Chapter 10 D.3 JASCO Browse to North West Shelf Noise Modelling Study

Browse to North West Shelf Project Noise Modelling Study

Assessing Marine Fauna Sound Exposures

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Arne De Vos
Jacobs
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Authors:

Craig McPherson
Jorge Quijano
Michelle Weirathmueller
Karen Hiltz
Klaus Lucke

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JASCO Applied Sciences (Australia) Pty Ltd.
Unit 1, 14 Hook Street
Capalaba, Queensland, 4157
Tel: +61 7 3823 2620
www.jasco.com

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Executive Summary

The Browse Joint Venture (BJV) proposes to develop the Brecknock, Calliance, and Torosa fields (collectively known as the Browse resources) via the development drilling of wells and the installation of subsea production system that will supply two 1100 Million standard cubic feet per day (annual daily export average) Floating Production Storage and Offloading (FPSO) facilities. The Browse to North West Shelf (NWS) Project gas will be transported from the FPSO facilities to the existing North West Shelf (NWS) Project infrastructure via a ~900 km trunkline. Each FPSO will have a turret mooring system that will be stabilised using mooring lines secured to the seabed by piles. These piles may have to be installed using impact piling methods.

Underwater noise will be generated during the following activities considered in this modelling study:

- The installation of one subsea FPSO mooring pile per day through impact piling using either a medium or high power hammer,
- The operations of a Mobile Offshore Drilling Unit (MODU),
- Vertical Seismic Profiling (VSP) during drilling operations,
- FPSO operational noise for Torosa and Brecknock FPSO's under normal operating conditions and with Dynamic Positioning (DP) operating,
- FPSO operational noise during offtake, including the FPSO under DP, an Offshore Support Vessel (OSV) near each FPSO (presented in isolation also) and a noiseless condensate tanker, and
- Aggregate scenarios which include FPSOs under normal operating conditions (without DP), as well as offtake operations at both locations simultaneously.

The objective of the modelling study was to determine ranges to acoustic exposure thresholds representing the best available science for potential injury, temporary threshold shift (TTS), and behavioural disturbance of marine fauna including marine mammals, turtles, and fish. For pygmy blue whales and green turtles during pile driving, an additional objective of this modelling study was to predict the number of animals that may be exposed to sound levels that could result in permanent threshold shift (PTS), TTS, or behavioural disturbance.

Acoustic fields caused by pressure were modelled and are presented as sound pressure levels (SPL), zero-to-peak pressure levels (PK), and either single-impulse (i.e., per-strike, per-pulse) or accumulated sound exposure levels (SEL) as appropriate for different noise effect criteria for either continuous (vessels) or impulsive (piling and VSP) noise sources. The effects of range-dependent environmental properties on sound propagation in the study area were accounted for by the numerical models.

For pygmy blue whales and green turtles, the JASCO Animal Simulation Model Including Noise Exposure (JASMINE) was used to integrate the sound fields with species-specific behaviour. JASMINE results provide an estimate of the probability of sound exposure, which can be compared to acoustic thresholds and then scaled to estimate the number of animals expected to receive sound levels that may cause PTS, TTS or behavioural disturbance. To assist with exposure modelling, a modified Biologically Important Area (BIA) for inter-nesting green turtles and a migrating area were considered, along with the pygmy blue whale BIAs for migrating and foraging.

FPSO Anchor Pile Installation

The predicted distances to all per-strike isopleths (contours of equal sound level) are farthest from the piles at the start of piling, when most of the pile remains in the water column, and shortest at the end of piling, when most of the pile is buried in the sediment. This is despite the increased frictional resistance of sediments and stronger stress-wave reflections at the pile toe at later stages of insertion.

For exposure criteria based on SEL_{24h} metrics, the ranges must be considered in context of the duration of operations. The modelling assumed one pile will be driven per day; therefore, the corresponding sound level is denoted as SEL_{24h}; however, the estimated times for driving piles are 78.5 or 45.5 minutes (Torosa) and 80.1 or 47.4 minutes (Brecknock) for medium and high-power

hammers, respectively. SEL_{24h} is a cumulative metric that reflects the dosimetric impact of noise levels within the driving period, assuming that an animal is consistently exposed to such noise levels at a fixed position. The radii that correspond to SEL_{24h} typically represent an unlikely worst-case scenario for SEL-based exposure because, more realistically, marine fauna (mammals or fish) would not stay in the same location or at the same distance from a sound source for an extended period. Therefore, a reported radius for SEL_{24h} criteria does not mean that any animal travelling within this radius from the source *will* be exposed to PTS or TTS, but rather that it *could* be exposed if it remained within that range for the entire duration of the pile driving.

Animal Movement and Exposure Modelling

To present more biologically relevant results, JASMINE was applied for pygmy blue whales and green turtles. The potential risk of acoustic exposure for these species was estimated by finding the accumulated SEL and maximum PK or SPL each simulated animal (animat) received over the duration of the simulation, using acoustic exposure thresholds representing the best available science for PTS, TTS, and behavioural disturbance. The results include the range within which 95% of the exposure exceedances occur (95th percentile ranges, P_{95}) and the projected number of individual animals exposed to sound levels above threshold values. The number of individuals was determined by scaling the number of animats exposed above threshold in the simulation using available density data and considering the relevant BIAs. The modelling considered the behaviour of pygmy blue whales while migrating and foraging, and green turtles while inter-nesting and migrating. For migratory green turtles, no density data were available, so results are presented in terms of 95th percentile ranges only. Mitigation of potential impacts through exclusion zones for pygmy blue whales and turtles (2000 and 500 m, respectively) were considered in the modelling.

Torosa Location

The number of green turtle exposures above PTS PK or PTS SEL_{24h} thresholds was zero, regardless of hammer type. The number of pygmy blue whale exposures above PTS PK was zero, and there were between 0.02 and 0.03 migrating or foraging pygmy blue whale exposures above the PTS SEL_{24h} threshold for either hammer without mitigation.

No inter-nesting green turtle animats were predicted to be exposed above threshold levels for PTS or TTS for either hammer. Densities were not available for migratory turtles; however, no turtle animats were predicted to be exposed to noise levels above PTS PK, PTS SEL_{24h}, or TTS PK thresholds. No migratory pygmy blue whales were predicted to be exposed to noise above PTS PK or TTS PK thresholds. With exclusion zones in place, exposures to injury threshold criteria for both species and both hammers were reduced to zero. TTS SEL_{24h} was still predicted to occur, with no substantial change to exposure numbers. This is because a large proportion of animats exposed above that threshold occurred at ranges greater than the exclusion zones.

The overall potential for behavioural impacts is also predicted to be low for both species. None are predicted for inter-nesting green turtles. While no real-world densities for migratory green turtles are available, the 95th percentile ranges for the most conservative case (the high power hammer and the 166 dB SPL behavioural response threshold) were between 2.54 and 4.64 km from the pile. The number of individual pygmy blue whales predicted to be exposed to noise levels exceeding the behavioural threshold was between 0.56 and 1.41 individuals, depending upon the hammer size.

Applying exclusion zones had less influence on exposures above behavioural thresholds. Ranges associated with migrating green turtles showed no substantial change, except that all animats exposed to the 175 dB SPL behavioural disturbance threshold, which were within 50 m of the pile, were removed from consideration. Therefore, the application of the exclusion zone reduced the number of animats exposed above threshold by 100%, or to zero. Both foraging and migrating pygmy blue whale exposures above the 160 dB SPL threshold, for both hammers, decreased slightly.

Brecknock Location

Results predicted that green turtles were unlikely to be exposed the noise above threshold levels for PTS, TTS, or behavioural disturbance, even without applying a 500 m exclusion zone. This is because the Brecknock pile location is more than 40 km from either the modified inter-nesting or migration area BIAs.

With no exclusion zone, pygmy blue whales were not exposed to noise levels above PTS PK or TTS PK for either hammer, exposures above the threshold for PTS SEL_{24h} ranged from 0.02–0.04 for either the medium or high powered hammer, respectively. TTS SEL_{24h} exposures for migrating blue whales ranged from 1.56–1.67 for either the medium or high powered hammer, respectively. The number of predicted exposures above TTS SEL_{24h} threshold for foraging pygmy blue whales was much lower than for migrating pygmy blue whales because the Brecknock piling location is 10.3 km from the foraging BIA.

With the 2000 m exclusion zone in place, PTS SEL_{24h} exposures reduced to zero for either hammer. The number of predicted exposures for foraging pygmy blue whales did not change as a result of applying an exclusion zone because of the large distance to the BIA.

Torosa and Brecknock Ranges to Exposure Thresholds

The analysis considered multiple effects criteria commonly used in pile driving noise assessments. Key results of the acoustic modelling are summarised below.

Marine Mammals

- United States National Marine Fisheries Service (NMFS 2014) acoustic threshold for behavioural effects in cetaceans: Pile driving impulse sounds are predicted to exceed the SPL threshold of 160 dB re 1 µPa for behavioural effects of marine mammals within 10.48 or 17.15 km (Torosa), or 7.06 or 13.97 km (Brecknock), of the pile (medium and high power hammer, respectively), are associated with the shallowest penetration of 17 m for both hammers.
- The results for the NMFS (2018) criteria applied for marine mammal PTS and TTS consider both metrics within the criteria (PK and SEL), with SEL assessed here for a single pile within a 24 h period, i.e., a single pile per day. The metric with the longest distance must be applied, and these maximum distances along with the relevant metric are summarised in Table 1.

Table 1. *Marine mammal injury and hearing sensitivity changes*: Maximum-over-depth distances (in km) from the pile to PTS and TTS thresholds (NMFS 2018).

Hearing group	PTS				TTS			
	IHC S-600		IHC S-1200		IHC S-600		IHC S-1200	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Torosa								
LF cetaceans	5.15#	5.00#	5.35#	5.12#	26.10#	20.79#	29.46#	22.60#
MF cetaceans	<0.02†		<0.02†		0.03#		0.06#	0.06#
HF cetaceans	0.21†		0.26†		0.35†	0.30#	2.20#	2.06#
Brecknock								
LF cetaceans	4.58#	4.05#	4.62#	4.40#	23.11#	20.04#	24.75#	20.80#
MF cetaceans	<0.02†		<0.02†		<0.02†		0.05#	0.05#
HF cetaceans	0.19†		0.26†		0.36†	0.31#	2.33#	2.20#

† PK (L_{pk}; dB re 1 µPa)
# Frequency weighted SEL_{24h} ($L_{E,24h}$). For the SEL_{24h} criteria, the model does not account for shutdowns.

Turtles

- The maximum distances to the two criteria considered in relation to turtle behaviour, behavioural response and disturbance, are associated with the shallowest penetration of 17 m for both hammers, with the maximum distances summarised in Table 2.
- The results for the Finneran et al. (2017) criteria applied for turtle PTS and TTS consider both metrics within the criteria (PK and SEL), with SEL assessed here for a single pile within a 24 h period, i.e., a single pile per day. The metric with the longest distance must be applied, and these maximum distances along with the relevant metric are summarised in Table 3.

Table 2. *Turtle behaviour*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile to modelled maximum-over-depth behavioural response thresholds, maximum across all three penetration depths.

SPL (L_p; dB re 1 µPa)	IHC S-600		IHC S-1200	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Torosa				
175†	0.68	0.64	1.87	1.79
166‡	5.11	4.99	9.11	5.66
Brecknock				
175†	0.67	0.63	1.87	1.77
166‡	2.87	2.70	6.38	5.92

† Threshold for turtle behavioural response to impulsive noise (McCauley et al. 2000a, 2000b).
‡ Threshold for turtle behavioural response to impulsive noise (NSF 2011).

Table 3. *Turtle injury and hearing sensitivity changes*: Maximum-over-depth distances (in km) from the pile to turtle PTS and TTS thresholds (Finneran et al. 2017).

Hearing group	PTS				TTS			
	IHC S-600		IHC S-1200		IHC S-600		IHC S-1200	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Torosa								
Turtles	0.24	0.23	0.25	0.25	4.79	2.36	5.07	4.94
Brecknock								
Turtles	0.24	0.23	0.25	0.24	2.58	2.44	2.60	2.47

All distances are associated with frequency weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s), not PK (L_{pk}; dB re 1 µPa). For the SEL_{24h} criteria, the model does not account for shutdowns.

Fish, Fish Eggs, and Fish Larvae

- The modelling study assessed the ranges for quantitative criteria from Popper et al. (2014) associated with mortality and potential mortal injury and impairment (as defined in the criteria) in the following:
  - Fish without a swim bladder (also appropriate for sharks in the absence of other information)
  - Fish with a swim bladder not used for hearing
  - Fish that use their swim bladders for hearing
  - Fish eggs, and fish larvae
- The distance from pile driving at which sound levels exceeded mortality and potential mortal injury for the most sensitive fish groups from the piles was as follows for the medium or high-powered hammer, respectively:
  - Torosa, 210 or 220 m (SEL_{24h} metric),
  - Brecknock, 200 or 220 m (SEL_{24h} metric)
- Fish (including sharks) could experience TTS from the proposed pile driving activity. It is predicted that this will occur within the following distances of the pile for the medium or high-powered hammer, respectively:
  - Torosa, 9.05 or 9.15 km
  - Brecknock, 6.12 or 6.27 km

Vertical Seismic Profiling

The modelling scenarios for VSP considered a single 750 in^3 array suspended at 6 m at the MODU location at both Torosa TRD Well and Brecknock, and these scenarios assessed both individual impulses and multiple impulses within a 24 h period to determine SEL_{24h}.

The analysis considered multiple effects criteria commonly used in seismic survey noise assessments. Key results of the acoustic modelling are summarised below.

Marine mammals

- The maximum distance where the NMFS (2014) marine mammal behavioural response criterion of 160 dB re 1 µPa (SPL) could be exceeded varied between 1.6 and 1.7 km, with the distance being longer at Brecknock.
- The results for the criteria applied for marine mammal PTS, NMFS (2018), consider both metrics within the criteria (PK and SEL_{24h}), and a range of impulses within 24 h, from 1 to 150. The applicable metric from the criteria, associated with the longest distance associated with either metric, depends upon the number of impulses with the 24 h. The ranges presented are based upon no more than 150 impulses within 24 h.

  PTS and TTS are not predicted to occur in mid-frequency cetaceans. For PTS in high-frequency cetaceans, the PK metric is always associated with the longest range (68 m), while for PTS in low-frequency cetaceans, for less than 10 impulses the range is greater due to the PK metric (12 m), but otherwise the range is determined by SEL_{24h}, with the maximum distance of 200 m being associated with 150 impulses at either Torosa TRD Well or Brecknock.

  For TTS in high-frequency cetaceans the PK metric is always associated with the longest range (141 m), while for TTS in low-frequency cetaceans the range is determined by SEL_{24h}, with the maximum distance of 1.69 km for 150 impulses at Torosa TRD Well or Brecknock.

Turtles

- The VSP source is not predicted to cause PTS in turtles, as it doesn't cause either the PK or SEL_{24h} criteria from Finneran et al. (2017) to be exceeded at a distance greater than the horizontal modelling resolution (20 m) from the source.

As with marine mammals, the SEL_{24h} considers a range of impulses within 24 h, from 1 to 150. While the TTS criteria due to the PK metric isn't exceeded, depending upon the number of impulses, the TTS SEL_{24h} criteria can be exceeded at up to 160 m for 150 impulses at Torosa TRD Well or Brecknock.

- The distances at where the two criteria considered in relation to turtle behaviour, behavioural response and disturbance could be exceeded are summarised in Table 4.

Table 4. *Turtle behaviour*: Distances to behavioural response criteria for VSP.

SPL (L_p; dB re 1 µPa)	R_{max} (km)	$R_{95\%}$ (km)
Torosa TRD Well		
175†	0.23	0.23
166‡	0.81	0.77
Brecknock		
175†	0.23	0.23
166‡	0.72	0.69

† Threshold for turtle behavioural response to impulsive noise (McCauley et al. 2000a, 2000b).
‡ Threshold for turtle behavioural response to impulsive noise (NSF 2011).

Fish, fish eggs, and fish larvae

- This modelling study assessed the ranges for quantitative criteria based on Popper et al. (2014) and considered both PK (seafloor and water column) and SEL_{24h} metrics associated with mortality and potential mortal injury and impairment in the groups listed in the piling section
- The distance from pile driving at which sound levels exceeded mortality and potential mortal injury for the most sensitive fish groups was 40 m (PK metric).
- Sound levels at the seafloor do not exceed any of the fish criteria, and SEL_{24h} metrics for injury were not exceeded in the water column

Sponges and Coral

- To assist with assessing the potential effects on sponges and coral receptors, the PK sound level at the seafloor directly underneath the VSP source was estimated at both modelling sites. It was found that the sound level of 226 dB re 1 µPa PK, a sound level associated with no effect (Heyward et al. 2018) was not reached.

Vessel Operations

The modelled scenarios for vessels consider the following sources or scenarios:

- Two FPSO facilities 370 m long and 67 m wide, both under typical operations, with no thrusters and no offtake, only topsides equipment, and under dynamic positioning representative of typical operational loads during moderate weather conditions;
- A representative OSV, a dynamic positioning Class 2 (DP2) vessel within 700 m of each FPSO under dynamic positioning representative of typical operational loads during moderate weather conditions;
- A representative MODU that is 100 × 80 m under dynamic positioning, representative of typical operational loads during moderate weather conditions;
- FPSO operational noise during offtake, including the FPSO under DP, an Offshore Support Vessel (OSV) near each FPSO (presented in isolation also) and a noiseless condensate tanker, and
- Aggregate scenarios which include FPSOs under normal operating conditions (without DP), as well as offtake operations, at both locations simultaneously.

The analysis considered multiple effects criteria commonly used, with key results of the acoustic modelling are summarised below.

Marine mammals

- The results for the NMFS (2018) criteria applied for marine mammal PTS and TTS for vessels are assessed here for a 24 h period. The maximum distances to PTS are summarised in Table 5.
- The maximum distances to the NMFS (2014) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) are summarised in Table 6.
- For aggregate scenarios considering both FPSO's, it was found that due to the separation between the sites, distances to PTS, TTS, and behavioural thresholds remained unaltered compared to the individual operations. This was quantified by verifying that the total aggregate area within threshold isopleth for marine mammal behavioural response to continuous noise (NMFS 2014) area equals the sum of the areas for the individual operations.

Table 5. *Marine mammal injury*: Maximum (R_{max}) horizontal distances (km) to modelled maximum-over-depth PTS thresholds from NMFS (2018) for vessel-based scenarios.

Hearing group	Threshold for PTS, SEL_{24h} (dB re 1 µPa²·s) #	Distance R_{max} (km)				
		MODU	OSV	FPSO on DP	FPSO without DP	FPSO offtake
Torosa						
LF cetaceans	199	0.11	0.05	0.12	-	0.12
MF cetaceans	198	-	-	<0.02	-	<0.02
HF cetaceans	173	0.15	0.07	0.28	-	0.28
Brecknock						
LF cetaceans	199	0.11	0.06	0.12	<0.02	0.12
MF cetaceans	198	-	-	<0.02	-	<0.02
HF cetaceans	173	0.15	0.07	0.28	<0.02	0.28

Frequency weighted.
A dash indicates the level was not reached.
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Table 6. *Marine mammal behaviour*: Summary of maximum behavioural disturbance distances for vessel-based scenarios.

SPL (L_p; dB re 1 µPa)	Distance R_{max} (km)				
	MODU	OSV	FPSO on DP	FPSO without DP	FPSO offtake
Torosa					
120†	10.50	2.25	8.77	0.57	8.89
Brecknock					
120†	8.84	2.39	8.78	0.54	8.89

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Turtles

- The results for the Finneran et al. (2017) criteria applied for turtle PTS for vessel-based scenarios are assessed here for a 24 h period, and the maximum distances are summarised in Table 7.

Table 7. *Turtle injury*: Maximum-over-depth distances (in km) to PTS threshold (Finneran et al. 2017) for vessel-based scenarios.

SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Distance R_{max} (km)				
	MODU	OSV	FPSO on DP	FPSO without DP	FPSO offtake
Torosa					
220†	0.06	0.06	<0.02	-	<0.02
Brecknock					
220†	0.06	0.06	<0.02	-	<0.02

† Threshold for turtle-weighted SEL_{24h} (Finneran et al. 2017).
A dash indicates the level was not reached.
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Fish

- Sound produced by the vessel operations could cause physiological effects, and recoverable injury, to some fish species, but only if the animals are in very close proximity to the sound sources–within a planar distance of 60 m, for 48 h. Temporary impairment due to TTS could occur at similar short distances if fish remain at the same point within the sound field for long periods of time (12 h). The distances are farther for the MODU, and smallest for the FPSO without DP.
- For offtake operations, recoverable injury and temporary impairment could happen if fish remain within planar distances of <20 m and 40 m, respectively, from the FPSO or the OSV thrusters.
- There is no increased risk to fish from aggregate scenarios, with ranges to thresholds from the individual sources unchanged.

1. Introduction

JASCO Applied Sciences (JASCO) performed a modelling study of underwater sound levels associated with the Browse to North West shelf (NWS) Project development of the Brecknock, Calliance, and Torosa fields (collectively known as the Browse resources) by the Browse Joint Venture (BJV). This will involve the development drilling of wells and the installation of subsea production system that will supply two 1100 Million standard cubic feet per day (annual daily export average) Floating Production Storage and Offloading (FPSO) facilities. Gas will be transported from the FPSO facilities to the existing North West Shelf (NWS) Project infrastructure via a ~900 km trunkline. Each FPSO will have a turret mooring system that will be stabilised using mooring lines secured to the seabed by piles.

The modelling study considers:

- The installation of a single subsea FPSO mooring pile per day through impact piling using either a medium or high power hammer;
- The operations of a Mobile Offshore Drilling Unit (MODU);
- Vertical Seismic Profiling (VSP) during drilling operations;
- FPSO operational noise for Torosa and Brecknock FPSO's under normal operating conditions and with Dynamic Positioning (DP) operating;
- FPSO operational noise during offtake, including the FPSO under DP, an Offshore Support Vessel (OSV) near each FPSO (presented in isolation also) and a noiseless condensate tanker; and
- Aggregate scenarios which include FPSOs under normal operating conditions (without DP), as well as offtake operations at both locations simultaneously.

The modelling study specifically assessed distances from operations where underwater sound levels reached thresholds corresponding to various levels of impact to marine fauna. The animals considered here included marine mammals (pygmy blue whales, *Balaenoptera musculus brevicauda*), turtles, and fish (including fish eggs and larvae). Due to the variety of species considered, there are several different thresholds for evaluating effects, including: mortality, injury, temporary reduction in hearing sensitivity, and behavioural disturbance.

The modelling methodology considered source directivity and range-dependent environmental properties. Estimated underwater acoustic levels are presented as sound pressure levels (SPL, L_p), zero-to-peak pressure levels (PK, L_{pk}), and either single-impulse (i.e., per-strike) or accumulated sound exposure levels (SEL, L_E) as appropriate for different noise effect criteria for either continuous (vessels) or impulsive (piling and VSP) noise sources.

In addition to the propagation modelling, this report describes the modelled predictions of sound levels that individual animals may receive during the operations. Sound exposure distribution estimates for pygmy blue whales and green turtles (*Chelonia mydas*) to pile driving operations are determined by moving large numbers of simulated animals through a modelled time-evolving sound field, computed using specialised sound source and sound propagation models. This approach provides the most realistic prediction of the maximum expected SPL, PK, and the temporal accumulation of SEL that are considered the most relevant sound metrics for impact assessment. The most recent science in the peer-reviewed literature regarding sound propagation and animal movement modelling was used.

The geographic coordinates for the modelled sites are provided in Table 8 and an overview of the modelling area is shown in Figure 1.

Table 8. Location details for the modelled sites.

Site	Source	Latitude (S)	Longitude (E)	MGA (GDA94), Zone 51		Water depth (m)
				X (m)	*Y* (m)	
Torosa	FPSO Anchor Pile	13° 58' 16.97"	122° 00' 05.23"	392148	8455212	448
	FPSO (turret)	13° 58' 15.06"	122° 01' 28.53"	394647	8455281	463
	OSV (bow)	13° 58' 15.06"	122° 00' 50.38"	393502.3	8455276	463
Torosa TRD Well	MODU (centre)	14° 00' 26.64"	121° 57' 23.58"	387315	8451207	391
	VSP (MODU centre)					
Brecknock	FPSO Anchor Pile	14° 31' 10.31"	121° 37' 50.58"	352456	8394373	506
	FPSO (turret)	14° 31' 51.44"	121° 36' 38.47"	350305	8393096	515
	OSV (bow)	14° 31' 14.19"	121° 36' 38.55"	350300.3	8394241	515
	MODU (centre)	14° 26' 49.45"	121° 38' 52.09"	354250	8402400	467
	VSP (MODU centre)					

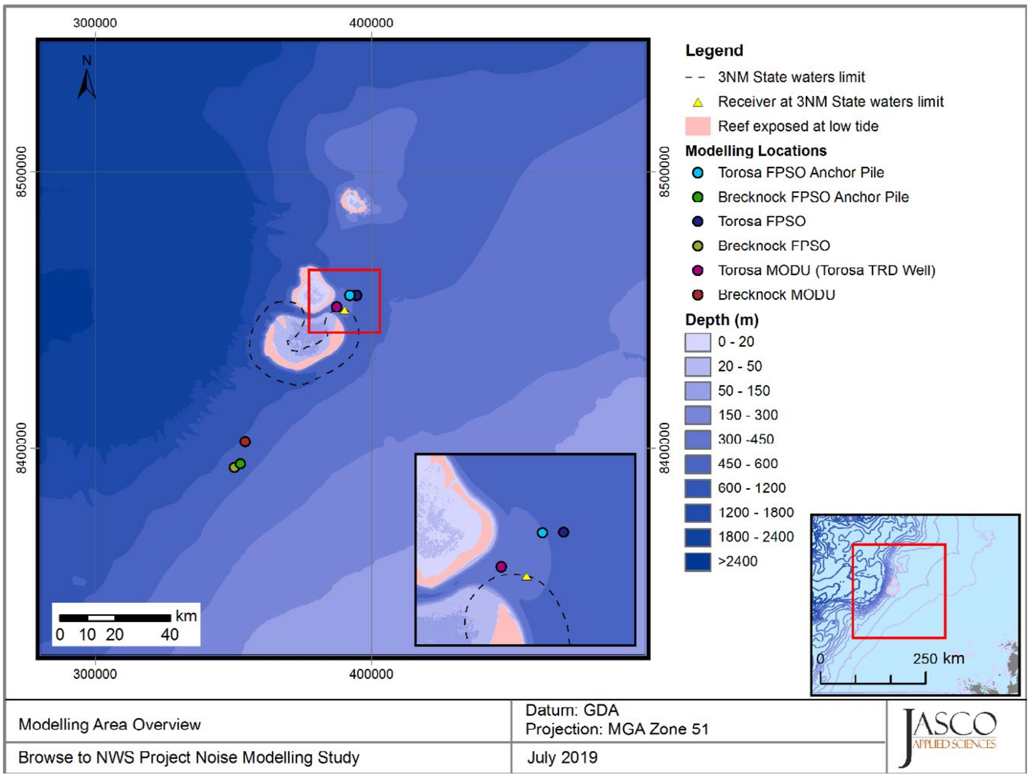

Figure 1. Overview of the modelled area and local features.

1.1. Acoustic Modelling Scenario Details

The modelling scenario for pile driving of the Torosa FPSO anchor pile (Section 3.4) considers a pile 53.25 m long, 5.5 m in diameter with 60 mm thick walls, driven a total of 51.5 m into the seabed. Two pile driving hammers were considered in this study: the IHC S-600 with 600 kJ per-strike energy and the IHC S-1200 with 1200 kJ. The modelling assumed one pile will be driven per day; therefore, while the corresponding sound level is denoted SEL_{24h}, the period of accumulation considered in the scenario is determined based upon the estimated time for driving the single pile.

The modelled scenarios for vessels (Section 3.6) consider:

- Two FPSO facilities 370 m long and 67 m wide:
  - Both under typical operations, with no thrusters and no offtake, only topsides equipment;
  - Under dynamic positioning representative of typical operational loads during moderate weather conditions;
  - Under offtake, during which the FPSO is under DP, and an OSV under DP is located 700 m behind the FPSO, and a noiseless condensate tanker is between the FPSO and the OSV; and
  - Aggregate scenarios which include FPSOs under normal operating conditions (without DP), as well as offtake operations at both locations simultaneously.
- A representative OSV, a dynamic positioning Class 2 (DP2) vessel 87.08 m long, within 700 m of each FPSO under dynamic positioning representative of typical operational loads during moderate weather conditions.
- A representative MODU that is 100 × 80 m under dynamic positioning, representative of typical operational loads during moderate weather conditions.

The modelling scenarios for VSP (Section 3.5) consider a single 750 in^3 array suspended at 6 m at the MODU location at both Torosa TRD Well and Brecknock, and these scenarios assessed both individual impulses and up to 150 impulses within a 24 h period.

Table 9. Modelled receiver location for Torosa FPSO Anchor Piling

Sound field sampling location	Latitude (S)	Longitude (E)	MGA (GDA94), Zone 51		Relevant modelled scenario	Distance from sampling location to modelled site (km)	Water depth (m)
			X (m)	*Y* (m)			
3NM State waters limit	14° 01' 02.5404"	121° 59' 03.5282"	390318	8450117	Torosa FPSO anchor pile	5.41	414

2. Noise Effect Criteria

To assess the potential impacts of a sound-producing activity, it is necessary to first establish exposure criteria (thresholds) for which sound levels may be expected to have a negative impact on animals. Whether acoustic exposure levels might injure or disturb marine fauna is an active research topic. Since 2007, several expert groups have developed SEL-based assessment approaches for evaluating auditory injury, with key works including Southall et al. (2007), Finneran and Jenkins (2012), Popper et al. (2014), and United States National Marine Fisheries Service (NMFS 2018). The number of studies that investigate the level of behavioural disturbance to marine fauna by anthropogenic sound has also increased substantially.

Several sound level metrics, such as PK, SPL, and SEL, are commonly used to evaluate noise and its effects on marine life (Appendix A). In this report, the duration of the SEL accumulation is defined differently depending on the source considering, as per the following:

- For piling: As either a "per-strike" value (i.e., integrated over the time of a single strike), or over all strikes that occur over the driving of a single pile, one pile per 24 h time period.
- For VSP: As either a "per-pulse" value (i.e., integrated over the time of a single pulse), or over all impulses that occur in a 24 h time period.
- For vessels: Integrated over a 24 h time period.

Appropriate subscripts indicate any applied frequency weighting applied (Appendix A.3). The acoustic metrics in this report reflect the updated ANSI and ISO standards for acoustic terminology, ANSI S1.1 (R2013) and ISO 18405:2017 (2017).

This study applies the following noise criteria (Sections 2.1–2.2 and Appendix A.2), chosen for their acceptance by regulatory agencies and because they represent current best available science:

1. Peak pressure levels (PK; L_{pk}) and frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from the U.S. National Oceanic and Atmospheric Administration (NOAA) Technical Guidance (NMFS 2018) for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in marine mammals.
2. Marine mammal behavioural threshold based on the current interim U.S. National Marine Fisheries Service (NMFS) criterion NMFS (2014) for marine mammals of 160 dB re 1 µPa and 120 dB re 1 µPa SPL (L_p) for impulsive and non-impulsive sound sources, respectively.
3. Sound exposure guidelines for fish, fish eggs, and larvae (Popper et al. 2014).
4. Peak pressure levels (PK; L_{pk}) and frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Finneran et al. (2017) for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in turtles.
5. Turtle behavioural response threshold of 166 dB re 1 µPa SPL (L_p) (NSF 2011), as applied by the US NMFS, along with a sound level associated with behavioural disturbance 175 dB re 1 µPa (SPL) (McCauley et al. 2000a, 2000b).

Additionally, for comparison to published literature, for VSP only, a sound level of 226 dB re 1 µPa PK (L_{pk}), a no effect sound level, is reported for comparing to Heyward et al. (2018) for sponges and corals.

2.1. Marine Mammals

The criteria applied in this study to assess possible effects of pile driving noise and vessel noise on marine mammals are summarised in Tables 10 and 11 and detailed in Sections 2.1.1 and 2.1.2, with frequency weighting explained in Appendix A.3.

Table 10. Acoustic effects of impulsive noise on marine mammals: Unweighted SPL, SEL_{24h}, and PK thresholds

Hearing group	NMFS (2014)	NMFS (2018)			
	Behaviour	PTS onset thresholds* (received level)		TTS onset thresholds* (received level)	
	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	PK (L_{pk}; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	PK (L_{pk}; dB re 1 µPa)
LF cetaceans	160	183	219	168	213
MF cetaceans		185	230	170	224
HF cetaceans		155	202	140	196

* Dual metric acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS onset. If a non-impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds should also be considered.
L_p denotes sound pressure level period.
$L_{pk,flat}$ denotes peak sound pressure is flat weighted or unweighted.
L_E denotes cumulative sound exposure over a 24 h period.

Table 11. Acoustic effects of continuous noise on marine mammals: Unweighted SPL and SEL_{24h} thresholds.

Hearing group	NMFS (2014)	NMFS (2018)	
	Behaviour	PTS onset thresholds (received level)	TTS onset thresholds (received level)
	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)
LF cetaceans	120	199	179
MF cetaceans		198	178
HF cetaceans		173	153

L_p denotes sound pressure level period and has a reference value of 1 µPa.
L_E denotes cumulative sound exposure over a 24 h period and has a reference value of 1 µPa²s.

2.1.1. Behavioural response

Numerous studies on marine mammal behavioural responses to sound exposure have not resulted in consensus in the scientific community regarding the appropriate metric for assessing behavioural reactions. However, it is recognised that the context in which the sound is received affects the nature and extent of responses to a stimulus (Southall et al. 2007, Ellison and Frankel 2012, Southall et al. 2016). Because of the complexity and variability of marine mammal behavioural responses to acoustic exposure, NMFS has not yet released technical guidance on behaviour thresholds for use in calculating animal exposures (NMFS 2018). The NMFS currently uses a step function to assess behavioural impact. A 50% probability of inducing behavioural responses at a SPL of 160 dB re 1 µPa was derived from the HESS (1999) report which, in turn, was based on the responses of migrating mysticete whales to airgun sounds (Malme et al. 1983, Malme et al. 1984). The HESS team recognised that behavioural responses to sound may occur at lower levels, but significant responses were only likely to occur above a SPL of 140 dB re 1 µPa. An extensive review of behavioural responses to sound was undertaken by Southall et al. (2007, their Appendix B). Southall et al. (2007) found varying responses for most marine mammals between a SPL of 140 and 180 dB re 1 µPa, consistent with the HESS (1999) report, but lack of convergence in the data prevented them from suggesting explicit step functions.

2.1.1.1. Impulsive noise

The absence of controls, precise measurements, appropriate metrics, and context dependency of responses (including the activity state of the animal) all contribute to the variability of the behavioural response of individuals. Therefore, unless otherwise specified, this study applied NMFS's relatively simple sound level criterion for potentially disturbing a marine mammal. For impulsive sounds, this threshold is 160 dB re 1 µPa SPL for cetaceans (NMFS 2014).

2.1.1.2. Continuous noise

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

2.1.2. Injury and hearing sensitivity changes

There are two categories of auditory threshold shifts or hearing loss: permanent threshold shift (PTS), a physical injury to an animal's hearing organs; and Temporary Threshold Shift (TTS), a temporary reduction in an animal's hearing sensitivity as the result of receptor hair cells in the cochlea becoming fatigued.

To assist in assessing the potential for effects to marine mammals, this report applies the criteria recommended by NMFS (2018), considering both PTS and TTS (Tables 10 and 11). Appendix A.2 provides more information about the NMFS (2018) criteria.

