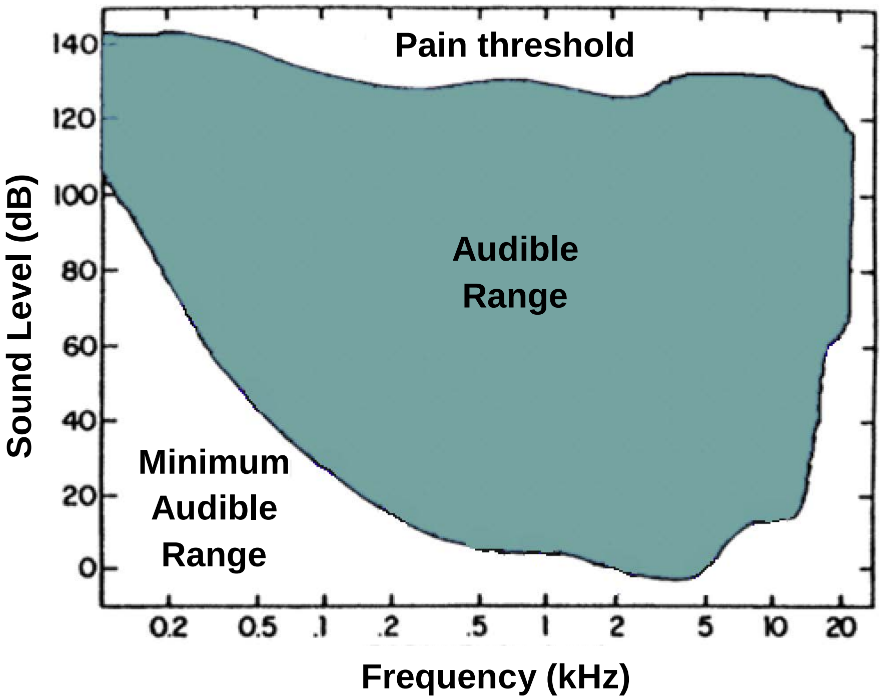


Figure 8. Examples of marine fauna sensory structures for detecting sound and vibration

Despite differences in hearing sensitivity among species, individuals and age classes, all species are the same in that they are more sensitive to some frequencies than others. For instance, for an animal to hear sounds close to the upper or lower frequency limits of its hearing range, it needs to be exposed to a higher sound level than sounds closer to the middle of its frequency ranges. This means that animals are less sensitive to sounds approaching the limits of their hearing range. Hearing sensitivity of animals is generally described by 'audiograms', which are plots of sound levels as a function of frequency usually resembling a 'U' shape (Figure 9). Usually only the baseline curve is plotted to show limits of hearing sensitivity, but in Figure 9 the point at which pain begins to be felt by humans (the threshold of pain) is shown, which is at very high audible levels. There are no data on pain thresholds in marine animals.



Source: modified from http://www.d.umn.edu/~jfitzake/Lectures/MedSchool/InnerEarPhysiology/ConductiveHearingLoss/SPLAudiogram.htm)

Figure 9. Human audiogram (dB relative to absolute reference level)

In humans, this can be obtained through hearing tests, where sounds are played to a subject at a range of frequencies at levels close to the expected hearing threshold. Each sound is played one at a time, and each time the subject indicates whether they have heard the sound. If they have, the level is adjusted, and played again, until the threshold is found. For this approach to work for animals, subjects need to be in captivity and trained to respond in a certain way as confirmation that a sound has been heard. For many animals, training captive animals is not feasible. Either they cannot be trained or cannot be kept in captivity (e.g. they are too large or require high pressure because of the deep water they inhabit). An alternative methods of obtaining audiograms includes measuring the auditory brain stem response (ABR) to sounds, using electrodes placed on the skin of the head. To accurately measure auditory evoked potentials from electrical activity in the brain using electrodes, they must be located at a place without excessive movement of the animal which would disrupt the measurement. When ABR is not possible or practical, the only last option is to obtain an approximation of hearing sensitivity through biomechanical and structural modelling of the auditory system anatomy. This is done through computerized tomography (CT and MRI), dissections, and histology of the head of carcasses (Yamato et al. 2008). From these results, the hearing sensitivity can be estimated (modelled).

3 Potential impacts of sound and vibration

Marine fauna that have evolved to sense sound and vibration in the marine environment are also susceptible to impacts (negative effects) from sound and vibration produced by human activities. Prolonged exposure to high levels of noise can cause physical damage to the sensory organ and noise-induced hearing loss. This hearing loss can result from intense sound exposure over a brief period, or from ongoing exposure at lower levels. Other impacts may also be experienced, such as changes in physiology associated with stress. If the exposure is intense enough, it is thought that resonance of air spaces in organs or dissolved nitrogen gas bubble growth within tissues can result in ruptured tissues or organs. The potential impacts resulting from exposure to sound and vibration depend directly on the characteristics (intensity, level, duration, frequency, etc.) of the sound as well as the animal's physiology and morphology.

Based on research on impacts of sound on animals, a range of possible direct effects have been grouped according to the type and severity (bearing in mind that no effect is also possible). The range of effects include: masking of sounds animals produce for communication and navigation, or which are biologically important cues for their survival and function; changes in behaviour that can affect energetics, such as group cohesion, displacement, attraction or avoidance; physiological stress-related responses; and in more extreme situations, hearing impairment or non-hearing related physiological injury.

Each of the direct effects shown in are described in detail in the boxes that follow. Indirect effects, such as impacts on an animal's prey, can also occur but are not discussed here.

1. Masking

If man-made noise is sufficiently high in level and similar in frequency and timing to a signal of interest, it has the potential to 'mask' that signal (e.g. Erbe and Farmer 1998). Masking occurs when the perception of one sound is affected by the presence of another. So, in the case of an animal receiving a communication sound from another animal of the same species (a conspecific), the intensity of the communication sound would need to be increased for it be detectable above the masking noise. The amount of masking is the difference in detection threshold between the scenarios where the masker is absent versus present. An individual's susceptibility to masking can be expressed as the ratio of the intensity of a [tonal] signal to the power spectral density of [broadband] masking noise centred on the frequency of the signal, when the signal is just detectable in the noise, and is called the critical ratio (e.g. Johnson 1968). Critical ratios vary among species and depend on frequency. Low critical ratios imply better hearing ability in noise.

In assessing the level of masking caused by a noise other factors must also be considered, such as the temporal variability of signal and noise. If the noise is intermittent and the signal is long enough in duration to last into or through the noise gap, then only part of the signal will be masked, and in many cases the signal might be recognisable from the bits that emerge through the gaps in the noise (Erbe 2008). There are masking release mechanisms such as a spatial release from masking, where an animal's directional hearing capabilities aid signal detection if signal and noise arrive from different directions (e.g. Holt and Schusterman 2007). Comodulation masking release occurs when noise is comodulated in amplitude across multiple frequency bands and an animal can correlate the received energy across multiple bands to detect changes in the masked band (e.g. Branstetter and Finneran 2008). In addition, in the case of animal communication, the caller can actively reduce the likelihood of masking by calling louder, shifting frequencies outside of the band of maximum noise, or repeating the signal. Such responses are collectively known as the Lombard Effect.

The biological significance of masking is unknown at this stage. Masking can interfere with important communications between conspecifics, such as related to mating or nursing. Toothed whales (odontocetes) are equipped with a biosonar system that emits echolocation clicks to navigate and hunt for prey, and high-frequency noise can interfere with these typically high-frequency echolocation clicks. Invertebrates, on the other hand, may use sound directly from the environment as a trigger to move to the next lifecycle stage. For instance, the sound from coral reefs may be a necessary cue for larval settlement (Radford *et al.* 2007). If these sounds are masked, animals may not respond to their environment effectively.

Assessing the potential for masking in animals is complicated and for most species is nearly impossible to do with an acceptable level of uncertainty. A review of what considerations need to be made in assessing masking in marine mammals is given by Erbe et al. (2016b). Examples of how masking can be conceptualised and how zones of masking in the wild can be illustrated are given by Erbe (2015).

2. Behavioural response

Behavioural responses are varied and can include changes in: swim speeds or direction; diving and surfacing frequency and duration (for animals that rise to the surface of the water to breathe, for example); breathing rates; vocalisation behaviour; activities such as foraging, mating, resting or socialising; the frequency and/or duration of vigilant and/or defensive behaviours; and moving toward or away from a sound source. Behavioural responses can range from a brief change in behaviour to a longer lasting change in a sub-population or population of a species. Changes in behaviour can be beneficial when used to mitigate the potential effects of underwater noise, they can be detrimental if they deteriorate the function and survival of an animal or species, or they may be inconsequential and fit into an animal's normal tolerance zone. For instance, a temporary movement away from a noise at close range causing significant stress to an animal would likely be beneficial for that individual. Conversely, the movement of a vulnerable animal away from a key foraging ground over an extended period could be detrimental to the health and survival of that animal.

The direct behavioural response of an animal or group of animals to noise depends on many factors. Firstly, to respond to a noise, an animal (or group) needs to perceive the noise. The response will likely vary with the level, characteristics, and duration of the noise. Behavioural responses will also be influenced by the animals' prior experience with the noise. For example, prior habituation or sensitization to the noise can result in a lesser or greater response than might normally occur, depending on the nature of the previous experiences. The behavioural state and life stage of an animal or group of animals is also important. As an example, if undernourished foraging animals are habituated to a noise, they may not stop foraging upon re-exposure to the same noise since their motivation to feed may be greater than their motivation to respond. Alternatively, if animals are resting and have not had previous experiences or had negative experiences with the noise, they may be more likely to interpret it as a threat and respond. Younger animals may be more curious, while older animals may be more cautious. Individuals that are at their energetic limit with young to care for may be less likely to move away from an acoustic stressor than strong, healthy solitary individuals if the area has an abundant food source.

Changes in behaviour can also be a secondary response to the primary effect from a noise. Let's say masking is the primary effect. Animals may change their vocal behaviour to try to overcome the effects of masking. For instance, they may increase the intensity of the sounds they produce, or shift the frequencies and/or repetition rates of their vocalisations. Conversely, there may be a lack of response in cases where there normally would be a response (such as moving away from a potential threat). The latter scenario could also occur where an animal has had a temporary or permanent loss of hearing (a threshold shift) as a primary effect. Behavioural response can be the first effect experienced by an animal or group of animals, but would most likely be proceeded by stress (as the first response).

3. Threshold shift and auditory hearing damage (TTS/PTS)

At sufficiently high doses, sound can cause fatigue of the hair cells in the inner ear or cause the brain to 'turn down' the intensity of signal perception. Fatigue causes a decrease in the sensitivity in an animal's hearing, meaning that the threshold of hearing shifts. A threshold shift can also be caused by a structural disarrangement of the neuronal endings of the hair cells. The effect can be temporary or permanent. An example of a temporary threshold shift (TTS) is when humans attend a loud concert and experience 'partial deafness' for several hours afterwards. Permanent threshold shift (PTS) occurs when there has been permanent damage to the hair cells or their attached neurons and hearing does not return to normal function. There have also been cases of gross damage to and around the auditory structure of marine mammals, including haemorrhages in the ears. However, there has been no conclusive evidence that the damage has been from direct acute acoustic exposure (Ketten 2005).

While TTS has been traditionally considered as reversible damage, there has been relatively recent work showing that moderate to high levels (up to 40 dB) of TTS in terrestrial animals can result in degeneration of the cochlear nerves (Kujawa and Liberman 2006, 2009). If the same is true for marine animals, this means that even if hearing threshold shifts from noise exposure were temporary, if TTS were from moderate to high level exposure then permanent damage via nerve degradation may occur.

Noise exposure criteria for regulatory purposes in many countries are based on the levels of noise that are expected to cause injury (auditory and non-auditory). Historically, injury has been based on levels causing PTS. However, as new research is undertaken, if moderate TTS is observed to cause permanent damage in marine fauna, then whether TTS should fall within the definition of auditory injury would need reconsideration. For the practical purpose of assessing the potential for TTS and PTS for marine mammals, species are assigned to one of five groups based on their 'functional hearing' – that is, their ability to hear sound at different frequency ranges. These 'functional hearing' groups are low-frequency cetaceans (LF, baleen whales), mid-frequency cetaceans (MF, such as dolphins), high-frequency cetaceans (HF, such as porpoises), and pinnipeds (seals) in air and underwater (Southall *et al*. 2007). Recently, the number of groups has been extended to nine to include marine turtles. The pinnipeds have been split into eared seals (otariids) and true seals (phocids) in air and in water, and sirenids (dugongs and manatees) and turtles have been categorised as a separate functional hearing group.

Auditory weighting functions have been proposed for marine mammals, specifically associated with PTS acoustic threshold levels expressed in the cumulative sound exposure level metric (NOAA 2015). Currently, comparable auditory weighting functions have been developed for marine species. These functions are employed to account for the differential auditory sensitivity in marine species to sound. By emphasizing the sound received at frequencies of good hearing sensitivity as compared to de-emphasizing the sound pressure levels at frequencies of low hearing sensitivity, this approach compensates for the difference in hearing sensitivity across a subject's entire functional frequency range. Ideally, these functions should be based on experimental data describing the onset of TTS or PTS for a range of exposure frequencies, species and individual subjects within each functional hearing group.

The level of TTS and PTS also depends on the characteristics, duration and frequency (duty cycle) of the noise received. The characteristics include the noise level, rise time, and spectrum. While TTS has been measured for some animals for certain sounds, PTS has not. PTS is sometimes estimated using information on levels causing TTS.

4. Physiological response

A physiological response is a change of a physiological attribute within an organism. For example noise can induce stress, causing the release of the hormone adrenalin, which increases heart rate, gas exchange and blood flow to the brain and muscles for a fight-or-flight response. Stress responses are intended to increase the probability of survival from an immediate threat but prolonged or repeated stress responses can be deleterious to health. For example, chronic stress in humans can cause coronary disease, immune problems, anxiety, depression, cognitive and learning difficulties, and infertility. Long-term effects can also occur to the neuroendocrine system, development, metabolism, cognition and sleep, and even DNA integrity (Knight and Swaddle 2011). Studies on reproduction have correlated environmental noise with premature births (American Academy of Paediatrics Committee on Environmental Health 1997). Other studies have shown that pregnant rats exposed to elevated levels of environmental noise had greater developmental instability (Møller and Swaddle 1998).

Physiological responses may also be secondary to a primary response to noise. For instance, stress might occur as a result of behavioural disturbance or masking. As an example, animals spending less time undertaking other fundamental activities such as foraging or spawning as a behavioural response to noise may experience weight loss and deterioration in condition (Anderson *et al*. 2011; Purser and Radford 2011).

Physiological responses can vary depending upon sensitisation, habituation, hearing sensitivity, and health, age, and behavioural context of the animals, among other factors. Physiological responses can commence when the noise is first audible, or may occur when the noise level is much greater and already causing masking, threshold shifts or tissue damage.

5. Organ and non-auditory tissue damage

More severe damage can occur as a result of high noise levels, particularly from signals with a very short rise time in energy received. In the case of intense impulse signals, the ability to cause physiological damage may be exacerbated if sound transmission phenomena cause a phase-inverted pulse to follow immediately after the impulse signal, as happens with a surface bounce. A large positive amplitude impulse will cause gas spaces to rapidly contract. If a sufficiently large amplitude negative pulse follows the contraction in a short enough time, the gas space can overexpand and rupture tissue or even bones.

Organ or tissue damage can also occur as a secondary response. For instance, noise may cause a behavioural response such as a rapid rise from a dive, which has the potential to cause other physiological effects. Alternatively, an animal may respond to a noise and in doing so may move directly in the line of some other threat (e.g. a vessel propeller or too shallow water). Mostly, the expected range over which direct organ and non-auditory tissue damage might occur is very close to the source. However, damage as a secondary response can occur at longer ranges.

Some authors have conceptualised the potential impacts resulting from exposure to noise, based on severity of effects and distance from the noise source at which the effects are likely to occur. Most severe effects will occur within close proximity and the least severe effects at long distances from the source, with effects often shown in conceptualised zones (Figure 10). The assumption in such conceptual diagrams is that sound levels increase with increasing proximity to the source. In reality, in most cases, there will be pockets of constructive and destructive interference of sound, disrupting the simplified concept of monotonically decreasing received levels as a function of increasing range from the source. While such diagrams present theoretical scenarios to help readers conceptualise the relative severity of impacts, the zonation will ultimately depend on the characteristics of the sound at its source, how it propagates through the environment, and the sensitivity and responses of individual animals, subpopulations, populations or species.

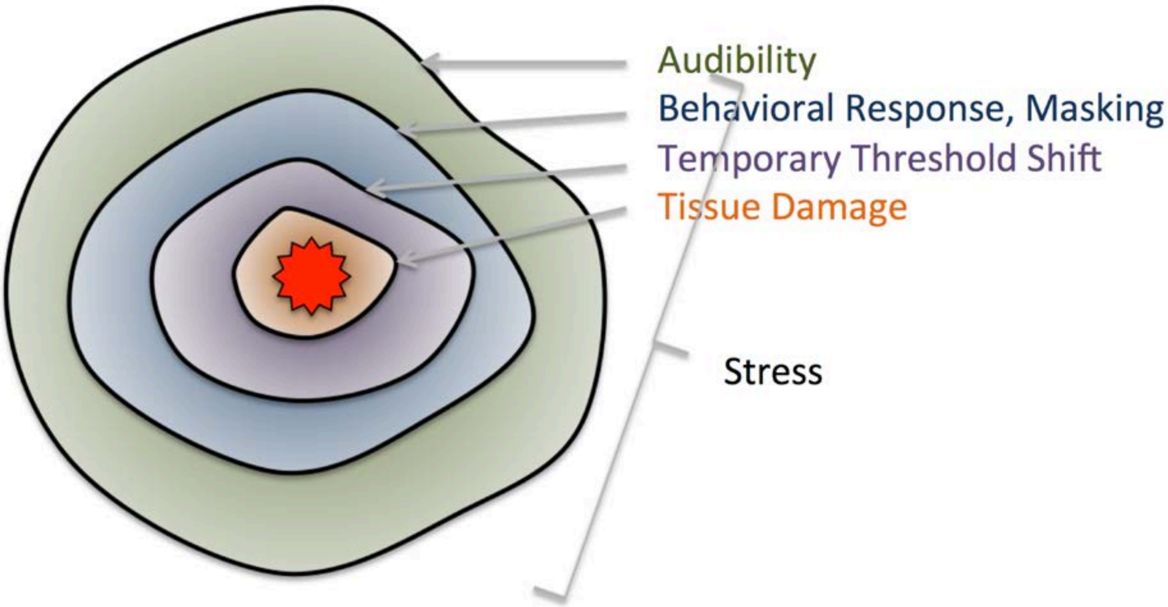


Figure 10. Theoretical zones of impact around a noise source, with stress potentially occurring across all levels of impact

While any one of these effects may be the primary effect, a primary effect may cause cascading effects (Figure 11). For example, animals exposed to noise experiencing stress may change behaviour by moving to different locations where noise levels are lower. Although their stress levels may decrease, the new locations may be sub-optimal habitat. Another example is an animal with noise-induced hearing loss may not respond in fight or flight situations, and hence has an increased risk of mortality. Similarly, if key sounds associated with survival or reproduction are masked, the ability to survive or reproduce may be impaired. As well as cascading effects, primary effects may occur simultaneously. If there are multiple effects, they can potentially impact exposed animals in a synergistic manner.

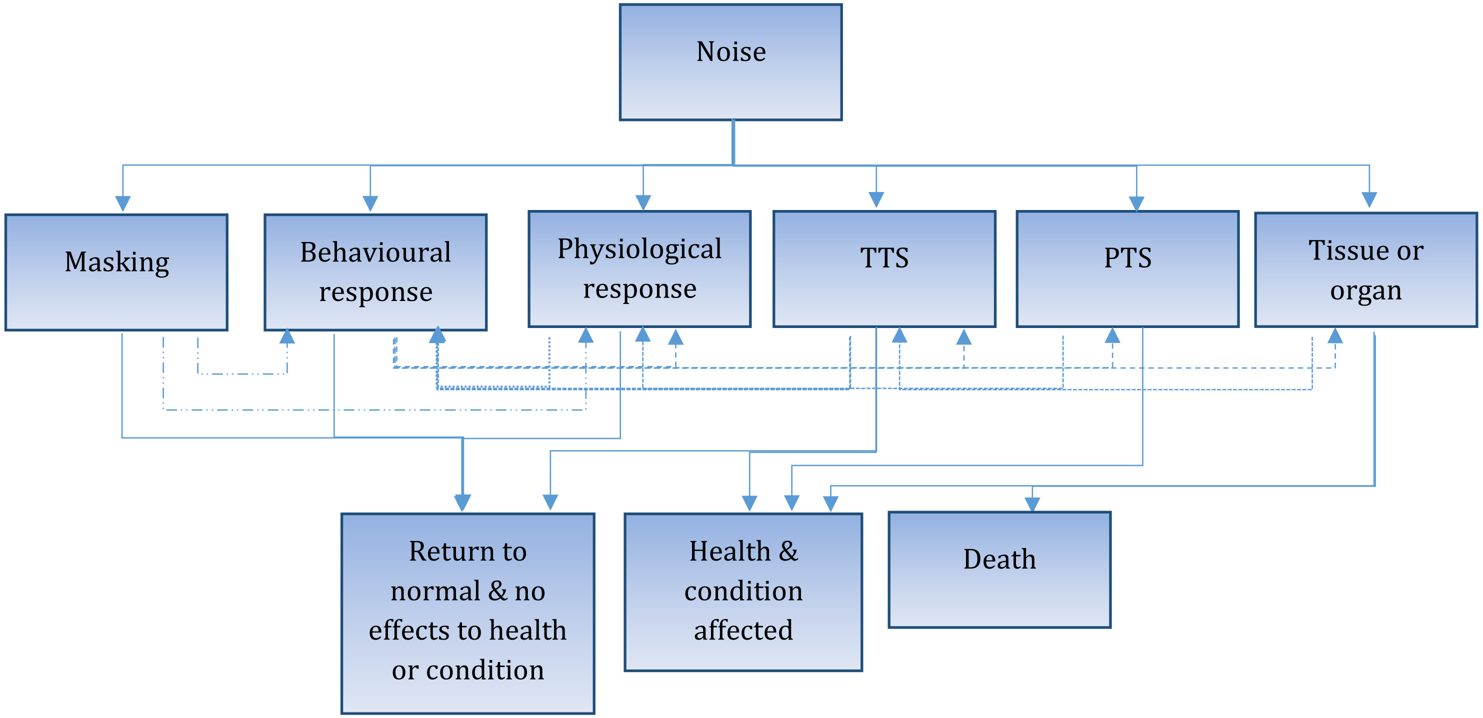


Figure 11 Possible noise exposure impact pathways in marine fauna

By evaluating the primary, cascading and synergistic effects on an individual and on the biota the individual depends upon, an overall impact assessment for the individual can be made. Known impacts at the individual level must then be integrated with knowledge on the behavioural ecology of the species to assess the resulting impacts at the community, subpopulation or population level (Figure 12). That is, how do masking, behavioural changes or physiological responses experienced by individuals affect the community, subpopulation, population or species? What are the reproductive and survival outcomes of a group of animals in which a proportion have been exposed?

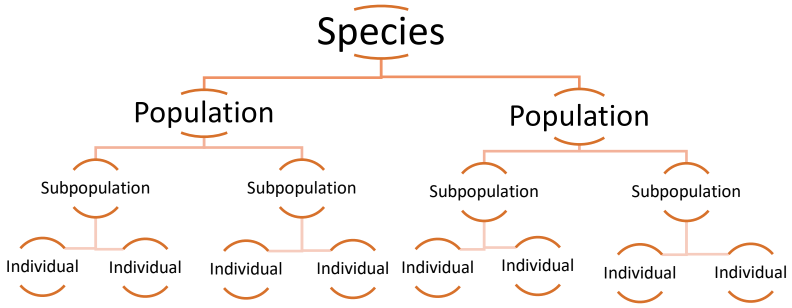


Figure 12. Individual, subpopulation, population, and species levels to be considered in assessing impact severity

Lastly, the long-term cumulative effects of underwater noise on both individual and population levels need to be considered. That is, the effects of exposure to multiple events or to ongoing events need to be known.

4 Regulating the oil and gas industry

Many countries have legislation to control the potential impacts of underwater noise to fauna in the marine environment. Some countries have legislation that applies specific 'do-not-exceed thresholds' across differing species, environments and sound sources (Erbe 2013). Australia uses a conceptual requirement of 'minimising impacts to an acceptable level' (Offshore Petroleum and Greenhouse Gas Storage (Environment) Regulations 2009).

In Australia the responsibility is with the proponent planning activities to define achievable 'acceptable levels' of impacts for their specific operation and environment, and to demonstrate compliance with the Offshore Petroleum and Greenhouse Gas Storage Act 2006 (OPGGS Act). More specifically, according to the OPGGS (Environment) Regulations 2009 (the Environment Regulations), the proposed activity must be:

- "carried out in a manner consistent with the principles of ecologically sustainable development" (as set out in section 3A of the *Environment Protection and Biodiversity Conservation Act 1999*, the EPBC Act)

- “carried out in a manner by which the environmental impacts and risks of the activity will be reduced to as low as reasonably practicable”
- “carried out in a manner by which the environmental impacts and risks of the activity will be of an acceptable level”.

Monitoring and enforcing compliance with the OPGGS Act is currently administrated by the National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA). In the Environment Regulations for offshore projects and the Environment Plans for all petroleum activity submissions required by NOPSEMA, matters protected by the EPBC Act must be considered as part of the relevant sensitivities of the environment and an evaluation of impacts and risks of the proposal on those sensitivities must be included. The Environment Regulations do not prescribe a specific approach to environmental risk reduction to matters protected by the EPBC (e.g. acoustic exposure thresholds); rather, operators are encouraged to be flexible in their approach and employ innovative measures that are tailored to their specific circumstances. The regulations recognise that every situation (local environment, fauna, operations) is different, that no single approach (threshold or minimum standard) suits all situations, and that what is ‘reasonably practicable’ changes over time as technology, expertise and our understanding of environmental impacts evolve.

Most oil and gas industry activities occur in Commonwealth waters (waters beyond the first 3 nautical miles from the coast), and as such are subject to Commonwealth environmental legislation referred to in the Environment Regulations. If a project proponent plans on undertaking their activities in state or territory waters (waters less than 3 nautical miles from the state or territory coast), state and territory environmental legislation also applies.

Knowledge obtained through research on the potential impacts of sound and vibration on marine fauna is used to comply with the required legislation. However, this knowledge can only be used to achieve best practices when it is based on rigorous work that is readily available to users.

5 Underwater sound and vibration from petroleum activities

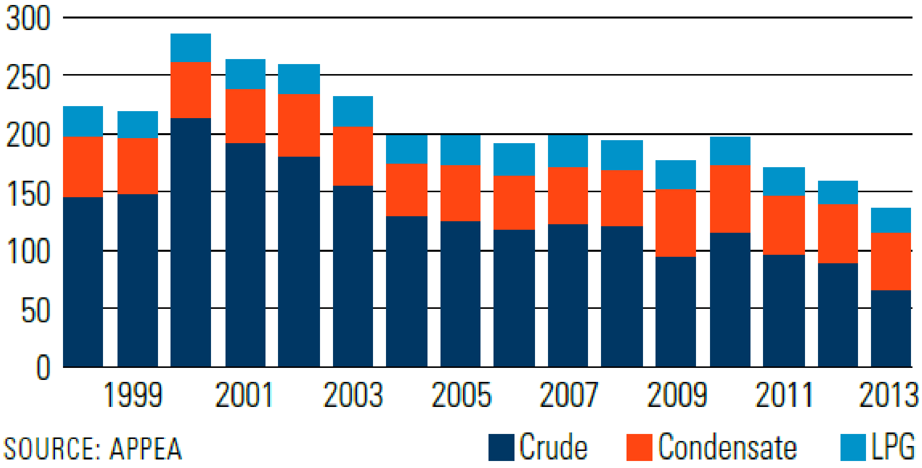
5.1 Australian oil and gas reserves

A synthesis and review of current knowledge on impacts of sound and vibration on marine fauna from petroleum activities in Australia require a foundation from which to work – in this case, an understanding of the extent and nature of potential exposure. That is, what is the extent of sound- and vibration-producing activities in space and time? Do these activities result in sound and vibration with broadly ranging attributes? In this section we provide this foundation by providing an overview of current petroleum activities in Australia and briefly describing sound and vibration associated with those activities.

In Australia, oil and gas represents a significant source of energy resources and contributes about 0.3% to the world's oil reserves (Geoscience Australia and BREE 2014). Oil reserves in Australia are finite, however, and production has been decreasing since reaching a peak in 2000 (Figure 13; APPEA 2014). While this is the general trend of current fields, further growth at existing fields as well as new discoveries in deep water basins are possible. Large areas of the southern Australian continental shelf – such as the Great Australian Bight – have oil and gas reserves but are yet to be fully explored.

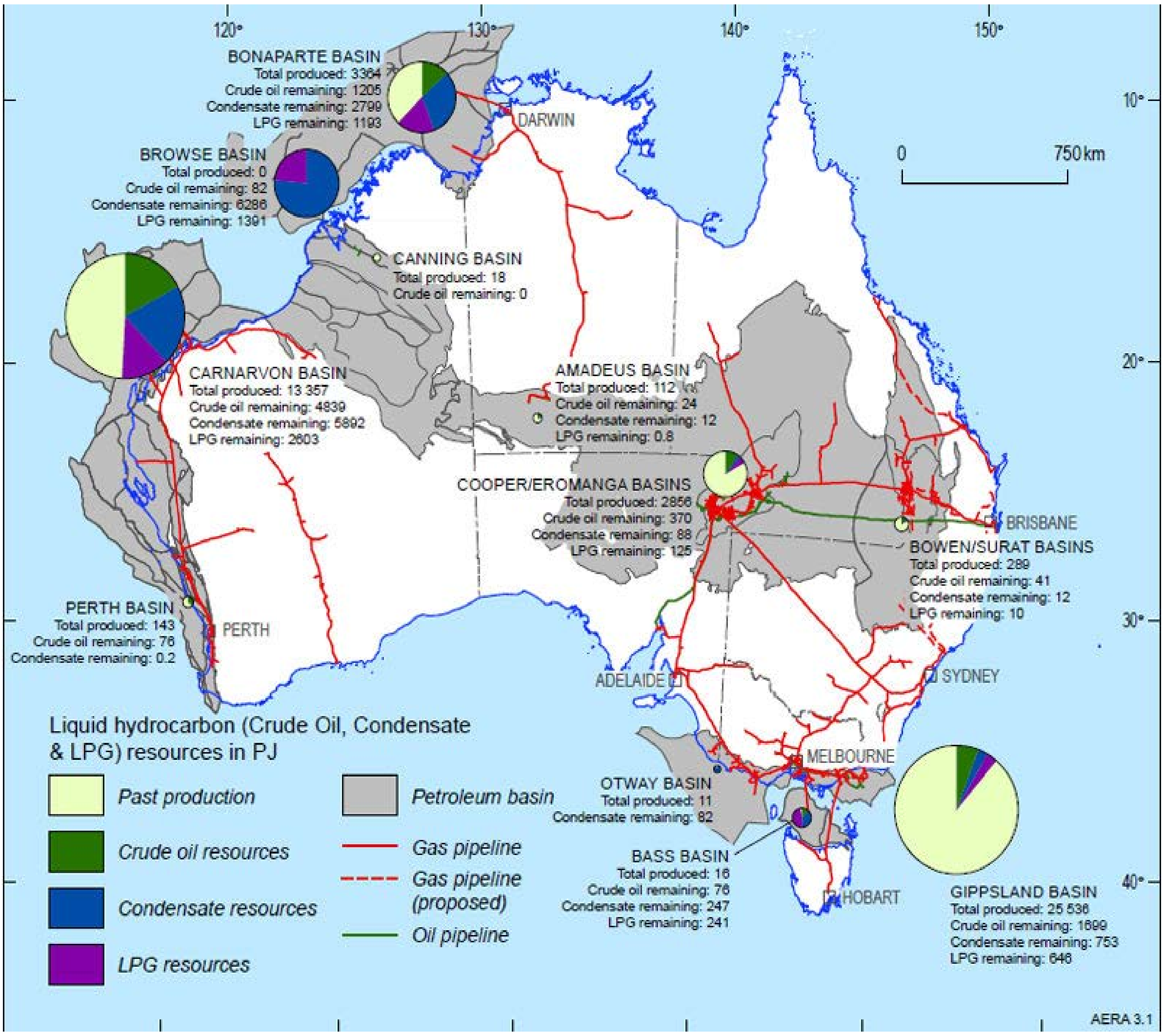
The largest known oil reserves of crude, condensate, and liquefied petroleum gas (LPG) are currently in large offshore fields in the Bonaparte Basin, Browse Basin, and Carnarvon Basin along the northwest shelf, with smaller reserves elsewhere (Figure 14; Carson 2014). The current oil projects in Australian waters are located in depths of approximately 10–800 m (Geoscience Australia 2013).

In contrast to oil, Australia has large gas reserves, mostly in the form of natural gas. The production of natural gas in Australia has doubled in the past decade (Figure 18, APPEA 2014) and currently makes up about 1.6% of the world's natural gas resources (Geoscience Australia and BREE 2014). Conventional gas reserves in Australia are widespread – occurring both on and offshore – with most in the Bonaparte, Browse and Carnarvon Basins (Figure 14).



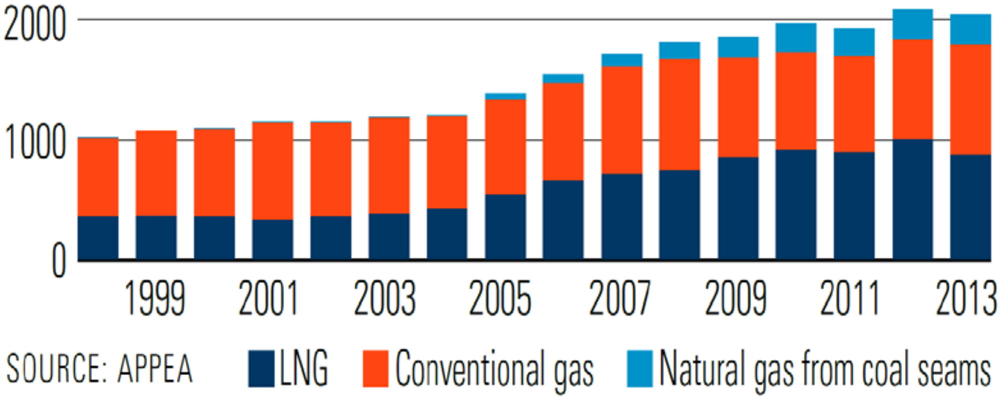
Source: APPEA 2014; http://www.appea.com.au/wp-content/uploads/2014/05/Key-Stats_2014.pdf

Figure 13. Production (millions of barrels) of Australian crude oil, condensate and naturally-occurring LPG resources



Source: Carson 2014

Figure 14. Australian liquid hydrocarbon resources, infrastructure, past production and remaining reserves



Source: APPEA 2014; http://www.appea.com.au/wp-content/uploads/2014/05/Key-Stats_2014.pdf

Figure 15. Australia's natural gas (in mmcf) production

The oil and gas extraction process involves exploration for oil and gas reserves, development for extraction, oil and gas production and decommissioning of infrastructure (Figure 16). The equipment, facilities and associated noise involved with these activities are described in the following section.

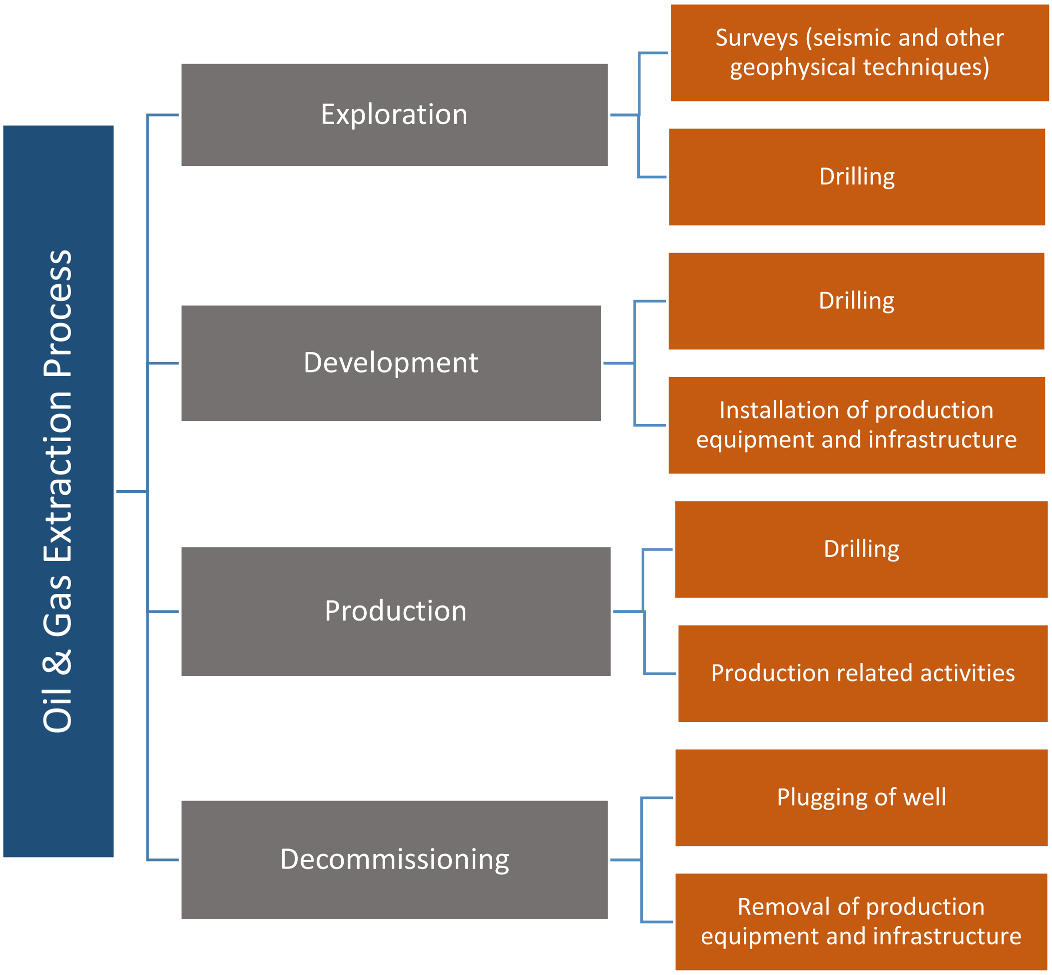


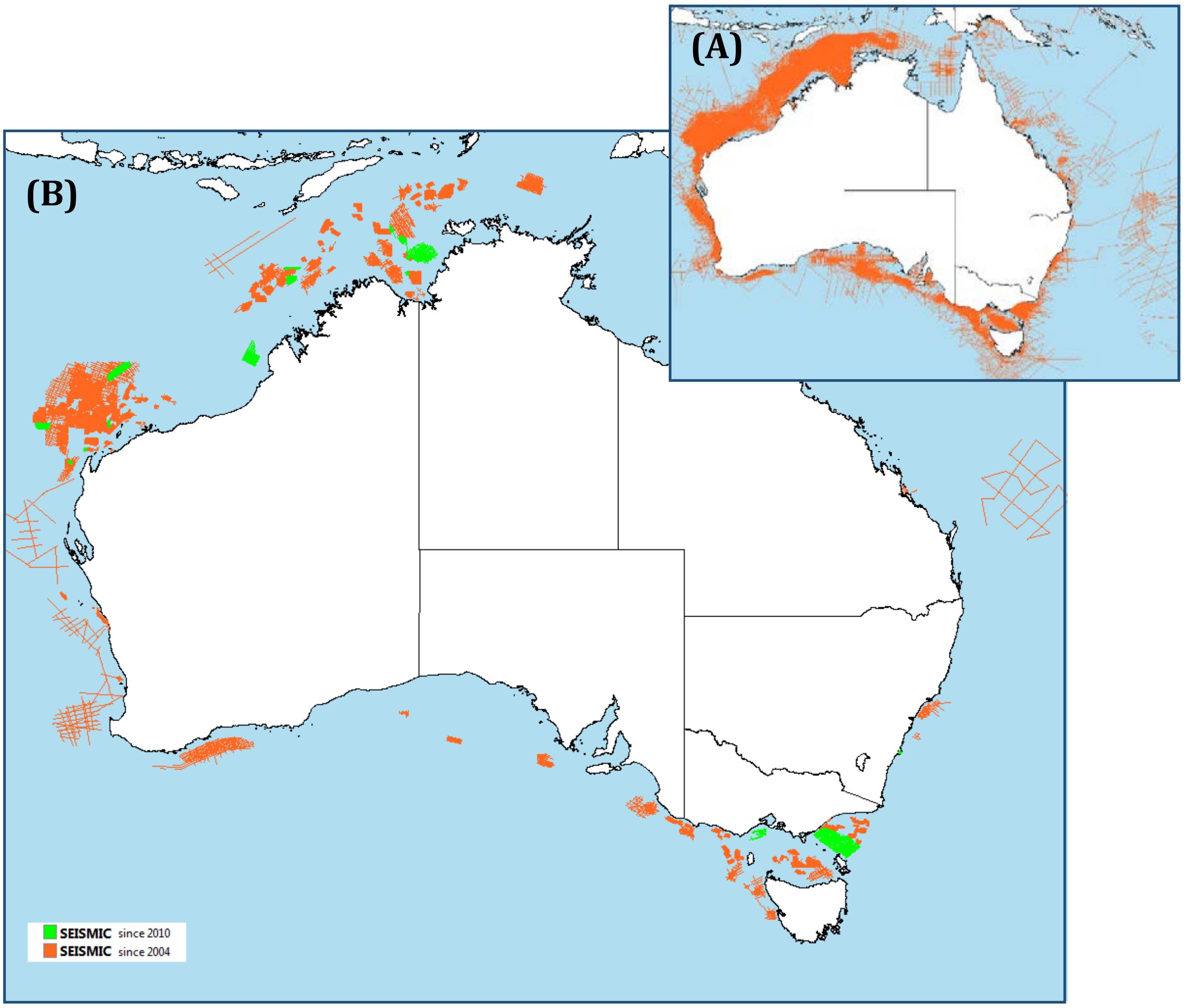
Figure 16. Activities involved in the overall process of oil and gas extraction

5.2 Exploration for oil and gas reserves

Initial exploration is via geophysical surveys to identify the location and extent of hydrocarbon reserves. Various sound sources may be used by the offshore oil and gas industry during exploration and surveying to obtain information about the structure of the seabed. These sound sources range from large arrays of low frequency acoustic sources called airguns that are used to search for reserves that may be 10 km or more below the seabed, through to smaller, higher frequency devices called sub-bottom profilers that form an acoustic image of the tope few metres or tens of metres of the seabed. The latter are used for geotechnical surveys prior to constructing offshore platforms and pipelines. Sonar may also be used during exploration activities.

