Appendix O.

Underwater noise modelling study - FPSO facility operations (JASCO 2016b)

Potential Impacts of Underwater Noise from Operation of the Barossa FPSO Facility on Marine Fauna

ConocoPhillips Barossa Project

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1. Introduction

JASCO Applied Sciences (Australia) (JASCO) predicted underwater sound levels associated with the ConocoPhillips Barossa floating production, storage and offloading (FPSO) facility and the potential impacts on marine fauna.

This assessment focuses primarily on the continuous sounds produced by the FPSO facility and other vessels in association with the FPSO facility operation. The animal types considered here include: marine mammals, fishes (including whale sharks and fish eggs and larvae), plankton, turtles, sea snakes and invertebrates. To provide context, other anthropogenic sounds in the marine environment, such as those due to shipping, and natural ambient sounds are discussed where relevant.

2. General Effects of Continuous Sound on Marine Species

When marine animals are exposed to underwater anthropogenic sounds, the types and scale of their responses—physiological, behavioural, and acoustic—vary depending on the level of exposure, the physical environment in which the subjects are at the time of exposure, and other factors unique to each animal. Important factors can include the location of the animal in relation to the sound source, how long the animal is exposed to the sound, how often the sound repeats (repetition frequency), and the ambient sound level. Factors specific to each animal that determine how it responds include its activity level, its reproductive and metabolic states at time of exposure, and how well it hears and how it perceives the sound. For example, an animal that hears a sound while it is in an area it uses for mating or rearing offspring might respond much differently than the same animal in another area or time period unrelated to its reproductive state. An individual that has historically been exposed to sound could also have a different response than an animal lacking such exposure. If its prior exposure to a sound type or intensity did not result in physical harm, the animal could have learned to distinguish between dangerous and benign sounds.

This assessment focuses primarily on the continuous sounds produced by an FPSO facility and other vessels in association with the FPSO facility operation. The animal types considered here include: marine mammals, fishes (including whale sharks and fish eggs and larvae), plankton, turtles, sea snakes and invertebrates. To provide context, other anthropogenic sounds in the marine environment, such as those due to shipping, and natural ambient sounds are discussed where relevant. Throughout Section 2, the FPSO facility is included with noise from commercial shipping, due to the similarity of the sound sources.

Sounds from large commercial vessels rarely exceed the acoustic injury levels required to induce Permanent Threshold Shift (PTS) unless the animal is in very close proximity to the vessel (usually within meters). The typical source levels of large vessels only approach threshold levels in very low frequencies (<100 Hz, Figure 1) and when travelling at high velocities or when vessel propulsion systems are not well maintained, which is due to cavitation sounds that contribute to the measured sound levels in higher frequencies. The accumulation of shipping noise in an area, however, can reduce the suitability of a habitat if non-injurious sound levels that exceed behavioural thresholds consistently.

The main concerns are for potential negative effects of shipping sounds on marine fauna. Therefore, this assessment primarily focusses on behavioural disruption, including masking and non-auditory health effects.

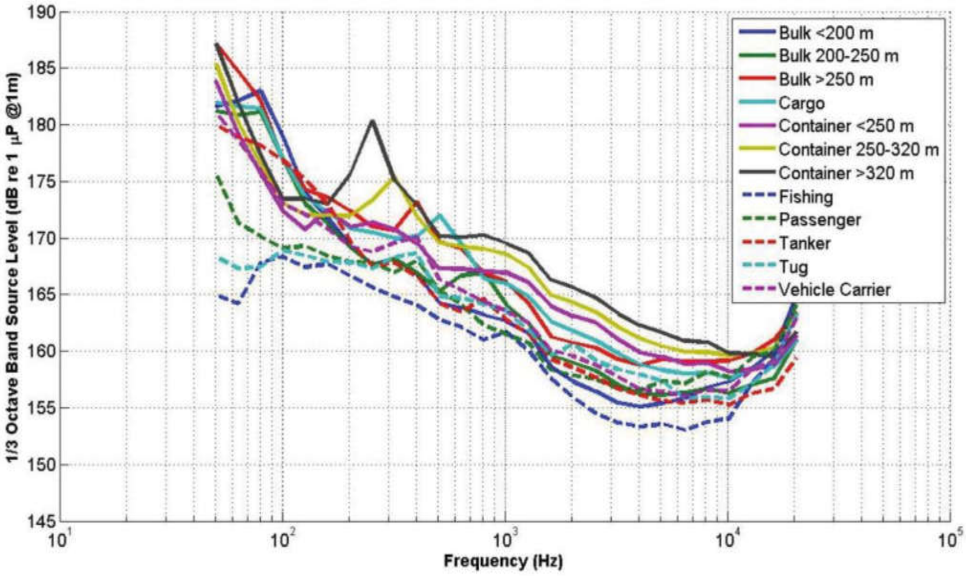

Figure 1. TWMBR recorded mean third octave band source levels for different vessel types (Hemmera et al. 2014).

2.1. Marine Mammals

Because the sounds that marine mammals hear and generate carry information relevant for their survival and reproduction, variation in the acoustic characteristics of these sounds—fundamental frequency, frequency bandwidth, spectral energy, temporal patterning, and directivity—is also relevant. The effects of anthropogenic and ambient sounds on these characteristics can be cumulative and can have significant implications for individuals and populations. Behavioural disruption, including masking and non-auditory health effects are reviewed below, followed by a summary of the circumstances under which marine mammals could be exposed to sounds from this operation.

2.1.1. Acoustic Masking

Acoustic masking occurs when sounds interfere with an animal's ability to perceive biologically relevant sounds. It can be defined as a reduction in communication and listening space (active acoustic space) that an individual experiences due to an increase in background noise (ambient and anthropogenic) in the frequency bands relevant for communicating and listening. For example, acoustic masking can decrease the range over which an animal might communicate with conspecific individuals, or detect predators or prey, by decreasing their listening space or total active acoustic space (Clark et al. 2009). Masking can occur naturally from wind, precipitation, wave action, seismic activity, and other natural phenomena. For example, the ranges over which fish-eating killer whales use echolocation clicks to detect chinook salmon can be reduced by more than 50% in moderate rain (Au et al. 2004). Biological sounds can also naturally mask signals. Some fish, for example, create low-frequency sounds (50–2000 Hz, but most often 100–500 Hz) that can form a significant component of local ambient sound levels (Zelick et al. 1999). Snapping shrimp in many locations produce high-amplitude sounds over a broad range of frequencies that often dominate the underwater sound field.

Marine mammals almost certainly have adapted to naturally occurring signal masking, yet the reduced active acoustic space under noisy natural conditions is a physical constraint that cannot be overcome completely and must be taken into consideration in acoustic assessments. Anthropogenic sounds contribute to the ambient soundscape, and can mask biologically important sounds, potentially reducing the active (perception) space to levels that cannot support active foraging and socialising. The amount of masking an animal experiences is determined by the amplitude, timing, and frequency content of the interfering sounds, as well as how sounds are spatially distributed.

Studies on acoustic masking in the ocean have traditionally focused on mysticetes (a suborder of cetaceans that use baleen plates to filter their food; includes humpback, rorquals, blue, fin, minke and right whales) and shipping sounds (Clark et al. 2009). Mysticetes communicate using calls with energy primarily in low-frequency bands that overlap completely with the bands carrying the main energy of shipping sounds (Arveson and Vendittis 2000, Allen et al. 2012, Bassett et al. 2012). Over the past 50 years, commercial shipping, the largest contributor of masking noise (McDonald et al. 2008), has increased the ambient sound levels in the deep ocean at low frequencies by 10–15 dB (Hatch and Wright 2007). Hatch et al. (2012) estimated that shipping noise could be responsible for North Atlantic right whales (*Eubalaena glacialis*) losing, on average, 63–67% of their communication space. Dunlop (2016) suggested that humpback whales may not be able to cope with an increase in anthropogenic noise in the same way they cope with an increase in natural noise when comparing communication source levels and repertoire. This may be due to the specific overlap of noise in important frequency bands.

Sound output from ships can also extend to relatively high frequencies (e.g., up to 30 kHz, Arveson and Vendittis 2000, and up to 44.8 kHz, Aguilar Soto et al. 2006) and therefore can affect odontocetes (toothed whales) especially at shorter ranges. Aguilar Soto et al. (2006) used a Digital Acoustic Recording Tag (DTAG) attached to a Cuvier's beaked whale (*Ziphius cavirostris*) to record a passing vessel, which demonstrated that vessel sounds masked the whale's ultrasonic vocalisations and reduced the whale's maximum communication range by 82% when it was exposed to a 15 dB increase in ambient sound levels at the vocalisation frequencies. The study also determined that the effective detection distance of Cuvier's beaked whales' echolocation clicks by conspecifics would be reduced by 58%. Noise profiles from ships are highly variable, and high-frequency components attenuate more rapidly than do low frequencies (Hatch and Wright 2007), which limits the area over which Cuvier's beaked whales would be affected.

Some cetaceans might compensate for masking, to a limited degree, either by increasing the amplitude of their calls (Lombard effect) or by changing their spectral (frequency content) or temporal vocalisation properties (Hotchkin and Parks 2013). North Atlantic right whales produced calls with a higher average fundamental frequency and lowered their call rate in high noise conditions (Parks et al. 2007), whereas blue whales increased their discrete, audible calls when ship sounds were nearby (Melcon et al. 2012).

2.1.2. Behavioural disturbance

Behavioural responses to underwater sound are difficult to determine because animals vary widely in their response type and strength, and conspecifics who are exposed to the same sound react differently (Nowacek et al. 2004). An individual's response to a stimulus is influenced by the context in which the animal receives the stimulus and how relevant the individual perceives the stimulus to be. A number of biological and environmental factors can affect an animal's response—behavioural state (e.g., foraging, travelling or socializing), reproductive state (e.g., female with or without calf, or single male), age (juvenile, sub-adult, adult), and motivational state (e.g., hunger, fear of predation, courtship) at the time of exposure as well as perceived proximity, motion, and biological meaning of the sound and nature of the sound source.

Animals might temporarily avoid anthropogenic sounds, but could display other behaviours, such as approaching novel sound sources, increasing vigilance[1], hiding and/or retreating, that might decrease their foraging time (Purser and Radford 2011). Marine mammals have also reduced their vocalisations in response to anthropogenic sounds, sometimes ceasing to call for weeks or months (IWC 2007). Some cetaceans might also compensate for masking, to a limited degree, either by increasing the amplitude of their calls (Lombard effect) or by changing their spectral (frequency content) or temporal vocalisation properties (Hotchkin and Parks 2013). North Atlantic right whales produced calls with a higher average fundamental frequency and lowered their call rate in high noise conditions (Parks et al. 2007), whereas blue whales increased their discrete, audible calls when ship sounds were nearby (Melcon et al. 2012). Whales seemed most reactive when the sound level was increasing, which they could perceive as an approaching sound. An animal could exhibit a startle effect at the onset of a sound. Although limited data are available, cetaceans respond less to stationary anthropogenic activities that produce continuous sounds (such as dredging, drilling, and oil-production-related activities) than they do to moving and/or transient sound sources, including seismic surveys and ships (Richardson et al. 1995). Some cetaceans may partially habituate to continuous sounds (Richardson et al. 1995).

The BRAHSS (Behavioural Response of Australian Humpback whales to Seismic Surveys) project conducts studies at Peregian Beach, Qld, and Dongara, WA, to better understand the behavioural responses of humpback whales to noise from the operation of seismic air gun arrays (Cato et al. 2013). It has also considered behavioural responses to ships. Results from the first sets of experiments have recently been published (Dunlop et al. 2015, Dunlop et al. 2016, Godwin et al. 2016), together with concurrent studies of the effects of vessel noise on humpback whale communications (Dunlop 2016). Dunlop et al. (2016) used land based observations of behavioural responses in migrating humpback whales to playbacks of the first stages of air-gun ramp-up operations and playbacks of 'constant' source sounds, and compared the results with the observed behaviours during 'controls' in which shipping sounds where present and the array was towed but not operated. The behavioural baseline used for the identification of responses was established using observations of groups in the absence of the source vessel. In most exposure scenarios a distance increase from the sound source was observed and interpreted as potential avoidance. The study, however, found no difference in the 'avoidance' response to either 'ramp-up' or the constant source (vessel) producing sounds at a higher level than early ramp-up stages. In fact, a small number of groups showed inspection behaviour of the source during both treatment scenarios. 'Control' groups also responded, which suggested that the presence of the source vessel alone had some effect on

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[1] Scanning for the source of the stimulus.

the behaviour of the whales. Despite this, the majority of groups appeared to avoid the source vessel at distances greater than the radius of most seismic injury based mitigation zones.

A review by Southall et al. (2007) found no responses or limited responses by low-frequency cetaceans to continuous (non-pulsed) received levels up to 120 dB re 1 µPa, but an increasing probability of avoidance and other behavioural responses beginning at 120 to 160 dB re 1 µPa. In relation to high-frequency cetaceans, in the Bay of Fundy, Nova Scotia, Polacheck and Thorpe (1990) noted that harbour porpoises, which are high-frequency cetaceans, tended to swim away from approaching vessels. Off the western coast of North America, Barlow (1988) observed that harbour porpoises within 1 km of a survey vessel moved rapidly out of its path. Cuvier's beaked whales responded to ship sounds by decreasing their vocalisations when they attempted to catch prey (Aguilar Soto et al. 2006). Foraging changes were observed in Blainville's beaked whales (*Mesoplodon densirostris*) when they were exposed to vessel noise (Pirotta et al. 2012). Groups of Pacific humpback dolphins (*Sousa chinensis*) that contained mother-calf pairs increased their rate of whistling after a boat had transited the area (Van Parijs and Corkeron 2001). The authors postulated that vessel sounds disrupted group cohesion, especially between mother-calf pairs, requiring it to be re-established by vocal contact after boat noise masked communication. In response to high levels of boat traffic, killer whales increased the duration (Foote et al. 2004) or the amplitude (Holt et al. 2009) of their calls. Bottlenose dolphins (*Tursiops truncatus*) have been observed to produce more whistles when boats approached (Buckstaff 2004).

