TOTAL E&P PNG LIMITED

PAPUA LNG

Upstream Environmental Impact Statement

Volume 3: Technical Studies

Part 1

Underwater Noise Modeling for Impact Assessment

TOTAL

TOTAL E&P PNG LIMITED

ERIAS Group Pty Ltd

Papua LNG Project

Underwater Noise Modeling for Impact Assessment

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1. Introduction

Total E&P PNG Limited (TEP PNG) proposes to develop the Papua Liquefied Natural Gas (LNG) Project (the Project) to commercialize the Elk-Antelope gas reserves within Petroleum Retention License 15 (PRL-15), located in Gulf Province, Papua New Guinea. The Project involves producing and processing the gas and then transporting it via pipeline overland and then offshore through the Gulf of Papua to Caution Bay, Central Province.

The Project will comprise upstream production well development and associated infrastructure at the gas field within PRL-15, construction of an upstream central processing facility (CPF) and delivery of gas and condensate via onshore and offshore export pipelines to new liquefied natural gas (LNG) facilities to be co-located within the existing PNG LNG Facilities at Caution Bay, Central Province, 20 km northwest of Port Moresby. The new LNG facilities at Caution Bay are subject to a separate environment impact statement (EIS) and approvals process. The design life for the Project will be 25 years.

This report presents the method and results of underwater noise modeling undertaken for the Project. This report also presents information on the hearing mechanisms and abilities of aquatic fauna found within the Project area of influence (PAOI) and the basis for the derivation of acoustic threshold criteria to be adopted for the impact assessment. This information will inform the impact assessment presented in the EIS (Volume 1).

2. Hearing Ability of Aquatic Fauna

A review of the scientific literature was undertaken to characterize the hearing sensitivities of key aquatic fauna. The selection of key aquatic fauna is based on sensitive aquatic fauna potentially present in the study area that are summarized in the EIS (Chapters 7 and 8 of Volume 1). Additional information on the distribution of aquatic fauna is extracted from the baseline characterization of freshwater and estuarine biodiversity (Volume 2, Part 5) and marine biodiversity (Volume 2, Part 12) of the EIS.

2.1 Hearing in Cetaceans

Table 1 gives the hearing frequency ranges for cetaceans, some of which may be expected to occur in the PAOI. Most of the frequency ranges listed in Table 1 represent the range of frequencies in which these cetacean species vocalise and communicate. The higher frequency range (0.5 kHz to 130 kHz) of the large toothed whales also reflects their echolocation frequencies.

Table 1 – Hearing Frequency Ranges for Selected Large Cetacean Species

Common name	Scientific name	Frequency range
Baleen whales (Mysticeti):		
Humpback whale	*Megaptera novaeangliae*	20 Hz to 10 kHz
Blue whale	*Balaenoptera musculus*	12 Hz to 31 kHz
Bryde's whale	*Balaenoptera edeni*	70 Hz to 950 Hz
Gray whale	*Eschrichtius robustus*	20 Hz to 2 kHz
Dwarf Minke whale	*Balaenoptera acutorostrata*	60 Hz to 20 kHz

Table 1 – Hearing Frequency Ranges for Selected Large Cetacean Species (cont'd)

Common name	Scientific name	Frequency range
Baleen whales (Mysticeti) (cont'd)		
Sei whale	*Balaenoptera borealis*	1.5 kHz to 3.5 kHz
Fin whale	*Balaenoptera physalus*	14 Hz to 28 kHz
Toothed Whales and Dolphins (Odontoceti):		
Killer whale	*Orcinus orca*	0.5 kHz to 120 kHz
False killer whale	*Pseudorca crassidens*	1.1 kHz to 130 kHz
Bottlenose dolphin	*Tursiops truncatus*	40 Hz to 150 kHz
Spotted dolphin	*Stenella attenuata*	3.1 kHz to 21.4 kHz
Spinner dolphin	*Stenella longirostris*	1 kHz to 65 kHz
Risso's dolphin	*Grampus griseus*	80 Hz to 100 kHz

Source: Howorth (2003).

The upper limits of the hearing range for toothed whales and dolphins in Table 1 include the ultrasonic frequencies used by species that use echolocation.

2.2 Hearing in Dugongs

Hearing mechanisms and audiograms of sirenians has been poorly studied; however, more information has been provided for manatees than for dugongs. Notwithstanding, the hearing abilities of manatees and dugongs are assumed to be similar. Dugongs have no external pinnae (ear flaps) and the ear openings are small. Dugongs appear to vocalize more often than the manatees (Frankel, 2018).

Table 2 summarizes the hearing and vocalization frequencies of manatees and dugongs based on a literature review.

Table 2 – Hearing and Vocalization Frequency Ranges of Manatees and Dugongs

Species	Scientific Name	Hearing Range	Vocalization Range	Reference
Manatees				
West Indian manatee	*Trichechus manatus*	600 Hz to 5 kHz	Data not available	Reynolds and Rommel (1999)
West Indian manatee	*Trichechus manatus*	400 Hz to 46 kHz (best sensitivity 16 to 18 kHz)	Data not available	Nowacek et al. (2003); Phillips et al. (2004)
West Indian manatee	*Trichechus manatus*	1 kHz to 1.5 kHz	Data not available	Bullock et al. (1982)
Antillean manatee	*Trichechus manatus manatus*	300 Hz to 90 kHz	Data not available	Rivera-Chavarria et al. (2015)
Amazonian manatee	*Trichechus inunguis*	Data not available	600 Hz to 10 kHz (Stress calls up to 35 kHz	Reynolds and Rommel (1999)
Dugongs				
Dugong	*Dugong dugon*	400 Hz to 46 kHz	Data not available	Zeh et al. (2015)
Dugong	*Dugong dugon*	Data not available	500 Hz to 18 kHz (peak range 1 and 8 kHz	Anderson and Barclay (1995); Frankel (2018)

Dugong	*Dugong dugon*	Data not available	Chirp squeaks (3 to 18 kHz)	Anderson and Barclay (1995); Frankel (2018)
Dugong	*Dugong dugon*	Data not available	Barks (500 Hz to 2.2 kHz)	Anderson and Barclay (1995); Frankel (2018)

Dugongs produce three major sound types: chirp squeaks between 3 and 18 kHz, barks between 500 Hz and 2.2 kHz, and trills between 3.1 kHz and 3.9 kHz (Anderson and Barclay, 1995; Frankel, 2018). Since dugong hearing will be attuned to their vocalization calls, dugong hearing frequency range would be expected to be between 500 Hz and 18 kHz, which reflects the range of vocalization frequencies. The source levels of these different call types ranges from 135 to 158 dB re 1 µPa at 1 m (Parsons et al., 2013).

2.3 Hearing in Fish

Marine and freshwater fish tend to only respond consistently to sounds and vibrations of either very low or very high frequencies (Knudsen et al., 1994; Nestler et al., 1992) and sounds in the mid-frequency range (50 Hz to 2 kHz) generally produce only short-term startle responses at the onset of the sound (Knudsen et al., 1994; Westerberg, 1995).

Sound energy propagates from a source as both particle motion and sound pressure. Particle motion is the primary component of near-field low frequency (100 Hz to 1 kHz) sound, whereas sound pressure is the primary component of far-field higher frequency (greater than 1 kHz) sound (Popper and Fay, 2011). Particle motion is a vector quantity with both magnitude and direction and is measured by oscillatory displacement (m), velocity (m/s) or acceleration (m/s^2) of fluid particles in a sound field (Popper et al., 2014). All fish can detect ('feel') particle motion along their lateral line system where hair cells (neuroblasts) receive low-frequency sound waves and send nerve impulses to the brain.

Beside the generic ability to sense particle motion, most fish are also sensitive to sound pressure via otoliths in their ears, while some fish are also able to detect sound pressure via the swim (or gas) bladder or other gas-filled structure, which relays sound energy in the form of particle motion to the otoliths of the ear (Popper et al., 2014). The hearing mechanisms and audiograms for various species of fish have been relatively well researched and hearing ability varies. Most fish species detect sounds from below 50 Hz up to 1,500 Hz. A smaller number of species can detect sounds to over 3 kHz, while a very few species can detect sounds to well over 100 kHz (Popper and Hastings, 2009).

The hearing abilities and sensitivities of fish vary depending on whether they are bony fish (Osteichthyes) or cartilaginous fish (Chondrichthyes), which are described in more detail in the following sections.

2.3.1 Bony Fish (Osteichthyes)

Hearing in bony fish (Osteichthyes) may be generally divided into two categories; namely, a) hearing generalists and b) hearing specialists (Popper, 2012). Distinctions between the groups are based on whether the species has specialised organs for improving sound reception. Hearing generalists hear within a narrow bandwidth and are sensitive to particle motion and, therefore, typically do not show a significant response to sound pressure levels. In contrast, hearing specialists have well-developed sound pressure sensitivity and relatively low hearing thresholds.

Their sensitivity is related in part to the fact that they have anatomical connections between their inner ear and swim or gas bladder or other gas-filled structures. The swim bladder is a gas-filled sac located in the dorsal portion of certain species of fish, which is vulnerable to underwater acoustic pressure. It has flexible walls that contract or expand according to the ambient pressure.

According to Popper and Hastings (2009), hearing specialists include all the Otophysi (e.g., catfishes) and Clupeiformes (e.g., anchovies, herrings, and sardines), Perciformes (e.g., tuna and sciaenid drums and croakers) and Beryciformes (e.g., holocentrids such as squirrelfish). Clupeiformes have specialised auditory systems that include a structure called the prootic bulla (a gas-containing sphere evolved from the bones of the ear capsule [Blaxter, 1980; Nedwell et al., 2004]). A membrane divides the bulla into an upper part containing fluid and a lower part containing gas. Movements of the prootic bulla stimulate both the utricular macula (pouch in the floor of the utricule [otolith organ] that receives the utricular nerve) and the lateral line, improving sound receptivity (McCauley and Salgado-Kent, 2008). Fish with the prootic bulla generally have higher sensitivity than those with a swim bladder, and those with a swim bladder usually have greater sensitivity than non-specialists with no swim bladder (Nedwell et al., 2004).

Popper (2012) divided fish into the following four groups based on hearing abilities:

Group 1: Fish that do not have a swim bladder.

- These fish are likely to use only particle motion for sound detection. The highest frequency of hearing is likely to be no greater than 400 Hz, with poor sensitivity compared to fish with a swim bladder. Fish within this group would include flatfish, some gobies, some species of tuna, and all elasmobranchs (i.e., sharks, skates and rays).

Group 2: Fish that detect sounds from below 50 Hz and up to perhaps 800 to 1,000 Hz (though several probably only detect sounds to 600 to 800 Hz).

- These fish have a swim bladder but no known structures in the auditory system that would enhance hearing, and sensitivity (lowest sound detectable at any frequency) is therefore considered to be poor. Sounds would have to be more intense to be detected when compared to fishes in Group 3 (described below).

Group 3: Fish that have some kind of structure that mechanically couples the inner ear to the swim bladder (or other gas bubble), thereby resulting in detection of a wider bandwidth of sounds and lower intensities than fish in other groups.

- These fish detect sounds to 3,000 Hz or more, and their hearing sensitivity, which is pressure driven, is better than in fish of Groups 1 and 2. There are not many marine species known to fit within Group 3, but this group may include some species of sciaenids (drummers and croakers). It is also possible that a number of deep-sea species fall within this category, but that is only based on morphology of the auditory system. Other members of this group would include all of the Otophysi fish, though few of these species other than catfishes are found in marine waters.

Group 4: All of these fish are members of the herring family and relatives (Clupeiformes).

- These fish hear sounds below 1,000 Hz in a similar manner to fish in Group 1, but their hearing range extends up to at least 4,000 Hz (e.g., sardines), and some species (e.g., American shad) are able to detect sounds to over 180 kHz (Mann et al., 2001).

Bony fish with thin-walled, lightly damped and large swim bladders with a resonant frequency near 100 Hz may be most susceptible to mechanical damage or trauma from underwater noise (Hastings and Popper, 2005; Popper and Hastings, 2009). Other bony fish, such as scombrids (mackerels and tuna) and many of the flatfishes such as pleuronectids (flounders) and soleids (soles) do not possess a swim bladder and so are not susceptible to swim bladder-induced trauma (McCauley, 1994). Unlike some scombrids, yellowfin tuna (*Thunnus albacares*), which occurs in the Project area, do have swim bladders (Allen and Demer, 2003).

2.3.2 Cartilaginous Fish (Chondrichthyes)

Cartilaginous fish (Chondrichthyes), such as sharks, skates and rays, only possess inner ear labyrinths, which allows them to detect particle motion (Myrberg, 2001). They have no accessory organs of hearing often found in bony fishes, such as a swim bladder or bony connections between the swim bladder and the labyrinths (Amundsen and Landrø, 2011), or gas-filled spheres (prootic bulla) as in clupeid fish (e.g., herring, anchovies, pilchards and sprats).

Studies of the hearing abilities of sharks have demonstrated highest sensitivity to low frequency sound between 40 Hz and 800 Hz, which is sensed solely through the particle motion component of an acoustical field (Myrberg, 2001).

Casper et al. (2003) showed that the hearing sensitivities of four species of skate (Rajidae) were between 200 and 800 Hz, with the most sensitive hearing between 200 Hz and 300 Hz. Pelagic cartilaginous fish are hypothesised by Casper et al. (2003) to have more sensitive hearing than bottom-living cartilaginous fish such as skates.

Free-ranging sharks are also attracted to sounds possessing specific characteristics, such as irregularly pulsed and broadband tones, with the most attractive frequencies below 80 Hz (Myrberg, 2001).

2.4 Hearing in Turtles

Both sea and freshwater turtles occur within the PAOI; therefore, the hearing abilities of both types have been considered in the following sections.

2.4.1 Sea Turtles

Sea turtle hearing ability is not well studied. A few preliminary investigations using adult green (*Chelonia mydas*), loggerhead (*Caretta caretta*), and Kemp's ridley (*Lepidochelys kempi*) turtles suggest that they are most sensitive to low-frequency sounds (Ridgway et al., 1969; Lenhardt et al., 1983; Moein-Bartol et al., 1995). Bone-conducted hearing appears to be a reception mechanism for at least some of the sea turtle species (except the leatherback turtle), with the skull and shell acting as receiving structures (Lenhardt et al., 1983).