5.2.1 Seismic surveys using airguns

Most marine seismic surveys are carried out using arrays of airguns. In Australian waters, the area covered by these seismic surveys is significant (Figure 17) and has increased considerably over the last decade (APPEA 2014). The scale of seismic survey activity in Australian waters is dependent on oil and gas price and demand, with the number of surveys dropping by 2014 (APPEA 2014).



Source: APPEA survey statistics 2014, http://www.appea.com.au/wp-content/uploads/2013/05/Industry-trends-charts.xls

Figure 17. Seismic surveys conducted since (A) the 1960's to 2014 and (B) from 2004–2010 (red) and from 2010–2014 (green)

Seismic surveys in Australia range from short (several days only) to relatively long duration (i.e. up to six months). Using a sample dataset of 41 seismic surveys (Centre for Marine Science and Technology's unpublished data, 2000–2015), the mean duration was 29 days and the mean number of airgun discharges per survey was 98,000 (Table 4). Data used for these estimations are based on the authors' associating measured airgun signals with the seismic survey source location by using navigation information supplied by companies. The navigation information includes the date, time and location of the centre of the airgun array for all seismic survey signals (collected for survey purposes). Some seismic signals do not occur in the source navigation files. For example, airguns may not be operating when the seismic vessels are turning. However, the source navigation files can be considered to encapsulate the majority of airgun signals in a survey.

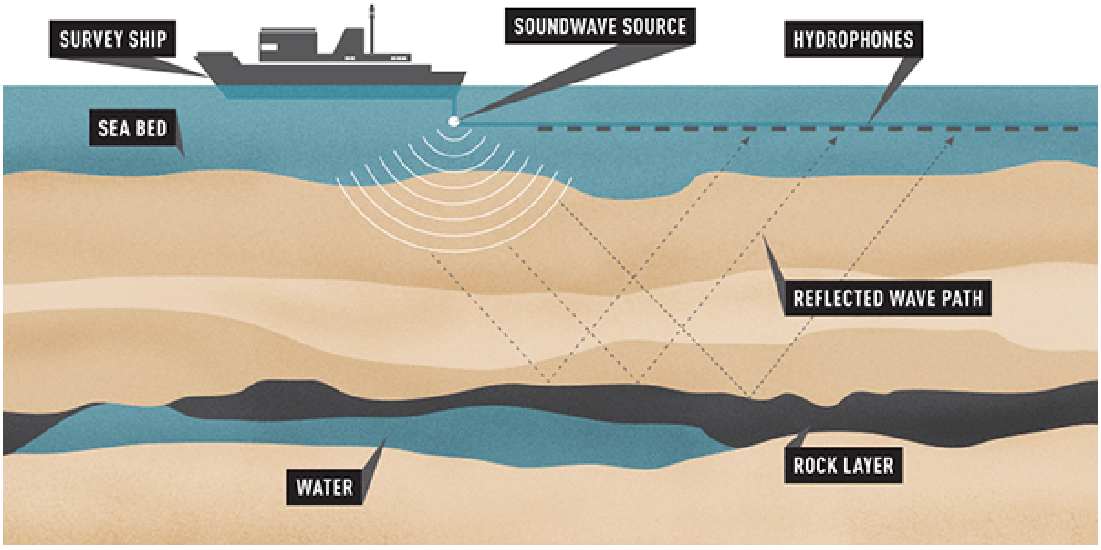
Table 4. Seismic survey statistics from 41 surveys completed between 2000 and 2015

Metric	Range	Mean ± 95% CI	N
Length of survey (days)	3.4–186.8	29.3 ± 10.4	41
Number of shots/survey	4033–790,392	97,647 ± 41,103	41
Number of survey lines/ survey	13–165	52.9 ± 13.6	41
Minimum line length (km)	<1–24.6	7.1 ± 2.1	41
Maximum line length (km)	4.5–206.5	65.2 ± 14.7	41
Mean line length (km)	1.6–113.5	34.2 ± 7.7	41
Time between one line and the next (hours)	0.3–23.4	3.6 ± 0.1	2044
Distance between one line and the next (km)	<1–206.5	36.2 ± 1.5	2167

Source: CMST (unpublished data)
CI = confidence interval, N = number (of surveys)

Seismic reflection

Seismic surveys using airguns are carried out using a vessel towing an array of sound sources (the airguns) and receivers (hydrophones; Figure 18.). Airguns consist of a cylinder filled with a fixed volume of high-pressure air that is suddenly released into the water. The release of air creates a sharp pulse of sound followed by a decaying series of pulses due to the oscillation of the resulting air bubble (see Figure 19). These additional pulses are called bubble pulses. The signal shown in Figure 19 (and in the other examples in this section) was computed using the CMST's airgun array model. This model is based on the method described in Johnson (1994) and has modifications to the rise time and damping, as well as including airgun interaction effects to achieve a good match to measured signals.



Source: http://www.appea.com.au/oil-gas-explained/operation/seismic-surveys/

Figure 18. Example seismic survey configuration showing airguns and receivers trailing behind the vessel and the associated wave pattern of reflections off the seabed

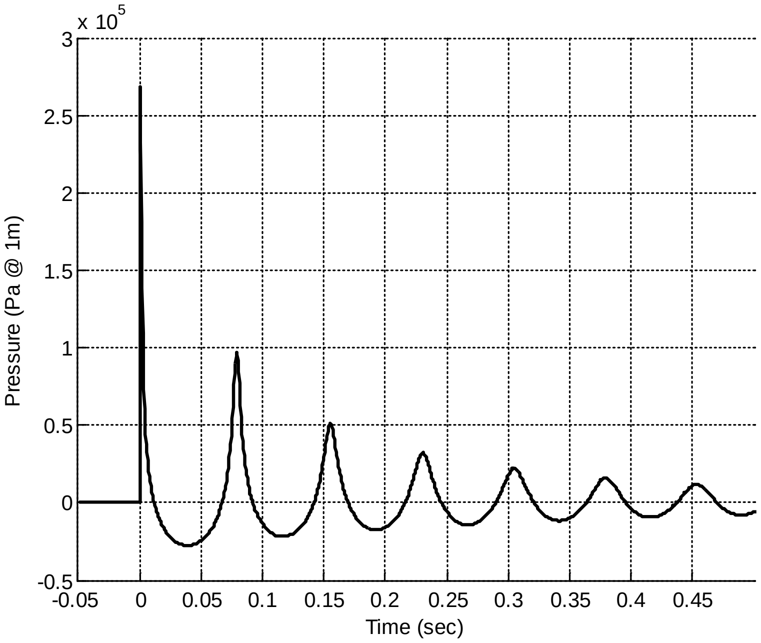


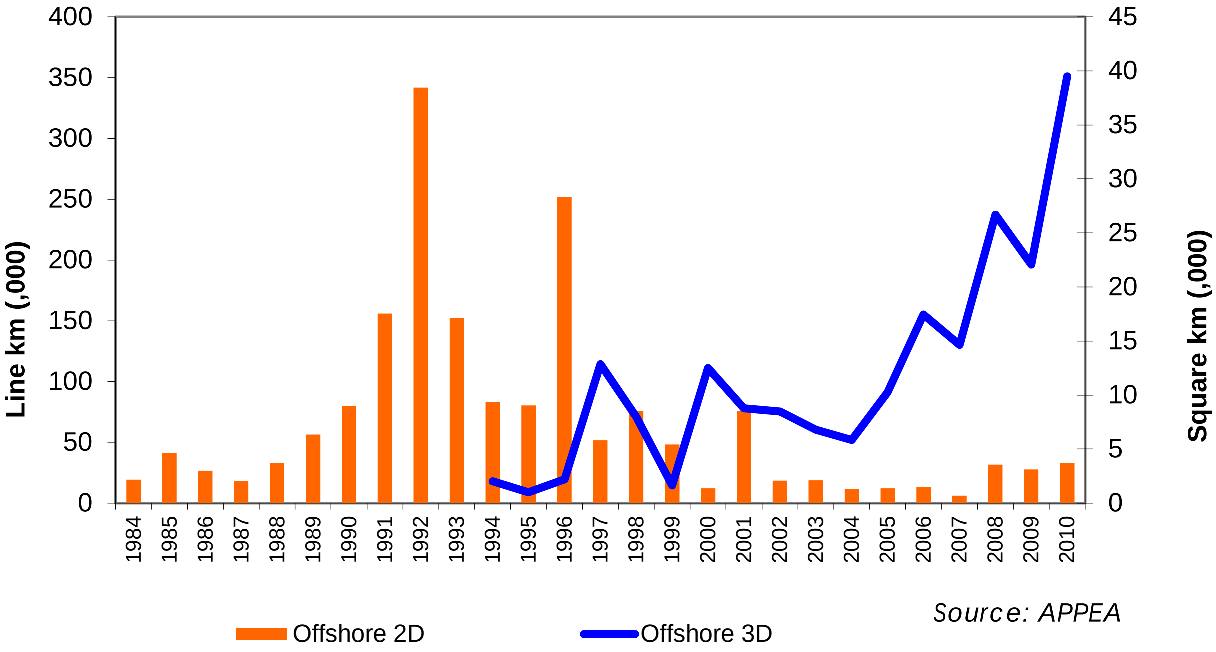
Figure 19. Typical signal from an airgun in the absence of surface reflections

When this acoustic energy is directed downward it penetrates the seabed, which transmits sound reasonably well over the frequency range 5–80 Hz. Airgun signals are reflected off layers in the ground and recorded by the streamers of hydrophones in the water. Based on the arrival time and spectral characteristics of the reflected signal, the depth and density of boundary strata within the seabed can be discerned and the corresponding seafloor profile including potential oil and gas reservoirs can be identified (McCauley et al. 2000a). Sub-bottom profiles from seismic surveys can be visualised as images with layers corresponding to the composition of the material.

The nature of the underwater noise produced by a seismic survey will depend upon the configuration (geometry), tow depth and size (volume) of individual airguns used in the source arrays. Airguns are usually characterised by the volume of compressed air they contain prior to release, which for historical reasons is most often specified in cubic inches (cui). When used as a sound source for offshore seismic surveys, airguns are operated in arrays that may consist of as many as 50 individual airguns of varying volumes. The volumes of the individual airguns in an array typically range between 20 cui and 250 cui, and the sum of the volumes of all the guns in an array is typically between 1000 and 8000 cui. A combination of varying volumes is used to increase the 'bandwidth' of the source, as smaller volume airguns have most energy at slightly higher frequencies than larger volume airguns. The time between the unwanted bubble pulses depends on the volume of each airgun, so using a combination of different volumes ensures bubble pulses from different guns occur at different times and therefore tend to cancel out.

In most arrays the airguns are positioned on a rectangular grid. These are typically all towed at the same depth, which is usually between 4 and 10 m below the sea surface depending on the aims of the survey. This arrangement results in highest sound levels produced in the vertically downward direction, but significant sound energy radiated at angles near horizontal that can travel long distances in some circumstances.

Seismic surveys can be either two- or three-dimensional. Two-dimensional (2D) surveys have one airgun array with 100 or more hydrophone towed in a single line behind the vessel, a single vertical profile through the seabed only, capturing information from a ‘cross-section’ beneath the survey line over a limited spatial coverage. For greater spatial resolution 'image' of seabed geology, a three-dimensional (3D) survey typically has two arrays with 1000 or more hydrophones on 12 or more streamers spaced 100 m apart across the ship’s tow line. The 3D airgun arrays are arranged as sub-arrays of 30–40 airguns (Islam and Khan 2007), and paired sub-arrays are operated alternately. Since 2000, 3D surveys have been the most common method used (Figure 20).

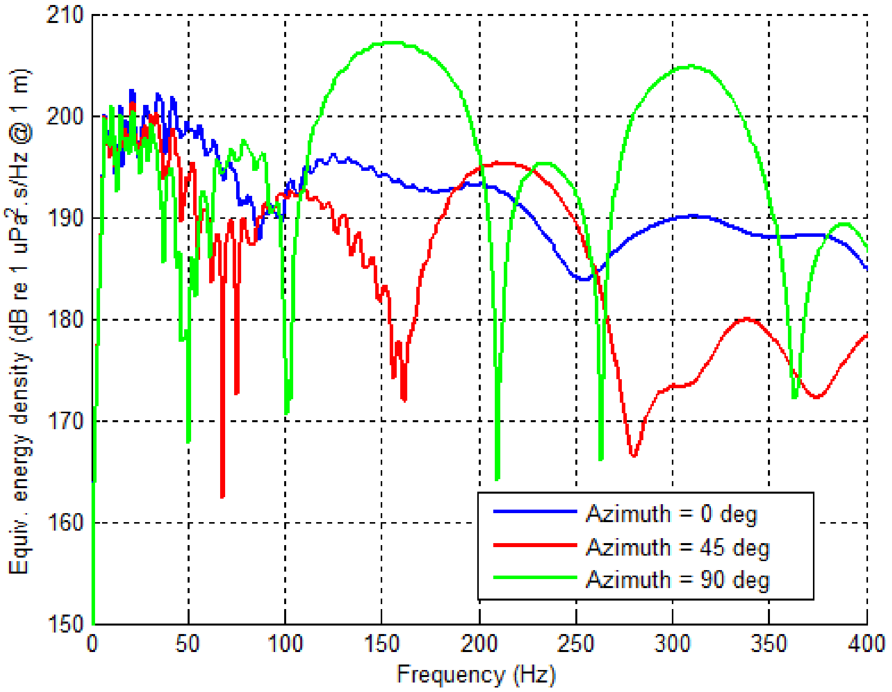


Source: APPEA survey statistics 2014, http://www.appea.com.au/wp-content/uploads/2013/05/Industry-trends-charts.xls

Figure 20. Australian 2D and 3D seismic surveys conducted between 1984 and 2010

As an airgun array is towed a few metres below the sea surface, the sound received at any location in the water is the sum of the sound that travelled directly from each airgun to the receiver and the sound that reflected off the sea surface. The seafloor is typically less reflective and much farther from the airguns than the sea surface and hence contributes less to the sound field in the water. Sound produced by the signals reflecting from the sea surface interferes with sound travelling directly to the receiver. This interference is destructive (i.e. the signals tend to cancel one another out), in particular at low frequencies and near horizontal angles; thereby increasing the importance of the array's output at frequencies above 100 Hz for receivers at some horizontal distance from the array (since it is attenuated less by destructive interference from the sea surface). Given that airguns in an array are not arranged in circular symmetry but often only show symmetry about the tow direction, a pattern of destructive and constructive interference is seen about the array which is most pronounced at angles near the horizontal. The effect varies markedly with direction, with output typically being higher in one direction (mostly commonly in the cross-line direction) than another. An example of this effect is shown in Figure 21. The diagram shows an example of the output of a typical array, including the effects of the surface reflection as a function of frequency and azimuth for a depression angle 15° below the horizontal. This array has its highest output in the cross-line directions (90° and 270°) where its spectrum is dominated by the strong peak that occurs between 100 and 200 Hz. In contrast, in the in-line directions (0° and 180°) the spectrum is dominated by frequencies below 100 Hz. Integrating these results over frequency gives the array's effective source sound exposure level as a function of azimuth (including the surface reflection) plotted in Figure 22.

There is a strong maximum in the cross-line direction and a weaker maximum in the in-line direction, which is a common but not universal characteristic of seismic source arrays. Additional examples of horizontal emission beampatterns of seismic airgun arrays of different size and configuration can be found in Erbe and King (2009). It should be noted that these plots represent energy at or close to the source. The local environment will determine how this signal transmits at ranges greater than a few times the water depth.



Note: Frequency increases radially and 0° corresponds to the in-line direction.

Figure 21. Simulated output of the airgun array shown in Error! Reference source not found. **as a function of direction and frequency for a depression angle 15° below the horizontal, including the effects of the sea surface reflection**

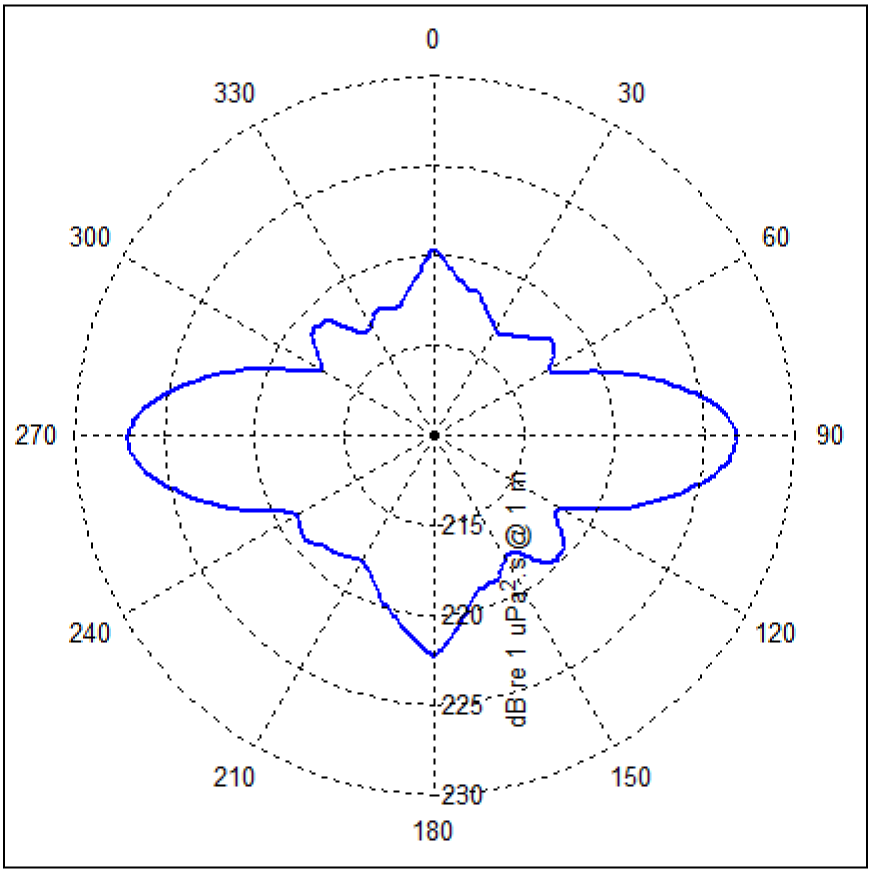


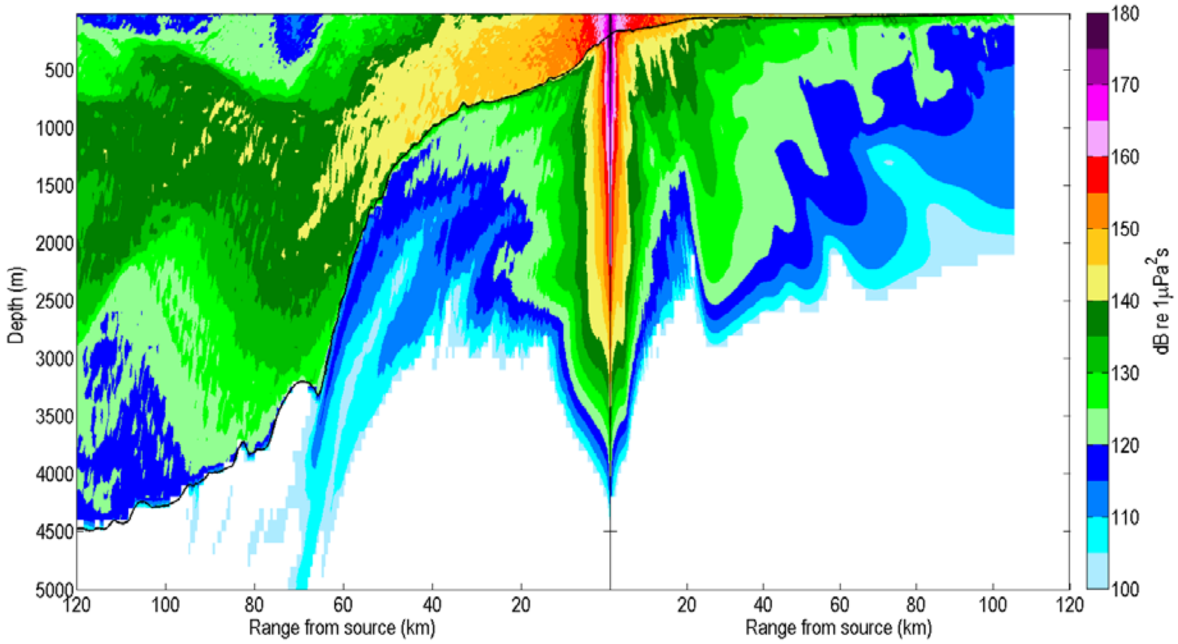
Figure 22. Source sound exposure level as a function of azimuth for a depression angle 15° below the horizontal and including the effects of sea surface reflection

Marine seismic surveys are usually carried out with the vessel steaming along a predefined set of long, straight lines. As a result, these beam pattern effects are systematic and can be predicted with reasonable precision using numerical models.

CMST has been analysing airgun signal transmission in Australian waters since the early 2000s and has built a large library of measured airgun signals from commercial and experimental sources measured around Australia in shallow coastal and deep oceanic waters. The resulting variability in signals in the library indicates that sound transmission is highly complex and strongly dictated by the local environment. Measurements of the signals show that noise from the same seismic source operated in different environments may have completely different sound transmission characteristics. For example a seismic source operating just seawards of a steep continental slope was not detected at receivers less than 150 km away inshore of the survey, but was detected at receivers in excess of 2000 km away in deep ocean waters towards Antarctica. . This is a common phenomenon, which is predicted by modelling and borne out by measurements. Essentially, if a near-surface source such as an airgun array is over the continental slope, then in the downslope direction consecutive reflections from the seabed flatten the rays, allowing them to be trapped in the Deep Sound Channel (DSC, defined in Section 2.1 and in Appendix A).

Conversely, in the upslope direction, successive reflections from the seabed steepen the rays leading to more and more frequent reflections from the sea surface and seabed, leading to more rapid attenuation. This effect is counteracted to some extent by the sound energy being compressed into a smaller and smaller depth range, so that levels often remain fairly constant while sound is travelling up the slope, but decay rapidly when the seabed flattens out on the continental shelf.

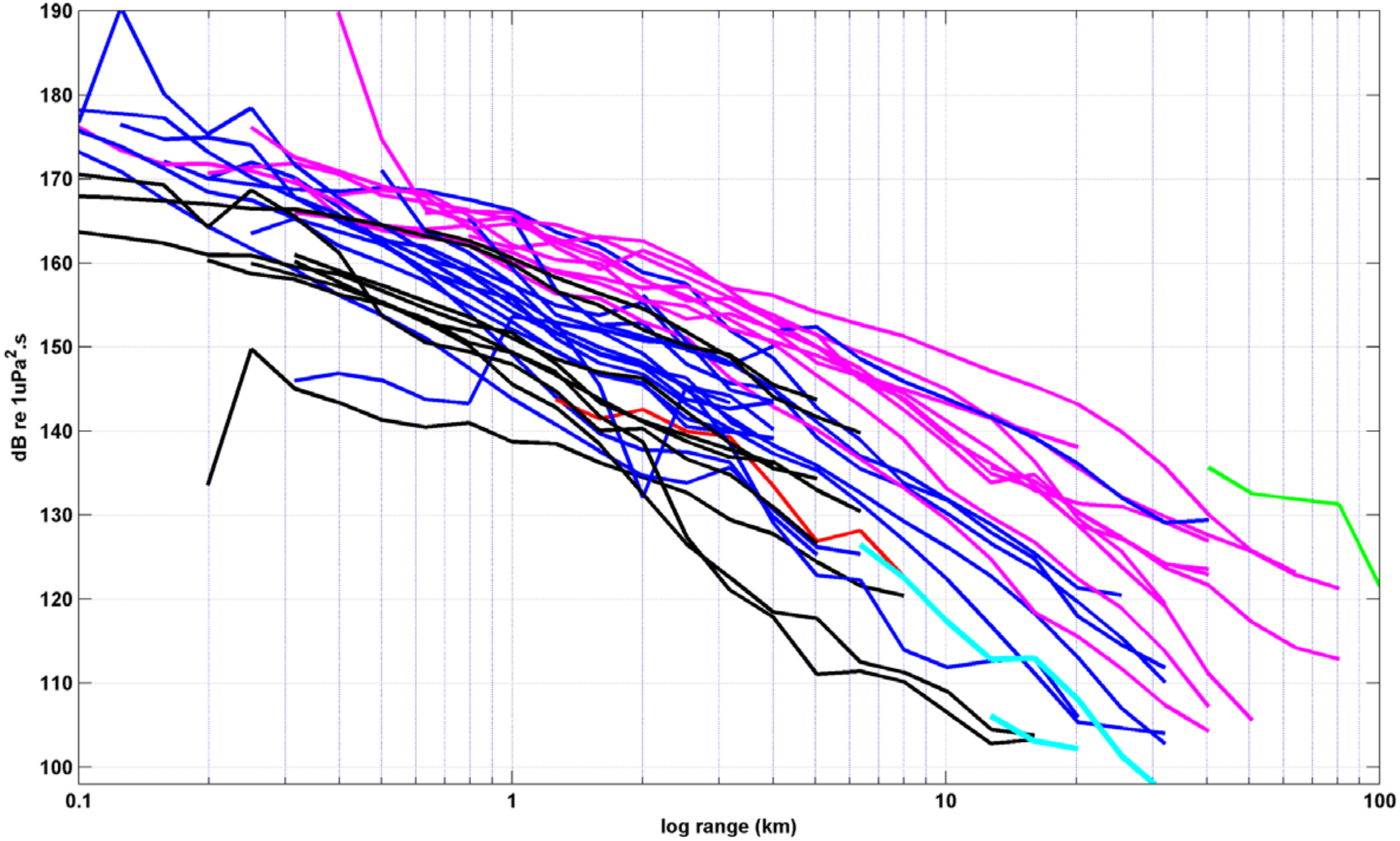
Figure 23 shows an example demonstrating these effects for a fictional seismic survey off the southwest coast of Western Australia.



Note: The black line is the seabed, and the seismic source is in the centre of the plot.

Figure 23. Vertical cross-section through the modelled sound field from a seismic source over a continental slope

The influence of the local environment and bathymetry on sound transmission, in addition to the wide range of sound characteristics produced by the large diversity of airgun array sources available, means that underwater noise predictions for airgun arrays will not necessarily be accurate if one set of measurements or transmission modelling from one location is applied to a separate location. To illustrate this, mean sound exposure levels (SELs) as a function of range from 49 seismic sources in the library have been plotted in Figure 24. Mean SELs were calculated in range bins that increased logarithmically in size (1/3 octave frequency bounds used for the range bins) with the 95% confidence limits added. Hence values presented encapsulate the normal variability within measured airgun signals, with 95% of signals measured falling at or below the value presented. The curves in Figure 24 are colour coded by the array source volume. From the figure it is evident that for similar size sources a variability of 10 dB at a given range is common, and in cases where the sound transmission environment differs the differences in received levels are considerably greater.



Note: The sources are colour coded according to their volume as: 0 to 1,000 cui =black; 1,000 to 2,000 cui = red; 2,000 to 3000 cui = blue; 3,000 to 4,000 cui = magenta; 4,000 to 5,000 cui = green.

Figure 24. Mean received noise levels from 49 seismic survey sources measured by CMST as a function of range (mean value in logarithmic range bins with 95% confidence limits added)

Vertical seismic profiling

Once a reservoir has been discovered, other types of seismic surveys may be carried out to more accurately characterise the reservoir and/or to monitor the extraction process. Vertical Seismic Profiling (VSP) is one such method and involves placing a string of hydrophones in a borehole and transmitting to them from a near-surface seismic source, which in the marine environment is typically an airgun array. The transmission path lengths involved in VSP are typically much shorter than in seismic reflection surveys and airgun array volumes are therefore correspondingly smaller, usually consisting of a compact array of airguns with a total volume of less than 1000 cui (Schlumberger 2002).

Modified airguns and marine vibrators

Marine seismic surveys rely primarily on sound at frequencies below 100 Hz that propagates vertically down into the seabed with little attenuation. However, as described in the previous section, airgun arrays emit considerable amounts of acoustic energy at higher frequencies that may affect receivers in the water at significant horizontal range from the array. Further, the signal produced by an airgun is a high-intensity short impulse –a feature used in signal processing to locate reflectors.

There is scope for reducing the environmental impact of marine seismic surveys by using sources that have a reduced output at higher frequencies and that do not rely on an intense, short impulse signal (LGL and MAI 2011). Two distinctly different ways of achieving this are currently being developed by the seismic industry: a change to airgun design that increases the rise time of the initial impulse, thereby reducing the high-frequency content of the signal (see, for example, Bolt 2014), and the use of electrically driven sources known as marine vibrators or marine vibroseis. Marine vibrators output a similar amount of energy to an airgun array but in a patterned form spaced over a longer time period (PGS 2005; Pramik 2013). Neither approach leads to a large reduction in broadband received SELs, but marine vibrators produce substantially lower peak sound pressure levels than airguns and significantly reduce SELs within the hearing frequency band of the smaller cetaceans (LGL and MAI 2011).

Geophysical survey sources

Smaller, higher frequency sound sources are often preferred to airguns for obtaining high-resolution acoustic images of the geological structure of the upper part of the seabed. The choice of source will be a compromise between the better bottom penetration achievable at low frequencies and the better resolution at high frequencies. Common source types include:

- **Sparkers** create a high-voltage discharge that vaporises the water. The resulting plasma bubble expands rapidly, producing a short pulse of high-intensity sound (Verbeek and McGee 1995; Genesis 2011).
- **Boomers** use a coil to create an electromagnetic pulse that forces two submerged metal plates apart, thus creating a sound pulse (Edgerton and Hayward 1964; Simpkin 2005; Verbeek and McGee 1995). In the oil and gas industry, boomers have been largely superseded by more flexible electrically driven sources (Genesis 2011).

- **Electrically driven sources** based on piezoelectric ceramics produce an acoustic signal proportional to the driving signal. These are, therefore, extremely flexible and can produce a variety of acoustic waveforms. Sources of this type can be described by a variety of names including 'pingers', 'chirpers', and sub-bottom profilers, although the latter term usually refers to a complete system that includes both a source and receiver.
- **Parametric sources** are a more recent development, also based on piezoelectric ceramics. They simultaneously transmit two high-amplitude, high-frequency signals at slightly different frequencies. Nonlinear mixing of these two signals in the water below the transducer creates a signal at a frequency equal to the difference between the two high frequencies. This type of source produces a narrow beam at the difference frequency, and allows this frequency to be swept over a considerable frequency range with minimal change to the beamwidth – something that is otherwise very difficult to achieve. The main disadvantage of this type of source is that the nonlinear mixing process is quite inefficient so it is difficult to achieve high source levels at the difference frequency. There are several manufacturers that now offer sub-bottom profilers based on this principle (Innomar 2015; Kongsberg 2015; Tritech 2015).

Acoustic communication and positioning systems

Since radio waves travel only very short distances in the ocean, marine acoustic systems are used for similar purposes that they would be used for on land, such as position fixing (accurately measuring the position of underwater vehicles and subsea infrastructure) and wireless communication. The latter are used as backup monitoring and control systems for subsea infrastructure, for communication with autonomous underwater vehicles, and for retrieval of data from seabed-mounted environmental monitoring instruments. The technologies used for position fixing and wireless communications are similar and several manufacturers offer instruments that can do both.

Manufacturers of acoustic communication and positioning systems offer a variety of devices designed to operate over ranges from a few hundred metres to as much as 25 km (e.g. Applied Acoustics 2015, EvoLogics 2015, Kongsberg 2015, L3 Oceania 2015, Sonardyne 2015, Teledyne Benthos 2015). Increasing acoustic attenuation with increasing frequency means that lower frequencies are required for the longer ranges resulting in a compromise between range and data rate for communication systems, and between range and positional accuracy for positioning systems. Systems offered by the above manufacturers have centre frequencies between 7 and 70 kHz and source levels in the range 180 to 206 dB re 1 µPa rms @ 1 m. Omni-directional or hemispherical beam pattern transducers are most commonly used, but transducers with conical beam patterns may give improved performance in some situations. Higher source levels are associated with the more directional transducers.

A summary of the typical acoustic characteristics of these various sources is given in Table 5.

Table 5. Acoustic characteristics of some typical seismic, geophysical survey, and acoustic communication and positioning sound sources

Source type	*Typical maximum source sound pressure level (dB re 1 µPa @ 1 m)*	*Typical pulse duration (ms)*	*Approximate peak or centre frequency (Hz)*	*Approximate upper 10 dB frequency (Hz)*	*Nominal source sound exposure level (dB re 1 µPa^2.s @ 1 m)*	*Directional characteristics of sound field*	*Notes*
Single 20 cui airgun	226 (peak)	500	21	45	200	Omnidirectional if surface reflection is excluded. If surface reflection is included the vertical beam pattern below 100 Hz will be approximately dipole (i.e. amplitude proportional to cosine of angle from vertical). The vertical beam pattern at higher frequencies will be more complicated.	Derived from measured data held by the authors from hydrophones located 0.5–0.8 m from a single airgun operating at between 5 and 6 m depth and 2000 psi. Values have been corrected to a range of 1 m assuming spherical spreading. For hydrophones this close to an airgun the signal is dominated by the direct path so this is effectively a measure of the source level without the surface reflection. The pulse duration includes bubble pulses and is nominal.
Single 45 cui airgun	224 (peak)	500	15	30	203		
Single 150 cui airgun	223 (peak)	500	11	83	207		
Airgun array, 3000 cui	258 (peak)	500	45	220	233	Complicated. Depends on array geometry.	Computed for the vertically downward direction for specific array configurations using the Centre for Marine Science and Technology (CMST) airgun array model and includes the surface reflection. All parameters are highly dependent on direction. Pulse duration includes bubble pulses and is nominal. In this direction the bulk of the energy arrives in the first 40 ms.
Airgun array, 5200 cui	263 (peak)	500	8	262	238		

Table 5 continued…

Source type	*Typical maximum source sound pressure level (dB re 1 μPa @ 1 m)*	*Typical pulse duration (ms)*	*Approximate peak or centre frequency (Hz)*	*Approximate upper 10 dB frequency (Hz)*	*Nominal source sound exposure level (dB re 1 μPa²·s @ 1 m)*	*Directional characteristics of sound field*	*Notes*
VSP source consisting of 3 x 250 cui airguns	239	500	8	83	216	Omnidirectional if surface reflection is excluded. If surface reflection is included the vertical beam pattern below 100 Hz will be approximately dipole. The vertical beam pattern at higher frequencies will be more complicated.	Computed for the vertically downward direction for a specific array configuration (equilateral triangle array with 1 m airgun spacing) using the CMST airgun array model and includes the surface reflection. Pulse duration includes bubble pulses and is nominal.
Sparker	216–226 (peak)	0.2–1.3	250–1200	800–4000	175–200	Approximately dipole.	Data sources: Applied Acoustics (2015), SIG (2015).
Boomer	210–227 (peak)	0.2	850–4500	7000–10,000	170–190	Approximately dipole.	Data sources: Applied Acoustics (2015), Ashtead (2015)
Electrically driven sources used for sub-bottom profiling	200–215 (root mean square)	5–40	1000–25,000	1000–25,000	185–200	Broad conical beam. Beam width in range 15–45°.	Data sources: Edgetech (2015), Kongsberg (2015).
Parametric sources (primary frequencies)	240–245 (root mean square)	0.04–30	10,000–115,000	10,000–115,000	198–224	Narrow conical beam. Beam width approx. 3.5°.	Data sources: Innomar (2015), Kongsberg (2015).
Parametric sources (difference frequency)	202–205 (root mean square)	0.04–30	500–30,000	500–30,000	190 with a 30 ms-long pulse	Narrow conical beam. Beam width approx. 1.5–6°.	
Acoustic communication and positioning systems	180–206 (root mean square)	0.001 to virtually continuous	7000–70,000	Bandwidth is determined by specific signalling method	Not a relevant measure for continuous sources	Omnidirectional, hemispherical or conical.	Data sources: Applied Acoustics (2015), EvoLogics (2015), Sonardyne (2015). Kongsberg (2015), L-3 Oceania (2015), Teledyne Benthos (2015).

5.2.2 Exploration drilling

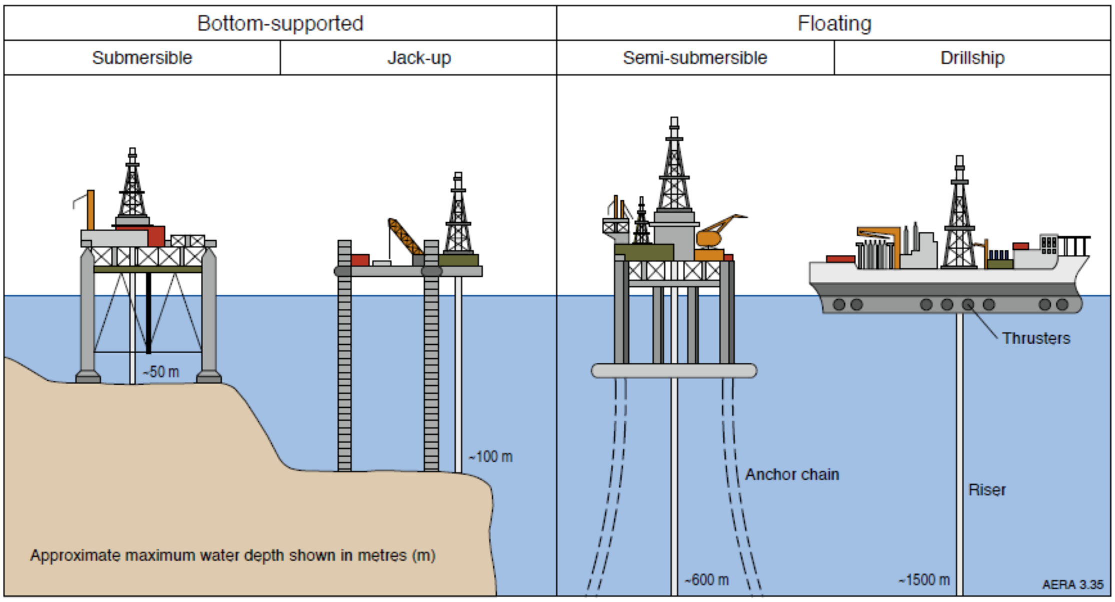
While seismic surveys provide a general guidance on the presence of hydrocarbons based on the structure of the subsurface, exploratory drilling confirms their presence. Exploration drilling involves the same general processes as in appraisal, construction, and production drilling. However, drilling related to exploration (and appraisal and production) tends to be less intense as the drill cutting head is commonly much closer to the seabed surface than during construction drilling. Drilling is described in detail in Section 5.3.1.

5.3 Development and production

Once it has been determined that there is a commercially viable oil or gas field, drilling of the well and construction of infrastructure required for production can begin (Islam and Khan 2007). Development and production include activities such as drilling, the installation of support structures and equipment for drilling and production, piling for fixing structures in place, and dredging and pipe laying for the transportation of extracted material during the production phase.

5.3.1 Drilling

Drilling – whether for exploration, appraisal, construction, or production – involves the installation of a support structure or rig, the type of which depends upon the marine environment and substrate. Rigs can be submersible (for seabed depths up to ~50 m), jack-up (for depths up to ~100 m), semi-submersible (for up to ~600 m), or floating drillships (for depths up to ~1500 m) (Figure 25).



Source: Wilkinson 2006

Figure 25. Offshore drilling platforms and vessels

After being floated to the drill site, submersibles are ballasted so they sit directly on the seabed to provide a stable drilling platform. Semi-submersibles are either towed into position or have their own propulsion, and are either anchored or use dynamic positioning to maintain position and stability. Semi-submersibles have hulls (or pontoons) that are ballasted so that they sit below the water surface for drilling stability, making them relatively stable in rough weather (Wilkinson 2006). Jack-up rigs are towed to the drill site and mechanically jack their legs to the seabed to provide stability. Drillships maintain stability in relatively calm waters by being anchored or maintaining position with a dynamic positioning system.