2.1.3. Non-auditory effects

Non-auditory physiological responses to noise exposure have been studied mainly in humans (Stansfeld and Matheson 2003), but some studies exist on the physiological stress response to noise in captive marine mammals.

Thomas et al. (1990) played drilling noise to four captive beluga whales and found no changes in their blood adrenaline or noradrenaline levels, measured immediately after. Miksis et al. (2001) found that the heart rate in a captive bottlenose dolphin increased in response to threat sounds produced by other dolphins. Rolland et al. (2012) concluded that right whales might feel chronic stress when they are exposed to low-frequency ship noise.

2.2. Fishes

A working group of experts reviewed available data and determined broadly applicable sound exposure guidelines for fishes and sea turtles. The working group's recommendations are available in a technical report, Popper et al. (2014), which was developed and approved by the Accredited Standards Committee S3/SC 1 Animal Bioacoustics and registered with the American National Standards Institute (ANSI). The technical report contains the most recent and thorough synthesis of available information, recommending sound exposure guidelines which were used as the criteria to assess the potential for noise impacts on fish, fish larvae, and fish eggs.

2.2.1. Behavioural disturbance

The National Research Council (NRC) (2005) discussed the possible effects of sound on marine mammal behaviour, including on communication between conspecifics and on detection of predators and prey. This is applicable to fish, and as such Popper et al. (2014) summarised, "In its report, the NRC states that an action or activity becomes biologically significant to an individual animal when it interferes with normal behaviour and activity, or affects the animal's ability to grow, survive, and reproduce. Such effects might have consequences at the population-level and might affect the viability of the species" (NRC 2005).

Studying the responses of fish to anthropogenic sound is complex as many factors could influence the results, and a careful approach based on well-designed experiments must be adopted. Experiments done with caged animals need to be considered in conjunction with studies on free-living animals, as results might differ due to the different ecological factors that influence an animal's behaviour in the wild.

A range of responses have been observed when the behaviour of wild fishes has been studied in the presence of anthropogenic sounds. Studies suggest that fish will generally move away from a loud acoustic source in order to minimise their exposure, but this response might depend on the animal's motivational state. Anthropogenic sounds have been shown to cause changes in schooling patterns and distribution, including in relation to ships (including commercial shipping, trawlers, ferries and research vessels) (Engås et al. 1996, Engås and Løkkeborg 2002, Sara et al. 2007, De Robertis and Handegard 2013). As there is currently a lack of quantification of sound exposure levels that elicit responses to ships makes it impossible to provide numerical guidelines for behavioural responses of fish to sounds from ships (Popper et al. 2014).

2.2.2. Acoustic Masking

Masking impairs an animal's hearing with respect to the relevant sounds normally detected within the environment and can have long-lasting effects on survival, reproduction and population dynamics of fishes (Popper et al. 2014). The consequences of masking for fishes, however, have not yet been fully examined. Popper et al. (2014) surmised, "It is likely that increments in background sound within the hearing bandwidth of fishes and sea turtles may render the weakest sounds undetectable, render some sounds less detectable, and reduce the distance at which sound sources can be detected. Energetic and informational masking may increase as sound levels increase, so that the higher the sound level of the masker, the greater the masking."

While limited scientific information is available, it has been demonstrated that oyster toadfish respond to vessel disturbances by calling less when vessels are present. The authors of the study suggested that toadfish cannot call over loud vessel noise, reducing the overall calling rate, and may have to call more often when vessels are not present (Luczkovich et al. 2016).

2.3. Elasmobranchs

The effect of anthropogenic noise on elasmobranchs (i.e. cartilaginous fish) is not well understood as relatively few studies have been undertaken. Elasmobranchs are not known to utilise acoustic communication, and therefore anthropogenic noise would most likely be an issue for masking of the sounds of prey species. Bullock and Corwin (1993) noted a degree of acoustic masking in Carcharhinidae and Triakidae tropical sharks with sounds of flowing water, white noise and with swimming, artificial white noise and of relevance to anthropogenic noise from shipping masking around 100 Hz by a 100 Hz tone. There are no stress studies examining the effect of noise on elasmobranchs.

Casper and Mann (2009) demonstrated that the Atlantic sharpnose (Carcharhinidae) had a peak sensitivity at 20 Hz in terms of particle acceleration which when converted to pressure units was comparable to an ambient signal level of 83 dB re 1 µPa, a level readily exceeded by many vessels at a broad range of distances. Casper et al. (2012) considered that little information was available to consider noise masking of elasmobranchs.

2.4. Turtles

The Popper et al. (2014) report examined sea turtles and fish, ultimately recommending criteria to assess the potential for noise impacts on turtles. Data on sea turtles are less conclusive than for other species, from the perspective of both the level of harm inflicted and the animal's reaction to sound. Recommendations on studies that could be done to increase the understanding of the impact of anthropogenic noise on turtles are provided in Willis (2016).

The majority of studies have focused on airguns, which can be applied to other impulsive sources such as pile driving, however are difficult to apply to continuous sound sources such as shipping. Sea turtles have been shown to avoid low-frequency sounds (Lenhardt 1994), and in a playback study of diamondback terrapins (*Malaclemys terrapin terrapin*) using boat noise, some animals were observed to increase or decrease swimming speed while others did not alter their behaviour at all (Lester et al. 2013).

2.5. Sea Snakes

There is currently no scientific information on how sea snakes use sound or how susceptible they might be to underwater noise, although this is an area of current research. For this assessment, because snakes and turtles are both marine reptiles, it has been assumed that sea snakes are similarly or less sensitive to low level sounds than are turtles. Therefore, the thresholds established for turtles are a reasonable proxy for sea snakes. However, as quantifiable distances for assessing impacts from continuous sounds only exist for fish, fish have been used as a surrogate for this assessment (Section 3.3).

2.6. Invertebrates

The existing body of scientific information on the direct effects of exposure to anthropogenic sound on marine invertebrates is very limited, with few peer-reviewed papers published (Morley et al. 2014). However, there is evidence of the potential for adverse effects on invertebrates. Based on the physical structure of their sensory organs, marine invertebrates appear to be specialised to respond to particle displacement components of an impinging sound field and not to the pressure component (Popper et al. 2001).

de Soto (2016) provides the most recent review of anthropogenic noise on marine invertebrates considering a broad range of taxa and their ontogenetic stages, with the summarised studies showing that the noise effects on marine invertebrates range from apparently null through to behavioural/physiological responses and possible mortalities. However, caution was urged in regards to the conclusion of a number of the reports, particularly in relation to ensuring peer-review, and that ‘the conclusions must be scientifically correct and fit the power of the experimental protocol. Studies target discrete questions and their conclusions should not be over interpreted.’ and ‘survival in the laboratory is not comparable to survival in the wild’. Therefore, the conclusions of the summarised studies must be considered carefully.

There is limited information on the direct effects on marine invertebrates to exposure to shipping-related sounds, however a summary of the information is provided below. It should be noted that the majority of these studies relate to actual shipping in shallow water, and a close proximity between the source and the fauna. This is a different scenario to that which will occur in relation to the FPSO facility.

Squid

Squid were found to respond to sound between 30 and 500 Hz, being most sensitive between 100 and 200 Hz. This suggests that squid detect sound similarly to most fish, with the statocyst acting as an accelerometer through which squid detect the particle motion component of a sound field (Mooney et al. 2010).

Nudibranch

In a field experiment Nedelec et al. (2014) used playbacks to investigate the effect of boat noise on the early life and survival of a coral reef marine invertebrate, the sea hare *Stylocheilus striatus.* Nedelec et al. (2014) found that exposure of the nudibranch to small boat-noise playback compared to ambient-noise playback, stopped development of nudibranch embryos by 21%. For the nudibranch embryos remaining, a further mortality of 22% occurred for hatched larvae.

Lobster

Filiciotto et al. (2014) and Celi et al. (2014) conducting exposure studies with European panilurid lobster to short duration shipping sounds observed significant biochemic and immune response effects. Furthermore, simulated exposure of the Norway lobster (*Nethrops norvegicus*) to continuous ship noise (equivalent to 100 m distance) or pile driving sound (equivalent to 60 m distance) for seven days repressed burying and bio-irrigation behaviour with both treatments, and reduced locomotor activity compared to controls (Solan et al. 2016).

Prawns

Lagardère (1982) reproduced shipping noise at 30 dB above ambient sound levels for three months across the known hearing range of the northern hemisphere prawn *Crangon crangon* and noted a significant reduction in growth and reproduction rates of the prawn and to a lesser extent increased cannibalism.

The common decapod European prawn *Paleomon serratus*, is an animal that usually burrows or takes shelter in rocky crevices. When exposed to as little as 30 minutes of a range of vessel noises it was noted that the prawn remained out of available shelters possibly due to acoustic resonance (increased sound pressure level) within the structures, and showed a wide range of significant biochemical changes (Filiciotto et al. 2016). This prawn is related to Australia’s freshwater and brackish Macrobranchium.

Crabs

Wale et al. (2013b) demonstrated a potential association between shipping noise and a predation risk increase in small shore crabs due to a behaviour change. While shipping noise did not alter the speed and success of crabs targeting their prey, the noise was associated with a reduced rate of crabs righting themselves (such as may occur in a predatory attack) and a slower rate of seeking shelter after an attack.

Underwater playback of ship noise to shore crabs demonstrated an increase in oxygen uptake potentially indicating increased stress (Wale et al. 2013a), and hermit crabs (*Pagurus bernhardus*) have been shown to be sensitive to substrate-borne vibration and anthropogenic noise (Roberts et al. 2016).

Bivalves

Exposure of the bivalve clam *Ruditapes philippinarum* to simulated continuous ship noise (equivalent to 100 m distance) or simulated pile driving sounds typical during offshore wind turbine construction (equivalent to 60 m distance) for seven days appeared to effect the clam’s behaviour by repressing the burying and bio-irrigation behaviour, and potentially reducing locomotor activity compared to controls (Solan et al. 2016). The observed behaviour change increased predation risk, demonstrated a potential concern for shell degradation through acidosis and potentially modified the soil environment.

3. Acoustic Thresholds

3.1. Marine Mammals

Acoustic modelling results can be compared against various sound level threshold effects assessment criteria for underwater noise. This assessment considered the following criteria for marine mammals:

- Current interim U.S. National Marine Fisheries Service (NMFS) (NMFS 2014) threshold for behavioural response criteria for to non-pulsed noise.
- Cetacean criteria recommended by Southall et al. (2007).

There are two categories of auditory threshold shifts or hearing loss:

- Permanent threshold shift (PTS), a physical injury to an animal's hearing organs.
- Temporary threshold shift (TTS), a temporary reduction in an animal's hearing sensitivity, the result of receptor hair cells in the cochlea becoming fatigued.

3.1.1. Behavioural responses

Southall et al. (2007) extensively reviewed marine mammal behavioural responses to sounds. Their review found that most marine mammals exhibited varying responses between SPLs of 140 and 180 dB re 1 µPa, but lack of convergence in the data from multiple studies prevented them from suggesting explicit step functions. Variations between studies included lack of control groups, imprecise measurements, appropriate metrics, and context dependency of responses including the animal's activity state. To create meaningful qualitative data from the collected information, Southall et al. (2007) proposed a severity scale that increases with increased sound levels.

The NMFS non-pulse noise criteria were selected for this assessment because it represents the most commonly applied behavioural response criterion by regulators. The distances at which behavioural responses could occur were determined to therefore occur in areas ensonified above an unweighted SPL of 120 dB re 1 µPa (NMFS 1995, NMFS 2000, NMFS 2014).

3.1.2. Injury and hearing sensitivity changes

The Noise Criteria Group, sponsored by NMFS, an office of the U.S. National Oceanic and Atmospheric Administration (NOAA) within the Department of Commerce, was established in 2005 to address shortcomings of the SPL based criteria mentioned above, which was initially implemented in 2005 (NMFS and NOAA 2005). The Group's goal was to review the literature on marine mammal hearing and their behavioural and physiological responses to anthropogenic noise and to propose new noise exposure criteria. In 2007, the findings were published by an assembly of experts (Southall et al. 2007). They introduced dual criteria consisting of both zero-to-peak (peak) SPL thresholds, expressed in dB re 1 µPa, and cumulative sound exposure level (SEL) thresholds, expressed in dB re 1 µPa^2·s. A received sound exposure was assumed to cause PTS if it exceeds the peak SPL criterion, the SEL criterion, or both. The peak SPL is not frequency-weighted whereas the SEL is frequency-weighted for different marine mammal functional hearing groups (Section 3.1.1). These criteria included categories for pulsed and non-pulsed sound. While recommendations for updates to the criteria from Southall et al. (2007) for pulsed sound have been made (Wood et al. 2012), the non-pulsed criteria remain the same. The Southall et al. (2007) SEL threshold for injury (PTS) is defined as being 215 dB re 1 µPa^2·s for all cetacean hearing groups. When multiple events, or continuous sound occur over 24 hours, SELs are integrated over 24 h or the duration of the activity (Southall et al. 2007). However, the criteria were not applied in this assessment as the modelled sound levels did not reach the threshold.

3.1.1. Marine mammal frequency weighting

The potential for sound to affect marine fauna depends on whether and how well the animals can hear the frequency of the received sound. Loud sounds (noises) are less likely to disturb or injure an animal if they are at frequencies that the animal cannot hear well. An exception occurs when the sound pressure is so high that it can cause physical injury through non-auditory mechanisms (i.e., barotrauma). For sound levels below such extremes, frequency weighting can be applied to scale the importance of sound components at particular frequencies in a manner reflective of an animal's sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

Based on a literature review of marine mammal hearing and on physiological and behavioural responses to anthropogenic sound, Southall et al. (2007) proposed standard frequency weighting functions—called M-weighting functions (similar to C-weighting of noise in disturbance assessments on human hearing) —for five functional hearing groups of marine mammals:

- Low-frequency cetaceans—mysticetes (baleen whales).
- Mid-frequency cetaceans—some odontocetes (toothed whales).
- High-frequency cetaceans—odontocetes specialised for using high-frequencies.
- Pinnipeds in water—seals, sea lions, and walrus (not addressed here).
- Pinnipeds in air (not addressed here).