2.2. Fish, Turtles, Fish Eggs, and Fish Larvae

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

- Mortality, including injury leading to death,
- Recoverable injury, including injuries unlikely to result in mortality, such as hair cell damage and minor haematoma, and
- TTS.

Masking and behavioural effects can be assessed qualitatively, by assessing relative risk rather than by specific sound level thresholds. However, as these depend upon activity-based subjective ranges, these effects are not addressed in this report and are included in Tables 12 and 14 for completeness only. Because the presence or absence of a swim bladder has a role in hearing, fish's susceptibility to injury from noise exposure depends on the species and the presence and possible role of a swim bladder in hearing. Thus, different thresholds were proposed for fish without a swim bladder (also appropriate for sharks and applied to whale sharks in the absence of other information), fish with a swim bladder not used for hearing, and fish that use their swim bladders for hearing. Turtles, fish eggs, and fish larvae are considered separately.

2.2.1. Impulsive noise

Impulsive noise from both piling and airguns (VSP) is assessed in this study, the relevant effects thresholds from Popper et al. (2014) are listed in Table 12. In general, whether an impulsive sound adversely effects fish behaviour depends on the species, the state of the individual exposed, and other factors.

The SEL metric integrates noise intensity over some period of exposure. Because the period of integration for regulatory assessments is not well defined for sounds that do not have a clear start or end time, or for very long-lasting exposures, an exposure evaluation time must be defined. Southall et al. (2007) defines the exposure evaluation time as the greater of 24 h or the duration of the activity. Popper et al. (2014) recommend a standard period of the duration of the activity; however, the publication also includes caveats about considering the actual exposure times if fish move. Integration times in this study for piling have been applied over the time a single pile was driven since only one pile is expected to be driven per day, while for VSP operations it is over the total number of impulses per day.

Table 12. Criteria for pile driving and seismic noise exposure for fish, adapted from Popper et al. (2014).

Type of animal	Mortality and Potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: No swim bladder (particle motion detection)	> 219 dB SEL_{24h} or > 213 dB PK	> 216 dB SEL_{24h} or > 213 dB PK	>> 186 dB SEL_{24h}	Pile driving: (N) Moderate (I, F) Low Seismic: (N, I, F) Low	(N) High (I) Moderate (F) Low
Fish: Swim bladder not involved in hearing (particle motion detection)	210 dB SEL_{24h} or > 207 dB PK	203 dB SEL_{24h} or > 207 dB PK	>> 186 dB SEL_{24h}	Pile driving: (N) Moderate (I, F) Low Seismic: (N, I, F) Low	(N) High (I) Moderate (F) Low
Fish: Swim bladder involved in hearing (primarily pressure detection)	207 dB SEL_{24h} or > 207 dB PK	203 dB SEL_{24h} or > 207 dB PK	186 dB SEL_{24h}	Pile driving: (N, I) High (F) Moderate Seismic: (N, I) Low (F) Moderate	(N, I) High (F) Moderate
Fish eggs and fish larvae	> 210 dB SEL_{24h} or > 207 dB PK	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	Pile driving: (N) Moderate (I, F) Low Seismic: (N, I, F) Low	(N) Moderate (I, F) Low

Peak sound pressure level dB re 1 µPa; SEL_{24h} dB re 1µPa^2·s.
All criteria are presented as sound pressure even for fish without swim bladders since no data for particle motion exist.
Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).

2.2.1.1. Turtles

There is a paucity of data regarding responses of turtles to acoustic exposure, and no studies of hearing loss due to exposure to loud sounds. McCauley et al. (2000a) observed the behavioural response of caged turtles—green (*Chelonia mydas*) and loggerhead (*Caretta caretta*)—to an approaching seismic airgun. For received levels above 166 dB re 1 µPa (SPL), the turtles increased their swimming activity and above 175 dB re 1 µPa they began to behave erratically, which was interpreted as an agitated state. The 166 dB re 1 µPa level has been used as the threshold level for a behavioural disturbance response by NMFS and applied in the Arctic Programmatic Environment Impact Statement (PEIS) (NSF 2011). At that time, and in the absence of any data from which to determine the sound levels that could injure an animal, TTS or PTS onset were considered possible at an SPL of 180 dB re 1 µPa (NSF 2011). Some additional data suggest that behavioural responses occur closer to an SPL of 175 dB re 1 µPa, and TTS or PTS at even higher levels (Moein et al. 1995), but the received levels were unknown and the NSF (2011) PEIS maintained the earlier NMFS criteria levels of 180 and 166 dB re 1 µPa (SPL) for injury and behavioural response, respectively. Popper et al. (2014) suggested injury to turtles could occur for sound exposures above 207 dB re 1 µPa (PK) or above 210 dB re 1 µPa^2·s (SEL_{24h}). Sound levels defined by Popper et al. (2014) show that animals are very likely to exhibit a behavioural response when they are near an airgun (tens of metres), a moderate response if they encounter the source at intermediate ranges (hundreds of metres), and a low response if they are far (thousands of meters) from the airgun.

Finneran et al. (2017) presented revised thresholds for turtle injury (PTS) and TTS, considering both PK and frequency weighted SEL, which have been applied in this study, along with the NMFS criterion for behavioural response (SPL of 166 dB re 1 µPa), and a criterion for behavioural disturbance (SPL of 175 dB re 1 µPa) (Moein et al. 1995, McCauley et al. 2000a, 2000b) (Table 13).

Table 13. Acoustic effects of impulsive noise on turtles: Unweighted SPL, SEL_{24h}, and PK thresholds

NSF (2011)	Moein et al. (1995), McCauley et al. (2000a), (2000b)	Finneran et al. (2017)			
Behaviour		PTS onset thresholds* (received level)		TTS onset thresholds* (received level)	
SPL (L_p; dB re 1 µPa)		Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s)	PK (L_{pk}; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s)	PK (L_{pk}; dB re 1 µPa)
160	175	204	232	189	226

* Dual metric acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS onset. If a non-impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds should also be considered.
L_p denotes sound pressure level period and has a reference value of 1 µPa.
$L_{pk,flat}$ denotes peak sound pressure is flat weighted or unweighted and has a reference value of 1 µPa.
L_E denotes cumulative sound exposure over a 24 h period and has a reference value of 1 µPa^{2}s.

2.2.2. Continuous noise

Table 14 lists the relevant effects thresholds from Popper et al. (2014) for shipping and continuous noise. Some evidence suggests that fish sensitive to acoustic pressure show a recoverable loss in hearing sensitivity, or injury when exposed to high levels of noise (Scholik and Yan 2002, Amoser and Ladich 2003, Smith et al. 2006); this is reflected in the SPL thresholds for fish with a swim bladder involved in hearing.

Finneran et al. (2017) presented revised thresholds for turtle injury, considering frequency weighted SEL, which have been applied in this study for vessels (Table 15).

Table 14. Criteria for vessel noise exposure for fish, adapted from Popper et al. (2014).

Type of animal	Mortality and Potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: No swim bladder (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder not involved in hearing (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder involved in hearing (primarily pressure detection)	(N) Low (I) Low (F) Low	170 dB SPL for 48 h	158 dB SPL for 12 h	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Turtles	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) High (I) Moderate (F) Low
Fish eggs and fish larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

Sound pressure level dB re 1 µPa.
Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).

Table 15. Acoustic effects of continuous noise on turtles, weighted SEL_{24h}, Finneran et al. (2017).

PTS onset thresholds* (received level)	TTS onset thresholds* (received level)
Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa2·s)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa2·s)
204	189

L_E denotes cumulative sound exposure over a 24 h period and has a reference value of 1 µPa^{2}s.

3. Methods

The operations considered in this study will take place at the Torosa and Brecknock fields, respectively, at depths 391–567 m (Appendix F.3.1). For the sites within the Torosa field, sound propagation is partially blocked in some directions by the reefs, due to a sharp decrease in water depth. Activities could take place at any time in the year. For this reason, the most conservative water sound speed profile (i.e., the profile leading to the longest acoustic propagation) was selected for modelling (Appendix F.3.2). Directly under the modelled sites, the seabed consists of silt, typical of the continental slope (Appendix F.3.3). When approaching the reefs, however, the seabed transitions from silt to sand/gravel, and then to limestone at the reefs.

This section described the methods used to characterise acoustic sources (driven piles, vessels and VSP), as well as the acoustic propagation models and frequency ranges considered for estimation of acoustic fields.

3.1. Pile driving

To predict the acoustic field around the pile driving at frequencies from 10 Hz to 1 kHz, JASCO's Pile Driving Source Model (PDSM; Appendix B) was used in conjunction with JASCO's Full Waveform Range-dependent Acoustic Model (FWRAM, Appendix E.2). In addition, a model-based extrapolation was applied to these results to extend the modelling range up to 25 kHz. Three different seafloor penetration depths were accounted for.

The SEL results for the entire pile were determined through the accumulation of energy across the entire pile driving operation, accounting for the sound fields from each strike and how the sound field changes as the pile penetrates further into the seafloor.

3.2. Vertical Seismic Profiling

The pressure signature of the individual airguns and the composite 1/3-octave-band point-source equivalent directional levels (i.e., source levels) of the 750 in^3 VSP source operated at 6 m were modelled with JASCO's Airgun Array Source Model (AASM, Appendix C.1).

Three sound propagation models were used to predict the acoustic field around the VSP source:

- Combined range-dependent parabolic equation and Gaussian beam acoustic ray-trace model (MONM-BELLHOP, 10 Hz to 25 kHz, Appendix E.3).
- Full Waveform Range-dependent Acoustic Model (FWRAM, 0.5 Hz to 1024 Hz, Appendix E.2).
- Wavenumber integration model (VSTACK, 10 Hz to 2048 Hz, Appendix E.4).

The models were used in combination to characterise the acoustic fields at short and long ranges in terms of SEL, SPL, PK, and PK-PK. Appendix E details each model. MONM was used to calculate SEL of a 360° area around each source location. VSTACK was used to calculate close range PK, PK-PK, and SEL along transects at the seafloor from the broadside direction of the seismic source. For the VSP source, FWRAM was used to calculate PK in the entire water column along four selected transects, and to obtain a conversion factor to estimate SPL from the MONM-BELLHOP SEL results.

3.3. Vessel noise (MODU, OSV, and FPSO)

JASCO's Marine Operations Noise Model (MONM-BELLHOP Appendix E.3) was used to predict the acoustic field at frequencies of 10 Hz to 63 kHz for all vessels.

For all vessels, the sound exposure level (SEL) modelling results were converted to SPL by the duration of the measurement, which is appropriate for a continuous noise source. As SEL was assessed over 24 h, the conversion to SPL was obtained by reducing the levels by $10*\log_{10}(T)$, where T is 86,400 (the number of seconds in 24 h).

3.4. Pile Driving Modelling

3.4.1. Per-strike Modelling

For impact pile driving sounds, time-domain representations of the pressure waves generated in the water are required for calculating sound pressure level (SPL), sound exposure level (SEL), and peak sound pressure level (PK). Appendix A.1 describes these sound level metrics. The following steps comprise the general approach applied in this study to model sounds from impact pile driving activities:

1. Piles driven into the sediment by impact driving are characterised as sound-radiating sources. This characterisation strongly depends on the rate and extent of pile penetration, pile dimensions, and pile driving equipment.
2. The theory of underwater sound propagation is applied to predict how sound propagates from the pile into the water column as a function of range, depth, and azimuthal direction. Propagation depends on several conditions including the frequency content of the sound, the bathymetry, the sound speed in the water column, and sediment geoacoustics (Appendix F.3 describes environmental properties such as bathymetry, sound speed profile, and geoacoustics).
3. The propagated sound field is used to compute received levels over a grid of simulated receivers, which distances to criteria thresholds and maps of ensonified areas are generated from.

To model sounds resulting from impact pile driving of cylindrical pipes, PDSM (Appendix B), a physical model of pile vibration and near-field sound radiation (MacGillivray 2014), is used in conjunction with the GRLWEAP 2010 wave equation model (GRLWEAP, Pile Dynamics 2010). JASCO modelled the IHC S-600 and IHC S-1200 impact hammers. Figure 2 shows the force at the top of the pile that is produced by GRLWEAP.

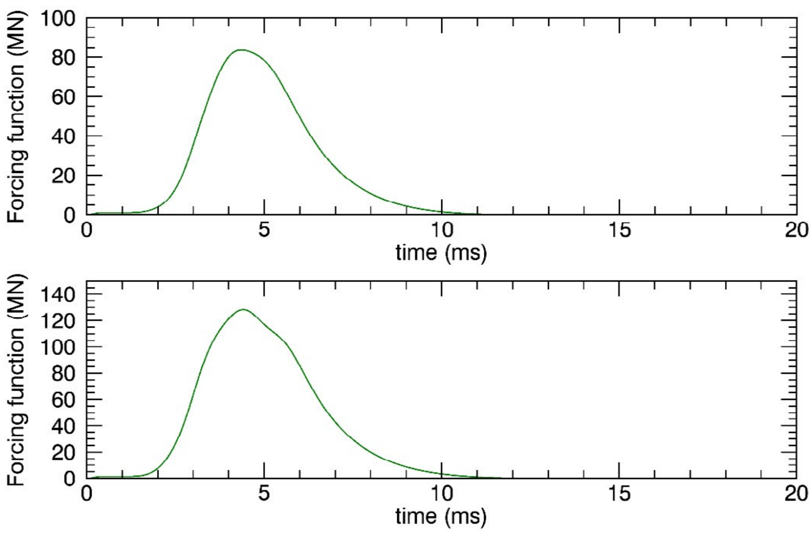

Figure 2. Force (in meganewtons) at the top of the pile corresponding to impact pile driving of a 5.5 m diameter pile, computed using the GRLWEAP 2010 wave equation model for the (top) IHC S-600 and (bottom) IHC S-1200 impact hammers.

The forcing functions (Figure 2) are used by the PDSM to obtain equivalent pile driving signatures for a vertical array of discrete point sources (Appendix B). These represent the pile as an acoustic source and account for parameters (pile type, material, size, and length), the pile driving equipment, and approximate pile penetration rate. The amplitude and phase of the point sources along the pile are computed so they collectively mimic the time-frequency characteristics of the acoustic wave at the pile wall that results from a hammer strike at the top of the pile. This approach accurately estimates spectral levels within the band 10–1000 Hz where most of the energy from impact pile driving is concentrated.

Time-domain Full Waveform Range-dependent model (FWRAM; Appendix E.2) calculates sound propagation from physically distributed impulsive sources and is valid at all distances. In the present study, received sound levels were calculated using FWRAM along transects at 28 azimuths out to 80 km from the source every 10 m, generating a total modelling area of 20000 km^2. Modelling was conducted in non-uniform azimuth increments, with a higher concentration of transects in the direction of bathymetric features of interests, such as reefs around the pile. Grids of received sound levels with 3° azimuth resolution were constructed. To this end, each 3° resolution transect was assigned the received levels corresponding to the modelled transect with the most similar bathymetry.

Source band levels at 1000 Hz were extrapolated up to 25 kHz using a 20 dB/decade decay rate to match acoustic measurements of impact pile driving of similarly sized piles (Illingworth & Rodkin 2007, Matuschek and Betke 2009).

Receiver depths are chosen to span the entire water column over the modelled areas, from 1 to 2600 m, with step size that increase with depth. To produce maps of received sound level distributions and to calculate distances to specified sound level thresholds, the maximum-over-depth level is calculated at each modelled easting and northing position within the considered region. The radial grids of maximum-over-depth levels are then resampled (by linear triangulation) to produce a regular Cartesian grid. The contours and threshold ranges are calculated from these flat Cartesian projections of the modelled acoustic fields (Appendix F.1).

3.4.2. Accumulated SEL Modelling

The modelling approach outlined in Sections 3.4.1 provides per-strike SEL for three stages of pile driving (i.e., three penetration depths). Several noise effect criteria, however, depend on accumulated SEL over many strikes (Section 2). For the purposes of modelling, one pile will be driven per day; therefore, while the corresponding sound level is denoted SEL_{24h}, the period of accumulation is determined based upon the estimated time for driving a single complete pile. Therefore, the accumulated SEL over a single pile, or the SEL_{24h}, depends on the total number of strikes.

Total driving time was estimated assuming continuous piling at a rate of approximately 0.67 strikes/second (40 strikes/minute) and 0.52 strikes/second (31 strikes/minute) for the IHC S-600 and the IHC S-1200 hammers, respectively. The number of strikes required for the driving of the pile were determined based upon a drivability assessment provided by Woodside for these two hammers operating at 95% efficiency. A summary of the total number of strikes per penetration depth and over the entire pile is provided in Tables 16 and 17.

Table 16. *Torosa*: total number of strikes and driving time. Strikes were broken down into stages corresponding to the three modelled penetrations.

Hammer	Modelled penetration (m)	Penetration range for accumulated SEL (m)	Number of strikes	Penetration rate (mm/strike)	Total number of strikes	Time for full penetration (min)
IHC S-600	17	10–24	595	19.9	3141	78.5
	31	24–38	1026	13.4		
	45	38–51.5	1520	8.0		
IHC S-1200	17	10–24	256	38.5	1412	45.5
	31	24–38	488	28.4		
	45	38–51.5	668	18.3		

Table 17. *Brecknock*: total number of strikes and driving time. Strikes were broken down into stages corresponding to the three modelled penetrations.

Hammer	Modelled penetration (m)	Penetration range for accumulated SEL (m)	Number of strikes	Penetration rate (mm/strike)	Total number of strikes	Time for full penetration (min)
IHC S-600	17	10–24	582	19.7	3203	80.0
	31	24–38	1043	12.7		
	45	38–51.5	1578	7.49		
IHC S-1200	17	10–24	264	38.0	1470	47.4
	31	24–38	497	27.0		
	45	38–51.5	709	16.9		

3.5. VSP Modelling

3.5.1. Per-pulse Modelling

To assess sound levels with MONM-BELLHOP, the sound field modelling calculated propagation losses up to distances at least 150 km from the source, with a horizontal separation of 20 m between receiver points along the modelled radials. The sound fields were modelled with a horizontal angular resolution of $\Delta\theta$ = 2.5° for a total of N = 144 radial planes. Receiver depths were chosen to span the entire water column over the modelled areas, from 2 m to a maximum of 3100 m, with step sizes that increased with depth. To supplement the MONM results, high-frequency results for propagation loss were modelled using Bellhop for frequencies from 2 to 25 kHz. The MONM and Bellhop results were combined to produce results for the full frequency range of interest.

FWRAM was run to 80 km, but along only four radials (fore and aft endfire, and port and starboard broadside) for computational efficiency, from 5 to 1024 Hz in 1 Hz steps. This was done to compute SEL-to-SPL conversions (Appendix F.2) but also to quantify water column PK and PK-PK. The horizontal range step is dependent on frequency and ranges from 50 m at lower frequencies to 10 m above 800 Hz.

The maximum modelled range for VSTACK was 1500 m and a variable receiver range increment that increased away from the source was used. The increment increased from 5 to 50 m. Received levels were computed for receivers at seafloor

3.5.2. Multiple-pulse Modelling

The VSP operation was assessed in this report by considering several potential scenarios for a maximum number of pulses per 24 h. The SEL was assessed over 24 h by adjusting the single-pulse SEL by $10*\log_{10}(N)$, where the total number of pulses N was 1, 5, 10, 15, 25, 50, 100, and 150 at each location (Torosa TRD Well and Brecknock).

3.6. Acoustic Source Parameters for MODU, OSV, and FPSO

3.6.1. Mobile Offshore Drilling Unit (MODU)

The estimates of the MODU, or semi-submersible platform, acoustic source levels and sound spectrum were based on the *Seadrill West Sirius* (Figure 3). *Seadrill West Sirius* is reportedly equipped with eight Rolls-Royce UUC 355 thrusters.

The parameters for the UUC 355 thruster are:

- 3.5 m propeller diameter,
- 177 rpm nominal propeller speed, and
- 3800 kW maximum continuous power input.

For modelling, all eight thrusters were assumed to operate at 50%. The vertical position of the thrusters was 18 m below the sea surface (draft of the rig during drilling operations). Figure 4 shows the thruster locations.

Figure 3. *Seadrill West Sirius* semi-submersible platform.

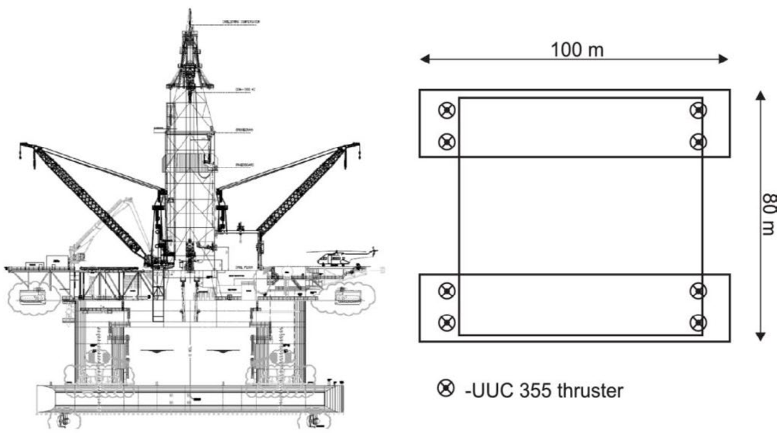

Figure 4. *Seadrill West Sirius* dimensions and thruster locations (circles).

The source levels and the sound spectrum for vessel thrusters were estimated based on the thruster specifications (diameter, revolutions-per-minute (rpm)) and the method described in Section 3.6. It is expected that the MODU at Torosa and Brecknock will operate under dynamic positioning representative of typical operational loads during moderate weather conditions. Measurements and modelling of thruster noise from the Technip *Deep Orient* (Quijano and McPherson 2018) suggest that the broadband source levels decrease when the vessel operates under mild environmental conditions compared to rough weather. Based on the monopole source levels calculated for the Technip *Deep Orient* during the measurement study, we decreased the MODU thruster levels by 5.75 dB, to account for the typical scenario with moderate environmental conditions. Figure 8 shows the MODU source levels used for this modelling, compared to measurements obtained from a similar MODU and a drillship (West Aquarius and Stena IceMAX, see Martin et al. (2019)). For additional reference, MODU thruster source levels corresponding to full capacity (i.e., rough weather) from Zykov (2016) are shown. Note that the MODU source levels correspond to the noise generated by eight thrusters operating simultaneously, while the modelling considers each thruster as an individual source.

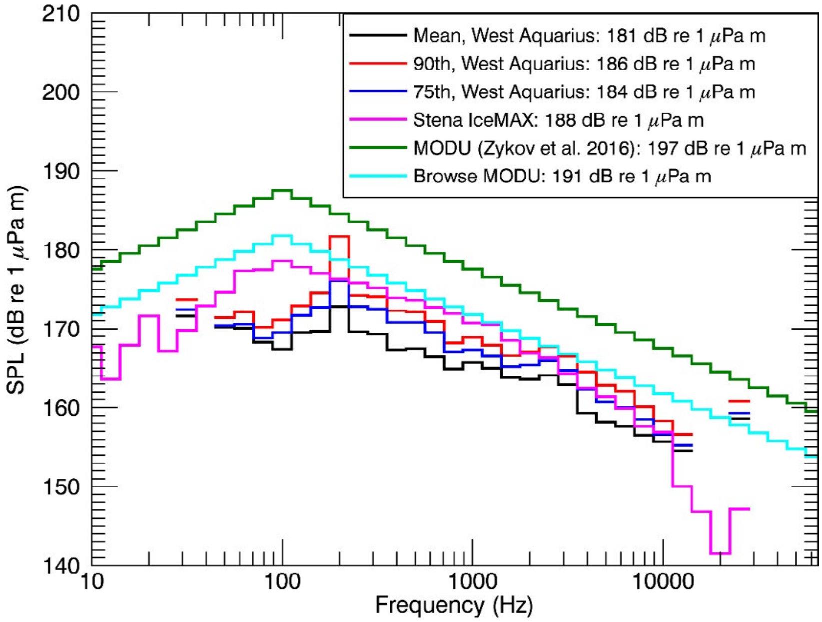

Figure 5. *MODU*: One-third-octave-band source levels. The levels assume operation of the MODU at 50% load, and account for the presence of eight thrusters. For comparison, source levels obtained from measurements of the noise generated by the West Aquarius and the Stena IceMAX (Martin et al. 2019) are provided. In addition, predicted source levels for the same MODU considered in this study under heavy operating conditions (Zykov 2016) are presented.

3.6.2. Offshore Support Vessel (OSV)

The estimates of acoustic source levels and sound spectrum for the support vessel were based on the *MMA Inscription* platform supply vessel, referred to in this report as an Offshore Support Vessel (OSV) (Figure 6). The *MMA Inscription*, of length 87.08 m, breadth of 18.8 m and maximum draft of 5.9 is equipped with two bow (main) azimuthal thrusters, one stern retractable azimuthal thruster, and one bow thruster. Since parameters such as propeller size or thruster vertical position were not available, thrusters were modelled at depth 5.9 m, equal to the draft. The bow thrusters are 2000 kW maximum continuous power input each, while the bow thruster is 910 kW maximum continuous power input. For this modelling, the stern retractable thruster was not included. Figure 7 shows the thruster locations.

Source levels for the *MMA Inscription* were obtained based on those of the Damen platform supply vessel 3300CD (length 80.08 m, breadth of 16.8 m and maximum draft of 6.9), which was used in previous studies (Zykov 2016). For the Damen 3300CD, the bow (main) thrusters are 2000 kW maximum continuous power input each, while smaller bow thrusters are 735 kW maximum continuous power input. Unlike Zykov (2016), in which thrusters were assumed to operate at full capacity, modelling in this study was conducted assuming a 25% capacity. For this reason, thrusters levels from Zykov (2016) were offset by $10*\log_{10}(0.25)$ for the main thrusters, and by $10*\log_{10}(0.25)+10*\log_{10}(910/735)$ for the bow thruster. The source levels for individual thrusters are shown in Figure 8.

Figure 6. Image of the *MMA Inscription* (MMA Offshore 2019).

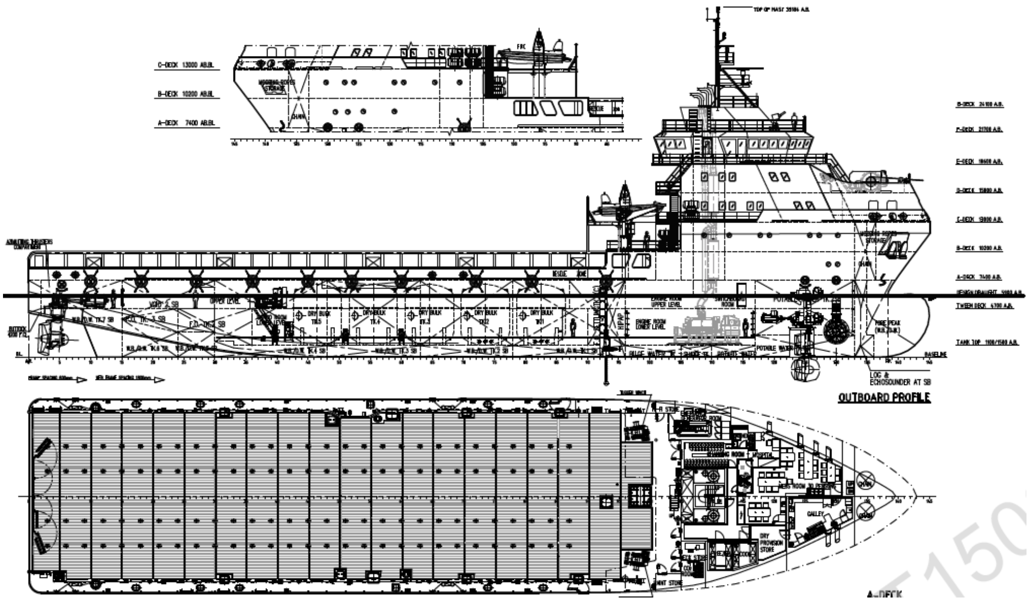

Figure 7. Nominal dimensions and thruster locations (circles) of the *MMA Inscription* (MMA Offshore 2019).

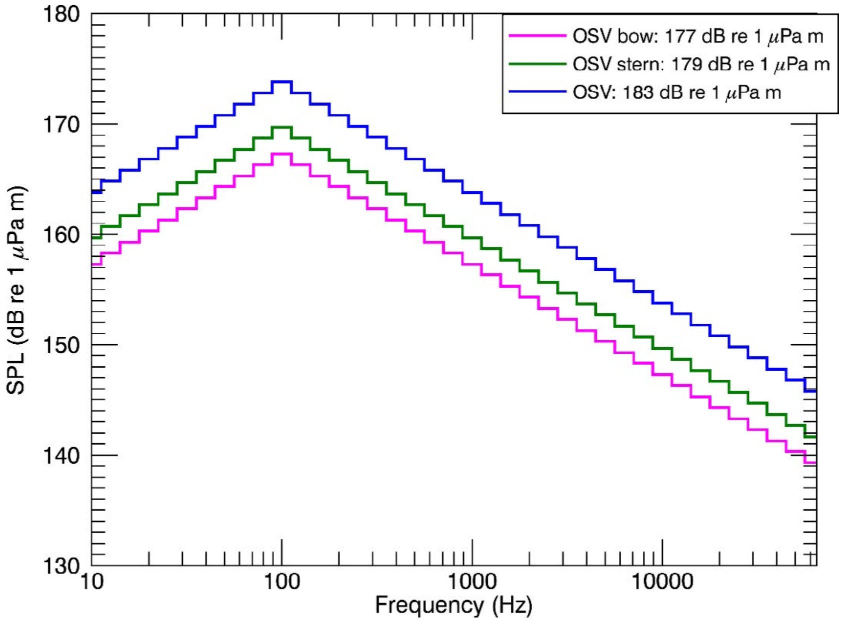

Figure 8. *OSV*: One-third-octave-band source levels of individual bow and stern thrusters. The OSV curve include the two individual stern thrusters and the bow thruster.

3.6.3. Floating Production, Storage, and Offloading (FPSO) facility

The proposed FPSO facility is a dynamically positioned production vessel approximately 370 m long and 67 m wide with a draft of 16 m. While in DP mode, it operates on two stern thrusters positioned laterally on the keel at the stern of the ship, right next to each other. Each thruster is rated at 5 MW. The vessel type and specifications are similar to the Woodside FPSO facilities *Ngujima Yin* and *Nganhurra* (with the important exception of the two thrusters rated at 2.94 MW each), from which JASCO gathered measurements in 2010 (Erbe et al. 2013). The measured spectra for these two vessels were averaged and used as a surrogate for the FPSO facility. Because the *Ngujima Yin* and *Nganhurra* were moored, they were not offloading, and the weather was calm, they were not under DP when they were measured. These averaged source levels were used in this report to model FPSO operations without DP.

To model operations that include DP, sound levels of thruster noise were added to the (non-DP) source spectrum. Sound levels for DP thruster noise were based on measurements of the dive support vessel *DSV Fu Lai* (MacGillivray 2006). The composite source spectrum (i.e., non-DP and DP components) was adjusted for the difference in total operational power level between the DSV *Fu Lai* and the FPSO facility using the following equation:

$$SL = SL_{FuLai} + 10\log\left(HP/HP_{ref}\right) , \qquad (1))$$

where HP_{ref} is the level of reference power. The source spectrum was additionally modified to consider the operational level of the *Fu Lai* thrusters relative to the desired operational level for the FPSO facility. Given that DP does not require full thrust, the *Fu Lai*'s thrusters only operated at between 20% and 30% of capacity when measured. To achieve a conservative estimate, FPSO facility thrusters were modelled at 50% power capacity. In addition to the adjustment in Eq.1, an offset of $10*\log_{10}(5/2.94)$ was applied to the composite source spectrum, to account for the difference in thruster power between the *Ngujima Yin* and *Nganhurra*, and the FPSO considered in this study.

The acoustic modelling source depth was determined by assuming the bottoms of the thrusters were at the draft of the vessel, but the noise from cavitation is known (Wright and Cybulski 1983) to be centralised at approximately three quarters of the propeller's height.

In the absence of information about the propeller diameters and vertical position, modelling was conducted assuming point sources at 16 m to be conservative. For modelling, it was assumed that both thrusters operated at the middle (50%) of their constant power range, at a constant speed. The thrusters are located at the stern section of the vessel; for modelling purposes, however, the source location was placed in the planar centre of the vessel to approximate a point source. Because this assessment is focused on the far-field noise from all sources on the vessel (including not just thruster noise, but also noise from ancillary equipment for power generation, etc.) the point source approximation is suitable. Figure 9 shows 1/3-octave-band source levels for the FPSO facility (with and without DP).

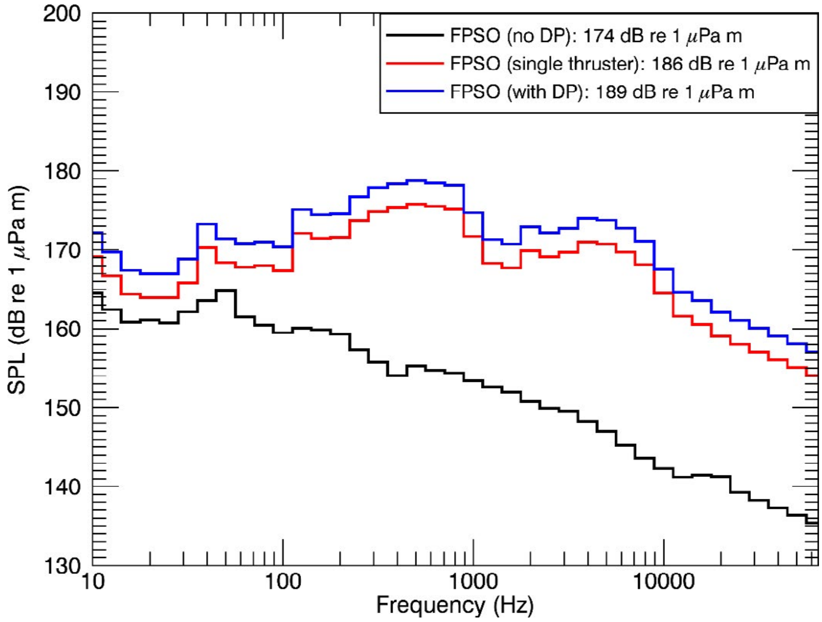

Figure 9. *FPSO*: One-third-octave-bands of modelled FPSO facility without DP, with DP (single thruster), and with DP (two thrusters).

3.6.4. FPSO Offtake

Offtake operations considered in this study consist of an FPSO on DP, a condensate tanker, and an OSV (Figure 10). The modelling scenario includes the tanker (which is considered noiseless in this study) is between the FPSO and the OSV, with the bow 80 m from the stern of the FPSO, and the OSV 700 m from the stern of the FPSO, pointing away from the FPSO. The offtake scenarios were modelled by adding the contributions from the maximum-over-depth grids computed for the individual vessels detailed in Sections 3.6.2 and 3.6.3.