Regardless of the support structure used the process of drilling is generally the same and involves the motorised rotation of a drill bit attached to the end of a drill pipe entering the substrate. Various drill bits can be used, depending upon the hardness of the formations. A casing is installed in the well and pumps, and prime movers operate to circulate drilling fluid through to the bit and remove drilling cuttings. Rock from the well is removed and typically deposited on the seabed. Wells are commonly drilled up to depths of 4000–5000 m, although they can be shallower or deeper, and can have diameters around 90 cm at the surface and narrow to 6 cm at the bottom of the well.

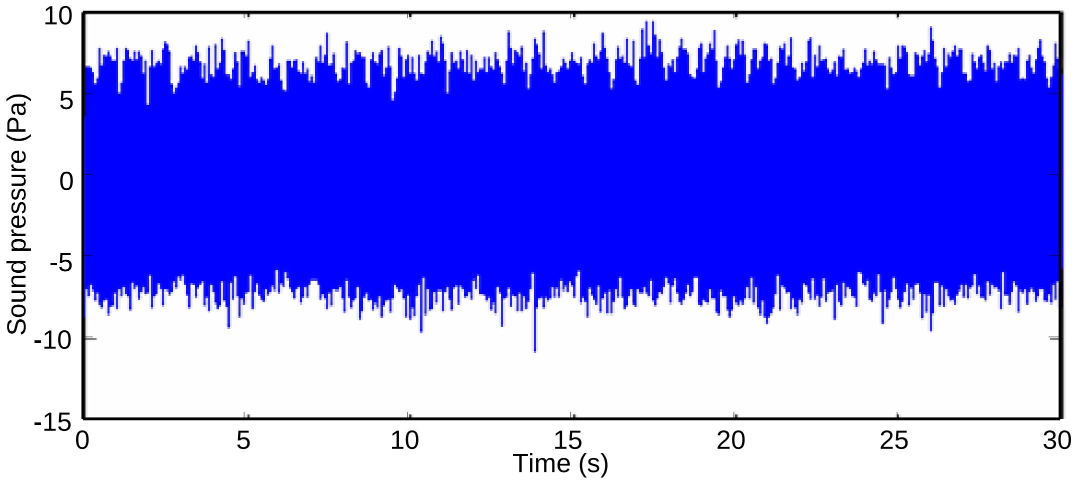
During drilling, underwater noise is created from sources such as tugs towing rigs to drill sites, dynamic positioning of semi-submersibles and drillships, on-site rig tenders operating in dynamic positioning mode or with high thrust, machinery, pumps and generators located on the rigs, rig tenders or barges, and the drilling itself.

Sound produced during drilling

Limited research or measurements have been done to assess underwater noise levels from subsea drilling. Most of the existing measurements are related to oil and gas exploration and production drilling (e.g. McCauley 1998 and Blackwell et al. 2004). Construction drilling (e.g. drilling sockets in rocky substrates for piles) usually produces more intense noise in the water column than drilling related to exploration or production, as the drill cutting head is typically much closer to the seabed surface during construction drilling. The major sources of noise during a drilling operation are ground vibrations created at the drill-rock interface, mechanical vibration of the drill in water, and noise transmitting from the support platform. The ground vibrations result in compressional and shear waves in the ground that transform into sound in the water column at the water-ground interface. The mechanical vibrations of the drill radiate sound directly into the water column by the drill shaft.

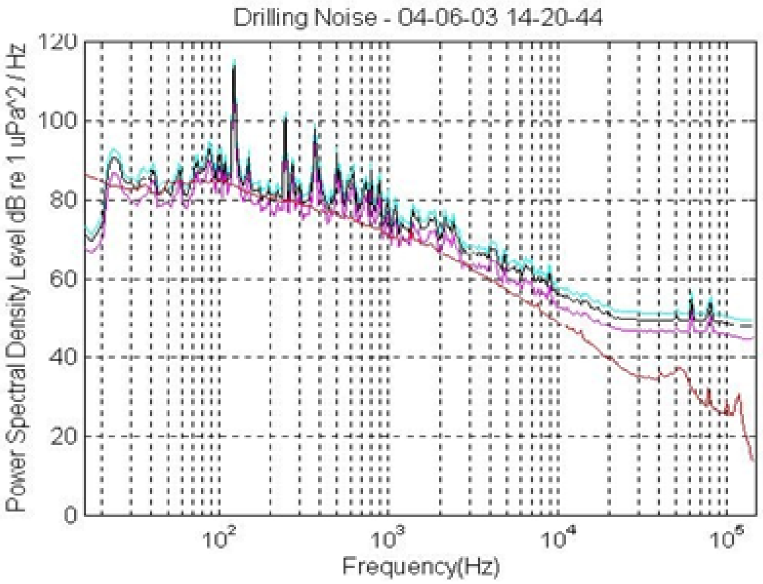
No measurements of underwater noise from shallow water constructional drilling operations have been reported in openly available literature before 2003 (Nedwell and Howell 2004), and very few measurements have been made over the last decade. In 2003, measurements of underwater drilling noise were made during construction of the UK's large scale offshore wind farm at North Hoyle, 5 miles off the North Whales coast in water depths of 7–11 m (Nedwell et al. 2003). The construction required 30 large piles – each 50 m long and 4 m diameter – to be driven into the seabed. As the seabed substrate at North Hoyle consisted primarily of sandstone and other hard sediments, pile sockets had to be drilled in the underlying sandstone after initial impact hammering to half the depth, followed by about 20 hours of drilling to allow each pile to be hammered to its final depth.

The measurements were made at various distances from about 160 m to nearly 10 km. Figure 26 shows the waveform of noise recorded at 160 m from the drilling platform. The rms pressure at this distance was about 5 Pa and the sound pressure level was about 135 dB re 1 µPa. The Power Spectral Density (PSD) of underwater noise during the drilling operation at 160 m is shown in Figure 27, where the brown line shows the mean level of background noise in the absence of any construction and other noise-making activity nearby. Seabed drilling contributed significantly to underwater noise levels only between 120 Hz and 1 kHz, where the maximum difference in the spectral levels of the drilling and background noise reached nearly 30 dB at 120 Hz.



Source: Nedwell et al. 2003

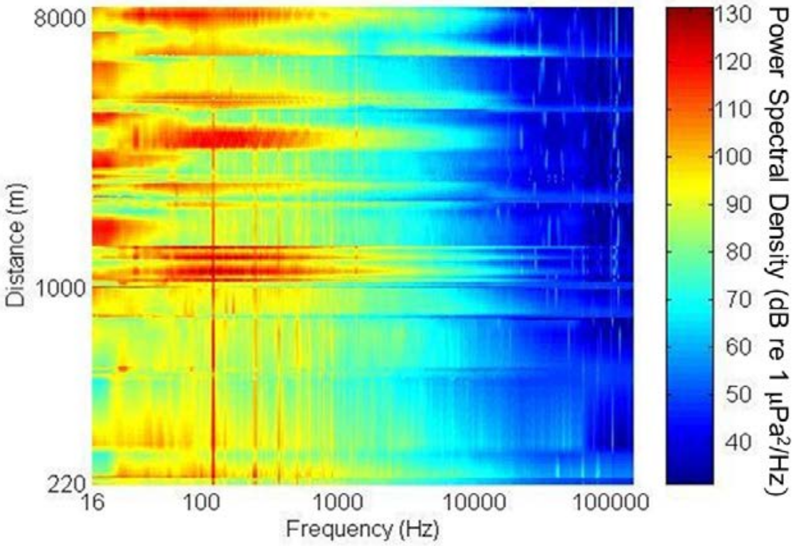
Figure 26. Sound pressure waveform of underwater noise recorded at 160 m distanc during construction drilling for a wind farm at North Hoyle, UK



Source: Nedwell et al. 2003
Black and brown lines: background (ambient) noise in the study area.
Magenta and cyan lines: low and high bounds of the measured PSD levels.

Figure 27. Mean Power Spectral Density (PSD) of underwater noise during construction drilling for a wind farm at North Hoyle, UK

Changes in the PSD level versus distance and frequency are shown in Figure 28. Noise from the drilling operation is seen as vertical spectral lines of higher intensity from about 120 Hz to 1 kHz. The horizontal bands of higher broadband noise levels at certain distances (e.g. at about 1 km, 3 km and 8 km) resulted from other man-made sources of noise, primarily ships operating nearby during the measurements.



Source: Nedwell et al. 2003

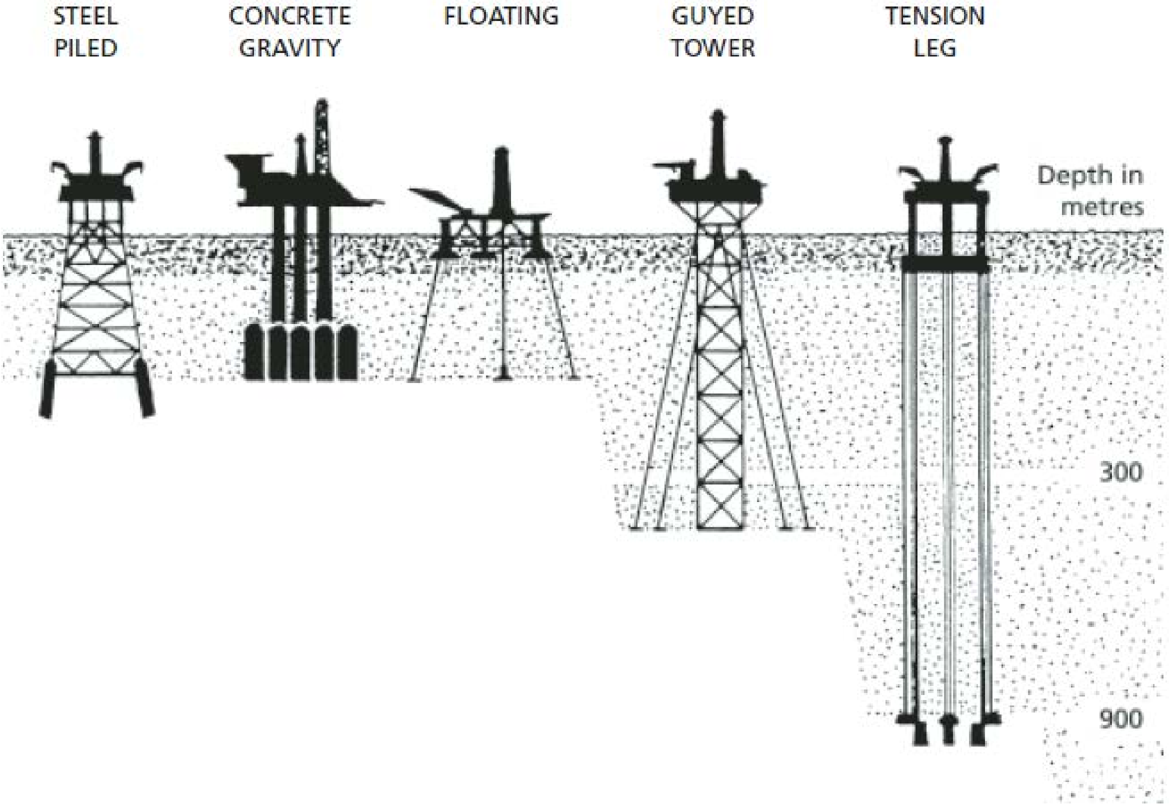
Figure 28. Underwater noise levels versus frequency and distance to the drilling platform during construction drilling for a wind farm at North Hoyle, UK

The narrowband sound radiated by seabed drilling can be distinguished from background noise at distances up to about 7 km. However, the PSD levels of this noise are comparable to or smaller than the spectral levels of noise from other man-made sources in the area even at short distances. Based on this observation, it was concluded that rock socket drilling was a relatively low-level noise source that was not expected to cause any significant environmental effects compared to other noise sources (Nedwell et al. 2003).

5.3.2 Installation of production platforms and infrastructure

During the development phase of an oil or gas field, drilling rigs are removed and the site is left with production platforms and infrastructure necessary for extraction. The type of production platform used is based on site conditions and size and type of hydrocarbon reserve. For reserves within sufficient range of a mainland facility or to a central main processing platform, a small platform with a pipeline extending to the main processing facility can be used. In more remote fields, subsea units with flexible flow lines leading to a buoyed riser can be installed to feed into a fixed platform, a floating production and storage unit, or an offtake tanker. In these systems, processing occurs at the platform or floating production unit, or at an onshore facility.

Fixed production platforms are ‘fixed’ to the seabed such as by steel piles driven into the seabed, jacked up on legs (converted jack-up rigs), by gravity concrete or steel structures held on the seabed by their own weight, or by vertical or radiating cables anchored to the seabed (tension leg platforms or guyed towers, respectively; Figure 29). The platforms’ support structures not only provide anchorage but also protect the well pipes and casings by serving as a protective ‘jacket’, and remain on site during the life of the project. Production can occur over several decades, depending upon the size of the oil or gas reserve, and platforms can often have 10–15 wells (Islam and Khan 2007).

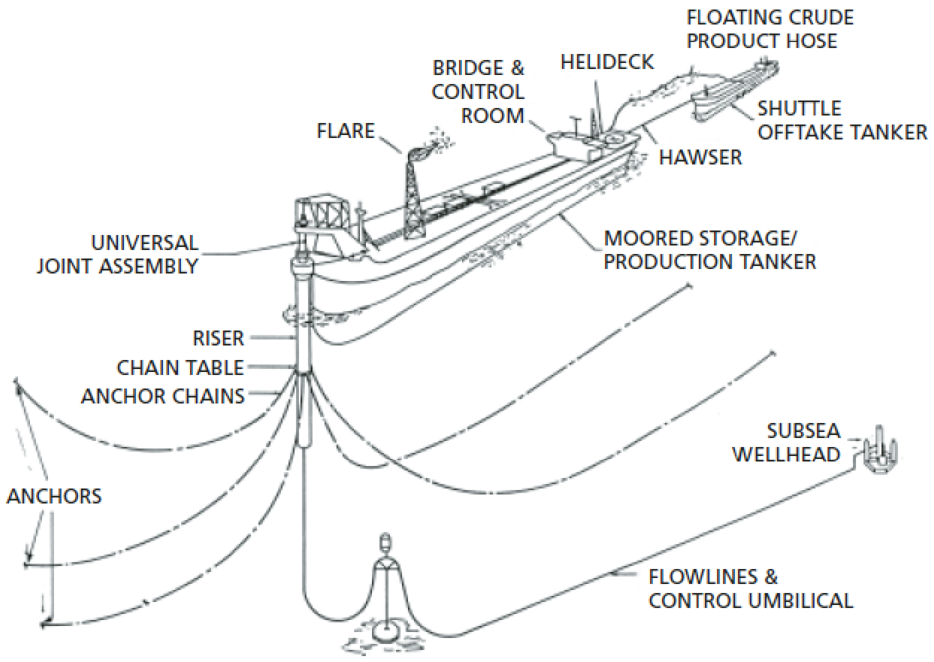


Source: Wilkinson 2006

Figure 29. Examples of offshore production platforms

As production of oil targets deeper and more remote fields, Floating Production, Storage and Offloading (FPSO) units, which are un-fixed structures, are becoming more common. FPSOs have oil processing and storage capability and are moored into place but can rotate freely around the receiving point. FPSOs are favoured in remote offshore environments, in small fields that won't produce for decades and in cyclone-prone regions because they are easy to install and disconnect from the moorings and do not require pipeline infrastructure to transport oil (Shimamura 2002).

The equivalent for liquefied natural gas – Floating Liquefied Natural Gas (FLNG; Figure 30) vessels – are a new technology for extracting and liquefying natural gas on-board a vessel and are currently under development. The first (Shell's Prelude) is under construction and is planned to commence work in 2017. Some fields will require several FLNGs.



Source: Wilkinson 2006

Figure 30. Schematic of a Floating Production, Storage, and Offloading vessel

Underwater noise during development and production is created by sources such as machinery, generators, and pumps on platforms and vessels. Vessels including FPSO vessels, rigs, tugs, tenders, and tankers produce sound from propeller cavitation. For vessels with dynamic positioning systems, while machinery or equipment on the vessels create noise, the largest contribution to noise entering the water is from thrusters used during dynamic positioning of the vessel, although machinery or equipment on-board also create noise (McCauley 2002; Erbe et al. 2013). Many platforms are also constructed with helidecks, and helicopters operating in the area can also be a source of underwater noise.

5.3.3 Pile driving

Piles are driven into the seabed to support exploration and production platforms and to build piers and other infrastructure for oil and gas production and transportation. High-intensity underwater noise from marine pile driving may affect marine fauna. The extent of impact depends upon the intensity of sound at its recipient, which is a function of range. The range at which an impact may occur depends on several factors and parameters of the pile driving operation, such as:

- pile type (e.g. steel pipe, cast-in-steel shell (CISS), steel H-type, steel sheet, concrete and timber piles)
- geometric and physical characteristics of the pile (e.g. diameter/width, wall/sheet thickness, length, material density, Young’s modulus and Poisson ratio)

- driving type (impact or vibratory)
- driving force (impact energy or vibratory force)
- underwater noise mitigation means, if implemented (e.g. hammer cushioning, air bubble curtains or air shield)
- environmental characteristics (water depth, sound speed profile in water and physical/ geoacoustic properties of the seabed.

Impact marine pile driving produces impulsive underwater noise. Hammer strikes are typically repeated at 1–5 second intervals. Figure 31 shows the typical waveform of impact piling signals (left panel), recorded underwater at about 50 m from a pile driven nearshore, and its PSD level (right panel). The sound peak pressure level (SPL_{p-p}) exceeds 200 dB re 1 µPa at such short distances. Although the signal spectrum is broad, a frequency band from about 20 Hz to 2 kHz contains most of the energy of underwater piling sound. Typical values of the peak sound pressure level (SPL_{Pk}), RMS pressure level (SPL_{RMS}), sound exposure level (*SEL*) and their variations measured at 10 m from various impact-driven piles at 5–15 m water depth are summarized in Table 6 based on the data review in Illinworth and Rodkin (2007). Examples of levels recorded from impact pile driving in Australia can also be found in Erbe (2009).

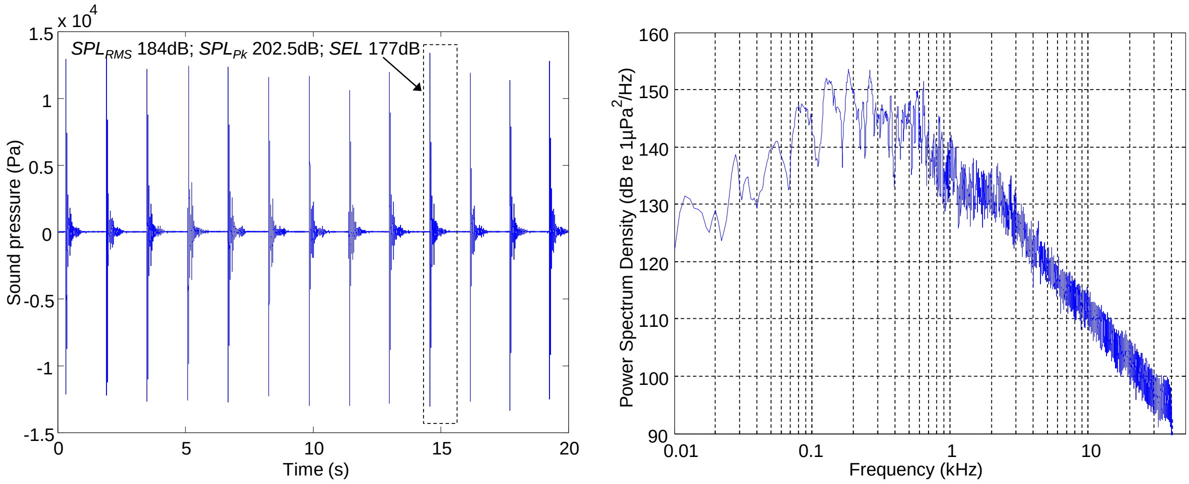


Figure 31. Typical waveform (left) and spectrum level (right) of underwater sound signal from marine pile driving

Table 6. Characteristics of impulsive underwater noise measured during impact pile driving

Pile type (diameter/width)	**Sound characteristics***		
	SPL_{Pk} **(dB re 1 µPa)**	***SPL_{RMS}*** **(dB re 1 µPa)**	***SEL*** **(dB re 1 µPa^2.s)**
Steel H-type (0.3 m, thin and thick)	190–195	175–183	160–170
Steel sheet (0.6 m)	205	190	180
Concrete (0.6 m)	185–188	170–176	160–166
Steel pipe (0.3 –1 m)	192–210	177–193	174–183
Steel (Cast-in-steel-shell, 1.5–2.4 m)	210–220	195–205	185–195

**Measured at 10 m from impact driven piles of different geometry, size and material*

In contrast to the impact-driven piles, vibratory-driven piles produce continuous underwater noise. Typical peak pressure levels in water produced during vibratory piling are considerably lower than those of impact piling noise. However, the sound exposure level of vibratory piling noise can be as high as that of impact piling noise. The level of noise also increases with the force of the vibratory driver at the pile head and the cross-section area of the pile. Typical values of SPL_{Pk}, SPL_{RMS} and *SEL* and their variations measured at 10 m from various vibratory-driven piles are given in Table 7 (Illinworth and Rodkin 2007).

Table 7. Characteristics of impulsive underwater noise measured during vibratory pile driving

Pile type (diameter/width)	**Sound characteristics***		
	SPL_{Pk} **(dB)**	***SPL_{RMS}*** **(dB)**	***SEL*** **(dB)**
Steel H-type (0.3 m)	165	150	150
AZ steel sheet (0.6 m)	175–182	160–165	160–165
Steel pipe (0.3–1.8 m)	171–195	155–180	155–180

**Measured at 10 m from impact driven piles of different geometry, size and material*

A hammer impact or driver vibration applied to a pile head produces both radial and axial deformation of the pile wall in the form of a bulge that propagates downwards along the pile with the travel speed slightly lower than the sound speed in the pile material. The radial displacement of the pile wall generates sound in the surrounding medium. The deformation wave travels along the pile faster than sound in water and hence forms a sound wave in the water column and seabed, which is similar to the so-called Mach cone from a supersonic jet in air. The downward wave in the pile is partly reflected from the pile toe and then propagates upward to the pile head to be reflected again, forming a series of waves propagating down and up the pile with a decaying amplitude due to radiation of sound energy. Sound emission from an impact driven pile was numerically modelled by Reinhall and Dahl (2011) and Zampolli et al. (2013), who used a Finite Element Method, and by Tsouvalas et al. (2012) using a semi-analytical solution.

The peak pressure of the sound emitted in water by a pile after a hammer impact is governed by the initial downward propagating deformation wave (Reinhall and Dahl 2011; Gavrilov et al. 2014) whose amplitude depends primarily on hammer speed at the time of impact and the pile cross-sectional area (Deeks 1992). In contrast to the peak pressure, the sound energy emitted into the water column and, consequently, the sound exposure level, also depend on the hammer mass (or vibratory force), pile length, penetration depth into the seabed and seabed material (Gavrilov et al. 2014).

Accurate predictions of underwater noise levels from marine pile driving require complex numerical modelling, such as that described by Reinhall and Dahl (2011) and Gavrilov et al. (2014).

5.3.4 Vessels

A variety of vessels are used by the offshore petroleum industry during exploration, construction, production and decommissioning (Table 8). All vessels emit underwater noise. This noise is partly due to machinery on the vessel, such as generators, engines, pumps, etc., which transmit sound through the hull into the water when operating. Fluid flow past the vessel can cause resonance and strumming of appendages or cavities. For propeller-driven ships, the loudest source of noise is propeller cavitation (Ross 1976; Urick 1983). A rotating propeller creates low-pressure areas near the blades. If the propeller turns fast enough, and the pressure becomes low enough, bubbles are created which grow, collapse and rebound—all the while emitting noise. The phenomenon is similar to boiling water producing bubbles, although boiling is a result of an increase in temperature whereas bubbles produced by cavitation are a result of a decrease in pressure. Propeller cavitation noise is broadband due to the range of bubble sizes involved, from a few Hz to tens of kHz. Cavitation noise peaks at low frequency, typically between 20 and 200 Hz. Propeller cavitation noise is amplitude modulated by the blade rate, i.e. the product of the number of blades and the propeller's rotations per minute (rpm). The overall ship noise spectrum usually shows the broadband shape of the cavitation spectrum, plus overlain tonal components below a few 100 Hz related to the blade rate and harmonic overtones, and to gear and engine tones (Arveson and Vendittis 2000; Wright and Cybulski 1983).

Table 8. Types of offshore vessels used by the offshore petroleum industry

Exploration	Construction	Production	Support
seismic survey vessel	dredge	drillship	tug
seafloor survey vessel	rock laying vessel	semi-submersible	tender
geotechnical survey vessel	cable, umbilical and flexible lay vessel	FPSO	supply ship
	pipe layer	FLNG	workboat
	jack-up	tanker	accommodation ship
	barge		RHIB
			crewboat

Note: FLNG –Floating Liquified Natural Gas, FPSO - Floating Production Storage and Offloading, RHIB – Rigid-hulled inflatable boat.

The level of ship noise typically increases with vessel size, tonnage and speed (Hamson 1997; McKenna et al. 2013; Ross 1976; Trevorrow et al. 2008; Urick 1983). Stronger noise is emitted from vessels when operating under load (e.g., tug boats or icebreakers). Vessel noise is not omni-directional. Rather, more noise is emitted towards the vessel sides, whereas radiation towards the bow is reduced by the shielding effect of the hull and with noise towards the back reduced by scattering and absorption by the bubble cloud in the ship's wake (Arveson and Vendittis 2000).

Figure 32 shows a spectrogram of the noise emitted by a large vessel. Strong tones are visible, primarily at 6 Hz and corresponding harmonic overtones (12 Hz, 18 Hz, 24 Hz, etc.). Although the distance is unknown, the ship was closest to the hydro-acoustic station about 700 s into the recording. There is a U-shaped pattern to the broadband cavitation spectrum about this point in time, resulting from the Lloyd mirror effect. As the vessel noise originates close to the sea surface, the direct path interacts with the surface-reflected path yielding an alternating pattern of constructive and destructive interference over a broad range of frequencies. Smaller vessels typically have engines with higher rpm, hence higher propeller blade rates, and the cavitation spectrum peak is shifted to higher frequencies.

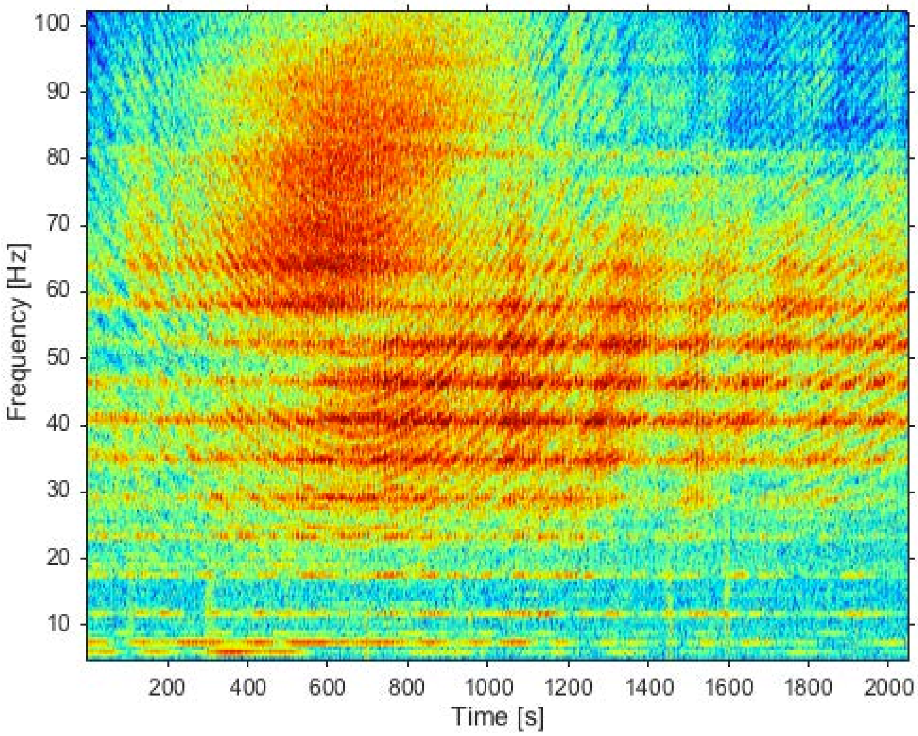


Figure 32. Spectrogram of a passing ship as measured by the Cape Leeuwin Hydro-Acoustic Station in south-western Australia

The broadband source level (SLbb) of vessels of varying sizes have been reported. Of those, small boats (<10 m) with outboard or inboard motors, propeller or jet propulsion, ranged from 157 to 182 dB re 1 µPa @ 1 m, increasing with speed (Kipple and Gabriele 2003; Kipple and Gabriele 2007). Rigid-hull inflatable boats that commonly support nearshore operations or large ships had SLbb of 125–147 dB re 1 µPa @ 1 m at slow cruising speeds of 10–11 km/h, and 150–170 dB re 1 µPa @ 1 m at speeds of 31–55 km/h (Erbe 2002a). Survey vessels in the absence of an operating acoustic source have SLbb of 180–191 dB re 1 µPa @ 1 m (Hannay et al. 2004; Wyatt 2008). Icebreakers, which are commonly used in the polar regions as survey, research or transport vessels, or to clear the path for industrial operations, when involved in ice breaking work are among the loudest vessels, in particular during reversing-and-ramming manoeuvres, with SLbb of 190–205 dB re 1 µPa @ 1 m (Erbe and Farmer 2000; Roth et al. 2013; Thiele 1988). Barges used to carry cargo or as platforms for construction are mostly not self-propelled and are towed into position by tugs, so the associated noise therefore depends largely on the operations on the support tug (Wyatt 2008). Tugs are louder when pushing or towing as opposed to transiting and SLbb of 165–192 dB re 1 µPa @ 1 m have been reported (Bassett *et al.* 2012; Hannay *et al.* 2004; Hatch *et al.* 2008; Wyatt, 2008). The situation is similar for Floating Production Storage and Offloading (FPSO) vessels, which are moored in place while producing oil. A statistical approach was employed to quantify the noise emitted by six FPSOs off the coast of Western Australia during a multitude of operations that included tug boat and tanker contributions at times. The median SLbb was 181 dB re 1 µPa @ 1 m, range 173–188 dB re 1 µPa @ 1 m (Erbe et al. 2013). Tankers have been reported with SLbb of 177–185 dB re 1 µPa @ 1 m (Hatch *et al.* 2008; McKenna et al. 2012; Table 9).

Table 9. Reported broadband source levels (SLbb) produced by various vessels

Vessel type	**SLbb (dB re 1 µPa @ 1 m)**
jetskis	122–149
boats, RHIB, 10 km/h	125–147
boats, RHIB, >31 km/h	150–170
tugs	165–192
barges	167–179
FPSOs	173–188
container ships	173–197
cruise ships	174–194
fishing vessels	174–195
tankers, chemical product	177–185
ferries, car	178–184
cargo ships, coal	178–192
icebreakers	179–205

Source: data from Erbe 2012, Erbe 2002, Bassett et al. 2012, Wyatt 2008, Hatch et al. 2008, Erbe et al. 2013, McKenna et al. 2013, McKenna et al. 2012, Kipple 2002, Kipple 2004, Allen et al. 2012, Arveson and Vendittis 2000, Roth et al. 2013, Erbe and Farmer 2000, Thiele 1988.

Note: FPSO - Floating Production Storage and Offloading, RHIB – Rigid-hulled inflatable boat.

A U.S. standard exists for the measurement of ship noise (ANSI-ASA S12.64-2009, American National Standards Institute 2009), and the International Standardization Organization (ISO) is currently finalising an international standard (ISO/TC 43/SC 3/WG 1). Standards for the measurement, data analysis and reporting of ship noise are needed to allow a comparison of recorded ship noise to the noise of other vessels and to noise emission policies (Erbe et al. 2016a). In environmental impact assessments, ship noise reported in the literature is commonly used to predict noise emission from other vessels in other environments. This is problematic because the environment affects sound propagation and levels recorded at some range depend on the specific hydro- and geoacoustic environment at the time and location of the recordings. Unless the environment was well understood, and the source levels were corrected for the effects of the environment, specific recordings cannot be used in new situations.

5.3.5 Dredging

Dredging is the removal of seafloor material and its transfer to a location for deposition. In the oil and gas industry, dredging is generally required to create pipeline trenches and to deepen harbours and shipping channels. Dredgers used for removal include Cutter Suction Dredgers (CSDs), Trailing Suction Hopper Dredgers (TSHDs), backhoe dredgers, and grab dredgers. The dredgers vary greatly in the way that they operate. TSHDs are similar to large ships in that they are self-propelled. They remove material from the seafloor by trailing dragheads beneath the dredger as the vessel moves forward. CSDs are also self-propelled but move at a much slower rate because they are constrained by a rotating cutterhead that is embedded in the material being cut and swings laterally in front of the dredger. They advance by transferring between wires or ‘spuds’ that anchor the dredger in place (Reine et al. 2014). Grab and backhoe dredgers use a mechanical bucket or backhoe to scoop material from the seafloor.

Most TSHD noise comes from the propeller and engines but noise is also generated by pumps and generators and the draghead scraping along the substrate. Noise from CSDs is mostly generated by the rotating cutterhead ‘cutting’ into the substrate, pumps and impellers, sounds of material being transported through pipes, machinery, and the vessel itself. Noise from TSHDs and CSD noise is largely continuous, broadband. Noise from grab and backhoe dredgers is produced mainly from scraping when ‘scooping’ the material into the bucket. Hydraulic pumps and winches used for moving and dumping material onto barges also produce noise, as do tugboats and tenders used for the barges. Noise produced by grab and backhoe dredgers is broadband, continuous by nature, but occurs intermittently.

Source levels can range widely depending upon the equipment used and substrate dredged, with most energy below 1 kHz (Clarke et al. 2002; Miles et al. 1987; Table 10). Highest levels recorded have been from large capacity TSHDs (Parvin et al. 2008) and lowest levels are generally from bucket dredgers (Miles et al. 1986).

Table 10. Examples of broadband source levels of dredgers

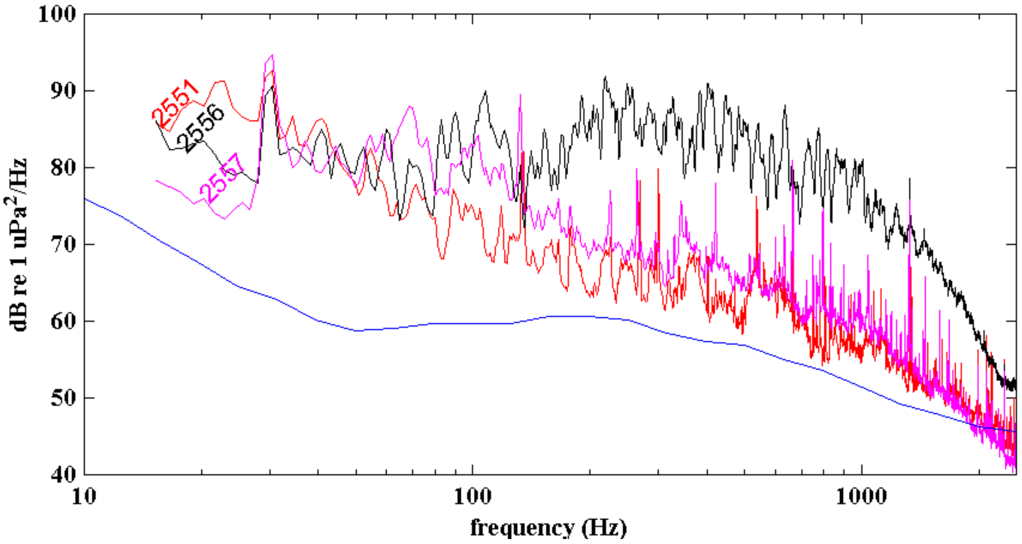
Dredger type	Frequency (Hz)	SPL (dB re 1µPa @ 1 m rms)	Reference
Medium TSHD	–	161–178	Reine et al. 2013
TSHD (2700 m^3)	20–80,000	186	Parvin et al. 2008
TSHD	31.6 Hz to 39.8 kHz in 1/3 octave band levels	189	Robinson *et al.*, 2011
CSD	3–20,000	175*	Reine et al. 2012
Backhoe dredger	20–100,000 30–20,000	163* 179*	Nedwell et al. 2008; Reine et al. 2012
Bucket dredger	–	150–162	Miles et al. 1986; Miles et al. 1987

*Notes: *back-calculated, TSHD = Trailing Suction Hopper Dredger, CSD=Cutter Suction Dredger, SPL=Sound Pressure Level, rms = root mean square.*

5.3.6 Machinery and flow noise

Noise can be generated by machinery used for propulsion (e.g. motors, engines, thrusters) and for supporting operations (e.g. pumps, generators, air-conditioners). Energy from vibration and noise passes into the water when these are coupled to structures such as vessels or oil and gas platforms, which are in turn coupled to the water. Vibration can be caused by cavitation and turbulence in pipes, pumps, and valves and by rotating shafts or blades.

There have been few studies of underwater source levels of liquid or gaseous flow through pipes and valves. McCauley (2002) measured noise from above a wellhead and pipelines using a calibrated mid-water receiver drifted across several seabed wellheads and associated pipework. The power spectra of various sources measured are shown in Figure 33. High frequency noise between 100 Hz and 2.5 kHz was observed in the wellhead recording. Above 2.5 kHz snapping shrimp noise began to dominate, but the wellhead noise probably extended to higher frequencies. This wellhead noise was broadband in nature (i.e. not made of distinct tones) suggesting cavitation within the wellhead pipelines as the source. The broadband level of the wellhead signal was low at 113 dB re 1 μPa rms. There was evidence of noise from the pipeline but it was a weaker signal and difficult to differentiate from the noise of a nearby FPSO.



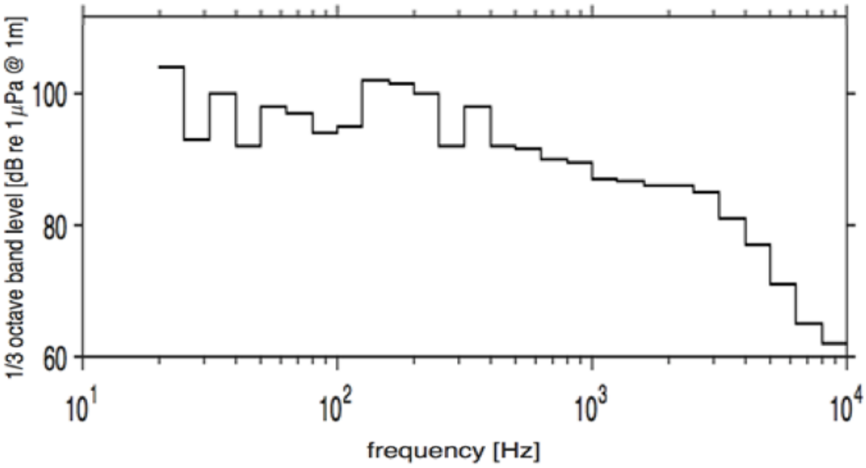
Note: Underwater sound (1.27 Hz analysis bandwidth, 3 minute averages) recordings were made over the wellhead at 5.97 km from the stern of the Cossack Pioneer (black line); over pipeline at 3.87 km from the stern of the Cossack Pioneer (magenta); and 4 km from pipeline and 3.5 km from the stern of the Cossack Pioneer (red). The lower blue line represents the lowest ambient sea noise levels (given the wind conditions during recordings and no deep ocean noise input).

Figure 33. Time averaged spectra from drifting recorders over a wellhead and pipelines

5.3.7 Helicopters

There are very few reports on underwater noise generated by overhead helicopters. Generally, acoustic energy underwater received from an overhead helicopter diminishes with increasing altitude of the helicopter and with decreasing depth of the receiver (Urick 1972, Richardson et al. 1995b). Most acoustic energy from helicopter noise underwater has been reported to be low frequency (<500 Hz; Richardson et al. 1995b; Figure 34). Most energy produced is from the rotor and propeller blades, and is generally broadband and composed of many tones. Dominant tones reported for a Bell 212, Bell 214ST, and Sikorsky 61 were 10.8 + harmonics, 11.8 Hz + harmonics, and at 68 and 103 Hz, respectively (Urick 1972; Moore et al. 1984; Greene 1985;

Richardson et al. 1990). Received levels of a 22 Hz tone from the Bell 212 ranged from 101 to 109 dB re 1 uPa at distances ranging from 152 to 610 m.



Source: Greene 1985 and Richardson *et al.* 1995.
Notes: Spectra produced by back-propagated to the water surface

Figure 34. Underwater recording of the one-third octave source spectra of a helicopter flying at 305 m above the sea surface

5.4 Decommissioning

Decommissioning occurs when an oil or gas reserve is exhausted or is no longer considered economically viable and usually occurs in stages. Decommissioning requires the preparation of the platform removal, the wells to be plugged and abandoned, the mobilisation and demobilisation of Derrick barges (for moving heavy objects), the complete or partial removal of the platform, the decommissioning and removal of pipelines and power cables, the disposal of materials, and site clearance (Abshire et al. 2012). Methods for plugging and abandonment (P&A) depend upon the environment and the facilities and structures in place. The platform is prepared for decommissioning by first flushing and cleaning all equipment and pipes and disposing of remaining hydrocarbons, and then removing all equipment on the platform as well as underwater. The wells are plugged by removing the downhole equipment, cleaning out the wellbore, and plugging the well at several locations within the well. Subsurface casings near the ocean floor are removed. Cutting the casing at the desired depth is done either by the use of explosives or by mechanical or abrasive cutting. The casings are then removed and transported to an onshore site for disposal. For removal of the platform, dismantling of the platform may be required, depending upon the size. For heavy equipment Derrick barges are used. Removal of the jacket, including subsurface sections of piles near the seabed, is done through the use of explosives, mechanically, by torches, or through abrasive cutting. Materials from the platform are either reused, recycled, or disposed of. A survey follows removal of material to ensure that any remaining obstructions are removed.