The discount applied by the M-weighting functions for less-audible frequencies is less than that indicated by the corresponding audiograms (where available) for member species of these hearing groups. The rationale for applying a smaller discount than suggested by audiograms is due in part to an observed characteristic of mammalian hearing that perceived equal loudness curves increasingly have less rapid roll-off outside the most sensitive hearing frequency range as sound levels increase. This is why, for example, C-weighting curves for humans, used for assessing loud sounds such as blasts, are flatter than A-weighting curves, used for quiet to mid-level sounds. Additionally, out of band frequencies, though less audible, can still cause physical injury if pressure levels are sufficiently high. The M-weighting functions therefore are primarily intended to be applied at high sound levels where effects such as temporary (TTS) or permanent (PTS) hearing threshold shifts might occur. Figure 2 shows the decibel frequency weighting of the four underwater M-weighting functions.

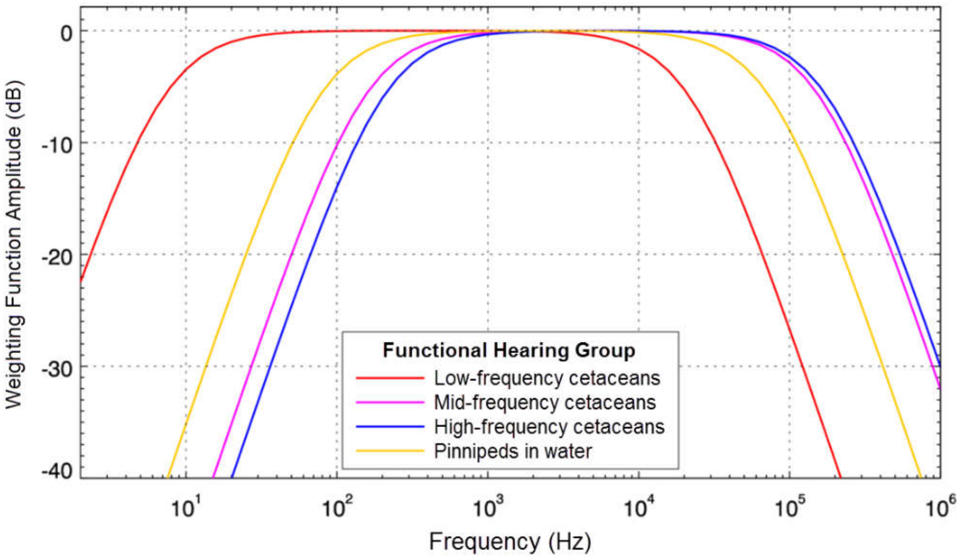


Figure 2. The standard M-weighting functions for the four underwater marine mammal functional hearing groups (Southall et al. 2007).

The M-weighting functions have unity gain (0 dB) through the passband and their high and low frequency roll-offs are approximately –12 dB per octave. The amplitude response in the frequency domain of the M-weighting functions is defined by:

$$G(f) = -20\log_{10}\left[\left(1+\frac{a^2}{f^2}\right)\left(1+\frac{f^2}{b^2}\right)\right] \tag{1}$$

The roll-off and passband of this function are controlled by the parameters *a* and *b*, the estimated lower and upper hearing limits, respectively, of the given functional hearing group (Table 1).

Table 1. The low (a) and high (b) frequency cut-off parameters of the standard M-weighting functions for the four underwater marine mammal functional hearing groups (Southall et al. 2007).

Functional hearing group	*a* (Hz)	*b* (Hz)
Low-frequency cetaceans	7	22 000
Mid-frequency cetaceans	150	160 000
High-frequency cetaceans	200	180 000
Pinnipeds in water	75	75 000

3.2. Fish, Sea Turtles, Plankton, Fish Eggs and Fish Larvae

In 2006, the Working Group on the Effects of Sound on Fish and Turtles was formed to continue developing noise exposure criteria for fish and sea turtles, on which work was begun by a NOAA panel two years earlier. The resulting guidelines (Popper et al. 2014) included specific thresholds for different levels of effects and for different groups of species. These guidelines defined quantitative thresholds for three different types of immediate effects:

- Mortality: includes injury leading to death.
- Recoverable injury: Injuries unlikely to result in mortality, such as hair cell damage and minor haematoma.
- Temporary Threshold Shift.

Masking and behavioural effects were assessed qualitatively, by assessing relative risk rather than by a specific threshold. Because the presence or absence of a swim bladder has a role in hearing, sounds differentially affect animals' susceptibility to injury from noise exposure. Thus, different thresholds were proposed for fish without a swim bladder (including sharks), fish with a swim bladder that is not used for hearing, and fish that use their swim bladders for hearing; sea turtles, fish eggs, and fish larvae are considered separately. Whale sharks are treated as fish without swim bladders for this assessment, although they have a different hearing apparatus. The effects thresholds are summarised in Table 2

This report applied the Popper et al. (2014) threshold criteria and likelihood of impacts for fish, sea turtles, fish eggs, and fish larvae (including plankton) exposed to continuous sound.

The likelihood of impairment due to masking or a behavioural change considers the distance of a fish from a source. The ranges, relative to the source, were quantified as near—within tens of metres—intermediate—within hundreds of metres—and far—in thousands of metres.

The relative risk of an effect was then rated as being "high," "moderate," and "low" with respect to source distance and animal type. Popper et al. (2014) make no assumptions about source or received levels because there are insufficient data to quantify what these distances might be. However, in general, the nearer the animal is to the source, the higher the likelihood is that it will be exposed to high energy and exhibit a response. In determining these distances and the potential effects, actual source and received levels, along with the sensitivity to the sources by the animals of concern, were considered. Popper et al. (2014) admit that the ratings for effects exhibited by animals discussed are highly subjective; however, because the authorship group represents some of the most respected experts in the field, and the ratings represent the general consensus of the group, they are used in this assessment.

As with fish, Popper et al. (2014) suggest relative risks for turtles as a function of distance. For exposure to shipping noise, the relative risks for turtles are the same as fish, except that potential behavioural disruption near the source is expected to be high.

Table 2. Relevant criteria / risk for assessment of FPSO facility, tanker and support vessel, derived from criteria for shipping and continuous sounds, adapted from Popper et al. (2014). For the most part, data in this table are based on knowing that fish will respond to sounds and their hearing sensitivity, but, as discussed in the text, there are no data on exposure or received levels that enable guideline numbers to be provided.

Type of Animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
Fish: no swim bladder (particle motion detection)	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing (particle motion detection)	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder is involved in hearing (primarily pressure detection)	170 dB SPL for 48 h	158 dB SPL for 12 h	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Sea turtles	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) High (I) Moderate (F) Low
Eggs and larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

Notes: SPL dB re 1 µPa; All criteria are presented as sound pressure even for fish without swim bladders since no data for particle motion exist. Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).

3.3. Sea Snakes

No criteria exist for assessing the impact of sound on sea snakes. Previous assessments have suggested using cetaceans as a surrogate for sea snakes, however a sea snake, being a reptile, has an anatomy more similar to a turtle. It was initially proposed to use turtles as a surrogate for sea snakes for this assessment. However, as quantifiable distances for assessing impacts from continuous sounds only exist for fish, fish have been used as a surrogate for this assessment.

4. Methodology for Predicting Sound Propagation from the FPSO Facility

4.1. Modelling Overview

The main source of underwater noise introduced by the Barossa project will be the FPSO facility and associated support vessels. The modelling scenarios include the modelling of an operational FPSO facility (Scenario 1, Section 4.1.1), and an FPSO facility with offloading tanker and a support vessel in attendance (Scenario 2, Section 4.1.2), located at the proposed FPSO facility site in the Barossa field, as shown in Figure 3.

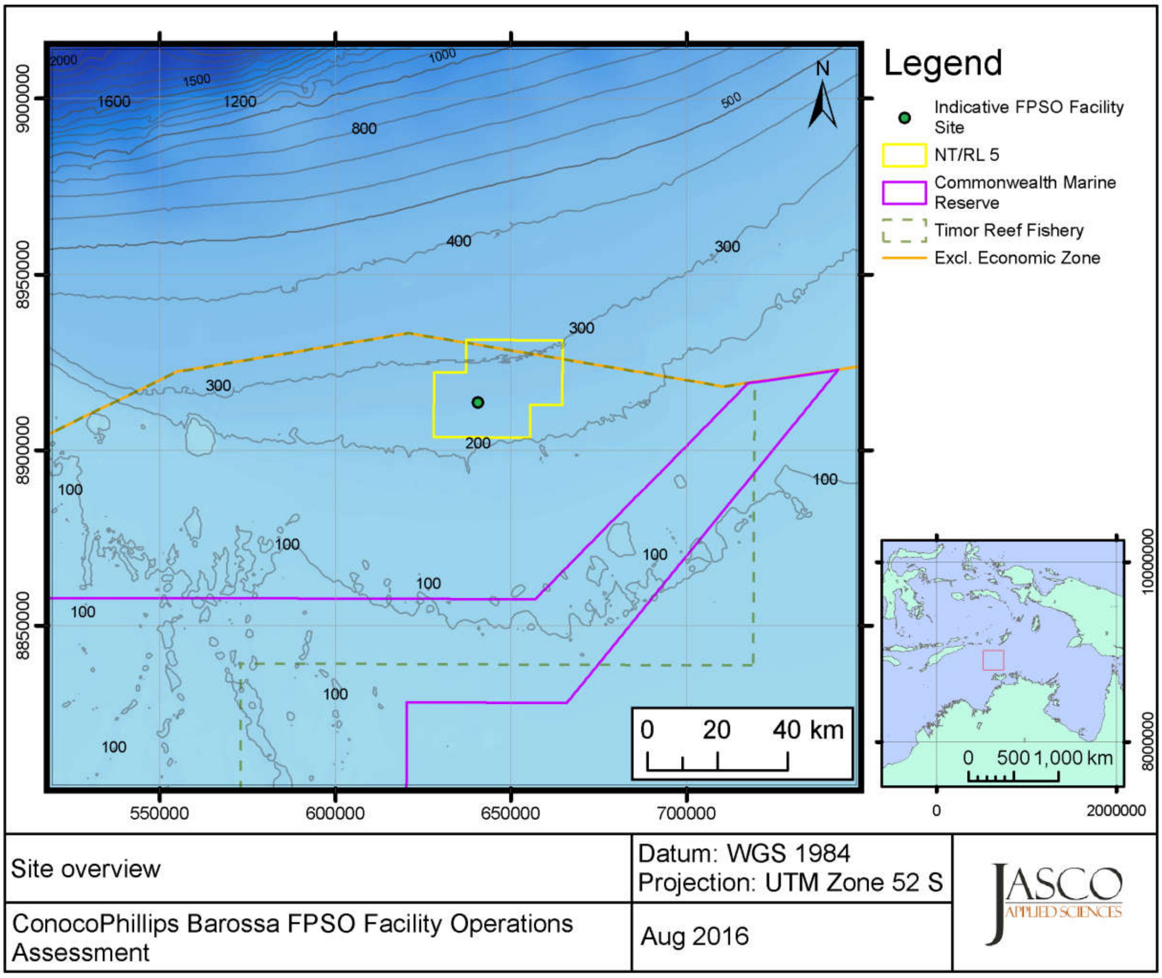


Figure 3. Survey region for the ConocoPhillips Barossa FPSO facility acoustic modelling.

4.1.1. Scenario 1

Scenario 1 assumes an FPSO facility maintaining position in the Barossa field at 9° 49' 33.17" S, 130° 16' 56.31" E without the use of thrusters. The geometric centre of the vessel was used as its acoustic source location.

4.1.2. Scenario 2

Scenario 2 assumes an FPSO facility maintaining position in the Barossa field at 9° 49' 33.17" S, 130° 16' 56.31" E using dynamic positioning (DP) with thrusters. The assessment as assumed that offloading will occur in conjunction with a fuel tanker 250 m east of the FPSO facility and a support vessel 250 m south of the FPSO facility (Figure 4). The tanker distance is an edge-to-edge distance, while the support vessel distance is a centre-to-centre distance. All vessels were modelled on DP; the tanker and FPSO facility were assumed to use no more than 50% of their maximum power while operating. The geometric centre of each vessel was used as its acoustic source location.

Table 3. Location details for acoustic source centres.