Sea turtles have a relatively weak vocalization ability and mostly in the range 100 to 700 Hz (Richardson et al., 1995). Ridgway et al. (1969) used aerial and vibrational stimuli on green turtles and showed that they detected limited sound frequencies (200 to 700 Hz) with a high level of sensitivity at about 400 Hz. Yudhana et al. (2010) experimentally determined that juvenile green

turtles have a slightly broader hearing range (100 to 800 Hz with a peak sensitivity between 600 and 700 Hz) than sub-adults (range 100 to 500 Hz); however, many of these studies were conducted in air.

Piniak et al. (2016) assessed both underwater and aerial hearing sensitivities in five green turtle juveniles by measuring auditory evoked potential responses to tone pip stimuli. In water, green turtles detected acoustic stimuli between 50 and 1,600 Hz with maximum sensitivity between 200 and 400 Hz, whereas green turtles detected aerial stimuli between 50 and 800 Hz, with a maximum sensitivity of between 300 and 400 Hz in air. When underwater and aerial hearing sensitivities were compared in terms of pressure, green turtle aerial sound pressure thresholds were lower than underwater thresholds; however, they detected a wider range of frequencies underwater. When thresholds were compared in terms of sound intensity, green turtle sound intensity level thresholds were 2 to 39 dB lower underwater, particularly at frequencies below 400 Hz.

2.4.2 Freshwater Turtles

Freshwater turtles were thought to be 'silent reptiles', neither vocalizing nor hearing very well; however, Wever (1978) report that freshwater turtles have a peak sensitivity between 1,000 and 1,500 Hz and South American river turtles (*Podocnemis expansa*) can vocalize between 30 Hz and 6 kHz (Ferrara et al., 2012).

2.5 Hearing in Crocodiles

Crocodiles have a complex of bony air-filled passages and a branching eustachian tube[1] (Kaplan, 2014). This high degree of development of the middle and inner ears indicates the effectiveness of crocodilian hearing over a wide range of frequencies between 100 Hz and 6 kHz (IUCN, 2019).

2.5.1 Saltwater (Estuarine) Crocodiles

Crocodiles produce sound such as bellows, roars, head or jaw slaps and infrasound pulses, which are important components of crocodilian behavior (Dinets, 2013). Saltwater or estuarine crocodiles (*Crocodylus porosus*) are known to respond to low frequency sounds in the 50 to 1,500 Hz range (Kaplan, 2014). In addition to their hearing system, they have apical pits on the scales of their face and bodies that are sensitive to vibrations travelling through water (Kaplan, 2014).

2.5.2 New Guinea Freshwater Crocodiles

Little is known of the hearing ability of the New Guinea freshwater crocodile (*Crocodylus novaeguineae*). Therefore, a literature review of hearing in other freshwater crocodilians was undertaken.

Caimans and alligators also produce sound such as bellows, roars, head or jaw slaps and infrasound pulses, which are important in their long-distance communications (Dinets, 2013). The spectacled caiman (*Caiman crocodilus*) show best hearing sensitivity between 300 and 2,000 Hz,

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[1] Tube connecting the palate to the middle ear of a crocodile.

[2] While the baseline accumulation period of 24 hours is recommended by NMFS (2018), they acknowledge that there may be specific exposure situations where this accumulation period requires adjustment (e.g., if an

but sensitivity falls off progressively for lower tones and especially higher tones (Wever, 1978). Similarly, in the American alligator (*Alligator mississipiensis*) the best hearing sensitivity was between 100 and 1,000 Hz, and again there was a decline in sensitivity for lower tones and especially for tones above 3000 Hz (Wever, 1978. These hearing sensitivity ranges are similar to that of the saltwater crocodile (10 to 1,500 Hz); however, differences in sensitivity may be expected for the New Guinea freshwater crocodile, since the separation of alligatorid (caimans and alligators) and crocodile (crocodiles) lineages happened during the Cretaceous period (Senter, 2008). In the absence of hearing sensitivity for freshwater crocodiles, the best hearing sensitivity range of 50 to 1,500 Hz for saltwater crocodiles has also been adopted for the New Guinea freshwater crocodile for the purposes of the present report.

3. Acoustic Threshold Criteria for Aquatic Fauna

There are no explicit underwater noise acoustic threshold criteria or guidelines for aquatic fauna in Papua New Guinea. Therefore, a literature search was conducted to collate overseas underwater noise level criteria for the protection of noise-sensitive aquatic fauna such as those described in Chapter 2. The assessment criteria adopted in this chapter are based on peer-reviewed and widely accepted literature. Where acoustic threshold criteria for aquatic fauna were not available, a literature review was undertaken to identify the distances at which noise-sensitive aquatic fauna may show behavioral reaction to various identified noise sources and the received sound pressure or sound exposure levels that initiated the reaction.

The key underwater acoustic units used in the presentation of acoustic threshold criteria and the modeling results are explained below:

- Sound pressure level (SPL) root mean square (rms) expressed in units of dB re 1μPa_{rms}. The rms pressure is the decibel value of the root mean of the squared pressure over a defined period of a signal.
- Sound pressure level zero-to-peak expressed in units of dB re 1μPa_{Pk}. Peak pressure represents the maximum pressure recorded and is measured from the mean of the signal to the maximum excursion from the mean.
- Sound pressure level peak-to-peak units of dB re 1 $\mu Pa_{pk\text{-}pk}$, which is the algebraic difference between the maximum positive and maximum negative instantaneous peak pressure.
- Sound exposure level (SEL) expressed in units of dB re 1 μPa^2•s. SEL is a measure of energy with the dB level of the time integral of the squared-instantaneous sound pressure normalized to a one-second period.
- Cumulative sound exposure level (SEL_{cum}) expressed in units dB re 1 μPa^2•s. Sound exposure level is the same as SEL above but the subscript ‘cum’ indicates the designated

marine mammal auditory weighting function for low-frequency, mid-frequency and high-frequency cetaceans and that the recommended accumulation period is 24 hours[2].

Further description of acoustic metrics is provided in Section 8.7 of Volume 1 and, in more detail, in Attachment 8.1 (Volume 1).

The principal fauna groups for which acoustic threshold criteria have been formulated are cetaceans, (whales and dolphins), dugongs, bony fish (with and without air bladders), sea and freshwater turtles, and crocodiles. These criteria are discussed in more detail in the following sections.

3.1 Cetaceans

There are no acoustic threshold criteria or guidelines for cetaceans published in Papua New Guinea; therefore, international acoustic threshold criteria and guidelines were reviewed to derive and collate acoustic threshold criteria to be used in the impact assessment (Volume 1).

3.1.1 International Acoustic Threshold Criteria

In Australia, the Commonwealth of Australia *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) does not specifically mention underwater noise impact criteria; however, an underwater noise-related policy statement associated with the act is the EPBC Act Policy Statement 2.1–Interaction between offshore seismic exploration and whales (DEWHA, 2008). The aim of the policy statement is to:

- Provide practical standards to minimize the risk of acoustic injury to whales in the vicinity of seismic survey operations.
- Provide a framework that minimizes the risk of biological consequences from acoustic disturbance from seismic survey sources to whales in biologically important habitat areas or during critical behaviors.
- Provide guidance to both proponents of seismic surveys and operators conducting seismic surveys about their legal responsibilities under the EPBC Act.

The EPBC Act Policy Statement 2.1 guidelines are based on acoustic damage and acoustic disturbance of whales if exposed to marine seismic surveys (towed airgun arrays), which are representative of loud, high-energy impulsive underwater noise sources. The received sound acoustic threshold criteria that are presented in DEWHA (2008), which were developed by McCauley et al. (2000a) and Environment Australia (2001), are:

- Received SPL of 180 dB re 1 μPa_{rms} for acoustic damage such as injury, tissue or auditory damage, and permanent threshold shift (PTS) onset (an irreversible reduction in hearing sensitivity).

[2] While the baseline accumulation period of 24 hours is recommended by NMFS (2018), they acknowledge that there may be specific exposure situations where this accumulation period requires adjustment (e.g., if an activity lasts less than 24 hours or for situations where receivers are predicted to experience unusually long exposure durations).

- Received SPL of 160 dB re 1 μPa_{rms} for acoustic disturbance such as disruptive behavioral changes (e.g., changes in breathing and diving rates, startle responses and long term avoidance) and temporary threshold shift (TTS) onset (a reversible reduction in hearing sensitivity with full recovery of hearing after exposure).

The literature search revealed that a number of regulatory agencies and researchers identify a received SPL threshold level of 120 dB re 1 μPa_{rms} for non-impulsive, continuous broadband noise as a minimum level at which slight disturbance to whales may occur. For example, the following references refer to the use of this lower 120 dB re 1 μPa_{rms} acoustic threshold criterion:

- Southall et al. (2007) suggests moderate level changes in behavior by humpback whales to non-impulsive, continuous broadband noise at received levels above 120 dB re 1 μPa_{rms} and below 150 dB re 1μPa_{rms}.
- The U.S. National Marine Fisheries Service (NMFS) recognizes 120 dB re 1 μPa_{rms} as the received SPL for behavioral disturbance harassment (Level B Criterion) from a continuous noise source (NMFS, 2018).
- McCauley and Duncan (2008) consider that 120 dB re 1 μPa_{rms} is the level at which baleen whales will largely avoid an area due to continuous broadband underwater noise; although, some individuals may tolerate higher levels for short periods.

3.1.2 Adopted Criteria

For the purposes of this assessment, the acoustic threshold of 120 dB re 1 μPa_{rms} has been adopted as the lower threshold above which potential acoustic disturbance to baleen whales (e.g., humpback whales) by non-impulsive, continuous broadband noise may be expected to occur. Table 3 presents a summary of adopted acoustic threshold criteria used in this assessment.

Table 3 – Adopted Acoustic Threshold Criteria for Cetaceans

Acoustic Impact	Acoustic Threshold Criterion (dB re 1μPa_{rms})	Reference
High-level behavioral reaction to impulsive noise and potential permanent physiological auditory damage (i.e., irreversible reduction in hearing sensitivity).	180	McCauley et al. (2000a); Environment Australia; (2001) and DEWHA (2008).
Moderate-level behavioral reaction to impulsive noise and potential temporary physiological auditory damage (i.e., reversible reduction in hearing sensitivity with full recovery after exposure).	160	McCauley et al. (2000a). Environment Australia; (2001) and DEWHA (2008).
Moderate-level behavioral reaction to non-impulsive, continuous broadband noise but with no physiological auditory damage.	120	McCauley et al. (2000a); Environment Australia; (2001), Southall et al., (2007), DEWHA (2008) and NMFS (2018).

International acoustic threshold criteria relevant to cetacean hearing have also been established for both non-impulsive and impulsive noise (NMFS, 2018; Finneran, 2016). Acoustic damage impacts to cetaceans relates to potential irreversible tissue damage (i.e., the onset of PTS). At some level and duration, sound can cause hair cells of the inner ear to fatigue, yielding an

increase in auditory threshold by an amount called the TTS. The sound level at which the TTS occurs depends on many factors, including noise spectral content, level, exposure duration, time after noise exposure, continuous or intermittent manner of exposure, and the subject cetacean. After some quiet time (minutes to days), TTS is reversible and hearing returns to pre-disturbance 'normal' levels within a few hours or days after exposure (Erbe et al., 2011).

Table 4 provides the most recent peer-reviewed non-impulsive PTS and TTS onset acoustic threshold criteria for low frequency, mid-frequency and high frequency hearing cetaceans (NMFS, 2018).

Table 4 – Non-impulsive Noise Acoustic Threshold Criteria for Cetaceans

Hearing Group	Hearing Range (frequency)	Non-impulsive Sound Exposure Level (SEL) (dB re 1 μPa^2•s)	
		Permanent Threshold Shift	Temporary Threshold Shift
Low frequency hearing cetaceans (baleen whales)	7 Hz to 35 kHz	199	179
Mid-frequency hearing cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)	150 Hz to 160 kHz	198	178
High frequency hearing cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger and L. australis*)	275 Hz to 160 kHz	173	153

Source: NMFS (2018); Finneran (2016).

The PTS and TTS threshold SEL values in Table 4 have been adopted in this report for subsequent assessments of Project-related non-impulsive underwater noise impacts to cetaceans.

Impulsive underwater noise will be generated in the marine environment by sheet pile driving at the shore crossing of the export pipeline corridor. Table 5 presents dual impulsive noise threshold criteria for the onset of PTS and TTS in low frequency, mid-frequency and high frequency hearing cetaceans.

Table 5 – Summary of Adopted Impulsive Noise Acoustic Threshold Criteria for Cetaceans

Hearing Group*	Hearing Range (frequency)	Permanent Threshold Shift		Temporary Threshold Shift	
		SEL	SPL_{pk}	SEL	SPL_{pk}
		dB re 1μPa^2•s	dB re 1μPa_{rms}	dB re 1μPa^2•s	dB re 1μPa_{rms}
Low frequency hearing cetaceans (baleen whales)	7 Hz to 35 kHz	183	219	168	213

Table 5 – Summary of Adopted Impulsive Noise Acoustic Threshold Criteria for Cetaceans (cont'd)

Hearing Group*	Hearing Range (frequency)	Permanent Threshold Shift		Temporary Threshold Shift	
		SEL	SPL_{pk}	SEL	SPL_{pk}
		dB re 1µPa²•s	dB re 1µPa_{rms}	dB re 1µPa²•s	dB re 1µPa_{rms}
Mid-frequency hearing cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)	150 Hz to 160 kHz	185	230	170	224
High frequency hearing cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger and L. australis*)	275 Hz to 160 kHz	155	202	140	196

Source: NMFS (2018). SEL threshold criteria include a marine mammal auditory weighting (Finneran, 2016). SPL_{pk} is peak SPL.

The dual PTS and TTS threshold values (SEL and SPL_{pk}) in Table 5 have been adopted in this report for subsequent assessments of Project-related impulsive underwater noise impacts (e.g., impact pile driving) to cetaceans.

3.2 Dugongs

A review of the literature for acoustic damage threshold criteria for sirenians (manatees and dugongs) found impulsive noise acoustic threshold criteria for PTS onset are a peak SPL of 226 dB re 1 μPa_{pk} and a weighted SEL of 190 dB re 1 μPa^2•s and acoustic threshold criteria for TTS onset are 220 dB re 1 μPa_{pk} and a weighted SEL of 175 dB re 1 μPa^2•s (Finneran, 2016).

A literature review did not reveal any peer-reviewed acoustic threshold criteria for behavioral effects on dugongs. Dugong hearing range appears to be most sensitive in the middle frequencies (between 1 and 18 kHz [URS, 2004]).