5.4.1 Sound and vibration from decommissioning

During decommissioning underwater noise is created from propeller cavitation from vessels on site, from machinery, equipment and pumps, and from abrasive cutting and explosives if used.

Platform decommissioning often requires the use of explosives to cut through well casings and platform legs (Rigzone 2015). Explosives are also used to break up rock during harbour construction, channel clearance, and other construction activities.

The signal from an explosion is similar to that from an airgun in that it consists of an initial sharp pulse followed by a decaying series of bubble pulses. The main difference is that the rise time of the initial pressure pulse is much faster in the case of an explosion, and forms a nonlinear shock wave. Airguns produce a longer, finite rise time and do not produce a shock wave.

A formula for the peak pressure from an unconstrained explosive charge as a function of the charge weight and range (MTD 1996, Nedwell and Edwards 2004, Genesis 2011) has been used to plot the peak sound pressure level as a function of source-to-receiver range and charge weight (Figure 35). Peak levels can be substantially reduced if the blast is completely confined within a structure, but this may not be achieved in practice (Nedwell et al. 2001).

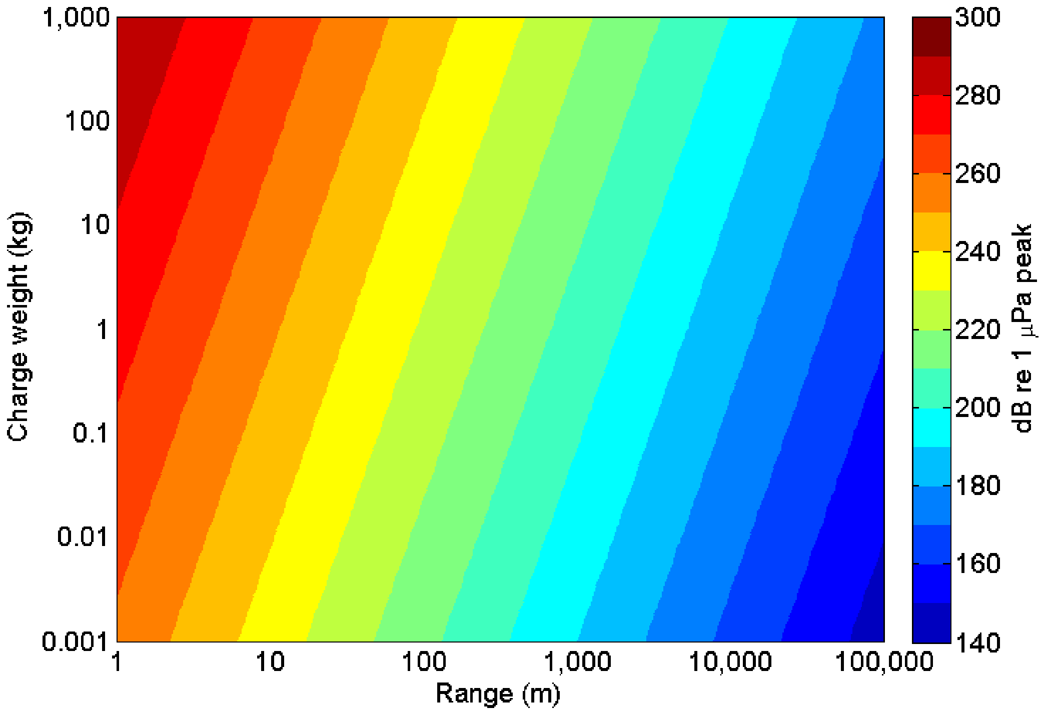
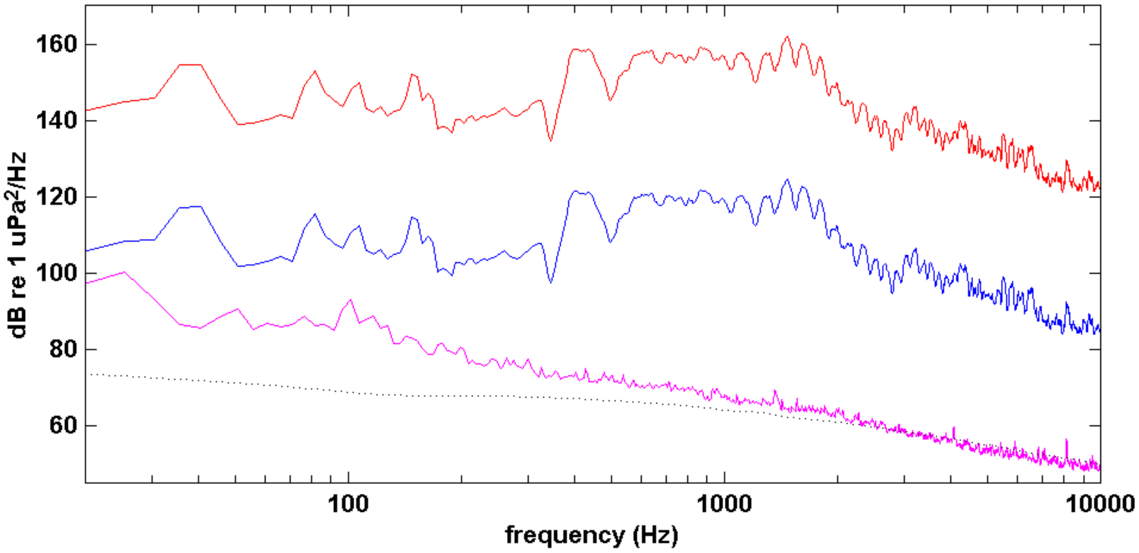


Figure 35. Peak sound pressure level from an unconstrained explosive charge as a function of source-receiver range and charge weight

Decommissioning of offshore infrastructure also often involves mechanical or abrasive cutting. Data on this type of underwater noise are scarce but McCauley (2004) found that jet cutting of a wellhead below the seabed in 80 m of water on the north-west shelf of Australia produced broadband noise that was above background levels from 10 Hz to more than 10 kHz and had a broad peak centred around 1 kHz. A time-averaged measured received spectrum and an estimated source spectrum are shown in Figure 36. The source spectrum was estimated from the received spectrum without accounting for the effects of sea surface and seabed reflections and should therefore be considered approximate, although the broadband nature of the source will have reduced the significance of seabed or sea surface. The estimated broadband source level was 189 dB re 1 μPa rms @ 1 m.



Source: McCauley 2004.

Notes: The blue curve was measured by a hydrophone 75 m above the seabed. The red curve is an estimated source spectrum referenced to a range of 1 m from the source (this correction was made using spherical spreading and therefore ignores the effects of seabed and sea surface reflections. The magenta curve is the average received spectrum when cutting was not taking place

Figure 36. Time averaged spectra of wellhead cutting noise in 80 m of water

Underwater noise from sources such as vessels, machinery, pumps, and generators used during decommissioning are described in Sections 5.3.4 and 5.3.6.

5.5 Summary of sound and vibration produced by oil and gas activities

As may be seen from the preceding sections, many of the activities undertaken by the offshore oil and gas industry result in increased levels of underwater noise in the marine environment. From an environmental perspective, the most significant of these sources are likely to be the airgun arrays used during seismic exploration for new oil and gas reserves. This is because of the high sound levels they produce combined with the frequent operation of the sources (typically every ten seconds), and the long durations of many of these surveys (weeks to months). The airguns are not fired during line changes or other pauses in operations, so there is some respite for animals in their vicinity, but they do operate for a considerable proportion of the time.

Pile driving associated with offshore and coastal construction also produces high underwater sound levels (and also ground vibration), particularly during the construction of major port facilities where pile driving may occur over extended time periods.

Underwater explosives are another source of very high underwater sound levels, however they tend to be used very infrequently by the offshore industry.

Sources of continuous noise such as ships, dredgers, drill ships, wellheads, valves and helicopters produce much lower peak sound levels than the three impulsive sound sources mentioned above, but the signals last much longer. Of these, the most significant source is the cavitation noise produced by thrusters on support ships and other vessels operating under the control of dynamic positioning systems.

Geophysical survey sources such as boomers, sparkers and sub-bottom profilers can produce quite high peak sound levels but the total amount of sound energy they put into the water is much lower than that produced by airgun arrays. Similarly, some hull mounted sonar systems have quite high source levels, but they use very short duration pulses, resulting in relatively low acoustic energy. The rapid attenuation due to the high acoustic frequencies of many sonars, and narrow beamwidths also mean the high levels occur over a restricted region of the water column.

Underwater communication and position fixing systems typically have much broader beam patterns than sonar systems and substantially lower source levels, but may transmit much longer signals. Attenuation due to their relatively high acoustic frequencies restricts their geographical footprint.

6 Effects of sound on Australian marine fauna

In the previous section we have seen that underwater sound produced during oil and gas activities varies widely in its frequency range (or bandwidth), duration, intensity, and how it propagates through different environments. We know that the level of effect on fauna will not only depend upon the nature and duration of sound exposure, but also upon an animal's hearing sensitivity and physiology. We have also reviewed the idea that not only direct effects described above can occur, but marine fauna can experience indirect effects if species which they depend upon for survival have been impacted (Section 3). This is of key importance for accurate assessments of impacts to marine fauna. Ultimately, an assessment of the sensitivity of an animal and the biota that it depends upon, the characteristics of the sound it is exposed to, and the response of the animals are used to assess the consequences of noise exposure to the individual. Through an understanding of the demographics and the ecology of the population, the impacts to the population can be evaluated (Figure 37). This type of approach is similar to the Population Consequences of Acoustic Disturbance (PCAD) model developed by US authorities as a framework for characterising the ecological consequences of noise exposure for marine mammals (NRC 2005).

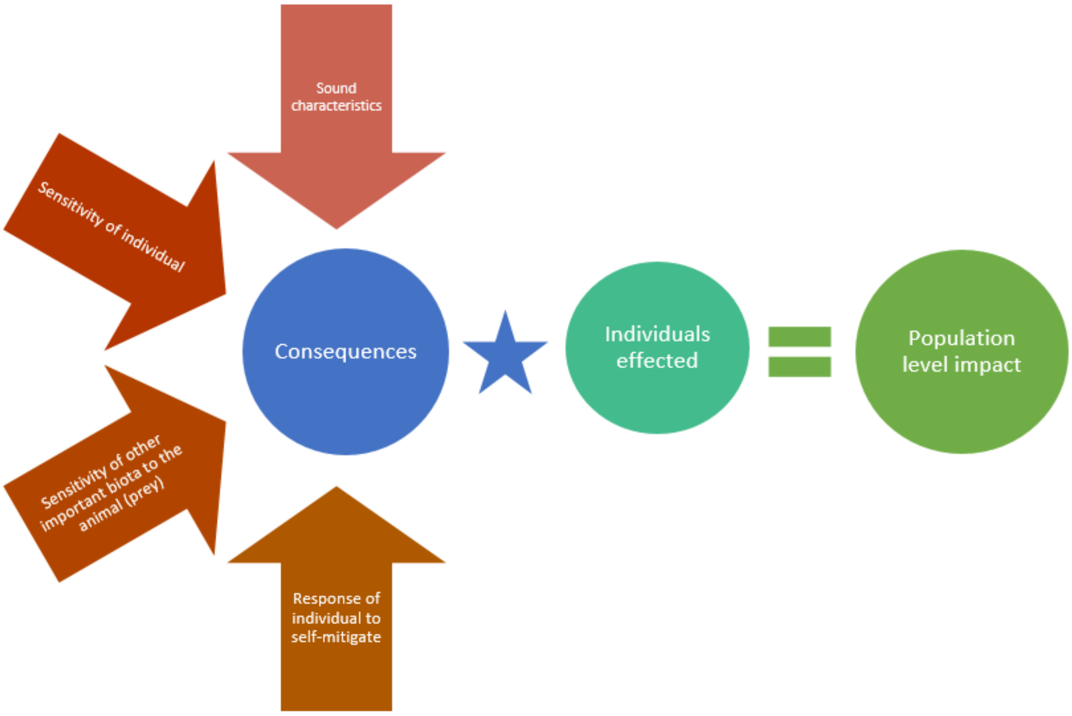


Figure 37. Some of the factors determining the level of underwater sound exposure impacts to marine fauna

In this section, a synthesis of current knowledge on hearing sensitivities and impacts of underwater sound produced during petroleum activities on Australian species is presented. For each faunal group we provide a brief description of the species in the group, summarise what is known about their sensitivity to sound, and review the existing research on underwater noise impacts. We end each faunal group section by identifying gaps that exist in current knowledge.

6.1 Marine mammals

There are approximately 130 species of marine mammals worldwide, including seals, sea lions, whales, dolphins, porpoises, otters, walruses, manatees and dugongs (listed by common and species name in Appendices C–E). In Australia, 60 species of marine mammals reside or migrate through Australian waters. The IUCN (2015) lists nearly half of these (25) as data deficient, meaning there is not enough information on their behaviour, demographics, population size, abundance, distribution, and vulnerability to threats to assess their status. Half (30) of the Australian marine mammal species are protected by the EPBC Act and include those listed as:

- endangered and migratory (blue whale and southern right whale; *Balaenoptera musculus* and *Eubalaena australis*)
- vulnerable and migratory (sei whale, fin whale and humpback whale)
- vulnerable and marine (Australian sea lion, Subantarctic fur seal, and southern elephant seal) those that are marine but not listed as threatened (Antarctic fur seal, Australian fur seal, Hooker's sea lion, leopard seal, crab-eater seal, Weddell seal, Ross seal, and New Zealand fur seal)
- migratory but not listed as threatened (Antarctic minke whale, Bryde's whale, pygmy right whale, the SE Asian population of Fraser's dolphin, dusky dolphin, Australian snubfin dolphin, killer whale, spectacled porpoise, sperm whale, Indo-Pacific humpback dolphin, the Tropical Pacific and SE Asian populations of the spotted dolphin and long-snouted spinner dolphin, the Arafura/Timor Sea populations of spotted bottlenose dolphin, and the dugong).

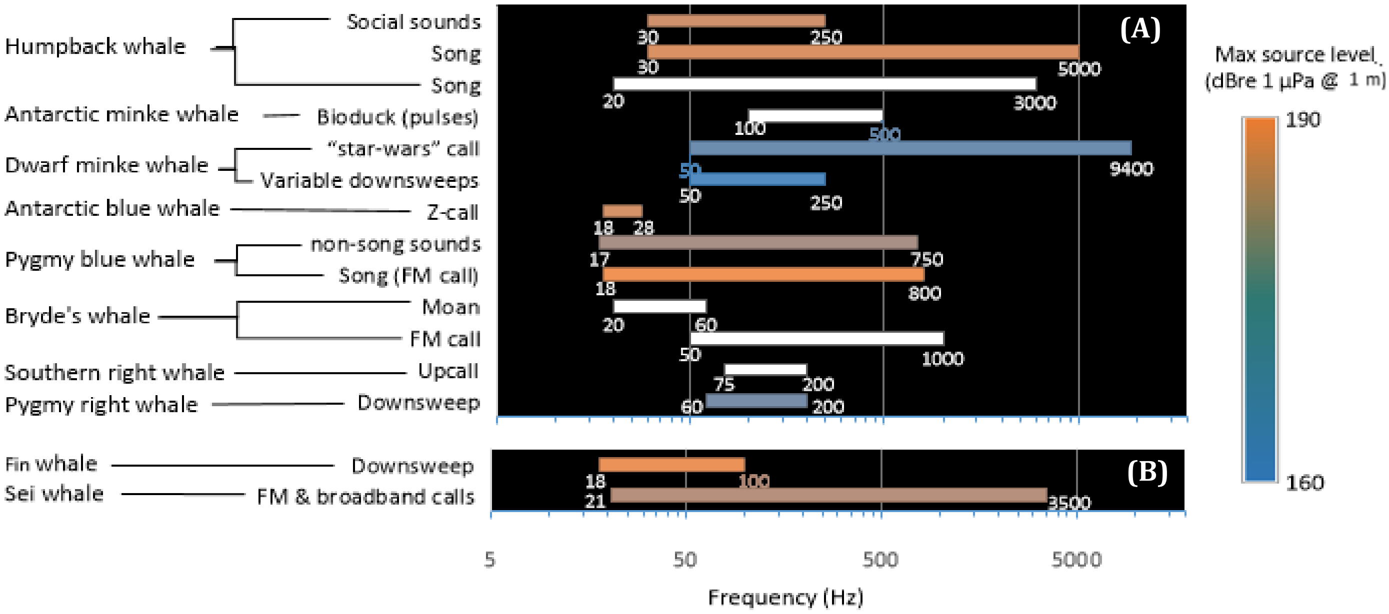
Marine mammals fall within the same broad taxonomic grouping, but have vastly different evolutionary adaptations. The direction of morphological evolution of marine mammals has led to very different anatomical development and complexity, behaviours, and physiologies. For instance, the baleen whales (mysticetes) are some of the largest animals living on earth, ranging from 6 to 30 m in body length. This group of animals includes the blue, humpback, southern right, fin, Bryde's, minke and sei whales. They have evolved baleen plates in adulthood instead of teeth for filtering prey such as plankton from water. In contrast, toothed whales (odontocetes) are generally small compared to mysticetes. Odontocetes include the sperm whales, orcas, pilot whales, beaked whales, dolphins and porpoises and have teeth throughout their lives. With their divergent morphology and physiology, these two groups of cetaceans are adapted to occupy different ecological niches. Mysticetes feed on plankton, which are at the base of the food chain base, while odontocetes are adapted to hunt and consume higher order prey such as squid, fishes, turtles and marine mammals (such as seals hunted by killer whales). Also, most mysticetes regularly undertake long annual migrations from feeding grounds in high latitudes to breeding grounds in lower latitudes. In contrast, odontocetes generally have smaller home ranges where they reside, reproduce and feed year-round. Odontocetes have highly developed high frequency sonar systems for locating and tracking prey, which are absent in the mysticetes. The wide range in behaviours, body sizes and ecological niches has led to a diversity of sound production and hearing capabilities in marine mammals.

6.1.1 Mysticetes

Hearing sensitivity

Because of their large body sizes there are no direct measures of hearing sensitivities for mysticete whales. However, the range in which animals create and respond to sound can give us insight into their hearing range. This is not, however, an accurate measure of hearing sensitivity and should be used with caution, especially for species that may mainly listen for rather than produce sounds.

Mysticetes are capable of producing low-frequency sounds between approximately 10 Hz and >24 kHz (Au et al. 2006; Erbe 2002b), although the peak energy emitted by most species is less than 300 Hz (Wartzok and Ketten 1999). In Australia, underwater recordings of a range of sounds have been attributed to humpback, Antarctic blue, pygmy blue, southern right, pygmy right, dwarf minke, Antarctic minke, fin, sei, and Bryde's whales. As in other areas of the world, humpback whales in Australian waters have been recorded to have one of the greatest frequency ranges from 20 Hz to >5 kHz. Dwarf minke whales also have a large frequency range, particularly the 'star-wars' call that has been documented between 50 Hz and 9.4 kHz. Blue (Antarctic and pygmy), southern right and pygmy right whale sounds recorded in Australia have lower frequency ranges. Estimated source levels range from 123 to 189 dB re 1 μPa @ 1 m (Figure 38; Appendix B, Table 1), with the highest levels estimated for humpback and blue whales and the lowest for humpback whale social sounds (Figure 38; Appendix B, Table 1). Overall, sounds recorded in Australia generally fall within the range of those recorded elsewhere in the world. For sei and fin whales, data are unavailable from Australian waters and have instead been drawn from studies from elsewhere in the world (Appendix B, Table 1).



Data source: Appendix B, Table 1.

Notes: (A) recorded in Australian waters and (B) examples from elsewhere in the world. White bars indicate absence of source level estimates. Limited frequency ranges in the diagram may reflect limited samples of recordings so far obtained rather than the absolute range for some species.

Figure 38. Frequency range and maximum estimated source levels of sounds so far recorded from mysticete whale species that occur in Australia

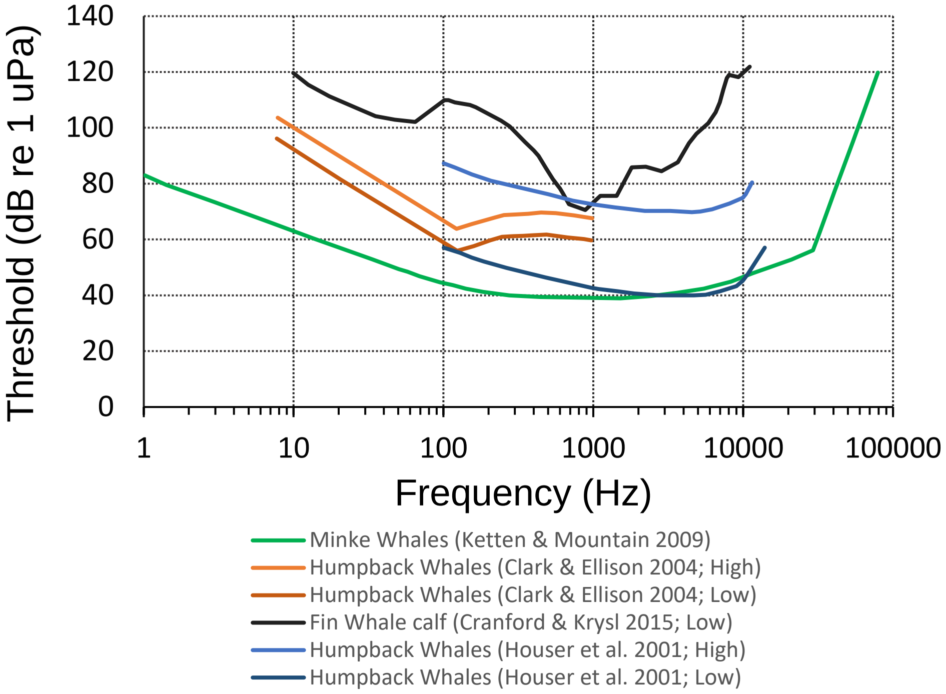
While the range in sound production is indicative, the best way to obtain information on hearing sensitivity is to measure an animal's ability to detect sounds at different frequencies and create audiograms to illustrate hearing thresholds as a function of frequency. Mysticetes cannot be practically maintained in captivity and trained or experimented on to obtain audiograms using auditory brain stem responses (ABR). Current ABR techniques work best for animals with auditory centres that are large relative to the brain and body size, and close enough to the surface of the head for surface electrodes to detect neural responses (Ketten and Mountain 2009). Furthermore, measurements are complicated by the need to access live stranded animals, which occurs rarely in mysticetes. Only one effort has been made to measure the auditory brains stem response of a grey whale calf (*Eschrichtius robustus*) during medical treatment and rehabilitation (Ridgway and Carder 2001), however the animal and acoustic conditions were poor. Alternative methods for ABR on mysticetes could be for insertion of electrodes to achieve a stronger signal, however this is a more invasive approach and would require ethical considerations.

For these reasons, expected hearing sensitivities have been drawn from known vocal ranges described above, observed responses to sounds, anatomical studies in combination with known parameters of well-studied land mammals, or biomechanical and structural modelling.

Predictive audiograms are available for three species that occur in Australian waters – minke, humpback and fin whales – although the carcasses used were not from Australian populations. Based on predictions, the best hearing range of minke, humpback and fin whales are expected to be between 10 Hz and 12 kHz, 20 Hz and 6 kHz, and 200 Hz and 5 kHz, respectively (Figure 39;

Houser et al. 2001, Clark and Ellison 2004, Ketten and Mountain 2009, Cranford and Krysl 2015). Greatest sensitivities for these species were predicted to be at 1.5 kHz, 885 Hz and 2.7 to 4.6 kHz, respectively. Note that the methods used by Houser et al. (2001) and Clark and Ellison (2004) do not show absolute audiograms, rather they are relative in terms of sensitivity as a function of frequency. No anatomical studies have been conducted in Australia to determine whether there is significant variation among populations.

The frequency range of vocalisations of species occurring in Australia (presented in Figure 38) mostly fall within the predictions, with the exception of the fin whale with downsweeps at frequency ranges lower than that predicted.



Note: based on biomechanical and structural modelling of the auditory sensory system.

Figure 39. Auditory sensitivity predictions for a minke (preliminary), humpback and fin whale

Experimental studies measuring impacts

Knowledge specific to responses of baleen whales to oil and gas activities in Australia has been mainly obtained during two substantial research programs; one completed in 2000, and the second which is currently underway (and reported in Section 0). These studies investigated the behavioural response of humpback whales to underwater noise from airguns and airgun arrays (Figure 40). There have been no targeted studies on behavioural responses of mysticetes to underwater noise created by FPSOs, dredging, drilling, machinery, shipping, pile driving, or explosives during oil and gas industry activities in Australia.

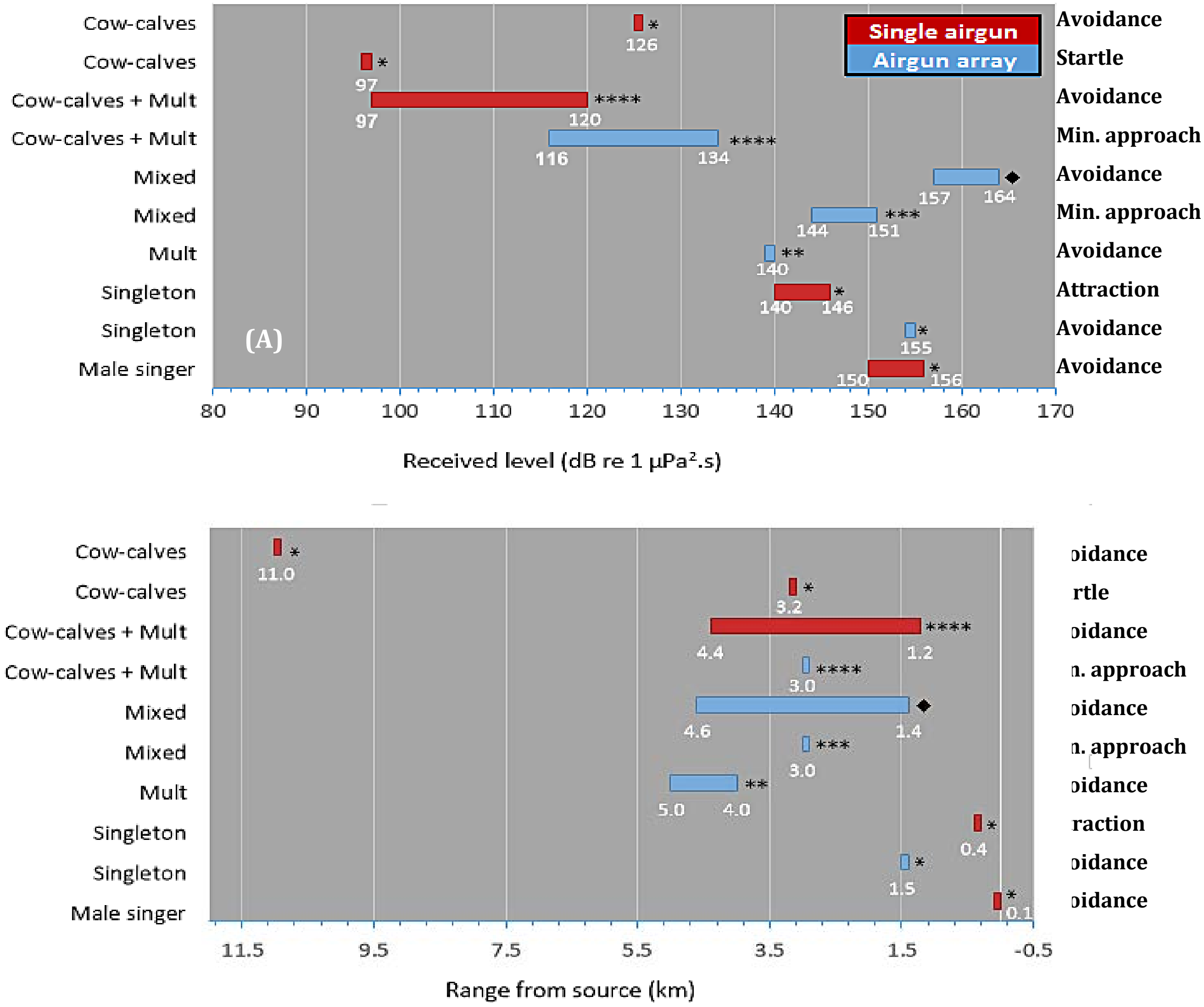
The first major Australian study on the response of humpback whales to seismic surveys reported no major change in the migratory route of southbound whales off Western Australia during a 3D seismic survey using a 2678 cui array (McCauley et al. 1998, 2000a, 2000b, 2003b Table 11). Whales sighted from the seismic survey vessel were reported to be detected in greater numbers at distances of more than ~3 km when the airguns were operating. This was attributed to avoidance or to animals spending more time at the surface when the airguns were operating.

'Focal follow' trials were also completed, whereby all surface behaviours of selected groups were recorded in detail throughout the trials. During offshore trials, four groups were focal-followed as they passed the operating seismic survey vessel. All animals responded in some way that resulted in the maintenance of distance or a reduction in sound loading from the active airguns.

During the same study (McCauley et al. 1998, 2000a, 2000b, 2003b), in 16 focal follow trials with resting humpback groups inside Exmouth Gulf, a single 20 cui airgun that was fired at 5 km range was towed on a course expected to intercept the whale groups if they did not change course or speed. During these trials, avoidance responses were recorded for all groups except a cohort of large single whales that approached the source in several experiments. Although the sample size was limited, groups with resting cows and calves displayed avoidance responses at lower thresholds than groups without cows and calves, and lower than offshore migrating animals (Figure 40, Table 11). Single animals – likely males – had the highest thresholds (Figure 40, Table 11) and were believed to be the animals that deliberately approached the airgun on occasion. In general, whale behaviour resulted in the maintenance of a certain distance from the airgun but on several occasions whales were seen to reduce the distance between themselves and the airgun.

Although not related to petroleum activities, short-term behavioural responses of southerly migrating humpback whales to the presence of whale-watching vessels have been studied in Hervey Bay (Queensland) and in NSW (Corkeron 1995 and Stamation et al. 2010, respectively; Table 11). Varied responses to whale-watching vessels were observed, with groups of whales showed a mixture of avoidance and approach behaviours as well as changes in time spent at the surface, diving rates and surface activity. Changes observed tended to be linked to group composition, with groups with calves generally being more sensitive to closely approaching vessels than non-calf pods.

The studies described above have limitations associated with difficulties in measuring responses of large marine mammals that spend most of their time below the surface of the water. All observation techniques used introduce a bias. Vessel-based observations can confound results by causing a response themselves. Land-based observations mitigate this effect but usually are based much farther away from the animals, with the result being reduced detection of behaviours.



*Notes: *=observation of one group, **=observation of two groups, ***= observation of 3 or 4 groups, ****= observation of 14 groups, ◆ proportion of 51 groups not specified, Singleton = single animal making up group, and Mult=multiple animals in group*

Figure 40. Sound exposure levels (A) and range from source (B) in which avoidance, minimum approach ('stand-off') and startle responses were observed in McCauley et al. 2003b

Table 11. Humpback whale behavioural studies conducted in Australia investigating response to underwater noise created by oil and gas activities and/or some similar sources

Year	Location	Response measured	Behavioural context/ cohort	Source	Observation methods	Limitations	SEL threshold level (dB re 1 µPa².s) [Range in km]	Level of response reported	R	Reference
1996	North West Cape, WA	Changes in distribution over broad migratory corridor	Southerly migrating whales	2678 cui 3D seismic airgun array in ~120 m water depth	Aerial surveys (8)	No control, limited sample size (effect size would have had to be large for detection), biases in experimental design due to inherent migratory behaviour	–	None	3	McCauley et al. *(*1998, 2000a, 2003a)
		Changes in distribution within observable range of the seismic vessel			Observations from seismic vessel (43 days, 51 groups)	No control, biases in experimental design inherent to observations conducted from a vessel	157–164* [1.4–4.6]	Avoidance or behavioural change at ~3 km		
		Changes in direction, speed, blow rate, & surface intervals based on focal follows	Mixed groups (4) of southerly migrating whales		Observations from a vessel following whale groups intercepting the array (4 focal follows)	Low sample size (4), mixed cohort of animals, biases in experimental design inherent to observations conducted from a following vessel, statistical analyses not possible	126 [11]	Avoidance of single cow-calf		
							140 [4-5]	Avoidance of two groups		
							155 [1.5]	Avoidance of singleton		
							144–151 [~3]	‘Stand-off’ (of 75% of animals)		
	Exmouth Gulf, WA	Changes in direction & speed, & surface behaviours based on focal follows	Mixed groups, most with cow-calf pairs	Approach (interception) of single 20 cui airgun in 15–20 m water depth	Observations from research vessel (16 groups: 12 having cow-calf pairs, 1 singleton, 1 single male singer, and one group of 5 animals)	No control for the presence of the vessel without active airguns, pre exposure period only, small sample size for some cohorts, groups in mixed social context, biases in experimental design inherent to observations conducted from a following vessel, behavioural/environmental context not included in statistical analyses (spatial analysis only considered)	97–132 [1.22–4.4]	Avoidance of all groups with cow-calf pairs + group of 5		
							116–134	‘Stand-off’ at range by groups with cow-calf pairs + group of 5		
							150–156 [0.1]	Maximum exposure for male singer		
							97 [3.2]	‘Startle’ response of group with cow-calf		
							140–146 [0.4] (165 [100])	Consistent attraction of adult singletons (9 of 16 experiments)		

Table 11 continued…

Year	Location	Response measured	Behavioural context /cohort	Source	Observation methods	Limitations	Thresh range (in km)	Level of response reported	R	Reference
1988–1989	Hervey Bay, QLD	Changes in surface behaviours, blow rate, & surface intervals based on focal follows	Southerly migrating non-calf groups	Vessels (whale watching)	Observations from research vessels (64 groups observed, ~50% of observations were of cow-calf groups)	Sample size of cow-calf pods were small, biases in experimental design inherent to observations conducted from a vessel, behavioural/ environmental context not included in statistical analyses, pseudo-replication (multiple observations on the same group, and independent groups used as independent observations), no received or source levels measured, specific distances not measured	Vessel presence (defined as within 300 m)	Likelihood of diving increased	1.5	Corkeron (1995)
								Rates of surface behaviour varied (increased rates of breaches and pectoral fin slaps observed), but not significant		
								No change in blow rate		
			Southerly migrating groups with calves					Likelihood of diving increased		
								Increased rates of surface behaviours observed (particularly breaches, pectoral fin slaps, fluke and peduncle slaps), but not significant		
								No change in blow rate		
								Decreased surface behaviour		

Table 11 continued…

Year	Location	Response measured	Behavioural context /cohort	Source	Observation methods	Limitations	Thresh range (in km)	Level of response reported	R	Reference
2002, 2003, 2005	Eastern Australia (off NSW)	Changes in surface behaviours, direction, blow rate, & surface intervals based on focal follows	Southerly migrating groups (including with calves)	Vessels (whale watching)	Observations from land and from the whale watching vessel (350 groups observed)	Behavioural/ environmental context not included in statistical analyses, no received or source levels measured, specific distances not measured	Vessel presence (<300 m, but partic. if ≤100 m)	Avoidance (17%, which were more likely to roll and have higher blow rates than groups that didn't respond to the vessel, and of which the time submerged and dive time were greater than for groups that approached the vessels)	1.5	Stamation et al. (2010)
							Vessel presence (<300 m, but partic. if >100 m)	Approach (23% – 12 of the 15 groups did not have calves. These were more likely to fluke swish than those that avoided, and more likely to trumpet blow, fluke swish, spy hop and float than those that did not respond to the vessel)		
							Vessel presence (<300 m)	No difference in overall proportion of surface active pods		
								Groups with calves increased percentage time on the surface (blow interval was longer, and decreased dive time)		
								No difference in dive rate, blow rate		
								Decreased frequency of peduncle slaps and side fluke		
								Groups with calves had a lower breach and roll frequency		
								Non-calf groups had lower pectoral wave frequency		
								Increased frequency of rise, slip under (particularly groups with calves within 100 m) and fluke down		

Criteria	Score
The work addressed a significant knowledge gap at the time it was undertaken relevant to petroleum activities	1
The metrics and exposure type were relevant to petroleum activities	1
The study conclusively identified the level of effects due to underwater noise on the subjects	1
The study can be generalised to the community/population/species targeted in the study	1
Total possible score	**4**

*Notes: Criteria is for a qualitative assessment rank of contribution to knowledge gaps at the time the work was produced. PAM = Passive acoustic monitoring; 'Stand-off' range = limit at which whales were not observed to approach; * = msp dB re 1μPa; R = Relevance (described in the Relevance Criteria at the bottom of the table); SEL = Sound Exposure Level.*

International research relevant to Australia

The responses of baleen whales to noise from oil and gas activities in Australia are consistent in their variability and range when compared with studies elsewhere on species not occurring in Australia. Early work in the 1970s reported changes in behaviour of bowhead whales in Alaska and Canada caused by noise associated with oil and gas activities (Fraker and Fraker 1981; Awbrey et al. 1983). More recently, a review by Moore and Clarke (2002) reported a summary of gray whale avoidance probabilities associated with a range of sound pressure levels for playbacks of noise associated with oil and gas industry activities from studies conducted by Malme et al. (1984, 1988) and Dahlheim (1987). Playback recordings including sounds from airgun signals, drillships, semi-submersibles, drilling platforms, production platforms, helicopters, tripping operations. Airgun arrays and single airguns were also used in experiments by Malme et al. (1984, 1988). Their results indicated that responses of migrating whales to airgun signals included abrupt changes in feeding and avoidance, resumption of feeding after exposure and changes in swim speed and direction consistent with avoidance (Malme et al. 1984; Malme et al. 1988). The probabilities of avoidance were 0.1 probability at 164 dB re 1 µPa, 0.5 at 170 dB re 1 µPa, and 0.9 at >180 dB re 1 µPa (rms). The probability of changes in feeding behaviour was 0.1 at 163 dB re 1 µPa (rms). Changes in call structure and rates and surface behaviour in response to airgun noise was also reported (Dahlheim 1987), with 0.5 probability at 173 dB re 1 µPa (rms) and 'increased milling' reported at levels between 110 and 130 dB re 1 µPa (rms). A 0.1 probability of avoidance was reported by Dahlheim (1987) for recordings of helicopters, drillships, semi-submersibles, drilling platforms, and production platforms sounds between 110 and 120 dB re 1 µPa (rms). For these same playback recording sounds, 0.5 probability of avoidance was reported for levels between 117 and 123 dB re 1 µPa (rms); and 0.9 probability for levels >127 dB re 1 µPa (rms).

In a different study (Ljungblad et al. 1985), baleen whale (e.g. bowhead, gray whales) responses, including short-term avoidance and startle responses, were reported at distances of 7–30 km from seismic sources. Responses to other sources such as pingers, sonar, FM sweeps and ATOC (a low frequency noise source used for ocean-scale temperature monitoring) have included none detected, avoidance, increase in swim speed, cessation of song, increased song duration, longer dives, approaches, changes in swim direction, and startle responses at levels ranging from 80 to 169 dB re 1 µPa (rms) (e.g. Frankel and Clark 1998, 2000; Croll et al. 2001; Miller et al. 2000; Melcón et al. 2012).

In a recent study on potential masking in marine mammals occurring in Antarctic waters, models were developed for Antarctic blue whale and fin whales exposed to noise from airguns (Siebert et al. 2014). Airgun noise was modelled based on signals from surveys carried out over 22 years between 1985 and 2007, in Southern Ocean waters protected by the Antarctic Treaty (Boebel et al. 2009). Most surveys were carried out in waters deeper than 4000 m and in such environments, long-range transmission can stretch airgun pulses in time. The effect may result in a greater masking potential since the duration of the noise pulses is longer and the interval with no noise is shorter (Gedamke and McCauley 2010). Noise was modelled for receivers at 100, 500, 1000 and 2000 km from the sound source and at depths of 10, 50 and 200 m. Results showed that signal stretching can potentially result in continuous noise at ranges beyond 1000–2000 km from the source. Communication spaces for baleen whale species were predicted to be reduced at ranges up to 500–2000 km, but depended on the species (and the frequency of the vocalisations used). For blue and fin whales, 90–99% loss of communication ranges were estimated. The authors indicated that the models could be improved by better understanding of the hearing processes.