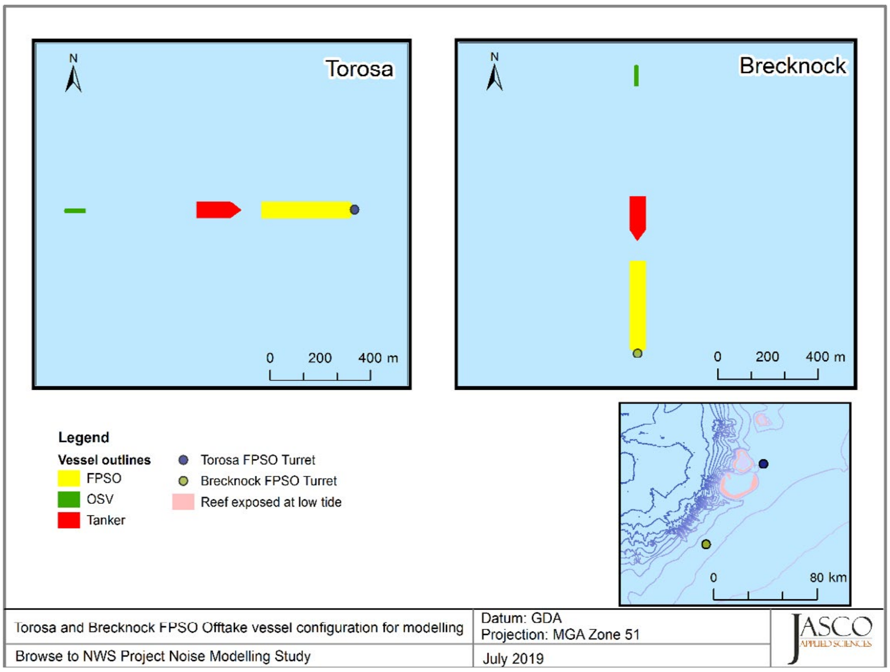

Figure 10. Torosa and Brecknock FPSO Offtake vessel configuration for modelling, showing FPSO, tanker, and OSV.

3.7. Animal Movement and Exposure Modelling

The JASCO Animal Simulation Model Including Noise Exposure (JASMINE) was used to predict the exposure of animats (virtual marine mammals) to sound arising from the pile driving. Sound exposure models like JASMINE integrate the predicted sound field with biologically meaningful movement rules for each marine mammal species (here: pygmy blue whales and green turtles) that result in an exposure history for each animat in the model. In JASMINE, the sound received by the animats is determined by the proposed pile driving activity pattern. As shown in Figure 11, animats are programmed to behave like the marine animals that may be present in the area. The parameters used for forecasting realistic behaviours (e.g., diving and foraging depth, swim speed, surface times) are determined and interpreted from marine mammal studies (e.g., tagging studies) where available, or reasonably extrapolated from related or comparable species. An individual animat's sound exposure levels are summed over a specified duration, such as 24 h or the entire simulation, to determine its total received energy, and then compared to the threshold criteria (for detailed information on JASMINE see Appendix G).

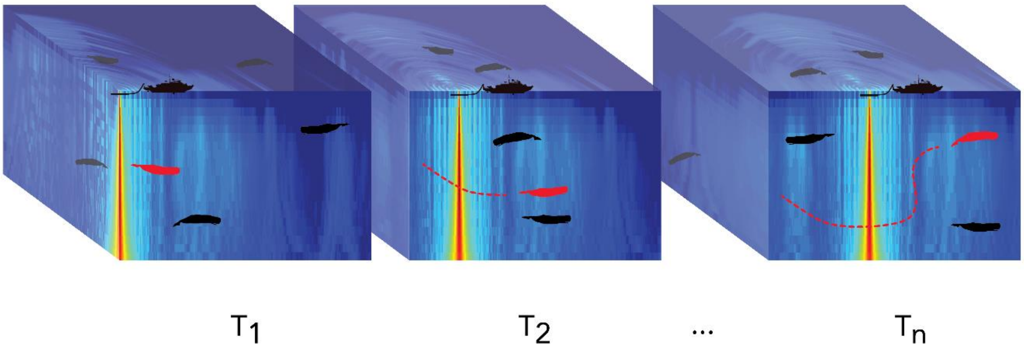

Figure 11. Cartoon of animats in a moving sound field. Example animat (red) shown moving with each time step (T_x). The acoustic exposure of each animat is determined by where it is in the sound field, and its exposure history is accumulated as the simulation steps through time.

3.7.1. Methodology

The exposure criteria for impulsive sounds (described in Section 2) were used to determine the number of animats exceeding thresholds. Model simulations were run with animat densities of 15 animats/km^2 for pygmy blue whales and 15 animats/km^2 green turtles to generate a statistically reliable probability density function for each species. To evaluate potential injury (PTS), TTS, and behavioural disturbance, exposure results were summed over the driving of a single pile (Table 16), which represents the exposure over 24 h, represented by animats described in Appendix G.

Specific areas of interest are defined for both pygmy blue whales and green turtles depending on behavioural mode (e.g., migrating, foraging, inter-nesting). Figures 12 and 14 show maps of the modified Biologically Important Areas (BIAs) for migrating and inter-nesting green turtles, while Figures 13 and 15 show the Department of Environment and Energy (DoEE) BIAs for migrating and foraging pygmy blue whales. Both of these maps also show the extents of the modelling and animat simulation area. For the final calculations, BIA areas are clipped to the extents of the simulation. To account for the difference between the animat simulation area and the BIAs, the final exposure estimates are scaled by the ratio of the clipped BIA relative to the simulation area.

The modified BIA for green turtle inter-nesting area is restricted to the 50 m contour around North and South Scott Reef, and connects between the two Reefs (Figure 12), this area was defined based upon the best available science (turtle tagging data (Guinea 2011) and external advice), and has been applied in this study instead of the DoEE defined inter-nesting BIA boundary around Scott Reef. While the simulations assume the inter-nesting green turtles are evenly distributed within the defined area of interest, the majority are concentrated on or next to Sandy Islet (Guinea 2009). The migratory area has been defined based upon tagged turtles (Guinea 2011) and the area prescribed is based upon the distance a turtle would transit within 24 h.

The animal simulation model requires detailed behavioural information on how the modelled species moves in the water column. This is detailed in Sections 3.7.2 and 3.7.3 for pygmy blue whales and green turtles, respectively.

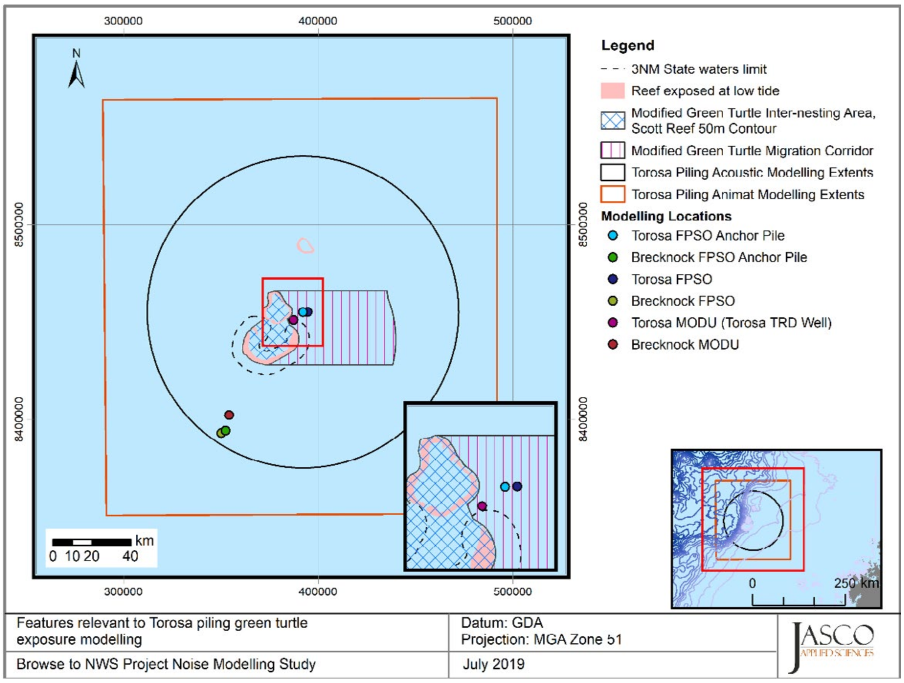

Figure 12. *Torosa:* Map of green turtle exposure modelling features, including modified BIAs for inter-nesting and migrating green turtles, along with extents for acoustic propagation modelling and animat modelling.

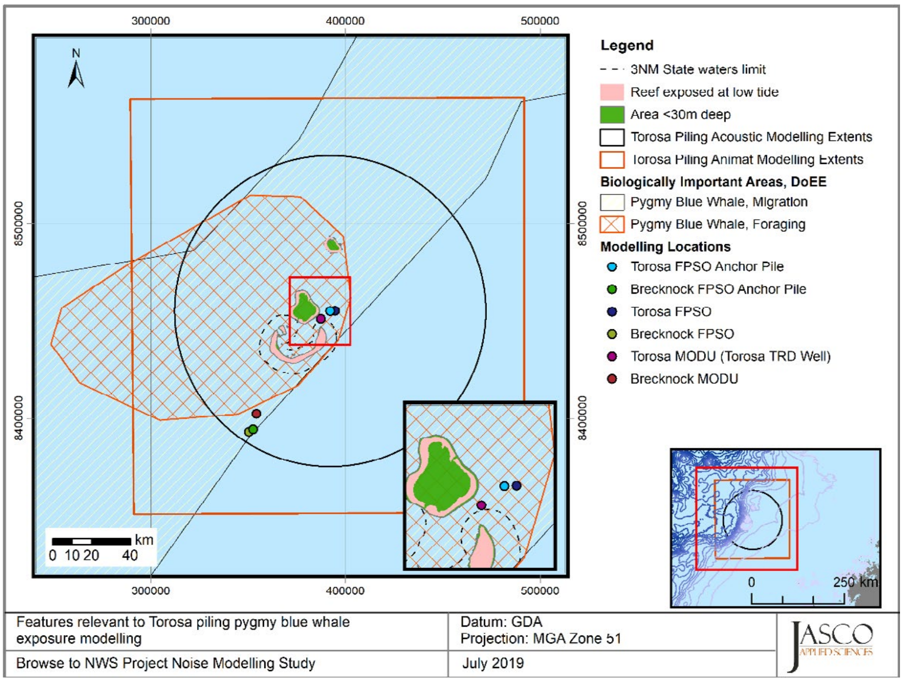

Figure 13. *Torosa*: Map of pygmy blue whale exposure modelling features, including BIAs for foraging and migrating pygmy blue whales, along with extents for acoustic propagation modelling and animat modelling.

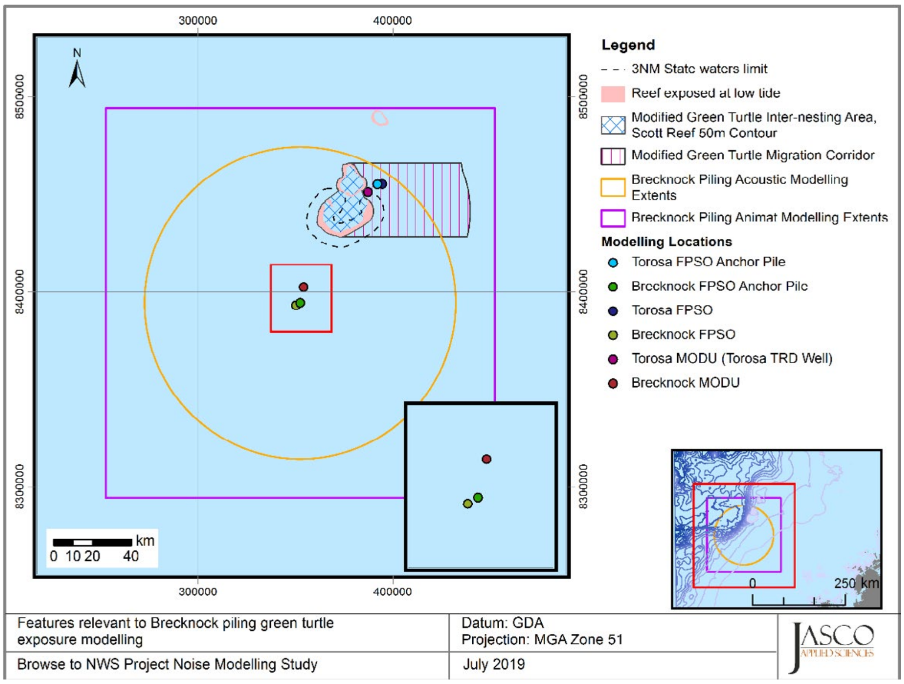

Figure 14. *Brecknock:* Map of green turtle exposure modelling features, including modified BIAs for inter-nesting and migrating green turtles, along with extents for acoustic propagation modelling and animat modelling.

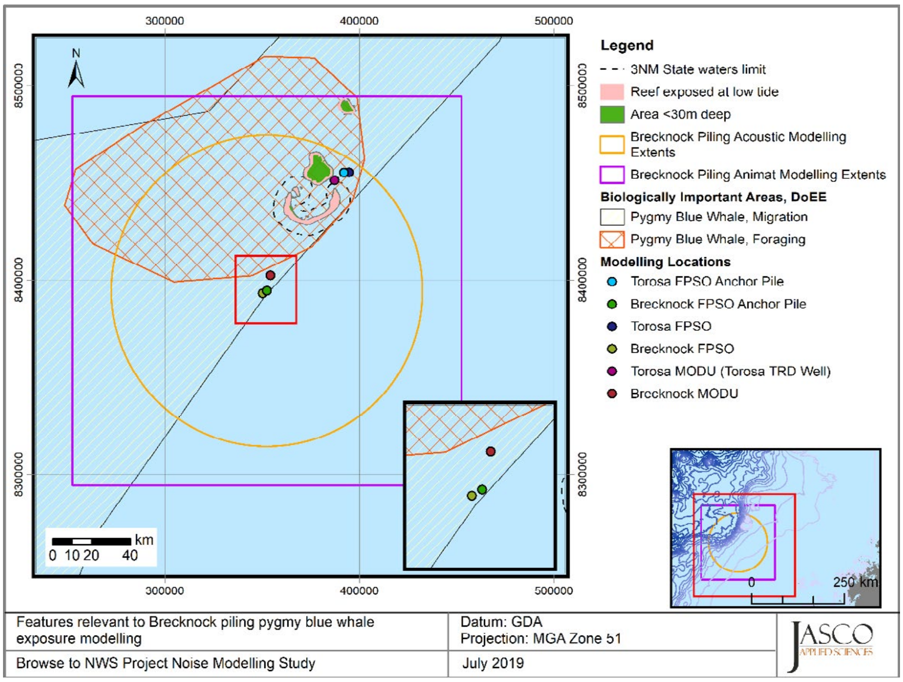

Figure 15. *Brecknock*: Map of pygmy blue whale exposure modelling features, including BIAs for foraging and migrating pygmy blue whales, along with extents for acoustic propagation modelling and animat modelling.

In the case of the inter-nesting green turtles, the pile location is approximately 7.9 km away from the closest point of the BIA. To ensure that no animats are impacted outside the relevant BIA, exposures occurring at ranges smaller than the minimum distance between the pile and the BIA were not included in the final count. This effectively reduces the simulation area by πr^2, where r = 7.9 km. Therefore, the final area-based scaling S_A is

$$S_A = \frac{BIA_{clipped}}{(A_{full} - \pi r^2)}, \quad (2)$$

where $BIA_{clipped}$ is the BIA clipped to the full animat simulation area A_{full}. Pygmy blue whales are not expected in water depths less than 30 m, so the clipped BIA is reduced by the area within the 30m depth contour (Figure 13). A summary of the BIA areas and the various inputs to exposure scaling for each of the animat modelling scenarios can be found in Table 18.

The total number of animats exposed above behaviour, TTS and PTS threshold criteria were scaled using the seeded density D_S and the real-world density D_R, where available. The scaling factor S_D is therefore

$$S_D = \frac{D_R}{D_S}. \quad (3)$$

The total number of real-world animals N_{exp} expected to be impacted above threshold is computed from the raw animat exposures and the scaling factors as

$$N_{exp} = S_A S_D. \quad (4)$$

The distribution of ranges of exposed animats was used to estimate the 95th percentile ranges at which the animats were exposed above threshold. Within the 95th percentile range, there are generally some proportion of animats that did not exceed threshold criteria.

During pile driving operations, exclusion zones of 500 m for turtles and 2000 m for pygmy blue whales will be in place. These will be managed using mitigation protocols determined by Woodside, and through their implementation, exposures to turtles and pygmy blue whales near the pile where sound levels are highest will be limited. The overall effect of implementing these exclusion zones was estimated using animat modelling by removing any exposures occurring within the exclusion zone.

Table 18. Exposure modelling scenarios and associated areas of concern for the simulation, along with estimated animal densities.

Animat scenario	Full area (km^2)	R_{min} (km)	Adjusted A_{full} (km^2)	$BIA_{clipped}$ (km^2)	30 m exclusion zone (km^2)	Adjusted $BIA_{clipped}$ (km^2)	Area-based scaling, S_A	Animal density (# per km^2)
Torosa								
Pygmy blue whale migrating	40000.0	0.0	40000.0	20162.0	370.7	19791.3	0.49	0.06902
Pygmy blue whale feeding	40000.0	0.0	40000.0	9839.0	370.7	9468.3	0.24	0.06902
Green turtle migrating	40000.0	0.0	40000.0	2015.9	NA	2015.9	0.05	NA
Green turtle inter-nesting	40000.0	7.9	39804.1	658.2	NA	658.2	0.02	1.79
Brecknock								
Pygmy blue whale migrating	40000.0	0.0	40000.0	20287.0	370.7	19916.3	0.5	0.06902
Pygmy blue whale feeding	40000.0	10.3	39664.1	11063.0	370.7	10692.3	0.3	0.06902
Green turtle migrating	40000.0	42.0	34458.2	2015.9	NA	2015.9	0.1	NA
Green turtle inter-nesting	40000.0	40.4	34872.4	658.2	NA	658.2	0.02	1.79

3.7.2. Pygmy blue whales

3.7.2.1. Animal behaviour

Two behavioural profiles were considered for pygmy blue whales, foraging and migration. The research summarised in this section was used to inform the species behavioural definition (Appendix G.2). Detailed, fine-scale diving behaviour of a migrating pygmy blue whale was derived from Owen et al. (2016) who equipped an individual with a multi-sensor tag off the west coast of Australia. The study identified areas of high residence using the horizontal movement data; the analysis of the dive data showed that the depth of migratory dives was highly consistent over time and unrelated to local bathymetry. Blue whales (*Balaenoptera musculus*) are known to primarily migrate and feed in the first few hundred metres of the water column (Croll et al. 2001, Goldbogen et al. 2011), with the deepest dive being reported from a pygmy blue whale being 506 m (Owen et al. 2016). Dives were identified as migratory, feeding, or exploratory behaviour. The mean depth of migratory dives (82% of all dives) was 14 m ± 4 m, and the whale spent 94% of observed time and completed 99% of observed migratory dives at water depths of less than 24 m. A total of 21 feeding dives were identified during the duration of the tag deployment (one week) with a mean maximum depth of 129 ± 183 m (range 13–505 m). The mean maximum depth of exploratory dives (107 ± 81 m, range 23–320 m) was similar to the mean maximum depth of feeding dives (129 m) and did not appear to be related to seafloor depth.

The behaviour of pygmy blue whales was modelled without migration bias, i.e. the animats were resident in the animat modelling area over the entire modelling period. In reality, pygmy blue whales can be expected to transit through the area in less than half a day (based on McCauley and Jenner 2010); accordingly, the approach used is conservative as it results in higher exposure levels and higher number of animals exposed to levels exceeding the criteria thresholds.

The two migratory behaviours (migratory dives and exploratory dives) were modelled at an even probability of occurrence (i.e. probability for transitioning from one behaviour to another was 0.5 for both) while dive data published by Owen et al. (2016) suggest a higher likelihood for migratory dives to occur. This approach was chosen in the absence of quantitative information on the true proportion between the two dive behaviours. It represents another conservative measure, given the assumption that for sub-sea piling, exposure levels are higher at depth as compared to the surface.

3.7.2.2. Density estimates

The entire region off the northwestern coast of Australia is a poorly studied with regard to the abundance and distribution of pygmy blue whales. As described in McCauley et al. (2018), there are two estimates for the Eastern Indian Ocean pygmy blue whale population size along the coastline of Western Australia (WA), the first calculated in 2004 by McCauley and Jenner (2010) at 662–1559 southbound animals, using passive acoustics, and the second calculated over 2002–2006 by Jenner et al. (2008) of 712–1754. Neither of these estimates account for whales further west in the Indian Ocean, and there is evidence that along the WA coast north of latitude ~ 19° S that the migratory pathway spreads out (Gavrilov et al. 2018), with not all animals following the Australian coastline; therefore it is unknown what proportion of the Eastern Indian Ocean pygmy blue whale population either follow the coast or travel further west (McCauley et al. 2018).

However, while near the coast, the observations in McCauley and Jenner (2010) suggested most pygmy blue whales pass along the shelf edge out to water depths of 1000 m but centred near the 500 m depth contour. The boundaries of the DoEE pygmy blue whale migration BIA are designed to reflect this general migratory pattern. The areas considered in this simulation were greater than the acoustic modelling region to provide a buffer zone around the sound fields to account for the possibility of animats moving into and out of the modelled sound fields.

McCauley et al. (2018) provides an estimate for the annual growth rate of pygmy blue whales at Portland (Victoria) of 4.3% per year. However, as pointed out by the authors, this growth rate applies only to the proportion of the population using the south eastern Australian coast, and as such may not reflect the growth rate of the full population. However, in the absence of other population growth estimates, this estimate has been applied as a conservative estimate to the proportion of the population also using the WA coast, in particular the migratory BIA.

Considering an annual growth rate of 4.3%, the two population estimates provided in McCauley and Jenner (2010) and Jenner et al. (2008) have been considered to determine the potential current population, and thus the possible percentage increase since the estimate was derived, as shown in Table 19.

Table 19. Population growth estimates based on 4.3% per annum.

Source	Year	Minimum estimate	Maximum estimate	Percentage increase
Based on McCauley and Jenner (2010)	2004, Estimated	662	1559	
	2019, Extrapolated	1245	2932	188%
Based on Jenner et al. (2008)	2002-2006, Estimate	712	1724	
	2019, Extrapolated	1231	2980	173%

The acoustic detection data published by McCauley and Jenner (2010) revealed a maximum of three pygmy blue whales on a single day passing through the area during their southward migration (November to late December). McCauley and Jenner (2010) estimated the listening range of this noise logger to be 120 km, which is assumed to be a radius, however, to apply precaution in this assessment the recorder listening area was conservatively calculated using a 60 km radius. Based on an average swimming speed for the southbound pygmy blue whales of five knots (9.26 km/hr), McCauley and Jenner (2010) calculated a transit time through the area of 0.54 days; therefore, the number of animals detected per day equates to an estimated density for vocalising animals in the area of 0.0031207 animals per km^2 for their study. As not all animals are emitting calls during their migration, this density estimate has to be corrected for the percentage of animals calling ('calling rate'). McCauley and Jenner (2010) proposed that 8.5–20% of the animals present in an area could be vocalising, considering information relating to humpback whales (8.5%, Cato et al. (2001)), and pygmy blue whales (<20%, (McCauley et al. 2001), to take a precautionary approach this study has adopted the lower bound (8.5%), with the resulting density shown in Table 20, which has been used in this assessment. If the vocalisation rate of pygmy blue whales in the Perth Canyon is applied, the resulting density of vocalising animals would be 2.35 times greater, and thus the correction factor for calling animals would be only 5, rather than 11.76.

The maximum number of three pygmy blue whales per day occurred in associated with the population estimate of 662–1559 whales presented in McCauley and Jenner (2010). If the population increases, it is estimated that the number of whales present on any one day would also increase proportionally. Therefore, the population increase estimate of 4.3% per year, and a corresponding Scaling Factor of 188% (Table 19), has been applied in this study, as shown in Table 20. This results in a revised estimate of the maximum number of animals which could be detected within the listening area per day being 5.64, and a real-world density of 0.0690392 animals per km^2.

Table 20. Density calculations

Variable / Factor	Estimate using data from McCauley and Jenner (2010)	Estimate considering 4.3% population growth since 2004
Number of animals in listening area (animals detected per day in listening area)	3	5.64
Recorder listening area (km²) (McCauley and Jenner 2010)	11309.73	
Density of Vocalising Animals (animals/km²)	0.0031207	0.0058683
Calling rate based on humpbacks (8.5% of animals present vocalise)	8.5%	
Correction factor for calling animals	11.76	
Real World Density of animals (D_R) (animals/km²)	0.03671	0.0690392
Seeded Density (D_S) (animats/km²)	15	
Scaling Factor (S_D)	0.0024476	0.0046026
Increase in Scaling Factor considering population growth		188%
Comparison of Seeded Density (D_S) to Real World Density of animals (D_R)	408.56	217.27

3.7.3. Green turtles

3.7.3.1. Animal behaviour

Two behavioural profiles were considered for green turtles, inter-nesting and migrating. The research summarised in this section inform the species behavioural definition (Appendix G.3). The migratory behaviour and habitat use of green turtles has been studied at various locations throughout their distribution range for Western Australia, but few studies provide quantitative information on the swim and dive behaviour of these animals.

Studies of the green turtle population nesting on Sandy Islet, Scott Reef by Guinea (2010, 2011), however, include behavioural parameters. Inter-nesting turtle records indicate a maximum dive depth of 45 m and an average dive duration of 15–25 minutes, with a dive duration range of 20 seconds to 55 minutes (Guinea 2011). Migratory turtle records indicate a maximum dive depth of 80 m (average: 49 m) and an average dive duration of 10–15 minutes.

Inter-nesting turtle swimming speeds are not available for the Scott Reef green turtle population. An analogue based on information from a satellite tagging study of green turtle behaviour and movements conducted by the Department of Biodiversity, Conservation and Attractions (DBCA) during the 2018 and 2019 nesting period at Ningaloo has been derived. The inferred average inter-nesting swimming speed for green turtles at Scott Reef adopted for this study was 1.4 km/h.

For the Scott Reef population, the average swim speed of migrating green turtles ranged from 1.3–2.7 km/h (Pendoley 2005, Guinea 2011).

3.7.3.2. Density estimates

Based on beach monitoring at Scott Reef, Guinea (2009) estimated a green turtle abundance of 779 ± 383 (± se) in the years 2008 and 2009. These numbers included counts of green turtles with flipper tags and an estimate from marking and recapturing individuals (identified by sprayed painted carapace) at Sandy Islet. The density of inter-nesting green turtles was defined by the highest estimates of green turtles (1162 individuals) at Scott Reef as recorded by Guinea (2009) and an estimated density of 1.79 turtles/km^2 based on the highest estimate, primarily using an inter-nesting area defined by the 50 m bathymetry around North and South Scott Reef. No density estimates were calculated for migrating green turtles because no data were available.

4. Results

4.1. Pile Driving: Torosa FPSO Anchor Piles

4.1.1. Received levels at 10 m

Since piles are distributed and directional sources, they cannot be accurately approximated by a point source with corresponding source levels. It is possible to compare the maximum modelled levels at short distances from the piles. Figure 16 shows the 1/3-octave-band levels for the receiver with the highest SEL at the closest horizontal range (10 m), for the three modelled penetrations. The levels above 1000 Hz were extrapolated using a 20 dB/decade decay rate to match acoustic measurements of impact pile driving of similarly sized piles (Illingworth & Rodkin 2007, Matuschek and Betke 2009). The modelled results at a distance of 10 m are included to provide results comparable to other pile driving reports and literature, such as Illingworth & Rodkin (2007), and Denes et al. (2016).

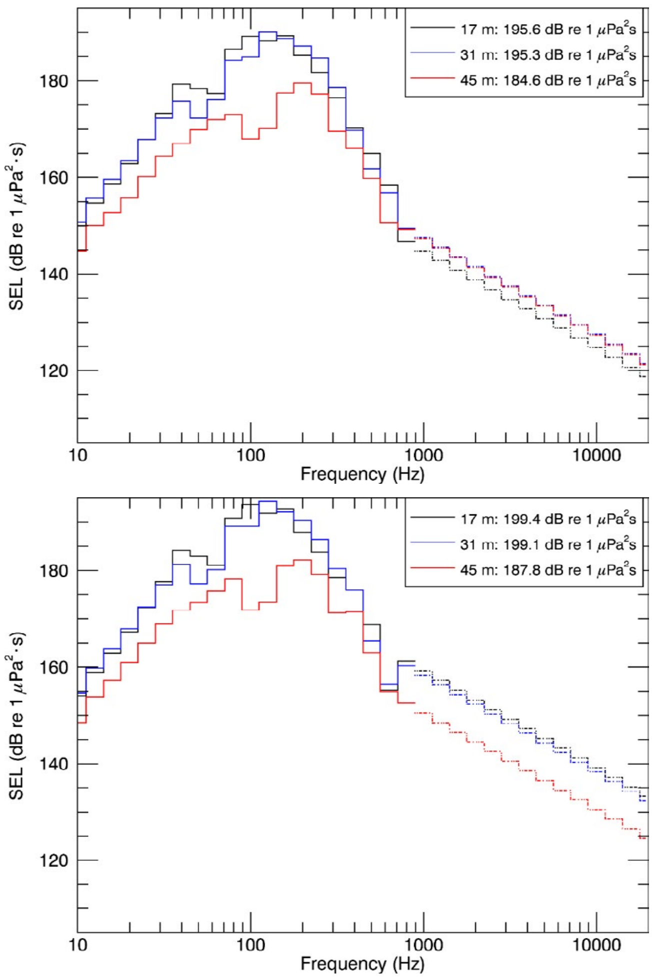

Figure 16. *Torosa*: One-third-octave-band levels for the receiver with highest SEL at 10 m horizontal range for impact pile driving using the IHC S-600 (top) and the IHC S-1200 (bottom), after high-frequency extrapolation (dashes indicate extrapolated portion of the spectrum). Legend items indicate the modelled pile penetration (Table 16) and the broadband SEL in dB re 1 µPa²·s.

4.1.2. Per-strike sound fields

Per-strike results for the proposed pile driving are presented in this section for maximum-over-depth SPL, SEL, and PK (tables in Section 4.1.2.1), maps and sound field vertical slices (Section 4.1.2.2).

4.1.2.1. Tabulated results

Tables 21–26 show the estimated distances for the various applicable per-strike effects criteria and isopleths of interest as maximum-over-depth.

Table 21. *Torosa piling, per-strike SEL:* Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile to modelled maximum-over-depth isopleths.

Per-strike SEL (L_E; dB re 1 µPa²·s)	IHC S-600						IHC S-1200					
	Penetration depth (m)						Penetration depth (m)					
	17		31		45		17		31		45	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.05	0.05	0.03	0.03	<0.02	<0.02	0.08	0.08	0.05	0.05	<0.02	<0.02
180	0.14	0.13	0.10	0.09	0.04	0.04	0.22	0.21	0.14	0.14	0.08	0.08
170	0.39	0.37	0.28	0.26	0.17	0.17	0.68	0.64	0.45	0.43	0.29	0.28
160	2.22	2.10	0.95	0.90	0.65	0.63	5.50	5.31	5.32	5.20	1.20	1.15
150	11.98	8.86	10.48	5.81	5.36	5.13	19.70	14.79	17.05	11.55	12.03	8.60
140	31.14	24.80	29.45	22.37	18.02	14.26	44.42	36.94	44.06	33.03	29.15	19.83
130	79.98	57.15	59.09	50.60	44.06	32.87	>79.98	*	>79.98	*	56.87	46.33
120	>79.98	*	>79.98	*	>79.98	*	>79.98	*	>79.98	*	>79.98	*

* Radii unresolvable due to R_{max} exceeding maximum modelled distance.

Table 22. *Torosa piling, SPL:* Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile to modelled maximum-over-depth isopleths.

SPL (L_p; dB re 1 µPa)	IHC S-600						IHC S-1200					
	Penetration depth (m)						Penetration depth (m)					
	17		31		45		17		31		45	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	0.04	0.03	0.03	0.03	<0.02	<0.02	0.07	0.07	0.04	0.04	<0.02	<0.02
190	0.13	0.13	0.09	0.09	0.04	0.04	0.20	0.18	0.13	0.12	0.07	0.07
180	0.33	0.31	0.25	0.23	0.15	0.15	0.59	0.57	0.40	0.38	0.26	0.25
170	2.08	1.99	0.79	0.75	0.55	0.52	5.27	5.05	4.83	1.97	0.93	0.90
160	10.48	6.74	9.14	5.57	5.28	5.11	17.15	11.63	16.29	10.95	9.68	5.51
150	29.72	22.93	25.15	18.23	17.11	13.09	44.23	34.18	38.69	29.81	24.22	17.97
140	65.33	55.01	58.31	46.69	38.63	29.94	>79.98	72.49	79.98	65.70	56.27	42.87
130	>79.98	*	>79.98	*	>79.98	*	>79.98	*	>79.98	*	>79.98	*

* Radii unresolvable due to R_{max} exceeding maximum modelled distance.

Table 23. *Torosa piling, marine mammal and turtle behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile to modelled maximum-over-depth isopleths per penetration depth.

Threshold	IHC S-600						IHC S-1200					
	Penetration depth (m)						Penetration depth (m)					
	17		31		45		17		31		45	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Marine mammal behavioural response (160 dB re 1 µPa SPL) (NMFS 2014)	10.48	6.74	9.14	5.57	5.28	5.11	17.15	11.63	16.29	10.95	9.68	5.51
Turtle behavioural response (166 dB re 1 µPa SPL) (NSF 2011)	5.11	4.99	2.07	1.97	0.95	0.91	9.11	5.66	9.06	5.46	4.84	4.46
Turtle behavioural disturbance (175 dB re 1 µPa SPL) (McCauley et al. 2000a, 2000b)	0.68	0.64	0.43	0.40	0.29	0.28	1.87	1.79	0.72	0.69	0.48	0.46

Table 24. *Torosa piling, marine mammal and turtle PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (in m) from the pile to maximum-over-depth isopleths.

Hearing group	PTS							TTS						
	PK threshold (L_{pk}; dB re 1 µPa)	IHC S-600			IHC S-1200			PK threshold (L_{pk}; dB re 1 µPa)	IHC S-600			IHC S-1200		
		Penetration depth (m)			Penetration depth (m)				Penetration depth (m)			Penetration depth (m)		
		17	31	45	17	31	45		17	31	45	17	31	45
LF cetaceans	219	<20	<20	<20	51	32	<20	213	76	51	<20	99	58	32
MF cetaceans	230	<20	<20	<20	<20	<20	<20	224	<20	<20	<20	<20	<20	<20
HF cetaceans	202	214	142	86	260	216	130	196	351	275	192	544	400	286
Turtles	232	<20	<20	<20	<20	<20	<20	226	<20	<20	<20	<20	<20	<20

Table 25. *Torosa piling, mortality and potential mortal recoverable injury thresholds (peak pressure level metric) for fish, fish eggs, and fish larvae*: Maximum (R_{max}) horizontal distances (in m) from the pile.

Marine animal group	PK threshold (L_{pk}; dB re 1 µPa)	IHC S-600			IHC S-1200		
		Penetration depth (m)			Penetration depth (m)		
		17	31	45	17	31	45
Fish: No swim bladder	213	76	51	<20	99	58	32
Fish: Swim bladder not involved in hearing, Swim bladder involved in hearing Fish eggs, and larvae	207	127	91	42	166	121	58

Table 26. *Torosa piling, modelled maximum-over-depth per-strike SEL, SPL, and PK at the receiver located at the Scott Reef coastal waters limit*.

Metric	IHC S-600			IHC S-1200		
	Penetration depth (m)			Penetration depth (m)		
	17	31	45	17	31	45
Unweighted SEL (L_E; dB re 1 µPa²·s)	152.3	149.4	145.1	156.7	153.9	149.0
SPL (L_p; dB re 1 µPa)	160.8	157.9	153.7	165.2	162.5	157.6
PK (L_{pk}; dB re 1 µPa)	175.0	172.7	169.4	178.6	176.3	172.8

4.1.2.2. Sound field maps and vertical slices

Maps of the per-strike SPL results associated with the three modelled penetration depths are shown in Figures 17, 18, and 19 for the IHC S-600, and in Figures 20, 21, and 22 for the IHC S-1200. Per-strike SEL maps are shown in Appendix H.1. For each hammer, the shallowest modelled penetration has the farthest distances to all per-strike isopleths. Additionally, maps showing the isopleths for marine mammal behavioural criteria (160 dB re 1 µPa) for each of the three considered penetration depths are provided in Figures 23 and 24 for the IHC S-600 and the IHC S-1200, respectively, to demonstrate visually the reduction in extent with increased penetration depth. Vertical slice plots for all penetrations are shown in Figures 25–27 (IHC S-600) and Figures 28–30 (IHC S-1200).