McPherson et al. (2017) noted that published curves of underwater audiograms for sirenians (dugongs and manatees), odontocetes (toothed whales and dolphins), and pinnipeds (seals and sea lions) illustrated similar trends in hearing sensitivity. Based on these similarities among marine mammal audiogram curves, Erbe et al. (2011) and McPherson et al. (2017) consider it reasonable to assume that dugong hearing also falls somewhere between pinnipeds and cetaceans. Until further studies are conducted, McPherson et al. (2017) consider that impact assessments should make conservative assumptions such as using a combination of low and mid-frequency cetacean acoustic threshold criteria.

3.2.1 Adopted Criteria

In the absence of dugong-specific acoustic threshold criteria for behavioral disturbance, the Australian non-impulsive noise threshold criterion of 120 dB re 1µPa_{rms} for behavioral disturbance to cetaceans to underwater noise shown in Table 3 has been adopted and is considered applicable to dugongs.

Based on Finneran (2016), the impulsive noise acoustic threshold criteria for PTS onset of a peak SPL of 226 dB re 1 µPa_{pk} or a weighted SEL of 190 dB re 1 µPa^2•s, and for TTS onset a peak SPL of 220 dB re 1 µPa_{pk} or a weighted SEL of 175 dB re 1 µPa^2•s, has been adopted in this assessment.

3.3 Fish

A literature review was carried out to identify and collate international underwater acoustic threshold criteria for fish, representative of the types found in Papua New Guinea. The results indicated that acoustic threshold criteria have only been formulated for bony fish (Osteichthyes). Cartilaginous fish (Chondrichthyes) have no accessory organs of hearing often found in bony fishes, such as a swim bladder or bony connections between the swim bladder and the labyrinths (Amundsen and Landrø, 2011), and they only respond to particle motion and vibration (Myrberg, 2001).

Most of the peer-reviewed literature about the effects of underwater noise and vibrations on fish are based on caged fish or fish exposed under laboratory conditions, which typically do not represent unconstrained free-ranging fish in their natural habitats. Caged experiments do not differentiate between received sound pressure and particle motion (vibration) in such confined conditions (e.g., aquaria).

As described in Section 2, Hastings and Popper (2005) classified fish as belonging to either of two hearing groups based on their hearing frequency ranges:

- Hearing generalists (or non-specialists): hearing range between 50 Hz and 1,500 Hz.
- Hearing specialists: hearing range between 50 Hz and 100 kHz.

Most fish are classified as ‘hearing generalists’ and do not have specializations to enhance hearing and principally detect the particle motion component of the sound field. The ‘hearing specialists’ have a greater hearing bandwidth and sensitivity due to a coupling between gas filled organs (such as the swim bladder) and inner ear (Hastings and Popper, 2005).

3.3.1 Bony Fish (Osteichthyes)

Underwater noise level threshold criteria for bony fish (Osteichthyes) have been developed in recent studies (e.g., Halvorsen et al., 2012a,b; Casper et al., 2012a,b; Casper et al., 2013a,b). Current threshold criteria for onset of physiological effects (e.g., TTS onset) are:

- Peak sound pressure level (SPL_{pk}):
  - 206 dB re 1 µPa_{pk} for fish of all weights.
- Cumulative sound exposure level (SEL_{cum}):
  - 203 dB re 1µPa^2•s for fish of all weights.

The peak SPL value of 206 dB re 1 μPa_{pk} is based on interim criteria originally developed by FHWG (2008) and has been retained by subsequent authors as it was based on experiments with caged fish. This value may be overly conservative when applied to unconstrained, free-ranging bony fish, which are capable of avoiding underwater acoustic gradients. The above two criteria have been adopted in this report and represent a dual approach to assessing potential Project-generated impulsive noise impacts to bony fish.

In general, there are no underwater noise level criteria that are promulgated to minimize acoustic disturbance to fish; however, WSDOT (2019) suggested an acoustic disturbance criterion of 150 dB re 1 μPa_{rms} for all marine fish, which was based on impulsive noise (e.g., pile driving).

3.3.1.1 Adopted Criteria

Table 6 presents a summary of adopted acoustic threshold criteria for bony fish. For the purposes of this report, an acoustic disturbance criterion of 150 dB re 1 μPa_{rms} has been adopted as a threshold criterion for both non-impulsive and impulsive noise. Above this threshold, acoustic disturbance of bony fish may be expected.

Table 6 – Summary of Adopted Acoustic Threshold Criteria for Bony Fish

Acoustic Impact	Acoustic Threshold Criterion	References
Fish injury thresholds and onset of PTS	Received peak SPL of 206 dB re 1 μPa_{pk} rms	Halvorsen et al. (2012a,b); Casper et al. (2012a,b); Casper et al. (2013a,b).
	Cumulative Sound Exposure Level (SEL) of 203 dB re 1 $\mu Pa^2 \cdot s$	
Behavioral disturbance	150 dB re 1 μPa_{rms}	WSDOT (2019)

3.3.2 Cartilaginous Fish (Chondrichthyes)

Cartilaginous fish, such as sharks, skates and rays, possess inner ear labyrinths that allow them to detect particle motion rather than sound pressure (Myrberg, 2001). A literature review did not reveal any peer-reviewed acoustic threshold criteria for particle motion or vibration for cartilaginous fish. Notwithstanding, the literature review identified and collated observed behavioral effects of anthropogenic noise on cartilaginous fish (e.g., distances at which effects may be observed).

Ryan et al. (2018) presented artificial sounds of varying frequencies (from 20 Hz to 20 kHz) and intensities (SPL 114 to 157 dB re 1 µPa) to captive Port Jackson (*Heterodontus portusjacksoni*) and epaulette (*Hemiscyllium ocellatum*) sharks, and to wild white sharks (*Carcharodon carcharias*). The artificial sound playback did not directly elicit any changes in the feeding behavior of these species.

In a more recent field study, Chapuis et al. (2019) employed a baited underwater camera rig to record the behavioral responses of eight species of sharks (seven reef and coastal shark species) and the white shark (*Carcharodon carcharias*) to playbacks of two distinct sound stimuli in the wild; an orca (*Orca orcinus*) call sequence and an artificially generated sound. When the sounds were played continuously, reef and coastal sharks were less numerous in the immediate area of the sound source (i.e., the near field), had fewer interactions with the baited test rigs and displayed less inquisitive behavior, compared to silent control trials. No behavioral effects on the white shark were noted. In addition, Chapuis et al. (2019) noted that some sharks changed their behavior in response to relatively low sound pressure levels (e.g., 150 dB re 1 μPa_{rms} at a

distance of 2 m from the artificial sound source. This confirms that sharks do respond to sound pressure or particle motion within the near field of sound sources. However, there is contradictory evidence that sharks can also sense sound in the far field as there are published accounts of sharks being attracted by sounds (e.g., prey, boats, and swimmers) from hundreds of meters away (Wisby and Nelson, 1964; Myrberg et al., 1972).

3.3.2.1 Adopted Criteria

In the absence of peer-reviewed acoustic threshold criteria for cartilaginous fish and based on recent studies by Chapuis et al. (2019), an acoustic threshold criterion of 150 dB re 1 μPa_{rms} has been adopted as a level above which behavioral disturbance of cartilaginous fish may occur in the near field surrounding a Project noise source.

3.4 Turtles

Both sea turtles and freshwater turtles are present in the PAOI. A literature review was undertaken to collate published or peer-reviewed acoustic threshold criteria or guidelines for marine and freshwater turtles.

3.4.1 Sea Turtles

Sea turtle hearing sensitivity has been scantily investigated and a literature review did not reveal any published acoustic damage or acoustic disturbance threshold criteria for unconstrained, free-ranging sea turtles in coastal or offshore areas.

Gavrilov et al. (2016) reviewed information from Popper et al. (2006) and noted that peak SPLs of between 208 dB re 1 μPa_{pk} and 222 dB re 1 μPa_{pk} have the potential to cause physical injury in adult sand turtle hatchlings. In the absence of peer-reviewed acoustic damage threshold criteria for adult sea turtles, a peak SPL of 208 dB re 1 μPa_{pk} has been adopted in this report as a level above which injury or tissues damage to sea turtles may occur.

In terms of acoustic disturbance acoustic threshold criteria, McCauley et al. (2000a,b) conducted a trial on a caged green and a loggerhead turtle with an airgun. This study found that above a received SPL of 166 dB re 1 μPa_{rms} both turtles increased their swimming activity noticeably compared to non-airgun operations. Above a received level of 175 dB re 1 μPa_{rms} their behavior became erratic, which was concluded by the authors to be approximately equal to the point at which unrestrained turtles may show avoidance behavior.

3.4.1.1 Adopted Criteria

For the purposes of impact assessment, a received SPL of 175 dB re 1 μPa_{rms} has been adopted as an acoustic threshold criterion, above which behavioral effects in non-constrained free-ranging sea turtles may be expected to occur. Table 7 provides the adopted acoustic damage and acoustic disturbance threshold criteria for sea turtles.

Table 7 – Summary of Adopted Acoustic Threshold Criteria for Sea Turtles

Acoustic Impact	Acoustic Threshold Criterion	References
Sea turtle physical injury and onset of PTS	Received peak SPL of 208 dB re 1 μPa_{pk}	Gavrilov et al. (2016) and Popper et al. (2006)
Behavioral disturbance (swimming speed and behavior becomes increasingly erratic with avoidance probable)	Received average SPL of 175 dB re 1 μPa_{rms}	McCauley et al. (2000a)

3.4.2 Freshwater Turtles

No acoustic threshold criteria were found in the scientific literature for freshwater turtles. Therefore, the acoustic threshold criteria for sea turtles (see Table 7) have also been adopted for freshwater turtles, which may be expected to have similar auditory responses to underwater noise.

3.5 Crocodiles

Review of the literature did not reveal any acoustic threshold criteria for crocodiles. Therefore, for the purposes of impact assessment, the acoustic thresholds for sea turtles (see Table 7) have been adopted for estuarine and freshwater crocodiles given that they are also aquatic reptiles and may be expected to have similar auditory responses to underwater noise.

3.5.1 Adopted Criteria

The received peak SPL of 208 dB re 1 μPa_{pk} for sea turtles has been adopted as an acoustic threshold criterion above which acoustic damage and PTS onset in crocodiles may be expected. The received SPL of 175 dB re 1 μPa_{rms} for sea turtles has been adopted as an acoustic threshold criterion above which behavioral effects in non-constrained, free ranging freshwater and estuarine crocodiles may be expected to occur. This crocodilian acoustic disturbance threshold is considered conservative since, unlike sea or freshwater turtles, crocodiles have earflaps that they close when entering water or when submerged, which would reduce underwater noise entering their ear canals.

4. Results of Underwater Noise Modeling

This chapter provides details of the calculations of underwater noise attenuation using transmission loss equations considering typical noise source levels of Project activities. These calculations have been used to predict distances to nominal isopleths (i.e., lines of equal sound pressure) representing acoustic damage or acoustic disturbance criteria or levels for potential effects on aquatic fauna. This information has been used to inform the residual impact assessment presented in the EIS (Volume 1).

The proposed construction activities at the Logistics Base includes:

- Construction of a platform for buildings, container yard and aggregate buffer stockyard.
- Rock dumping during installation of concrete ramps for landing craft tank (LCT) vessels and barges.
- Outer quay sheet pile wall comprising interlocked individual Z-shaped sheet piles.
- Inner quay 550 mm diameter steel tube anchor piles and tie-back rods to sheet pile wall.
- Dredging of riverbed sediments adjacent to the quay.

Construction of the Logistic Base's main platform is mainly an onshore activity. In-water rock dumping to install landing craft and barge ramps will generate short-term and transient, non-impulsive broadband noise. These construction noise sources have not been considered further, given their anticipated low intensity noise. Noise levels from pile driving are considered in

Section 4.1. The noise from dredging of riverbed sediments adjacent to the quay is addressed separately in Section 4.2.

4.1 Pile Driving Activities at the River Quay

During the construction phase, the driving of steel tube anchor piles and sheet piles into the riverbed is required during the construction of the river quay at the Logistics Base, which is described in more detail in the EIS (Volume 1). The quay is located about 10 km downstream of the existing wharf at Herd Base.

4.1.1 Pile Driving Noise Source Levels

The sheet pile wall facing (and in contact with) the Purari River at the river quay will be approximately 152 m long and require about 200 Z-shaped sheet piles, based on the existing wharf sheet pile density at Herd Base. In addition, about 60 steel tube anchor piles of 550 mm (21.6 inch) diameter, which will be filled with concrete, will be driven behind the sheet pile wall and spaced at 3-m intervals.

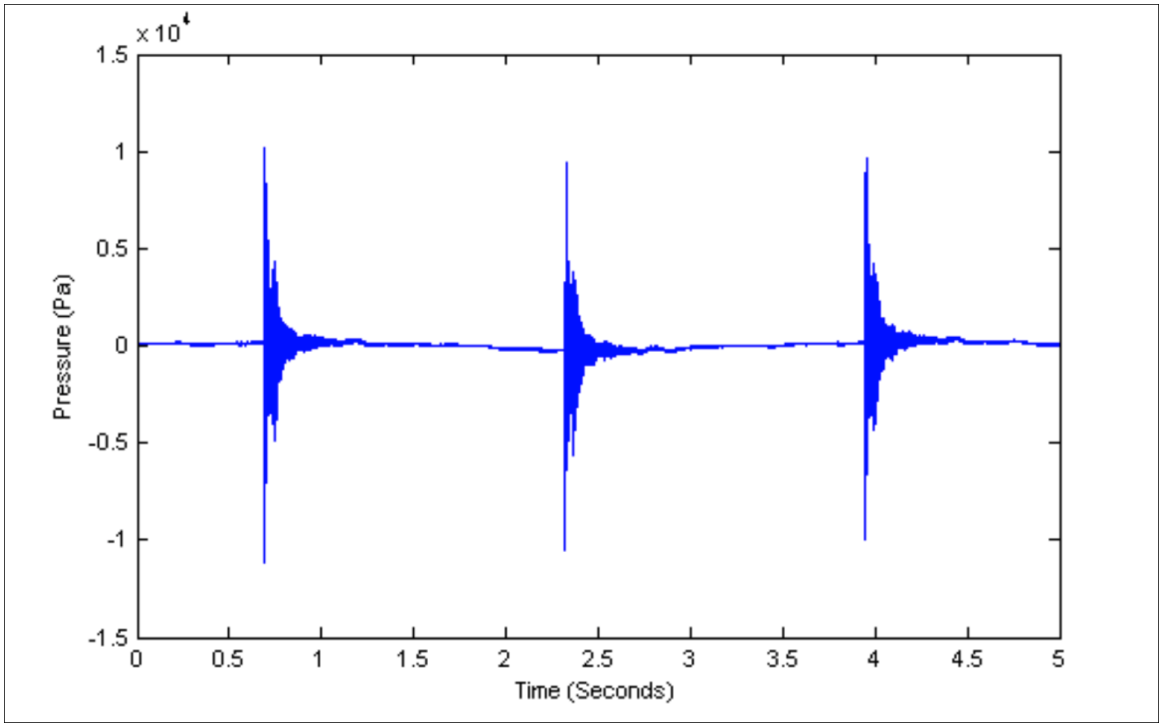
There are two types of pile driving methods that may be used; namely, impact hammers or vibratory hammers. The underwater noise characteristics in terms of pressure-time history, power spectrum density and frequency of these two piling methods are described below.