Physiological responses due to elevated stress are likely to occur at certain noise doses but have not been investigated in Australia. Stress has been studied in only a small number of animals in captivity because sampling itself causes stress (e.g. obtaining blood samples), much baseline work needs to be done to understand natural variability of stress hormones, and many animals are difficult to access in the wild. This is particularly true for baleen whales. A recent study (Rolland et al. 2012) has recently been published on a decrease in baseline levels of stress-related faecal hormone metabolites (glucocorticoids) in North Atlantic right whales (*Eubalaena glacialis*) in association with a reduction of ship noise (by 6 dB) due to less large vessel traffic in the Bay of Fundy. The authors state that the study provides 'compelling evidence of a stress response to ship noise in right whales' but that there were limitations in that the study was a 'retrospective analysis based on a non-repeatable event, with all of the inherent limitations'. For example, the noise measurements in this study were very brief (only 90 minutes of recording), used a hydrophone on a spar buoy over the side of a boat (potentially adding noise artefacts from the deployment), and the intra- and inter-annual variation in fecal glucocorticoids was large over the 5-year measurement period, larger than the drop seen around 9/11, 2001 (Rolland et al. 2012).

No data are available on auditory and non-auditory tissue and organ damage, or on lethal effects on baleen whales from underwater noise produced from oil and gas activities. There are some corollary data of very high noise levels being associated with death, organ trauma and tissue damage in marine fauna (Frantzis 1998, Balcomb and Claridge 2001) but no definitive evidence of causation. Detection of mortalities and assessment of their causes is confounded by the fact that most dead animals sink to the bottom of the ocean. However, marine animals would have to be very close to a source to experience levels high enough to be lethal (Urick 1983; Cato et al. 2004).

Other research currently underway in Australia but not completed

A major Australian study Australia – Behavioural Responses of Australian Humpbacks to Seismic Surveys (BRAHSS) project (Cato et al. 2012, 2013a,b, Dunlop et al. 2015; Table 14) – is nearing completion. The project is one of the largest and most complex studies worldwide on whale behavioural responses.

The responses of humpback whales to a seismic sources and ramp up (20, 60, 140, and 440 cui airguns) were measured during the southerly humpback whale migrations off Peregian (Queensland) and Dongara (Western Australia) (Table 12). The efficacy of ramp up procedures were also measured. Potentially influencing environmental conditions, social context (e.g. behaviour and whale group types in the vicinity) and received sound levels at the location of whales were observed. Humpback whales are highly social so behavioural changes are often associated with the presence and behaviours of other whales around them. The study aimed at teasing out responses due to factors not associated with the seismic source (such as social interactions with other whales) from responses directly related to the source. Controls allowed for effects associated with active airgun noise to be separated from effects of the vessel running without the airguns firing. The treatment and control for the vessel presence was compared to behaviours of whales in the absence of the vessel towing airguns in the area.

Table 12. Humpback whale behavioural studies underway in Australia investigating response to underwater noise by oil and gas activities and/or some similar sources

Year	Location	Response measured	Behavioural context/ cohort	Source	Observation methods	Reference
2010	Off Peregian, QLD	Changes in: • distribution • direction • surface & underwater behaviours • swim speed • blow rate • surface intervals, and • down times based on focal follows & scan samples	Southerly migrating whales	Single 20 cui airgun	• Observations from seismic vessel, research vessels, and land stations, • tags • biopsies • PAM	Cato et al. (2012, 2013a,b), Dunlop et al. (2015)
2011				Airgun array (440 cui), 20 cui airgun		
2014	Off Dongara, WA			Airgun array (440 cui)		
2015	Off Peregian, QLD			Seismic survey		

Note: PAM = Passive acoustic monitoring.

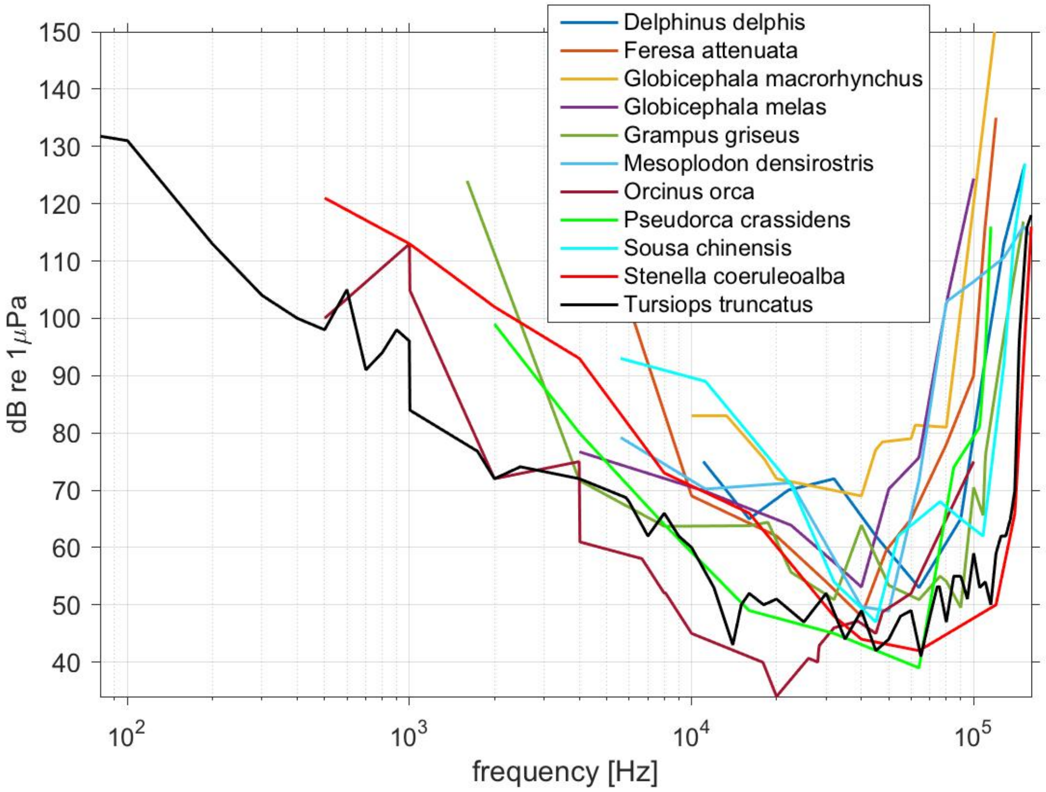
Results published to date report on the response of humpback whales to a single 20 cui airgun (Dunlop et al. 2015), the same source used an earlier study in Exmouth Gulf (McCauley et al. 2003a). Humpback whale groups responded to the airgun source by decreasing dive time and speed of southwards movement, though the response magnitude was not found to be related to the proximity of the source vessel, the received level of the airgun, the tow path direction or the exposure time (Dunlop et al. 2015). There was no evidence of orientation of the groups towards or away from the source vessel in the 'during' phase. This behavioural response was observed in the 'control' trials as well as the 'active' trials, suggesting the whales responded similarly to the source vessel (Dunlop et al. 2015).

6.1.2 Odontocetes

Hearing sensitivity

Odontocetes are sensitive to higher frequencies than mysticetes, which is reflected in the sounds they produce typically within the tens of kHz or higher. Odontocetes use sound for navigation, foraging, and communication (e.g. for maintaining group cohesion at relatively small ranges). Navigation and location of objects (such as prey) is achieved using high-frequency bio-sonar called echolocation.

Audiograms are available from direct measurements on 11 odontocetes that occur in Australian waters, including the common dolphin (*Delphinus delphis*), short and long-finned pilot whale (*Globicephala macrorhynchus, Globicephala melas*), killer whale (*Orcinus orca*), false killer whale (*Pseudorca crassidens*), Indo-Pacific humpback dolphin (*Sousa chinensis*), and bottlenose dolphin (*Tursiops* spp.) (Figure 41). For a complete list of audiogram data currently available, see Erbe et al. 2016b and (Figure 41). Although the audiograms are from animals that were in waters outside of Australia, the general range in sensitivity could be expected to be comparable to individuals of the same species within Australian waters. Based on these audiograms, the greatest sensitivity ranges from above 1 kHz to above 100 kHz, depending upon the species.



*Source: Blainville's beaked whale (Mesoplodon densirostris, Pacini et al. 2011), common dolphin (Delphinus delphis, Popov and Klishin 1998), pygmy killer whale (Feresa attenuata, Montie et al. 2011), short-finned pilot whale (Globicephala macrorhynchus, Schlundt et al. 2011, Greenhow et al., 2014)*_ENREF_238*, long-finned pilot whale (Globicephala melas, Pacini et al. 2010), Risso's dolphin (Grampus griseus, Nachtigall et al. 1995, Nachtigall et al. 2005, Mooney et al. 2015), killer whale (Orcinus orca, Hall and Johnson 1972, Szymanski et al., 1999), false killer whale (Pseudorca crassidens, Thomas et al. 1988, Yuen et al. 2005), Indo-Pacific humpback dolphin (Sousa chinensis, Li et al. 2012), striped dolphin (Stenella coeruleoalba, Kastelein et al. 2003).*

Figure 41. Example audiograms (minimum threshold) for 11 species occurring in Australian waters

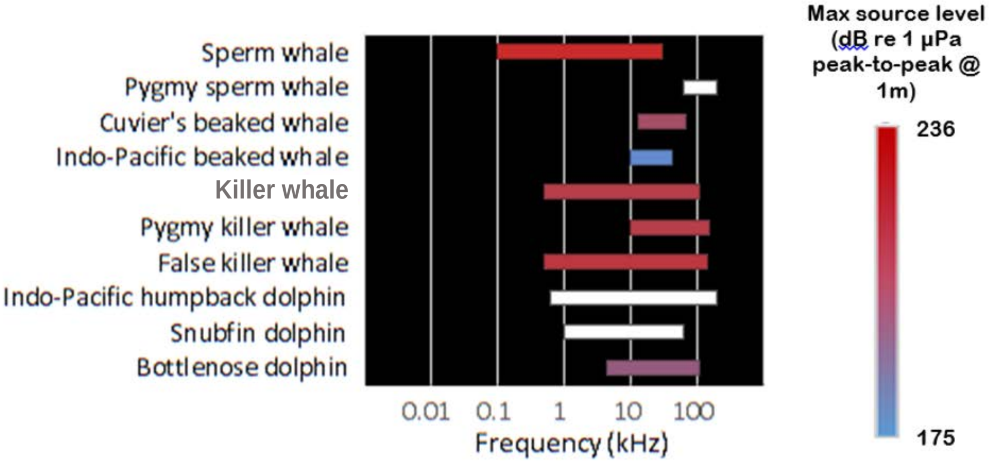
Audiograms are not available for other species occurring in Australia, so hearing sensitivity is inferred from recordings of their sounds and behavioural responses to acoustic signals. Sperm whale sounds have been recorded from many locations around the world. They use sounds for communication, individual identification, echolocation and locating prey (Madsen et al. 2002, Whitehead 2002, Miller et al. 2004). Sounds produced are described as squeals, creaks and clicks (Mullins et al. 1988) at frequencies from 100 Hz to 30 kHz and source levels up to 236 dB re 1 µPa peak-to-peak @ 1 m (Møhl et al. 2003). Recordings in Australian waters have captured sounds within this frequency range (CMST's unpublished data). For pygmy sperm whales, sounds recorded elsewhere in the world range in frequency from 60 to 200 kHz (Marten 2000, Ridgway and Carder 2001) but no sounds have been recorded in Australia for this species.

A range of beaked whales are reported to occur in Australian waters although very little is known about these species. Sounds ranging from 2 to 80 kHz have been attributed to these animals at various locations around the world (Johnson et al. 2004, 2006; Arranz et al. 2011). For Cuvier's beaked whales sounds ranging from 13 to 64 kHz have been recorded (Frantzis et al. 2002; Zimmer et al. 2005). Sounds including clicks and pulses from Indo-Pacific beaked whale (Longman's beaked whale) have been recorded in the range of 10 to 40 kHz (Rankin et al. 2011). In Australia, a study on beaked whales in the Coral Sea reported the effective bandwidth of individual clicks attributed to this species to be around 4 kHz with mean peak frequency slightly lower at approximately 34 kHz, but still within the range of that reported for Mesoplodon and Ziphius species elsewhere (Parnum et al. 2011).

No published information is available on sounds produced by other beaked whales known to occur in Australia, namely Gingko-toothed whales, Arnoux's beaked whales, True's beaked whales, Andrew's beaked whales, Gray's beaked whales, Hector's beaked whales, Shepherd's beaked whales and strap-toothed whales.

Sounds from dolphins (delphinid species) are among the most studied. These species produce whistles, burst-pulses, and echolocation clicks. Among the largest of the delphinids are the killer whales. Sounds recorded from killer whales range from 500 Hz to 75 kHz (Ford 1989; Ford, 1991; Miller 2006; Samarra et al. 2010). Pygmy killer whale sounds recorded range from 10 to 150 kHz (Madsen et al. 2004a). Recent recordings of sounds produced by killer whales in Australian waters fall within this range (Wellard et al. 2015), with the frequency of fundamental contours ranging from 600 Hz to 29 kHz and harmonics occurring above these frequencies.

In Australia, bottlenose dolphin sounds have been recorded from a range of locations (Table 13). Sounds recorded from Australian Indo-Pacific humpback dolphins range from an average of 1.2 to >22 kHz (Table 13) but the sample rate used in these recordings was limited to below 22 kHz. Echolocation clicks of the same species near Hong Kong ranged from at least 30 kHz to a minimum of 200 kHz (Goold and Jefferson 2004). Snubfin dolphin sounds have been recorded within frequencies ranging from an average of 3.1 to 22 kHz (although 22 kHz was the maximum frequency of some of the recording systems used; Table 13). A similar species, the Irrawaddy dolphin, has been reported to produced clicks from 30 kHz to 130 kHz (Bahl et al. 2007). No information on sounds produced by Fraser's dolphin, dusky dolphin, spectacled porpoise, spotted dolphin, long-snout spinner dolphin, pilot whales, dwarf sperm whales, or southern right whale dolphins could be located by the authors.



Data source: Madsen et al. 2002, Whitehead 2002, Miller et al. 2004, Mullins et al. 1988, Møhl et al. 2003, Marten 2000, Ridgway and Carder 2001, Johnson et al. 2004, 2006; Arranz et al. 2011, Frantzis et al. 2002; Zimmer et al. 2005, Parnum et al. 2011, Ford 1989, Ford, 1991, Miller 2006, Samarra et al. 2010, Madsen et al. 2004a, Wellard et al. 2015.

Notes: White bars indicate absence of source level estimates. Limited frequency ranges in the diagram may reflect limited samples of recordings so far obtained rather than the absolute range for some species.

Figure 42. Frequency range and maximum estimated source levels of sounds recorded from odontocete species that occur in Australia

Table 13. Frequency range of sounds attributed to delphinids in Australian waters

Species	Frequency range (kHz)	Location	Source (mean dB re 1 µPa @ 1 m)	Reference
Indo-Pacific humpback dolphin	1.2– >22	Eastern Australia	–	Schultz and Corkeron (1994), Van Parijs and Corkeron (2001a,b,c), Smith (2000), Soto et al. (2014)
Snubfin dolphin	3.1– >22	Eastern Australia	–	Van Parijs et al. (2000), Soto et al. (2014)
Bottlenose dolphin	4.3– >18	Western Australia	146.7 ± 6.2 (whistles)	Jensen et al. (2012), Hawkins and Gartside (2010), Salgado-Kent et al. (2012b), Van Parijs and Corkeron (2001), Scarpaci et al. (2000) Lemon et al. (2006), Ward et al. (2016)
Killer whale	0.6–29	South-western Australia	–	Wellard et al. (2015)

Note: '–' indicates data that is not available.

Experimental studies measuring impacts

There have been no targeted studies on behavioural responses of toothed whales to underwater noise created by FPSOs, dredging, drilling, machinery, shipping, pile driving, and explosives during oil and gas industry activities in Australia. One study on Indo-Pacific bottlenose dolphin occurrence during pile driving to increase wharf capacity within the Fremantle Inner Harbour was undertaken in 2010 (Salgado Kent et al. 2011, Paiva et al. 2015; Table 14). Dolphins were detected more frequently in the study area when pile driving was absent compared to during pile driving but differences were not statistically significant in this preliminary analysis (Salgado Kent et al. 2011) using a small sample size. Subsequent analyses of a larger subset of the data revealed significant differences between the number of dolphins detected during piling and non-piling periods, with greater numbers before than during pile driving (Paiva et al. 2015). Measured noise levels indicated that dolphins would have been exposed to SELs ranging from 140 to 161 dB re 1 μPa^2.s during impact pile driving and SPLs ranging from 145 to 175 dB re 1 μPa during vibratory pile driving.

While current knowledge on behavioural responses of toothed whales to underwater noise from oil and gas industry activities in Australia is limited, there are more than a dozen studies on responses to vessel noise (Table 14). All are on bottlenose or humpback dolphin responses and many focus on the impact of tourism operations, although none of the studies separated the effects of noise from the combined effects of vessel presence and vessel noise. While these vessels are recreational and tourism-related vessels, some relevant information may be gleaned from these given that the oil and gas industry often uses a range of small vessels during operations.

Short-term changes in surface behaviour of bottlenose dolphins in response to a dolphin-watching vessel have been reported in Koombana Bay, Western Australia (Arcangeli and Crosti 2009). Dolphins were attracted to the vessel during 20% of cases and avoided it in 28% of cases. The time spent resting and feeding decreased in the presence of the tour vessels, whereas time spent travelling increased. When tour boats were present, the frequency of travelling, resting and feeding increased. Dolphins were observed to spread in more groups of fewer animals in the presence of the tour vessel than in its absence.

Short-term changes in surface behaviour were also reported for bottlenose dolphins exposed to powerboat approaches in Jervis Bay, New South Wales (Lemon et al. 2006). Dolphins tended to alter their surface behaviour and change travel direction. Distances in which responses were elicited were >30 m. Acoustic measurements made during this study showed whistle rates did not change nor did the duration of echolocation click bouts during vessel approaches. Similarly, in a study in Moreton Bay (Queensland), dolphin click train and burst pulse rates from humpback dolphins were not affected by the passage of vessels (Van Parijs and Corkeron 2001) but whistle rates increased immediately after a vessel moved through the area at ranges less than 1.5 km. This occurred more often in groups with calves than in groups without calves. Van Parijs and Corkeron (2001) suggested that in mother-calf pairs there was a greater risk of disturbance since these groups exhibited an increased need to re-establish vocal contact. Similarly, whistle rates of bottlenose dolphins increased in the presence of commercial dolphin-watch and swim-with tours in Victoria (Scarpaci et al. 2000). The investigators suggested that physical separation of individual dolphins or an increased background noise may have caused dolphins to whistle more frequently to maintain contact.

Short-term behavioural responses have been the focus of most studies because measures can be made easily over a short period. Longer-term effects require studies over a long duration, for which funding is often difficult to obtain. Only one study in Australia has assessed long-term impacts on marine mammals and focused on the response of bottlenose dolphins to vessel activity in Shark Bay, Western Australia (Bejder et al. 2006). An average decline in dolphin abundance was observed in association with an increase in the number of dolphin-watching operators above two. The study was limited to one control site and one tourism site, meaning that the link between the decline in dolphin abundance and increased vessel activity is not absolutely conclusive.

Table 14. Dolphin behavioural studies completed in Australia investigating response to underwater noise created by oil and gas activities and/or some similar sources

Year	Species	Location	Response measured	Source	Observation methods	Limitations	Threshold level (dB re 1 μPa².s), range (m), presence /absence	Level of response reported	R	Referenc
2010	Indo-Pacific bottlenose dolphin	Fremantle Inner Harbour, WA	Reduced dolphin detections	Pile driving	• Video camera with stereo still cameras mounted on a 3 m tower • Vessel-based acoustic recordings	Study was limited to camera's field of view and to dolphin detections (individuals were not followed through time, rather detections were)	140 to 161 (SEL)	0.4 of the total detections made when pile driving was occurring than when it was not	2.5	Salgado Ke et al. (201 Paiva et al (2015)
2008–2009	Indo-Pacific bottlenose dolphin	Port Stephens, NSW	Behavioural state, movement direction, group cohesion, group composition	Vessels (dolphin-watch, commercial and recreational)	Vessel-based observations	Potential disturbance from presence of the research vessel, limitations in accuracy of distances (although more accurate measures were not the objective of the study), speed restricted and control zones consisted of different habitats preventing the separation of effects of vessels from those of habitat, replication of speed restricted and	Presence whale-watch vessel	• 66.5% less time feeding • 44.2% less time socialising • 406.8% more time milling • 28.8% more time travelling • Decrease in neutral directional movement, and increase towards or away vessels • Greater group cohesion	2	Steckenreu et al. (2012a,b)
							Decreased distance of whale-watch vessel (<50 m than >50–<100 m)	• Increase in milling • Decrease in socialising • Decreasing in feeding • Increase in movement away		

						control zones was absent	Increased number of whale-watch vessels	Increase in movement away		
							Presence of other vessels (kayaks, sailing boats, personal watercraft, ferries, and oyster boats)	No significant difference		
							Speed restricted vs. control zone	No significant difference in behavioural state, group cohesion, group composition, and directional movement		
1999	Pacific humpback dolphin	Stradbroke Island, QLD	• Acoustic behaviour • Visual observations of group size, composition, and surface behaviour	Vessels (transiting small vessel traffic)	Land (pier)-based observations	There was a potential effect of masking of vocalisations during vessel transits (the authors indicate that this occurred with some burst-pulses), and it is unclear whether dolphins were located in similar ranges and acoustic transmission conditions (between the dolphins and the hydrophone) before, during, and after vessels transits resulting in equivalent acoustic detection probability	Transiting vessels	• No significant difference in echolocation clicks or burst pulses before during or after boat presence • Median number of whistles was greater after the presence of a boat, compared to before and during (with groups with two calves whistleing significantly more than those with fewer)	2	Parijs and Corkeron (2001)
							Vessel presence	Higher whistle rates for groups with no calves than all groups when vessels were absent		

2001–2003	Indo-Pacific bottlenose dolphin	Jervis Bay, NSW	• Acoustic behaviour • Visual observations of group size, composition, travel direction, and surface behaviour	Vessel (powerboat)	Vessel-based observations	Potential disturbance from the presence of the research vessel, there were assumptions in testing the potential for masking to have affected detections however these were conservative so masking was unlikely, and the recorder was limited to record up to 20 kHz	Vessel transit (vs. no vessel transit)	• Change in travelling to milling (9 of 12 or 75%) • Avoidance (9) and return to original direction (in 5) • No difference in whistle rate, time, or duration • No difference in echolocation click bout duration	2.5	Lemon et a (2006)
1995–1996	Indo-Pacific bottlenose dolphin	Jervis Bay, NSW	• Whistle rate • Behavioural states	Vessels (swim-with-dolphin tour vessel)	Vessel-based observations	Potential disturbance from the presence of the research vessel, there was a potential effect of masking of vocalisations when vessels were near effecting detection probability (the authors indicate that whistles could be detected within 200 m of the research vessel), and the recorder was limited to 20 Hz to 16 kHz	Vessel presence	• Whistle rate increased during travel, feeding, and socialising behavioural states	2	Scarpaci e (2000)
2000	Bottlenose dolphin	Koombana Bay, WA	• Behavioural state • Group size • Number of groups	Vessels (dolphin-watch tours)	Vessel-based observations	Potential disturbance from the presence of the research vessel, acoustic measurements were not part of the study (which was not	Vessel presence (as defined as <150 m)	• Increase in travelling • Decrease in resting • Decrease in foraging • number of groups detected increased	2	Arcangeli a Crosti (200

						within the objectives), and vessel 'absence' was defined as >150 m although they may have been acoustically present		Attraction 20% of cases Avoidance in 28% of cases Neutral in 52% of cases		
1988–1993	Bottlenose dolphin	Shark Bay, WA	Abundance	Vessels (tour and research vessels)	Vessel-based photo-identification	Potential disturbance from the presence of the research vessel, survey design may have varied over years resulting in potential variability in detection probability and statistical power, treatment and control zones not replicated, and environmental drivers for potential decline over years not evaluated decline in abundance not evaluated	>2 tourism operators	Decrease in long-term (years) dolphin abundance in tourism site with increasing number of tour operators	2	Bejder et a (2006)

Criteria	**Score**
The work addressed a significant knowledge gap at the time it was undertaken relevant to petroleum activities	1
The metrics and exposure type were relevant to petroleum activities	1
The study conclusively identified the level of effects due to underwater noise on the subjects	1
The study can be generalised to the community/population/species targeted in the study	1
Total possible score	**4**

Note: Criteria is for a qualitative assessment rank of contribution to knowledge gaps at the time the work was produced. PAM = Passive acoustic monitoring; R = Relevance (described in the Relevance Criteria at the bottom of the table); SEL = Sound Exposure Level.

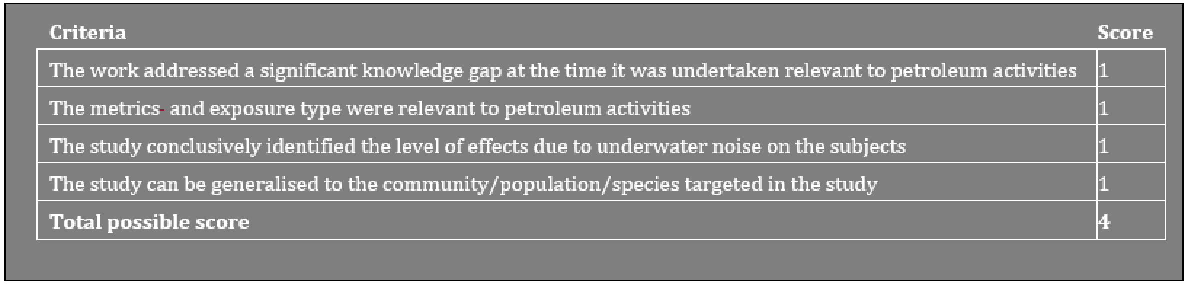
The studies described above were not aimed at separating the effects of underwater vessel noise from the presence of the vessels. Additionally, no underwater noise levels and/or frequency ranges corresponding to the observed responses were reported; in fact, most of the studies did not involve acoustic measurements.

Masking has not been the focus of any studies on the underwater noise effects of oil and gas activities on marine mammals in Australia. However, two studies have attempted to estimate the masking of bottlenose dolphin whistles by vessel noise in Australia (Table 15). In one study, the communication range of bottlenose dolphins in Koombana Bay, Western Australia, was estimated to have been reduced by 26% within 50 m of small vessels travelling at 5 kn in shallow water (Jensen et al. 2009). Increased cavitation noise at higher speeds was expected to increase the impact on the communication range. In a separate study, masking thresholds of Indo-Pacific bottlenose dolphin whistles in Jervis Bay, NSW, were exceeded by 16 dB by power boat transits at a distance of 100 m (Lemon et al. 2006). Some additional data (including critical ratios, critical bandwidths, masking-release phenomena) is available on the potential of masking by underwater noise in toothed whales (Erbe et al. 2016b).

No studies on masking, threshold shift, auditory damage, physiological responses, or organ and non-auditory tissue damage have been undertaken on toothed whales in association with underwater noise produced by oil and gas activities in Australia.

Table 15. Studies completed in Australia investigating the potential masking of sounds relevant to bottlenose dolphins by oil and gas activities and/or related sources

Year	Species	Location	Response measured	Source	Observation methods	Limitations	Threshold range (m)	Level of response reported	R	Reference
2001–2003	Indo-Pacific bottlenose dolphin	Jervis Bay, NSW	• Acoustic behaviour • Visual observations of group size, composition, travel direction, and surface behaviour	Vessel (powerboat)	Acoustic measurements	Limitations relating to assumptions used for estimation, and the directional capabilities of animals were not considered	100	Exceeded by 16 dB by power boats	2	Lemon et al. (2006)
2007	Bottlenose dolphin	Koombana Bay, WA	Masking	Small vessels	Acoustic measurements	Limited speeds and water depths used (5 kn in shallow water), and the directional capabilities of animals were not considered	50	Communication reduced by 26%	2	Jensen et al. (2009)



Criteria	Score
The work addressed a significant knowledge gap at the time it was undertaken relevant to petroleum activities	1
The metrics and exposure type were relevant to petroleum activities	1
The study conclusively identified the level of effects due to underwater noise on the subjects	1
The study can be generalised to the community/population/species targeted in the study	1
Total possible score	**4**

Note: Criteria is for a qualitative assessment rank of contribution to knowledge gaps at the time the work was produced; R = Relevance (described in the Relevance Criteria at the bottom of the table).

International research relevant to Australia

Overall, responses so far observed in Australia are consistent in their variability and range with observations elsewhere in the world on species not occurring in Australia. Studies in the 1970s reported changes in behaviours in beluga whales in Alaska and Canada caused by oil and gas activity associated noise (Fraker and Fraker 1981; Awbrey et al. 1983). Other work reported responses to ships by dolphins and killer whales (e.g. Au and Perryman 1982, Williams et al. 2014). More recent work has focused on the response of harbour porpoises to pile driving in the North Sea (associated with wind farm installation). Thompson et al. (2013) reported harbour porpoises displaying avoidance behaviour to airgun noise from a 470 cui array used in a 2D seismic survey in the North Sea over ranges of 5–10 km and received peak-to-peak SPLs of 165–172 dB re 1 µPa and SELs of 145–151 dB re 1 $\mu Pa^2 \cdot s$. Animals were typically detected again within a few hours, with levels of response declining over the 10-day seismic survey period. Whether the behaviour was a primary or secondary response (to effects on prey, for example) could not be determined. The authors noted that a proportion of the noise energy emitted from seismic activities would have been below the expected hearing sensitivity of harbour porpoises.

Studies on masking have been done in other areas of the world, with the most detailed results of masking impacts obtained from studies on captive bottlenose dolphins and beluga whales (see review by Erbe et al*.* 2016b). These studies show the extent of masking effect in relation to different sound characteristics and also different strategies animals employ to overcome the masking effects on their communication. Captive experiments are not possible for larger species.

For physiological response due to elevated stress, only a few studies have been carried out on animals in captivity and with varying results. Captive beluga whales exposed to playbacks of drilling noise showed no changes to levels of the stress hormones adrenaline and noradrenaline in the blood (Thomas et al. 1990). In contrast, changes in stress hormones in bottlenose dolphins and a beluga whale in captivity were reported in response to underwater noise from a seismic water gun and 1-s, 3-kHz pure tones (Romano et al. 2004). In 2009, a review of stress physiology and behavioural research was compiled following an international workshop hosted by the U.S. Office of Naval Research (ONR 2009).

Finneran (2015) recently reviewed the available information on hearing threshold shifts in marine mammals. TTS and PTS experiments have focused on measuring these effects in toothed whales exposed to intense tones, band-limited noise, and underwater impulses with various sound pressure levels, frequencies, durations, and temporal patterns (Finneran 2015).

Other relevant research currently underway in Australia but not completed

There are several studies investigating behaviour of odontocetes to human activities, however, no projects specifically on the impact of underwater noise generated by oil and gas activities on odontocetes are known to be underway. Postgraduate projects include investigating dolphin behaviour in coastal environments with vessels, shipping, and port activities.

6.1.3 Pinnipeds

Hearing sensitivity

In pinnipeds, hearing has been adapted for life in terrestrial and aquatic environments. Pinnipeds that breed on land produce in-air vocalisations for mothers and pups to recognise each other and for males to compete amongst each other (e.g. Fernández-Juricic et al. 1999; Insley et al. 2003; Tripovich et al. 2008; Van Opzeeland et al. 2010). For pinnipeds that mate in water, males are thought to display vocal behaviour underwater to compete for and to attract females (Van Parijs 2003; Van Opzeeland et al. 2010). Females of some pinniped species are also known to vocalise underwater.

Of the pinnipeds occurring in Australian waters (including sub-Antarctic and Antarctic regions), information is available on vocalisations for eight species (Table 16). Australian fur seals have the smallest reported frequency range of vocalisations at just 108–827 Hz (Tropovich et al. 2011) whereas Weddell seals have the greatest at 50–15,000 Hz (Schevill and Watkins 1965, Ray and Schevill 1967, Kooyman 1968, Thomas 1979, Pahl et al. 1997, Terhune and Dell'Apa 2006) (Table 16).

Table 16. Frequency range of sounds attributed to pinnipeds in Australian waters

Species	Frequency range (Hz)	Location	Source (mean dB re 1 µPa @ 1 m)	Reference
Leopard seal	40–5900	In water, Antarctica	153–177	Stirling and Siniff (1978), Rogers et al. (1995), Rogers (2007, 2014), Klinck (2008)
Crabeater seal	<100– >8000	In water, Antarctica	None in water	Stirling and Siniff (1978), Klinck (2010)
Australian fur seal	108–827	In air, Antarctica	None in water	Tropovich et al. (2011)
Southern elephant seal	50–3000	In air, Antarctica	None in water	Sanvito and Galimberti (2000a,b), Sanvito et al. (2007a,b)
Antarctic fur seal	100–8000	In air, Antarctica	None in water	Page et al. (2002)
Ross seal	140–6700	In water, Antarctica	None in water	Watkins and Ray (1985), Seibert (2007)
Weddell seal	50–15,000 50– >11,800	In air, Antarctica In water, Antarctica	None in water 148–193	Thomas (1979), Schevill and Watkins (1965), Kooyman (1968), Ray and Schevill (1967), Pahl et al. (1997), Terhune and Dell'Apa (2006), Moors and Terhune (2004), Thomas and Kuechle (1982), Thomas (1979)
Australian sea lion	400–2100	In air, Kangaroo Island, SA	None in water	Charrier and Harcourt (2006)

In-air hearing sensitivities are similar to those of terrestrial carnivores (Fay 1988; Mulsow et al. 2011). In water, ABRs have been recorded for a male leopard seal (Tripovich et al. 2011) for three tones and an Australian sea lion for broadband sounds (Lucke et al. 2016). The leopard seal was sensitive to all tones played ranging between 1 and 4 kHz, with most sensitivity at 4 kHz. Attempts were made to measure an audiogram for Weddell seals (Kindermann et al. 2007) but results remain unpublished. For a complete list of audiogram data for the various pinniped species, please see the recent review by Erbe et al. (2016b).

Experimental studies measuring impacts

Research on behavioural responses of seals and sea lions to noise in Australia is limited a study on responses to boat noise in air. Australian fur seals on breeding islands in Bass Strait oriented themselves towards or moved away from boats with a relatively high sound level (Tripovich et al. 2011). Seals also responded more aggressively with one another and were more alert in the presence of boats emitting relatively high noise levels. Vocalisation changed at various sound intensities, and barks became faster as the boat noise increased in level (Tripovich et al. 2011).

The recent study conducted on potential masking in marine mammals from airgun noise in Antarctic waters described in Section 6.1.1 not only developed models for whales, but also did so for Weddell seals (Siebert et al. 2014). Results for Weddell seals were highly variable with a predicted range of 8–99% loss of communication range due to airgun noise. The study did not consider the directional capabilities of the hearing system of the receiving animals.

International research relevant to Australia

The work in the 1970s on behavioural responses in beluga and bowhead whales in Alaska and Canada to noise from oil and gas activities also included responses in ringed seals (Fraker and Fraker 1981, Awbrey et al. 1983). Finneran (2015) reviewed the available information on hearing threshold shifts (TTS and PTS). The TTS and PTS experiments have focused on measuring these effects in pinnipeds exposed to intense tones, band-limited noise, and underwater impulses with various sound pressure levels, frequencies, durations, and temporal patterns. However, no information is currently available for non-auditory tissue and organ damage or lethal effects from underwater noise produced from oil and gas activities.

Other relevant research currently underway in Australia but not completed

No studies are known to be currently underway on the impact of underwater noise generated by oil and gas activities on pinnipeds.

6.1.4 Dugongs

Hearing sensitivity

There are no audiograms published for dugongs. Sounds recorded that have been attributed to dugongs range in frequencies from 500 Hz to 18 kHz (Anderson and Barclay 1995; Ichikawa et al. 2006; Parsons et al. 2012; Table 17). Audiograms (behavioural and Auditory Evoked Potential) are available on hearing sensitivity of a close cousin of the dugong—the manatee, *Trichechus manatus*. If dugong hearing is similar to that of the manatee, hearing sensitivity is expected to be best between several kHz and ~25 kHz (Bullock et al. 1980; Klishin et al. 1990; Popov and Supin 1990; Gerstein et al. 1999).

Table 17. Frequency range of sounds attributed to dugongs in Australian waters

Species	Frequency range (Hz)	Location	Reference
Dugong	500–18,000	Western Australia	Anderson and Barclay (1995)
	731–5250	Western Australia	Parsons et al. (2012)

Note: no source levels have been measured.

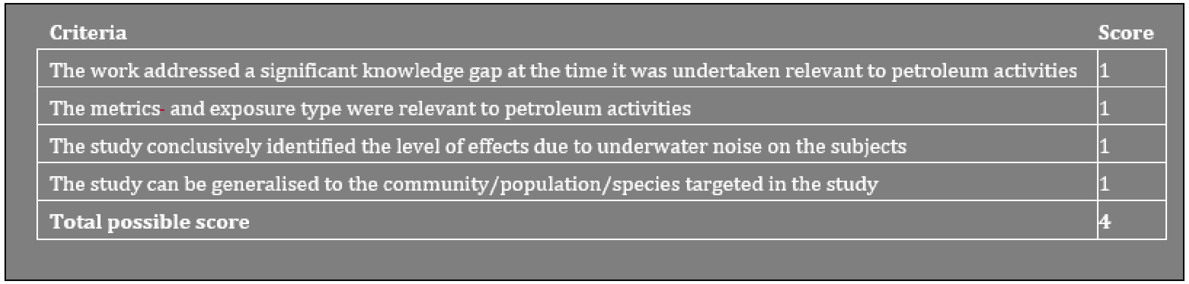
Experimental studies measuring impacts

There have been no direct studies on effects on dugongs of underwater noise created by oil and gas industry activities in Australia. Research in Australian waters on impacts of human activity with associated underwater noise on dugongs is limited to a single study into changes in dugong feeding and travelling activity due to boat traffic in Moreton Banks, Queensland (Hodgeson 2004; Hodgeson and Marsh 2007; Table 18). Dugongs were found to be less likely to continue feeding if the experimental vessel passed within 50 m than at greater ranges. Furthermore, feeding dugong herds were observed to move en-masse in response to experimental and opportunistically observed vessels passing at a range of speeds and distances of <50 m to >500 m, but this only lasted for ~2 min. Behavioural disturbance from the amount of boat traffic observed by Hodgeson and Marsh (2007) was estimated to reduce the feeding time budget by a maximum of 0.8–6%. Evasive behaviour in response to vessel traffic has also been observed in Shark Bay, Western Australia (Anderson 1981). Dugongs were observed to aggregate and move away in the presence of vessels moving at 5–8 kn at a distance of 150 m. However, an evasive response was reported to not have been observed on an occasion when a vessel was approaching at 27 kn (Anderson 1981). Studies in other areas of the world have reported dugongs decreasing their use of areas with heavy vessel traffic, and moving to deeper waters (Richardson et al. 1995b).

Gaspard et al. (2012) measured critical ratios in the West Indian Manatee, but no other studies have been carried out on masking, hearing threshold shifts, non-auditory tissue and organ damage, or lethal effects from underwater noise.

Table 18. Dugong behavioural studies completed in Australia investigating response to underwater noise created by oil and gas activities and/or some similar sources

Year	Species	Location	Response measured	Source	Observation methods	Limitations	Threshold level (range in m)	Level of response reported	R	Reference
2002	Dugong	Moreton Banks, QLD	• Behaviour (feeding/ travelling). • Travel direction and distance • Subsurface times	Passing vessels	Remote controlled surveillance camera mounted on a blimp	Acoustic measurements of the source and received levels were not made, water depths were mostly shallower than 2 m meaning that dugongs are more limited in their ability to dive, and the study would apply to sound transmission conditions in very shallow environments	<50	Cessation of focal animal feeding (time budget was 0.8–6%)	2	Hodgeson and Marsh (2007), Hodgeson (2004)
							<50 m to >500 m	• Significant herd responses (movement of >50% of animals interrupted their feeding • Travelled in a coordinated group, then resumed feeding – 122 s duration)		
							<50 m to >500 m	No change in focal animal travel direction		
							<50 m to >500 m	No change in focal animal distance		
							<50 m to >500 m	No difference in focal animal subsurface times		



Criteria	Score
The work addressed a significant knowledge gap at the time it was undertaken relevant to petroleum activities	1
The metrics and exposure type were relevant to petroleum activities	1
The study conclusively identified the level of effects due to underwater noise on the subjects	1
The study can be generalised to the community/population/species targeted in the study	1
Total possible score	**4**

Note: Criteria is for a qualitative assessment rank of contribution to knowledge gaps at the time the work was produced. PAM = Passive acoustic monitoring; R = Relevance (described in the Relevance Criteria at the bottom of the table).

International research relevant to Australia

No studies are known to have been done on the effects of underwater noise generator by oil and gas activities on dugongs.

Other relevant research currently underway in Australia but not completed

No studies are known to be currently underway on the impact of underwater noise generator by oil and gas activities on dugongs.