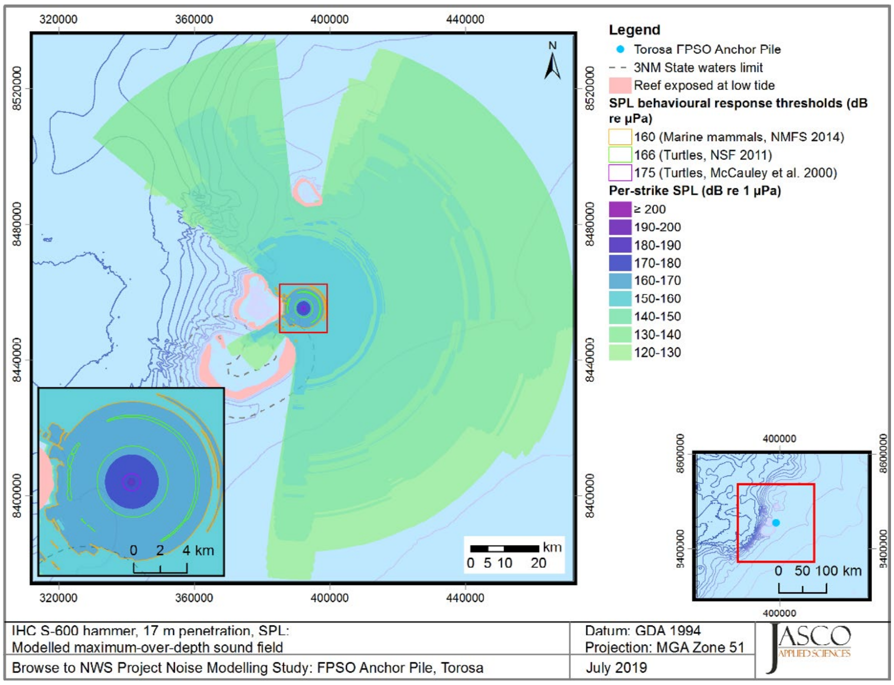

Figure 17. *Torosa, IHC S-600, SPL, 17 m penetration depth*: Sound level contour map, showing maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

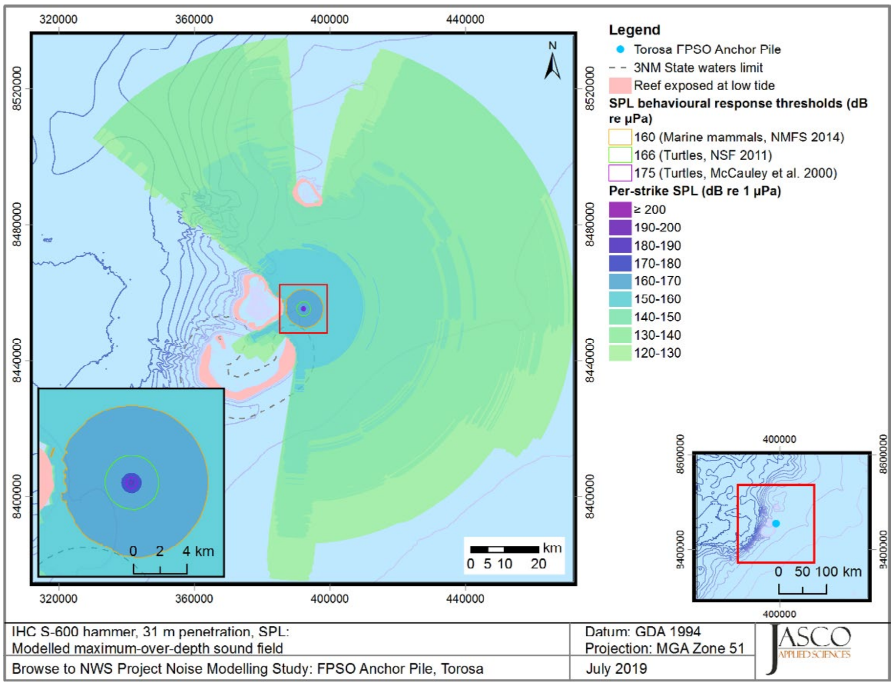

Figure 18. *Torosa, IHC S-600, SPL, 31 m penetration depth*: Sound level contour map, showing maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

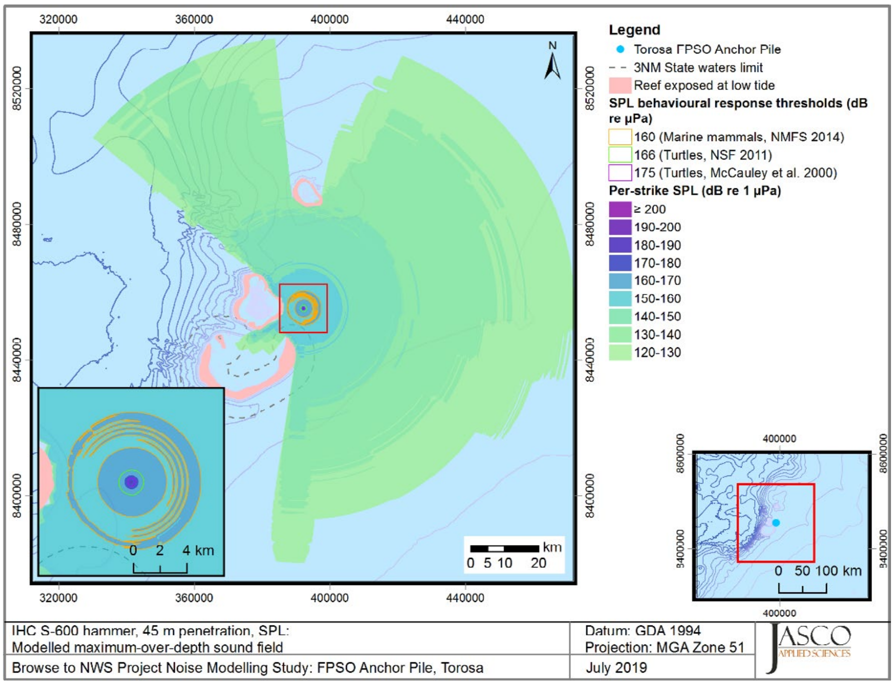

Figure 19. *Torosa, IHC S-600, SPL, 45 m penetration depth*: Sound level contour map, showing maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

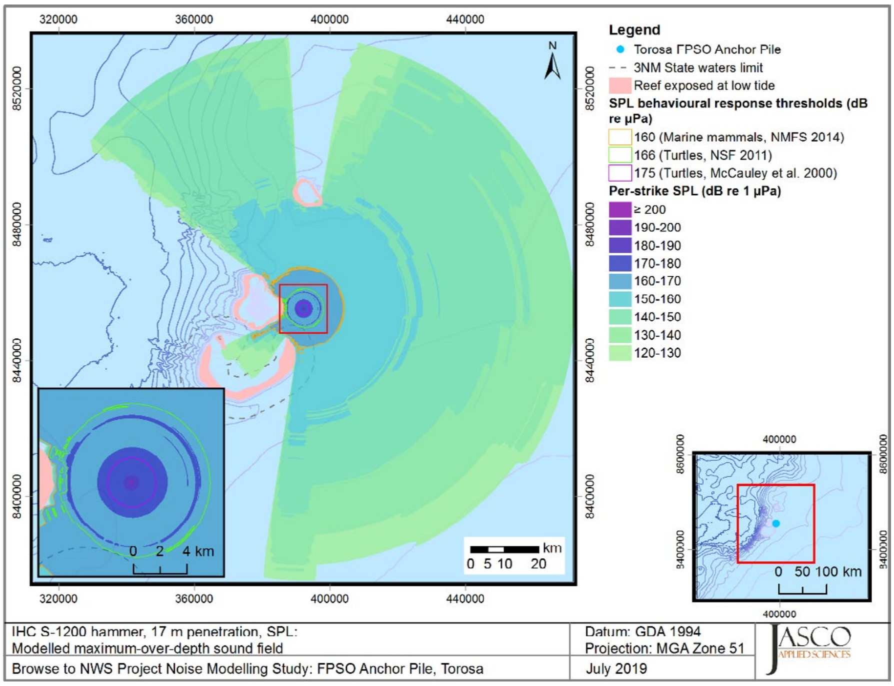

Figure 20. *Torosa, IHC S-1200, SPL, 17 m penetration depth*: Sound level contour map, showing unweighted maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

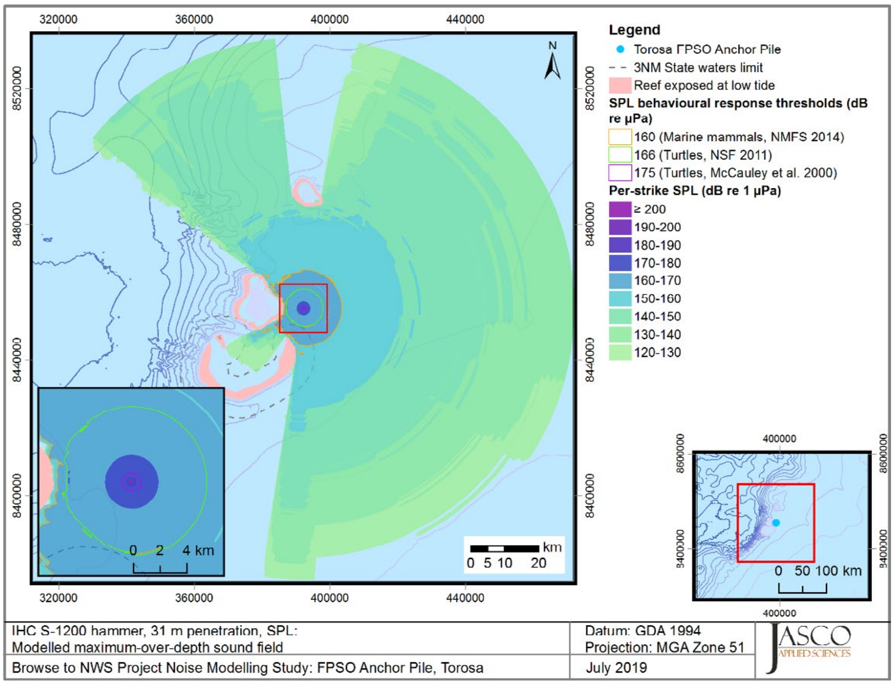

Figure 21. *Torosa, IHC S-1200, SPL, 31 m penetration depth*: Sound level contour map, showing maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

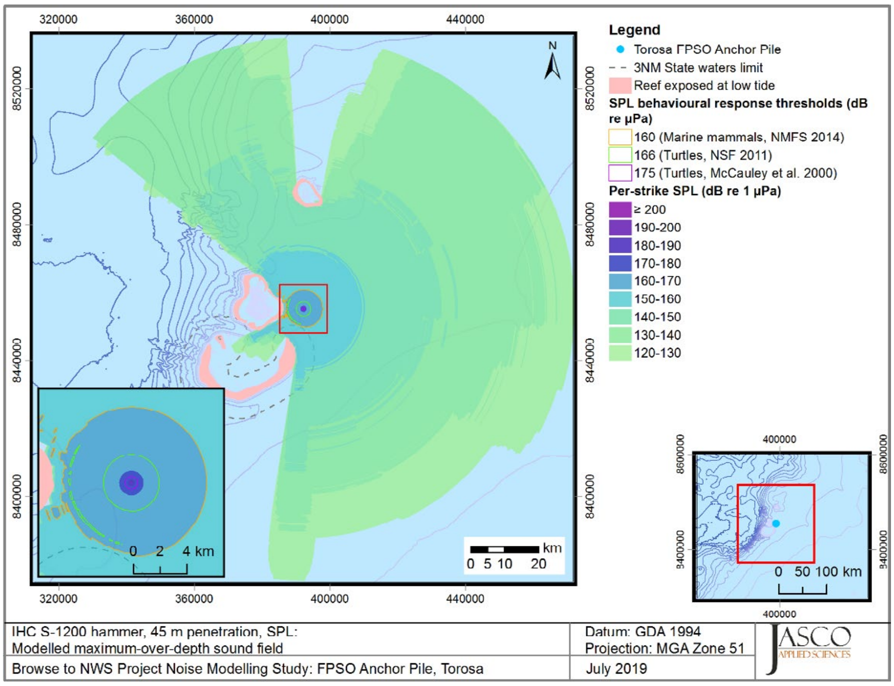

Figure 22. *Torosa, IHC S-1200, SPL, 45 m penetration depth*: Sound level contour map, showing maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

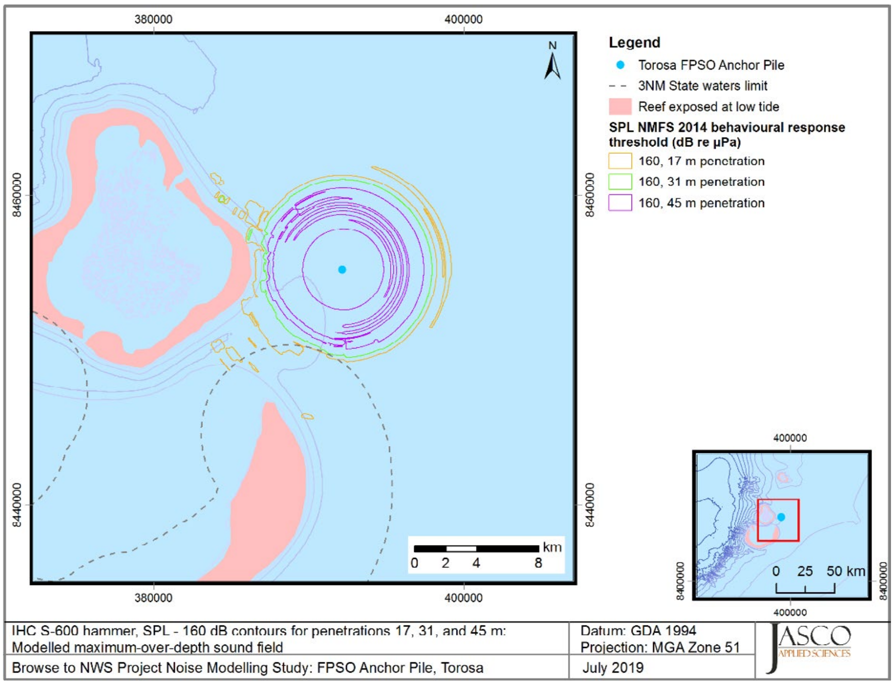

Figure 23. *Torosa, IHC S-600, SPL*: Sound level contour map showing unweighted maximum-over-depth SPL marine mammal (160 dB re 1 µPa) behavioural criteria results for all modelled penetration depths.

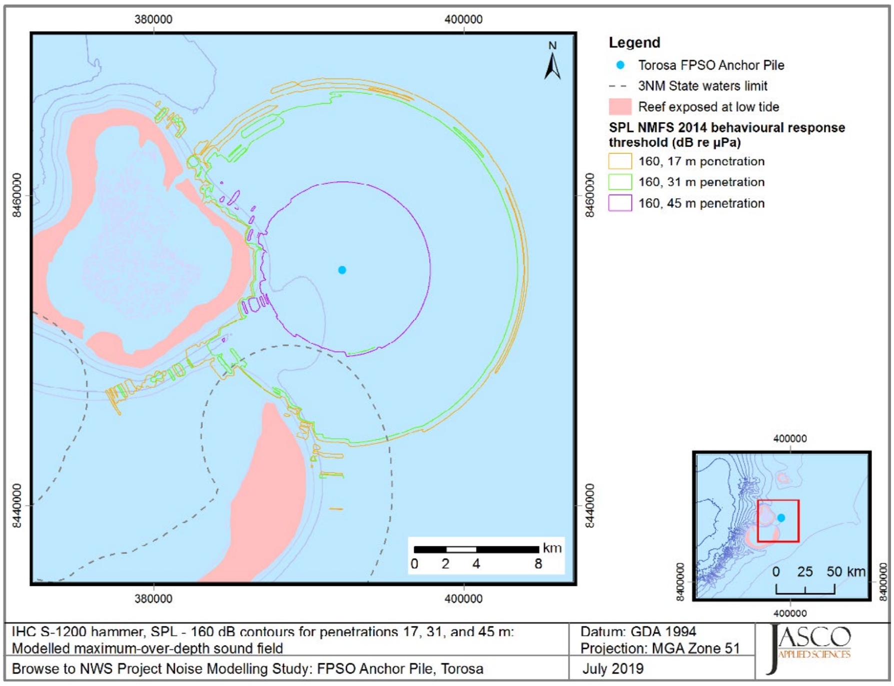

Figure 24. *Torosa, IHC S-1200, SPL*: Sound level contour map showing unweighted maximum-over-depth SPL marine mammal (160 dB re 1 µPa) behavioural criteria results for all modelled penetration depths.

4.1.2.2.1. Vertical slice plots

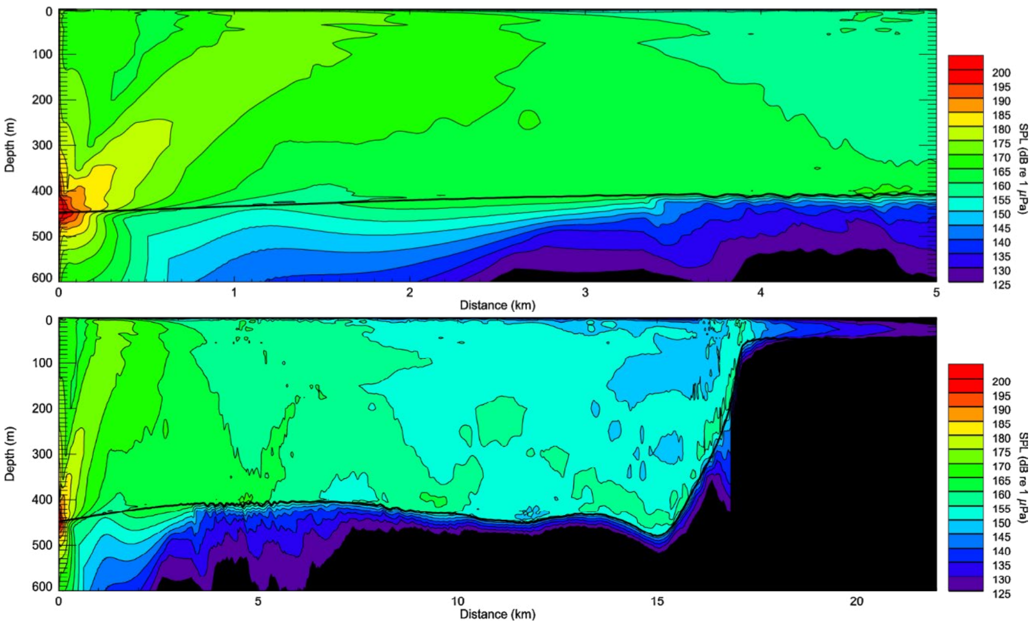

Figure 25. *Torosa, vertical slice, IHC S-600, SPL, 17 m penetration depth*: 0–5 km (top) and 0–22 km (bottom). Levels are shown along a single transect of azimuth 240°. The seabed outline is shown as a thick black line.

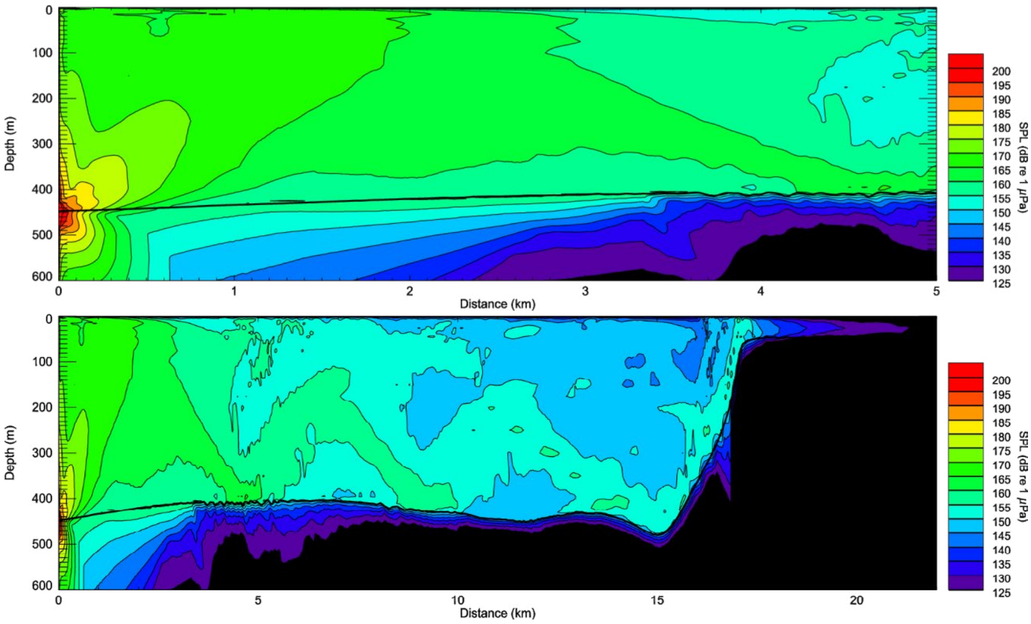

Figure 26. *Torosa, vertical slice, IHC S-600, SPL, 31 m penetration depth*: 0–5 km (top) and 0–22 km (bottom). Levels are shown along a single transect of azimuth 240°. The seabed outline is shown as a thick black line.

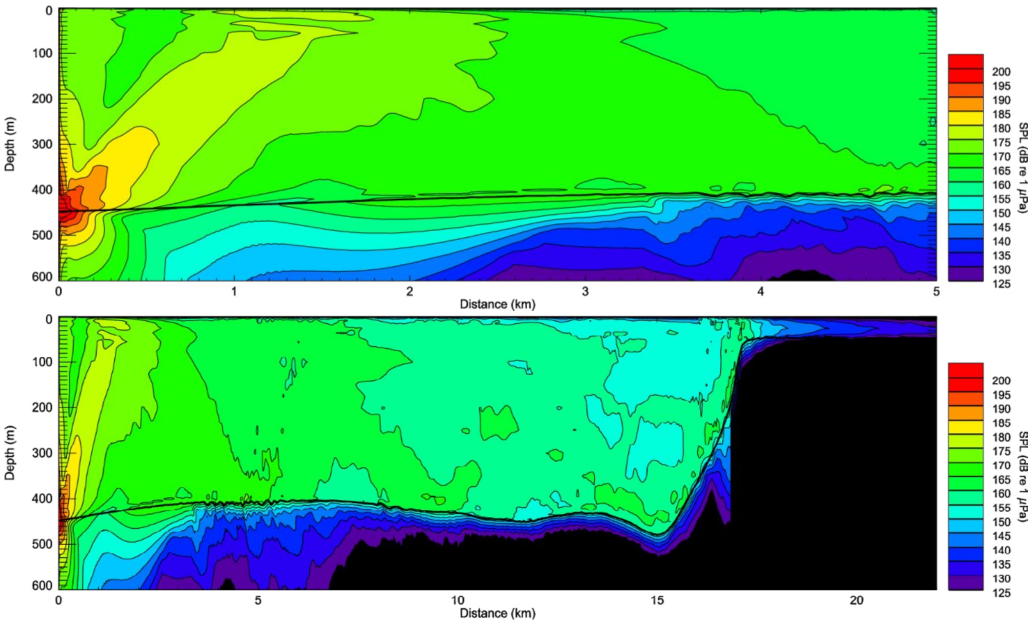

Figure 27. *Torosa, vertical slice, IHC S-600, SPL, 45 m penetration depth*: 0–5 km (top) and 0–22 km (bottom). Levels are shown along a single transect of azimuth 240°. The seabed outline is shown as a thick black line.

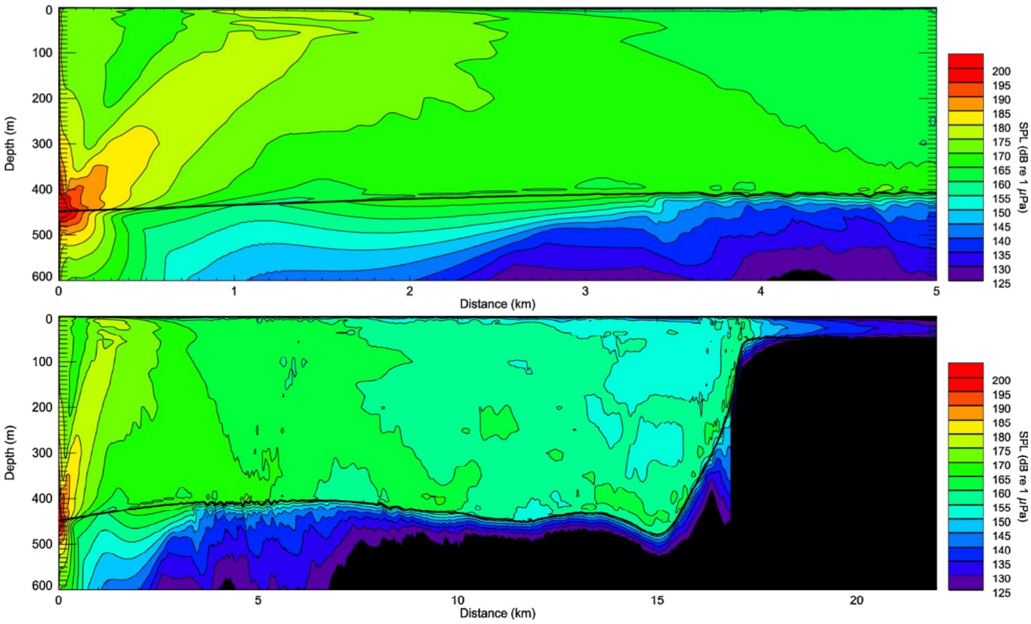

Figure 28. *Torosa, vertical slice, IHC S-1200, SPL, 17 m penetration depth*: 0–5 km (top) and 0–22 km (bottom). Levels are shown along a single transect of azimuth 240°. The seabed outline is shown as a thick black line.

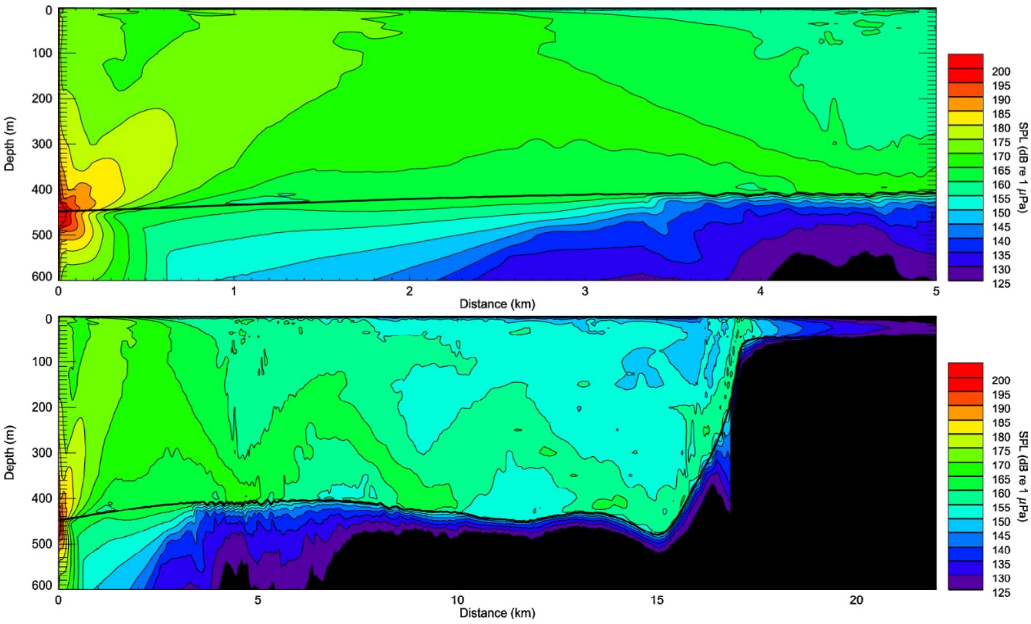

Figure 29. *Torosa, vertical slice, IHC S-1200, SPL, 31 m penetration depth*: 0–5 km (top) and 0–22 km (bottom). Levels are shown along a single transect of azimuth 240°. The seabed outline is shown as a thick black line.

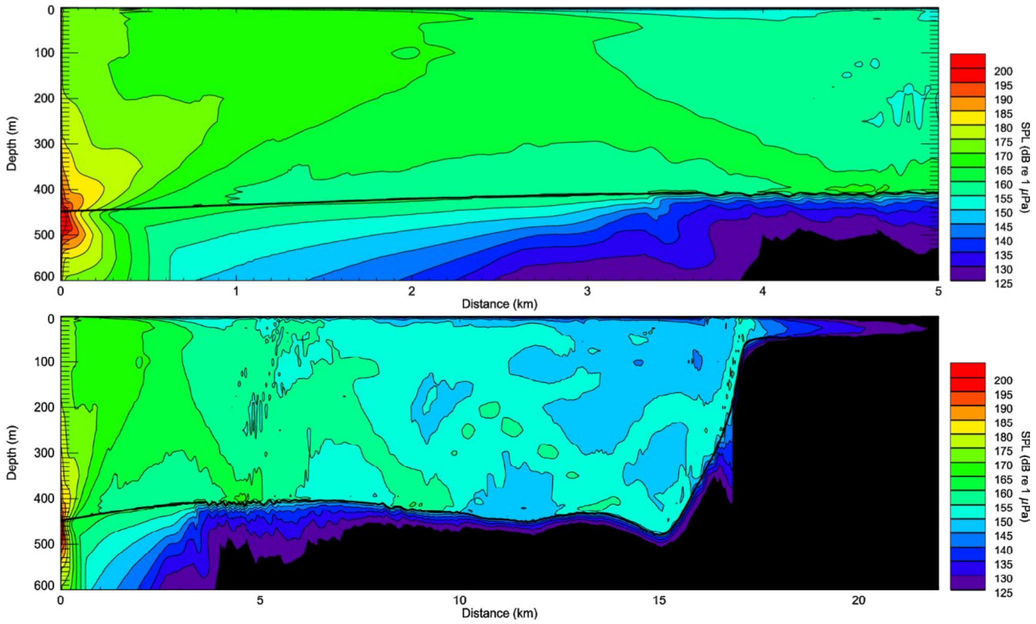

Figure 30. *Torosa, vertical slice, IHC S-1200, SPL, 45 m penetration depth*: 0–5 km (top) and 0–22 km (bottom). Levels are shown along a single transect of azimuth 240°. The seabed outline is shown as a thick black line.

Detailed plots of the sound fields along two transects for both the IHC S-600 and IHC S-1200 hammers relevant to the pygmy blue whale migratory behavioural profile (Table G-2) are shown in Figures 31–34. These plots highlight 1) the mean migratory dive depth (14 m), 2) 23 m – almost the deepest point of the migratory dives but the start point for exploratory dives, 3) the mean exploratory dive depth (107 m), and 4) the deepest point for exploratory dives (320 m), with all values from Owen et al. (2016).

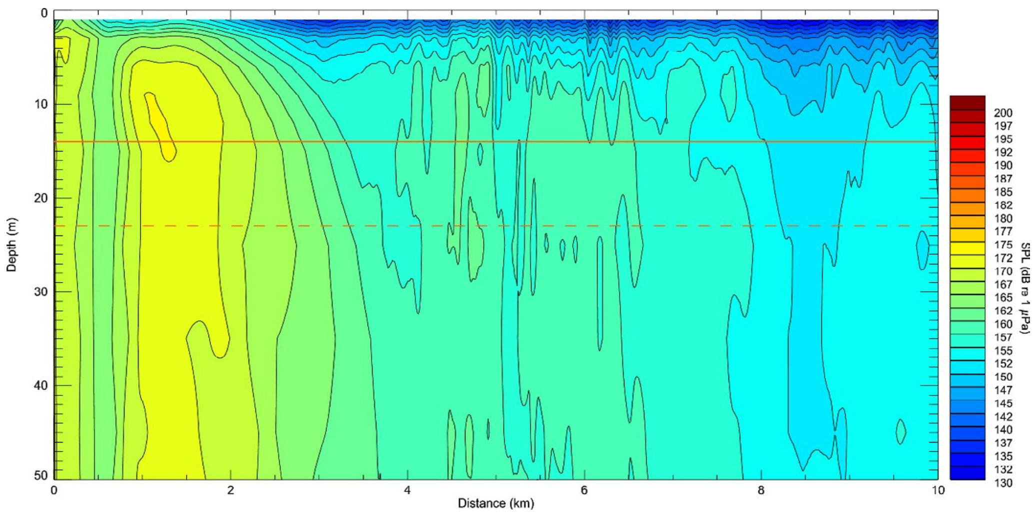

Figure 31. *Torosa, vertical slice, IHC S-600, SPL, 17 m penetration depth*: Levels are shown along a single transect of azimuth 240°, out to 10 km range, and down to 50 m depth, highlighting the depths of 14 and 23 m.

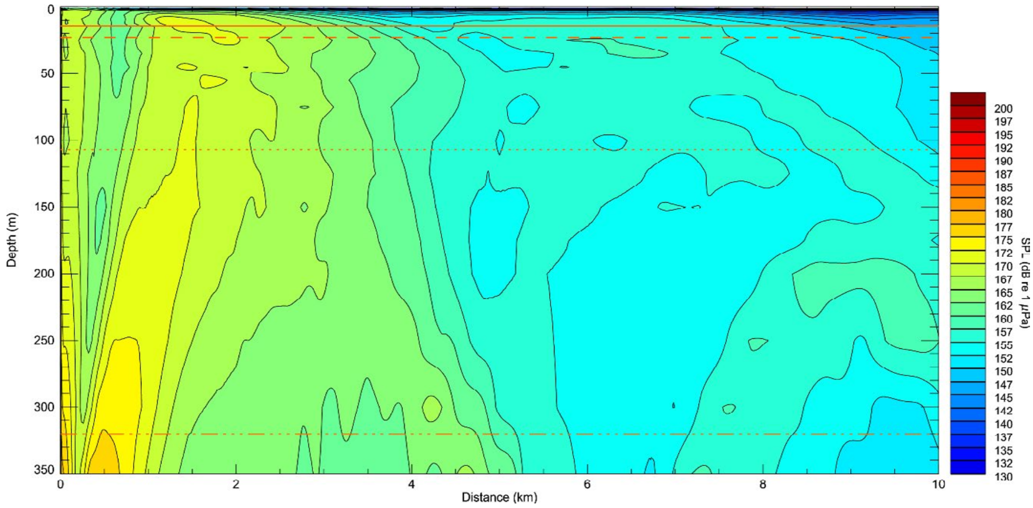

Figure 32. *Torosa, vertical slice, IHC S-600, SPL, 17 m penetration depth*: Levels are shown along a single transect of azimuth 240°, out to 10 km range, and down to 350 m depth, highlighting the depths of 14, 23, 107 and 320 m.