4.1.1.1 Impact Hammer Pile Driving Noise Characterization

The noise source level from in-water impact hammer pile driving is complex because the noise penetrates both the water column and through the riverbed's substratum. In general, the sound generated results from a rapid release of energy as the hammer hits the top of the pile being driven. Some aerial sound penetrates the adjacent water column but is minor compared to in-water sound generation from the pile being driven. The sound from the impact generates a stress sound wave that propagates down the length of the pile and causes cylindrical and spherical sound waves to radiate outward through the surrounding water column and riverbed sediment.

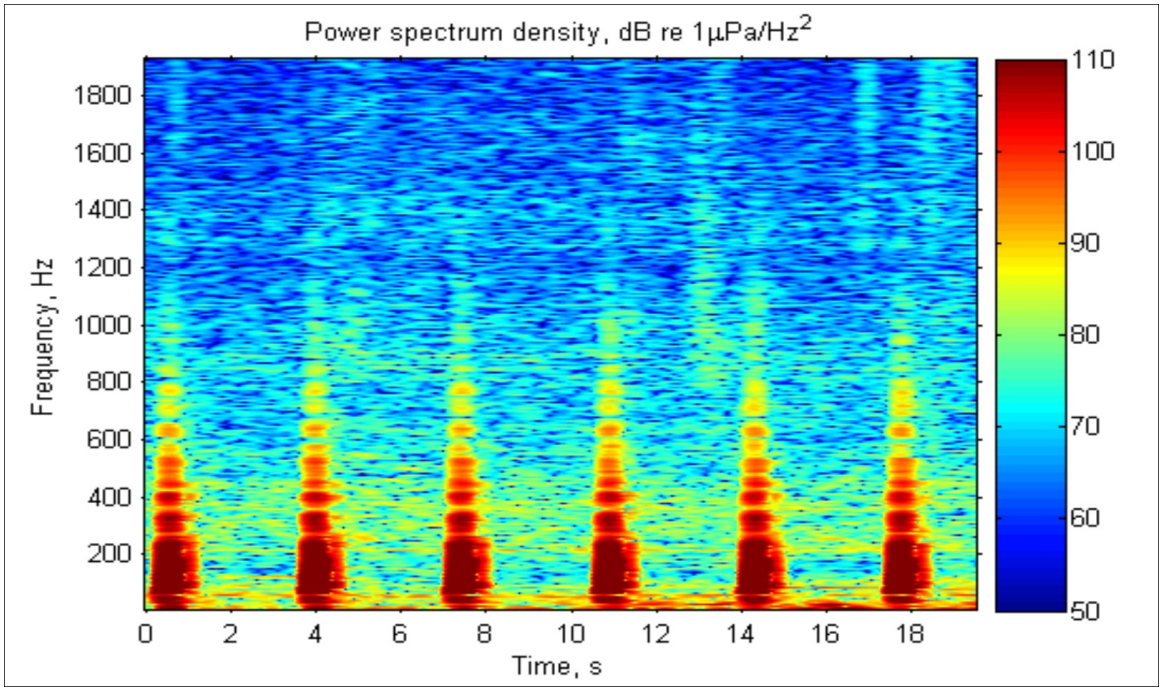
Pile driving sound is impulsive, transient and discontinuous broadband noise. Most of the sound frequencies of impact pile driving range from a few Hertz up to 600 Hz (Salgado-Kent et al., 2012). Typically, underwater pile driving noise is characterized by multiple rapid increases and decreases in sound pressure over a very short period of time. Figure 1 illustrates a typical pressure time history (i.e., sound pressure versus time) for a five second period of pile driving. The time history was recorded at a distance of 100 m from the pile driving (Nedwell et al., 2007).

Figure 2 shows an example of the power spectrum density associated with impact pile driving (Salgado-Kent et al., 2012), which shows a spectrogram of underwater noise generated by impact pile driving. In Figure 2 most of the noise is from a few Hertz to up to 600 Hz, with the bulk of the noise below 250 Hz.



Source: Nedwell et al. (2007).

Figure 1 – Example of Typical Pressure-time History of Impact Hammer Pile Driving Noise



Source: Salgado-Kent et al. (2012).

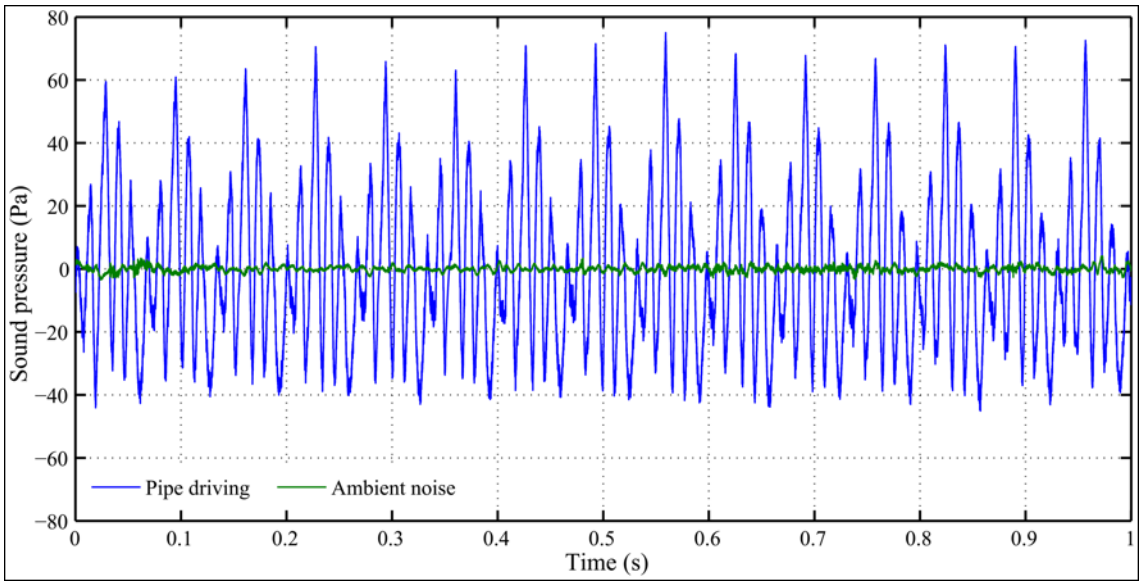
Figure 2 – Example of Power Density Spectrum for Impact Hammer Pile Driving

4.1.1.2 Vibratory Hammer Pile Driving Noise Characterization

Compared with the conventionally used impact hammers, the vibratory hammer has several advantages including a lighter weight and faster operation at a lower noise level compared to conventional hammers. Vibratory hammers also do not require a temporary guide frame for driving of freestanding piles (Jonker, 1987). Accordingly, it represents an alternative tool, or a complementary tool, to impact hammers.

Vibration is created by vertical movements produced by counter-rotating eccentric weights in the head of the equipment. The continuous pulses of energy transferred from the vibratory hammer pile displaces soil at the penetrating pile tip, and can create excess pore water pressures or even complete fluidization of the soil. As a consequence, the pile's frictional and tip resistances are strongly reduced during vibratory driving, enabling the pile to penetrate the riparian soil or riverbed sediments.

Figure 3 illustrates a typical pressure time history (i.e., sound pressure versus time) for a one second period of pile driving (about 15 vibrations per second).



Source: Wang et al. (2014).

Figure 3 – Example of Typical Pressure-time History of Vibratory Hammer Pile Driving Noise

The operating vibratory hammer waveform in Figure 3 is representative of non-impulsive, continuous broadband noise. Vibratory hammers have higher rates of penetration and reduced ground vibration and noise levels compared to impact hammers (GDG, 2015).

4.1.2 Adopted Pile Driving Noise Source Levels

The construction of the quay includes driving of 600-mm wide sheet piles to form a sheet pile wall and 550-mm (21.6-inch) diameter steel tube anchor piles spaced at 3-m intervals. Based on a literature review, Table 8 presents measured pile driving sounds for representative impact and vibratory hammers. The source and SEL values in Table 8 are back-calculated using the practical spreading loss ($15Log_{10}R$) equation.

Table 8 – Measured and Back-calculated Noise Source Levels of Pile Driving

Pile type	Peak SPL (dB re 1 µPa$_{pk}$)	SPL (dB re 1 µPa$_{rms}$)	SEL (dB re 1 µPa^2•s)
600-mm-wide Sheet Pile Driven by an Impact Hammer			
Measured noise level at 10 m	205	190	180
Back-calculated source level at 1 m	220	205	195
600-mm-wide Sheet Pile Driven by a Vibratory Hammer			
Measured noise level at 10 m	175	160	160
Back-calculated source level at 1 m	190	175	175
508-mm (20-inch) Diameter Steel Tube Anchor Pile Driven by an Impact Hammer*			
Measured noise level at 10 m	208	187	176
Back-calculated source level at 1 m	223	202	101

Source: Rodkin and Pommerenck (2014). * The 508-mm diameter pipe is nearest to the 550-mm diameter anchor piles proposed for the quay.

Underwater noise from steel tube anchor pile driving will be reduced due to the sheet pile wall being installed first, which presents a physical barrier (shield) that greatly reduces radiated noise from steel tube anchor pile driving reaching the river main channel. Therefore, the underwater noise generated by sheet pile driving has been used as a noise source level for impact assessment.

The method for sheet piling at the quay is yet to be determined so for the purposes of the impact assessment, a conservative source SPL of 205 dB re 1 µPa at 1 m has been adopted based on using an impact hammer. The louder underwater noise generated by the impact hammer sheet pile driving method has been conservatively selected for the following reasons:

- The vibratory hammer pile driving method still requires final proofing using an impact hammer to drive the sheet piles to final depth or depth to refusal.
- Vibratory pile driving noise source levels have generally been measured to be lower than impact hammer driving; for example, by 20 to 25 dB (McCauley and Salgado-Kent, 2008), 10 to 20 dB (Caltrans, 2017) and 20 to 30 dB (Rodkin and Pommerenck, 2014).
- While vibratory piling noise may reach high levels, it is not known to cause potential serious physiological impacts to aquatic fauna that impact pile driving is known to produce (McCauley and Salgado-Kent, 2008).

4.1.3 Pile Driving Noise Distances to Selected Isopleths

Noise propagation and transmission loss from sheet pile driving can be calculated using the generalized spreading model NLog_{10}R, where N is the spreading coefficient and R is the radial distance from the noise source in meters. In general, pile driving in shallow water with a constant depth has a spreading coefficient (i.e., N value) ranging from 10 to 15 (i.e., ranging from cylindrical spreading loss [10Log_{10}R] to practical spreading loss [15Log_{10}R]). Illingworth and Rodkin (2009) observed that small diameter steel pipe piles driven without attenuation (i.e., without, for example, drive caps or bubble curtains) have N values in the range of 15 to 25, while large diameter steel piles have N values in the range 18 to 23. Noise transmission loss for the small diameter steel pipes assessed by Illingworth and Rodkin (2009) is assumed to be the

nearest equivalent to the 600-mm wide sheet piles to be driven at the quay. Therefore, a spreading coefficient of 20 (i.e., midway between 15 to 25) has been selected.

Table 9 gives calculated distances to various nominal isopleths based on the adopted impact hammer pile driving underwater noise SPL source level of 205 dB re 1 μPa_{rms} at 1 m (see Table 8).

Table 9 – Calculated Distances from Sheet Pile Driving to Selected Isopleths

Source Level	Nominal Isopleth (dB re 1 μPa_{rms} received SPL)						
205 dB re 1µPa at 1 m	200	190	180	170	160	155	150
Distance to Isopleth (m)	1.2	5.6	18	56	177	316	562

Note: Sound pressure transmission loss based on spherical spreading loss equation.

Figure 4 shows the calculated isopleths within the Purari River main channel from the corner of the proposed quay at the Logistics Base.

The background noise level at the main channel of the Purari River at the Logistics Base quay is estimated to be an average of 120 dB re 1 μPa_{rms} with a range of 75 to 170 dB re 1 μPa_{rms} (see Attachment 8.1 in Volume 2). This estimated average background noise level is consistent with WSDOT (2019), which state that average ambient background levels in natural deep slow-flowing rivers are around 120 dB re 1 μPa_{rms}.

In Figure 4, the distance between the noise source at the new quay and across the Purari River main channel to the opposite bank is approximately 210 m.

4.1.4 Distances to Acoustic Threshold Criteria

4.1.4.1 Freshwater Fish

The acoustic damage threshold criterion of a peak SPL of 206 dB re 1μPa_{pk} for bony fish is exceeded within a distance of 5.6 m of impact hammer pile driving assuming the adopted peak source SPL of 220 dB re 1μPa_{pk} at 1 m (see Table 8) based on spherical transmission loss. Peak noise levels are predicted to only affect those individual fish that are stationary and within the 5.6 m acoustic damage impact zone.

The acoustic disturbance threshold criterion of 150 dB re 1 μPa_{rms} for fish is exceeded up to 562 m radius from the source (Table 9). The Purari River at this location is about 250 m wide; therefore, the 150 dB re 1 μPa_{rms} isopleth is exceeded across the total width of the river as well as 562 m both upstream and downstream of the impact piling source.

4.1.4.2 Freshwater Turtles and Crocodiles

Behavioral effects on non-constrained, free-ranging freshwater turtles and crocodiles may be expected to occur above the acoustic threshold criterion of 175 dB re 1 μPa_{rms}. This acoustic threshold criterion is exceeded within 32 m of the pile driving noise source.