6.1.5 Synthesis of known effects and gaps in knowledge

- Marine mammals are highly sensitive to sound and specialised to use sound for key life processes.
- Hearing sensitivity for several of the marine mammal species in Australia are have been studied. Among those with audiograms produced are several species of delphinids and pinnipeds. Very little beyond conceptual modelling is known about baleen whale, beaked whale, and dugong hearing.
- The behavioural response of marine mammals to underwater noise impacts is the effect most studied in and outside of Australia. However, research so far shows that responses vary widely among species and populations. Studies on humpback whales in Australia show some consistency in that animals demonstrate behavioural changes, such as maintaing a distance away from a source, changing dive times, or attraction for a cohort of animals, in the presence of a range of noise sources and levels. As a result some thresholds for airgun exposure have been adapted to apply for mitigating avoidance responses (McCauley et al. 2003b). New research currently under completion (Cato et al. 2012, 2013a,b, Dunlop et al. 2015) will significantly contribute to insight on exposure thresholds and mitigation effectiveness.
- Very little has been investigated in relation to masking on marine mammals in Australia and what has been done is mainly focuses on delphinids. Research done shows that masking can potentially disrupt communications significantly.
- Hearing threshold shifts (TTS and PTS) have not been measured for toothed whales in Australia, but there have been a few studies focusing on hearing threshold shifts internationally which has helped guide current guidelines. However, these are from populations or species elsewhere in the world. No information is available on TTS in baleen whales. Also, no information exists on non-auditory tissue and organ damage or lethal effects in marine mammals from underwater noise produced by oil and gas activities.
- Little is known about physiological, non-auditory tissue and organ damage or lethal effects from underwater noise produced from oil and gas activities, beyond conceptual models.

6.2 Penguins

Penguins are flightless, aquatic birds adapted to spend significant periods foraging in water. The most obvious of the adaptations is the transformation of their wings to flippers for swimming. Penguins nest or breed on land and forage out at sea mainly for squid, fish or krill. Most penguin species build nests on land to raise chicks in. For the non-nesting species, brooding of the eggs and small chicks occurs on their feet until the chicks are old enough to move by themselves (Jouventin and Aubin 2002). Of the 18 species of penguins worldwide, nine species occur in

Australian waters. Four of these (Adélie, emperor, chinstrap and gentoos penguins) occur on Antarctic coasts and another four (king, royal, rockhopper and macaroni penguins) on subantarctic islands. Only one species occurs along Australian coasts—the little penguin.

Hearing sensitivity

No work has been carried out on penguins' hearing sensitivity underwater but responses to vocalisation of predators underwater have been reported for African penguins (Frost et al. 1975). For species occurring in Australian waters, some idea of hearing sensitivity could be obtained from the sounds they produce but no studies have described vocal repertoires underwater. Early research suggested that penguins are able to vocalise underwater, with a macaroni penguin in a tank reported to have produced sounds over the range of 0.5 to 20 kHz but with most energy between 2.5 and 7 kHz and highest frequency sounds up to 120 kHz (Markov 1977). This work was limited to a single animal, however, and a note has been published since stating that the results reported did not match the results presented graphically in the paper (Woehler 2002).

Penguin sounds recorded in air have been reported to range between 110 Hz and 8 kHz (Jouventin 1982, Thumser and Ficken 1998; Figure 43). For example, sounds produced by emperor penguins have been reported to range from 5 to 6 kHz, and from 800 Hz to 5 kHz for Adélie penguins (Jouventin 1982, Woehler 2002). Calls from male king and emperor penguins have two acoustic sources; a lower 'voice' centred at 456 Hz and 371 Hz, respectively, and an upper 'voice' centred around 480 Hz and 431 Hz, respectively (Robisson 1992). Female vocalisations with two acoustic sources were reportedly 6–10 Hz higher (Robisson 1992).

While no other studies have reported underwater sounds produced by penguins, like other birds, penguins make a range of sounds at breeding and nesting sites that are important for communication. In fact, penguin colonies are often described as being loud. The importance of sound in their communication has been highlighted in previous research. For instance many studies have reported that chicks can identify distinct vocal signatures of their parents (Jouventin et al. 1999), indicating that among other purposes, sounds produced are important for parents to recognise and locate their chicks. Sounds recorded in air have been described as honks, screeches, peeps, moans, song, barking, growling, braying, and tweets and fall into three types – contact calls, agonistic calls, and display songs (Jouventin 1982). At sea airborne contact calls are thought to be the main type used by individual penguins to maintain contact (Woehler 2002), with agonistic calls used to a lesser extent. Two species of penguins have additional vocal complexity due to two acoustic sources in the syrinx, the structure that produces sound, which has two-parts that work independently (Aubin et al. 2000). The species having this structure are the non-nesting species, which include the king and emperor penguins (Jouventin and Aubin 2002).

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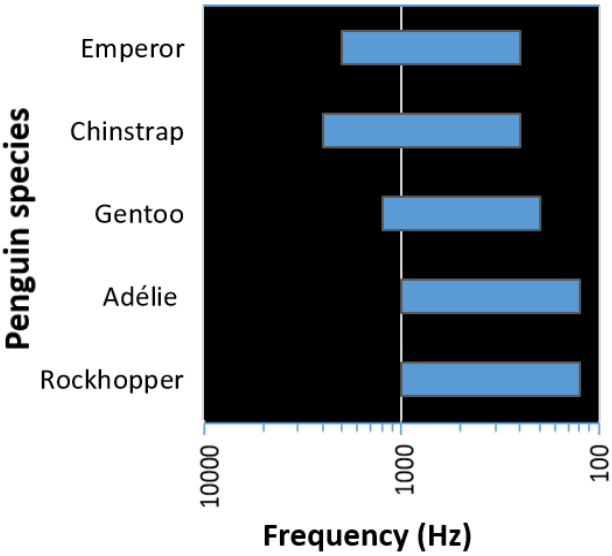


Note: data from Jouventin 1982, Robisson 1992, Thumser and Ficken 1998, and Woehler 2002.

Figure 43. Frequency range of sounds recorded in air from penguin species occurring in Australian waters

Experimental studies measuring impacts

One study measuring the impacts of noise on penguins has been published, in which behavioural changes within a breeding colony of emperor penguins in Antarctica were reported in response to helicopter flights passing overhead at 1000 m (Giese and Riddle 1999). No studies have been published on impacts of underwater noise on penguins.

International research relevant to Australia

Penguins have been reported dead and floating around explosive blast sites in Saldhana Bay, South Africa (Cooper 1982), and at the subantarctic Marion Island (Brown and Adams 1983). The authors indicated that the mortalities were likely to have been the lethal effects of underwater explosions.

Other research currently underway in Australia but not completed

No studies are known to be currently underway on the impact of underwater noise on penguins in Australia.

6.2.1 Synthesis of known effects and gaps in knowledge

- Penguins are known use vocalisation in air for key life processes. However no research has been conducted on their hearing sensitivity in water.
- No work has been carried out on penguins' hearing sensitivity underwater in Australia and hardly any work has been done elsewhere.
- No studies on the impacts of oil and gas activity underwater noise were located that have published research on impacts of underwater noise on penguins in Australia or internationally.

6.3 Marine reptiles

Marine reptiles include sea snakes, sea turtles and saltwater crocodiles (and the marine iguana, which does not occur in Australia). These reptiles have become adapted to life in the marine environment. Sea snakes comprise >80% of living marine reptile species. Of up to 53 true sea snake species in the world (Lukoschek and Keogh 2006), 32 occur in Australian waters (Cogger 1996). Sea turtles make up a much smaller proportion of marine reptile species and six out of seven species occur in Australian waters. A single saltwater crocodile species (*Crocodilus porosus*) occurs in coastal waters of Australia.

Hearing sensitivity

Very little is known about sea snake and crocodile underwater bioacoustics, including the sounds they make and their hearing capabilities. Comparatively more research has been undertaken on marine turtles. No studies have been published on sounds and hearing sensitivity of sea snakes during this synthesis, although some work is believed in progress.

Crocodiles are considered to be more social than other reptiles. They are also considered to have good hearing in air and produce a wide range of airborne sounds for communication. Sounds depend upon age, sex and behavioural context, and vary among species. Vocalisations have been associated with reproduction and aggression, and include distress and threat calls, chirps and bellows. No studies have been carried out on crocodile hearing in Australia but a study on the hearing sensitivity of the spectacled caiman (*Caiman crocodilus*) found in Central and South America showed that these related species had highest sensitivity between 150 Hz and 3 kHz (Wever 1976). A more recent study on the American alligator (*Alligator mississipiensis*), which used auditory brainstem responses, showed that in-water responses were elicited from tones between 100 Hz and 2 kHz, with peak sensitivity at around 800 Hz. In-air responses were elicited from tones from 100 Hz to 8 kHz and peak sensitivity was at ~1 kHz (Higgs et al. 2002).

At least 48 species of turtles have been documented to emit sounds associated with social and reproductive activities (Ferrara et al. 2013). Although there is less information available on marine than terrestrial turtles, there is evidence that marine species produce sound. The leatherback turtle (*Dermochelys coriacea)* was one of the earliest marine species to be reported to produce sound (Mrosovsky 1972). More recently, sounds from leatherback turtle embryos in eggs and from hatchlings were reported to produce airborne sounds ranging in frequencies from 119 Hz to 24 kHz (Ferrara et al. 2013). Female nesting leatherback turtle sounds have also been recorded (in air), with frequencies ranging from 300 Hz to 4 kHz (Mrosovsky 1972, Cook and Forrest 2005). Beyond these studies, little is known about sounds produced by marine turtles. Despite this, hearing sensitivity has been measured using auditory evoked potentials for most marine turtle species including most species that occur in Australia. Hearing sensitivity is mainly below 1.2–1.6 kHz (Bartol et al. 1999, Piniak 2011, Piniak et al. 2011, Martin et al. 2012; Figure 44) and is best between 100 and 700 Hz. Juvenile Ridley's turtles have sensitivities in higher bandwidths than adults (by a few hundred Hz; Bartol et al. 1999, Bartol and Ketten 2006, Bartol and Bartol 2014).

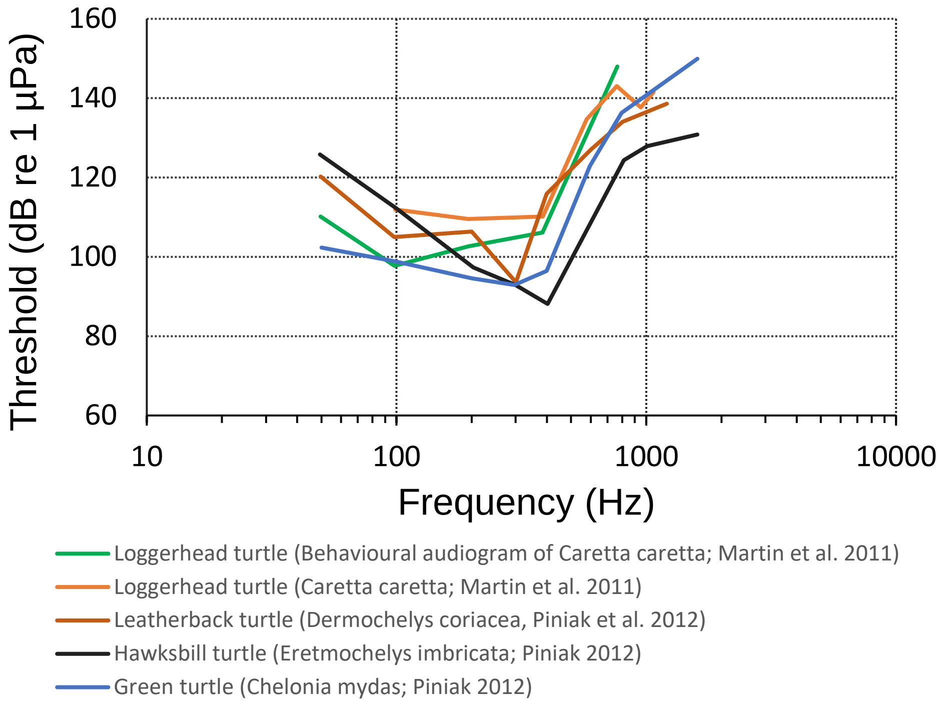


Figure 44. Audiograms for several marine turtle species that occur in Australian waters

Experimental studies measuring impacts

No studies on the impacts of underwater noise sources from oil and gas activities have been undertaken on crocodiles or sea snakes. While some work has been done in relation to marine turtles, the current research (with reports available) in Australia is limited to a single experiment investigating the behavioural response of two animals to a single approaching airgun (McCauley et al. 2003b, Table 19). This work was carried out opportunistically as the cage, turtles and airgun hardware were available. This work has not been emulated since. This research involved the controlled exposure of a green and loggerhead turtle held in a 10 x 6 x 3 m sea cage (length x width x depth) with an approaching and departing 20 cui airgun.

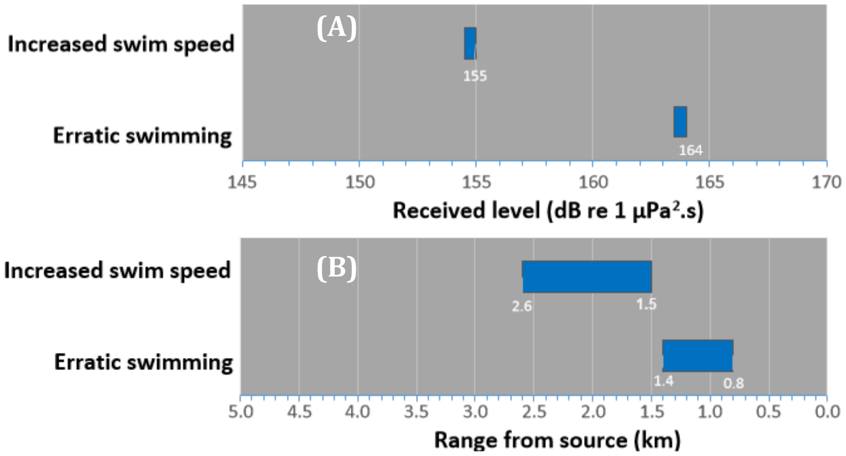
The turtles were observed to significantly and consistently increase their swim speeds at received sound exposure levels above 155 dB re 1 µPa2.s. Erratic swimming was observed at levels above approximately 164 dB re 1 µPa2.s (Figure 52). While these animals showed clear responses, the work was limited in that it involved only one individual of each species and noise from single airgun. Further, the study was carried out in winter off Perth, with water temperatures of 16° C. Turtles are cold blooded and these species would normally be found in much warmer waters, thus their typical responses may be more vigorous and at lower levels than observed by McCauley et al. (2003b).

Table 19. Marine turtle behavioural studies completed in Australia investigating response to underwater noise created by oil and gas activities and/or some similar sources

Year	Species	Location	Response measured	Source	Observation methods	Limitations	SEL threshold level (dB re 1 μPa^2.s) [range in km]	Level of response reported	R	Reference
1997–1998	Green and loggerhead turtle	Jervoise Bay, WA	• Swim speed • Vertical position in the water column • Vertical swim direction • Horizontal swim direction • Changes in swim direction and speed • Specific behaviours	20 cui airgun	Video cameras mounted on cage housing animals	The study was limited to two turtles (of different species), constraints of a large sea cage, audio signal was present during all video scoring (potential bias since tests were not completely blind), assumption of independence was made for consecutive experiments in a day (3 on one day and 2 on another day) on the same individuals and for the two animals in a single cage	>155 [1.5–2.6] >164 [0.8–1.4]	• Increase swim speed • Erratic swimming behaviour	3	McCauley et al. (2003b)

Criteria	Score
The work addressed a significant knowledge gap at the time it was undertaken relevant to petroleum activities	1
The metrics and exposure type were relevant to petroleum activities	1
The study conclusively identified the level of effects due to underwater noise on the subjects	1
The study can be generalised to the community/population/species targeted in the study	1
Total possible score	**4**

Note: Criteria is for a qualitative assessment rank of contribution to knowledge gaps at the time the work was produced. PAM = Passive acoustic monitoring; R = Relevance (described in the Relevance Criteria at the bottom of the table)



Note: McCauley et al. 2003b (n=10), where data are combined for the two species.

Figure 45. Sound exposure levels (A) and range from source (B) at which responses to a 20 cui airgun were observed in a green turtle and a loggerhead turtle

International research relevant to Australia

International research has included studies on the response of turtles to noise from seismic airgun sources. One study reported turtles staying a distance of greater than 30 m from a source with peak levels of 220–230 dB re 1 µPa (at 1 m) (pk) (O'Hara and Wilcox 1990). In another study on the response of loggerhead turtles to airguns, three source levels were tested to identify which resulted in avoidance response (Moein et al. 1994). Of 175, 177 and 179 dB re 1 µPa at 1 m (measured in the 100–1000 Hz range), the lowest value elicited avoidance. However, the decibel units nor the range were given. In West Africa, opportunistic data collected during a 10-month long 3D survey twice as many turtles were reported within 1 km of the array during periods in which airguns were not operating than when they were (Weir 2007). The study had a relatively robust sample size of 240 sightings, including 33 olive ridley, three leatherback, four loggerhead and 160 unidentified turtles. No differences were reported between the median distance of turtles sighted when the airguns were operating and when they were not, but biases in the sighting distance would have been inherent in the dataset given decreasing detection capability as a function of range. None of these studies reported received levels.

No studies were found which focused on masking, hearing threshold shifts, non-auditory tissue damage or physiological responses in reptiles associated with underwater noise sources from oil and gas activities. However, based on hearing physiology, Eckert et al. (1998) predicted temporary hearing threshold shifts at sound exposure levels of 185 dB re 1 µPa from airgun signals but did not specify decibel units.

Other research currently underway in Australia but not completed

Two studies on noise impacts on marine reptiles are currently underway in Australia. One study at the University of Adelaide is investigating the impacts of seismic surveys on sea snakes being carried out at the University of Adelaide, and one PhD research project at the University of Western Australia is attempting ABR experiments on sea snakes to establish their hearing capability. There are no studies on noise impacts on sea turtles or crocodiles.

6.3.1 Synthesis of known effects and gaps in knowledge

- Hearing sensitivity has been measured using auditory evoked potentials for most marine turtle species including those in Australia, however very little is known about hearing sensitivity of sea snakes and crocodiles. All species are known to sense, and use sound and associated vibration.
- Current research on the impacts of oil and gas industry activities in Australia is limited to a single experiment investigating the behavioural response of two animals to a single approaching airgun McCauley et al. (2003b). The turtles were observed to increase their swim speeds at received sound exposure levels above 155 dB re 1 µPa2.s. Erratic swimming was observed at levels above approximately 164 dB re 1 µPa2.s.
- No studies on the impacts of underwater noise sources from oil and gas activities have been undertaken on crocodiles or sea snakes.
- No studies focused on masking, hearing threshold shifts, non-auditory tissue damage or physiological responses in reptiles associated with underwater noise sources from oil and gas activities.
- Not only is there little work that has been done in Australia, but also internationally.

6.4 Fish

Australian waters have a high diversity of fish species. In the year 2012–2013, ABARES (2014) estimated that Australian commercial fisheries contributed ~$2.4 billion AUD (this includes invertebrates; refer to Section 6.5) to the Australian economy. Of this, fin-fish (those species that are not invertebrates) contributed more than $674 million at >92,800 tonnes of catch (including the top few species only). In 2012–2013, ABARES (2014) estimated that 8608 people were employed in the commercial fishing and aquaculture industry (fish and invertebrates), with 5050 employed in the fishing and 3558 in aquaculture enterprises. In addition to commercial fisheries, recreational and charter fishing (almost entirely fin-fish) were estimated to contribute about $1.8 billion to the national economy in 2003 (Campbell and Murphy 2005), with the survey in 2013 showing 3.4 million Australians engaged in recreational fishing and 90,000 employed in this sector (ABS 2013). Fishing activities in Australia for fin-fish and invertebrates are therefore an important economic contributor in the Australian economy, and perhaps more significantly, directly employ almost 100,000 people in the commercial and recreational sectors combined.

Given the economic and social importance of commercial and recreational fisheries in Australia, any impacts on the fishing sector from petroleum-related activities must be closely regulated and kept as low as possible. Reducing or eliminating impacts requires a good understanding of the biology of the species that may be impacted. The following subsections review the available information for fin-fish (for invertebrates refer to Section 3.5) with a focus on oil and gas activities that create intense impulse signals such as pile driving and seismic surveys, as they are the activities most likely to cause impacts. A subsection devoted to a large-scale program of experiments on fin-fish at Scott Reef, Western Australia, in 2007 is presented in Section 3.4.2.1. A discussion on potential changes in commercial fishery catch rates due to seismic operations is also included (Section 3.4.2.3). This section concludes with a synthesis of the known effects, the current knowledge gaps and a summary of relevant literature published since 2002 (Section 3.4.2.7).

6.4.1 Hearing sensitivity

Fin-fish have widely varying sensitivities to sounds. The hearing capability of fin-fish, their sensitivity to sound and potential impacts of noise on fish have been reviewed extensively (e.g. Popper and Fay 1993, Normandeau 2012) with a recent assessment of significant gaps in knowledge discussed in Fay and Popper (2012) and Hawkins et al. (2014a). Therefore, fin-fish hearing sensitivities are not elaborated in detail here except for a general summary of the hearing mechanism and how this may be impacted by anthropogenic sound. Reviews of fish response to sounds invariably repeat a small number of actual experimental works or field observations, so these reviews are largely not considered here.

Fish 'hear' by the relative motion of a dense calcareous mass, termed an otolith, and a membrane containing several thousand vertebrate type II hair cells coupled to the otolith and often found lying in a groove on the otolith's inside face. The otolith density is approximately three times that of sea water while the membrane and hair cells have a similar density to sea water (de Vries 1950). An impinging sound wave will create a differential motion between the membrane with hair cells and the otolith because of the density difference. This differential motion displaces the protruding hair cells' cilia or kinocilia. The hair cells produce a nervous response proportional to the amplitude and direction of bending of the 'hairs' or kinocilia (Pickles 1993). Thus, the relative motion of the otolith and its attached membrane results in nervous responses to the brain specific to the motion of the otolith and, inherent in this, information on the sound wave creating the differential motion. Fish have two laterally paired sets of three otolith organs in close proximity underneath the braincase, usually wholly or partially encapsulated in bone. All fin-fish otolith organs will respond to animal motion, orientation, vibration and potentially sound. Typically one of these sets of pairs is primarily (but not necessarily exclusively) used for the hearing response – often the largest otolith, usually the saggital otolith.

The relative motion of otolith and the membrane with sensory hairs is driven by the particle acceleration component of an impinging sound wave, or the backwards and forward motion of the water particles driving the differential motion between the dense mass and the hair cell lined membrane coupled to this. Fish with a swimbladder or bubble linked to the otolith can improve their hearing capability by coupling the sound pressure response of the gas filled bubble or swimbladder to the otolith. This can be via a mechanical link (i.e. Weberian ossicles) or direct coupling of the swimbladder to the otolith (e.g. Nestler et al. 1992, or for Priacanthidae as shown in McCauley 2001). These fish were called 'hearing specialists', although this term is no longer considered applicable as fish with poor swimbladder-to-otolith coupling may still have high hearing sensitivity (Fay and Popper 2012) and in some cases exhibit a wide frequency range of hearing sensitivity by utilising the smaller otoliths (e.g. Higgs et al. 2004).

Fish have been shown to exhibit a range of responses to man-made underwater sounds ranging from death in extreme and relatively rare events such as explosives (Yelverton et al. 1975), organ damage from exposure to short range or large numbers of pile driving signals (Halvorsen et al. 2012), hearing damage from airguns (McCauley et al. 2003a) where the otolith is driven into the hair cell membrane and damages it, behavioural responses including avoidance to high impulse sounds (Pearson et al. 1992, Fewtrell and McCauley 2012) or reductions or changes in catch rates from seismic surveys (Engås et al. 1996). Despite these documented responses to man-made sounds, we have a very limited understanding of the cumulative response to multiple exposures from a source or the fitness implications to wild fish of single and repeated exposures to intense sources (discussed in Popper and Hastings 2009a,b). Additionally, we know little of the implications of masking of signals of interest to fishes.

6.4.2 Experimental studies measuring impacts

In the Australian context, the largest recent study on underwater sound exposure impacts on fish was that conducted inside Scott Reef lagoon in September 2007. Scott Reef is a large coral reef atoll in north-western Australia that has two large lagoons separated by a deep channel. The southern lagoon where the study occurred reaches 60 m depth and is internally 26 km east-west and 19 km north–south. Experiments with a 2055 cui airgun array were carried out inside the southern Scott Reef lagoon to determine 1) measures of transmission of the airgun array for verification of cumulative sound exposure estimates for different habitat types within the lagoon, 2) if resident fish species were physically damaged by the airgun signals, 3) if the airgun signals changed the hearing response of resident fishes, 4) if the airgun signals damaged fish ears, 5) how the behaviour of fish exposed to airgun signals changed, and 6) if the seismic survey that followed the study influenced fish abundance and fish calling behaviour within the lagoon. Additional work was carried out observing coral response to the experimental and full-scale seismic program.

Another recent study in Australia attempted to correlate historical fisheries catch data with seismic survey activity using data from south-eastern Australia (Thomson et al. 2014). The work is limited, however, because the methods used to correlate catch data (Thomson et al. 2014) were incompatible in time and space with the known impact ranges of seismic surveys thus is not considered further here.

Scott Reef fin-fish study

As mentioned above, a study of fin-fish response to a 2055 cui airgun array was carried out in 2007 at Scott Reef, 430 km north of Broome in north-western Australia (Figure 46). Full results are published in the grey literature as a series of reports but the following research has been published to date in peer-reviewed journals:

- long-term changes of fish community structure within and around the lagoon (Miller and Cripps 2013)
- hearing response of fish exposed to seismic using a shipboard ABR (Hastings and Miksis-Olds 2012)
- fish hearing damage (McCauley and Salgado Kent 2012).

In a report to the WA State Government regulators, McCauley et al. (2008) gave a full description of the study including measures of airgun levels and an examination of fish behaviour and hearing damage. Scott Reef is located 430 km north of Broome in north-western Australia, with the general location shown in Figure 46 and the experimental seismic lines shown in Figure 47.

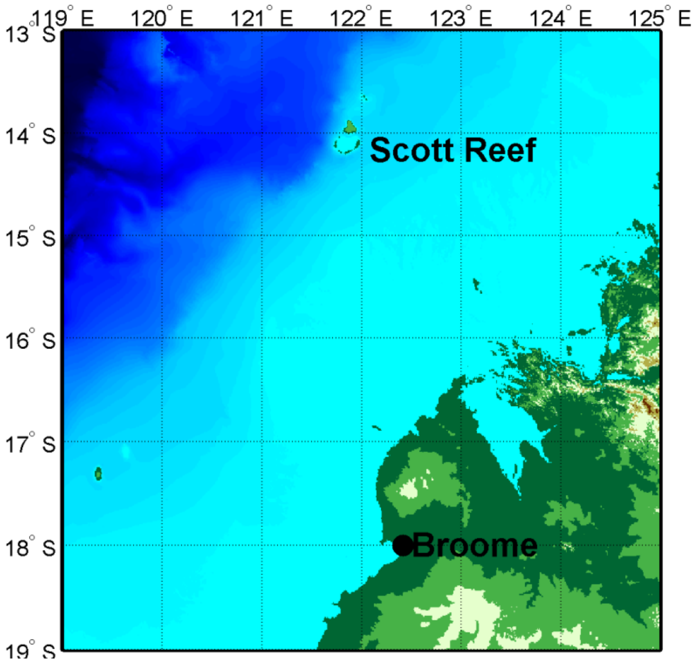


Figure 46. Location of Scott Reef with respect to Broome, in north-western Australia

The Scott Reef study aimed to gauge the response of hearing specialist fish, resident fish (Pomacentridae) and demersal fish to a seismic source, to assess potential impacts should a full-scale seismic program be carried out within the reef. Fish were collected by divers, held captive in sea cages suspended at 7 m depth and positioned at varying distances perpendicular to the seismic line (Figure 54), and exposed to high-amplitude airgun signals. Seven fish species were studied and included one from the family Lutjanidae (*Lutjanus kasmira*, bluestripe snapper), one Pomacentridae (the damselfish *Chromis viridis*, or green chromis), and five Holocentridae (the squirrelfish *Sargocentron caudimaculatum*, *S. spiniferum*, *S. lepros* and *S. diadema*, and the soldierfish *Myripristis murdjan*). Members of the Holocentridae family have adaptations linking the swimbladder to the otolith system. The damselfish *C. viridis* developed fungal infections during captivity (control and experimental) and so were not used in some analyses. The experiments involved fish behavioural observations, assessment of gross physiological impacts, shipboard ABR, otolith sampling for evidence of damage, noise logging to determine any changes to fish chorusing before and after the experimental and full-scale seismic programs, and diver transects to assess changes in fish abundance in relation to the seismic program. After the experiments, 100 bluestripe snapper were transported to Fremantle (WA) and held in captivity for time-series sampling of ABR shifts and hearing damage assessment.

The experimental design included 1) control with no seismic pass (where fish were held in cages, then recovered after 3 h), 2) seismic source active pass to measure seismic source (no fish in cages), 3) control with non-active source vessel pass, 4) active pass-1 and, 5) active pass-2. Fish were exposed to either one or two passes of the active source at three range (distance) categories (45–74 m, 105–131 m, 475–807 m).

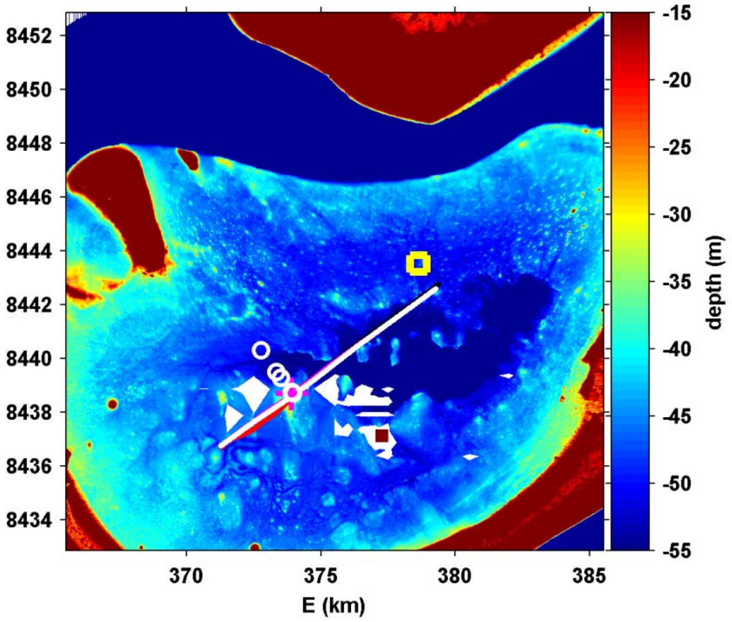


Figure 47. Location of experimental seismic lines inside southern lagoon of Scott Reef (lines running NE to SW), fish cages (white circles) and long-term sea noise logger (yellow square)

The hearing damage and caged fish behavioural results are presented in McCauley et al. (2008) and showed:

- There was statistically more ear damage on seismic exposed fish than on control fish but the damage was marginal and – assuming a linear relationship between hair cell density and hearing capability – implied that <1% of the fishes' hearing capability was impaired. Hearing damage was monitored through time on *L. kasmira* out to 60 days post seismic exposure and did not increase significantly through time with almost zero damage detected by 60 days.

Fish held in cages passed by with the operating airgun had too infrequent alarm responses (including the startle response) to include in analyses. However, agitation levels (defined by changing swim direction) in Holocentridae increased with increasing received sound level above 155–165 dB re 1 uPa^2.s (SEL). Agitation levels did not seem to increase with increasing received sound levels for the bluestripe snapper *L. kasmira*. The fish hearing threshold work of Hastings and Miksis-Olds (2012) using ABR equipment found no TTS in hearing resulting from exposure to one or two seismic passes up to cumulative levels of 192 dB re 1 μPa^2.s (SEL). The ABR was carried out over the frequency range 200–1600 Hz on *L. kasmira*, various Holocentridaeor *C. viridis* immediately after exposure to the airgun array. Sixty days post exposure, *L. kasmira* similarly showed no detectable changes in ABR thresholds.

Miller and Cripps (2013) used underwater visual census techniques to follow abundance of site-attached demersal fishes including Pomocentridae and larger roving demersal species within the lagoon of southern Scott Reef and around the reef rims. This work has continued for over a decade, including several years prior to and after the 2007 Scott Reef study. Using statistical modelling of fish species abundance and community structure, no changes attributable to the Scott Reef seismic survey program were found (Miller and Cripps 2013).

Immediately after experiments, fish exposed to the seismic passes were sampled for assessment of gross physiological damage by the Northern Territory Museum. Although this work does not appear in the available reports, observations by researchers present during dissections were that no detectable gross physiological damage was found in individuals from any of the seven species (McCauley and Salgado Kent 2012). Normal evening fish chorusing behaviour inside Scott Reef lagoon was monitored prior to the seismic survey program and for 3 years afterwards and is briefly reported in McCauley (2011). Apart from an apparent aberration during the seismic program (an increase in chorusing levels recorded), no long-term change in the fish chorus was observed. Sonar measurements made perpendicular to the seismic vessel track recorded changes in fish presence and plankton backscatter during the study, but these results are not presented here.

Fin-fish behavioural response to sound

Natural behavioural responses to underwater sound are described for many fish species, from the role of sound in the settlement of late stage larval fish (response to sound defined by Leis et al. 2002 and elaborated by Tolimieri et al. 2004 and Simpson et al. 2007) through to the use of sound for communication (Myrberg 1981). These findings emphasise the importance of underwater sound to fish during their life cycle and daily survival. There is ample evidence to suggest that fish respond behaviourally and often adversely – in the case of intense signals– to man-made underwater sound.

Obtaining the behavioural response of fish to sound stimuli is difficult. Fish kept in cages display constrained and altered behaviour. Several studies have highlighted the importance of cage size in fish behaviour experiments. Fish held in cage sizes 40–50 times their body showed clearly defined and consistent responses to an approaching seismic source (Fewtrell and McCauley 2012). Fish in smaller cages (around 5–8 times the body length) exposed to seismic signals showed restricted behavioural responses or the responses were at much higher received sound levels than for fish held in the larger cage experiments (McCauley et al. 2008, McCauley and

Salgado Kent, unpublished data). Fewtrell and McCauley (2012) reported on cage fish experiments carried out over 1996–1998 and also reported in McCauley et al. (2003b). These experiments used a 10 x 6 x 3 m sea cage (length x width by depth) and stationary or approaching and departing 20 cui airgun. Briefly in multiple experiments this work found similar behavioural results for the approaching airgun for several schooling fish species that as airgun noise levels increased the fish responded by swimming faster in progressively more tightly cohesive groups, then moved as far as possible to the bottom of the cage. Fewtrell and McCauley (2012) established thresholds at which the fish had compacted in the centre of the cage floor at or above 145–150 dB re 1 μPa^2.s (SEL). The cage work also found strong startle responses from fish exposed to nearby star- up of an airgun at short range but not when the airgun was ramped up by approaching from longer range, plus reduction of the startle response through time. McCauley et al. (2003b) gave the recovery time after airgun exposure for fish to utilise the entire cage with similar behaviours as to pre-exposure, of 11–31 min. Neo et al. (2015) report European seabass held in a large sea cage and exposed to impulse sounds generated with a speaker. Neo et al. (2015) report changes in swimming patterns and fish diving to the bottom of the cage at high received level and frequent pulse exposures. The Neo et al. (2015) observations re-inforce the results of a generic fish response to intense impulse signals as seen with caged fish exposed to seismic signals by Pearson et al.. (1992) and Fewtrell and McCauley (2012) as described above.

For high energy impulse signals, the most recent work of behavioural response to pile driving is that of Hawkins et al. (2014b). An array of sound speakers were used to generate simulated pile driving signals in an Irish loch while fish were monitored using a small sidescan sonar. Hawkins et al. (2014b) found that 1) behavioural responses increased with increased signal level, 2) on presentation of the sound stimulus sprat schools were more likely to disperse (laterally) and mackerel schools more likely to alter depth (dive), and 3) levels at which 50% of schools responded were 163 dB re 1 μPa peak-to-peak or for single strikes 135–142 dB re 1 μPa^2.s (SEL).

Observations of seismic operations impacts on the pelagic blue whiting (*Micromesistus poutassou*) in the North Sea using echosounders found that the fish dived deeper after exposure and that their abundance increased at long range from the seismic source (30–50 km) (Slotte et al. 2004). In contrast, no apparent change was observed in the swimming speed or direction (approximately into the prevailing current at around half the current speed) of feeding herring in response to a seismic vessel approaching from 27 to 2 km (Penä et al. 2013). The authors speculated that the motivation of the herring to feed may have overridden the motivation to flee, resulting in the lack of response compared with previous experiments.

Changes in fin-fish catch rates due to seismic surveys

The issue of changes in commercial fisheries catch rates due to seismic surveys is almost always contentious in Australia. Indeed in 2013 the Australian Commonwealth Fisheries Association applied (unsuccessfully) to have seismic surveys listed as a "key threatening process" under the Australian Federal EPBC Act. There is a long held belief by commercial fisherman in many parts of the world that seismic surveys changes the catching success of their fishing techniques, generally by reducing catches. This belief by fisherman has not been quantified, although there are techniques in the social sciences to formalise and apply statistics to opinions (i.e. by carefully constructing interview questions and statistically evaluating common themes in responses). There has been some effort to relate fisheries catch data to seismic survey effort, but this is fraught with difficulties such as: obtaining the correct spatial and temporal match of samples (fisheries catch data and seismic); by under-reporting or inappropriate scales in fisheries catch data (for comparing with seismic); or by the fact most fisherman will leave an area if catches drop so no samples will be available to correlate with seismic operations. To date none of the Australian efforts to relate fin-fish catch rates with seismic surveys have yielded results of any meaning.

An author (McCauley) has been on the edge of several 'conflicts' between fisherman and seismic proponents. The biggest single denominator in such conflicts was a lack of communication - in instances where seismic proponents communicated, listened and acted on concerns prior seismic there generally was less or little conflict compared to if communication did not occur or respective views were not listened to. Historically this was not helped by the fact many fishing industries were comprised of a collection of individuals operating independently as opposed to groups of fisherman operating under a collective. This has changed for the positive, most fisheries now have representative groups and Government policies (NOPSEMA) now insist on communication of intent by seismic proponents. On the fishing side industry has a current project funded by the Fisheries Research Development Corporation (FRDC project 2012/008, 2013/209, 2014/004) designed to improve communication links between fishing groups, seismic proponents and Government Regulators tasked with issuing seismic permits.

Several Norwegian studies involving commercial seismic surveys and monitoring of pelagic fin-fish abundance and catch rates have shown that fisheries catches from a variety of techniques have dropped and fish distributions have been altered during or after seismic operations (Løkkeborg 1991, Løkkeborg and Soldal 1996, Engås et al. 1996, Engås and Løkkeborg 2002, Slotte et al. 2004). Sonar observations by Penä et al. (2013) of herring apparently not responding to a commercial 3D seismic survey down to 2 km range confound this but suggest multiple factors may be involved in fin-fish response to seismic sources. These factors may include 1) behavioural factors that can alter fin-fish response to seismic sources, 2) changes in vertical received sound level profiles (i.e. reduction in received levels higher in the water column, which is exacerbated by seismic sources), or 3) normal fin-fish behavioural responses are overridden by those of their prey. Observations by Miller and Cripps (2013) of coral reef fin-fish community structure and abundance not changing in the long term after seismic operations suggest that at the many-year scale, seismic surveys do not have impacts on reef fishes, but this time scale is too large for local fishing effort.

The multiple controlled observations of high energy impulse signals (such as seismic) on fin-fish reinforce that most fin-fish will either flee a seismic source from some range (defined as within 2–5 km in McCauley et al. 2003b) or display greatly altered behaviour, potentially for the duration of the seismic survey at the least and in ways that will change their 'catchability'. For seismic surveys that persist in an area, questions remain as to what happens to displaced fish in the long term and how the seismic survey may influence fish prey fields.

Masking of fin-fish hearing system

There has been no recent work into masking of sound in fishes from anthropogenic noise sources (see review of Fay and Popper 2012). Fish can certainly inhabit noisy environments; they quickly colonise, remain at and form viable communities at offshore marine petroleum facilities, evidence they must be resilient to some degree to masking of signals of interest. How resilient fish are to sporadic or continual masking and how their fitness is altered by masking is currently unknown.

Threshold Shift and Auditory Damage in fin-fish

As discussed in the section above, a study of hearing threshold shifts using ABR techniques on caged fish exposed to seismic signals at tens to hundreds of m range showed no evidence of hearing threshold shifts despite moderate levels of exposure (up to 192 dB re 1 $\mu Pa^2.s$ cumulative SEL)(Hastings and Miksis-Olds 2012). As part of the same study, McCauley et al. (2008) found evidence of hearing damage in the form of ablated hair cells from the sagittal macula surrounding the otolith of *Lutjanis kasmiri*. The damage was marginal, however, impacting less than 1% of the fish maculae, did not show consistent relationships with exposure and had cleared by 60 days post exposure (McCauley et al. 2008). Popper et al. (2005) and Song et al. (2008) held fish in cages in a shallow river in North America and exposed them to nearby airgun signals. Popper et al. (2005) found only limited changes to the hearing capability of the fish following an 18–24 h recovery period after exposure while Song et al. (2008) found no evidence of damage to sensory hair cells on the fish macula.

These experiments of damage to fish hearing from exposure to intense impulse signals (in this case, airguns) contrast with those of McCauley et al. (2003a) whom found extensive evidence of hearing damage in ablated or missing hair cells on the macula of pink snapper some 58 days after exposure to a 20 cui airgun. The damage correlated with the fish behavioural response; based on video observations, the behavioural response was strong and obvious on the first exposure but not evident at all on the second exposure 58 days later (McCauley et al. 2003b). McCauley and Salgado Kent (2012) investigated differences in the airgun signal metrics between these sets of experiments and a further experiment in the Timor Sea. They found that while the pressure waveforms of signals between the experiments differed slightly in shape and measurement parameters, the differences were slight and not systematic in aligning with the damage observed or not observed. From this, it was concluded that we still have a relatively poor understanding of how fish ears may be damaged by high impulse signals (McCauley and Fewtrell 2012).