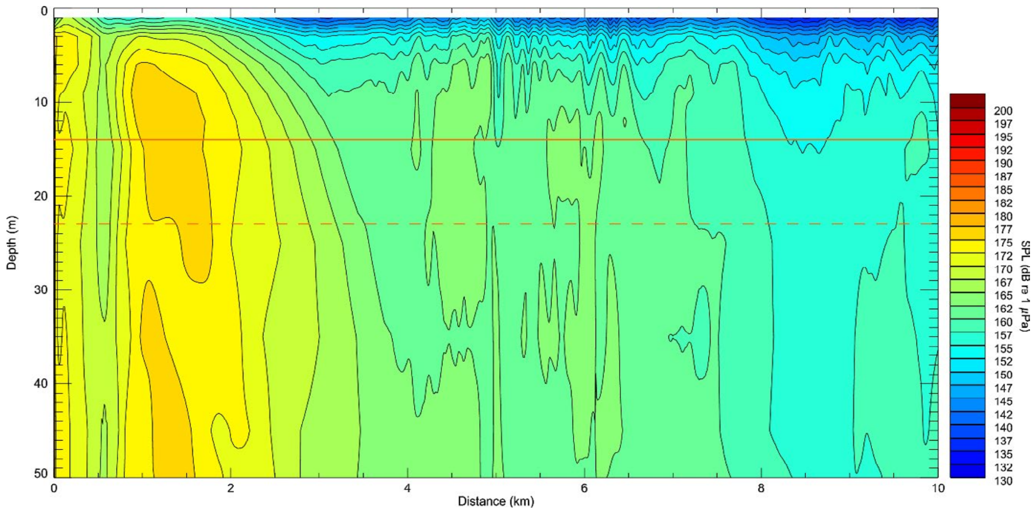

Figure 33. *Torosa, vertical slice, IHC S-1200, SPL, 17 m penetration depth*: Levels are shown along a single transect of azimuth 240°, out to 10 km range, and down to 50 m depth, highlighting the depths of 14 and 23 m.

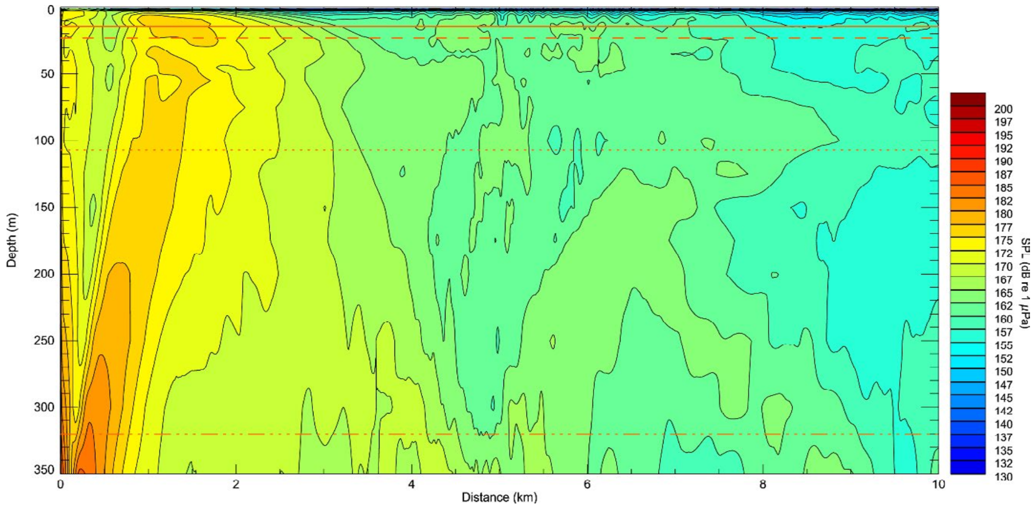

Figure 34. *Torosa, vertical slice, IHC S-1200, SPL, 17 m penetration depth*: Levels are shown along a single transect of azimuth 240°, out to 10 km range, and down to 350 m depth, highlighting the depths of 14, 23, 107 and 320 m.

4.1.3. Multiple Strike Sound Fields

Table 27 presents the SEL24h results relevant to marine mammals for the proposed pile driving operations, while Table 28 shows modelled distances to the cumulative exposure criteria contours for fish, fish eggs and larvae. The sound levels at the Scott Reef coastal waters limit are shown in Table 29. The sound level contour maps for cetaceans and turtles are presented in Figures 35 and 36 for the IHC S-600 and the IHC S-1200 hammers, respectively. The sound level contour maps for fish are presented in Figures 37 and 38 for the IHC S-600 and the IHC S-1200 hammers, respectively.

Table 27. *Torosa piling, SEL_{24}*: Maximum-over-depth distances (in km) to frequency-weighted SEL_{24h} based marine mammal PTS and TTS thresholds (NMFS 2018) and turtles (Finneran et al. 2017).

Hearing group	PTS					TTS				
	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s) #	IHC S-600		IHC S-1200		Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s) #	IHC S-600		IHC S-1200	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
LF cetaceans	183	5.15	5.00	5.35	5.12	168	26.10	20.79	29.46	22.60
MF cetaceans	185	-	-	-	-	170	0.03	0.03	0.06	0.06
HF cetaceans	155	0.07	0.07	0.17	0.16	140	0.32	0.30	2.20	2.06
Turtles	204	0.24	0.23	0.25	0.25	189	4.79	2.36	5.07	4.94

Frequency weighted.
A dash indicates the level was not reached.

Table 28. *Torosa piling, SEL_{24}*: Maximum-over-depth distances (in km) to SEL_{24h} based fish criteria. Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

Marine animal group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Distance			
		IHC S-600		IHC S-1200	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Fish mortality and potential mortal injury					
I	219	0.06	0.06	0.06	0.06
II Fish eggs and larvae	210	0.15	0.14	0.15	0.15
III	207	0.21	0.20	0.22	0.21
Fish recoverable injury					
I	216	0.09	0.09	0.09	0.09
II, III	203	0.32	0.30	0.34	0.33
Fish TTS					
I, II, III	186	9.05	5.41	9.15	5.56

Table 29. *Torosa piling, SEL_{24}*: Modelled maximum-over-depth SEL_{24h} at the receiver located at the Scott Reef coastal waters limit.

Frequency weighting	SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	
	IHC S-600	IHC S-1200
Unweighted	183.4	184.3
LF cetaceans	177.6	178.0
MF cetaceans	128.2	130.7
HF cetaceans	117.5	124.5
Turtles	182.0	182.7

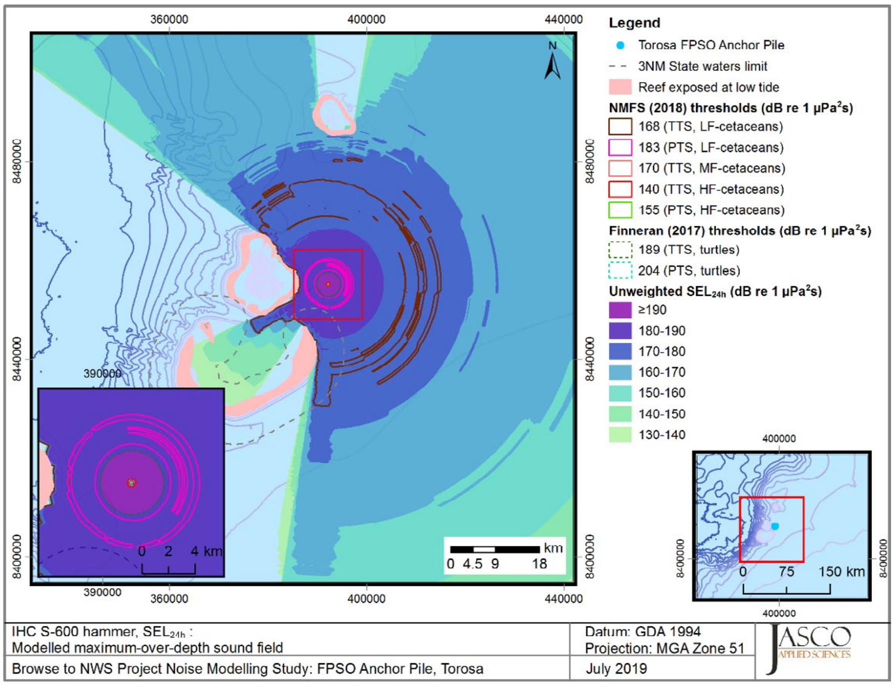

Figure 35. *Torosa, IHC S-600, SEL24h*: Sound level contour map showing unweighted maximum-over-depth SEL24h results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles. Threshold for mid-frequency cetacean PTS was not reached.

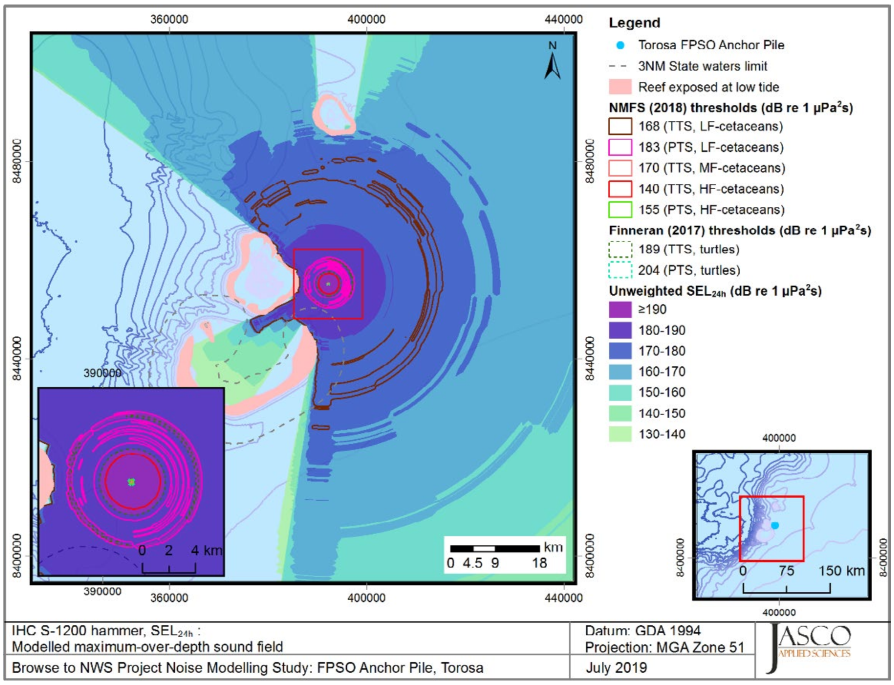

Figure 36. *Torosa, IHC S-1200, SEL24h*: Sound level contour map showing unweighted maximum-over-depth SEL24h results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles. Threshold for mid-frequency cetacean PTS was not reached.

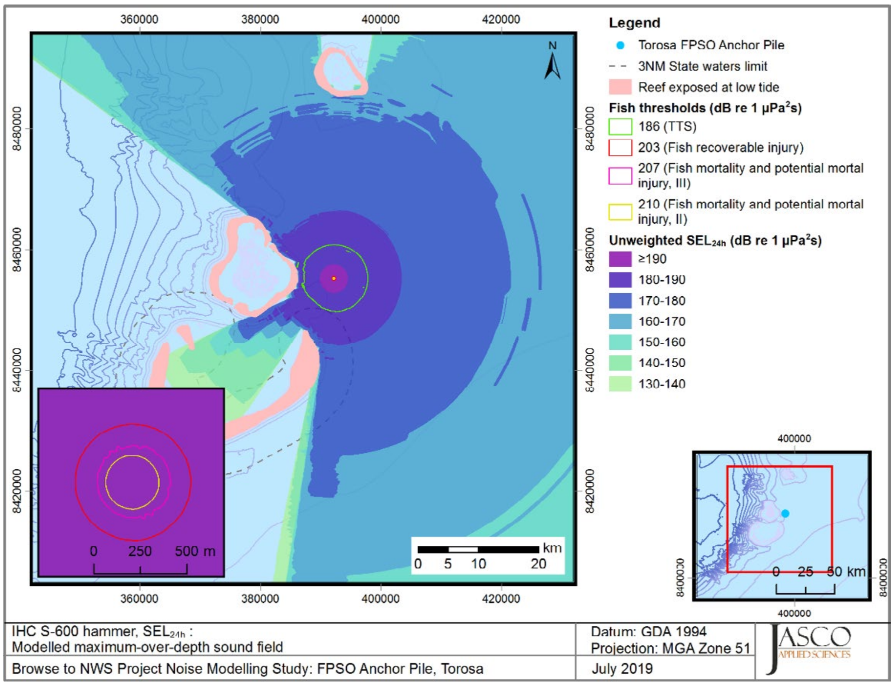

Figure 37. *Torosa, IHC S-600, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths relevant to fish injury and TTS. Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

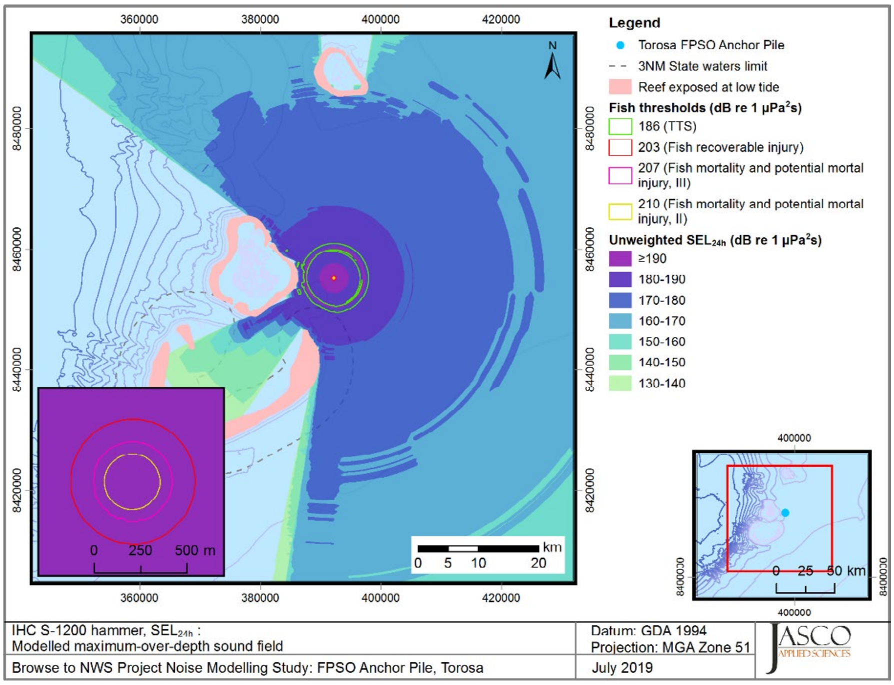

Figure 38. *Torosa, IHC S-1200, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL24h results, along with isopleths relevant to fish injury and TTS. Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.4. Animal Movement and Exposure Modelling

Summaries of the animat modelling results for inter-nesting and migrating green turtles are provided in Table 30, while those for migrating and foraging pygmy blue whales are provided in Table 31.

Table 30. *Torosa*: Summary of animat simulation results for migratory and inter-nesting turtles. Includes the distances to acoustic modelling thresholds (km), the 95th percentile exposure ranges (km), and the number of real-world individuals exposed above threshold (where densities are available). This summary includes both the original animat simulation results and the results excluding animats within a 500 m zone surrounding the pile, acoustic modelling results are presented in Tables 23, 24, and 27.

Threshold		Distance to threshold from acoustic modelling		Migratory turtles	Migratory turtles with 500 m exclusion zone		Inter-nesting turtles		Inter-nesting turtles with 500 m exclusion zone	
Threshold description	Sound level (dB)	R_{max} (km)	$R_{95\%}$ (km)	Range, P_{95} (km)	Range, P_{95} (km)	Reduction (%)	Range, P_{95} (km)	Number of individuals	Range, P_{95} (km)	Number of individuals
IHC S-600 hammer										
TTS, PK	226†	<0.02*		0.00	0.00	0	0.00	0.00	0.00	0.00
TTS, SEL_{24h}	189‡	4.79	2.36	1.65	1.69	20.67	0.00	0.00	0.00	0.00
PTS, PK	232†	<0.02*		0.00	0.00	0	0.00	0.00	0.00	0.00
PTS, SEL_{24h}	204‡	0.24	0.23	0.00	0.00	0	0.00	0.00	0.00	0.00
Behavioural response	166#	5.11	4.99	2.54	2.56	10.98	0.00	0.00	0.00	0.00
	175#	0.68	0.64	0.05	0.00	100.00	0.00	0.00	0.00	0.00
IHC S-1200 hammer										
TTS, PK	226†	<0.02*		0.00	0.00	0	0.00	0.00	0.00	0.00
TTS, SEL_{24h}	189‡	5.07	4.94	1.79	1.81	11.48	0.00	0.00	0.00	0.00
PTS, PK	232†	<0.02*		0.00	0.00	0	0.00	0.00	0.00	0.00
PTS, SEL_{24h}	204‡	0.25	0.25	0.00	0.00	0	0.00	0.00	0.00	0.00
Behavioural response	166#	9.11	5.66	4.64	4.71	4.25	0.00	0.00	0.00	0.00
	175#	1.87	1.79	1.77	1.78	6.25	0.00	0.00	0.00	0.00

† PK (L_{pk}; dB re 1 µPa)
‡ Turtle weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s)
# SPL (L_p; dB re 1 µPa)
* R_{max} reported for TTS PK and PTS PK from acoustic modelling

Table 31. *Torosa*: Summary of animat simulation results for migratory and foraging pygmy blue whales. Includes the distances to acoustic modelling thresholds (km), the 95th percentile exposure ranges (km), and the number of real-world individuals exposed above threshold (where densities are available). This summary includes both the original animat simulation results and the results excluding animats within a 2000 m zone surrounding the pile, acoustic modelling results are presented in Tables 23, 24 and 27.

Threshold		Distance to threshold from acoustic modelling		Migrating pygmy blue whales		Migrating pygmy blue whales with 2000 m exclusion zone		Foraging pygmy blue whales		Foraging pygmy blue whales with 2000 m exclusion zone	
Threshold description	Sound level (dB)	R_{max} (km)	$R_{95\%}$ (km)	Range, P_{95} (km)	Number of individuals	Range, P_{95} (km)	Number of individuals	Range, P_{95} (km)	Number of individuals	Range, P_{95} (km)	Number of individuals
IHC S-600 hammer											
TTS, PK	213†	0.08*		0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00
TTS, SEL_{24h}	168‡	26.10	20.79	7.27	1.28	7.72	1.05	10.75	1.65	10.84	1.52
PTS, PK	219†	< 0.02*		0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00
PTS, SEL_{24h}	183‡	5.00	5.00	0.91	0.02	0.00	0.00	1.45	0.06	0.00	0.00
Behavioural response	160#	10.48	6.74	6.29	0.56	6.87	0.32	6.72	0.58	6.91	0.43
IHC S-1200 hammer											
TTS, PK	213†	0.1*		0.00	0.00	0.00	0.00	0.1	0.00	0.00	0.00
TTS, SEL_{24h}	168‡	29.46	22.60	8.34	1.30	8.58	1.13	11.92	1.75	12.03	1.64
PTS, PK	219†	0.05*		0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00
PTS, SEL_{24h}	183‡	5.35	5.12	1.31	0.02	0.00	0.00	1.57	0.06	2.09	0.00
Behavioural response	160#	17.15	11.63	9.14	1.41	9.73	1.22	10.72	1.39	10.83	1.28

† PK (L_{pk}; dB re 1 µPa)
‡ LF-weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s)
# SPL (L_p; dB re 1 µPa)
* R_{max} reported for TTS PK and PTS PK from acoustic modelling

4.2. Pile Driving: Brecknock FPSO Anchor Piles

4.2.1. Received levels at 10 m

Since piles are distributed and directional sources, they cannot be accurately approximated by a point source with corresponding source levels. It is possible to compare the maximum modelled levels at short distances from the piles. Figure 39 shows the 1/3-octave-band levels for the receiver with the highest SEL at the closest horizontal range (10 m), for the three modelled penetrations. The levels above 1000 Hz were extrapolated using a 20 dB/decade decay rate to match acoustic measurements of impact pile driving of similarly sized piles (Illingworth & Rodkin 2007, Matuschek and Betke 2009). The modelled results at a distance of 10 m are included to provide results comparable to other pile driving reports and literature, such as Illingworth & Rodkin (2007), and Denes et al. (2016).

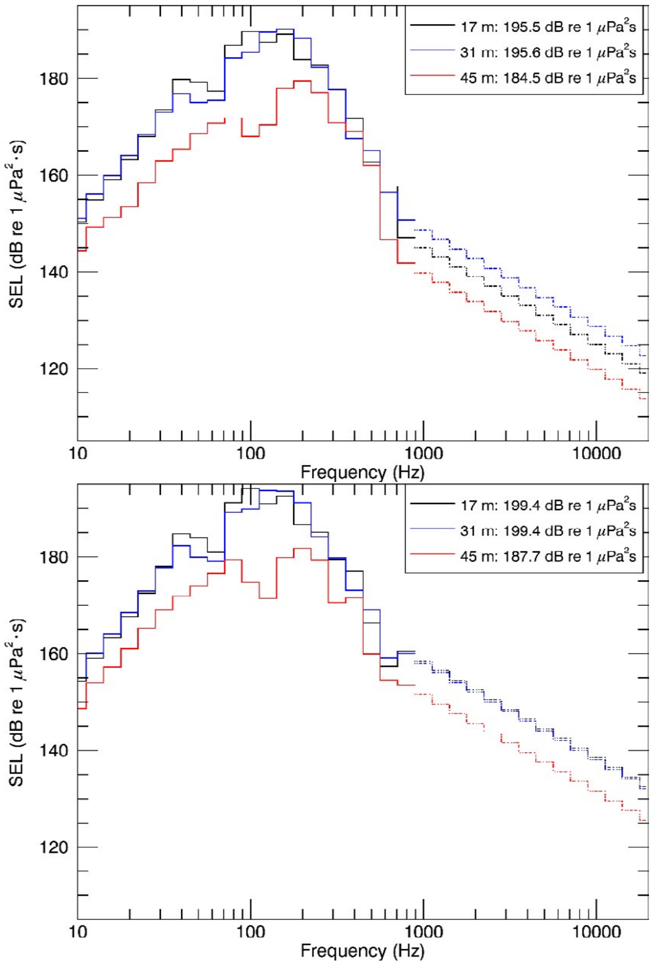

Figure 39. *Brecknock*: One-third-octave-band levels for the receiver with highest SEL at 10 m horizontal range for impact pile driving using the IHC S-600 (top) and the IHC S-1200 (bottom), after high-frequency extrapolation (dashes indicate extrapolated portion of the spectrum). Legend items indicate the modelled pile penetration (Table 16) and the broadband SEL in dB re 1 μPa^2·s.

4.2.2. Per-strike sound fields

Per-strike results for the proposed pile driving are presented in this section for maximum-over-depth SPL, SEL, and PK (tables in Section 4.2.2.1), maps and sound field vertical slices (Section 4.2.2.2).

4.2.2.1. Tabulated results

Tables 32–36 show the estimated distances for the various applicable per-strike effects criteria and isopleths of interest as maximum-over-depth.

Table 32. *Brecknock piling, per-strike SEL:* Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile to modelled maximum-over-depth isopleths.

Per-strike SEL (L_E; dB re 1 µPa²·s)	IHC S-600						IHC S-1200					
	Penetration depth (m)						Penetration depth (m)					
	17		31		45		17		31		45	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.03	0.03	<0.02	<0.02	-	-	0.06	0.06	0.03	0.03	-	-
180	0.12	0.11	0.09	0.09	0.04	0.04	0.20	0.20	0.14	0.13	0.07	0.07
170	0.38	0.37	0.28	0.25	0.16	0.15	0.67	0.63	0.44	0.41	0.27	0.26
160	2.31	2.18	0.91	0.85	0.61	0.57	5.76	5.21	2.26	2.13	1.01	0.97
150	10.60	7.42	6.62	6.24	5.41	5.03	17.06	13.23	13.07	10.99	6.40	5.89
140	28.89	23.24	23.11	19.12	16.63	12.42	43.63	35.59	39.08	28.08	23.02	18.45
130	>79.98	*	>79.98	*	41.18	29.74	>79.98	*	>79.98	*	79.69	73.15
120	>79.98	*	>79.98	*	>79.98	*	>79.98	*	>79.98	*	>79.98	*

* Radii unresolvable due to R_{max} exceeding maximum modelled distance.

Table 33. *Brecknock piling, SPL:* Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile to modelled maximum-over-depth isopleths.

SPL (L_p; dB re 1 µPa)	IHC S-600						IHC S-1200					
	Penetration depth (m)						Penetration depth (m)					
	17		31		45		17		31		45	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.05	0.05	0.03	0.03	<0.02	<0.02
190	0.11	0.10	0.08	0.07	0.03	0.03	0.18	0.17	0.13	0.12	0.06	0.06
180	0.33	0.31	0.25	0.23	0.14	0.13	0.56	0.54	0.39	0.37	0.24	0.23
170	2.04	1.94	0.77	0.72	0.51	0.49	2.87	2.70	2.02	1.92	0.83	0.78
160	7.06	6.40	6.40	5.78	4.54	4.41	13.97	11.87	11.51	10.26	6.19	5.61
150	24.76	21.29	21.35	17.05	13.92	10.99	42.30	30.79	31.07	25.70	21.39	16.94
140	>79.98	*	>79.98	*	31.59	26.41	>79.98	*	>79.98	*	74.59	63.09
130	>79.98	*	>79.98	*	>79.98	*	>79.98	*	>79.98	*	>79.98	*

* Radii unresolvable due to R_{max} exceeding maximum modelled distance.

Table 34. *Brecknock piling, marine mammal and turtle behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile to modelled maximum-over-depth isopleths per penetration depth.

Threshold	IHC S-600						IHC S-1200					
	Penetration depth (m)						Penetration depth (m)					
	17		31		45		17		31		45	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Marine mammal behavioural response (160 dB re 1 µPa SPL) (NMFS 2014)	7.06	6.40	6.40	5.78	4.54	4.41	13.97	11.87	11.51	10.26	6.19	5.61
Turtle behavioural response (166 dB re 1 µPa SPL) (NSF 2011)	2.87	2.70	2.06	1.95	0.84	0.80	6.38	5.92	5.93	5.51	2.12	2.04
Turtle behavioural disturbance (175 dB re 1 µPa SPL) (McCauley et al. 2000a, 2000b)	0.67	0.63	0.42	0.39	0.28	0.26	1.87	1.77	0.69	0.64	0.45	0.42

Table 35. *Brecknock piling, marine mammal and turtle PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (in m) from the pile to maximum-over-depth isopleths.

Hearing group	PTS							TTS						
	PK threshold (L_{pk}; dB re 1 µPa	IHC S-600			IHC S-1200			PK threshold (L_{pk}; dB re 1 µPa	IHC S-600			IHC S-1200		
		Penetration depth (m)			Penetration depth (m)				Penetration depth (m)			Penetration depth (m)		
		17	31	45	17	31	45		17	31	45	17	31	45
LF cetaceans	219	<20	<20	<20	<20	<20	<20	213	42	<20	<20	71	32	<20
MF cetaceans	230	<20	<20	<20	<20	<20	<20	224	<20	<20	<20	<20	<20	<20
HF cetaceans	202	186	148	76	258	216	121	196	364	275	177	559	402	270
Turtles	232	<20	<20	<20	<20	<20	<20	226	<20	<20	<20	<20	<20	<20

Table 36. *Brecknock piling, mortality and potential mortal recoverable injury thresholds (peak pressure level metric) for fish, fish eggs, and fish larvae*: Maximum (R_{max}) horizontal distances (in m) from the pile.

Marine animal group	PK threshold (L_{pk}; dB re 1 µPa)	IHC S-600			IHC S-1200		
		Penetration depth (m)			Penetration depth (m)		
		17	31	45	17	31	45
Fish: No swim bladder	213	42	<20	<20	71	32	<20
Fish: Swim bladder not involved in hearing, Swim bladder involved in hearing Fish eggs, and larvae	207	103	76	32	158	121	58

4.2.2.2. Sound field maps and vertical slices

Maps of the per-strike SPL results associated with the three modelled penetration depths are shown in Figures 40, 41, and 42 for the IHC S-600, and in Figures 43, 44, and 45 for the IHC S-1200. Per-strike SEL maps are shown in Appendix H.2. For each hammer, the shallowest modelled penetration has the farthest distances to all per-strike isopleths. Additionally, maps showing the isopleths for marine mammal behavioural criteria (160 dB re 1 µPa) for each of the three considered penetration depths are provided in Figures 46 and 47 for the IHC S-600 and the IHC S-1200, respectively, to demonstrate visually the reduction in extent with increased penetration depth. Vertical slice plots for all penetrations are shown in Figures 48–50 (IHC S-600) and Figures 51–53 (IHC S-1200).

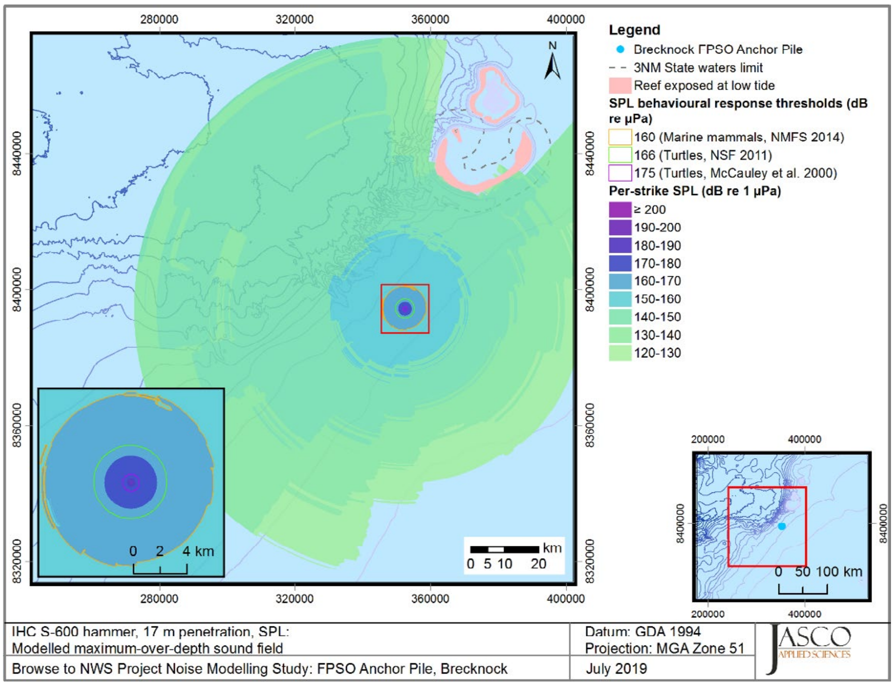

Figure 40. *Brecknock, IHC S-600, SPL, 17 m penetration depth*: Sound level contour map, showing maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

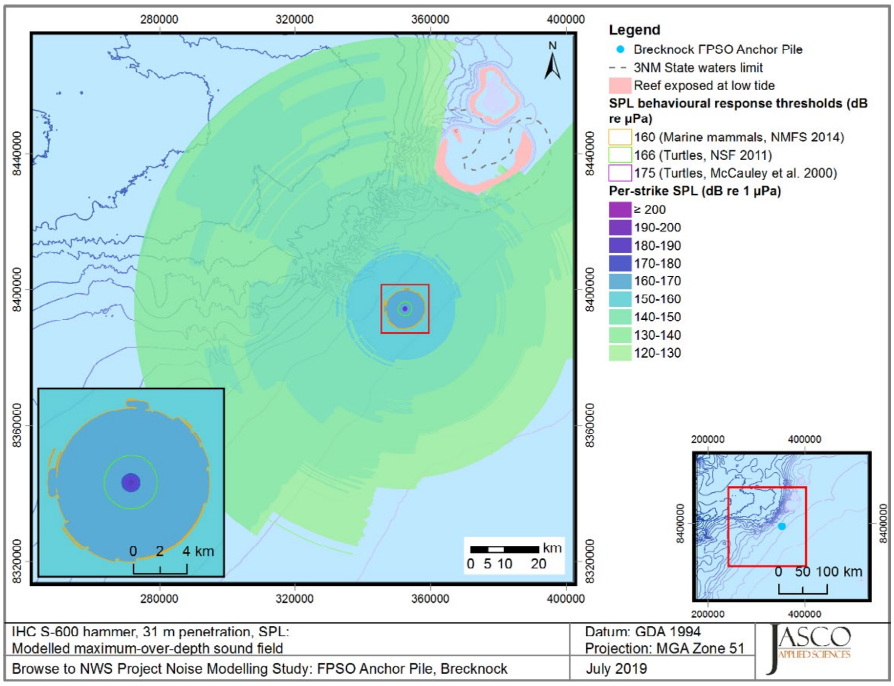

Figure 41. *Brecknock, IHC S-600, SPL, 31 m penetration depth*: Sound level contour map, showing maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

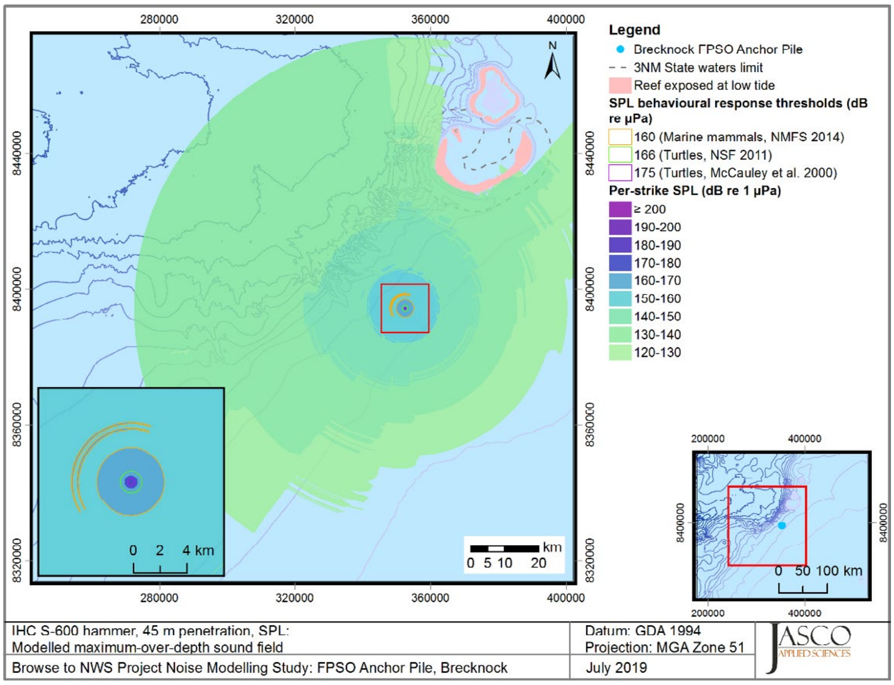

Figure 42. *Brecknock, IHC S-600, SPL, 45 m penetration depth*: Sound level contour map, showing maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

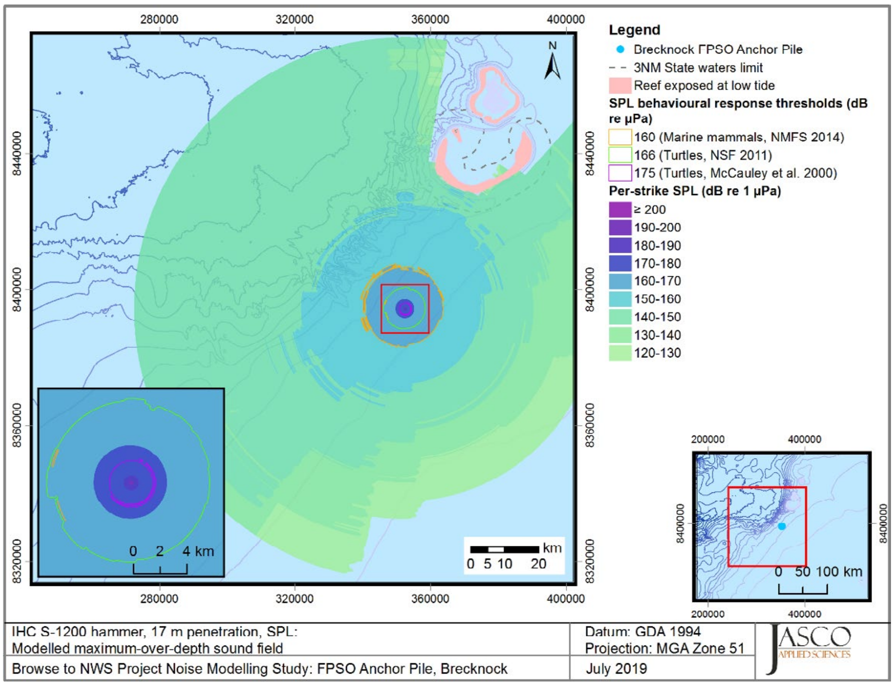

Figure 43. *Brecknock, IHC S-1200, SPL, 17 m penetration depth*: Sound level contour map, showing unweighted maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