Vessel	**Water depth (m)**	**Latitude**	**Longitude**	**UTM (Zone 52S)**	
				X (m)	**Y (m)**
FPSO facility	255.9	9° 49' 33.17" S	130° 16' 56.31" E	640620.5	8913570
Tanker	254.2	9° 49' 33.11" S	130° 17' 12.41" E	641111.0	8913570
Support vessel	255.1	9° 49' 41.31" S	130° 16' 55.85" E	640605.5	8913320

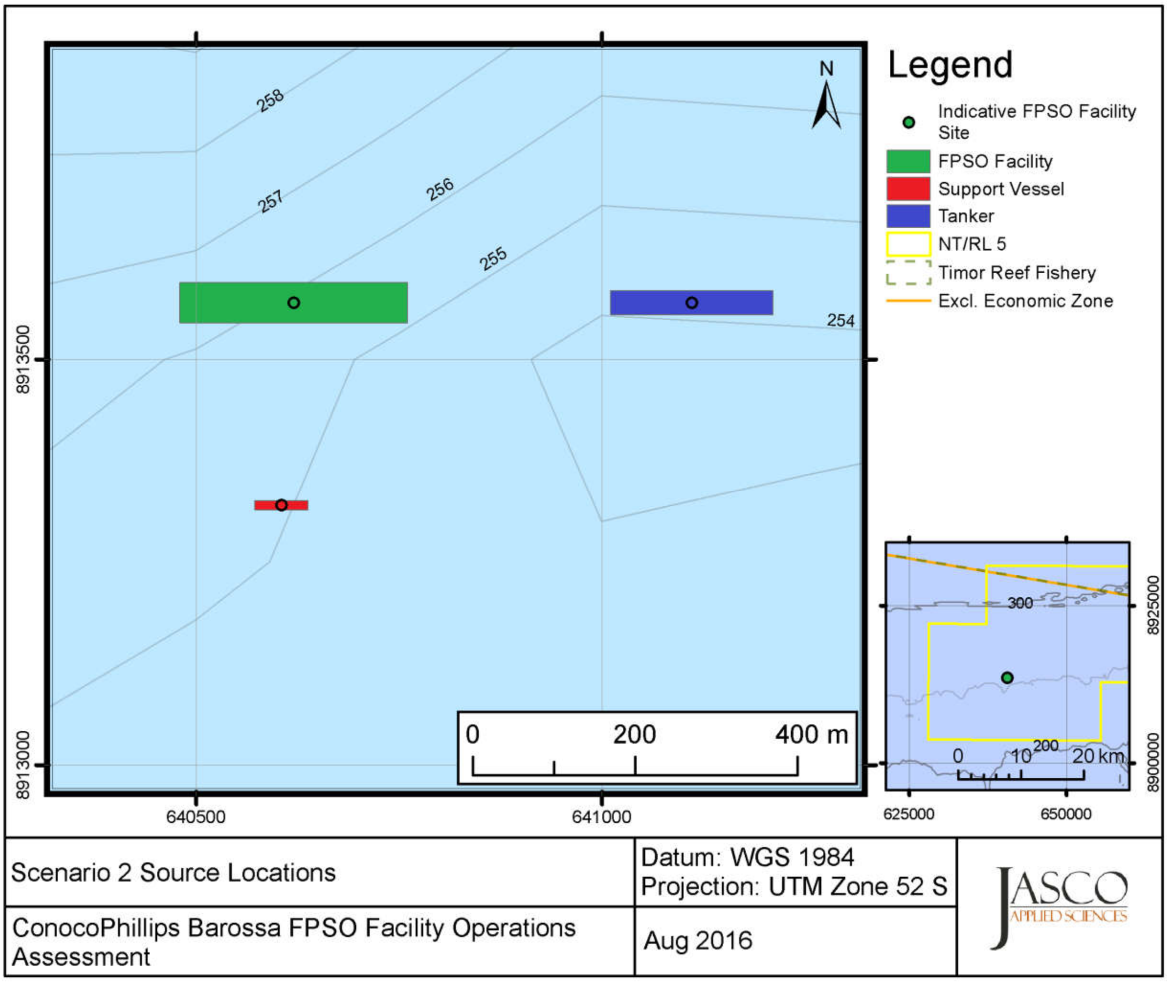


Figure 4. Proposed vessel placement for FPSO facility model, negligible orientation.

4.2. Sound Propagation Models

4.2.1. Marine Operations Noise Model

Underwater sound propagation was predicted with JASCO's Marine Operations Noise Model (MONM). This model computes transmission loss from acoustic sources via the Parabolic Equation model (Collins 1993) for low to mid frequencies (10 Hz–2 kHz), and the BELLHOP Gaussian beam acoustic ray-trace model (Porter and Liu 1994) for higher frequencies (2 kHz–20 kHz). MONM accounts for sound attenuation due to energy absorption through ion relaxation and water viscosity in addition to acoustic attenuation due to reflection at the medium boundaries and internal layers (Fisher and Simmons 1977). Sound attenuation from energy absorption is significant for frequencies higher than 5 kHz and cannot be neglected without noticeably affecting the model results.

MONM computes acoustic fields in three dimensions by modelling transmission loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as N×2-D. These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding $N = 360°/\Delta\theta$ number of planes. The angular step size of the radials is chosen to sufficiently sample the source beam pattern and the environmental variability. The transmission loss values from MONM are added to frequency-resolved sound source levels, and summed over frequency to provide broadband received sound level estimates. Frequency-weighting is optionally applied in the summation.

The modelled SEL field within each vertical radial plane is sampled at various ranges from the source with a fixed radial step size. At each range, the sound field is sampled at various depths. The received SEL at a planar sampling location is taken as the maximum value that occurs over all samples within the water column at that position, i.e., the maximum-over-depth received SEL. This conservatively predicts the received sound level around the source, independent of depth. These maximum-over-depth SELs are presented as colour contours around the source. In principle, the modelled sound field can be sampled at a vertical step size as fine as the acoustic field modelling grid, which varies from 2 m for low frequencies to 6 cm for high frequencies. However, the depth spacing between samples is chosen based on the vertical variability of the acoustic field and the depths of importance for the considered marine species.

For this assessment, the transmission loss was modelled along 144 radial profiles (angular step 2.5°) to a rectangular boundary 50 km to the north, south, east, and west of the source location. The modelling step along the radials was 30 m. A secondary model was run in a 10 km square boundary with radial steps of 10 m for finer resolution of the close range levels. At each planar location, the sound field was sampled at the following depths: 1 m, 2 m, 5 m, 10 m, 15 m, 20 m, 25 m, 30 m, 40 m, 50 m, 100 m, 200 m, 250 m, 300 m, 400 m, and 500 m.

4.3. Acoustic Source Parameters

4.3.1. Floating production, storage, and offloading facility

The proposed FPSO facility is a dynamically positioned production vessel approximately 281 m long and 51.6 m wide with a draft of 18.8 m. During DP, it operates on two stern thrusters, each rated at 4000 horsepower (HP). The vessel type and specifications are similar to production vessels *Ngujima* and *Nganhurra*, from which JASCO gathered measurements in 2010 (Erbe et al. 2013). The measured spectra for these two vessels were averaged and used as a surrogate for the FPSO facility. Because the *Nugujima* and *Nganhurra* were moored, they were not offloading, and the weather was calm, they were not under DP when they were measured; therefore, sound levels of thruster noise were added to the source spectrum to determine the source levels for Scenario 2. Sound levels for DP thruster noise were based on measurements of the dive support vessel *DSV Fu Lai* (MacGillivray 2006). The surrogate vessels' specifications are given in Table 4.

The final composite source spectrum for Scenario 2 was adjusted for the difference in total operational power level between the DSV *Fu Lai* and the FPSO facility using the following equation:

$$SL = SL_{FuLai} + 10\log(HP/HP_{ref}) \tag{2}$$

where HP_{ref} is the level of reference power. The source spectrum was additionally modified to consider the operational level of the *Fu Lai* thrusters relative to the desired operational level for the FPSO facility. Given that DP does not require full thrust, the *Fu Lai*'s thrusters only operated at between 20% and 30% of capacity when measured. To achieve a conservative estimate, FPSO facility thrusters were modelled at 50% power capacity.

The acoustic modelling source depth was determined by assuming the bottoms of the thrusters were at the draft of the vessel, but the noise from cavitation is known (Wright and Cybulski 1983) to be centralised at approximately three quarters of the propeller's height. Assuming a propeller of 1.7 m diameter and a draft of 18.8 m, the source depth was approximated at 17.5 m. For modelling, it was assumed that both thrusters operated at the middle (50%) of their constant power range, at a constant speed. The thrusters are located at the stern section of the vessel; for modelling purposes, however, the source location was placed in the planar centre of the vessel to approximate a point source. Because this assessment is focused on the far-field noise from all sources on the vessel (including not just thruster noise, but also noise from ancillary equipment for power generation, etc.) the point source approximation is suitable. Figure 5 shows 1/3-octave-band source levels for the FPSO facility and its proxy vessels.

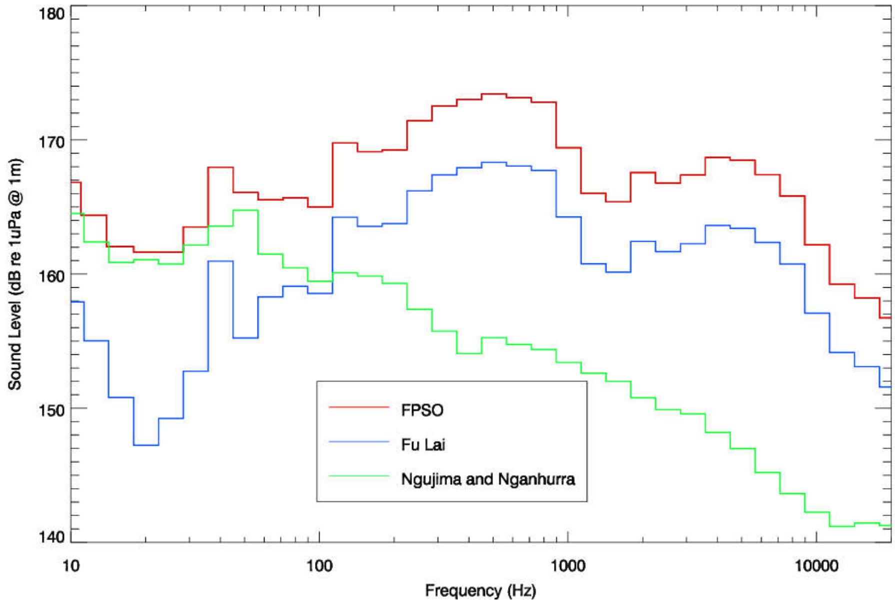


Figure 5. 1/3-octave bands of modelled FPSO facility without DP (Scenario 1, the *Ngujima/Nganhurra* average), the modelled FPSO facility for Scenario 2, and the *Fu Lai* is included for reference.

4.3.2. Tanker vessel

The proposed FPSO facility tanker vessel is approximately 200 m long with a 12 m draft. The main propulsion consists of a single bow thruster; the DP propulsion system consists of two transverse thrusters aft and two transverse thrusters forward, summing to a power of 12,605 HP. The sound spectrum of the DSV *Fu Lai* was used to model the tanker through power conversions using Equation 2. One-third octave-band source levels for both *Fu Lai* and the tanker are shown in Figure 6.

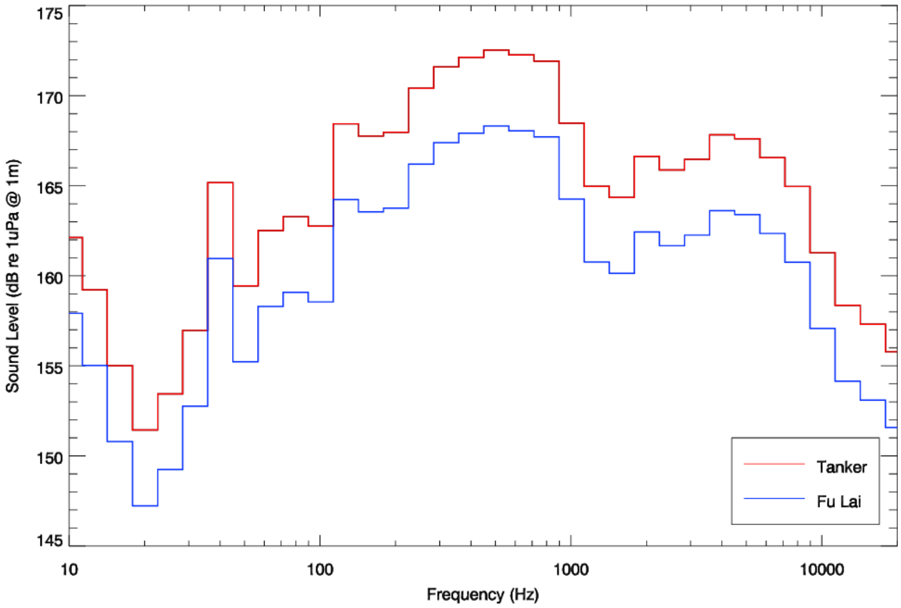


Figure 6. 1/3-octave bands of the tanker after power adjustment. 1/3-octave bands of *Fu Lai* are included as a reference.

4.3.3. Support vessel

Support vessel 1/3-octave-band source levels used in this report were derived from measured levels of the *Setouchi Surveyor* (Hannay et al. 2004). The *Setouchi Surveyor* is 64.8 m long with an 11.3 m beam. It operates on 4600 HP while producing a broadband source level of 186.1 dB at a depth of 3.4 m. Its acoustic levels are believed to be representative of the support vessel's noise production for the specific activities near the FPSO facility site. The 1/3-octave-band spectra for the *Setouchi Surveyor* are shown in Figure 7.

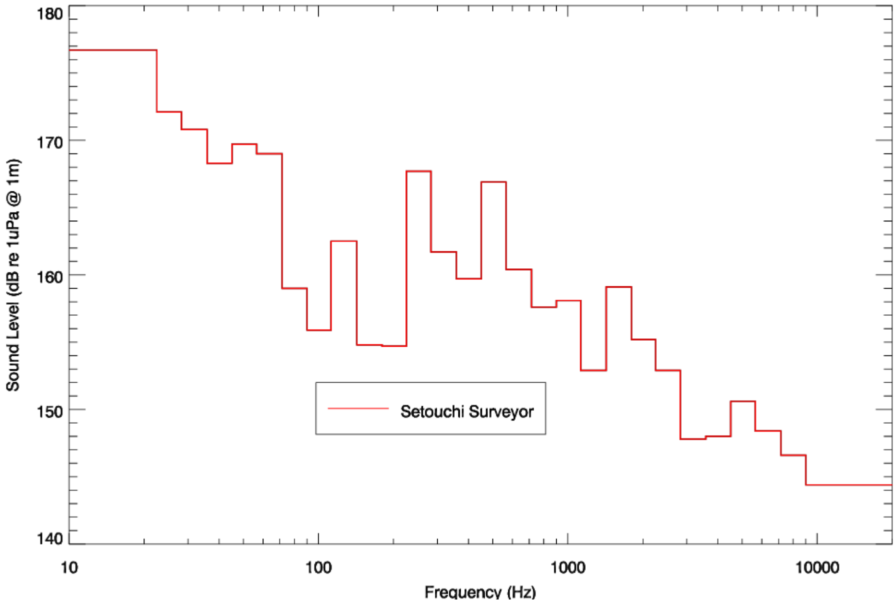


Figure 7. 1/3-octave-band source levels of side thruster on the *Setouchi Surveyor*.