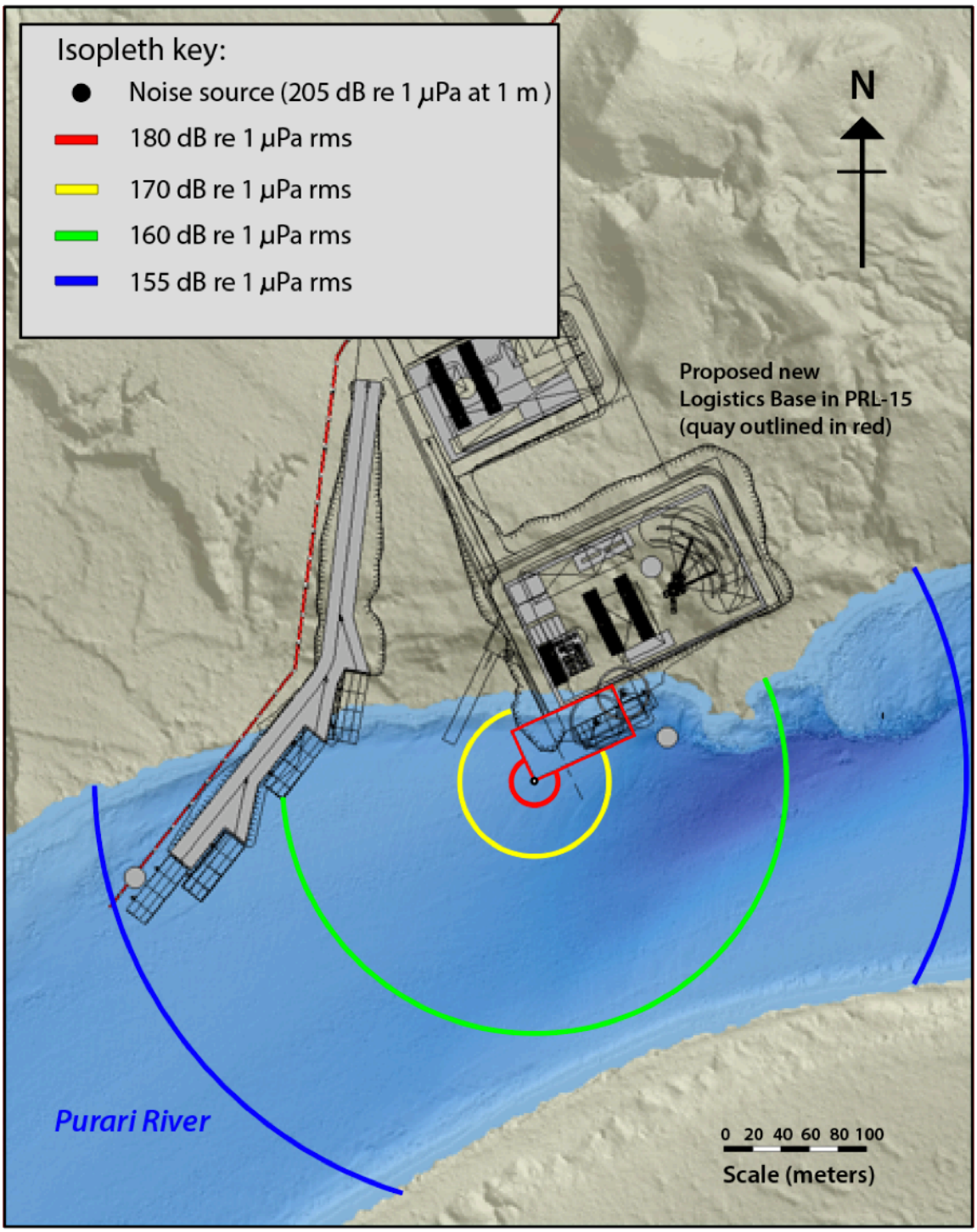


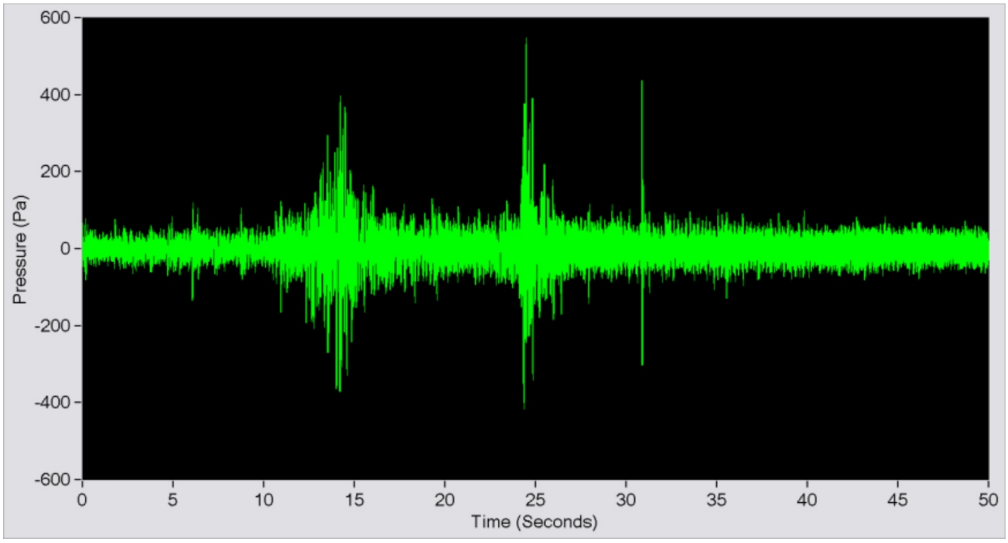
Figure 4 – Predicted Isopleths Generated by Pile Driving at Logistics Base Quay

4.2 River Dredging Activities

Dredging requirements will be determined during FEED; however, it is anticipated that dredging of approximately 6,000 m^3 of sand and sediment from the Purari River adjacent to the Logistics Base will be required to accommodate the drafts of various Project vessels and barges.

4.2.1 Dredging Noise Source Levels

Dredging is likely to be undertaken using a backhoe dredger with dredged material placed into a barge for disposal. Noise sources from a typical backhoe dredger arise during the dredge cycle, such as bucket bottom-impact (digging), hydraulic ram and barge dredged material loading. In general, bottom-impact noise is the loudest source of noise. Figure 5 shows an underwater noise time history (spectral levels) with the recording hydrophone at a distance of 7 m from the backhoe dredger (Nedwell et al., 2008).



Source: Nedwell et al. (2008).

Figure 5 – Example of Underwater Noise Spectra of an Operating Backhoe Dredger

Interpretation by Nedwell et al. (2008) of the spectral intervals in Figure 5 reveals the following.

Spectral interval between 0 and 10 seconds

- The noise spectrum is characterized by the underwater noise from generators, power plant and movement of the hydraulic rams (movement of arm of the excavator bucket).
- Generated noise during this period is typically at a peak to peak level of 100 Pa with one second RMS sound pressures of between 10 to 15 Pa and the noise source levels are between 140 and 145 dB re 1 μPa_{rms} at 1 m.

Spectral interval between 10 and 27 seconds

- The noise spectrum is characterized by increased noise as the bucket digs into the seabed, followed by a further higher noise source level as the bucket scrapes along the seabed and is lifted.
- Generated noise during this period increases to a maximum peak to peak level of 900 Pa with one second RMS sound pressures of between 15 Pa to 130 Pa and the noise source levels are between 145 and 162 dB re 1 μPa_{rms} at 1 m.

Spectral at 31 seconds

- Loading of dredged material into the supporting barge, but this activity adds little to overall noise as it is of extremely short duration.

Spectrum interval between 32 and 50 seconds

- The noise spectrum is characterized by a return to underwater noise from generators, power plant and movement of the hydraulic rams (movement of arm of the excavator bucket) (see the 0 to 10 second spectral interval above for details of generated noise).

In general, dredging produces low frequency sound between 100 and 500 Hz, but the bandwidth may vary from 20 Hz to 20 kHz depending on the dredging process and the types of material being extracted, with coarse gravel and pebbles causing greater sound levels (Clement, 2017). The proposed river and marine dredging will be undertaken mainly in fine-grained, unconsolidated sediments such as riverbed or seabed sediments (e.g., sands and silts).

Based on literature review, the range of noise source levels for backhoe dredging bottom-impact is between 163 dB re 1 µPa at 1 m (Nedwell, et al., 2008) and 179 dB re 1 µPa at 1 m (Reine et al., 2012). A conservative underwater noise source level of 180 dB re 1 µPa at 1 m has therefore been adopted for the purposes of the assessment.

4.2.2 Distances from Dredging to Selected Isopleths

Table 10 gives calculated distances to various nominal isopleths based on the adopted backhoe dredging underwater noise source level. Table 10 shows the general extent of underwater noise transmission loss with distance based on the spherical spreading loss equation ($20Log_{10}R$).

Table 10 – Calculated Distances from Backhoe Dredger to Selected Isopleths

Source Level	Nominal Isopleth (dB re 1 μPa_{rms} received SPL)						
180 dB re 1 µPa at 1 m	175	170	160	150	140	130	120
Distance to isopleth	1.8 m	3.2 m	10 m	32 m	100 m	316 m	1,000 m

Note: Sound pressure transmission loss based on spherical spreading loss equation.

The average ambient background noise level is 120 dB re 1 μPa_{rms} (range 70 to 170 dB re 1 μPa_{rms}) based on characterization of Assessment Location 7 in the Purari River (see Attachment 8.1 of Volume 2). The upper range value reflects transient peaks in underwater noise generated by passing TEP PNG exploration vessels, as well as landing crafts, log ships and community transport boats fitted with outboard engines.

4.2.3 Distances to Acoustic Threshold Criteria

4.2.3.1 Freshwater Fish

The acoustic damage threshold criterion of a peak sound pressure level of 206 dB re 1 μPa_{rms} for all fish is not exceeded at the dredging site based on an estimated peak SPL of 195 dB re 1 μPa_{pk} by adding an approximate 15 dB to the source SPL level of 180 dB re 1 µPa at 1 m.

The acoustic disturbance threshold criterion of 150 dB re 1 μPa_{rms} for all fish is exceeded from the underwater noise source (shallow-water backhoe dredger) out to 32 m (see Table 9).

4.2.3.2 Freshwater Turtles and Crocodiles

Acoustic damage impacts to freshwater turtles and crocodiles are not predicted given that the acoustic threshold criterion for tissue damage is a peak SPL of 208 dB re 1µPa_{pk} which does not exceed the estimated peak SPL of 195 dB re 1 µPa_{pk} during dredging (see Section 4.2.3.1 for derivation).

The acoustic threshold criterion of 175 dB re 1 µPa_{rms} for behavioral effects is exceeded within 2 m of the river dredging noise source

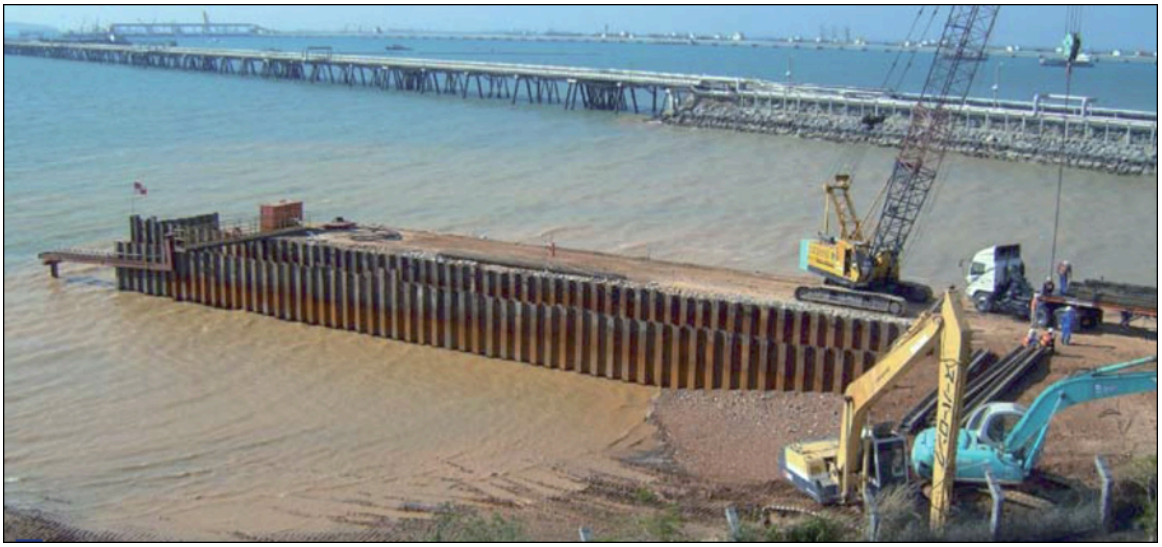
4.3 Nearshore Trenching and Piling Activities

Nearshore trenching is proposed at the shore-ends of the export pipeline route in Orokolo Bay and Caution Bay for pipeline installation and post-installation burial. Assessment has been undertaken of the proposed nearshore trenching activities in Orokolo Bay, which is also representative of underwater noise from nearshore trenching in Caution Bay. The trenching methods are yet to be determined and will be finalized during FEED. For the purposes of the impact assessment, a number of assumptions have been made, based on nearshore trenching activities undertaken for other projects. The assumed approach to nearshore trenching includes:

- The use of a land-based backhoe excavator to excavate an approximately 300-m-long and 3-m-deep onshore trench across coastal dunes from an anchor pull point to the water's edge at the high tide level.
- A further approximately 200-m long excavated trench within the intertidal zone (i.e., between the high and low tide levels), with the excavated material used to form a causeway which may be strengthened with additional coarse material (e.g., rock or gravel), if required.
- Generated noise source levels between 145 and 162 dB re 1 µPa at 1 m (see Section 4.2.1).
- A crane fitted with a suspended impact hammer (or vibratory hammer) will use the causeway for access to drive sheet piles into the ground or seabed near the water's edge, to form a temporary cofferdam.
- The trench within the cofferdam will be further excavated to the 3-m depth required to accommodate the export gas and condensate pipelines.

Following the removal of the seaward-end sheet pile wall of the cofferdam, the export condensate and gas pipes will be pulled from a pipe-lay barge (or pipe-lay vessel) to shore using a land-based winch located at an onshore anchor point. Upon completion of the pipe pull, the trench inside the cofferdam and the onshore trench will backfilled and the cofferdam either removed or the sheet piles cut off at about 0.5 to 1 m below final grade. A more detailed description of the nearshore approach and shore crossing of the export pipelines is given in the EIS (Volume 1).

Plate 1 shows an example of a typical shoreline and nearshore trenching operation across a sand substrate, including a sheet-piled cofferdam. This nearshore trenching operation was for the installation of a crude oil pipeline. The photograph shows the causeway (access track) and the cofferdam comprised of sheet piling walls.