This raises the question whether fish hearing systems are influenced differently by sounds arriving at different angles to the horizontal plane. The geometry in the experiments that have shown no or limited damage was such that most airgun energy would have arrived in the near-horizontal plane (Popper et al. 2005, Song et al. 2005, McCauley et al. 2008). In the studies by McCauley et al. (2003a, b) an almost equal amount of energy would have arrived from the horizontal and near-vertical planes due to direct and surface bounce arrivals. At least in some fish, the sensory epithelia containing the hair cells and which is coupled to the otolith sits inside a groove on the inside otolith edge (see Figure 2.5.9 in McCauley et al. 2003b). This groove is often long in the horizontal plane and narrow in the vertical plane (but not always; in some tuna the groove is slanted with respect to the fish horizontal plane). For fish with a deep groove that contains the sensory hair-lined epithelia and which is long in the horizontal plane and narrow in the vertical plane, proportionately more damage would be expected if signals arrive closer to the vertical than if signals arrive from near the horizontal direction. In the vertical plane a comparatively small displacement will force the otolith into contact with the sensory epithelia containing the hair cells, while the same displacement motion arriving in the horizontal plane will not as the groove is long horizontally. Indeed, McCauley et al. (2003b) present a spatial map of hearing damage across the epithelia of pink snapper exposed to seismic and did find most damage along the dorsal and ventral edges of the maculae, indicating that it may have been damaged by vertically arriving sound energy.

If the propensity for hearing damage in fish is in fact related to the direction of sound arrival at fish ears as well as the exposure signal magnitude and is worse for sounds arriving from above or below the fish, a reassessment of the potential for impacts from intense anthropogenic noise sources may be required. It should be noted that many petroleum-related noise sources have strong directionality in the sound fields they produce, especially seismic sources which produce much higher levels in the vertical plane.

Physiological response in fin-fish

The Scott Reef study (described at the beginning of this section) included an assessment of gross physiological damage in fish following seismic passes. No physiological damage – up to maximum received single shot levels of 207 dB re 1 µPa (peak-to-peak), 179 dB re 1 µPa^2.s, or a cumulative SEL (two airgun array passes) of 192 dB re 1 µPa^2.s – was observed in any individual fish from any of the seven species studied.

The most complete investigation of organ damage in fish from high impulse signals comes from the work of Colotelo et al. (2012) and Halvorsen et al. (2012), who used fish held inside a large diameter heavy walled steel tube designed to produce controlled signals at its centre. The tube, termed 'HICI-FT', controlled the sound pressure and particle motion with known relationships by using speakers at each end of the tube generating standing waves. The work of Colotelo et al. (2012) was designed to define physiological impacts of pressure changes induced by passage over a turbine blade in a hydroelectric station and is not considered here. Halvorsen et al. (2012) carried out elaborate experiments on the potential for physiological injury (various organ damage criteria) as produced by exposure to multiple pile driving signals on neutrally buoyant juvenile Chinook salmon. Halvorsen et al. (2012) found onset of physical injury in salmon after 1920 strikes of 179 dB re 1 µPa^2.s (a cumulative sum of 211 dB re 1 µPa^2.s) or after 960 strikes of 182 dB re 1 µPa^2.s (a cumulative sum of 210 dB re 1 µPa^2.s), implying that either a single strike at 210 dB re 1 µPa^2.s or a series of strikes adding up to 210–211 dB re 1 µPa^2.s led to physical injury onset. They found that the equal energy hypothesis, where the cumulative sum of many smaller stimuli equated to the response of a single larger stimuli, did not hold for fin-fish physiological injury but rather the onset of injury was set by the fish receiving signals above a certain threshold and the cumulative sum of these signals

One well-constructed experiment on the response of larval fish mortality to simulated sound has been carried out recently, that of Bolle et al. (2012). In a similar manner to Halvorsen et al. (2012), Bolle et al. (2012) constructed a heavy wall tube in which standing waves could be generated and the sound particle motion and pressure manipulated independently (the 'larvaebrator'). Bolle et al. (2012) exposed larvae of the flatfish, common sole (*Solea solea*) at stages 1 to 4a (of five larval stages) to from 1 to 300 simulated pile strikes, simulating piling occurring at ranges of 100–800 m. Bolle et al. (2012) sampled only for immediate mortality effects and found none related to the noise exposure, which was for maximum single strike zero to peak levels of up to 210 dB re 1 μPa, SEL up to 186 dB re 1 μPa^2.s and cumulative SEL up to 206 dB re 1 μPa^2.s. The sole larval stages 3 and 4 should have had inflated swimbladders during the exposures. While Bolle et al. (2012) found no evidence of mortality at the exposure levels used, they did not sample for sublethal effects and impacts on larval viability.

6.4.3 Synthesis of known effects and gaps in knowledge

This section summarise known impacts and gives a quick summary of some important knowledge gaps.

Synthesis of known effects

1. Studies to date have reported many consistencies in fish response to sound, but some anomalies also exist. For high-energy impulse signals, such as seismic survey signals, the following can be said: fish behaviour most often changes at some range near to an approaching seismic vessel and generalised changes include diving, lateral spread or fleeing an area (e.g. Pearson et al. 1996, McCauley et al. 2003b, Slotte et al. 2004, Fewtrell and McCauley 2012, Hawkings et al. 2014)

2. fish behaviour is strongly impacted by an approaching seismic source above received levels of 145–150 dB re 1 μPa^2.s (SEL) (McCauley et al. 2003b), which equates to around 2–10 km using measured airgun arrays >2000 cui (Figure 30)

3. avoidance to an approaching seismic vessel by fish may be partly driven by the fish behavioural state, with feeding fishes appearing to be more tolerant and in one instance not showing avoidance to an approaching seismic survey vessel (Penä et al. 2013)

4. catch rates in some fisheries are altered during and after seismic operations; prolonged seismic can cause large-scale displacement of fish resulting in decreased fish abundance in and near the seismic operations area and increased fish abundance at long range (tens of km) from the seismic operations area (Engås et al. 1996, Slotte et al. 2004)

5. fish held in cages such that most energy arrived in the near-horizontal plane showed no evidence of changes in hearing ability from nearby seismic operations based on ABR work (Popper et al. 2005, Hastings and Miksis-Olds 2012)

6. fish held in cages such that most energy arrived in the near-horizontal plane showed no or low evidence of damage to the fish auditory system from nearby seismic operations (Song et al. 2008, McCauley et al. 2008)

7. fish held in cages such that intense impulse signal energy arrived almost equally at horizontal and near-vertical elevations showed evidence of large-scale hearing damage supported by behavioural observations (McCauley et al. 2003a,b)

8. long-term monitoring of reef fish community structure before and after a seismic survey program showed no large-scale change in community structure (Miller and Cripps 2013) and fish sound production behaviour (chorusing) continued after a seismic program with no apparent change (McCauley 2011)

9. exposure to accurately emulated repeated pile driving signals suggest physical injury (organ damage) arises at levels equivalent to 1920 strikes at 179 dB re 1 μPa^2.s or 960 strikes at 182 dB re 1 μPa^2.s, or an equivalent single strike SEL of 210–211 dB re 1 μPa^2.s (Halvorsen et al. 2012).

In a review of experimental findings of sound on fishes Popper et al. (2014) present sound exposure guidelines for fin-fish in the form of estimated levels at which the following occur: 1) mortality and potential mortal injury; 2) impairment – recoverable injury; 3) impairment – TTS; 4) impairment – masking; and 5) behavioural changes. They present these impacts for three categories of fin-fish; 1) no swim bladder; 2) swim bladder present but no links to otolith system; or 3) swim bladder present with links to otolith system, plus sea turtles and eggs/larvae. Popper et al. (2014) present this data for sources of explosives, pile driving, airgun arrays, sonar and shipping. Given the lack of experimental evidence for most of these categories they were forced to: 1) either extrapolate from another exposure type, animal group or both; and 2) rather than presenting threshold levels often present the subjectively evaluated likelihood of an impact type occurring at 'near' (tens of m), 'intermediate' (hundreds of m) and 'far' (thousands of m) ranges. The thresholds listed for physical injury (mortality and impairment-recoverable injury) for pile driving and seismic air gun signals are the same, being primarily based on the pile driving work of Halverson et al. (2012). Readers are referred to Popper et al. (2014) for the particular thresholds for fin-fish and sound exposure type as the reader should see their text for the reasoning and caveats behind the values presented.

Knowledge gaps

There are many gaps in our knowledge of impacts of sound on fishes and as anyone whom has conducted experiments investigating this will quickly realise, there are commonalities, anomalies and experiments generally result in as many questions as answers. Several broad questions which can be considered as significant from an ecological and commercial fisheries scale and their justification include:

1. Are there impacts at lower trophic levels which impact fish from high impulse seismic survey or pile driving programs? Many animals may respond in the short and long term to how their prey respond to some stimuli, to a greater degree than their own response to the

stimuli. Where impacts occur on lower trophic groups, fish may be impacted for a considerable time by such changes, thus one will never understand the response of a higher order animal unless the response of key prey species are understood;

2. Are there differences in the susceptibility of fish to hearing damage due to the arrival elevation of an impinging sound wave (near-vertical or near-horizontal)? Hearing damage from seismic surveys may be occurring only to fish deeper in the water column where arrival angles are closer to vertical and the beam pattern of the seismic array becomes more focused.

3. Are there impacts on catch rates of commercial fishing operations due to seismic operations and if so, what are the mechanisms for such impacts? Historic evidence suggests fishing catch will change in the presence of nearby seismic survey but we cannot accurately say why this happens, if it always happens, for how long it will continue and if any negative effects observed are short term or have long-term implications.

   Hawkins et al. (2014a) present the most recent review of information gaps with respect to impacts of man-made noise on marine fishes and invertebrates. Many gaps identified relate to experimental methods, quantification of sources of noise, the transmission of sound and long-term monitoring programs (Hawkins et al. 2014a), which are issues addressed by this review or within Australia (e.g. for long-term monitoring the Integrated Marine Observing System (IMOS) Passive Acoustic facility has been running Australia-wide since 2008). The main information gaps presented by Hawkins et al. (2014a) that are relevant to the response of fin-fish to anthropogenic sound are:

4. quantification of anatomical parameters that influence sensitivity to sound
5. measures of hearing characteristics (including sensitivity, directionality, processing, anatomical adaptations)
6. evaluation of sound exposures levels and characteristics that cause injury and physiological damage
7. identification of species (groups) most at risk from anthropogenic sound, including those fish that routinely produce sound
8. the implications of masking of sound to fish
9. determination of fish response to substrate-borne sound energy or vibration
10. evaluation of wild fish behaviour to various sound types
11. identification of any dose-response relationships for fish behavioural response to sound
12. implications of long-term exposure to sound as a stressor.

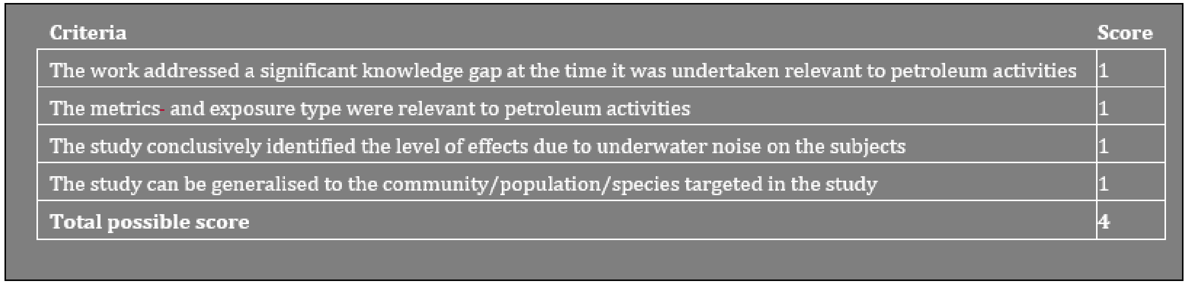
Table 20. Studies of fish response to underwater noise produced by oil and gas activities, post 2002

Species	Location	Response measured	Source	Observation methods	Limitations	Level SEL (dB re 1 μPa².s) or p-p (dB re 1 μPa), cum. SEL cumulative SEL (dB re 1 μPa².s) (range, km), response	R	Reference
Chinook salmon (*Oncorhynchus tshawytscha*)	Washington State, USA	Organ trauma due pile driving strike	Pile driving simulated in special tube that controlled pressure & particle motion	Animals, sacrificed, dissection	Tissue damage only	1920 strikes @ 177 SEL or cum. SEL of 210 or 960 strikes @ 180 SEL or cum. SEL 210	4	Halvorsen et al. (2012)
Bluestripe snapper (*Lutjanus kasmira*), green chromis (damselfish, *Chromis viridis*) (both Holocentridae spp.)	Scott Reef, WA	ABR, shipboard and land-based	2055 cui airgun array, experimental	ABR	Frequency range 200 Hz to 1.2 kHz	No change in ABR-derived hearing thresholds due to seismic	3	Hastings and Miksis-Olds (2012)
Sprat (*Sprattus sprattus*),mackerel	Lough Hyne, County Cork,	Sonar observations of movement & school density	Speaker simulating pile driving	Sidescan sonar	Use of speakers rather than actual source, no	>163 p-p or 135–142 SEL sprat disperse, mackerel dive	2	Hawkins et al. (2014b)

(*Scomber scombrus*)					visual confirmation of school ID or behaviour			
Various fin-fish	Jervoise Bay, WA (10 x 6 x 3 m sea cage)	Swim parameters, location in cage, specific behaviours, stress markers, ear damage	20 cui airgun, approach & depart	Video cameras mounted on cage housing, animals sacrificed	Behaviour biased by cage environment	>145 to 145 SEL (2–5 km) increased occurrence of startle/ alarm response, especially if start up nearby Tendency for animals to bunch up, move to lower part of cage >145–150 SEL (2–5 km) fish huddled on cage floor No measurable increase in stress associated with airgun operations Large-scale hearing damage with correlating behavioural shifts, max. single shot p-p 210 & SEL 181, cum. SEL 188	3	McCauley et al.(2003a,b), Fewtrell and McCauley (2012), McCauley and Salgado Kent (2012)
Bluestripesnapper (*Lutjanus kasmira*), various Holocentridae spp.	Scott Reef, WA (0.64 or 1 m^3 sea cages @ 7 m depth)	Behaviour, hearing damage	2055 cui airgun array, experimental & full scale	Video camera, animals sacrificed, noise loggers	Behaviour biased by small cage size, cages at 7 m depth so sound arrives horizontally oriented	>155–165 SEL agitation levels increase in Holocentridae, not snapper Hearing damage present but insignificant, clears at 60 days Short-term shifts in fish chorusing behaviour but no long term change in reef following full seismic program	3	McCauley et al. (2008), McCauley (2011)
Pomocentridae & various reef spp.	Scott Reef, WA	Abundance & community structure	2055 cui airgun array	Diver transects over decade+	Short-term impacts not assessed	No long-term change in community structure or abundance observed	3	Miller and Cripps (2013)

Herring (*Claupea harengus*)	North Sea	Sonar, movement	Airgun array, experimental line	Sonar	Sonar observations only, single line, no prey studies	Levels 125–155 SEL (27–2 km) no change in herring school patterns, movements or structure	3	Penä et al. (2013)
Pelagic herring, (*Claupea harengus*), blue whiting (*Micromesistius poutassou*) & unidentified spp.	North Sea	Sonar, movement	3090 cui airgun array, full scale	Sonar	Assumptions on sonar defined species and acoustic parameters, environmental factors not accounted for, levels not measured	Short-term (seismic survey line) displacement not evident Large-scale fin-fish displacement evident, away from seismic area	3	Slotte et al. (2004)

The response column gives either the level or range, or both, depending how it was reported. *Criteria for ranking the impact of the work in filling key knowledge gaps on the effects of underwater noise produced by petroleum activities at the time the work was conducted(where R in the table = Relevance). ABR = acoustic brainstem response technique. SEL = sound exposure level.



Criteria	Score
The work addressed a significant knowledge gap at the time it was undertaken relevant to petroleum activities	1
The metrics and exposure type were relevant to petroleum activities	1
The study conclusively identified the level of effects due to underwater noise on the subjects	1
The study can be generalised to the community/population/species targeted in the study	1
Total possible score	**4**

6.5 Invertebrates

Marine invertebrates include a large diversity of fauna with a corresponding diversity of sensory systems and use of sound and vibration. Commercially and ecologically important invertebrates include molluscs (clams, oysters, scallops, snails, slugs, cuttlefish, squid, octopi), crustaceans (crayfish, crabs, barnacles, prawns, krill), echinoderms (sea stars, sea urchins, sea cucumbers), worms, jellyfish, corals and anemones (cnidarians). Invertebrates can be sessile (site attached and fixed to the substrate) or mobile, and occur in all habitats from shallow coastal areas to deep ocean trenches. Invertebrates can range in size from barely visible with the naked eye (notably plankton) to many meters in length (e.g. squid or corals). Invertebrates make up much of the lower portion of the food web (secondary production) and are critical for supporting higher level trophic groups and marine biodiversity. Many invertebrates in Australia are commercially and recreationally important, and support commercial fisheries and the Australian tourism industry.

Only a small amount of literature exists on the impacts of underwater sound on marine invertebrates and much of it focuses only on mortality and serious physiological impacts. For this reason, a generic section on invertebrate sound and vibration sensors is included in Section 3.5.1. Invertebrate responses to sound are then dealt with in order of taxonomic groups (Section 3.5.2). This section concludes with a synthesis of the known effects, the current knowledge gaps and a summary of relevant literature published since 2002 (Section 3.5.2.6).

6.5.1 Hearing sensitivity

Despite the diversity and importance of marine invertebrates there is limited information on their response to underwater sound and vibration. A diversity of sensory systems suitable for detecting sound and vibration exist amongst invertebrates, which makes extrapolating experimental results among invertebrate species difficult beyond closely related species (such as those within the same families). Although there have been several well-designed experiments on marine invertebrate responses to sound, some have not considered the animals' sensory systems and the pathways of sound or vibration. Further, for those tank-based experiments the delivery of sound is problematic (Parvulescu 1967) – especially at low frequencies – in part due to the fact that invertebrates are known to respond to sound particle motion rather than sound pressure. Tank experiments typically have many confounding factors such as: issues with the propagation of sound frequencies and wavelengths within tanks; other sources of uncontrolled-for noise and vibration in the laboratory setting; sound pressure and particle motion in tanks are generally not related to each other (unlike in the open ocean where a linear relationship exists); errors in the measurement of particle motion at low frequencies using separated hydrophones, where the separation distance is significantly shorter than the sound wavelengths, and; the most commonly used underwater speaker systems have poor outputs at low frequencies (a function of the physics involved; low frequency underwater sound implies a big source). With these issues in mind, results from tank experiments are indicative of potential responses of invertebrates but caution must be taken when attempting to use such results to predict impacts to animals in their natural environment.

Given the diversity of invertebrates, it is first necessary to provide some background on the potential mechanisms of how sound may influence them. Many crustaceans and molluscs have sensory systems capable of detecting underwater sound or vibration that are an analogue to the fish otolith hearing system, in that they have statocyst (or statoreceptor) systems that directly drive sensory hair cells. Statocyst systems are known to be involved in balance and motion perception (e.g. in squids and sepiods; Arkhipkinand and Bizikov 2000) but are also known to respond to the particle motion of sound waves similar to the way fish otoliths function (although structurally they are vastly different). Several studies have shown that some invertebrates can 'hear' the particle motion of an impinging sound wave using their statocyst systems. These include the common prawn (*Palaemon serratus*; Lovell et al. 2005), the octopus (*Octopus ocellatus*; Kaifu et al. 2008) and the longfin squid (*Loligo pealeii*; Mooney et al. 2010).

Many benthic molluscs that are primarily fixed to the substrate possess functional statocyst systems. One would ask why these animals have this capability when they are essentially site attached. These animals may be responsive to either high energy waterborne sound, to sound energy transmitted through the seabed or to sound waves travelling along the seabed / seawater interface. Many seabed types allow low frequency sound transmission, either in the media making up the seabed or as interface waves at the seafloor/seawater boundary. A considerable amount of information is potentially available to a benthic animal from such seabed transmitted sounds, such as nearby surf conditions or an approaching predator, grubbing along the seafloor. Thus many invertebrates which inhabit benthic habitats, including molluscs and crustaceans, may be adapted to sense 'sound' energy transmitted through the seabed, as well as responding to high intensity waterborne sound energy.

It is possible that invertebrate statocyst systems can be over-driven by excessive motion of the coupled mass, and result in damage to the hair cells or membrane containing the hair cells. If this occurs it would likely result in a degradation of an animal’s sensory capability and ultimately its fitness. However, it is not known if: a) this does occur; b) if so, can invertebrates recover from any trauma to the statocyst system (fin-fish can repair hair cells); and c) what such a trauma would mean to the fitness of wild animals.

Many invertebrates do not possess statocyst organs and may be comprised primarily of soft tissue with no internal masses capable of vibrating hair cells. For small animals of a single or few cells, their response to a sound wave will be to vibrate largely in phase with the stimulus. For very intense impulse signals this mechanical motion may be sufficient to cause some form of physiological trauma to cells, although the required stimulus level to achieve this is currently unknown. Lee-Dadswell (2008, 2010) estimated physical forces on the soft tissue of snow crabs resulting from exposure to airgun signals. The study suggested that nearby airgun signals could cause mechanical trauma to snow crab internal tissues but suggested this needed verification by experimentation.

In assessing invertebrate responses to sound stimuli, larval stages must also be considered. Invertebrate larvae generally have multiple developmental stages of which the latter stages, just prior to settlement, have the most well-developed sensory systems. These pre-settlement larvae, which are critical for recruitment success, are those of most concern in terms of anthropogenic impacts. Many species' late-stage larvae have been shown to be responsive to sound cues for settlement, such as those of corals (Vermeij et al. 2010) and crabs (Stanley et al. 2009). Currently, we know little about how late-stage larvae respond to high-amplitude anthropogenic sounds.

6.5.2 Experimental studies measuring impacts

At the time of writing, two studies of potential impacts of seismic surveys on invertebrates were being undertaken in Australian waters. One study, funded by the Fisheries Research and Development Corporation (FRDC), is investigating the impacts of 45 and 150 cui airguns on plankton, scallops and berried and adult rock lobsters (Institute of Marine and Antarctic Studies, University of Tasmania, and Curtin University's CMST) and the second is investigating responses of fish and scallops to seismic passes of a 2D survey (Geoscience Australia). The FRDC program includes fine-scale behavioural and physiological measurements on experimental animals over a period of up to a year following each experiment. One paper from this study is in press (Day *et al.*, in press) and several more papers will be submitted in 2016.

Squid

McCauley et al. (2003b) and Fewtrell and McCauley (2012) described behavioural responses of squid (*Sepioteuthis australis*) to the start-up of a 20 cui airgun nearby and a ramped airgun approach. When started 30 m away from a sea cage holding squid, the 20 cui airgun caused a strong startle response; with the squid inking and jetting directly away from the airgun. The airgun's estimated level to cause inking was 163 dB re 1µPa^2.s (SEL). When the airgun was ramped up during approach to the cage from a start position ranging from 300-500 m away, the squid did not show the inking response. However, they did show: 1) an increase in movement away from the airgun once the signal level exceeded 140-150 dB re 1µPa^2.s (SEL); 2) a tendency to spend more time towards the surface; and 3) increased swimming speed initially as the airgun approached followed by a slower swimming speed once the airgun signal level exceeded 155 dB re 1µPa^2.s (SEL).

Guerra et al. (2004) suggested a link between marine seismic survey activity preceding two events of anomalous giant squid mortality in 2001 and 2003 in the Bay of Biscay. Guerra et al. (2004) found several specimens from these events with evidence of damaged statocyst organs. Some relatively fresh animals had damaged tissues and organs unlike the damage found in normally stranded animals or animals captured during fishing activities. The authors suggested a link between the observed damage to the tissue, organs and statocysts and the presence of seismic survey activity. However, there was no direct evidence to link the suggested cause and effect. André et al. (2011) found significantly more statocyst hair cell damage in four species of cephalopods (cuttlefish and octopi) subjected to tonal sweeps than compared with control animals in a laboratory experiment. While the damage was significant and unequivocal, the sound that animals in the tank were exposed to was produced by a loudspeaker in air adjacent to the tank. This meant that the stimuli producing the observed impacts was not correctly defined, making the study indicative only. In similar experiments, Solé et al. (2013) exposed squid (*Illex coindetii* and *Loligo vulgaris*) in a tank to tonal sweeps produced by a loudspeaker in air located above the tank. Damage to the squid hair cells was reported (Solé et al. 2013) but this experiment had the same limitations as that of André et al. (2011) in that the stimuli resulting in the damage was not accurately quantified.

Scallops

Parry et al. (2002) suspended adult scallops in lantern nets between 0.5 and 2.5 m above a seabed 22 m deep and exposed them to a 3542 cui 3D seismic survey source in eastern Bass Strait. Scallops were placed in three lines of three lantern nets each. Two lines were located under the airgun source and the third was within 200 m of the source. Similar nets with scallops were placed at a minimum of 20 km from any seismic activity as controls in the experiment. The scallop mortality and adductor muscle strength was compared between control and exposed animals sampled 17 days after exposure. Based on a robust sample size, Parry et al. (2002) did not find any significant differences between the exposed and control scallops. There are several potential limitations with this experiment. The first relates to scallops being suspended in the water column which is not where they naturally occur. Scallops naturally occur on the seabed, hence their sensory organs for detecting sound and vibration would be expected to have evolved to detect sediment borne motions (i.e. airgun signal energy coupled into the seabed). This sensory modality was not available to the scallops held in the water column. The experimental program was not setup to sample physiological factors, nor for sampling over an extended period of time (only one point in time was sampled). However, the experiment did show that short range exposure of scallops suspended in the water column to a large commercial airgun source did not cause any increase in scallop mortality or apparent change in adductor muscle strength, which is a crude reflection of the animals' physiological state.

Harrington et al. (2010) were not able to find a relationship between scallop (*Pecten fumatus*) deaths over a scallop bed at the eastern end of Bass Strait subjected eight week previously to a 2D seismic survey (which took place in late Feb-2010 to April-2010). This was a contentious seismic survey, there was a die off of scallops some time after the seismic survey which seriously impacted fishing effort and which had no obvious cause (although there was no planned systematic sampling for monitoring to determine such a cause). Harrington et al. (2010) conducted a small number of before and after dredge tows for scallops in impacted, non-impacted and semi-impacted areas for this seismic survey. They found no changes in the relative abundance of live scallops or condition of the scallop gonads or adductor muscles when comparing the exposed with control dredge samples. This study was in contrast to the fisherman, whom reported a die off of the scallop bed. Given the single time point sampling undertaken in the Harrington et al. (2010) study then no conclusions can be drawn as to if the seimsic survey did cause a die off of the scallops at a later date.

Crustaceans

In Australia, Parry and Gason (2006) analysed rock lobster catch rates and seismic survey activity from 1978 to 2004 in western Victorian waters. They attempted to factor in changes in differing airgun array source levels and number of signals generated per seismic survey, and to co-locate these as accurately as possible with catch data through time. No meaningful correlation could be found between seismic operations and rock lobster catch rates when analysed for 1–7 years after a seismic survey, at time scales of weeks to years after each survey (Parry and Gason 2006). The techniques used to estimate received airgun array levels at the seabed, the problems associated with using historical catch data, and the fact that fishermen often do not work in areas of seismic operations means that attempts to correlate past seismic operations with fisheries catch data often lacks fine spatial and temporal precision. This is reflected in the comparably low statistical power of the correlations made by Parry and Gason (2006), where they estimated that catch rate changes of >50% reduction were required to be detectable in their analysis. They did attempt to look at certain fine-scale catch data with respect to several individual seismic surveys but again found no correlation (Parry and Gason 2006), although this aspect of the study was hampered by a spatial offset of fishing effort (in shallow waters) relative to the area of seismic activity (mostly shelf break or deeper).

In a pilot study Payne et al. (2007) exposed the American lobster (*Homarus americanus*) to "low level" (~202 dB re 1 μPa peak-to-peak) and "high level" (~227 dB re 1 μPa peak-to-peak) airgun signals in a large tank ('low' received level, 10 cui airgun) and in the field ('high' received level, 40 cui airgun). Payne et al. (2007) found no effects on delayed mortality or mechano-sensory systems (as derived from animal righting times) but did find physiological impacts. They were not able to ascertain the significance of these impacts to the animals' fitness, but cautioned that more definitive experiments were required.

Andriguetto-Filhoa et al. (2005) carried out a study comparing catch (kg/hour) using an otter trawl net, of shrimp (*Litopenaeues scmitti, Farfantepenaeus subtillus* and *Xyphopenaeus kroyeri*) between control and airgun exposed (635 cui) regions in shallow (2–15 m) water in north-eastern Brazil. They found no changes in catch rates using the trawl net sampling 12–36 hours after seismic operations when compared with control trawls immediately prior to seismic operations. In ancillary experiments Andriguetto-Filhoa et al. (2005) reported no mortality and negligible histopathological damage of caged shrimp passed at short range by an operating airgun source.

Given the spatial overlap in seismic activities and the valuable snow crab industry in eastern Canada, considerable work has been carried out on the response of snow crabs to marine seismic surveys. A report by the Canadian Department of Fisheries and Oceans (DFO 2004) summarised the work and stated that seismic surveys did not cause acute or mid-term mortality to snow crab, that embryos carried by snow crabs survived exposure to early stage larvae, and that in the short term snow crab gills, antennules and statocyst organs were 'soiled' by exposure but that this cleared within 5 months after exposure. There were differences between control and airgun-exposed crabs in that exposed crabs had bruised hepatopancreases and ovaries, and crab orientation as given by righting time was delayed (DFO 2004). Although control sites were included, the results could not entirely be attributed to the airgun operations due to potential differences in environmental factors between control and impact sites. The DFO (2004) concluded that more work was required to determine the significance, persistence and effect on wild animal fitness of the physiological impacts observed.

Coral

In September 2007, a series of experiments investigating the impacts of a 2055 cui 3D seismic survey source on corals were carried out in the 60-m deep lagoon of Scott Reef, north-western Australia (see Section 3.4.2.1 for details on the broader study). Corals in and around the lagoon were exposed to seismic signals (both experimental seismic lines and a full seismic survey) using a 2055 cui source over a 59-day period. The experimental lines passed directly over the coral communities (source at 7 m depth, corals at ~60 m depth) whereas the full seismic survey passed within tens to 100s of metres (horizontal offset). McCauley (2014) estimated received seismic signal levels at coral impact sites to be a maximum peak-to-peak of 226–232 dB re 1 µPa, maximum SEL of 197–203 dB re 1 $\mu Pa^2.s$, maximum rms of 214–220 dB re 1 µPa, and maximum cumulative SEL of 197–203 dB re 1 $\mu Pa^2.s$. For plate corals, *Lobophytum* spp., and various soft corals including *Sarcophytum* spp., the proportion of dead and bare coral cover and the % cover of red algae were documented and no detectable effect was found from one or multiple passes of the seismic airgun array (Battershill et al. 2008). Further, there was no evidence of coral breakage, no signs of physiological impairment in the corals (polyp withdrawal or reduction in soft coral rigidity) and no long-term change in coral community structure related to the experimental or full seismic survey activities (Battershill et al. 2008).

Larvae/plankton

The effects of an operating 3542 cui 3D seismic array on plankton was investigated by Parry et al. (2002), alongside their work on scallops. Vertical plankton tows (20–0 m depth) were taken along transects running parallel and adjacent to seismic survey lines. A last-minute change to the seismic vessel track meant the initial balanced sampling design became five control transects (5 net tows ~500 m apart along each transect) and one impact transect (10 net tows). Plankton tows along the impact transect were made within 30–60 min of the seismic pass. Parry et al. (2002) found no detectable impacts on plankton based on their species composition and live/dead state but did concede that their statistical power to detect any impacts was low, requiring decreases in abundance of >30–40% for copepods and >80–90% for most other taxa.

Aguilar de Soto et al. (2013) carried out experiments where early D-stage scallop larvae held in a tank were exposed to simulated airgun signals produced by an underwater J9 loudspeaker placed 9 cm away from the larval test container. Morphological deformities were observed in all exposed larvae when compared with control larvae. While this experiment indicated that exposed larvae were impacted, the exact stimulus was poorly defined or not known owing to the experimental setup. The experiment was carried out in a tank with its inherent acoustic problems as discussed above and the sound projector was placed so close to the test animals it is probable that vibratory motion of the sound projector was transmitted to the larvae along with the test sound signal.

Day et al. (in press) exposed berried (with eggs) spiny lobster (*Jasus edwardsii*) to passes of a 45 and 150 cui chamber single airgun in open waters of southern Tasmania. Control and exposed spiny lobster were held in aquaria until the eggs hatched and the morphology and viability of eggs and larvae ascertained out to a week after hatching. No mortality of adult lobster or eggs could be attributed to the air gun exposure regimes used (up to cumulative SEL values of 199 dB re 1µPa^2.s). While there were some differences in exposed larvae morpholgy (slightly larger than controls) there were no differences found in larval hatching rates or viability / competency. The authors cautioned that these were early stage larvae without developed sensory organs and results of airgun exposure may differ for late stage lobster larvae.

6.5.3 Synthesis of known effects and gaps in knowledge

A short summary of known effects and gaps in knowledge are presented below.

Synthesis of known effects

Based on what is known of sensory physiology and the potential impacts of intense sound on invertebrates, the following can be said:

1. many marine invertebrates contain mass-loaded sensory systems (statocyst systems) that may be damaged by high-intensity sound overdriving the system, causing the mass to physically damage the coupled sensory hair cells

2. Many marine invertebrates do not have statocyst organs. For these animals damage from intense sound exposure may arise by cellular damage due to imposed shearing forces from the sound wave, although the forces required to do this are not known and it would be expected only very intense sound signals received at short range may produce this effect;

3. squid have been shown to have strong behavioural response to nearby seismic signals starting up or to approaching seismic survey sources (McCauley et al. 2003b, Fewtrell and McCauley 2012)

4. There is circumstantial evidence that giant squid may have been adversely impacts by seismic surveys in the Bay of Biscay but there is no direct evidence that this was the case;

5. In laboratory situations André et al. (2011) and Solé et al. (2013) have shown damage to the hearing system of several cephalopod species from exposure to tones, although due to the nature of the experimental set up, the exact stimuli was not well characterised. However, these experiments do highlight that cephalopod statocyst organs are likely damaged by intense sound exposure.

6. Experiments summarised by Parry et al. (2002) involving scallops suspended in the water column and passed at short range by an operating 3542 cui airgun array showed no increased mortality or change in adductor muscle strength due to the seismic pass;

7. Observations by Harrington et al. (2010) before and after seismic survey using dredge tows for scallops in Bass Strait showed no difference in relative abundance of live scallops, or the condition of scallop adductor muscles or gonad state. This study followed a die-off of scallops fisherman claimed was the result of a seismic survey but neither the fisherman nor

the study of Harrington et al. (2010) could definitively attribute the scallop die-off to a cause;

8. An analysis of seismic survey presence and rock lobster historic catch data by Parry and Gason (2006) in Victorian waters found no correlation of catch rates with seismic but their estimated sampling power required changes of >50% of catch rate to be detectable in the analysis;

9. Payne et al. (2007) found the American lobster subjected to airgun signals had no delayed mortality or mechano-sensory damage attributable to the airgun exposure but did show physiological impacts but the exact cause of these impacts was not clear;

10. Various experiments with snow crab and seismic exposure in Canadian waters have found no direct mortality, no impacts on crab eggs up to early stage larval development, but did find physiological impacts. The significance of physiological impacts for wild crabs is currently not clear;

11. A shallow water (2–15 m) artisanal shrimp fishery in Brazil showed no reductions in catch or physiological impacts from nearby seismic exposure in the short-term (Andriguetto-Filhoa et al. 2005);

12. A study of coral exposed to experimental passes of a 2055 cui seismic source and a 59-day commercial survey using the same source, found no evidence of damage of any sort on hard and soft corals or on coral community structure over several months after the seismic activity (Battershill et al. 2008).

13. Parry et al. (2002) found plankton net tows undertaken around an operating seismic source (3542 cui) had no detectable changes in plankton community presence, although the estimated statistical power to detect changes was relatively low (abundance changes of >30–40% for copepods and >80–90% for other taxa were required to be detectable).

14. Tank experiments by Aguilar de Soto et al. (2013) have shown strong evidence for morphological abnormalities in early stage scallop larvae from simulated airgun signals. These experiments were conducted in a tank with the sound projector close to test animals. Thus, the experiments have confounding acoustic parameters, but do demonstrate that it is possible for invertebrates without statocyst organs to suffer physiological damage from sound exposure.

15. Experiments with a 150 cui airgun in field conditions have shown that berried lobster egg mortality and viability were comparable between exposed and control samples although exposed lobster eggs were slightly larger (Day et al. in press).

The experiments and observations summarised above vary in their results with some showing impacts from sound and some not. However, there are sufficient instances of consistent results to suggest that:

- intense sound may impact the cellular structure of marine invertebrates

- invertebrates with statocyst organs may be damaged by intense sound exposures (especially cephalopods)
- there is mixed evidence of intense sound impacts on plankton and larvae
- corals do not appear to be impacted by seismic operations
- physiological impacts of intense sound exposure have been observed but the fitness implications for wild animals of any such changes are not known.

Fisheries lobster catch data currently show no impacts of seismic on lobster catch success, although the statistical power to detect changes has been low and the temporal and spatial scales and resolution of fishing and seismic activities used in these analyses often differ.

Knowledge gaps

There are a large number of unknowns with regards to impacts of sound on marine invertebrates. This is confounded by the high diversity of sensory systems and physical stimulation modalities involved, the different types of behavioural responses observed, the vastly different ecological roles played by invertebrates and the fact many invertebrate populations have naturally high mortality rates and fast life cycles. The common high intensity sound sources with high peak levels may be considered as those most likely to cause physiological damage to invertebrates, so these sources (seismic using airguns and pile driving) would be prioritised for study. Some of the primary unknown issues for invertebrates from the perspective of their prominence as prey species or for commercial fisheries and these high impulse signals are:

1. While limited available evidence suggests catch rates of commercial adult invertebrates studied (lobster, scallops, shrimp) do not drop with correlating seismic survey activity is this the case at the fine scale with more rigorous sampling? Does seismic exposure cause sub-lethal impacts to commercially important invertebrates and what happens to any physiologically compromised animals in the longer term and with respect reproductive output? If physiological damage is experienced by commercial adult invertebrates what are the mechanisms driving these impacts?

2. Squid and other cephalopods are responsive to many human sounds and their hearing systems may be compromised by intense sound exposure. How do seismic surveys change the behaviour of oceanic squid in the short and long term? If changes in squid behaviour occur in response to seismic how do these changes alter their availability to higher order predators? Are they easier to catch? Or do they respond in ways which make them harder to catch?

3. What are the physical impacts and scale of any impacts caused by marine seismic on invertebrate plankton? There are no reliable, fine scale and rigorous studies of the response of plankton with developed statocyst systems to high impulse noise sources so we cannot put a scale on impacts and so gauge the ecological consequences of any lethal or sub-lethal impacts to these fauna. While many authors have attempted to estimate the scale of seismic impacts on plankton from seismic, all of these studies have assumed small scale (< tens m) impacts (e.g. McCauley 1994), but is this the case? - There simply have been no well carried

out experiments to define any debilitation range to plankton from high impulse signals. What if the range plankton may be debilitated by intense impulse signals is at the km scale? Plankton, in the form of secondary production, are the base of the food chain for a diverse range of fauna, thus impacts on plankton may dramatically change and impact the behaviour of higher order predators. Changes to invertebrate prey fields are almost never accounted for correctly in studies of seismic on fin-fish or marine mammals.