Table 4. Vessels that will be engaged in the Barossa project during either scenario. The proxy vessel that was used to establish the broadband source level (indicated) is also provided for each proposed vessel.

Vessel type	Representative vessel			Proxy vessel	
	Power (kW)	Broadband SL (dB re 1 µPa at 1 m)	Source depth (m)	Vessel name	Total power (kW)
FSPO	N/A	173.9	17.4	*Ngujima* *Nganhurra*	27000 15800
FSPO (under DP)	6300	183.6	17.4	*Fu Lai* *Ngujima* *Nganhurra*	9600 27000 15800
Fuel Tanker	9400	182.4	7.2	*Fu Lai*	9600
Support Vessel	3400	184.1	3.4	*Setouchi Surveyor*	3400

Sound spectra for all vessels modelled in Scenario 2 are shown together in Figure 8.

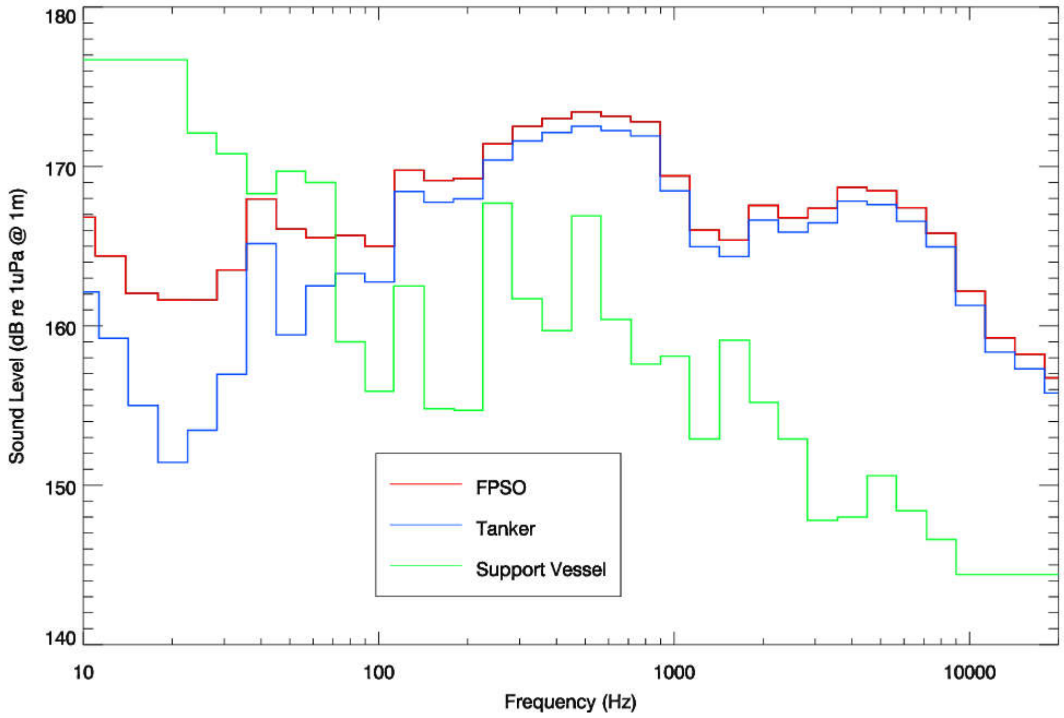


Figure 8. 1/3-octave-band source levels used to model Scenario 2.

4.4. Environmental Parameters

4.4.1. Bathymetry

High-accuracy bathymetry data for the Barossa field and the surrounding area with a regular grid spacing of 500 × 500 m was provided by ConocoPhillips. This dataset has been supplemented by bathymetry data extracted from a 250 × 250 m resolution grid of Australian waters (Whiteway 2009). For the modelling, bathymetry data for a 105 × 105 km area centred on the indicative FPSO facility site were extracted and re-gridded onto a grid with a regular spacing of 250 × 250 m. The resulting bathymetry and bathymetry extents is shown in Figure 9.

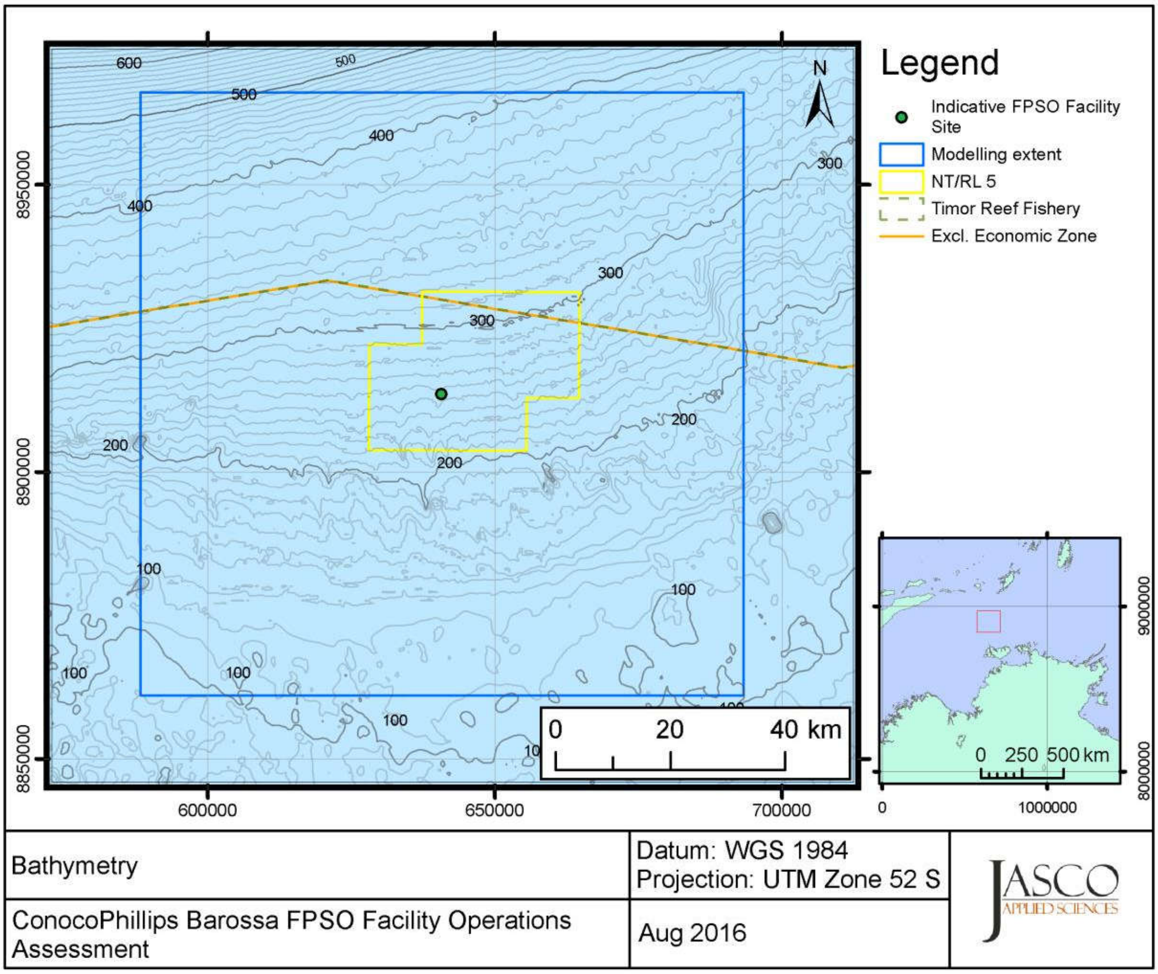


Figure 9. The bathymetry used for the modelling. The blue line indicates the extents of the modelling grid sampled at a 250 × 250 m resolution.

4.4.2. Geoacoustics

Geotechnical data were obtained from the ARUP report (Lane 2015) supplied to JASCO by ConocoPhillips, and a single geoacoustic profile representative of the top layer of sediment was derived from that analysis. The sediment thickness in the region is over 1200 m according to World Ocean Atlas (Whittaker et al. 2013). Consequently, it is assumed that at depths beyond 35 m, the sediment is composed of similar grain types. Parameters have been derived based on empirical relationships by Buckingham (2005). The geoacoustic profile used in the modelling is shown in Table 5.

Table 5. Estimated geoacoustic profile used in the modelling. Within each depth range, each parameter varies linearly within the stated range.

Depth below seafloor (m)	Material	Density (g/cm3)	P-wave speed (m/s)	P-wave attenuation (dB/λ)	S-wave speed (m/s)	S-wave attenuation (dB/λ)
0–9	Coarse Sand	2.09	1655.3 – 2133.8	0.76 – 1.46	322.7	0.246
9–35	Clay	1.46	1539.8 – 1582.9	0.33 – 0.51		
35–500	Medium Sand	2.08	2275.2 – 3453.2	1.73 – 2.82		

4.4.3. Sound speed profile

The sound speed profiles (SSPs) for the modelled sites were principally derived from temperature and salinity profiles provided to JASCO by ConocoPhillips comprising monthly data over the year. The data are provided for two sites although only sample depths from 33 m to the seafloor. The data is supplemented with results from the U.S. Naval Oceanographic Office's *Generalized Digital Environmental Model V 3.0* (GDEM; Teague et al. 1990, Carnes 2009). GDEM provides an ocean climatology of temperature and salinity for the world's oceans on a latitude-longitude grid with 0.25° resolution, with a temporal resolution of one month, based on global historical observations from the U.S. Navy's Master Oceanographic Observational Data Set (MOODS). The temperature-salinity profiles were converted to sound speed profiles according to the equations of Coppens (1981):

$$\begin{aligned} c(z,T,S,\phi) &= 1449.05 + 45.7t - 5.21t^2 - 0.23t^3 \\ &\quad + \left(1.333 - 0.126t + 0.009t^2\right)(S-35) + \Delta \\ \Delta &= 16.3Z + 0.18Z^2\,, \quad Z = \frac{z}{1000}\left[1 - 0.0026\cos(2\phi)\right], \quad t = \frac{T}{10} \end{aligned} \tag{3}$$

where z is water depth (m), T is temperature (°C), S is salinity (psu), and ϕ is latitude (radians).

For each monthly profile, the supplied data were extrapolated to provide results to the water surface based on the gradients of the profile from the GDEM data. The average of the SSPs taken across all months provides a representative SSP for the area across the year; this is shown in Figure 10.

The resulting SSP represents a mixed isothermal surface layer with a slight upward-refracting profile. Below 80 m depth the profile is driven by the reduction in temperature producing a steep downward-refracting profile. For depths within the modelling extent, no sound channel is realised in deeper waters.

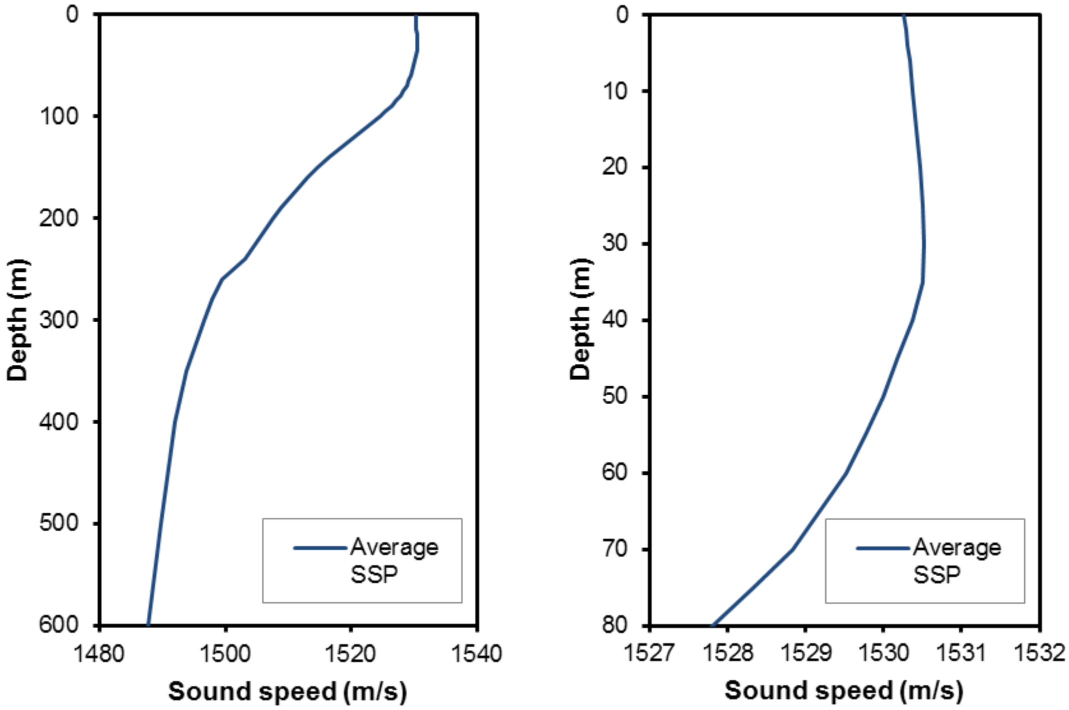


Figure 10. Sound speed profile used for the modelling taken as the average of all monthly profiles (a), and detail of the top 80 m of the SSP (b).