Source: Boskalis (2007).

Plate 1 – Example of Shoreline and Nearshore Pipeline Trenching Works

4.3.1 Nearshore Trenching and Sheet Piling Noise Source Levels

4.3.1.1 Trenching and Sheet Piling Noise Sources

For the purposes of the assessment, excavation of the nearshore and shoreline export pipeline trench by land-based backhoe excavators or a crane suspended clamshell bucket will produce non-impulsive, intermittent broadband noise. In addition, non-impulsive intermittent noise will be generated during sheet pile driving if a vibratory hammer is used. If an impact hammer is used to drive the sheet piles, then this will generate impulsive intermittent broadband noise.

Onshore and intertidal trench excavation will generate mostly airborne noise with some ground vibrations, which are unlikely to radiate into the adjacent nearshore marine environment at levels sufficient to cause impacts on marine fauna. There will be very limited in-water excavation at the seaward end of the pipeline trench, except for a very short period (less than an hour) when the cofferdam sheet pile end wall is removed to flood the trench. Therefore, trench excavation noise and potential very short-term and transient non-impulsive, broadband noise impacts on marine fauna are not considered further.

The principal source of underwater noise from nearshore trench construction will be the impulsive or non-impulsive broadband noise generated during sheet pile driving from an impact hammer or vibratory hammer, respectively. For the purposes of a conservative assessment, the use of an impact hammer for sheet pile driving has been assumed as the noise level generated by an impact hammer (i.e., impulsive noise) is louder than that generated by a vibratory hammer (non-impulsive noise). In addition, if a vibratory hammer was used, an impact hammer is generally required to conduct the final proofing of the sheet piles to the target depth or depth to refusal.

4.3.1.2 Impact Pile Driving Noise Source Levels

Underwater noise radiating from the impact hammer driving of sheet piles will be dampened since most of the sheet piles will be driven into the ground onshore or the exposed seabed of the intertidal zone during low tides, such that radiating noise and vibration will be ground-borne rather than waterborne. Some of the sheet piles at the seaward end of the cofferdam will be driven at

the water's edge and in very shallow water (typically less than 2 m depth) in the subtidal zone, which will generate waterborne noise that will radiate seawards with consequential potential impacts to nearshore marine fauna.

A review of the literature (Illingworth and Rodkin, 2009) revealed that thin-walled H-piles (nearest equivalent to Z sheet piles) of sheet pile driving in very shallow water (e.g., up to 2 m water depth) had typical peak SPL, rms SPL and SEL levels measured at 10 m distance of 190 dB re 1 μPa_{pk}, 165 dB re 1 μPa_{rms} and 155 dB re 1 $\mu Pa^2 \bullet s$. These measured values back calculate, using the practical spreading loss equation, to source levels at 1 m of 205 dB re 1 μPa_{pk}, 180 dB re 1 μPa_{rms}, and 170 dB re 1 $\mu Pa^2 \bullet s$, respectively. For the purposes of this assessment, a source SPL of 180 dB re 1 μPa_{rms} at 1 m has been adopted as representative of in-water sheet pile driving at the end of the nearshore trench.

4.3.2 Impact Pile Driving Noise Distances to Selected Isopleths

Table 11 gives calculated distances to various selected isopleths based on the adopted impact hammer sheet pile driving underwater noise SPL source level of 180 dB re 1 μPa_{rms} at 1 m.

A cylindrical spreading loss model ($10Log_{10}R$) is often used for pile driving noise in shallow water; however, in very shallow water of even depth, the below-seabed generated radiated noise from the pile travels through the seabed and resurfaces to enter the water column. As such, the values shown in Table 11 are based on a practical spreading transmission loss model.

Table 11 – Calculated Distances from Nearshore Sheet Pile Driving to Selected Isopleths

Source Level	Nominal Isopleth (dB re 1 μPa_{rms} received SPL)							
180 dB re 1 μPa_{rms} at 1 m	175	170	165	160	150	140	130	120
Distance to Isopleth	2.2 m	4.6 m	10 m	22 m	100 m	464 m	2.1 km	~10 km

Note: Sound pressure transmission loss is based on practical spreading transmission loss model.

Figure 6 shows the distances to selected isopleths in Orokolo Bay as well as Assessment Location 4 (AL4) where the average ambient background noise was estimated (Attachment 8.1 of Volume 2).

The average ambient background noise in Orokolo Bay at Assessment Location AL4 (2.75 km from shore) was estimated to be 130 dB re 1 μPa_{rms} (range 85 to 163 dB re 1 μPa_{rms}) (Attachment 8.1 of Volume 2). Closer to shore where impact pile driving will take place, the average ambient noise level may be expected to be higher owing to surf noise and wave action.

4.3.3 Distances to Acoustic Threshold Criteria

4.3.3.1 Cetaceans

The impulsive noise acoustic disturbance threshold of 160 dB re 1 μPa_{rms} for low frequency cetaceans is exceeded up to a distance of 22 m from the nearshore pile driving operation (see Table 11). Low frequency hearing cetaceans, i.e., baleen whales, are unlikely to approach the nearshore in-water pile driving given that they tend to avoid shallow water and that they will be able to detect the underwater impulsive noise gradient prior to approaching this potential behavioral disturbance zone. In contrast, mid-frequency and high frequency cetaceans, including smaller toothed whales and dolphins, are more tolerant of marine construction noise and some species may be attracted to the source of nearshore pile driving noise.

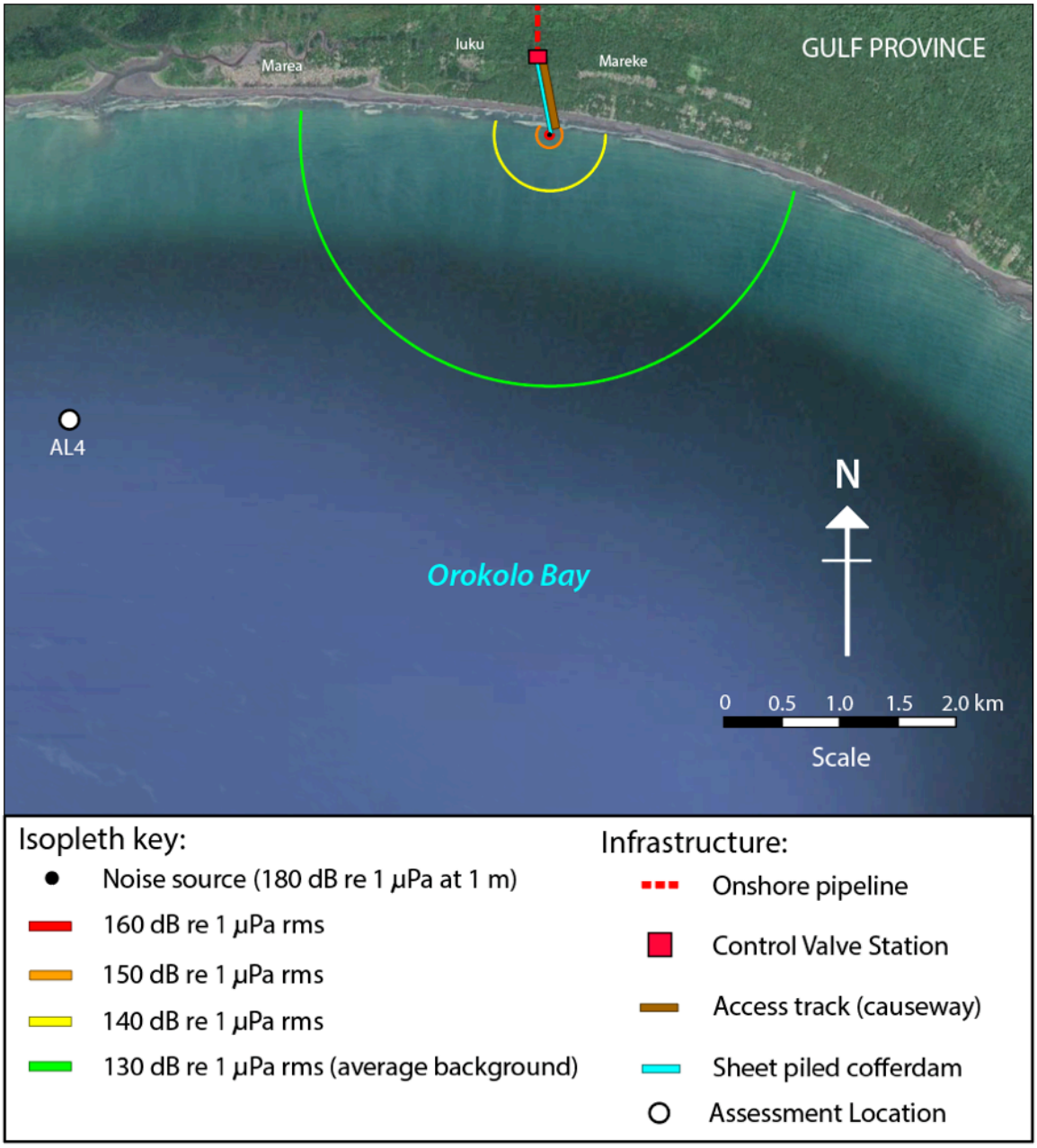


Figure 6 – Predicted Isopleths Generated by Nearshore Pile Driving in Orokolo Bay

4.3.3.2 Dugongs

The acoustic damage threshold criterion of 226 dB re 1 μPa_{pk} for dugongs is not exceeded in Orokolo Bay adjacent to nearshore pile driving activities, where the source peak SPL is 184 dB re 1 μPa_{pk} (see Section 4.3.1.1).

The acoustic disturbance threshold criterion of 120 dB re 1 μPa_{rms} for dugongs is exceeded within approximately 2.2-km radius of the nearshore trenching operation (see Table 11).

4.3.3.3 Sea Turtles and Crocodiles

The acoustic damage threshold criterion of a peak SPL of 208 dB re 1 μPa_{pk} is not exceeded at the sites of nearshore trenching activity, where a peak SPL of 195 dB re 1 μPa_{pk} is estimated (see Section 4.2.3.1 about adding 15 dB to a source SPL to estimate peak SPL). The acoustic threshold criterion of 175 dB re 1 μPa_{rms} for behavioral disturbance and temporary hearing loss (e.g., temporary threshold shift onset) for sea turtles and crocodiles is exceeded within 2.2 m of the site of nearshore in-water pile driving, which represents a very small impact zone within very shallow water.

4.3.3.4 Fish

The acoustic damage threshold criterion of a peak SPL of 206 dB re 1 μPa_{pk} for bony fish is not exceeded at the site of nearshore pile driving, where the peak SPL is estimated to be 195 dB re 1 μPa_{pk}.

The acoustic disturbance threshold criterion of 150 dB re 1 μPa_{rms} for bony fish is exceeded within 100 m of the nearshore pile driving activity (see Table 11), which represents a small impact zone of limited duration (i.e., one to two days of in-water pile driving).

4.4 River Vessel Traffic and Transportation

The Project requires a fleet of vessels to transport materials such as aggregates, pipeline and construction materials, which will be transported by barges up the Purari River to the Logistics Base close to the Central Processing Facility (CPF) in PRL-15. Other goods to be transported by towed barge or landing craft vessels include containers, vehicles, chemicals, and large module structures required for construction of the CPF.

Landrieu (2017) undertook an assessment of the number and types of vessels and barges to service the Project. This assessment assumed that the capacity to unload the barges at Herd Base and then at the quay at the new Logistic Base is two barges per day, which limits traffic in the river main channel and the number of barges to thirteen. The depth of the Purari River also restricts vessels to drafts to less than 2.5 m, a width of 15 m and a length of 64 m for a landing craft or 55 m for a towed barge.

Based on three years operational experience of unloading barges at Herd Base during the Project's exploration phase, the projected transportation plan during the first 16 months of construction includes:

- A total of 61 deliveries per month.
- Two barges of 1,500 t unloaded per day (30 working days per month).
- A fleet of 13 barges and one landing craft to transport aggregate material.

A round trip between Port Moresby to PRL-15 is between five and six days for a barge or landing craft. During the Project's exploration phase in 2016, TEP PNG and other commercial river traffic on the Purari River included a total of 190 return trips per year for TEP PNG's two main barges, and 24 return trips for log ships to the Evara commercial logging camp on the Purari River (see Part 22, Volume 2), i.e., a total of 214 return trips each year. This number of return trips represents a total of 428 vessels trips per year, or, 1.17 vessels per day passing a nominal single point on the Purari River between PRL-15 and Purivo Junction.

During the first 16 months of Project construction, there will be 732 landing craft vessel or barge return trips per year, which represents 1,464 vessels per year passing a single point in the river. If log ships to Evara logging camp continue to make 24 return trips per year, this represents a total of 1,512 vessels per year, or, 4.14 vessels per day passing the adopted nominal single point in the river. Comparing the baseline data with the projected number of vessels per day passing a single point in the river during the construction phase, there will be a 3.5-fold increase in daily vessel traffic at the nominal single point in the river. Different daily values for vessels passing through the 'lower' Purari River between Purivo Junction and the delta may be expected, as other river corridors may be used from time to time; for example, the Wame-Varoi distributary or the Urika-Ivo distributary.

The 3.5-fold increase in shipping during the first 16 months of construction represents a change from around one vessel every 20 hours, to one vessel every 6 hours. The baseline range of underwater noise of between 75 and 170 dB re 1 μPa_{rms} in the Purari River at Assessment Location 7 (Attachment 8.1 Volume 2) does not change notably, as the background upper range value of 170 dB re 1 μPa_{rms} has already accounted for passing commercial ships, landing craft vessels and local community outboard motor-driven boats plying the Purari River main channel. However, average underwater noise levels during Project construction and operations are expected to increase above the baseline average of around 120 dB re 1μPa_{rms} when averaged over a year, owing to the 3.5-fold increase in river vessel traffic

For the purposes of the impact assessment, underwater noise generated by Project shipping plying the river transport corridors during the first 16 months of construction, when there will be the greatest number of shipping movements, has been selected for modeling and impact analysis. The impact assessment also considers underwater noise generated by vessels or barges travelling along the main channel of a river as opposed to the more open waters of the estuaries and Gulf of Papua.

4.4.1 River Vessel Underwater Noise Source Levels

An average source SPL of 170 dB re 1 µPa at 1 m was adopted in the baseline study (Attachment 8.1 Volume 2) as a representative noise source level for Project-related vessels which typically travel at between five and seven knots in the rivers and estuaries. This source SPL has been used to calculate distances to isopleths of interest, including acoustic disturbance threshold criteria for fish, freshwater turtles and crocodiles.