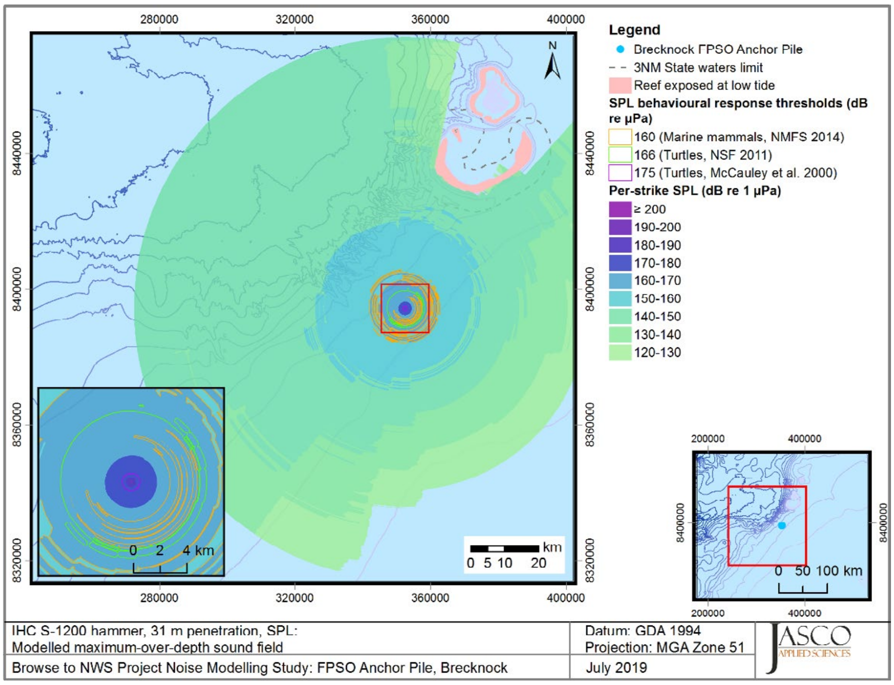

Figure 44. *Brecknock, IHC S-1200, SPL, 31 m penetration depth*: Sound level contour map, showing maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

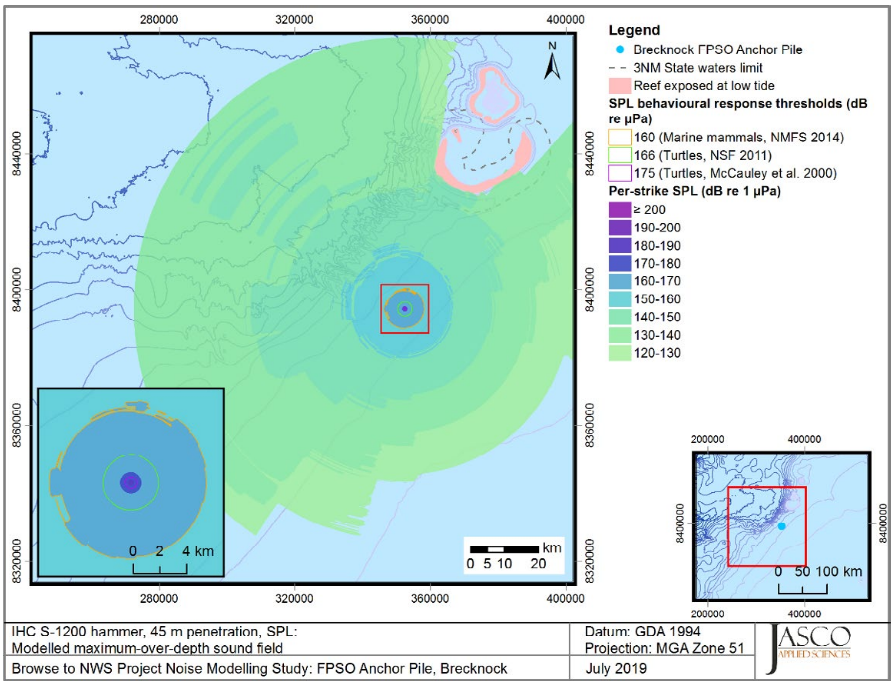

Figure 45. *Brecknock, IHC S-1200, SPL, 45 m penetration depth*: Sound level contour map, showing maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

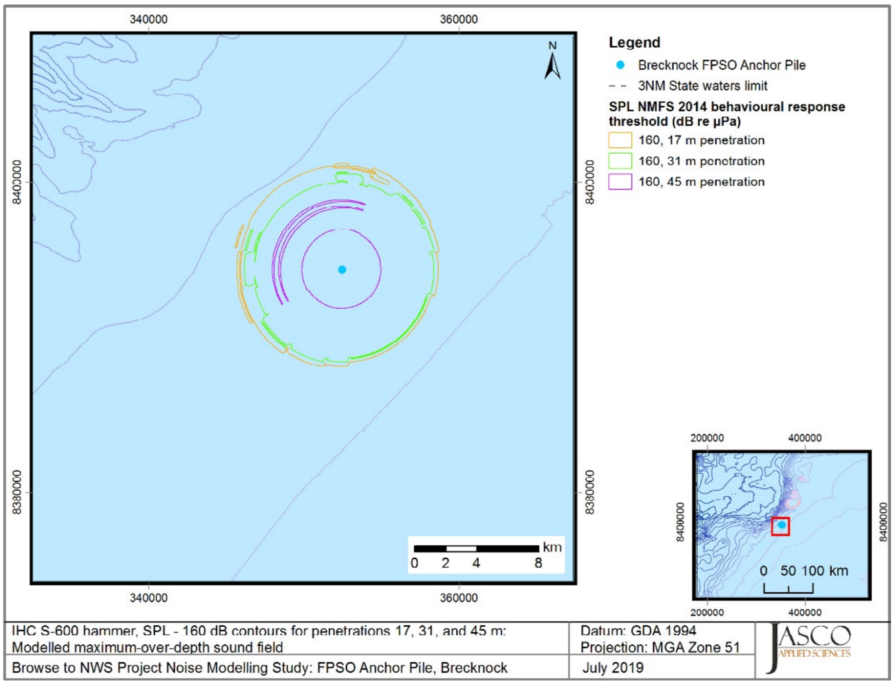

Figure 46. *Brecknock, IHC S-600, SPL*: Sound level contour map showing unweighted maximum-over-depth SPL marine mammal (160 dB re 1 µPa) behavioural criteria results for all modelled penetration depths.

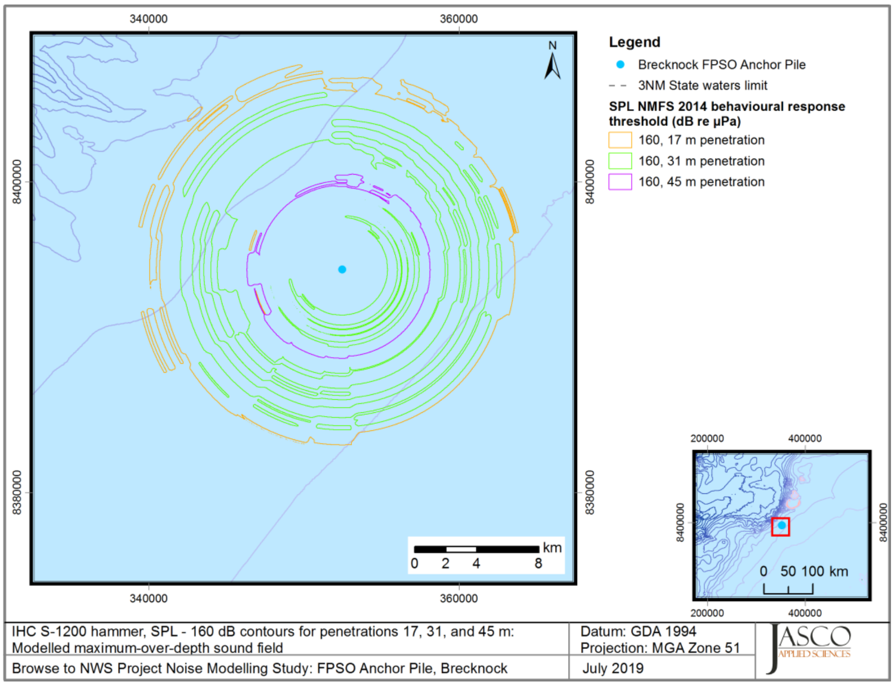

Figure 47. *Brecknock, IHC S-1200, SPL*: Sound level contour map showing unweighted maximum-over-depth SPL marine mammal (160 dB re 1 µPa) behavioural criteria results for all modelled penetration depths.

4.2.2.2.1. Vertical slice plots

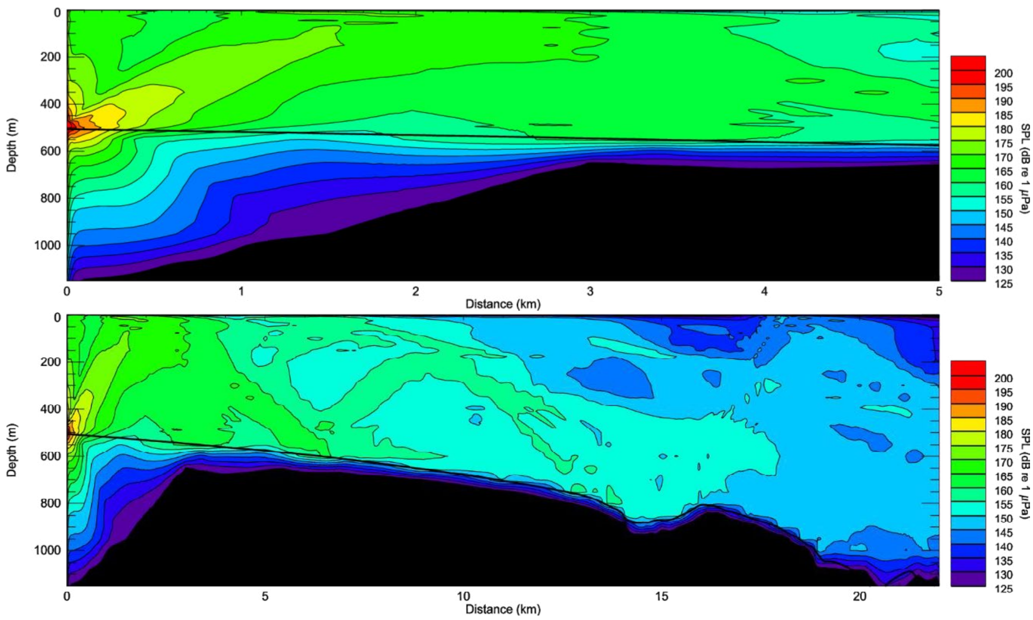

Figure 48. *Brecknock, vertical slice, IHC S-600, SPL, 17 m penetration depth*: 0–5 km (top) and 0–22 km (bottom). Levels are shown along a single transect of azimuth 315°. The seabed outline is shown as a thick black line.

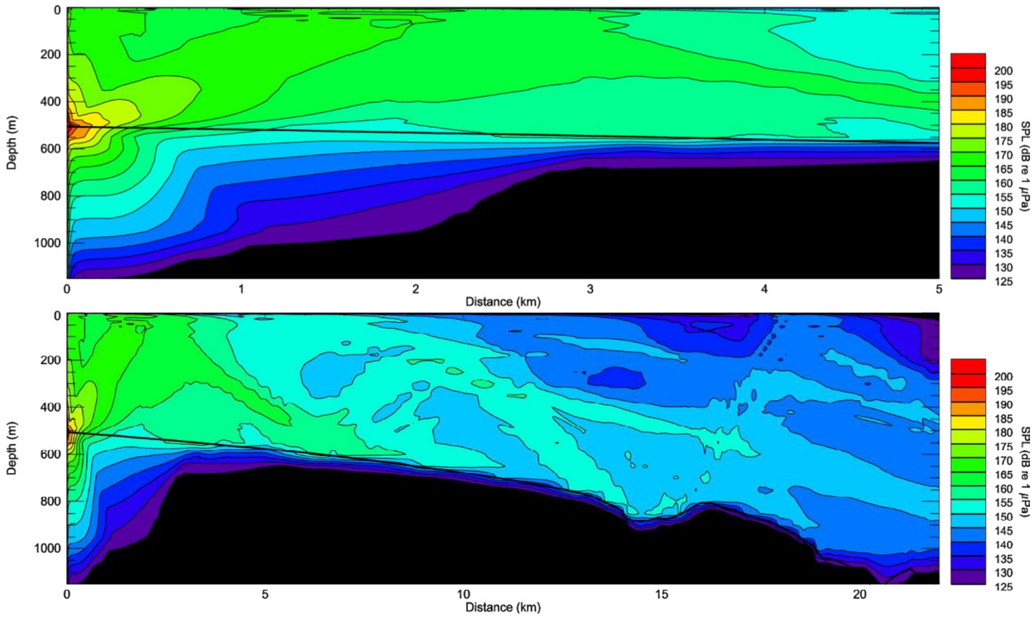

Figure 49. *Brecknock, vertical slice, IHC S-600, SPL, 31 m penetration depth*: 0–5 km (top) and 0–22 km (bottom). Levels are shown along a single transect of azimuth 315°. The seabed outline is shown as a thick black line.

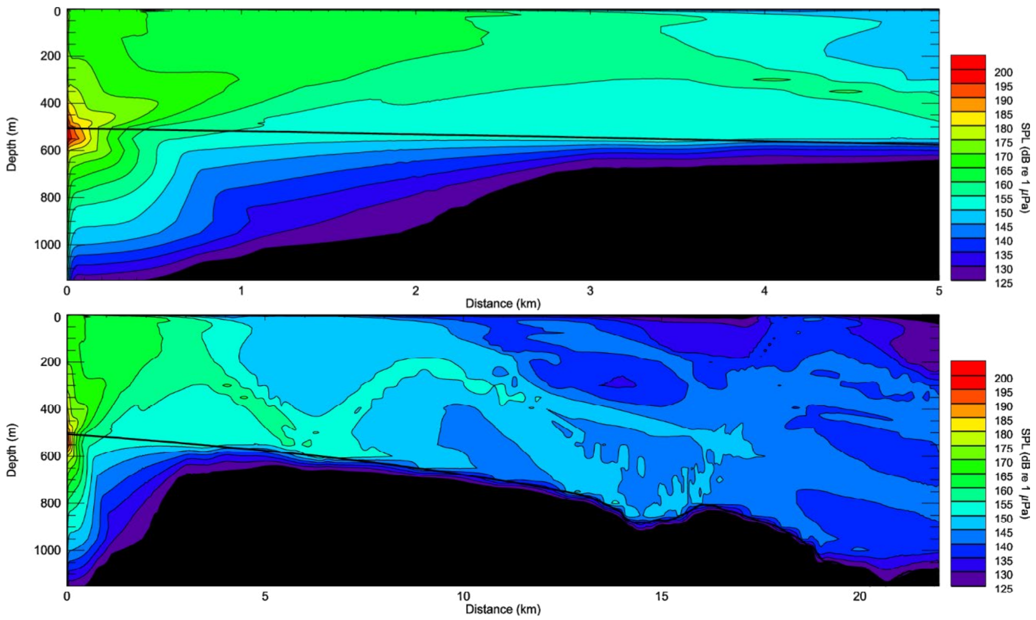

Figure 50. *Brecknock, vertical slice, IHC S-600, SPL, 45 m penetration depth*: 0–5 km (top) and 0–22 km (bottom). Levels are shown along a single transect of azimuth 315°. The seabed outline is shown as a thick black line.

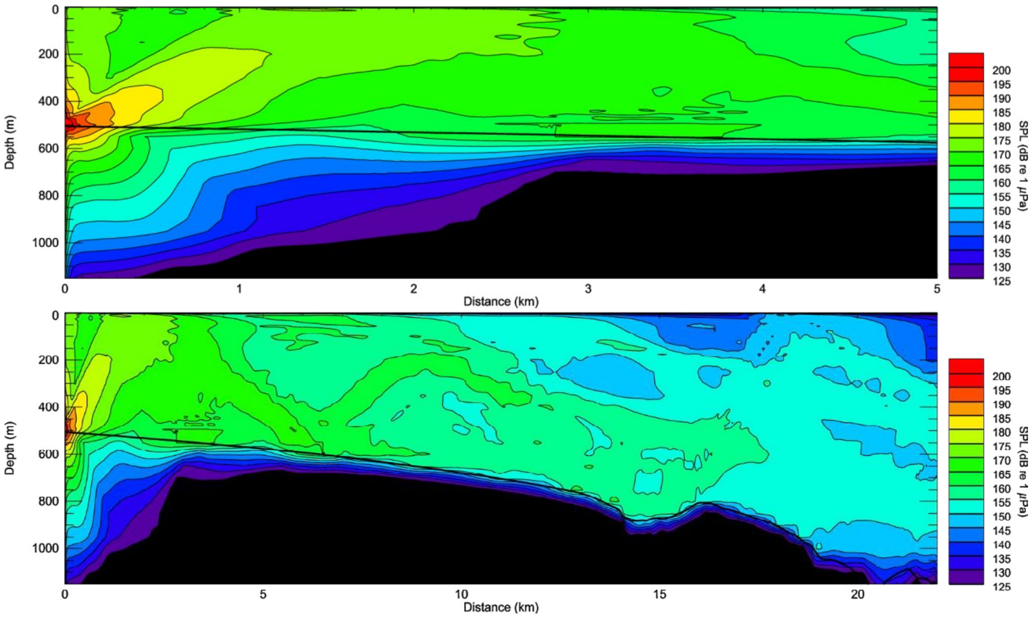

Figure 51. *Brecknock, vertical slice, IHC S-1200, SPL, 17 m penetration depth*: 0–5 km (top) and 0–22 km (bottom). Levels are shown along a single transect of azimuth 315°. The seabed outline is shown as a thick black line.

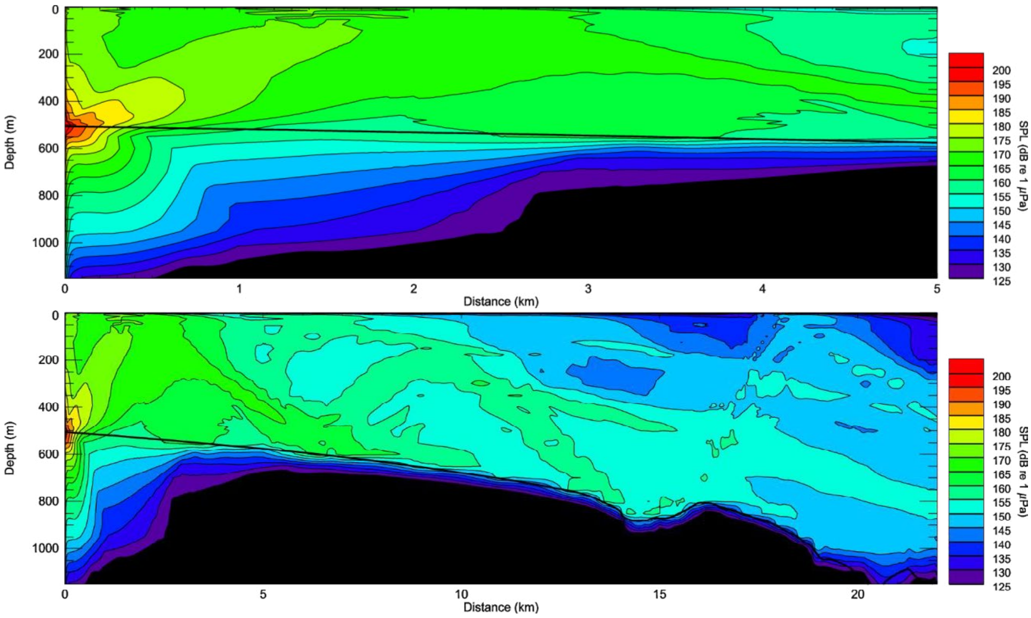

Figure 52. *Brecknock, vertical slice, IHC S-1200, SPL, 31 m penetration depth*: 0–5 km (top) and 0–22 km (bottom). Levels are shown along a single transect of azimuth 315°. The seabed outline is shown as a thick black line.

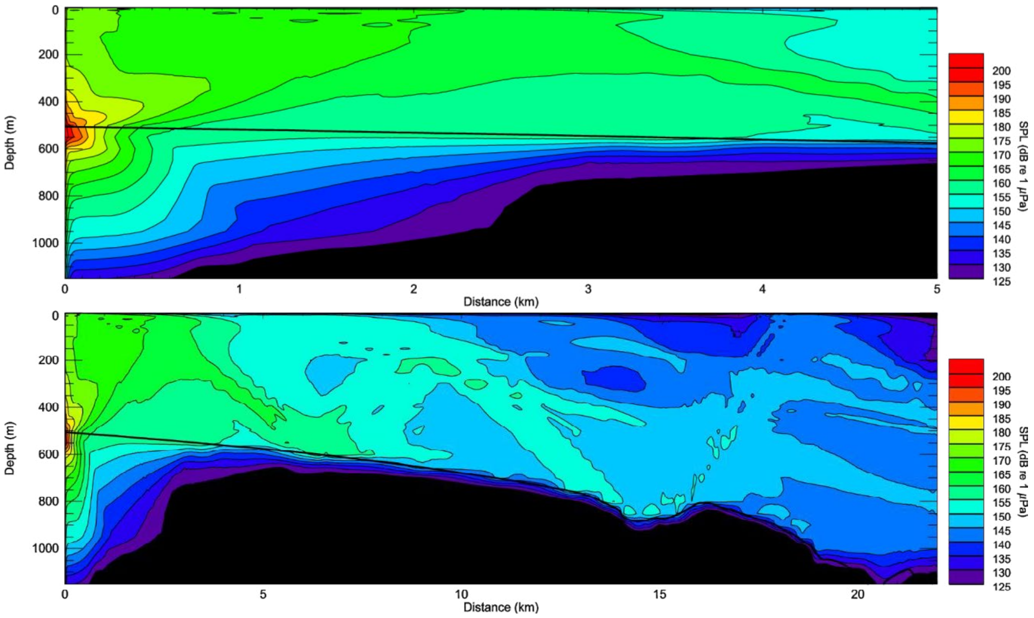

Figure 53. *Brecknock, vertical slice, IHC S-1200, SPL, 45 m penetration depth*: 0–5 km (top) and 0–22 km (bottom). Levels are shown along a single transect of azimuth 315°. The seabed outline is shown as a thick black line.

Detailed plots of the sound fields along two transects for both the IHC S-600 and IHC S-1200 hammers relevant to the pygmy blue whale migratory behavioural profile (Table G-2) are shown in Figures 58–61. These plots highlight 1) the mean migratory dive depth (14 m), 2) 23 m – almost the deepest point of the migratory dives but the start point for exploratory dives, 3) the mean exploratory dive depth (107 m), and 4) the deepest point for exploratory dives (320 m), with all values from Owen et al. (2016).

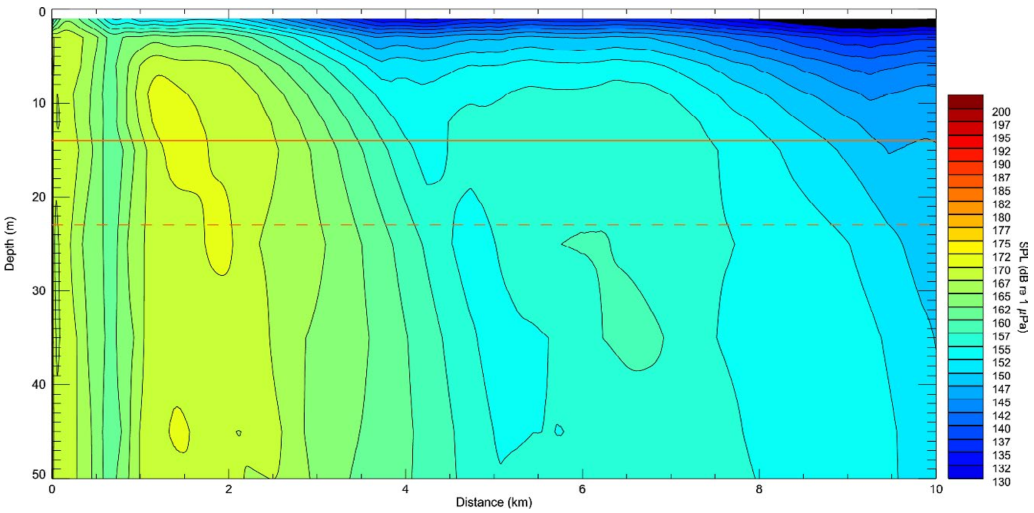

Figure 54. *Brecknock, vertical slice, IHC S-600, SPL, 17 m penetration depth*: Levels are shown along a single transect of azimuth 315°, out to 10 km range, and down to 50 m depth, highlighting the depths of 14 and 23 m.

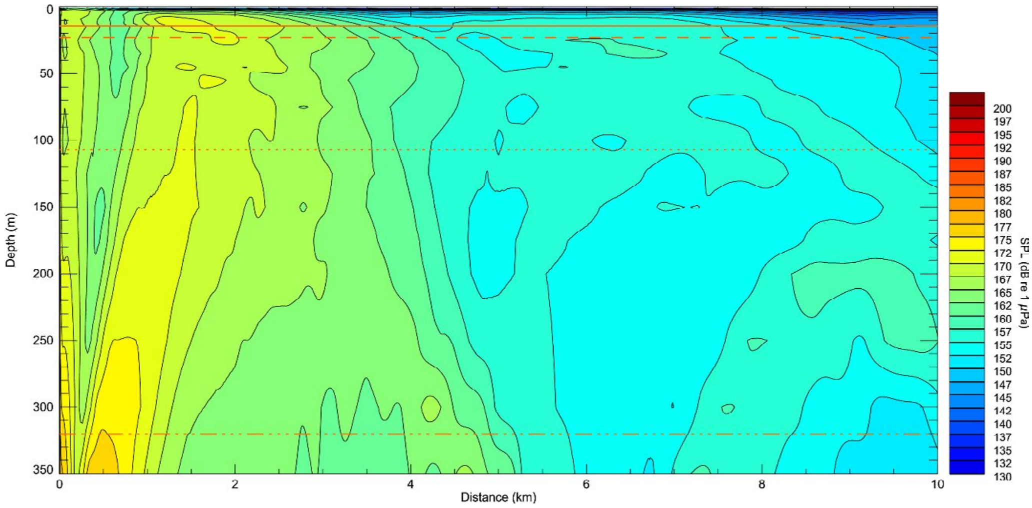

Figure 55. *Brecknock, vertical slice, IHC S-600, SPL, 17 m penetration depth*: Levels are shown along a single transect of azimuth 315°, out to 10 km range, and down to 350 m depth, highlighting the depths of 14, 23, 107 and 320 m.

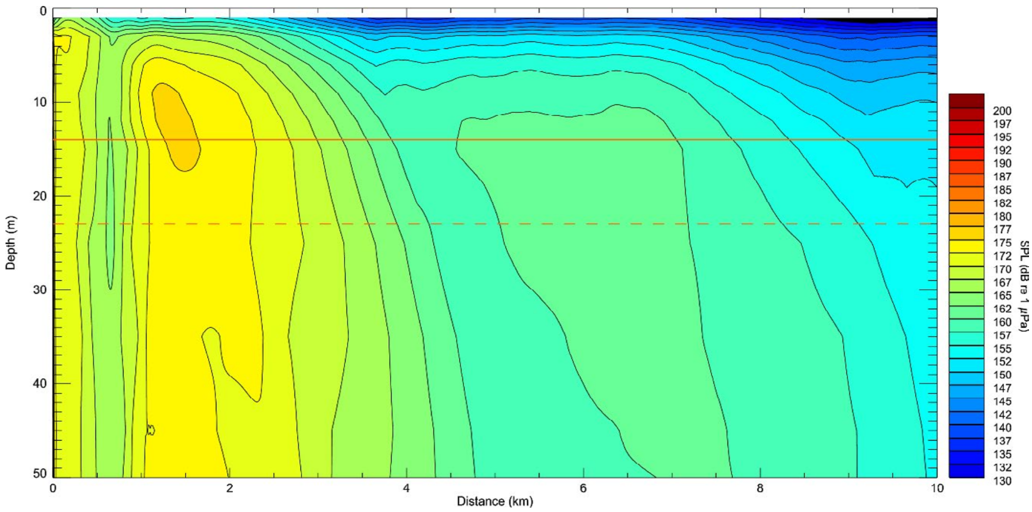

Figure 56. *Brecknock, vertical slice, IHC S-1200, SPL, 17 m penetration depth*: Levels are shown along a single transect of azimuth 315°, out to 10 km range, and down to 50 m depth, highlighting the depths of 14 and 23 m.

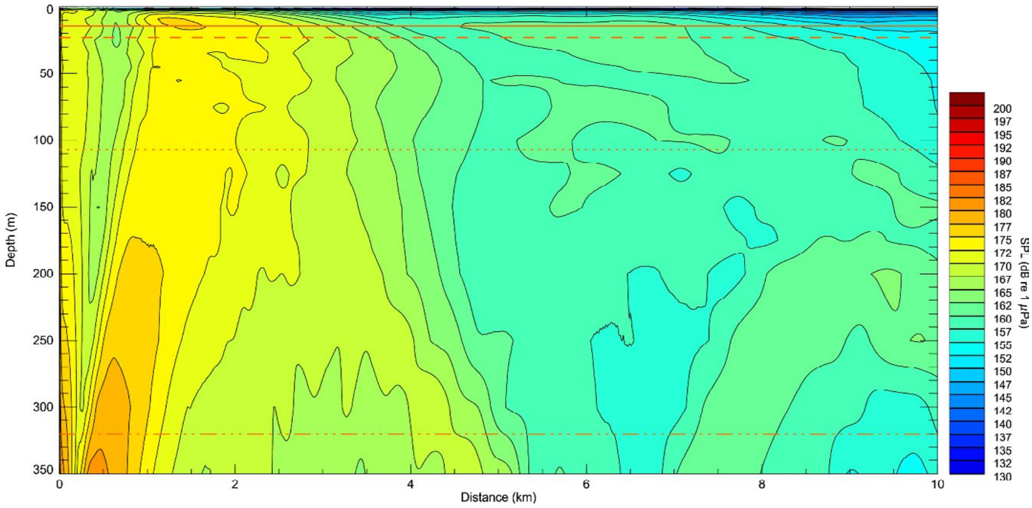

Figure 57. *Brecknock, vertical slice, IHC S-1200, SPL, 17 m penetration depth*: Levels are shown along a single transect of azimuth 315°, out to 10 km range, and down to 350 m depth, highlighting the depths of 14, 23, 107 and 320 m.

4.2.3. Multiple Strike Sound Fields

Table 37 presents the SEL_{24h} results relevant to marine mammals for the proposed pile driving operations, while Table 38 shows modelled distances to the cumulative exposure criteria contours for fish, fish eggs and larvae. The sound level contour maps for cetaceans and turtles are presented in Figures 58 and 59 for the IHC S-600 and the IHC S-1200 hammers, respectively. The sound level contour maps for fish are presented in Figures 60 and 61 for the IHC S-600 and the IHC S-1200 hammers, respectively.

Table 37. *Brecknock piling*: Maximum-over-depth distances (in km) to frequency-weighted SEL_{24h} based marine mammal PTS and TTS thresholds (NMFS 2018) and turtles (Finneran et al. 2017).

Hearing group	PTS					TTS				
	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s) #	IHC S-600		IHC S-1200		Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s) #	IHC S-600		IHC S-1200	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
LF cetaceans	183	4.58	4.05	4.62	4.40	168	23.11	20.04	24.75	20.80
MF cetaceans	185	-	-	-	-	170	<0.02	<0.02	0.05	0.05
HF cetaceans	155	0.06	0.06	0.17	0.16	140	0.33	0.31	2.33	2.20
Turtles	204	0.24	0.23	0.25	0.24	189	2.58	2.44	2.60	2.47

A dash indicates the level was not reached.
Frequency weighted.

Table 38. *Brecknock piling*: Maximum-over-depth distances (in km) to SEL_{24h} based fish criteria. Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

Marine animal group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Distance			
		IHC S-600		IHC S-1200	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Fish mortality and potential mortal injury					
I	219	0.04	0.04	0.04	0.04
II Fish eggs and larvae	210	0.14	0.13	0.15	0.15
III	207	0.20	0.19	0.22	0.21
Fish recoverable injury					
I	216	0.06	0.06	0.07	0.07
II, III	203	0.31	0.29	0.34	0.32
Fish TTS					
I, II, III	186	6.12	5.54	6.27	5.74

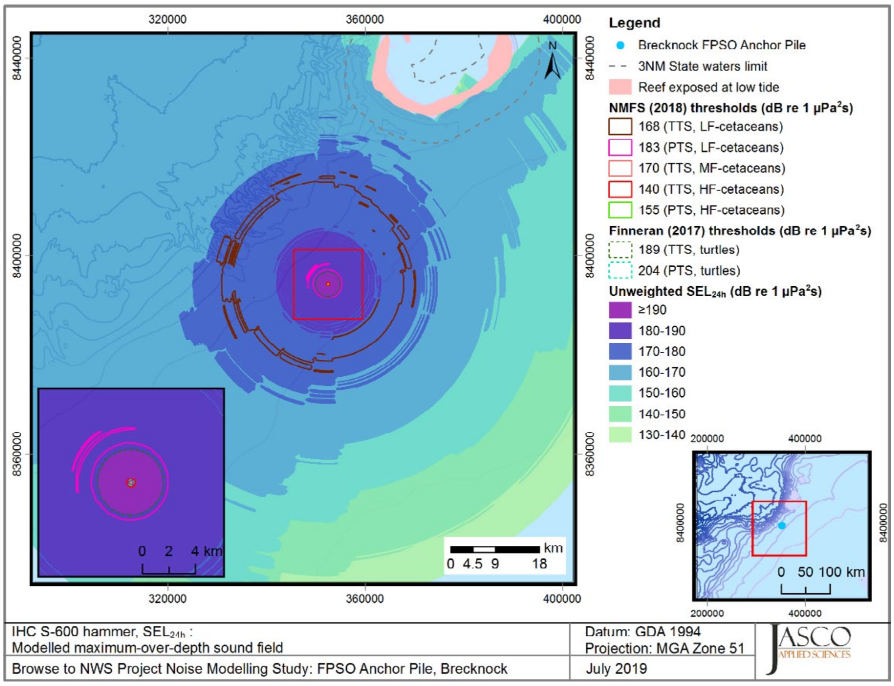

Figure 58. *Brecknock, IHC S-600, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles. Threshold for mid-frequency cetacean PTS was not reached.