5. Modelling Results

Modelled sound levels were summed over all sources to obtain the total, maximum-over-depth anthropogenic sound footprints associated with operation of the FPSO facility in the Barossa field. The maximum-over-depth levels are presented as coloured isopleths for the sound level thresholds of interest. Sound isopleths are shown in separate maps for SPL and for SEL accumulated over the appropriate activity duration—for Scenario 1, 24 hrs for the FPSO facility option, and for Scenario 2, 24 hrs for the FPSO facility with tanker offload. The appropriate M-weighting was applied to assess the areas of potential impact for different marine species. Because the sources are distributed, the zones of potential impact are non-circular and therefore expressed as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) for the pertinent thresholds for each species. $R_{95\%}$ is defined the radius of a circle that encompasses 95% of the area ensonified above a given threshold, and is often a more relevant distance to associate with a criterion because it ignores small, localised protrusions in the sound level contour that could force the maximum range to over-represent the effective extent of the sound exposure.

The maximum distances from either the FPSO facility or the centroid, to each of the thresholds are also provided. Where a noise level contour forms a single contiguous line around all three vessels, the R_{max} result is taken as the distance from the average of vessel location to the furthest distance at which the associated noise level is reached. Where the noise contours form separate zones of higher noise levels, the R_{max} result is taken as the maximum distance from any one vessel to its own noise contour at that level. This is illustrated graphically in Figure 11.

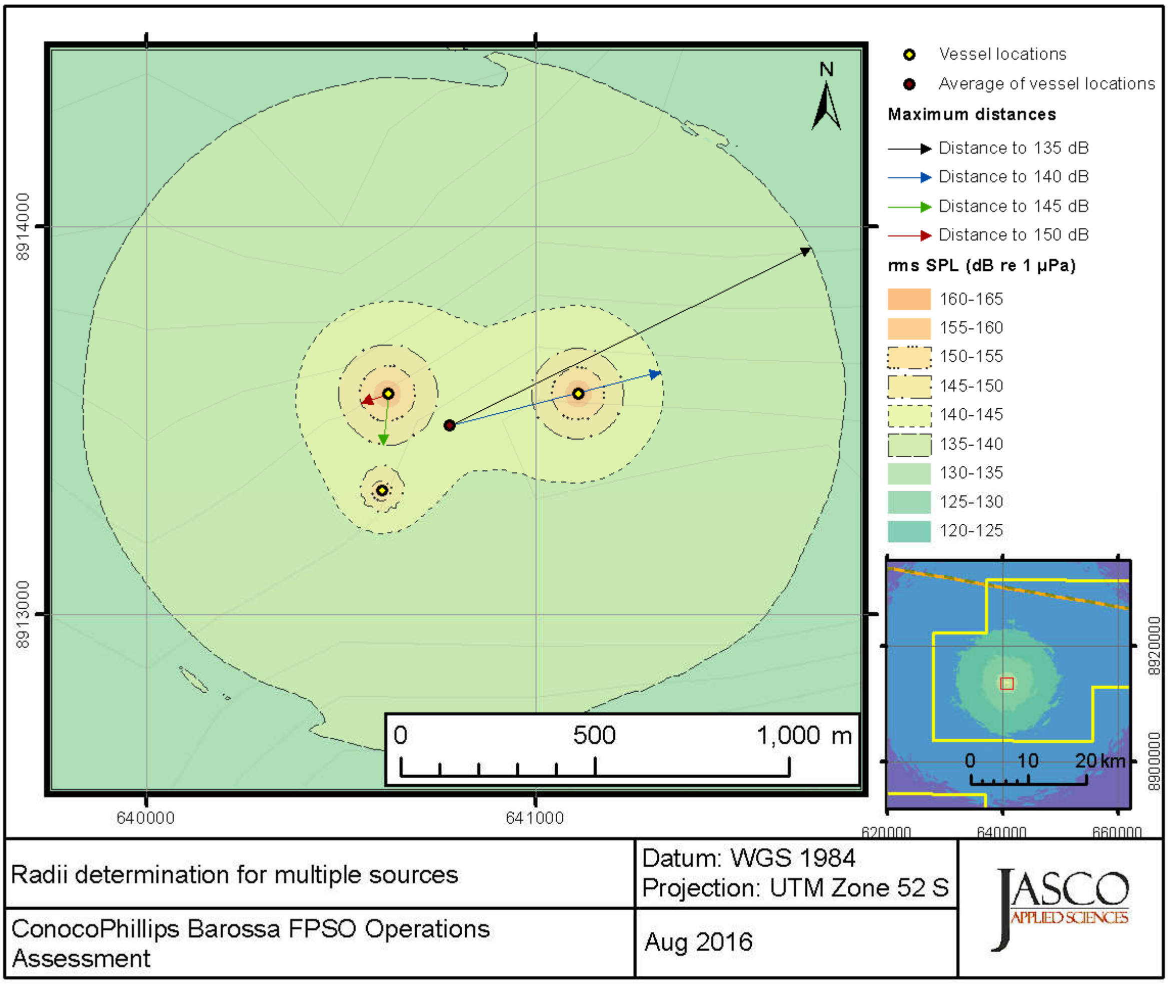


Figure 11. Determining the radii for multiple sources. Where the noise contour is a contiguous line around all sources, the average location (centroid) is assumed to be the source location for determining distances. Where the contours form separate areas around each vessel, the distances are determined from the original vessel locations.

5.1. Scenario 1

The modelling results associated with the 24 h operation of the proposed FPSO facility are presented in Tables 6–9, and shown graphically in Figures 12 and 13.

Table 6. Horizontal distances (in m) from the proposed FPSO facility to modelled maximum-over-depth unweighted SEL and SPL

Unweighted 24-hour SEL			SPL		
Threshold (dB re 1 µPa^2·s)	R_{max} (m)	$R_{95\%}$ (m)	Threshold (dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
210	<10	<10	160	<10	<10
200	20	20	150	20	20
190	60	60	140	70	70
180	200	200	130	220	210
170	1400	1290	120	1420	1330
160	5890	5100	110	6460	5430
150	18600	15000	100	20900	16000

Table 7. Horizontal distances (in m) from the proposed FPSO facility to modelled maximum-over-depth weighted 24 h SEL

Low-frequency cetaceans			Mid-frequency cetaceans			High-frequency cetaceans		
Threshold (dB re 1 µPa^2·s)	R_{max} (m)	$R_{95\%}$ (m)	Threshold (dB re 1 µPa^2·s)	R_{max} (m)	$R_{95\%}$ (m)	Threshold (dB re 1 µPa^2·s)	R_{max} (m)	$R_{95\%}$ (m)
205	<10	<10	205	<10	<10	205	<10	<10
200	20	20	200	<10	<10	200	<10	<10
195	30	30	195	<10	<10	195	<10	<10
190	60	60	190	20	20	190	20	20
185	110	100	185	50	50	185	40	40
180	190	190	180	90	90	180	80	80
175	560	540	175	160	150	175	140	130
170	1380	1110	170	280	270	170	240	240
165	3210	2620	165	780	750	165	640	620
160	5880	4980	160	1840	1590	160	1400	1300
155	10100	9150	155	5150	4180	155	4330	3580
150	18500	14800	150	11300	8320	150	9520	7130

Table 8. Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the proposed FPSO facility under normal operations to modelled maximum-over-depth SPL thresholds for marine mammals.

Threshold	Distance (km)	
	R_{max}	$R_{95\%}$
NMFS (2014) Behaviour, Unweighted SPL: 120 dB re 1 µPa	1.42	1.33

Table 9. Maximum horizontal distances (in m) from the proposed FPSO facility under normal operations to quantifiable thresholds for fish (Table 2). (Popper et al. (2014).

	Recoverable injury (170 dB SPL for 48 h)	TTS (158 dB SPL for 12 h)
	SPL (dB re 1 µPa)	SPL (dB re 1 µPa)
Fish: swim bladder involved in hearing	<10 m	<10 m

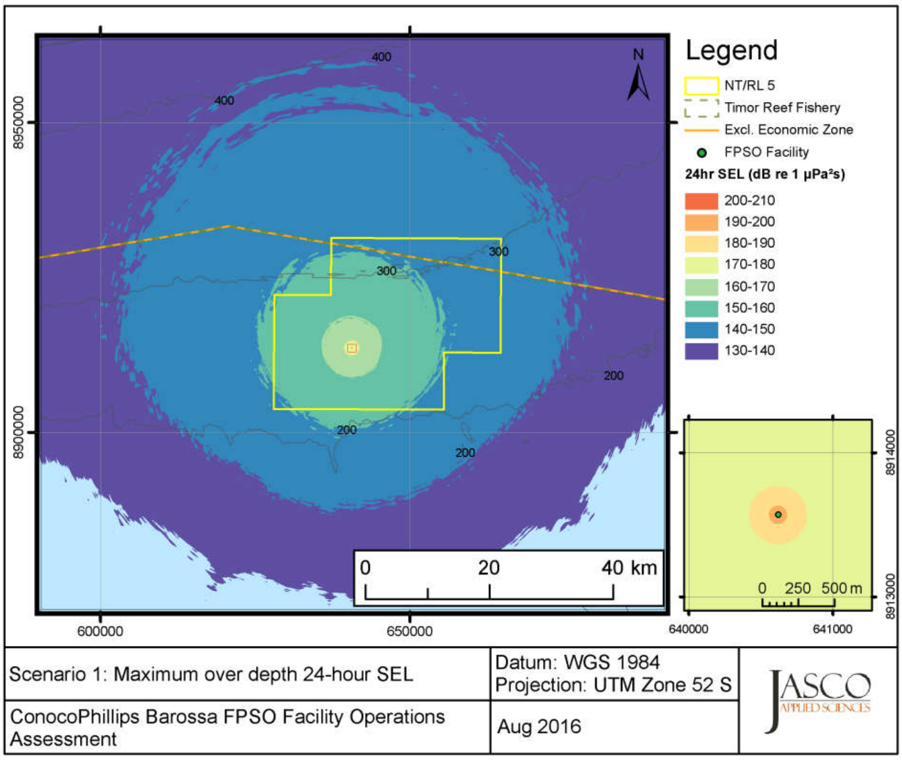


Figure 12. Scenario 1: Sound level contour map showing unweighted 24 h SEL results.

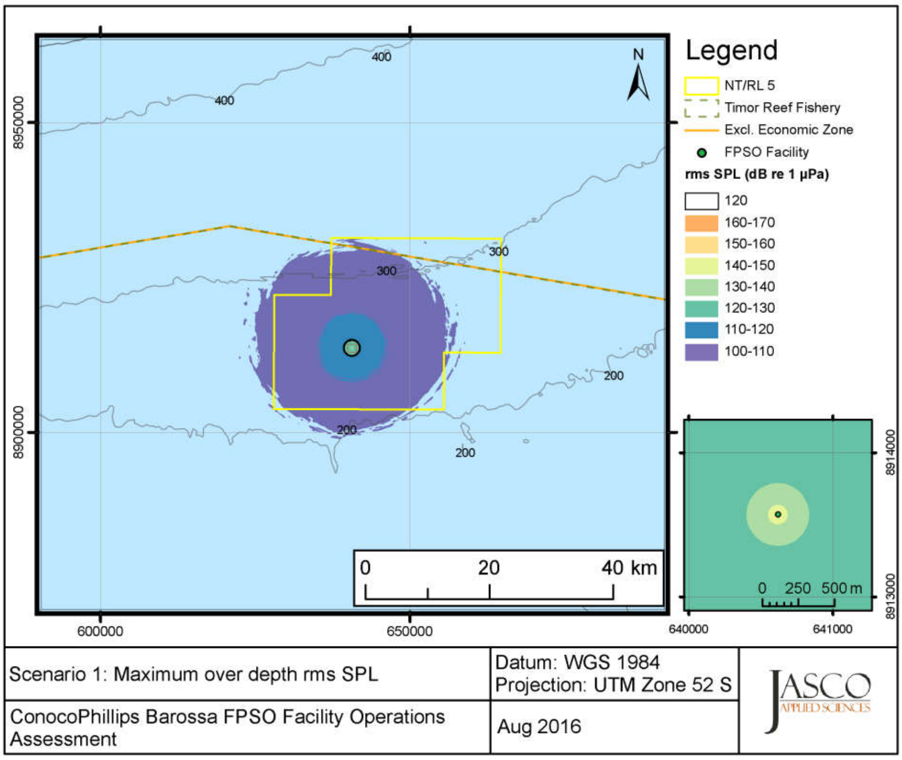


Figure 13. Scenario 1: Sound level contour map showing unweighted SPL results and the SPL 120 dB behavioural disturbance threshold for cetaceans.

5.2. Scenario 2

The modelling results associated with the 24 h operation of the proposed FPSO facility with tanker offload are presented in Tables 10–13 and shown graphically in Figures 14 and 15.

Table 10. Horizontal distances (in m) from the proposed FPSO facility during offload to modelled maximum-over-depth unweighted SEL and SPL. Levels indicated by an asterisk (*) show distances from individual sources instead of the average of source locations.

Unweighted 24-hour SEL			SPL		
Threshold (dB re 1 µPa^2·s)	R_{max} (m)	$R_{95\%}$ (m)	Threshold (dB re 1 µPa)	R_{max} (m)	$R_{95\%}$ (m)
210*	<20	<20	160*	<20	<20
200*	70	60	150*	70	70
190	540	470	140	560	490
180	1860	1660	130	2120	1840
170	10800	8330	120	11400	8880
160	28900	23400	110	29200	24800
150	>50000	>50000	100	>50000	>50000

Table 11. Horizontal distances (in m) from the proposed FPSO facility during offload to modelled maximum-over-depth weighted 24 h SEL. Levels indicated by an asterisk (*) show distances from individual sources instead of the average of source locations.