4.4.2 Distances from River Vessels to Selected Isopleths

Table 12 gives calculated distances to various nominal isopleths based on the adopted vessel underwater noise source level. The table shows the general extent of underwater noise propagation and transmission loss with distance based on the spherical spreading loss equation ($20Log_{10}R$), which is considered appropriate for a river cross section at a passing vessel's location.

Table 12 – Calculated Distances from River Vessels to Selected Isopleths

Source Level	Nominal Isopleth (dB re 1 μPa_{rms} received SPL)					
170 dB re 1µPa at 1m	165	160	150	140	130	120
Distance to isopleth (m)	1.8	3.2	10	31	100	316

Note: Sound pressure transmission loss is based on the spherical spreading loss equation.

4.4.3 Distances to Acoustic Threshold Criteria

4.4.3.1 Fish

The acoustic damage threshold criterion of a peak SPL of 206 dB re 1 μPa_{pk} for all fish is unlikely to be exceeded as the non-impulsive, broadband noise generated by a vessel's engines and propeller noise and the vessel's low speed does not generate a peak SPL value above 185 dB re 1 $\mu Pa_{pk.}$ This is based on the estimated peak level being typically about 15 dB higher than the source rms SPL of 170 dB re 1 µPa at 1m.

In terms of the acoustic disturbance threshold of 150 dB re 1 μPa_{rms} for freshwater fish, the 150 dB re 1 μPa_{rms} isopleth is calculated to be 10 m from a typical landing craft vessel or towed barge. Within this zone, fish may be expected to be temporarily vertically or horizontally displaced during the passage of the vessel in the river. Field studies have shown that vessel noise elicits startle responses in fish, i.e., going from a stationary position to swimming mode (Sara et al., 2007).

4.4.3.2 Freshwater Turtles and Crocodiles

The acoustic damage threshold criterion of a peak SPL of 208 dB re 1 μPa_{pk} and acoustic disturbance threshold criterion of 175 dB re 1 μPa_{rms} for freshwater turtles and crocodiles are not exceeded during the passage of a river vessel with an average noise source SPL of level 170 dB re 1 µPa at 1 m (see Table 12). The transient passage of a river vessel as it approaches, passes and leaves a river segment will be audible to freshwater turtles and crocodiles, which suggests some subtle non-disruptive behavioral reactions may occur during the passage.

4.5 Offshore Construction and Marine Vessel Traffic

The Project's offshore construction activities includes the use of a pipelaying vessel or barge and a fleet of offshore support vessels to install the gas and condensate pipelines on the seabed of the Gulf of Papua (including Orokolo Bay) and Caution Bay. In addition, seabed intervention works include the placement of rock mattress or rock dumping to protect the existing PNG LNG Gas Pipeline where it will be crossed by the Project's export pipelines. These offshore construction activities generate underwater noise, which has been modeled.

Underwater noise will also be generated by marine vessel traffic and towed barges plying the Gulf of Papua during Project construction and operations, which have also been modeled.

4.5.1 Offshore Construction – Pipelaying

4.5.1.1 Pipe Laying Operation Noise Source Levels

Pipe laying activities in the Gulf of Papua will likely include a pipe lay vessel and up to six to eight support vessels such as anchor handling tugs (AHTs), offshore supply vessels, a pipe supply vessel, crew transfer boats, a dive support vessel and a post-lay vessel monitoring vessel.

Given the shallow waters (up to approximately 80 m deep) along the proposed pipeline corridor across the Gulf of Papua, a typical pipe laying vessel would be a semi-submersible pipelaying barge or platform that uses a mooring system to facilitate accurate positioning and movement during operation. In addition, a typical semi-submersible pipelaying barge has a number of azimuthal thruster units which can be used for propulsion or to further enhance position keeping if required.

Table 13 provides measured underwater noise source levels for various pipelaying vessels or barges.

Table 13 – Measured Underwater Noise Source Levels of Selected Pipelay Vessels

Name	Length (m)	Beam (m)	Source Level (dB re 1 μPa at 1 m)	Reference
Semac 1	121.9	54.8	182.6	Johansson and Andersson (2012)
Semac 1	121.9	54.8	179.3	Hannay et al. (2004); Genesis (2011)
Castoro Sei	143.3	64.5	182.6	Johansson and Andersson (2012)
*Global 1200**	162.3	37.8	189–191	Duncan and McCauley (2008)
*Global Hercules**	148.0	42.6	189–191	Duncan and McCauley (2008)

Notes: * The underwater noise source levels for these two vessels were predicted by Duncan and McCauley (2008) for the PNG LNG Project based on upscaling an old (1986-built) offshore support vessel (AHT *Pacific Akiri*) under full dynamic positioning.

The semi-submersible pipelay barge *Semac 1* listed in Table 13 was used to lay the PNG LNG Gas Pipeline across the Gulf of Papua. This vessel was dismantled for scrap in 2016 (ShipsNostalgia.com, 2016); however, its sister vessel *Castoro Sei* (also listed in Table 13) is still operational (Werner Solken, 2019).

For the purposes of this assessment, an average source level of 183 dB re 1 μPa at 1 m has been adopted for a typical pipelay barge operating in the Gulf of Papua or Caution Bay, which is based conservatively on the measured underwater noise source level of the pipelay barge *Castoro Sei* during actual pipelaying. The type of noise produced by pipelaying is non-impulsive, continuous broadband noise (10 to 1000 Hz), with higher tonal frequencies (up to 10 kHz) due to thruster cavitation noise.

Account also needs to be taken of the maximum accumulated underwater noise generated by a typical pipelay operation, which includes combining the noise source levels of both the pipelay barge and attendant construction support vessels which, from time to time, will operate in the immediate area around the pipelay barge. In general, pipelay barges that are fixed by anchors generate lower sound levels than their support vessels and associated anchor handling vessels. Table 14 presents a summary of typical underwater noise source levels generated by construction support vessels maintaining position using dynamic positioning via bow and stern thrusters and a number of azimuthal thrusters.

Table 14 – Underwater Noise Source Levels of Selected Offshore Supply Vessels

Vessel	Length (m)	Beam (m)	Source Level (dB re 1 μPa at 1 m)	Reference
Far Samson (anchor handling tug built in 2009)	121.5	26.0	183.5	Johansson and Andersson (2012)
Katun (anchor handling tug built 2016))	72	17	184.6	Hannay et al. (2004); Genesis (2011)
Neftegaz 22 (anchor handling tug built in 1989)	81	16	182.5	Mathews and Zykov (2012)

The pipelay barge and its attendant fleet of anchor handling support vessels will have different characteristics and noise source levels; therefore, the exact source level of each individual vessel or combination of support vessels in proximity to the pipelay barge is not known. Notwithstanding, the noise source levels of two of the loudest construction support vessels (anchor handling tugs) have been used along with the noise source level of the pipelay vessel to determine the maximum combined noise source level of a pipelay operation using the rules of underwater noise addition[3] (US Navy, 1999).

For the purposes of modeling the maximum accumulative noise of the pipelaying operation, account has been taken of a typical pipelay barge using dynamic positioning (i.e., 183 dB re 1 μPa at 1 m) and the assumed presence of two construction support vessels in close proximity to the pipelay barge; namely, one anchor handling tugs with a noise source level of 185 dB re 1 μPa at 1 m and a second one with a noise source level of 182 dB re 1 μPa at 1 m. Under the rules of underwater noise decibel addition (US Navy, 1999), the accumulative underwater noise source is 189 dB re 1 μPa at 1 m. The generation of a maximum combined noise source level of 189 dB re 1 μPa at 1 m is only expected to occur infrequently and transiently when the anchor handling tugs approach the pipelay barge to retrieve and reposition its anchors, allowing progression of the pipelay barge along the pipeline route.

For the purposes of impact assessment, modeling of the more typical underwater noise source level of 183 dB re 1 μPa at 1 m, which occurs for a longer duration, has been used to assess the distances to acoustic thresholds.

4.5.1.2 Distances from Pipelay Operation to Selected Isopleths

Table 15 gives calculated distances from a typical pipelaying operation to selected isopleths based on the adopted pipelaying activity underwater noise source level. The table shows the general extent of underwater noise propagation and transmission loss with distance based on the spherical spreading loss equation ($15Log_{10}R$), which is appropriate and conservative for the relatively shallow water depth range (20 m to 80 m) along the proposed export pipeline corridor in the Gulf of Papua (including Orokolo Bay) and within Caution Bay.

Table 15 – Calculated Distances from Pipelay Activity to Selected Isopleths

Source Level	Nominal isopleth (dB re 1 μParms received SPL)						
183 dB re 1 μPa at 1 m	180	170	160	150	140	130	120
Distance to isopleth	1.6 m	7.5 m	34 m	158 m	735	~3.4 km	~15 km

Note: Sound pressure transmission loss is based on the practical spreading loss equation. Tilde sign (~) indicates crude estimate of distances to these selected isopleths as sound paths via sea surface and seabed reflection affects calculations.

In the case of the PNG LNG Project, predicted noise levels from a typical pipelaying activity were lower over the muddy seabed found in the western portion of the PNG LNG pipeline route than over the sandy seabed found in the eastern portion. Therefore, the distance to selected isopleths may possibly be further over sandy seabed in the eastern portion of the Project's export pipeline route corridor than those given in Table 15, which were calculated using a modeling approach that does not consider different substrate type.

[3] Two noises of equal level (1 dB) combine to raise the noise level by 3 dB. However, if two noises differ by more than 10 dB, there is no combined increase in the noise level.

4.5.1.3 Distances to Acoustic Threshold Criteria

Distances to acoustic threshold criteria for cetaceans, dugongs, sea turtles and fish are described below.

Cetaceans

The acoustic disturbance threshold criterion of 120 dB re 1 μPa_{rms} for non-impulsive, continuous broadband noise produced by pipelaying activity is exceeded up to a distance of approximately 15 km (see Table 15) from the activity. This represents a relatively small area or volume of water within the Gulf of Papua. Low frequency hearing cetaceans passing through the gulf are anticipated to avoid or deviate around Project vessels as they sense the underwater noise gradient, as they would do with other ships within the gulf.

Dugongs

Dugongs are generally absent in the offshore waters of the Gulf of Papua but do occur along the coast where they may be exposed to underwater noise propagating towards the coast from offshore construction activities.

The acoustic disturbance threshold criterion of 120 dB re 1 μPa_{rms} for dugongs is exceeded within a 15 km radius (see Table 15) of a pipelaying activity. Portions of the export pipeline route are located within 15 km of the coast near Central Province headlands and Caution Bay. Therefore, dugongs will be exposed to pipelay noise levels above the acoustic disturbance threshold criterion of 120 dB re 1 μPa_{rms}. This represents a relatively large acoustic impact zone within which coastal transiting dugongs may be exposed to residual continuous non-impulsive, broadband noise generated by offshore pipelaying activities that reaches the coast. However, background noise levels along the coast and near Caution Bay are around 110 dB re 1 μPa_{rms}, ranging from 90 to 161 dB re 1 μPa_{rms}, with the higher levels due to surf noise and passing marine vessels. Dugongs are therefore likely to be tolerant of short-term pipelaying activity noise within coastal waters.

Sea Turtles and Crocodiles

The acoustic damage threshold criterion of a peak SPL of 208 dB re 1 μPa_{pk} for sea turtles and crocodiles is not exceeded in the vicinity of the proposed pipelaying activity, based on the peak level of 198 dB re 1 μPa_{pk}, which is based on an approximate 15 dB above the received source level of 183 dB re 1 μPa_{rms}.

The acoustic threshold criterion of 175 dB re 1 μPa_{rms} for behavioral disturbance in sea turtles and crocodiles is not exceeded further than 3.4 m from a pipelay activity, which represents a very small acoustic disturbance impact zone.

Fish

The acoustic damage threshold criterion of a peak SPL of 206 dB re 1 μPa_{pk} for bony fish is not exceeded at the site of pipelaying activity, where the peak SPL is estimated to be 198 dB re 1 μPa_{pk}.

The acoustic disturbance threshold criterion of 150 dB re 1 μPa_{rms} for bony fish is exceeded within 158 m of the pipelaying activity (see Table 15), which represents a small behavioural disturbance impact zone of limited duration as the pipelaying progresses along the export pipeline route.

4.5.2 Offshore Construction – PNG LNG Gas Pipeline Crossing

The main components of seabed intervention works are the placement of either concrete mattresses or targeted rock dumping where the export pipelines cross the existing PNG LNG Gas Pipeline within the Gulf of Papua or Caution Bay.

4.5.2.1 PNG LNG Pipeline Crossing Works Noise Source Levels

The crossing of the existing PNG LNG Gas Pipeline requires seabed intervention works to enable protection of this existing asset. It is proposed that this will be undertaken by the emplacement of concrete mattresses that can be formed into piles to carry the Project's proposed export pipelines over the PNG LNG Gas Pipeline. The underwater noise assessment has also considered an alternative approach using targeted rock dumping employing a fallpipe rock dumping vessel.

Targeted rock dumping involves using a self-propelled fallpipe vessel with a flexible fallpipe through which rocks are dumped onto the seabed at selected positions to create a rock berm cover to protect the existing PNG LNG Gas Pipeline. Nedwell et al. (2012) noted that underwater noise measurements of rocks falling through a fallpipe tube were faint compared to the sound of the dynamic positioning thrusters of a fallpipe vessel. Li (2010) measured a received sound pressure level of 120 dB re 1 μPa_{rms} at a distance of 450 m from an unnamed 40,000 DWT fallpipe vessel, which back-calculates to a source level of 160 dB re 1 μPa at 1 m using practical spreading law (15Log 10 [R]).

Concrete mattresses are constructed out of long concrete segments linked together to form a flexible layer of concrete that can be placed on the seabed to protect the existing PNG LNG Gas Pipeline. In the case of concrete mattress emplacement, an ocean-going barge or platform with a crane is held in position by a number of offshore support vessels using dynamic positioning. The lowering and placement of concrete mattresses on the seabed is a relatively quiet operation. However, the presence of several attendant offshore supply vessels maintaining the barge in position generates loud noise, mainly from cavitation of their stern and and azimuth thrusters during dynamic positioning.

For the purposes of this assessment, a standalone operation to emplace concrete mattresses on the seabed over and adjacent to the existing PNG LNG Gas Pipeline has been assumed. It is understood that this seabed intervention works will be undertaken in advance of the pipelay vessel's arrival at the pipeline crossing location.