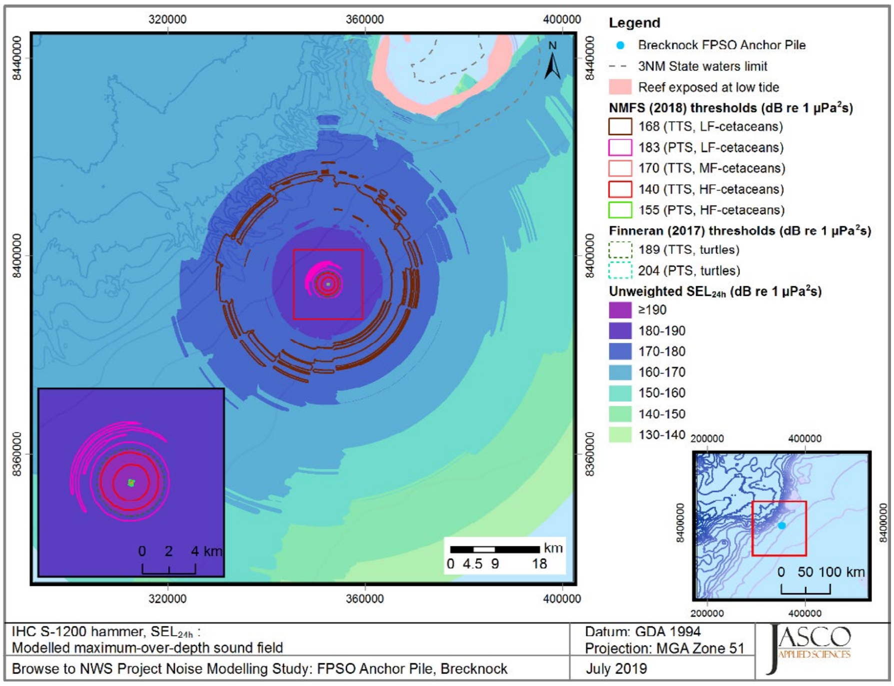

Figure 59. *Brecknock, IHC S-1200, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles. Threshold for mid-frequency cetacean PTS was not reached.

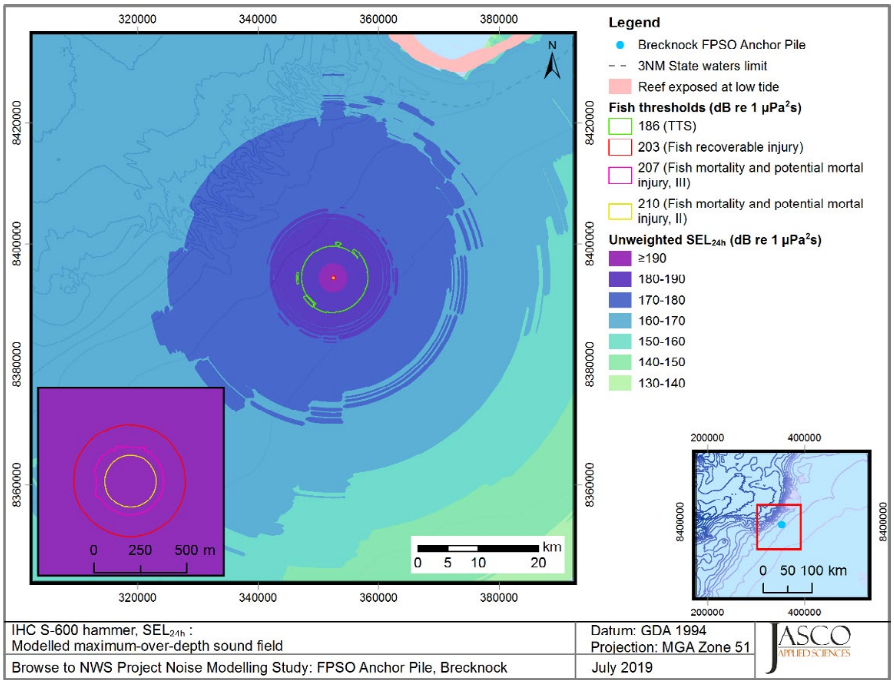

Figure 60. *Brecknock, IHC S-600, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths relevant to fish injury and TTS. Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

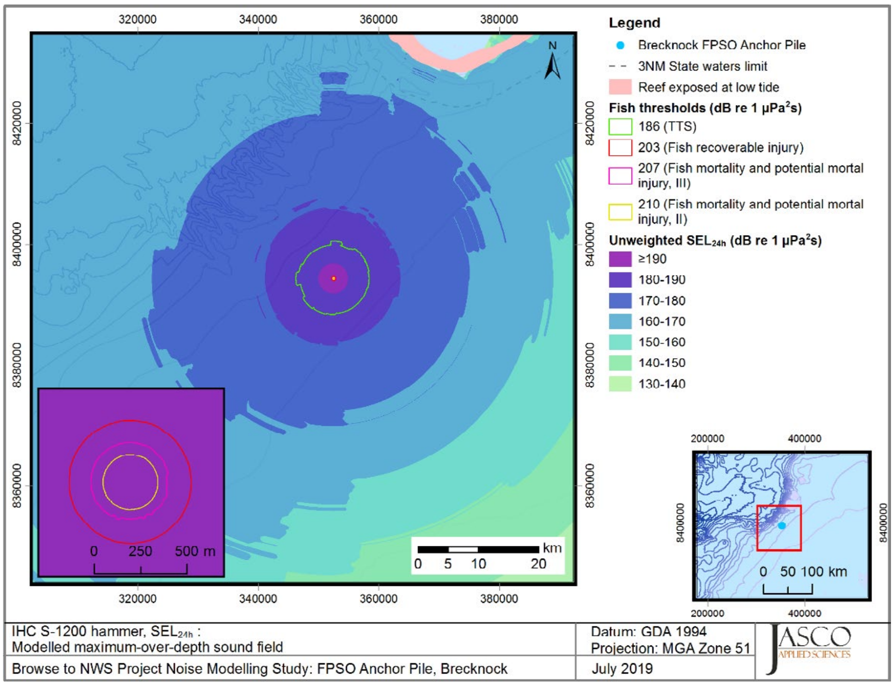

Figure 61. *Brecknock, IHC S-1200, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL24h results, along with isopleths relevant to fish injury and TTS. Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.2.4. Animal Movement and Exposure Modelling

Summaries of the animat modelling results for migrating and foraging pygmy blue whales are provided in Table 39. No exposures were recorded for migratory or inter-nesting turtles due to the distance from the pile of the Woodside defined BIAs.

Table 39. *Brecknock*: Summary of animat simulation results for migratory and foraging pygmy blue whales. Includes the distances to acoustic modelling thresholds (km), the 95th percentile exposure ranges (km), and the number of real-world individuals exposed above threshold (where densities are available). This summary includes both the original animat simulation results and the results excluding animats within a 2000 m zone surrounding the pile, acoustic modelling results are presented in Tables 34, 35, and 37.

Threshold		**Distance to threshold from acoustic modelling**		**Migrating pygmy blue whales**		**Migrating pygmy blue whales with 2000 m exclusion zone**		**Foraging pygmy blue whales**		**Foraging pygmy blue whales with 2000 m exclusion zone**	
Threshold description	Sound level (dB)	R_{max} (km)	$R_{95\%}$ (km)	Range, P_{95} (km)	Number of individuals	Range, P_{95} (km)	Number of individuals	Range, P_{95} (km)	Number of individuals	Range, P_{95} (km)	Number of individuals
IHC S-600 hammer											
TTS, PK	213†	0.04*		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TTS, SEL_{24h}	168‡	23.11	20.04	7.50	1.56	7.67	1.26	11.19	0.02	11.19	0.02
PTS, PK	219†	<0.02*		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PTS, SEL_{24h}	183‡	4.58	4.05	1.14	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Behavioural response	160#	7.06	6.40	3.75	0.62	3.91	0.32	0.00	0.00	0.00	0.00
IHC S-1200 hammer											
TTS, PK	213†	0.07*		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TTS, SEL_{24h}	168‡	24.75	20.80	8.07	1.67	8.18	1.45	12.05	0.08	12.05	0.08
PTS, PK	219†	<0.02*		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PTS, SEL_{24h}	183‡	4.62	4.40	1.26	0.04	0.00	0.00	0.00	0.00	0.00	0.00
Behavioural response	160#	13.97	11.87	8.65	1.88	8.73	1.65	12.03	0.08	12.03	0.08

† PK (L_{pk}; dB re 1 µPa)
‡ LF-weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s)
# SPL (L_p; dB re 1 µPa)
* R_{max} reported for TTS PK and PTS PK from acoustic modelling

4.3. Vertical Seismic Profiling (VSP)

Per-pulse results for the proposed VSP are presented in this section for maximum-over-depth SPL, SEL, and PK (tables in Section 4.3.1.1), maps and sound field vertical slices (Section 4.3.1.2). Multiple pulse results are presented in Section 4.3.2. Table 40 shows the PK and per-pulse SEL source levels in the horizontal-plane broadside (perpendicular to the array), endfire (in-line with the array), and vertical directions. The vertical source level that accounts for the “surface ghost” (the out of phase reflected pulse from the water surface) is also presented to make it easier to compare the output of other seismic source models.

Table 40. Far-field source level specifications for the 750 in^3 array, for a 6 m operational depth. Source levels are for a point-like acoustic source with equivalent far-field acoustic output in the specified direction. Sound level metrics are per-pulse and unweighted.

Direction	Peak source pressure level ($L_{S,pk}$) (dB re 1 µPa·m)	Per-pulse source SEL ($L_{S,E}$) (dB 1 µPa^{2}m^{2}s)	
		10–2000 Hz	2000–25000 Hz
Broadside	239.8	214.0	168.7
Endfire	240.1	214.1	175.3
Vertical	239.7	214.0	173.2
Vertical (surface affected source level)	239.7	216.2	176.1

4.3.1. Per-pulse Sound Fields

4.3.1.1. Tabulated results

Per-pulse results for the 750 in³ seismic source operating at 6 m are presented for SPL, SEL, PK, and PK-PK, including seafloor PK and PK-PK. Tables 41–43 list the estimated ranges for the various applicable maximum-over-depth per-pulse effects criteria and isopleths of interest. Table 44 lists the estimated ranges for seafloor per-pulse effects criteria and isopleths of interest.

Table 41. *VSP, per-pulse SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the 750 in^3 VSP array to modelled maximum-over-depth unweighted isopleths from the two modelled single impulse sites.

Per-pulse SEL (L_E; dB re 1 µPa²·s)	Torosa TRD Well		Brecknock	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	<0.04	<0.04	<0.04	<0.04
180	0.04	0.04	0.04	0.04
170	0.14	0.14	0.14	0.14
160†	0.53	0.52	0.46	0.45
150	1.74	1.65	1.98	1.85
140	5.10	3.98	4.86	4.37
130	12.81	11.19	16.12	14.38

† Low power zone assessment criteria DEWHA (2008).

Table 42. *VSP, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the 750 in^3 VSP array to modelled maximum-over-depth isopleths from the two modelled single impulse sites.

SPL (L_p; dB re 1 µPa)	Torosa TRD Well		Brecknock	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	<0.04	<0.04	<0.04	<0.04
190	<0.04	<0.04	<0.04	<0.04
180	0.13	0.13	0.13	0.13
175#	0.23	0.23	0.23	0.23
170	0.42	0.41	0.40	0.38
166†	0.81	0.77	0.72	0.69
160‡	1.60	1.52	1.70	1.59
150	4.20	3.60	3.98	3.22
140	11.22	10.33	13.43	11.20
130	28.23	22.32	27.84	23.36

Threshold for turtle behavioural response to impulsive noise (McCauley et al. 2000a).
† Threshold for turtle behavioural response to impulsive noise (NSF 2011).
‡ Cetacean behavioural threshold for impulsive sound sources (NMFS 2014).

Table 43. *VSP, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from the 750 in^3 VSP array to modelled maximum-over-depth peak pressure level (PK) thresholds based on the NOAA Technical Guidance (NMFS 2018) for cetaceans, and Popper et al. (2014) for fish and Finneran et al. (2017) for turtles, at the modelled sites (Table 8).

Hearing group	PK threshold (L_{pk}; dB re 1 µPa)	Distance R_{max} (m)	
		Torosa TRD Well	Brecknock
LF cetaceans (PTS)	219	12	12
LF cetaceans (TTS)	213	21	21
MF cetaceans (PTS)	230	—	—
MF cetaceans (TTS)	224	—	—
HF cetaceans (PTS)	202	68	68
HF cetaceans (TTS)	196	141	139
Fish: No swim bladder (also applied to sharks)	213	21	21
Fish: Swim bladder not involved in hearing; Swim bladder involved in hearing Turtles, fish eggs, and larvae	207	39	40
Turtles (PTS)	232	—	—
Turtles (TTS)	226	—	—

A dash indicates the level was not reached.

Table 44. *VSP, seafloor PK*: Maximum (R_{max}) horizontal distances (in m) from the 750 in^3 VSP array to modelled seafloor peak pressure level thresholds (PK) at the modelled sites (Table 8).

Hearing group/animal type	PK threshold (L_{pk}; dB re 1 µPa)	Distance R_{max} (m)	
		Torosa TRD Well	Brecknock
Sound levels for sponges and corals†	226	—	—
Fish: No swim bladder (also applied to sharks)	213	—	—
Fish: Swim bladder not involved in hearing; Swim bladder involved in hearing Turtles, fish eggs, and larvae	207	—	—

† Heyward et al. (2018)
A dash indicates the level was not reached.

4.3.1.2. Sound field maps and graphs

Maps of the per-pulse SPL results for the two VSP locations are shown in Figures 62 and 63. Per-pulse SEL maps are shown in Appendix H.2.

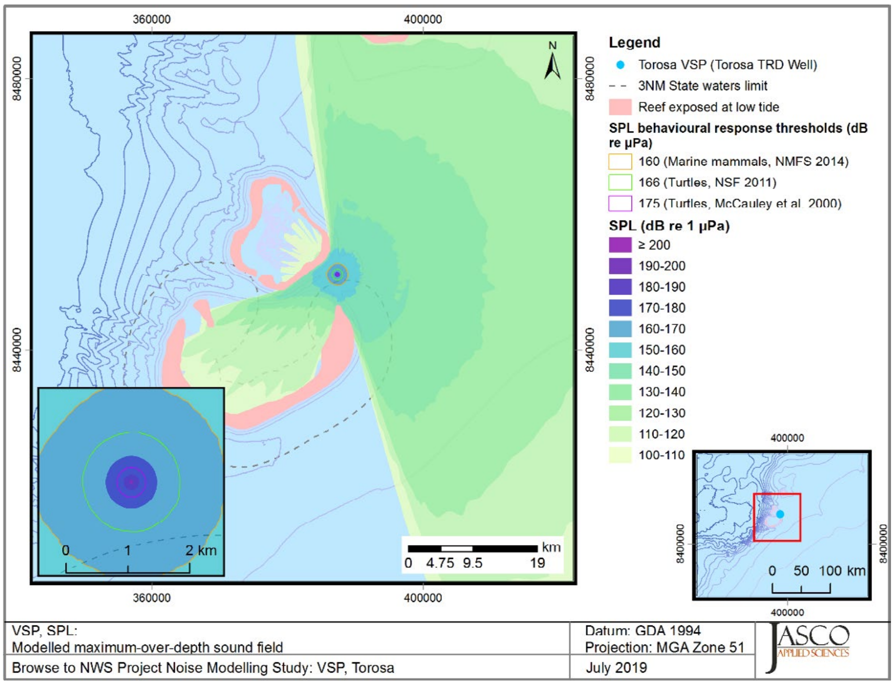

Figure 62. *Torosa TRD Well VSP, SPL:* Sound level contour map, showing maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

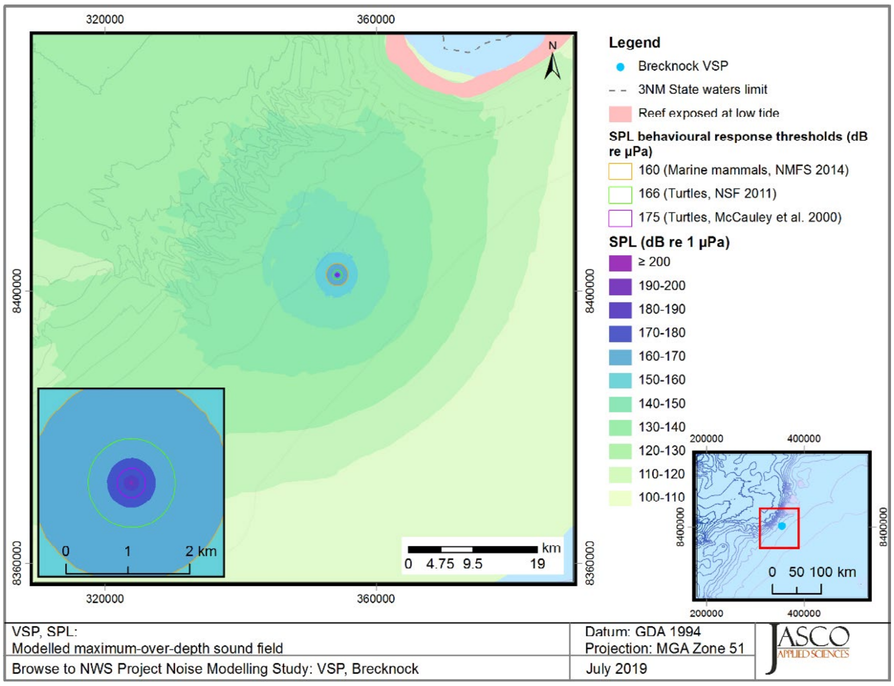

Figure 63. *Brecknock VSP, SPL:* Sound level contour map, showing maximum-over-depth results. Isopleths for turtles (166 and 175 dB re 1 µPa) and marine mammal (160 dB re 1 µPa) behavioural criteria are shown.

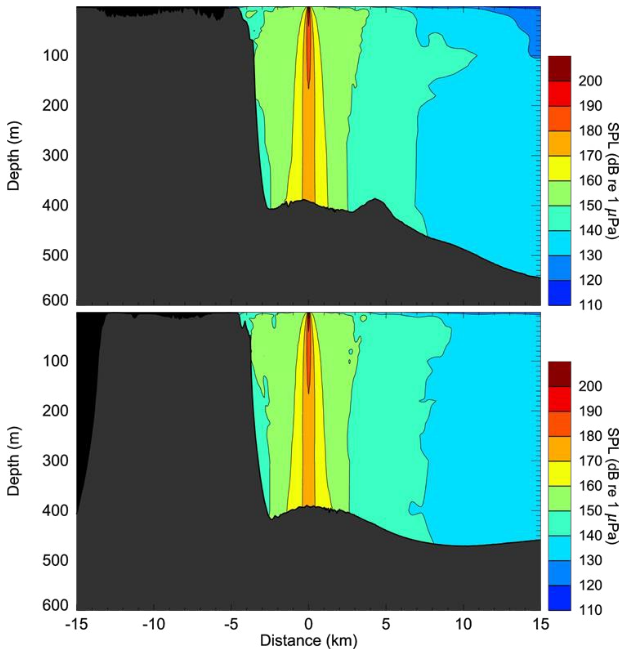

Figure 64. *Vertical slice, Torosa TRD Well VSP, SPL*: north–south (top) and east–west (bottom).

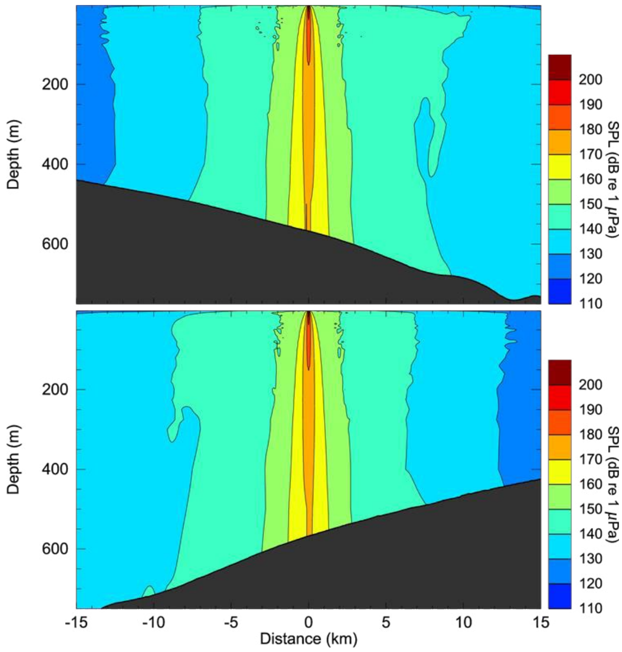

Figure 65. *Vertical slice, Brecknock VSP, SPL*: north–south (top) and east–west (bottom).Multiple pulse

Multiple pulse results for a range of VSP impulses which potentially could occur within a 24 h period are shown in Tables 45 and 46. These results assume both stationary source and receivers, and are frequency-weighted in accordance with NMFS (2018) and Finneran et al. (2017).

Table 45. Torosa *VSP, multiple-pulse SEL*: Maximum ranges to frequency-weighted SEL_{24h} based marine mammal PTS and TTS thresholds NMFS (2018) and turtles (Finneran et al. 2017) from VSP operations, assuming different numbers of impulses during a 24 h period.

Hearing group	Effect criteria	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s) #	Number of impulses							
			1 R_{max} (m)	5 R_{max} (m)	10 R_{max} (m)	15 R_{max} (m)	25 R_{max} (m)	50 R_{max} (m)	100 R_{max} (m)	150 R_{max} (m)
LF cetaceans	PTS	183	-	-	0.04	0.06	0.08	0.11	0.16	0.20
	TTS	168	0.09	0.22	0.29	0.36	0.46	0.65	1.10	1.69
MF cetaceans	PTS	185	-	-	-	-	-	-	-	-
	TTS	170	-	-	-	-	-	-	-	-
HF cetaceans	PTS	155	-	-	-	-	-	-	-	-
	TTS	140	-	-	-	-	-	0.04	0.06	0.09
Turtles	PTS	204	-	-	-	-	-	-	-	-
	TTS	189	-	-	0.04	0.04	0.06	0.09	0.13	0.16

A dash indicates the level was not reached.
Frequency weighted.

Table 46. Brecknock *VSP, multiple-pulse SEL*: Maximum ranges to frequency-weighted SEL_{24h} based marine mammal PTS and TTS thresholds NMFS (2018) and turtles (Finneran et al. 2017) from VSP operations, assuming different numbers of impulses during a 24 h period.

Hearing group	Effect criteria	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s) #	Number of impulses							
			1 R_{max} (m)	5 R_{max} (m)	10 R_{max} (m)	15 R_{max} (m)	25 R_{max} (m)	50 R_{max} (m)	100 R_{max} (m)	150 R_{max} (m)
LF cetaceans	PTS	183	-	-	0.04	0.06	0.08	0.11	0.16	0.20
	TTS	168	0.09	0.22	0.29	0.36	0.46	0.64	1.10	1.69
MF cetaceans	PTS	185	-	-	-	-	-	-	-	-
	TTS	170	-	-	-	-	-	-	-	-
HF cetaceans	PTS	155	-	-	-	-	-	-	-	-
	TTS	140	-	-	-	-	-	0.04	0.06	0.09
Turtles	PTS	204	-	-	-	-	-	-	-	-
	TTS	189	-	-	0.04	0.04	0.06	0.09	0.13	0.16

A dash indicates the level was not reached.
Frequency weighted.

4.4. Vessel noise (MODU, OSV, and FPSO)

Sound field results for the modelling scenarios involving the MODU, OSV and FPSO, both with and without DP and during offtake are presented for SPL (Tables 47–49) and SEL_{24h} (Tables 50 and 51) at Torosa and Brecknock. Areas within relevant threshold isopleths during offtake, including a comparison between individual FPSO's and aggregate FPSO's are presented for SPL and SEL_{24h} metrics in Tables 52–55. Ranges to fish thresholds are unchanged from the individual sources to aggregate scenarios, as the ranges are not greater than the modelling resolution.

4.4.1. Tabulated results

Table 47. *Torosa vessels, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the centroid of the modelled thrusters (MODU, OSV, and FPSO on DP) or from the centre of the vessel (FPSO without DP).

SPL (L_p; dB re 1 µPa)	MODU		OSV		FPSO on DP		FPSO without DP		FPSO offtake	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	<0.02	<0.02	-	-	-	-	-	-	-	-
180	0.05	0.05	<0.02	<0.02	<0.02	<0.02	-	-	<0.02	<0.02
170	0.06	0.06	0.05	0.05	<0.02	<0.02	<0.02	<0.02	0.04	0.04
160	0.06	0.06	0.05	0.05	0.04	0.04	<0.02	<0.02	0.04	0.04
150	0.17	0.17	0.07	0.07	0.12	0.12	<0.02	<0.02	0.13	0.13
140	0.52	0.51	0.18	0.17	0.40	0.40	0.04	0.04	0.92	0.81
130	2.32	2.22	0.57	0.55	1.83	1.77	0.17	0.17	2.13	1.96
120†	10.50	7.20	2.25	2.14	8.77	7.99	0.57	0.56	8.89	8.08
110	21.97	18.24	6.64	6.13	21.61	18.36	2.13	2.06	22.49	18.59
100	38.48	35.32	17.20	15.34	45.65	37.29	6.30	5.78	46.05	37.93

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).
A dash indicates the level was not reached.
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Table 48. *Brecknock vessels, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the centroid of the modelled thrusters (MODU, OSV, and FPSO on DP) or from the centre of the vessel (FPSO without DP).

SPL (L_p; dB re 1 µPa)	MODU		OSV		FPSO on DP		FPSO without DP		FPSO offtake	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	<0.02	<0.02	-	-	-	-	-	-	-	-
180	0.05	0.05	0.02	0.02	<0.02	<0.02	-	-	0.03	0.03
170	0.06	0.06	0.06	0.06	<0.02	<0.02	<0.02	<0.02	0.04	0.04
160	0.06	0.06	0.06	0.06	0.04	0.04	<0.02	<0.02	0.06	0.06
150	0.17	0.17	0.06	0.06	0.12	0.12	<0.02	<0.02	0.12	0.12
140	0.52	0.50	0.19	0.18	0.40	0.39	0.04	0.04	0.90	0.82
130	2.68	2.54	0.57	0.54	1.78	1.72	0.16	0.16	2.19	2.01
120†	8.84	8.11	2.39	2.27	8.78	7.70	0.54	0.52	8.89	7.84
110	24.58	19.46	7.76	7.14	22.19	17.51	2.27	2.16	22.44	18.27
100	>80.0	*	21.72	16.80	47.13	34.74	7.66	7.04	47.84	35.51

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).
* Radii unresolvable due to R_{max} exceeding maximum modelled distance.
A dash indicates the level was not reached.
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Table 49. *Vessels, SPL, fish effect thresholds*: Maximum (R_{max}) horizontal distances (km) from the vessels to modelled maximum-over-depth SPL thresholds based on the quantifiable thresholds for fish with a swim bladder involved in hearing (Popper et al. 2014).

SPL (L_p; dB re 1 µPa)	MODU		OSV		FPSO on DP		FPSO without DP		FPSO Offtake	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Torosa										
170†	0.06	0.06	0.05	0.05	<0.02	<0.02	-	-	0.04	0.04
158#	0.06	0.06	0.05	0.05	0.04	0.04	-	-	0.06	0.06
Brecknock										
170†	0.06	0.06	0.06	0.06	<0.02	<0.02	<0.02	<0.02	0.04	0.04
158#	0.06	0.06	0.06	0.06	0.04	0.04	<0.02	<0.02	0.06	0.06

† Recoverable injury
# TTS
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Table 50. *Torosa vessels, SEL_{24}*: Maximum-over-depth distances (in km) to PTS and TTS thresholds NMFS (2018) and turtles (Finneran et al. 2017) .

Hearing group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s) #	MODU		OSV		FPSO on DP		FPSO without DP		FPSO offtake	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS											
LF cetaceans	199	0.11	0.11	0.05	0.05	0.12	0.12	-	-	0.12	0.12
MF cetaceans	198	-	-	-	-	<0.02	<0.02	-	-	<0.02	<0.02
HF cetaceans	173	0.15	0.15	0.07	0.07	0.28	0.27	-	-	0.28	0.27
Turtles	220	0.06	0.06	0.05	0.05	<0.02	<0.02	-	-	<0.02	<0.02
TTS											
LF cetaceans	179	1.49	1.41	0.40	0.38	1.49	1.44	0.09	0.09	1.74	1.60
MF cetaceans	178	0.12	0.12	0.05	0.05	0.23	0.23	-	-	0.23	0.23
HF cetaceans	153	2.81	2.75	0.89	0.86	5.46	5.34	0.17	0.17	5.47	5.35
Turtles	200	0.13	0.13	0.05	0.05	0.06	0.06	-	-	0.06	0.06

A dash indicates the level was not reached.
Frequency weighted.
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Table 51. *Brecknock vessels, SEL_{24}*: Maximum-over-depth distances (in km) to PTS and TTS thresholds NMFS (2018) and turtles (Finneran et al. 2017).

Hearing group	Threshold for SEL_{24h} ($L_{E,24h}$ dB re 1 µPa²·s) #	MODU		OSV		FPSO on DP		FPSO without DP		FPSO offtake	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS											
LF cetaceans	199	0.11	0.11	0.06	0.06	0.12	0.12	<0.02	<0.02	0.12	0.12
MF cetaceans	198	-	-	-	-	<0.02	<0.02	-	-	<0.02	<0.02
HF cetaceans	173	0.15	0.15	0.07	0.07	0.28	0.27	<0.02	<0.02	0.28	0.27
Turtles	220	0.06	0.06	0.06	0.06	<0.02	<0.02	-	-	<0.02	<0.02
TTS											
LF cetaceans	179	1.00	0.97	0.40	0.38	1.33	1.28	0.09	0.09	1.68	1.54
MF cetaceans	178	0.12	0.12	0.06	0.06	0.23	0.23	<0.02	<0.02	0.23	0.23
HF cetaceans	153	2.78	2.74	0.89	0.86	5.45	5.34	0.17	0.17	5.47	5.35
Turtles	200	0.13	0.13	0.06	0.06	0.06	0.06	<0.02	<0.02	0.06	0.06

A dash indicates the level was not reached.
Frequency weighted.
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Table 52. *Vessels, SPL*: Areas (km^2, WGS84, geographic) for individual and aggregate FPSO offtake operations within isopleths corresponding to the threshold for marine mammal behavioural response to continuous noise (NMFS 2014).

SPL (L_p; dB re 1 µPa)	Torosa	Brecknock	Aggregate	Difference between combined individual and aggregate
	Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)
120†	192.9	181.5	374.4	0

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Table 53. *Vessels, SEL$_{24}$*: Areas (km^2, WGS84, geographic) for combined FPSO offtake and MODU operations within isopleths corresponding to the thresholds for maximum-over-depth PTS and TTS thresholds for cetaceans (NMFS 2018) and turtles (Finneran et al. 2017).

Hearing group	Threshold for SEL$_{24h}$ ($L_{E,24h}$ dB re 1 µPa^2·s) #	Torosa	Brecknock	Aggregate	Difference between combined individual and aggregate
		Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)
PTS					
LF cetaceans	199	0.06	0.062	0.12	0
MF cetaceans	198	< 0.001	-	< 0.001	0
HF cetaceans	173	0.27	0.29	0.55	0
Turtles	220	0.002	0.005	0.007	0
TTS					
LF cetaceans	179	8.26	7.14	15.4	0
MF cetaceans	178	0.19	0.19	0.371	0
HF cetaceans	153	93.7	93.4	187.1	0
Turtles	200	0.036	0.037	0.073	0

A dash indicates the level was not reached.
Frequency weighted.
Only areas > 0.001 km^2 are resolved.
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Table 54. *Vessels, SPL*: Areas (km^2, WGS84, geographic) for individual and aggregate FPSO (without DP) operations within isopleths corresponding to the threshold for marine mammal behavioural response to continuous noise (NMFS 2014).

SPL (L_p; dB re 1 µPa)	Torosa	Brecknock	Aggregate	Difference between combined individual and aggregate
	Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)
120†	1.0	0.9	1.9	0

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Table 55. *Vessels, SEL24*: Areas (km^2, WGS84, geographic) for combined FPSO offtake and MODU operations within isopleths corresponding to the thresholds for maximum-over-depth PTS and TTS thresholds for cetaceans (NMFS 2018) and turtles (Finneran et al. 2017).

Hearing group	Threshold for SEL_{24h} ($L_{E,24h}$ dB re 1 µPa²·s)	Torosa	Brecknock	Aggregate	Difference between combined individual and aggregate
		Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)
PTS					
LF cetaceans	199	0.001	0.001	0.006	0.004†
MF cetaceans	198	-	-	-	-
HF cetaceans	173	< 0.001	< 0.001	-	0
Turtles	220	-	-	-	-
TTS					
LF cetaceans	179	0.033	0.033	0.067	0.004†
MF cetaceans	178	-	< 0.001	< 0.001	0
HF cetaceans	153	0.1	0.1	0.2	0
Turtles	200	0.001	0.001	0.007	0.005†

A dash indicates the level was not reached.
Only areas > 0.001 km^2 are resolved.
†Difference due to gridding artefact.
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

4.4.2. Sound Field Maps and Graphs

Maps of the estimated sound fields, threshold contours, and isopleths of interest for SPL and SEL_{24h} sound fields have been presented at both modelling sites for individual locations for vessel modelling scenarios (Table 8) in Figures 66–85, and aggregate modelling scenarios in Figures 86–89.

4.4.2.1. Standalone scenarios

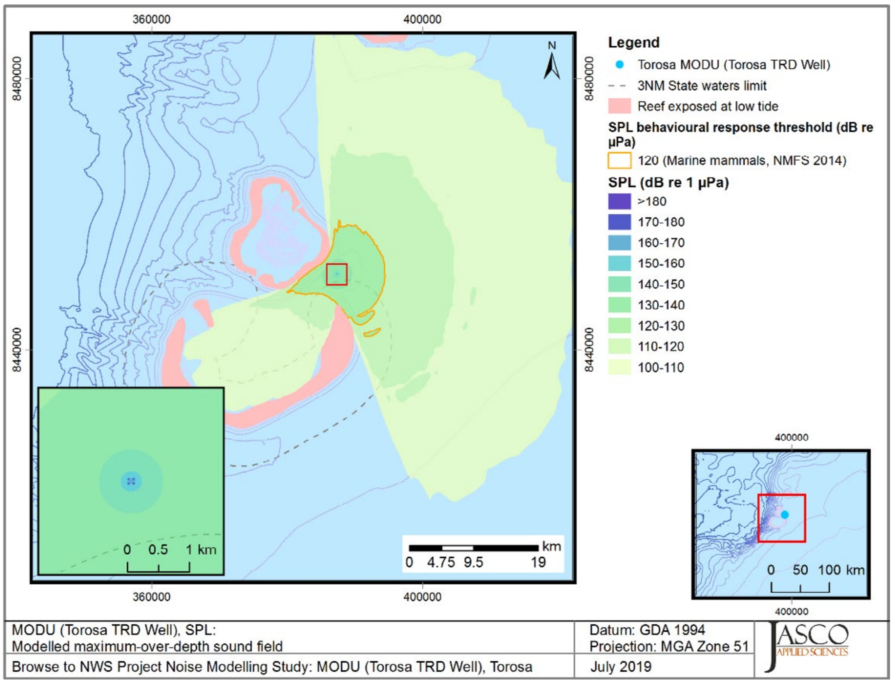

Figure 66. *Torosa, MODU, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

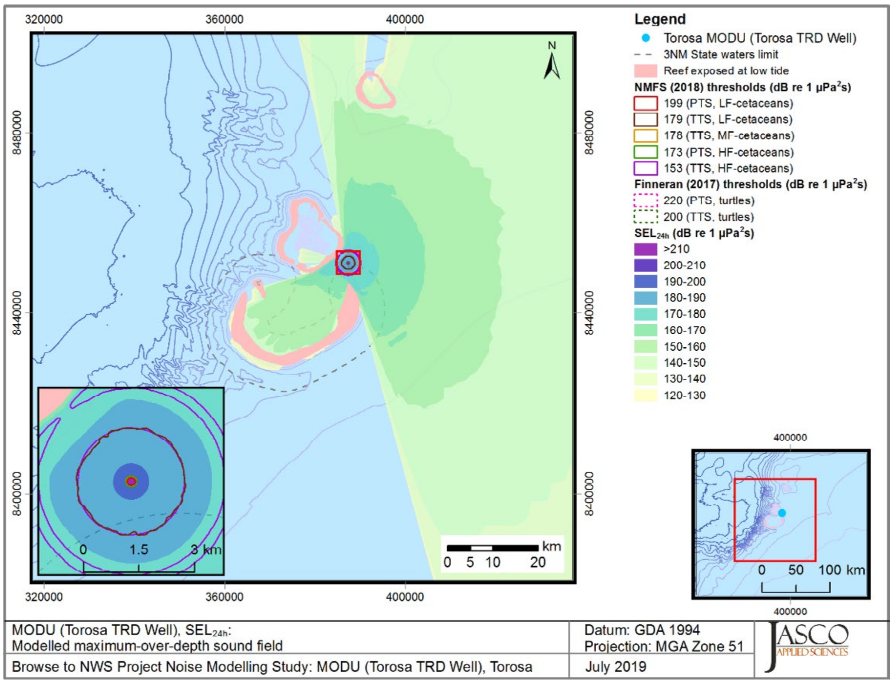

Figure 67. *Torosa, MODU, SEL$_{24h}$*: Sound level contour map showing unweighted maximum-over-depth SEL$_{24h}$ results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles. Threshold for mid-frequency cetacean PTS was not reached.