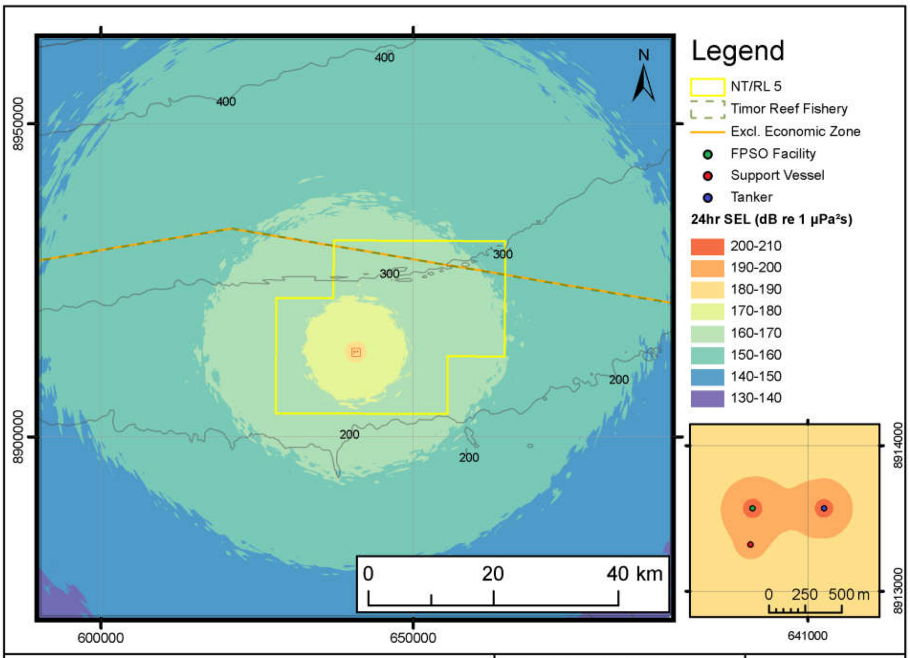
Low-frequency cetaceans			Mid-frequency cetaceans			High-frequency cetaceans		
Threshold (dB re 1 µPa^2·s)	R_{max} (m)	$R_{95\%}$ (m)	Threshold (dB re 1 µPa^2·s)	R_{max} (m)	$R_{95\%}$ (m)	Threshold (dB re 1 µPa^2·s)	R_{max} (m)	$R_{95\%}$ (m)
210*	<20	<20	210*	<20	<20	210*	<20	<20
205*	30	30	205*	30	30	205*	30	30
200*	70	60	200*	60	60	200*	60	50
195*	120	110	195*	110	100	195*	100	100
190	540	470	190	520	460	190*	200	180
185	970	880	185	740	640	185	680	600
180	1830	1640	180	1390	1250	180	1310	1160
175	5610	4140	175	4340	3440	175	4110	2790
170	10800	8280	170	9160	6980	170	9040	6480
165	17100	14100	165	15000	12300	165	15000	11800
160	28900	23300	160	25200	20800	160	24200	19600
155	46100	36600	155	41900	32500	155	37700	30800
150	>50000	>50000	150	>50000	>50000	150	>50000	>50000

Table 12. Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the proposed FPSO facility offloading to modelled maximum-over-depth SPL thresholds for marine mammals.

Threshold	Distance (km)	
	R_{max}	$R_{95\%}$
NMFS (2014) Behaviour, Unweighted SPL: 120 dB re 1 µPa	11.4	8.9

Table 13. Maximum horizontal distances (in m) from the proposed FPSO facility offloading to quantifiable thresholds for fish (Table 2). (Popper et al. (2014).

	Recoverable injury (170 dB SPL for 48 h)	TTS (158 dB SPL for 12 h)
	SPL (dB re 1 µPa)	SPL (dB re 1 µPa)
Fish: swim bladder involved in hearing	<10 m	<10 m



Scenario 2: Maximum over depth 24-hour SEL	Datum: WGS 1984 Projection: UTM Zone 52 S	JASCO APPLIED SCIENCES
ConocoPhillips Barossa FPSO Facility Operations Assessment	Aug 2016	

Figure 14. Scenario 2: Sound level contour map showing unweighted 24 h SEL results.

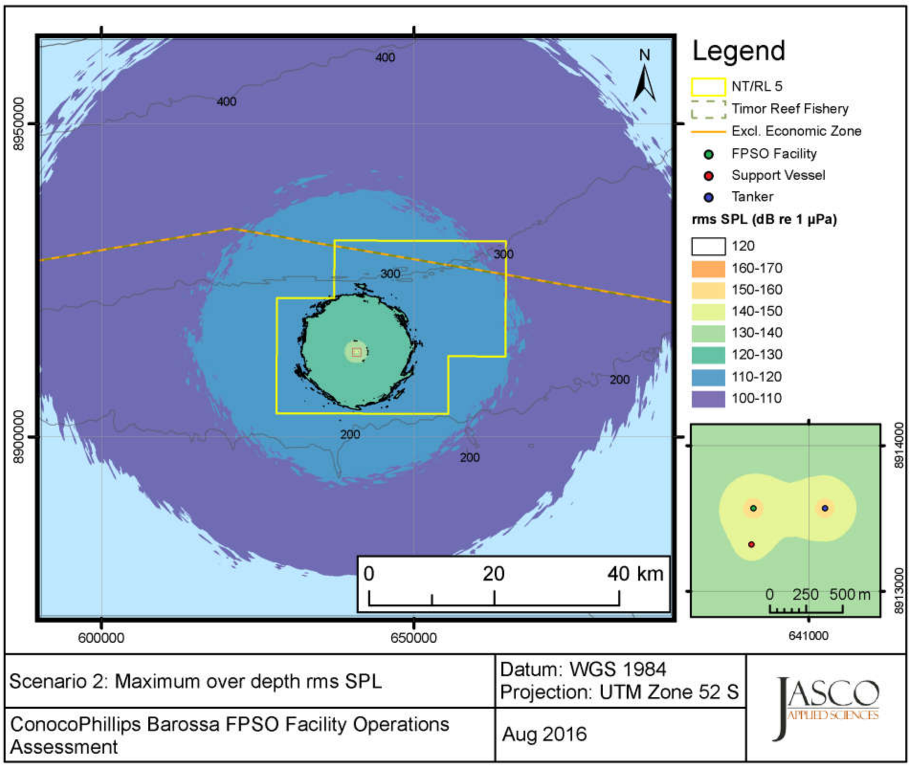


Figure 15. Scenario 2: Sound level contour map showing unweighted SPL results and the SPL 120 dB behavioural disturbance threshold for cetaceans.

6. Discussion

6.1. Relation to Ambient Soundscape

To characterise the soundscape, and determine typical ambient sound levels in the region, JASCO conducted a 12-month acoustic monitoring program at locations within and surrounding the Barossa field location (McPherson et al. 2016). For the purposed of the assessment the data periods influenced by the drilling program are excluded. This excludes the data recorded at one station (Station J2) from four months of Deployment 1.

The levels reported in the tables below are broadband, 10 Hz–24 kHz, and considered representative of typical ambient conditions. The minimum levels of ambient sound were consistent across all stations, with a mean minimum 1-min SPL of 81.4 dB re 1 µPa (s=1.4 dB). The mean median (L_{50}) and mean fifth percentile (L_5) 1-min SPL's were 96.7 dB re 1 µPa (s=3.1 dB) and 107.9 dB re 1 µPa (s=3.3 dB). The mean maximum at all stations was 145.5 dB re 1 µPa (s=2 dB). The median daily SELs from the ambient monitoring program (Table 14) were computed for periods from Deployment 1 not influenced by the Mobile Offshore Drilling Unit (MODU), and for all of Deployment 2, which overall was less influenced by the MODU. The mean median from all stations is 151.4 dB re 1 µPa²·s, accounting for the deployment duration. The mean maximum daily SEL from the two stations furthest from the MODU is 170.8 dB re 1 µPa²·s (s = 3.4 dB).

Table 14. Median daily SELs throughout the full deployment period but excluding periods influenced by drilling operations. SEL units: dB re 1 µPa²·s.

Station	Deployment 1 (without MODU periods)	Deployment 2
J1	149.4	151.9
J2	150.6	153.8
J3	146.3	152.8

The modelling outputs from Section 5 can be compared to the typical ambient noise conditions in the Barossa region in order understand the estimated sound levels in the acoustic context of the region in which the activity is proposed. This comparison can assist in assessing the impacts of the survey in terms of masking, non-auditory effects and behavioural impacts

Estimating the ranges at which the modelled SPLs and daily SELs from the proposed FPSO facility are equivalent to measurements from the acoustic monitoring program (as discussed above) provides an understanding of the spatial extent over which the sound from the activities exceeds the normal conditions (Tables 15 and 16).

Table 15. $R_{95\%}$ and R_{max} distances to SPL thresholds

Monitoring program representative equivalent sound level	Modelling study isopleth	Scenario 1		Scenario 2	
	SPL (dB re 1 µPa)	$R_{95\%}$ Distance (km)	R_{max} Distance (km)	$R_{95\%}$ Distance (km)	R_{max} Distance (km)
Mean maximum (145.5 dB, s=2)	140	0.07	0.07	0.49	0.56
Mean 5th percentile (107.9 dB, s=3.3)	110	5.4	6.5	24.8	29
Mean median (96.7 dB, s=3.1)	100	16	20.9	54	66

Table 16. $R_{95\%}$ and R_{max} distances to unweighted daily SEL levels

Scenario	Mean median daily SEL (~150 dB re 1 µPa²·s)		Mean maximum daily SEL (~170 dB re 1 µPa²·s)	
	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)
1	15	18.5	1.29	1.4
2	52.5	62	8.33	10.8

6.2. Potential Impacts to Marine Fauna

As the FPSO facility be present in the Barossa field year-round, the potential impacts of the operations should be considered over the entire year. To understand the usage of and movements through the region by marine mammals and fish JASCO conducted a baseline acoustic monitoring program over a period of 12 months in the Barossa field and surrounds (McPherson et al. 2016). The key findings of the monitoring program are outlined below, with further detail provided in McPherson et al. (2016):

- Pygmy blue whales were detected during their northward migration once in August 2014, primarily over the period 29 May-5 June 2015, and also on the 16 and 30 June, and 1 July 2015. The detections are over 400 km further east than the north-bound migration corridor of pygmy blue whales described in Double et al. (2014). No detections were logged from the south-bound migration, suggesting a different migration path. The highest calling rates of the three monitoring station occurred at the Barossa field, which may reflect its greater depth and proximity to the trench.
- Omura's whales, identified through descriptions of their acoustic repertoire by Cerchio et al. (2015), were present consistently from April to September inclusive (with detections increasing from February, and fading out in early November), with a peak in June and July. Based on the year of recordings, the whales seemed to enter the region in a south-west to north-east direction, then maintain a higher presence within the Barossa field area (than compared to the Evans Shoal or Caldita areas) for the autumn and winter months. They appeared to leave the region in a north-east to south-west direction, reversing their entry path, leaving the area by the end of October.
- Bryde's whales, assumed to be the source of downsweeping calls detected, and distinguished from the Omura's whales through variations in the spatial and temporal occurrence of vocalisations, were present in the region from summer (January) to the following spring (October). They appear to move into the area in a south to north direction during summer and autumn, then utilise the region with a preference for the shallower sections (Evans Shoal and Caldita field areas) over the Barossa field region. They then left the area in a north – south direction, with the last detections in early October.
- Odontocetes were extremely common. Many species were detected on a daily basis, with a primarily nocturnal diel cycle. Although systematic species differentiation was not performed, pilot whales were opportunistically identified.
- Beaked whales of an unknown species were detected on four days over the entire program at the stations at the Barossa and Caldita fields.
- Fish chorused at dawn and dusk over the entire deployment period at all three stations. Their chorusing varied in intensity over the deployment period, but was reasonably consistent in diel patterns.

6.2.1. Marine Mammals

If any marine mammals are exposed to sound levels above the PTS thresholds, auditory injury might result, which in extreme cases could lead to death as marine mammals rely on hearing to communicate with conspecifics, find food and/or avoid predators. However, as the 24 h PTS threshold ranges for all marine mammal hearing groups are less than 20 m (the minimum modelling resolution), the likelihood that any marine mammal will find itself at such close proximity to the source for hours on end is negligible. It is therefore expected that marine mammals will not experience PTS from any of the operations associated with the proposed FPSO facility. It is possible that behavioural responses could occur within 1.33 or 1.42 km during normal FPSO facility operations and 8.9 or 11.4 km during offload operations ($R_{95\%}$ and R_{max} distances respectively) using the 120 dB re 1 µPa NMFS criterion.

From the summary presented in Section 3.1, it is expected that there will be a reduced behavioural response to the proposed FPSO facility as it is stationary, in comparison to a moving and/or transient sound source, and that for resident animals there might be partial habituation. Should any resident animals spend long periods of time in the area (i.e. months) there might be partial habituation. However, the area of possible behavioural response in comparison to the available habitat is small, and therefore potential impacts are unlikely. The probability of the FPSO facility operations having a negative impacting on mysticetes marine mammals due to alteration of their migratory path to avert the immediate region of activities is considered low, given the presence nearby of similar oceanic environments and the natural width of the migratory corridors.

Due to the extremely limited use of the region by beaked whales, as determined by the acoustic monitoring program, it appears unlikely that they will interact with the FPSO facility activities to a significant extent at any time.