Based on the measured underwater noise source levels of offshore supply vessels in Table 14, an average noise source level for the pipeline crossing works has been assumed to be 183 dB re 1 μPa at 1 m.

4.5.2.2 Distances from Pipeline Crossing Seabed Works to Selected Isopleths

The distances from seabed pipeline works to selected isopleths are the same as those predicted in Table 15 for the pipelaying activity and are therefore not presented in a separate table.

4.5.2.3 Distances to Acoustic Threshold Criteria

The distances from pipeline crossing works to selected isopleths are the same as those modeled and predicted in Section 4.5.1.3 for pipelaying activity, given the same noise source levels.

4.5.3 Marine Vessel Traffic

For the impact assessment, underwater noise generated by Project shipping plying the Gulf of Papua transport corridor during the first 16 months of construction has been selected as a worst-case scenario. During this period there is estimated to be 732 landing craft or barge return trips per year across the Gulf of Papua. This represents a total of 1,464 vessels crossings per year as a result of the Project. The number of vessels during operations is estimated to be approximately 25% of the peak construction phase, giving a total of 366 vessels per year (Landrieu, 2017).

4.5.3.1 Marine Traffic Noise Source Levels

Unlike the speed restriction for vessels plying the river corridors, vessels plying the offshore waters of the Gulf of Papua can travel at higher speeds. A maximum average source SPL of 175 dB re 1 µPa at 1 m has been adopted for marine vessels, based on the higher speeds (7 to 12 knots) of TEP PNG exploration phase landing craft vessels. For example, the MV *Balimo Chief* has an estimated average noise source level of 170 dB re 1 µPa at 1 m and the MV *GFS Marine 01* has an average source level of 175 dB re 1 µPa at 1 m. Tugs towing barges across the Gulf of Papua to PRL-15 will be restricted to lower speeds and will therefore generate lower source SPLs.

4.5.3.2 Distances from Marine Vessels to Selected Isopleths

Table 16 gives calculated distances from marine vessels to selected isopleths based on the adopted vessel underwater noise source level. The table shows the general extent of underwater noise propagation and transmission loss with distance based on the spherical spreading loss equation ($20Log_{10}R$), which is appropriate for the deeper water (up to 90 m) environment of the Gulf of Papua.

Table 16 – Calculated Distances from Marine Vessels to Selected Isopleths

Source Level	Nominal isopleth (dB re 1 μPa_{rms} received SPL)					
175 dB re 1 µPa at 1 m	165	160	150	140	130	120
Distance to isopleth (m)	3.2	5.6	18	31	178	562

Note: Sound pressure transmission loss is based on the spherical spreading loss equation.

4.5.3.3 Distances to Acoustic Threshold Criteria

Cetaceans

Large low frequency hearing cetaceans, i.e., baleen whales, are occasionally present in the Gulf of Papua. The acoustic damage threshold criterion of 180 dB re 1 μPa_{rms} for all cetaceans (see Table 3) is not exceeded by underwater noise radiated by Project vessels crossing the Gulf of Papua as the vessel source SPL does not exceed 175 dB re 1 µPa at 1 m.

The acoustic disturbance threshold criterion of 120 dB re 1 μPa_{rms} for non-impulsive, continuous broadband noise produced by marine vessels underway is exceeded up to a distance of 562 m (see Table 16) from the vessels. This represents a very small area or volume of water within the Gulf of Papua. Low frequency hearing cetaceans passing through the gulf are anticipated to avoid or deviate around Project vessels as they sense the underwater noise gradient, as they would do with other ships within the gulf.

Unlike loud impulsive noise sources from seismic surveys, which use high intensity sound air guns in towed arrays, the non-impulsive continuous broadband noise generated by ships is less averse to low frequency hearing cetaceans. These cetaceans are sensitive to low frequency noise (20 Hz to 10 kHz), the lower end of which overlaps the main frequency range of shipping noise (29 Hz to 1 kHz); however, their reaction to ships depend on whether they are stationary or moving. Fast moving ships pose a greater perceived threat to baleen whales and initiate disruptive behavioral responses (e.g., swimming away from the noise source).

Dugongs

The acoustic damage threshold criterion of 180 dB re 1 μPa_{rms} for dugongs is not exceeded in the vicinity of Project vessels plying the coastal and nearshore waters of the Gulf of Papua, as the sound source of marine vessels does not exceed 175 dB re 1 µPa at 1 m. Therefore, acoustic damage impacts to dugongs are not predicted.

The acoustic disturbance threshold criterion of 120 dB re 1 μPa_{rms} for dugongs is exceeded within a 562 m radius (see Table 16) of Project vessels passing through the nearshore waters of the Gulf of Papua during their approach to and from the Purari River delta. This represents a small acoustic impact zone within which transiting dugongs may be behaviorally disturbed by the transient non-impulsive, broadband noise generated by passing vessels. There are no seagrass meadows (i.e., source of dugong food) within nearshore areas adjacent to the Purari Delta or Orokolo Bay, largely as a result of frequent alongshore drift of turbid water from the Purari River.

Coastal transiting dugongs are expected to avoid the immediate area of transient noise generated by passing marine vessels. Short-term behavioral responses indicative of disturbance from boats have been documented for dugongs (Preen, 1992; Hodgson and Marsh, 2007). Preen (1992) suggested that dugongs in deep water show little response to marine vessels and small boats compared with dugongs in shallow water.

Sea Turtles

The acoustic damage threshold criterion of a peak SPL of 208 dB re 1 μPa_{pk} for sea turtles is not exceeded in the vicinity of Project vessels plying the Gulf of Papua. Similarly, the acoustic threshold criterion of 175 dB re 1 μPa_{rms} for behavioral disturbance for sea turtles is not exceeded further than one meter from Project vessels.

Fish

The acoustic damage threshold criterion of a peak SPL 206 dB re 1 μPa_{pk} for bony fish is not exceeded in the vicinity of Project vessels plying the Gulf of Papua; therefore, acoustic damage to pelagic fish is not predicted from the non-impulsive, continuous broadband noise generated by shipping.

The acoustic disturbance threshold criterion of 150 dB re 1 μPa_{rms} for bony fish is exceeded within a radial distance of 18 m from a Project vessel (see Table 16). This represents a very small area or volume of surface waters within which pelagic fish may be exposed. The anticipated responses may be characterized by initial startle responses, increased grouping and schooling behavior, or temporary displacements both laterally and vertically as the Project vessels approach, pass and depart a fixed point in transit. Only near-surface pelagic fish are anticipated to be affected as deepwater pelagic, demersal and benthic fish are present outside of the zone of behavioral disturbance, as defined by the acoustic threshold criteria of 150 dB re 1 μPa_{rms}. At the seabed in

deep water of the gulf (with the deepest point along the export pipeline route being approximately 90 m water depth), the calculated received noise level is 136 dB re 1 μPa_{rms}, which is below the acoustic disturbance threshold criterion of 150 dB re 1 μPa_{rms}.

4.6 Summary of Underwater Noise Sources and Adopted Acoustic Threshold Criteria

Table 17 summarizes the Project's underwater noise types and adopted source levels used in the assessment. Summaries of acoustic threshold criteria adopted for assessment of impacts on various fauna species are provided in Table 3, 4 and 5 (cetaceans and dugongs), Table 6 (fish) and Table 7 (sea turtles and crocodiles).

Table 17 – Summary of Project Underwater Noise Sources, Types and Source Levels

Activity	Activity	Noise Type	Frequency	Source Level
Pile driving at river quay on Purari River	Impact hammer pile driving of sheet piles	Impulsive noise, transient broadband noise	10–600 Hz	205 dB re 1 μPa_{rms} 220 dB re 1 μPa_{pk} 190 dB re $\mu Pa^2 \cdot s$
	Vibratory hammer pile driving of sheet piles	Non-impulsive, transient and continuous broadband noise	20–40 Hz	175 dB re 1 μPa_{rms} 190 dB re 1 μPa_{pk} 175 dB re $\mu Pa^2 \cdot s$
River dredging at river quay on Purari River	Backhoe dredger	Non-impulsive, continuous noise during dredging	100–500 Hz	180 dB re 1 μPa_{rms}
Nearshore trenching and piling in Orokolo Bay	Land-based crane fitted with impact hammer driving sheet piles in very shallow water	Impulsive noise, transient broadband noise	10–600 Hz	180 dB re 1 μPa_{rms} 205 dB re 1 μPa_{pk} 170 dB re $\mu Pa^2 \cdot s$
River vessel traffic and transportation	Project vessels plying river main channels	Non-impulsive, continuous broadband noise	20–1,000 Hz	170 dB re 1 μPa_{rms}
Offshore construction	Pipelay barge maintained in position by anchors	Non-impulsive, continuous broadband noise	10–1,000 Hz (up to 10 kHz)	183 dB re 1 μPa_{rms}
	Concrete mattress installation or rock dumping at PNG LNG Gas Pipeline crossing	Non-impulsive, continuous broadband noise	20–1,000 Hz	183 dB re 1 μPa_{rms}
Marine vessel traffic and transportation	Project vessels plying offshore waters of the Gulf of Papua	Non-impulsive, continuous broadband noise	20–1,000 Hz	175 dB re 1 μPa_{rms}

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6. Abbreviations and Glossary

6.1 Abbreviations and Units

dB decibel(s)

dB re 1 µPa at 1 m decibels with reference to one microPascal at one meter

°C degrees Celsius

DWT dead weight tonnage

EIS environmental impact statement

Ha hectare(s)

Hz Hertz

kg kilogram

kHz kilohertz (1,000 Hz)

km kilometer

km^2 square kilometer

m meter

m^2 square meter

m^3 cubic meter

µPa microPascal(s)

Pa Pascal

PTS permanent threshold shift

SEL sound exposure level

SL source level

SPL sound pressure level

TTS temporary threshold shift

*µ*Pa microPascal (one-millionth of a Pascal)

6.2 Glossary

Alligatorid: as relating to caimans and alligators.

Ambient sound: Environmental background noise not of direct interest during a measurement or observation.

Auditory or hearing threshold: The hearing threshold representing the lowest signal level an animal can detect at a particular frequency, usually referred (and measured) as the threshold at which an animal will indicate detection 50% of the time.

Azimuthal thruster: Configuration of marine propellers placed in pods that can be rotated to any horizontal angle (azimuth) making a rudder unnecessary.

Background: The natural or pre-existing level of a variable.

Cavitation: Formation of bubbles in areas of low pressure around an impeller.

Decibel (**dB**): Logarithmic unit used to express the ratio of two values of a physical quantity, often power or intensity. Used to described sound – the base 10 logarithmic function of the ratio of the pressure fluctuation to a reference pressure. The reference pressure for seawater is 1 µPa compared to 20 µPa for air. The reference level must be known to ensure proper interpretation of the dB value.

Eustachian tube: Tube connecting the palate to the middle ear in crocodiles.

Frequency: Rate at which water particles move backwards and forwards, measured in cycles per seconds or Hertz (Hz).

Hearing or auditory threshold: The hearing threshold represents the lowest signal level an animal can detect at a particular frequency, usually referred (and measured) as the threshold at which an animal will indicate detection 50% of the time.

Hertz: The unit for frequency where 1 Hz = 1 cycle per second. One Kilohertz (kHz) is 1,000 cycles per second.

Impulse or impulsive sound: Transient sound produced by a rapid release of energy, e.g., from a piling impact or explosive. Impulse sounds are typically transient, brief (less than one second) and broadband and consist of high peak sound pressure with rapid rise time and rapid decay.

Isopleth: A line or curve of equal values; a line on a graph showing the occurrence or frequency of a phenomenon as a function of two variables.

Masking (auditory): Obscuring of sounds of interest by interfering sounds at similar frequencies.

Mitigation: Action(s) taken to avoid or reduce the impact of an activity on the environment, socio-cultural or socioeconomic interests.

Mysticete: Any whale of the suborder Mysticeti having plates of whalebone (baleen plates) instead of teeth. Mysticetes are filter-feeding whales, also referred to as baleen whales, such as blue, fin, gray and humpback whales.

Non-impulsive sound: Sounds that can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent and typically do not have a high peak sound pressure with rapid rise or decay time that impulsive sounds do.

Odontocete: Any toothed whale (i.e., cetacean without baleen plates) of the suborder Odontoceti, such as sperm whales, killer whales, beaked whales, dolphins and porpoises.

Peak level: The highest sound pressure level of an impulsive sound signal.

Pelagic: Of or relating to living in open oceans or seas; living at or near the surface of the ocean, far from land, especially relating to fish.

Permanent threshold shift (PTS): The permanent reduction in hearing sensitivity caused by irreversible damage to the sensory hair cells of the ear.

Prootic bulla: A gas-containing sphere evolved from the bones of the ear capsule found in clupeid fish (e.g., sardines, herrings and anchovies).

Pulse: A transient sound having a finite duration.

Sound exposure level (SEL): An acoustic metric that is most often used to compare the total energy in impulsive signals with different time durations, average pressure levels and temporal characteristics. Impulsive underwater noise sources for which the SEL noise descriptor is useful include piling, blasting and geophysical surveys.

Sound pressure level (SPL): Sound pressure expressed in the decibel (dB) base 10 logarithmic scale and with the standard reference pressure of 1 µPa for water.

Source level: A measure of the acoustic output of a source that is independent of the environment; may be related to sound energy or power output. Source level is sometimes stated as a spectral level as a function of frequency (e.g., in third-octave bands) or as a

broadband level (summed over all the frequencies of radiation). Units are expressed in dB re 1 µPa at 1 m.

Spectrum: Distribution of sound energy versus frequency.

Spherical spreading: Received level diminishes by 6 dB per doubling of distance from the source.

Swim (or air) bladder: A gas-filled sac located in the dorsal portion of certain species of fish, which is vulnerable to underwater acoustic pressure. It has flexible walls that contract or expand according to the ambient pressure.

Temporary threshold shift (TTS): Temporal and reversible elevation of the auditory threshold. A temporary reduction in hearing sensitivity caused by exposure to sound. Exposure to high levels of sound over relatively short time periods can cause the same amount of TTS as exposure to lower levels of sound over longer time periods. The duration of TTS varies depending on the nature of the stimulus.

Transmission loss: Reduction of the sound pressure level with distance from the noise source, which occurs through geometric spreading, absorption and scattering of sound energy.

Utricular macula: Pouch in the floor of the utricle (otolith organ) that receives the utricular nerve.

Utricule: Small auditory bone of the inner ear of fish.

Wavelength (sound): The length of the fundamental oscillation of the sound in the propagation medium.