4. What are the physical impacts of seismic on late stage invertebrate larvae which have well developed sensory systems? Invertebrate larvae typically go through many stages whilst planktonic, with the latter, immediate pre-settlement stage being that where the animals have the most well developed sensory systems and so the stage potentially most at risk from human impacts. These late stage larvae are also towards the end of the often massive normal mortality rates found in invertebrate larvae. That is, there are few of the final larval stages prior to settlement thus any wide scale impacts on this stage may have large negative recruitment implications. How do late stage invertebrate larvae respond to marine seismic

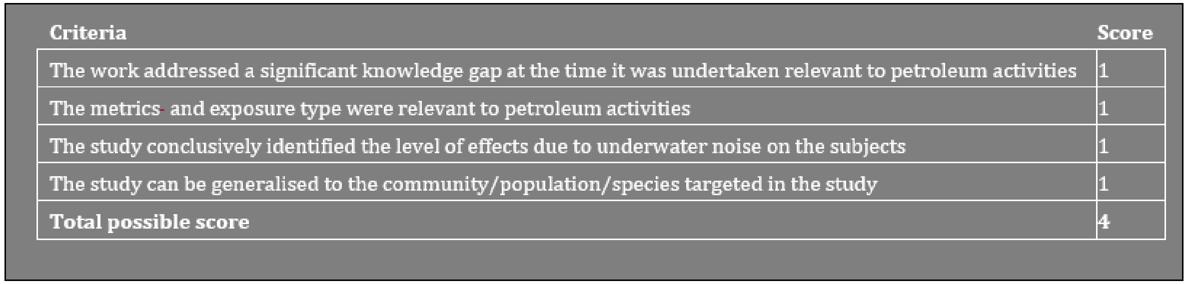
Table 21. Studies of invertebrate response to underwater noise created by oil and gas production and exploration activities post 2002

Species	Loc.	Response measured	Source	Observation Methods	Limitations	level SEL (dB re 1μPa^2.s) or p-p (dB re 1μPa), cum SEL cumulative SEL (dB re 1μPa^2.s) (Range, km), response	R	Reference
New Zealand scallop veliger larvae	tank	physical deformities	speaker 9 cm from larvae playing airgun signal	visual, microscope	stimulus not well defined tank experiments	unknown stimulus, exposed larvae had body deformations	1	Aguilar de Soto et al. (2013)
spiny lobster eggs / early larvae (*Jasus edwardsii*)	field	Egg & early larvae morphology, vitality	150 cui airgun	Histological, physiological	Single air gun as opposed to array	max cum SEL 199	4	Day et al. (in press)
cephalopods, *Loligo vulgaris*, *Sepia officinalis*, *Octopus vulgaris*, *Illex coindetii*	tank	hearing damage	2 hours of 50 to 400 Hz sweeps speaker in air adjacent tank	histological	stimulus not well defined and has no relationship with oil and gas noise tank experiments	unknown stimulus, exposed cephalopods had hearing damage	1	Andre et al. (2011)
shrimp, *Litopenaeus schmitti*, *Farfantepenaeus subtillus* & *Xyphopenaeus kroyeri*	field, Brazil	trawl catch rates	635 cui airgun array	catch rate analysis	shallow water (5-15 m) immediate impacts only (sampling within one day of seismic)	levels not measured no change in catch rates observed	3	Andriguetto-Filhoa et al. (2005)
various hard & soft coral spp.	Scott Reef	abundance & health	2055 cui airgun array	video transects	none	max p-p 226-232 max rms 214-220 max SEL 197-203	4	Battershill et al. (2008), McCauley (2014b, for level estimation)

						max cum SEL 197-204 no detectable effects on coral survival, health or community structure		
giant squid, *Architeuthis dux*	Spain, Bay Biscay	stranding rates	unknown	stranding carcasses	no data on causation	unknown why squid stranded or if they had been exposed to man-made noise aberration in numbers standing roughly correlating with seismic activity squid appeared to have hearing damage	1	Guerra et al. (2004)
scallop, *Pecten fumatus*	Bass Strait	mortality, morphology growth	4130 cui seismic survey	BACI trawl catches	post seismic samples at 2 months only	seismic lines over scallop patches no change in comparative mortality or morphology between impacted & control sites	3	Harrington et al. (2010)
squid, *Sepioteuthis australis*	sea cage WA, 10 x 6 x 3 m size	behaviour	20 cui airgun, started nearby or in approach-depart scenario	cameras placed in cage corners	immediate behavioural observations in relatively small cage do not give long term implications do not assess repeated seismic passes and potential for prey debilitation	163 SEL - strong startle (inking) and jetting response to stationary source started 30 m off 145-150 SEL - alarm responses become frequent to approaching source, squid move toward water surface and increase swimming speed > 155 SEL squid slow down, lie motionless often near surface	3	McCauley et al. (2003b), Fewtrell and McCauley (2012)
scallop, *Pecten fumatus*	Bass Strait	mortality	3452 cui airgun pass	live vs dead	scallops held in water column, so not	Two passes over nets, one within 200 m, probable > 180 SEL no mortality linked to airgun pass	2	Parry et al. (2002)

					coupled to ground borne energy no physiological parameters measured immediate (17 day after) mortality only	no change in adductor muscle strength linked to airgun pass		
plankton	Bass Strait	mortality & species abundance	3452 cui airgun pass	live vs dead	plankton tows after seismic pass low sample size no account for drift plankton & sample times	pass close by, no measures no change in live vs dead stated statistical power required > 30-40 % change for copepods &> 80-90% for other taxa	2	Parry et al. (2002)
Southern rock lobster, *Jasus edwardsii*	western Victoria	catch rates	historic seismic / catch rate comparison	correlate catch rate & seismic	spatial offset seismic / lobsters power estimated, required a > 50% catch reduction to be detectable	levels not known no change in catch rate data found	3	Parry and Gason (2006)
American lobster, *Homarus americanus*	tank / field	mortality, behaviour, physiological	10 & 40 cui airgun	live/dead, righting tests, pathological examination	no sound metrics controlled experiments, not long term	'low' or 'high' airgun levels only no delayed mortality no change righting behaviour subtle physiological changes	3	Payne et al. (2007)
squid, *Loligo vulgaris, Illex coindetii*	tank	ear damage	in-air loudspeaker adjacent tank 10-400 Hz sweep 2 hours	histology	stimulus not well defined and has no relationship with oil and gas noise tank experiments	unknown stimulus, exposed squid had hearing damage	1	Solé et al. 2013

The response column gives either the level of response reported or range, or both, depending how it was reported. *Criteria for a ranking the impact of the work in filling key knowledge gaps on the effects of underwater noise produced by petroleum activities at the time the work was conducted (where R in the table = Rank). BACI - Before, After, Control, Impact experiments.



Criteria	Score
The work addressed a significant knowledge gap at the time it was undertaken relevant to petroleum activities	1
The metrics and exposure type were relevant to petroleum activities	1
The study conclusively identified the level of effects due to underwater noise on the subjects	1
The study can be generalised to the community/population/species targeted in the study	1
Total possible score	**4**

7 Effects of vibration on Australian marine fauna

While auditory structures such as those in mammals and avians have evolved to be highly efficient in sensing changes in sound pressure, the lateral line systems, ears in fish, and statocysts in invertebrates can directly sense particle motion. Some examples of invertebrate species that are sensitive to vibration include ctenophores, jellyfish, lobster, and arrow-worms (Moriyasu et al. 2004). Functions of sensitivity to vibration have been suggested to include the detection of movement in the water within animals' proximity as well as vibration in the general environment. As an example, for the fiddler crab, studies suggest that males use vibration through drumming as females approach (Aicher et al. 1983). Impacts from vibration could range from behavioural responses, disruption of an animals' ability to sense vibration cues in their environment, to physiological effects, injury and mortality.

7.1 Sensitivity to vibration

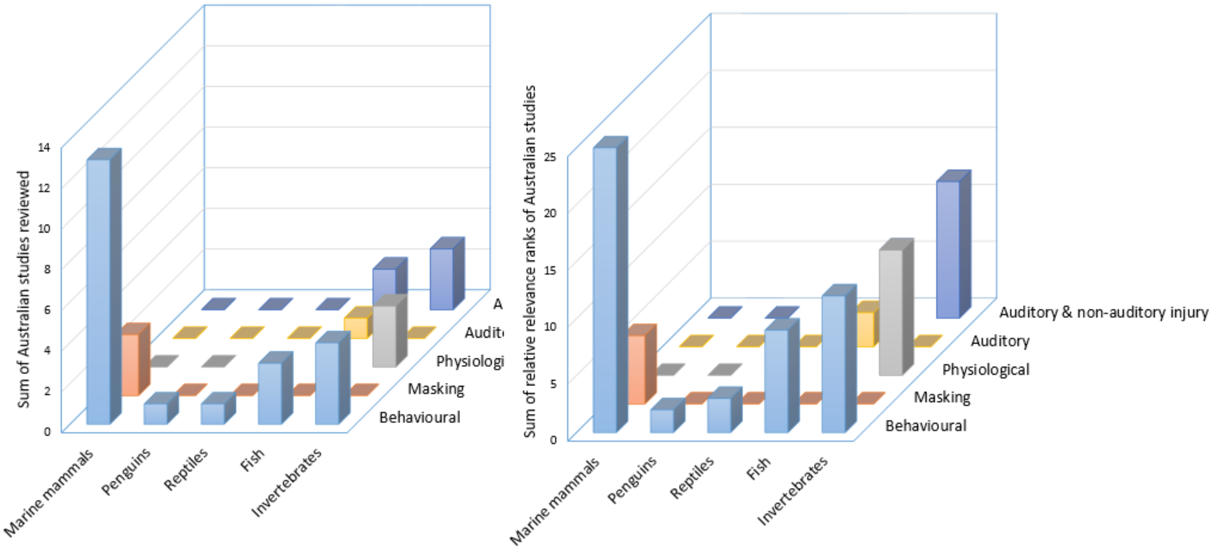
Work on this topic consists mainly of research on sensory mechanisms. Overall, relatively little is known about faunal sensitivity to particle motion. Several studies have been undertaken with the aim of measuring animals' sensitivities to vibration. For example, studies on crayfish (*Cherax destructor*) showed that maximum sensitivity to waterborne vibration was at frequencies ranging from 150 and 300 Hz, with an amplitude threshold of 0.2 μm particle displacement values (Tautz and Sandeman 1980). A different study on crayfish found two types of sensory hairs on antennae with maximum sensitivity reported to be between 40 Hz for smooth hairs and 90 Hz for feathered hairs (Tautz et al. 1981). Bivalves (*Macoma balthica*) have been shown to be sensitive to frequencies of vibration between 50 and 200 Hz (Franzen 1995). Sensitivity to low frequencies means that these animals are sensitive to substrate-borne vibration. Therefore animals that are resting on the seabed or a structure in which vibration transmits, generally have a high susceptibility to the effects of vibration.

7.2 Experimental studies measuring impacts

In Australia there has been no work done on establishing impacts of vibration on marine fauna apart from that described under fish and invertebrates in the sections above (Sections 6.4 and 6.5, respectively). In fact, very little work on the impacts of vibration on marine fauna has been carried out anywhere in the world. Relevant studies in Australia have been covered in sections above due to the close relationship between sound and vibration. Overall, limitations in many studies in assessing the role of vibration as a stressor consist of lack of quantification of particle motion or energy transmitted through the ground. While in many experiments sound pressure is measured as it is usually relatively easy to do (not always) the actual stimulus the fauna are responding to may be particle motion or energy transmitted through the ground. In many instances sound pressure and particle motion are linearly related (e.g. in the far field, in deep water), so measuring one parameter defines the other. There are many exceptions, however, where they are not linearly related, e.g. close to the source. Only a single program the authors are aware of has measured ground borne energy during experiments to gauge response of benthic fauna to intense noise and the analysis of this is still in progress (collaborative University of Tasmania and Curtin project studying the response of scallops and lobster to airgun signals).

8 Conclusions

Internationally, the number of studies on underwater noise impacts has grown exponentially since the 1980s (Williams et al. 2015). In Australia, over 30 studies in the last few decades have investigated the effects of human activities on marine fauna (Figure 48 and Figure 48). Several focus on oil and gas industry activity noise, while others have studied the effects of other noise-producing human activities that relate more loosely to oil and gas activities. Several studies specifically addressing the impacts of oil and gas activities on marine fauna in Australia were large, robust research programs. Such large programs employ a range of observational techniques and metrics simultaneously, which have achieved a relatively high degree of accuracy and statistical power. Furthermore, programs that include multiple observational techniques and controls are able to tease apart the effects of the noise from the effects of the structures or vessels producing the noise, from the effects of environmental covariates, and from the effects of inherent biases in the observational techniques. The most relevant studies have been those that have estimated sound levels received by animals as well as the range of the source to the animal. These measures allow for thresholds to be determined and implemented by managers to mitigate the effects of underwater noise. A larger number of smaller projects have been undertaken on the impacts of human activities producing noise on marine fauna. While these projects have been more limited in the observation tools and metrics used, by biases in the experimental design, and in their ability to evaluate the level and nature of impacts, they are more numerous because of their relatively low cost. Broad, comprehensive programs and smaller, more limited studies are both valuable in improving our current knowledge in this field.



Note: Sum of relative rank is the the sum of the scores studies were given (4 points maximum; see Table 2 for ranking metric)

Figure 48. Total number of Australian studies and their summed relative relevance ranks measuring behavioural, masking, physiological, auditory shifts in hearing, and auditory and non-auditory injury for faunal groups reviewed in this report

While the research so far provides improvements in current knowledge and decreases uncertainties in predicting potential impacts and mitigation effectiveness, large gaps in our current understanding remain. Impact prediction on marine fauna in Australia continues to rely heavily upon international literature for fundamental information on the physiology and biology of fauna, the characteristics of noise, and noise impacts. In some cases, the species are the same but are from different populations, and exposure histories likely vary by a large degree across the oceans. For many studies, the species are different, but provide the only information available for species of the same family.

Overall, faunal responses observed in Australian waters are broadly consistent in their variability and range with past work elsewhere in the world. These observations have highlighted variability in the potential and level of effects, which can be specific to species and populations, age, sex, health status, behavioural context and season (among other factors). In other words, guidance can be drawn from related species based on physiology and behaviour but accurate predictions with certainty can only be obtained if the ecology and biology of the focal community and species being assessed are well understood. Furthermore, accurate noise impact predictions require information on the noise characteristics and transmission from the specific activities and equipment used at the proposed location. The characteristics of the location where noise will be produced will have a large influence on how far the sound will travel, and the nature of the energy received by marine fauna. This information cannot be transferred from noise sources measured elsewhere in the world.

Most Australian studies have focused on particular species of marine mammals, fish and invertebrates. This focus is mainly driven by requirements of the EPBC Act 1999 and stakeholders' interest in particular species. Large gaps occur where species are not afforded protection by the EPBC Act or there is no direct commercial, recreational or community interest. In addition to gaps in knowledge of many species, ecological processes sustaining the species of concern are often not investigated or well understood. Impacts on krill, for example, could have significant repercussions on EPBC-protected whale species yet we do not fully understand what the impacts of underwater noise are on krill. Similarly, impacts on a range of invertebrates and small fish could have significant effects on commercial fish stocks yet research typically focuses only on the commercially targeted fish themselves.

From those studies reviewed here, most have had a focus on assessing the behavioural responses of underwater noise on large marine fauna or behaviour, mortality and physiological effects on fish and invertebrates (Figure 48). For behavioural studies on larger fauna, few studies separated the effects of noise from the structure or vessel producing the noise. Also, many studies did not measure noise characteristics and levels eliciting responses. Environmental variables which may also affect behaviour are hardly ever measured or monitored. Studies specifically aiming to assess faunal responses to underwater noise (and vibration) exposure are most relevant with appropriate acoustic measurements and controls in the experimental designs.

Studies on masking are limited in Australia and worldwide. Research to date indicates that with sufficiently high overlapping noise levels, animals are expected to experience decreased acoustic detection ranges (of certain sounds). Masking can potentially result in animals experiencing difficulties using acoustic information relevant to fundamental functions such as feeding and reproduction. In addition, a greater risk of mortality of young animals requiring contact with their mothers or animals with compromised health could result. To further understand the effects of masking, fundamental work is required on basic hearing physiology, sound production in fauna, and sound in the environment. This information can be used to feed into masking models applied to a range of marine environments. Furthermore, not all industry sources have been measured and transmission is site specific. To understand the full extent of the effects of masking, information on the soundscape is also needed since passive listening gives key information about the condition of the environment, prey and predators (among other things). No models currently exist for estimating the potential of masking of the soundscape, mainly due to the absence of valid assumptions for model. While the Australian oil & gas industry has funded many ambient noise baseline studies on prospective petroleum fields, long-term monitoring of the soundscape at any one site is rare and has only been possible due to Australia's National Collaborative Research Infrastructure Strategy (NCRIS) that funded the long-term underwater acoustic observatories of Australia's Integrated Marine Observing System (IMOS). An example of a comprehensive analysis of a long-term dataset on the marine soundscape was recently published for the Perth Canyon (Erbe et al. 2015).

Further studies on hearing physiology are needed to improve current knowledge on hearing impairment and auditory injury in vertebrates. For instance, while TTS has been traditionally considered as reversible damage, there has been relatively recent work showing that moderate TTS (reversible threshold shift) may result in degeneration of the cochlear nerves (Kujawa and Liberman 2006, 2009). One study on hearing threshold shifts has been carried out in Australia on fish but none have been conducted on penguins, reptiles or marine mammals. Research on captive animals outside of Australia has been used to feed into current knowledge and regulatory requirements. This research has been done on animals that are amenable to these tests, such as small dolphins in captivity. In the absence of sufficient TTS data, auditory threshold measurements (audiograms), equal latency contours, and predicted audiograms from anatomically based models, as well as TTS data have been used with knowledge of the hearing response of terrestrial vertebrates, to derive weighting functions and exposure thresholds. While Southall et al. (2007) developed the M-weighting functions as a first approximation, based on the tested or estimated hearing range, Finneran and Jenkins (2012) proposed an improved set of weighting functions for marine mammals. Analogous to the human A- or C-weighting, the weighting functions for marine species can be based on equal-loudness contours or equal-latency contours. Such information has now been collected for a small number of subjects from different functional hearing groups (mid- and high-frequency cetaceans as well as some pinniped species; Finneran et al. 2013; Reichmuth 2013, Wensveen et al. 2014). New weighting functions will emphasize the potential effects of seismic signals on baleen whales as well as on phocid (earless) and otariid (eared) seals, as these species show the greatest hearing sensitivity underwater at low frequencies. Caution needs to be applied with weighting functions, as knowledge on most species' full hearing capabilities is not available.

In general, studies on physiological responses in marine fauna are limited. While a handful of studies exist that show the potential for underwater noise to cause physiological responses, a workshop on the topic of physiological stress in marine mammals conducted in 2009 (ONR Workshop: Effects of Stress on Marine Mammals) highlighted the need for baseline information, including hormones and biomarkers that vary as a function of species, age, sex, reproductive status, health, season, and time of day, among other factors. The participants of the workshop also highlighted the need to ground-truth levels at different sites of the body, since sample location may also contribute to the variability in resulting measures. For large marine fauna, the limited number of studies that have been conducted on physiological responses is in part due to the difficulty in obtaining samples such as blood to measure stress hormones without causing increased stress. Furthermore, many animals are difficult to obtain samples from (such as marine mammals) due to their large home ranges and limited accessibility when sighted. Further work is required on developing methods of measuring physiological responses accurately; and for cases such as marine mammals, remote measures may be possible. Recent research has explored the potential for using blow (exhaled air by cetaceans) and faecal samples to obtain stress markers (such as faecal analyses in right whales; Rolland et al. 2012).

In Australia, a number of studies have been carried out on non-auditory injury and mortality but have been limited to certain species of fish and invertebrates. This work has been important in guiding current knowledge for these species. Injury and mortality studies on species such as marine mammals, reptiles, and penguins cannot be conducted ethically, and must be opportunistic.

There are many species, and in some cases entire faunal groups, of which very little is known. Penguins are one of those groups in which no work has been done to assess impacts of underwater noise. In fact, there is no work that has been carried out on penguin hearing sensitivity in Australia. Given that seismic surveys occur in the Southern and Indian Oceans (among other industry activities), having the required knowledge on sensitivities to long- and short-range noise transmission is critical for effective mitigation and management. Similarly, very little is known about marine reptiles. Australia has a large number of endemic sea snakes and has significant habitat for sea turtle nesting for most species occurring in the world. Studies have confirmed that sound is important for marine reptiles for functions related to reproduction, socialising, defence and navigation. Behavioural responses of marine turtles in enclosures to noise from seismic airguns have shown evidence of behavioural responses including increased swim speeds, changes in swim directions and avoidance. However, the information is based on very few animals and no other works on the responses to other sources of noise from oil and gas operations could be identified in this review. Loss of hearing, physiological stress responses, masking, and non-auditory hearing damage have been considered as possible consequences of noise exposure to sea turtles, but there is little to no empirical information available on the levels of exposure required to elicit these responses.

The development of standards (on noise measurement, baseline recording, animal observation, modelling, data analysis and reporting) is a key consideration in filling the gaps in knowledge listed above. For example, while some standards exist or are being finalised for the recording of noise from specific sources (e.g. ships, pile driving, sonars), standards for the measurement of the majority of noise data, for data analysis and for reporting are badly needed to be able to compare results across studies, as well as to noise emission policies (Erbe et al. 2016a).

Short-term behavioural responses have been the focus of most studies because measures can be made more easily over a short period. Longer-term effects require studies over a long duration, for which funding is often difficult to obtain. Mechanisms to allow for long-term studies to be conducted are required. This could be in the form of standardising data collection and systematically implementing monitoring during operations. In the absence of these mechanisms, long-term studies over years and decades are difficult and in most cases impossible to achieve.

Long-term studies would also allow for the effects of prolonged noise exposure, rather than from a single event, to be assessed. For example, the implications of changes in behaviour, stress, hearing threshold shifts and masking to critical biological functions over long periods is unknown. Long-term studies consist of multi-year or decadal observations; especially for long-lived animals, some of which live 30 to 80 or more years. Studies also need to be applied not only on the individual level, but also at the community and population levels (Barber et al. 2010). Such studies would allow for the assessment of cumulative (i.e., additive over time, and synergistic or antagonistic over different types of stressors) effects of underwater noise exposure with other environmental stressors, such as food scarcity and disease, on species fitness and survival at a population level. Because behavioural changes in response to noise is what is most often and easily detectable in marine mammals, its significance to life functions on an individual and population level have recently been the focus of international research. To this end, a framework for developing predictive models was developed by the US National Academies of Sciences National Resource Council (NRC 2005) called Population Consequences of Acoustic Disturbance (PCAD). Following this framework, several marine mammal species have been the focus of modelling studies that integrate ecological knowledge of species' response to their environment, thereby providing insight into population level effects of acoustic disturbance. The models so far developed have aimed at linking behavioural changes to effects on vital rates, and ultimately to the population (Muir et al. 2010). These models require species- and environment-specific information, thus highlight knowledge gaps needing to be filled to produce such models. Australian research has focused on the gaps themselves, and no work has yet been carried out on developing models within the PCAD framework.

Finally, there is significant scope for research and development of technologies to reduce underwater noise produced or transmitted through the environment. An example of this has been recent testing of bubble curtains to reduce the transmission of noise from pile driving activities. Similarly, options for using alternatives to standard marine seismic surveys by using sources that have reduced output at higher frequencies need to be further explored.

In summary, underwater noise impact predictions often draw on knowledge from studies conducted at other locations, at different times or on different species to base their conclusions on. In other instances, models are used in place of empirical evidence. In some cases 'surrogates' are the only current option for predicting impacts. For example, such is the case in predicting masking, physiological responses, and hearing damage and injury on many species such as large baleen or beaked whales. These species are difficult to study given experimentation cannot be conducted in captivity. However, there are a large number of species in which experimentation and measurements are more amenable. Often measurements of noise and faunal responses can be undertaken. Where predictions have a high level of associated uncertainty, and measurement and experimentation can be carried out to reduce the uncertainty, these are required to produce accurate assessments. Furthermore, predictions applied practically to impact assessments are currently limited by unknown associated uncertainties. In other words, scores that are given to estimate the level of impact and probability of it occurring are not reported with confidence intervals. Further work on how current scientific knowledge (and its uncertainties) is applied to practical applications would improve the accuracy of impact assessment and mitigation processes.

Lastly, this report endeavoured to collect and collate not only published papers but also unpublished works in the 'grey' literature. Often high quality research is produced but remains in the grey literature, and often is in the form of consulting reports temporarily accessible online. A workshop on the effects of noise on marine fauna, convened by the Centre for Marine Science and Technology, as part of the Australian Acoustical Society's annual conference in 2012, stressed the need for publication and data sharing to improve our common knowledge base, to accelerate the distribution of results and to enhance and accelerate the science transfer to management (Erbe 2013b). While the synthesis of current knowledge (within the framework of this work) accessed as much grey literature information as possible, not all data were available. Peer-review and open access of underwater noise research and monitoring is advocated, as ultimately the increased availability of fundamental and applied science will improve and facilitate progress.

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APPENDIX A: Terms and Definitions

Term
1/3 Octave Bands
Ambient Noise
Background Noise
Deep Sound Channel
Duty Cycle
Power Spectral Density
Power Spectral Density Level
Acoustic Pressure
Peak Sound Pressure
Peak Sound Pressure Level
Peak-to-Peak Pressure Level
RMS Sound Pressure
RMS Sound Pressure Level
SOFAR Channel

Sound Exposure Level

Source Level

APPENDIX B: Frequency ranges and source levels for mysticetes sounds in or near Australian waters

Table 1. Frequency ranges and source levels estimated for sounds attributed to mysticetes in or near Australian waters.

Species	Sound type	Location	Frequency range (Hz)	Source Level (mean dB re 1 µPa @ 1 m)	Reference
Humpback whale (*Megaptera novaeangliae*)	Social sounds	Eastern Australia	30–2500	123–183	Dunlop *et al.* (2007), Dunlop *et al.* (2008); Rekdahl *et al.* (2013), Dunlop *et al.* (2013)
	Song	Eastern Australia	30– >5000	176–185	Cato (1991) , Cato *et al.* (2001), Garland *et al.* (2013), Garland *et al.* (2015), Noad *et al.* (2000)
		Western Australia	20–<3000	–	Salgado-Kent *et al.* (2012a), Murray *et al.* (2012)
Antarctic minke whale (*B. bonaerensis*)	Bioduck (pulses)	Western Australia	100–500	–	CMST (unpublished data)
Dwarf minke whale (*Balaenoptera acutorostrata*)	'star-wars' call	Great Barrier Reef, Australia	50–9400	150–165	Gedamke *et al.* (2001), CMST (unpublished data)
	Variable downsweeps	Great Barrier Reef, Australia	50–250	148–160	Gedamke *et al.* (2001)
Antarctic blue whale (*B. musculus intermedia*)	Z-call	South-west Indian Ocean	18–28	179 ± 5	Samaran *et al.* (2010), Samaran and Guinet 2010), Gavrilov *et al.* (2012)
		South-west Australia	18–28	–	Stafford *et al.* (2004)
Pygmy blue whale (*B. musculus brevicauda*)	Non-song sounds	South-west Indian Ocean	17–750 (including harmonics)	168–176	Recalde-Salas *et al.* (2014), Gavrilov *et al.* (2011)
	Song (FM units)	Western Australia	18–800 (including harmonics	174–189	McCauley *et al.* (2001), Gavrilov *et al.* (2011)

Table 1 continued…

Species	Sound type	Location	Frequency range (Hz)	Source (mean dB re 1 µPa @ 1 m)	Reference
Bryde's whale (*B. edeni*)	Moan	Western Australia	20–60	–	CMST (unpublished data)
Bryde's whale (*B. edeni*)	FM call	Western Australia	50–1000	–	CMST (unpublished data)
Southern right whale (*Eubalaena. australis*)	Upcall	Southern Australia	70– >200	–	CMST (unpublished data)
Pygmy right whale (*Caperea marginata*)	Downsweep	South-eastern Australia	60– >200	153–167 *	Dawbin and Cato (1992)
Fin whale (*B. physalus)*	–	Southern Australia	–	–	CMST (unpublished data)
Sei whale (B. borealis)	–	–	–	–	CMST (unpublished data)
Fin whale ▲ (Balaenoptera physalus)	Downsweep	Antarctica	15–100	189 ± 4	Širović et al. (2007), Širović et al. (2009)
Sei whale ▲ (B. borealis)	FM & broadband calls	North-western Atlantic, Antarctica, Pacific Ocean (off Hawaii)	21–3500	156–179	Knowlton et al. (1991), Rankin and Barlow (2007), McDonald et al. (2005), Baumgartner et al. (2008), Newhall et al. (2012)

Note: CMST= Centre for Marine Science and Technology, Curtin University, – = data not available, ▲ = data are unavailable from Australian waters and have instead been drawn from examples elsewhere in the world.

APPENDIX C: Marine Mammal Conservation Status

Marine mammals do not fall in a single biological grouping, rather they have the commonality of being mammals. There are over 130 species of marine mammals worldwide that include seals, sea lions, whales, dolphins, otters, walruses, manatees and dugongs. Of these, 60 are found in Australian waters.

Of the 60 species in Australian waters, five are considered 'nationally threatened' under the EPBC Act, including the blue whale (*Balaenoptera musculus*, endangered), southern right whale (*Eubalaena australis*, endangered), sei whale (*Balaenoptera borealis*, vulnerable), fin whale (*Balaenoptera physalus,* vulnerable) and the humpback whale (*Megaptera novaeangliae*, vulnerable) (Table 2). These species are also considered migratory. The definition of 'migratory' in the EPBC Act has been adopted from that in the Bonn Convention (Convention on the Conservation of Migratory Species of Wild Animals Appendices I and II) as an 'entire population or any geographically separate part of the population of any species or lower taxon of wild animals, a significant proportion of whose members cyclically and predictably cross one or more national jurisdictional boundaries'. An additional 13 cetacean other species are also considered migratory (but not threatened), including the Antarctic minke whale (*Balaenoptera bonaerensis*), Bryde's whale (*Balaenoptera edeni*), pygmy right whale (*Caperea marginata*), the SE Asian population of Fraser's dolphin (*Lageno delphishosei*), dusky dolphin (*Lageno rhynchusobscurus*), Australian snubfin dolphin (*Orcaella heinsohni*), killer whale (*Orcinus orca*), spectacled porpoise (*Phocoena dioptrica*), sperm whale (*Physeter macrocephalus*), Indo-Pacific humpback dolphin (*Sousa chinensis*), the Tropical Pacific and SE Asian populations of the spotted dolphin (*Stenella attenuata*) and long-snouted spinner dolphin (*Stenella longirostris*), and the Arafura/Timor Sea populations of spotted bottlenose dolphin (*Tursiops aduncus*).

Of the IUCN listed species occurring in Australian waters, four species have a higher classification than that in the EBPC Act (e.g. endangered *vs.* vulnerable), and three have a lower classification than in the EPBC Act. The IUCN lists two species as near threatened, six as of least concern, and 25 as data deficient. Data deficient means there is not enough information to assess their status. The information presented here reflects the current status of species listed in the EPBC Act and the IUCN Red List, however species are continually under review and assessment so the list changes from year to year.

Table 2. Marine mammals occurring in Australian waters listed under the EPBC and IUCN Red List.

Common name	Species name	IUCN Red List Classification	EPBC		
			Threatened List Classification	Migratory	Marine
Baleen whales					
Blue whale	*Balaenoptera musculus*	Endangered	Endangered	Yes	–
Southern right whale	*Eubalaena australis*	Least concern	Endangered	Yes	–
Sei whale	*Balaenoptera borealis*	Endangered	Vulnerable	Yes	–
Fin whale	*Balaenoptera physalus,*	Endangered	Vulnerable	Yes	–
Humpback whale	*Megaptera novaeangliae*	Least concern	Vulnerable	Yes	–
Antarctic minke whale	*Balaenoptera bonaerensis*	Data deficient	–	Yes	–
Bryde's whale	*Balaenoptera edeni*	Data deficient	–	Yes	–
Pygmy right whale	*Caperea marginata*	Data deficient	–	Yes	–
Common minke whale	*Balaenoptera acutorostrata*	Least concern	–	-	–
Odontocetes					
Fraser's dolphin	*Lageno delphishosei*	Least concern	–	Yes	–
Dusky dolphin	*Lageno rhynchusobscurus*	Data deficient	–	Yes	–
Australian snubfin dolphin	*Orcaella heinsohni*	Near threatened	–	Yes	–
Pygmy killer whale	*Feresa attenuata*	Data deficient	–		–
Killer whale	*Orcinus orca*	Data deficient	–	Yes	–
Spectacled porpoise	*Phocoena dioptrica*	Data deficient	–	Yes	–
Sperm whale	*Physeter macrocephalus*	Vulnerable	–	Yes	–
Indo-Pacific humpback dolphin	*Sousa chinensis*	Near threatened	–	Yes	–
Spotted dolphin, Pantropical spotted dolphin	*Stenella attenuata*	Least concern	–	Yes	–
Long-snouted spinner dolphin	*Stenella longirostris*	Data deficient	–	Yes	–
Indo-Pacific bottlenose dolphin, spotted bottlenose dolphin	*Tursiops aduncus*	Data deficient	–	Yes (Arafura/Timor Sea populations)	
Long-beaked common dolphin	*Delphinus capensis*	Data deficient	–	–	–
Arnoux's beaked whale	*Berardius arnuxii*	Data deficient	–	–	–
Short-finned pilot whale	*Globicephala macrorhynshus*	Data deficient	–	–	–
Long-finned pilot whale	*Globicephala macrorhynshus*	Data deficient	–	–	–

Note: – = data not available.

Table 2 (continued). Marine mammals occurring in Australian waters listed under the EPBC and IUCN Red List.

Common name	Species name	IUCN Red List Classification	EPBC		
Indo-Pacific beaked whale	*Indopacetus pacificus*	Data deficient	–	–	–
Pygmy sperm whale	*Kogia breviceps*	Data deficient	–	–	–
Dwarf sperm whale	*Kogia sima*	Data deficient	–	–	–
Southern right whale dolphin	*Lisso delphisperonii*	Data deficient	–	–	–
Andrew's beaked whale	*Mesoplodon bowdoini*	Data deficient	–	–	–
Ginkgo-toothed beaked whale	*Mesoplodon ginkgodens*	Data deficient	–	–	–
Gray's beaked whale	*Mesoplodon grayi*	Data deficient	–	–	–
Hector's beaked whale	*Mesoplodon hectori*	Data deficient	–	–	–
Strap-toothed whale	*Mesoplodon layardii*	Data deficient	–	–	–
True's beaked whale	*Mesoplodon mirus*	Data deficient	–	–	–
False killer whale	*Pseudorca crassidens*	Data deficient	–	–	–
Shepherd's beaked whale	*Tasmacetus shepherdi*	Data deficient	–	–	–
Pinnipeds					
Australian sea lion	*Neophoca cinerea*	Endangered	Vulnerable	–	Yes
Subantarctic fur seal	*Arctocephalus tropicalis*	Least concern	Vulnerable	–	Yes
Southern elephant seal	*Mirounga leonina*	–	Vulnerable	–	Yes
Antarctic fur seal	*Arctocephalus gazella*	–	–	–	Yes
Australian fur seal	*Arctocephalus pusillusdoriferus*	–	–	–	Yes
Hooker's sea lion	*Phocarctos hookeri*	–	–	–	Yes
Leopard seal	*Hydrurga leptonyx*	–	–	–	Yes
Crabeater seal	*Lobodon carcinophagus*	–	–	–	Yes
Weddell seal	*Leptonychotes weddellii*	–	–	–	Yes
Ross seal	*Ommatophoca rossii*	–	–	–	Yes
New Zealand fur seal	*Arctocephalus forsteri*	–	–	–	Yes
Sirenians					
Dugong	*Dugong dugon*	Vulnerable	–	Yes	Yes

Note: – = data not available.

APPENDIX D: Penguin Conservation Status

Of the nine penguins occurring in Australian waters (including the Australian EEZ in Antarctic subantarctic waters), four are considered vulnerable, two near threatened, and three of least concern. None are listed as threatened or migratory under the EPBC Act, while eight are listed as marine (Table3).

Table 3. Penguins occurring in Australian waters listed under the EPBC and IUCN Red List.

Common name	Species name	IUCN Red List Classification	EPBC		
			Threatened List Classification	Migratory	Marine
Little penguin, little blue penguin, fairy penguin	*Eudyptula minor*	Least concern	–	–	Yes
Royal penguin	*Eudyptes schlegeli*	Vulnerable	–	–	–
Rockhopper penguin	*Eudypteschryso comefilholi*	Vulnerable	–	–	Yes
Macaroni penguin, royal penguin	*Eudypteschryso lophus* sensu lato	Vulnerable	–	–	Yes
Gentoo penguin	*Pygoscelis papuapapua*	Near threatened	–	–	Yes
Adélie penguin	*Pygoscelis adeliae*	Near threatened	–	–	Yes
Chinstrap penguin	*Pygoscelis antarcticus*	Least concern	–	–	Yes
King penguin	*Aptenodytes patagonicus*	Least concern	–	–	Yes
Emperor penguin	*Aptenodytes forsteri*	Near threatened	–	–	–

Note: – = data not available.

APPENDIX E: Reptile Conservation Status

Of the 32 sea snakes in Australian waters, the short-nosed and leaf-scaled sea snakes are considered ‘critically threatened’ under the EPBC Act and the IUCN Red List classification (Table4). No other species are considered threatened under the EPBC Act. However, under the IUCN Red List classification the Timor Reef snake is considered ‘Endangered’, the large-headed seasnake is considered ‘near threatened’, six additional species are considered ‘data deficient’, 22 are of ‘least concern’, and one has not been classified yet. All sea snake turtles are considered ‘marine’ under the EPBC Act.

All six species of marine turtles are listed in both the EPBC Act and the IUCN Red List but their levels of classifications differ in most cases. For example, the leatherback turtle is listed as ‘critically endangered’ in the IUCN Red List, and ‘endangered’ in the EPBC Act. The hawksbill is critically endangered in the IUCN Red List classification but ‘vulnerable’ in the EPBC Act. The loggerhead is listed as ‘endangered’ in both lists, while the green turtle is listed as ‘endangered’ in the IUCN Red List and ‘vulnerable’ in the EPBC Act. The olive ridley is listed as ‘vulnerable’ under the IUCN Red List classification but listed as ‘endangered’ under the EPBC Act. Finally, the flatback turtle is ‘vulnerable’ in the EPBC Act, and ‘data deficient’ in the IUCN Red List classification.

All the marine turtles are listed as ‘migratory’ and ‘marine’ under the EPBC Act. In the case of the saltwater crocodile, the species is listed as ‘migratory’ and ‘marine’ under the EPBC Act, and of ‘least concern’ under the IUCN Red List classification.

Table 4. Marine reptiles occurring in Australian waters listed under the EPBC and IUCN Red List.

Common name	Species name	IUCN Red List Classification	EPBC		
			Threatened List Classification	Migratory	Marine
Sea snakes					
Short-nosed sea snake	*Aipysurus apraefrontalis*	Critically endangered	Critically endangered	–	Yes
Leaf-scaled sea snake	*Aipysurus foliosquama*	Critically endangered	Critically endangered	–	Yes
Spiny-headed sea snake	*Acalyptophis peronii*	Least concern	–	–	Yes
Duboi's sea snake	*Aipysurus duboisii*	Least concern	–	–	Yes
Spine-tailed sea snake	*Aipysurus eydouxii*	Least concern	–	–	Yes
Timor Reef snake	*Aipysurus fuscus*	Endangered	–	–	Yes
Olive sea snake	*Aipysurus laevis*	Least concern	–	–	Yes
Brown-lined sea snake	*Aipysurus tenuis*	Data deficient	–	–	Yes
Stokes' sea snake	*Astrotia stokesii*	Least concern	–	–	Yes
Spectacled sea snake	*Disteira kingii*	Least concern	–	–	Yes
Olive-headed sea snake	*Disteira major*	Least concern	–	–	Yes
Turtle-headed sea snake	*Emydocephalus annulatus*	Least concern	–	–	Yes
North-western mangrove sea snake	*Ephalophis greyi*	Least concern	–	–	Yes
Black-ringed sea snake	*Hydrelaps darwiniensis*	Least concern	–	–	Yes
Black-headed banded sea snake	*Hydrophis atriceps*	Least concern	–	–	Yes
Faint-banded sea snake	*Hydrophis belcheri*	Data deficient	–	–	Yes
Dwarf sea snake	*Hydrophis caerulescens*	Least concern	–	–	Yes
Slender-necked sea snake	*Hydrophis coggeri*	Least concern	–	–	Yes
Fine-spined sea snake	*Hydrophis czeblukovi*	Data deficient	–	–	Yes
Bar-bellied sea snake	*Hydrophis elegans*	Least concern	–	–	Yes
Graceful small headed sea snake	*Hydrophis gracilis*	Least concern	–	–	Yes
Plane sea snake	*Hydrophis inornatus*	Data deficient	–	–	Yes
Small-headed sea snake	*Hydrophis mcdowelli*	Not yet classified	–	–	Yes
Black-banded sea snake	*Hydrophis melanosoma*	Data deficient	–	–	Yes
Ornate reef sea snake	*Hydrophis ornatus*	Least concern	–	–	Yes
Large-headed sea snake	*Hydrophis pacificus*	Near threatened	–	–	Yes
Estuarine sea snake	*Hydrophis vorisi*	Data deficient	–	–	Yes
Spine-bellied sea snake	*Lapemis hardwickii*	Least concern	–	–	Yes
Northern mangrove sea snake	*Parahydrophis mertoni*	Data deficient	–	–	Yes
Yellow-bellied sea snake	*Pelamis platurus*	Least concern	–	–	Yes
Yellow-lipped sea krait	*Laticauda colubrina*	Least concern	–	–	Yes
Brown-lipped sea krait	*Laticauda laticaudata*	Least concern	–	–	Yes

Note: – = data not available.

Table4 (continued). Marine reptiles occurring in Australian waters listed under the EPBC and IUCN red list.

Common name	Species name	IUCN Red List Classification	EPBC		
			Threatened List Classification	Migratory	Marine
Turtles					
Loggerhead turtle	*Caretta caretta*	Endangered	Endangered	Yes	Yes
Leatherback turtle	*Dermochelys coriacea*	Critically endangered	Endangered	Yes	Yes
Olive ridley turtle	*Lepidochelys olivacea*	Vulnerable	Endangered	Yes	Yes
Green turtle	*Chelonia mydas*	Endangered	Vulnerable	Yes	Yes
Hawksbill turtle	*Eretmochelys imbricata*	Critically endangered	Vulnerable	Yes	Yes
Flatback turtle	*Natator depressus*	Data deficient	Vulnerable	Yes	Yes
Crocodiles					
Estuarine or saltwater crocodile	*Crocodylus porosus*	Least concern	–	Yes	Yes

Note: – = data not available.