Aside from potentially inducing some avoidance or other behavioural reactions, the FPSO facility operations could result in longer-range acoustic masking effects. Masking due to anthropogenic sounds cannot be determined based on the broadband accumulated sound exposure level, because the effect depends on the spectral noise level within the frequency band of the sounds in question and therefore varies dynamically with receiver distance from the sound (noise) source. Masking is typically reported as a percent reduction of active acoustic space (Clark et al. 2009). In order to estimate the reduction quantitatively it is necessary to take into account parameters such as call source levels (and the adaptive compensation of the same in the presence of competing noise, known as Lombard response), detection thresholds based on the receiver perception capabilities, signal directivity, band-specific (spectral) noise levels, and noise and signal duration. The relationship between communication space and the health of the pygmy blue, Omura's and Bryde's whales is presently unknown, but it is reasonable to assume that communication serves an important purpose, as it does in other marine mammals, (e.g. attracting, mates, identifying and tracking offspring, and maintaining group structure) and that disruption in communication could affect an individual's and possibly a population's health. Adding anthropogenic noise decreases the communication space, so the possible effects of anthropogenic noise on Bryde's whales can be inferred by examining the reduction in the amount of communication space. A quantitative assessment is beyond the scope of the present work and therefore a qualitative assessment of masking is done here.

The $R_{95\%}$ exceedance distance (Table 15) for the 140 dB isopleth, used as a conservative surrogate for the mean maximum 1-minute measured ambient SPL of 146 dB re 1 µPa, was 0.07 and 8.9 km in for normal and offloading operations respectively. The calls from mysticetes known to use the area are typically at least several seconds in duration (15–25 seconds for blue whales, 2–10 seconds for Omura's and 0.5–2 seconds for Bryde's) (McPherson et al. 2016). The continuous nature of the sound from FPSO facility operations and its progressive increase in level with decreasing range from the facility will result in complete masking of calls within a certain boundary. The area over which this occurs will vary depending upon the vocalising marine mammal (pygmy blue, Omura's, Bryde's or odontocetes); a quantitative estimation is beyond the scope of this assessment. However, odontocetes will likely only experience masking for the low frequency components of their calls; this effect will be limited to the local area surrounding the facility and is not expected to influence the whales' ability to echolocate when feeding due to the frequency range of their echolocation clicks. Pygmy blue whales, Omura's and Bryde's whales will experience masking when in the vicinity of the FPSO facility, and given the lower vocalisation source levels for the latter two species, the area over which masking will occur will be larger than for pygmy blue whales. Masking from the FPSO facility activities is expected to be more relevant for Omura's and Bryde's whales because of their more regular presence within the region encompassing the Barossa field from summer through to early spring, whereas the migratory pygmy blue whales will only be affected for a short period of time.

Generally, the spatial and temporal scale of behavioural response effects on marine mammals would be limited to the localised area surrounding the proposed FPSO facility and the periods of intensified activities. These ranges will be greater during offload operations. Because the facility will be located at a static site, and therefore only influence a small region within the Timor Sea not known to be a critical habitat, significant effects at the population level are not expected.

6.2.2. Fishes

Sound produced by the FPSO and associated operations, such as offload activities, could cause physiological effects, and recoverable injury, to some fish species, but only if the animals are in very close proximity to the sound sources–within a planar distance of 10 m. No population-level effects would be expected given the restricted zone of pathological effects. Temporary impairment due to TTS could occur at similar short ranges if fish remain at the same point within the sound field for long periods of time (12 h). However, there is a tendency for fish to aggregate around oil and gas structures, particularly in featureless environments such as where the FPSO facility will be located (Rabaoui et al. 2015). Masking could occur within thousands of metres under a worst-case scenario (moderate risk, Table 2), however typically any effect will be limited to within hundreds of metres.

The same arguments about temporal and spatial scale of behaviour effects that were made for marine mammals (Section 6.2.1) can be applied to fish. Therefore, adverse behavioural effects on various life stages of fish caused by the operation of the FPSO facility are expected to be negligible.

6.2.3. Turtles

Despite the limited amount of literature available (Section 2.4), it is expected that the sound produced by the FPSO facility and associated operations, such as offload activities, has a low probability of inducing injury to turtles. No population-level effects would be expected given the restricted zone of pathological effects. Temporary impairment due to TTS could occur at close ranges (within tens of metres).

The same arguments about temporal and spatial scale of behaviour effects that were made for marine mammals (Section 6.2.1) and applied to fish can also be applied to turtles. Therefore, adverse behavioural effects on turtles caused by the operation of the FPSO facility are expected to be negligible. Although turtles are known to vocalise (Ferrara et al. 2014a, Ferrara et al. 2014b, Guinea et al. 2014), any masking effects will likely be restricted to ranges within hundreds of metres.

Generally, the temporal and spatial scale of behavioural response on turtles would likely be short-term and limited to the localised area surrounding the FPSO facility operations. Because of the small spatial scale of the area of effect, adverse effects on sea turtles caused by exposure to the FPSO facility are expected to be negligible.

6.2.4. Plankton, Fish Eggs, and Fish Larvae

The impacts on these species are expected to be extremely low, with mortality rates caused by exposure to operational sounds being low compared to natural mortality. Any impacts that do occur are likely to only occur in very close proximity (< 5 m) to the FPSO facility, the range at which they are likely to suffer mortality and tissue damage, and the proportion of population that can reasonably be expected to be effected will be miniscule. These impacts are considered to be very small.

6.2.5. Sea Snakes

Sea snakes are unlikely in the operational area, as most sea snakes have shallow benthic feeding patterns and are rarely found in water depths exceeding 30 m (Cogger 1975). However, very little is known about the distribution of the individual species of sea snakes in the region. Given the water depths and distance offshore it is unlikely that sea snakes will be present around the FPSO facility. However, if sea snakes were to be encountered, sound produced by the FPSO facility could cause physiological effects, or recoverable injury, if they are within a planar distance of 10 m, using fish as a surrogate.

6.2.6. Marine Invertebrates

There is no marine invertebrate fishery in the region. A study undertaken by Jacobs (2016) on benthic communities in the Barossa field and surrounds observed that benthic macrofauna groups appeared in relatively low numbers while infaunal communities were characterised by burrowing taxa and were present in low abundance and species diversity. The impact on marine invertebrates is expected to be confined to close to the FPSO facility, and using fish as a surrogate, confined to within a planar distance of 10 m of the facility. The probability of impacts occurring is expected to be small, and overall impacts limited.

6.3. Summary

Direct impacts associated with the proposed FPSO facility due to elevated noise levels are expected to primarily relate to masking the communication of marine mammals. There are not expected to be any ecologically significant impacts on marine mammals, fish, turtles, sea snakes or marine invertebrates.

Glossary

1/3-octave-band
Non-overlapping passbands that are one-third of an octave wide (where an octave is a doubling of frequency). Three adjacent 1/3-octave-bands make up one octave. One-third-octave-bands become wider with increasing frequency. Also see octave.

90%-energy time window
The time interval over which the cumulative energy rises from 5% to 95% of the total pulse energy. This interval contains 90% of the total pulse energy. Symbol: T_{90}.

90% root-mean-square sound pressure level (90% rms SPL)
The root-mean-square sound pressure levels calculated over the 90%-energy time window of a pulse. Used only for pulsed sounds.

attenuation
The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium.

audiogram
A graph of hearing threshold level (sound pressure levels) as a function of frequency, which describes the hearing sensitivity of an animal over its hearing range.

auditory weighting function (frequency-weighting function)
Auditory weighting functions account for marine mammal hearing sensitivity. They are applied to sound measurements to emphasise frequencies that an animal hears well and de-emphasise frequencies they hear less well or not at all (Southall et al. 2007, Finneran and Jenkins 2012, NOAA 2013).

azimuth
A horizontal angle relative to a reference direction, which is often magnetic north or the direction of travel. In navigation it is also called bearing.

bandwidth
The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., seismic airguns, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI/ASA S1.13-2005 R2010).

bar
Unit of pressure equal to 100 kPa, which is approximately equal to the atmospheric pressure on Earth at sea level. 1 bar is equal to $10^{6\ \mathrm{Pa}}$ or $10^{11\ \mu\mathrm{Pa}}$.

cetacean
Any animal in the order Cetacea. These are aquatic, mostly marine mammals and include whales, dolphins, and porpoises.

compressional wave
A mechanical vibration wave in which the direction of particle motion is parallel to the direction of propagation. Also called primary wave or P-wave.

communication space
A communication space assessment considers the region of ocean within which marine fauna can detect calls from conspecifics.

decibel (dB)
One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 R2004).

frequency
The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: *f*. 1 Hz is equal to 1 cycle per second.

functional hearing group
Grouping of marine mammal species with similar estimated hearing ranges. Southall et al. (2007) proposed the following functional hearing groups: low-, mid-, and high-frequency cetaceans, pinnipeds in water, and pinnipeds in air.

geoacoustic
Relating to the acoustic properties of the seabed.

hearing threshold
The sound pressure level that is barely audible for a given individual in the absence of significant background noise during a specific percentage of experimental trials.

hertz (Hz)
A unit of frequency defined as one cycle per second.

high-frequency cetacean
The functional hearing group that represents odontocetes specialised for using high frequencies.

impulsive sound
Sound that is typically brief and intermittent with rapid (within a few seconds) rise time and decay back to ambient levels (NOAA 2013, ANSI S12.7-1986 R2006). For example, seismic airguns and impact pile driving.

listening space
The term listening area, refers to the distance (three dimensionally) over which sources of sound can be detected by an animal at the centre of the space.

low-frequency cetacean
The functional hearing group that represents mysticetes (baleen whales).

mid-frequency cetacean
The functional hearing group that represents some odontocetes (dolphins, toothed whales, beaked whales, and bottlenose whales).

M-weighting
The process of band-pass filtering loud sounds to reduce the importance of inaudible or less-audible frequencies for broad classes of marine mammals. “Generalized frequency weightings for various functional hearing groups of marine mammals, allowing for their functional bandwidths and appropriate in characterizing auditory effects of strong sounds” (Southall et al. 2007).

mysticete
Mysticeti, a suborder of cetaceans, use their baleen plates, rather than teeth, to filter food from water. They are not known to echolocate, but use sound for communication. Members of this group include rorquals (Balaenopteridae), right whales (Balaenidae), and the grey whale (*Eschrichtius robustus*).

non-impulsive sound
Sound that is broadband, narrowband or tonal, brief or prolonged, continuous or intermittent, and typically does not have a high peak pressure with rapid rise time (typically only small fluctuations in decibel level) that impulsive signals have (ANSI/ASA S3.20-1995 R2008). Marine vessels, aircraft, machinery, construction, and vibratory pile driving are examples.

octave
The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

odontocete
The presence of teeth, rather than baleen, characterises these whales. Members of the Odontoceti are a suborder of cetaceans, a group comprised of whales, dolphins, and porpoises. The toothed whales' skulls are mostly asymmetric, an adaptation for their echolocation. This group includes sperm whales, killer whales, belugas, narwhals, dolphins, and porpoises.

parabolic equation method
A computationally-efficient solution to the acoustic wave equation that is used to model transmission loss. The parabolic equation approximation omits effects of back-scattered sound, simplifying the computation of transmission loss. The effect of back-scattered sound is negligible for most ocean-acoustic propagation problems.

peak sound pressure level (peak SPL)
The maximum instantaneous sound pressure level, in a stated frequency band, within a stated period. Also called zero-to-peak sound pressure level. Unit: decibel (dB).

permanent threshold shift (PTS)
A permanent loss of hearing sensitivity caused by excessive noise exposure. PTS is considered auditory injury.

pinniped
A common term used to describe all three groups that form the superfamily Pinnipedia: phocids (true seals or earless seals), otariids (eared seals or fur seals and sea lions), and walrus.

point source
A source that radiates sound as if from a single point (ANSI S1.1-1994 R2004).

power spectrum density
The acoustic signal power per unit frequency as measured at a single frequency. Unit: $\mu Pa^2/Hz$, or $\mu Pa^2 \cdot s$.

power spectrum density level
The decibel level ($10\log_{10}$) of the power spectrum density, usually presented in 1 Hz bins. Unit: dB re 1 $\mu Pa^2/Hz$.

pressure, acoustic
The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: p.

pulsed sound
Discrete sounds with durations less than a few seconds. Sounds with longer durations are called continuous sounds.

received level
The sound level measured at a receiver.

rms
root-mean-square.

rms sound pressure level (SPL)
The root-mean-square average of the instantaneous sound pressure as measured over some specified time interval. For continuous sound, the time interval is one second. Also see sound pressure level (SPL) and 90% rms SPL.

shear wave
A mechanical vibration wave in which the direction of particle motion is perpendicular to the direction of propagation. Also called secondary wave or S-wave. Shear waves propagate only in solid media,

such as sediments or rock. Shear waves in the seabed can be converted to compressional waves in water at the water-seabed interface.

signature
Pressure signal generated by a source.

sound
A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

sound exposure
Time integral of squared, instantaneous frequency-weighted sound pressure over a stated time interval or event. Unit: pascal-squared second ($\text{Pa}^2\cdot\text{s}$) (ANSI S1.1-1994 R2004).

sound exposure level (SEL)
A measure related to the sound energy in one or more pulses. Unit: dB re 1 $\mu\text{Pa}^2\cdot\text{s}$.

sound field
Region containing sound waves (ANSI S1.1-1994 R2004).

sound pressure level (SPL)
The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 R2004).

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 μPa) and the unit for SPL is dB re 1 μPa:

$$\text{SPL} = 10\log_{10}\left(p^2/p_0^2\right) = 20\log_{10}\left(p/p_0\right)$$

Unless otherwise stated, SPL refers to the root-mean-square sound pressure level (rms SPL).

sound speed profile (SSP)
The speed of sound in the water column as a function of depth below the water surface.

source level (SL)
The sound pressure level measured 1 meter from a theoretical point source that radiates the same total sound power as the actual source. Unit: dB re 1 μPa @ 1 m.

spectrum
An acoustic signal represented in terms of its power (or energy) distribution versus frequency.

temporary threshold shift (TTS)
Temporary loss of hearing sensitivity caused by excessive noise exposure.

transmission loss (TL)
Also called propagation loss, this refers to the decibel reduction in sound level between two stated points that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment.

wavelength
Distance over which a wave completes one oscillation cycle. Unit: meter (m). Symbol: λ.

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