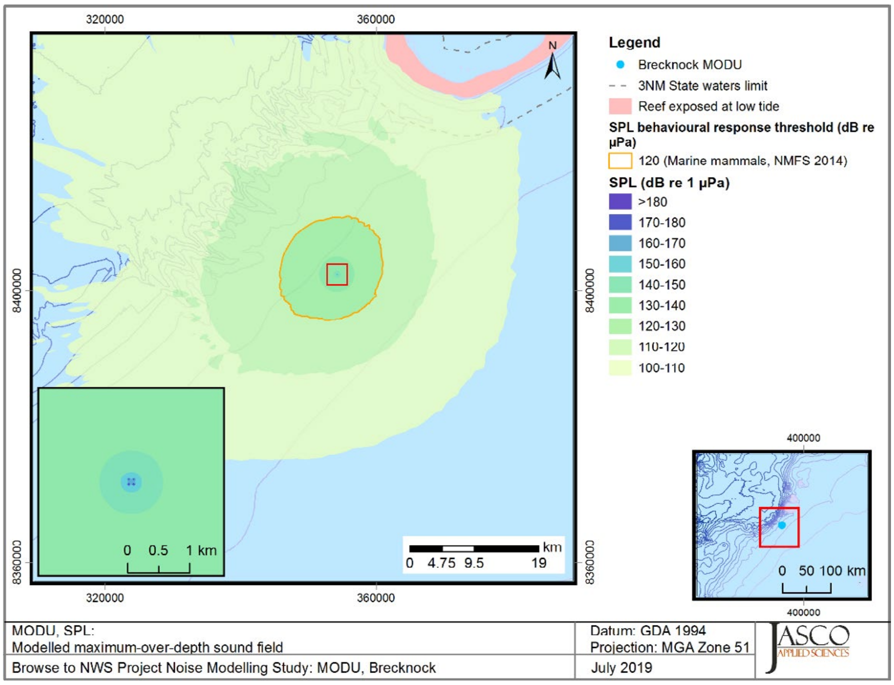

Figure 68. *Brecknock, MODU, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

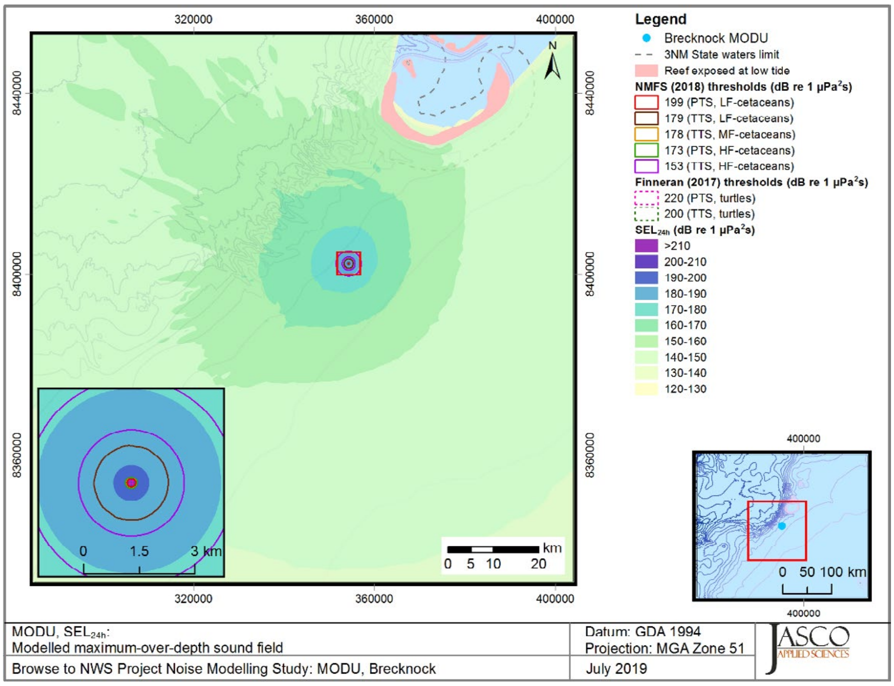

Figure 69. *Brecknock, MODU, SEL24h*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles. Threshold for mid-frequency cetacean PTS was not reached.

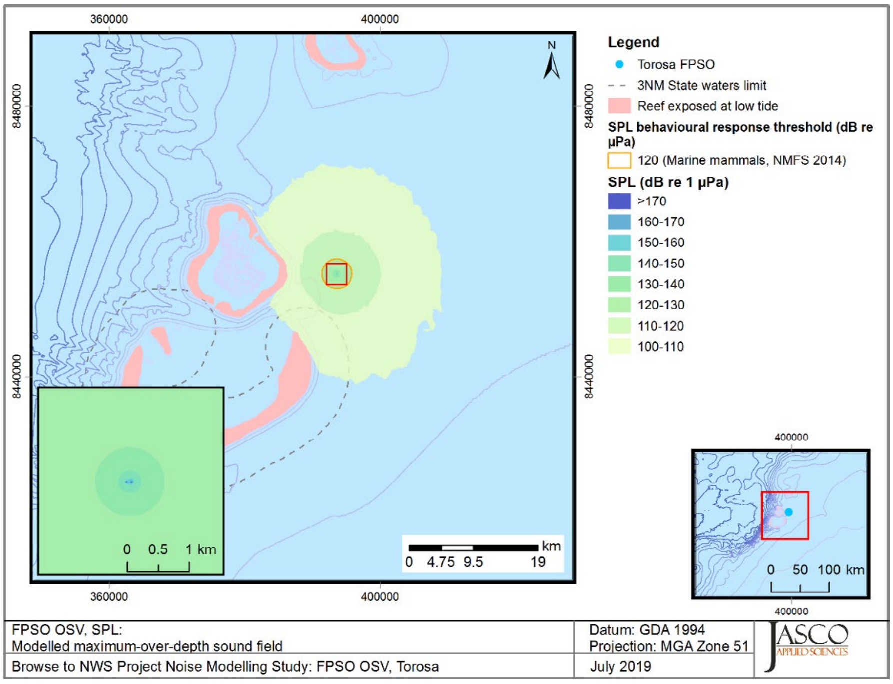

Figure 70. *Torosa, Support Vessel, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

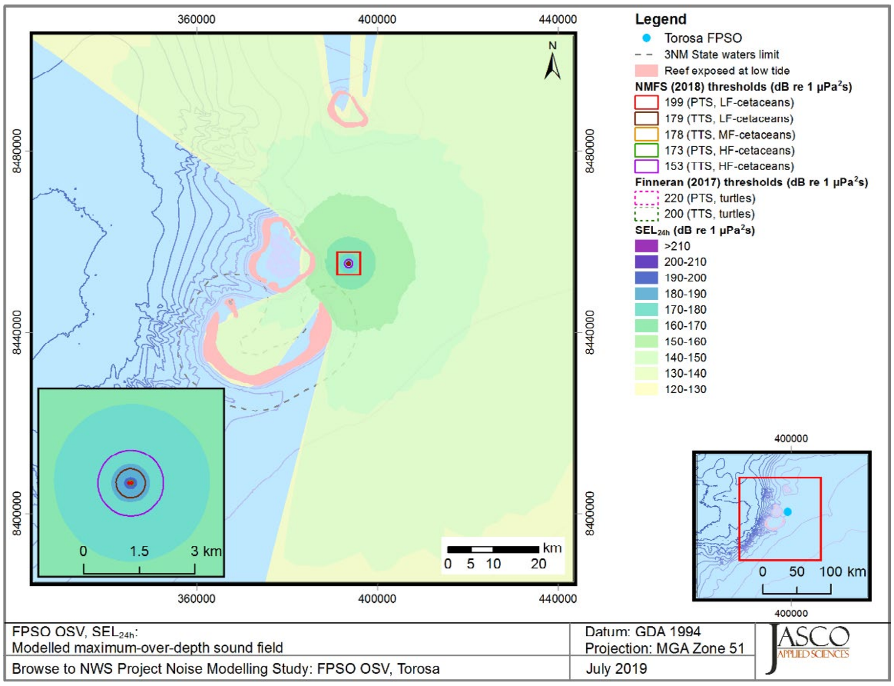

Figure 71. *Torosa, Support Vessel, SEL24h*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles. Threshold for mid-frequency cetacean PTS was not reached.

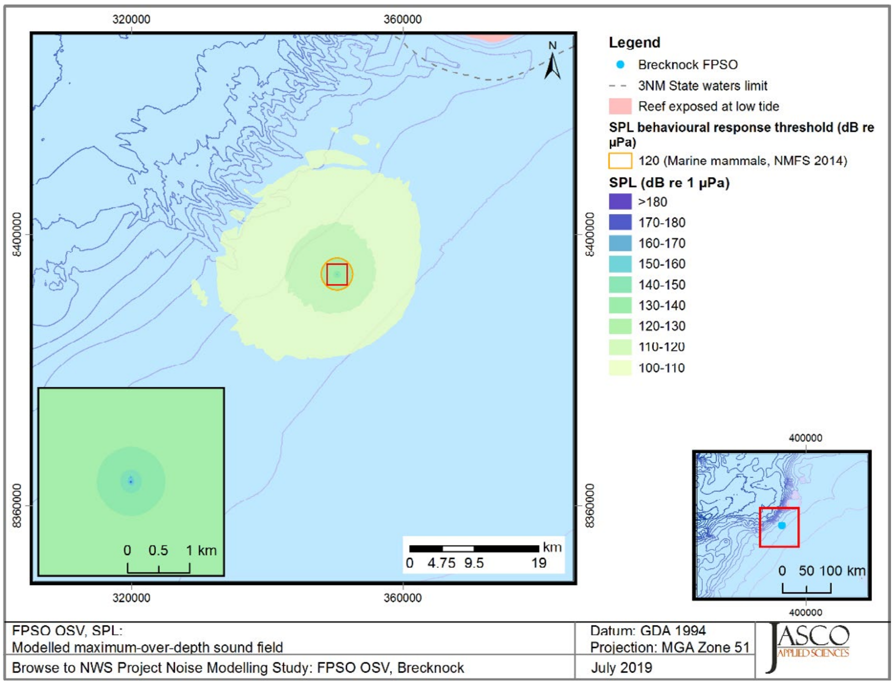

Figure 72. *Brecknock, Support Vessel, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

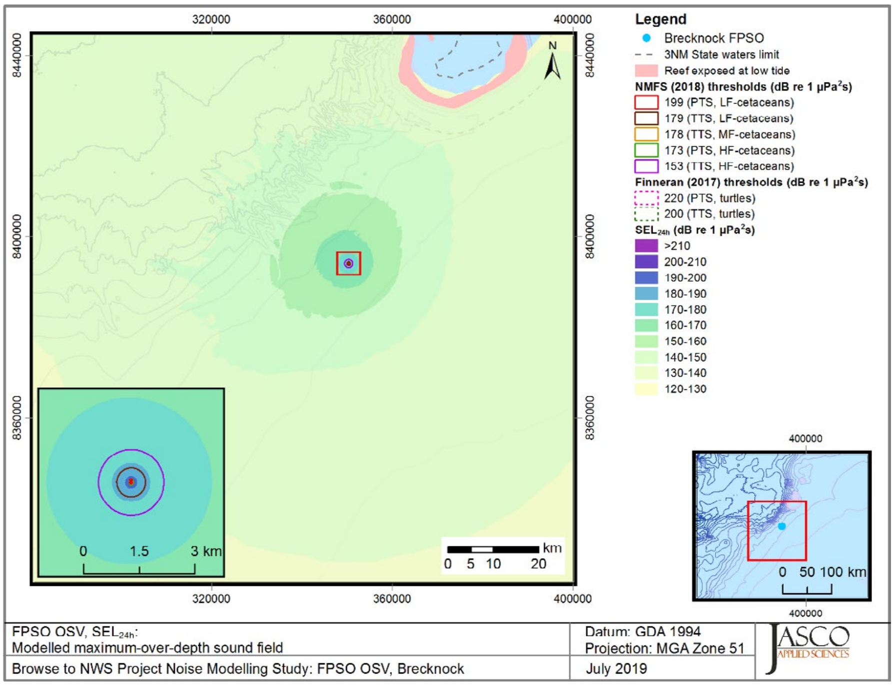

Figure 73. *Brecknock, Support Vessel, SEL₂₄ₕ*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles. Threshold for mid-frequency cetacean PTS was not reached.

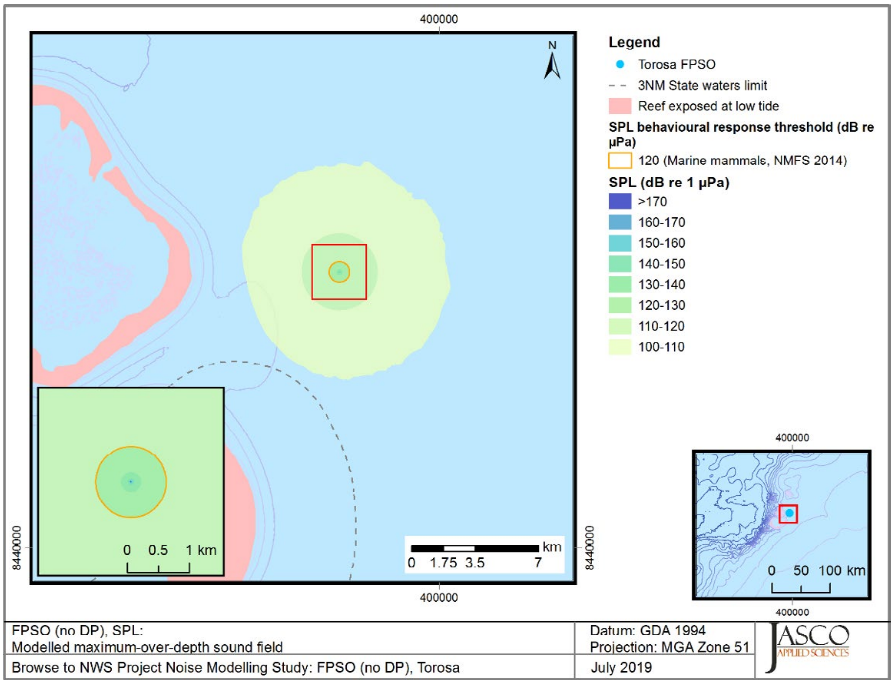

Figure 74. *Torosa, FPSO without DP, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

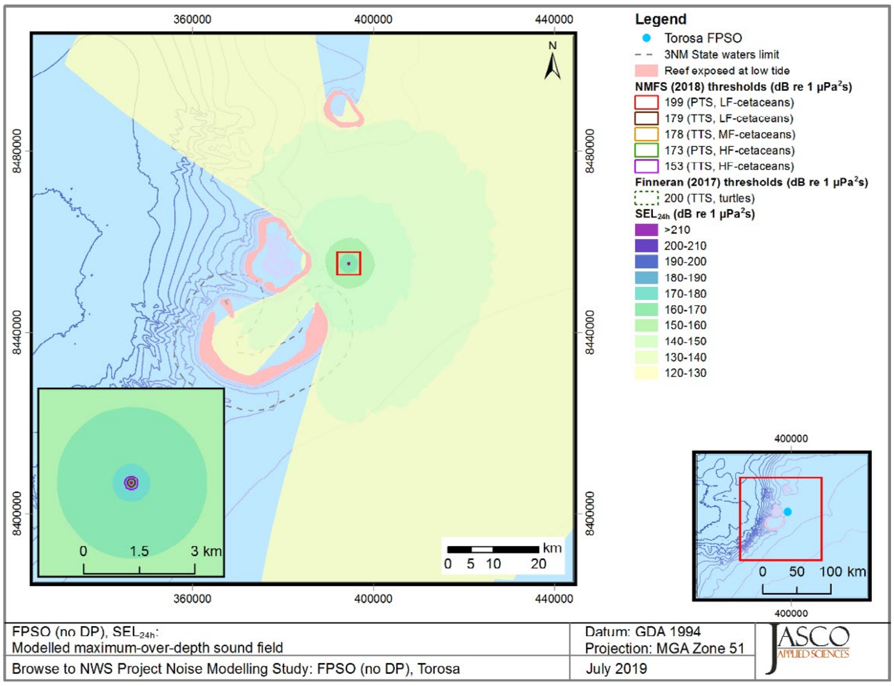

Figure 75. *Torosa, FPSO without DP, SEL24h*: Sound level contour map showing unweighted maximum-over-depth SEL24h results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles. Threshold for mid-frequency cetacean PTS was not reached.

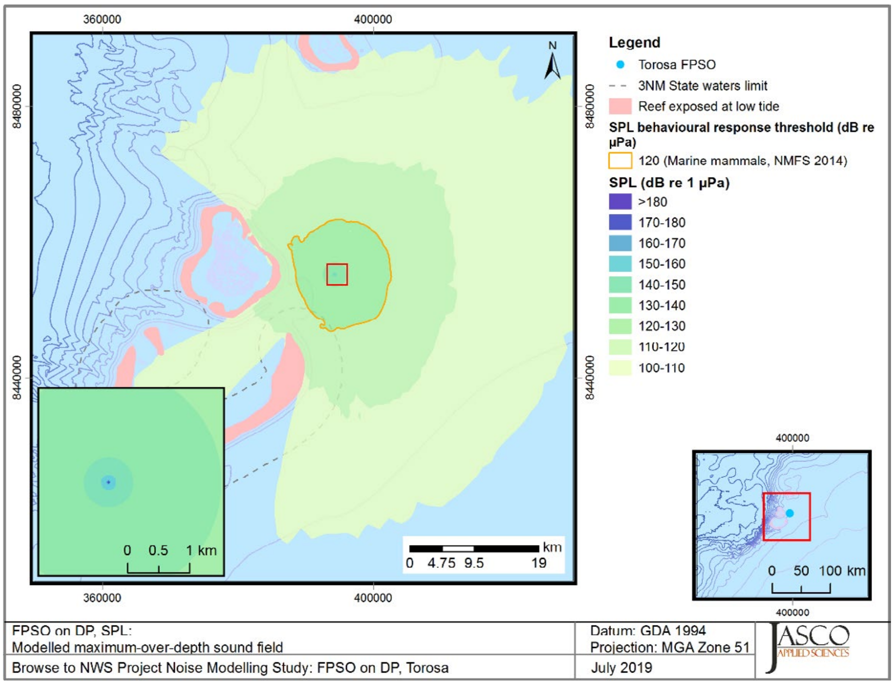

Figure 76. *Torosa, FPSO on DP, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

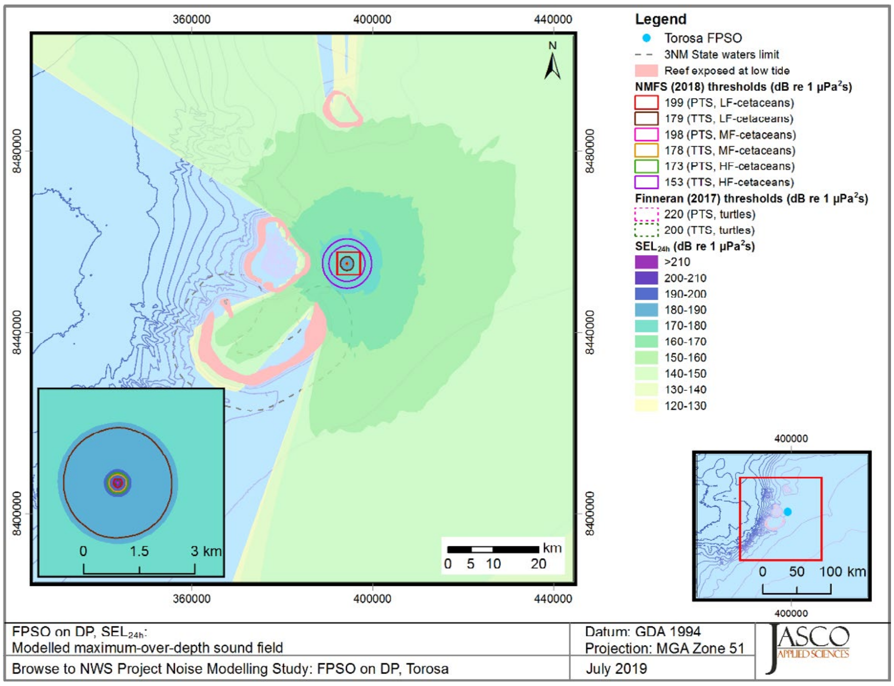

Figure 77. *Torosa, FPSO on DP, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles.

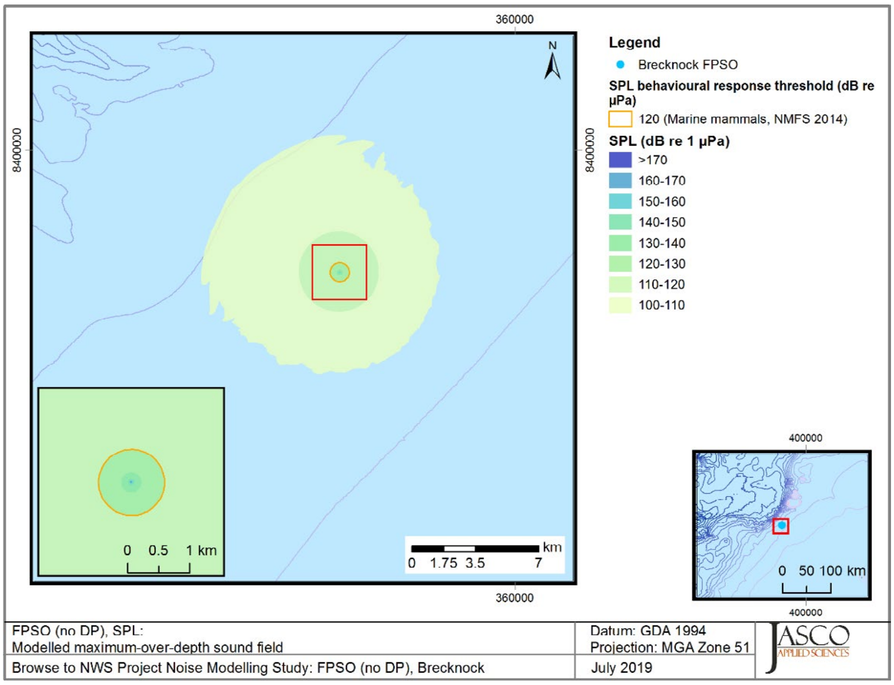

Figure 78. *Brecknock, FPSO without DP, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

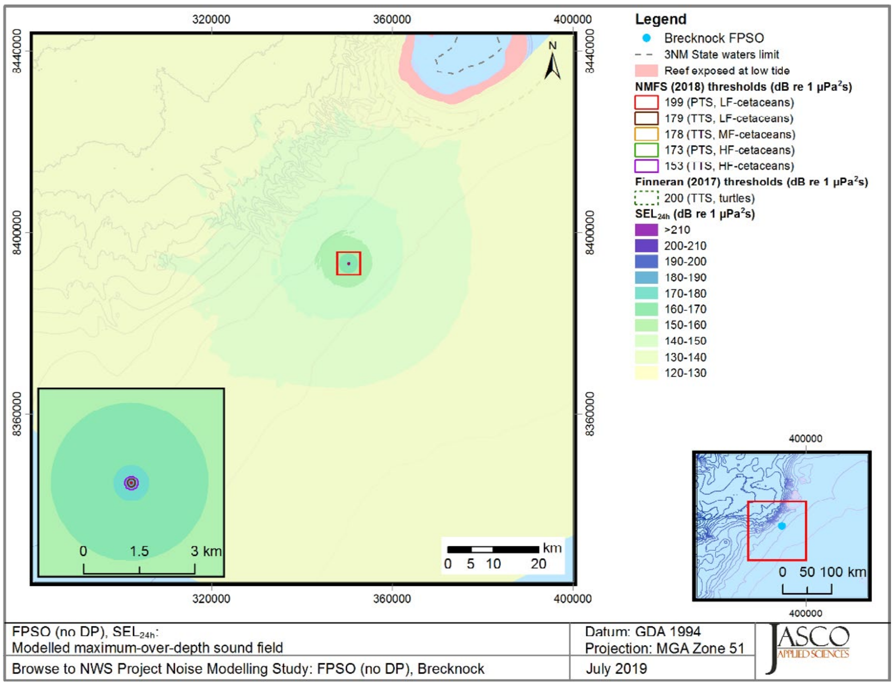

Figure 79. *Brecknock, FPSO without DP, SEL24h*: Sound level contour map showing unweighted maximum-over-depth SEL24h results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles. Threshold for mid-frequency cetacean PTS was not reached.

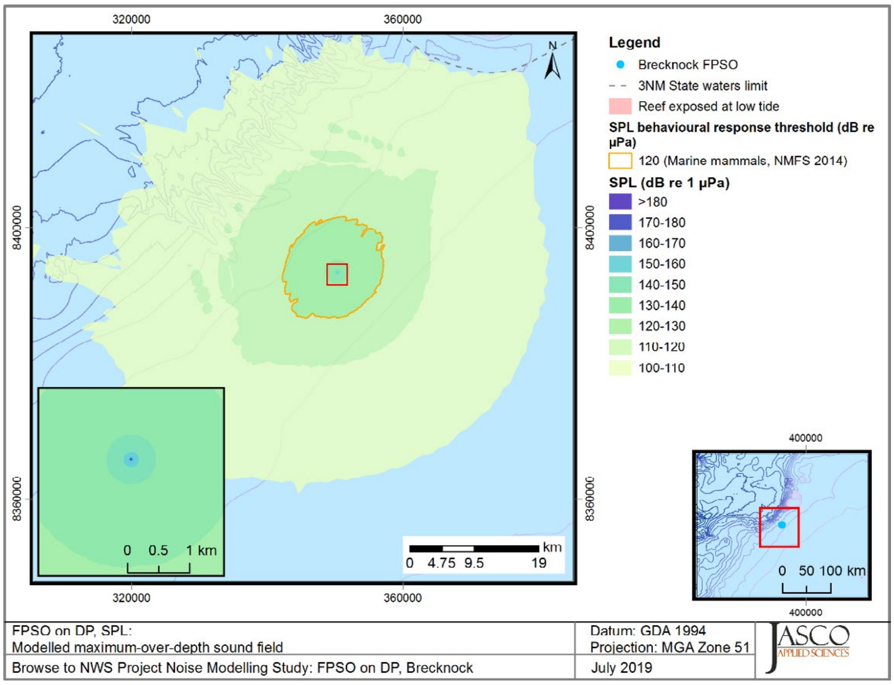

Figure 80. *Brecknock, FPSO on DP, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

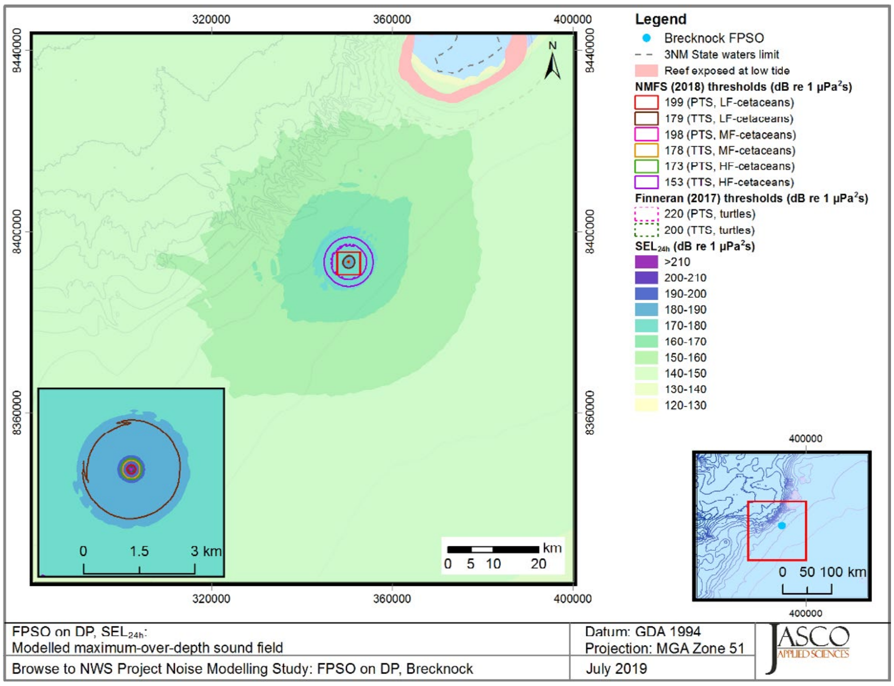

Figure 81. *Brecknock, FPSO on DP, SEL24h*: Sound level contour map showing unweighted maximum-over-depth SEL24h results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles.

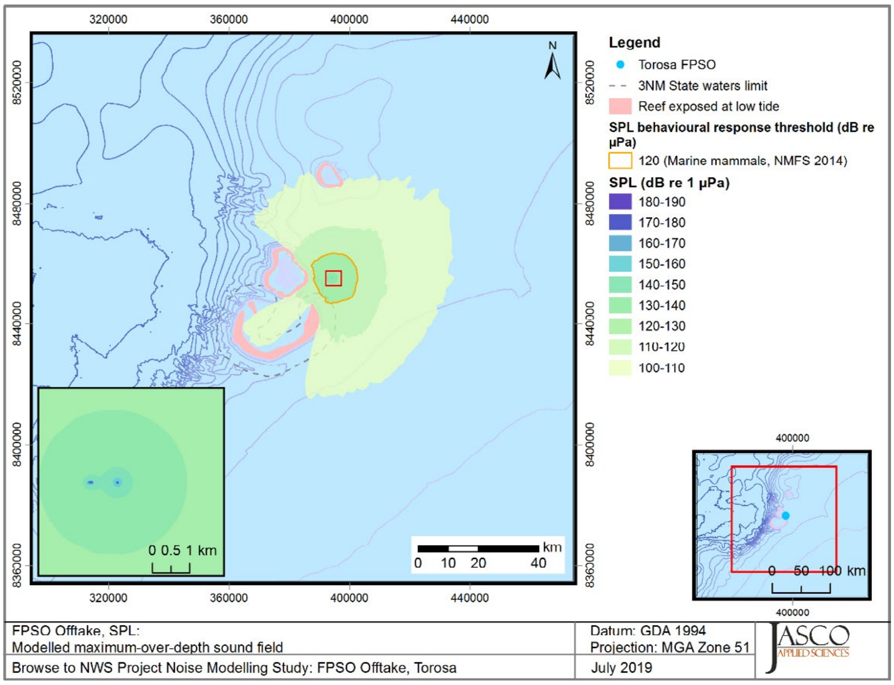

Figure 82. *Torosa, FPSO offtake, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

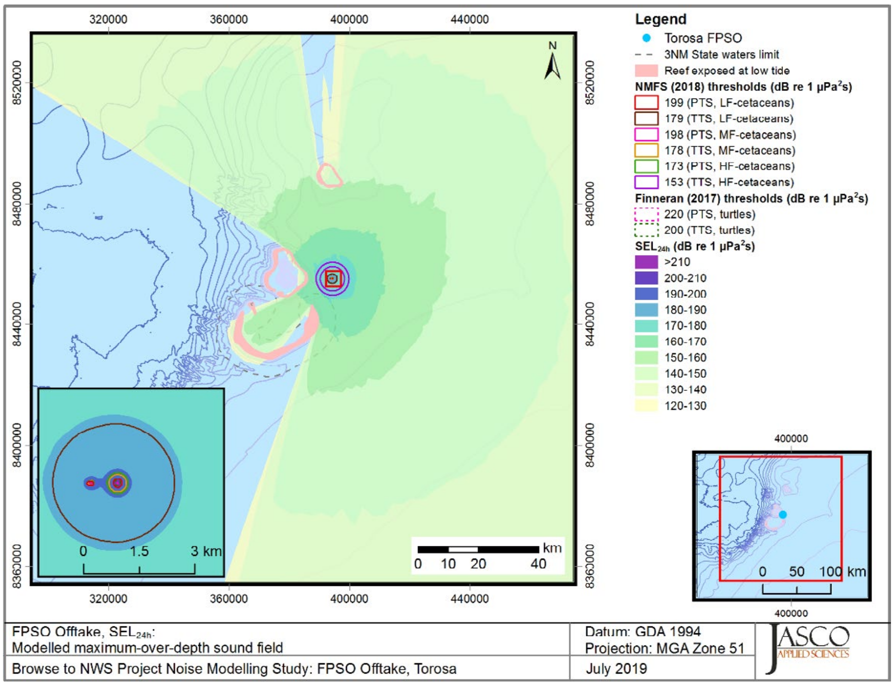

Figure 83. *Torosa, FPSO offtake, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles.

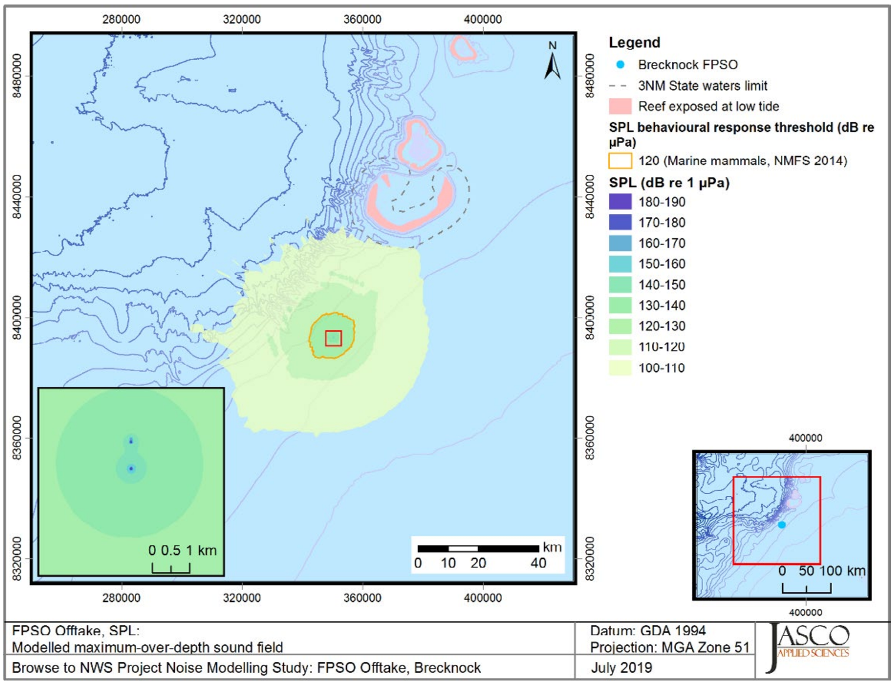

Figure 84. *Brecknock, FPSO offtake, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

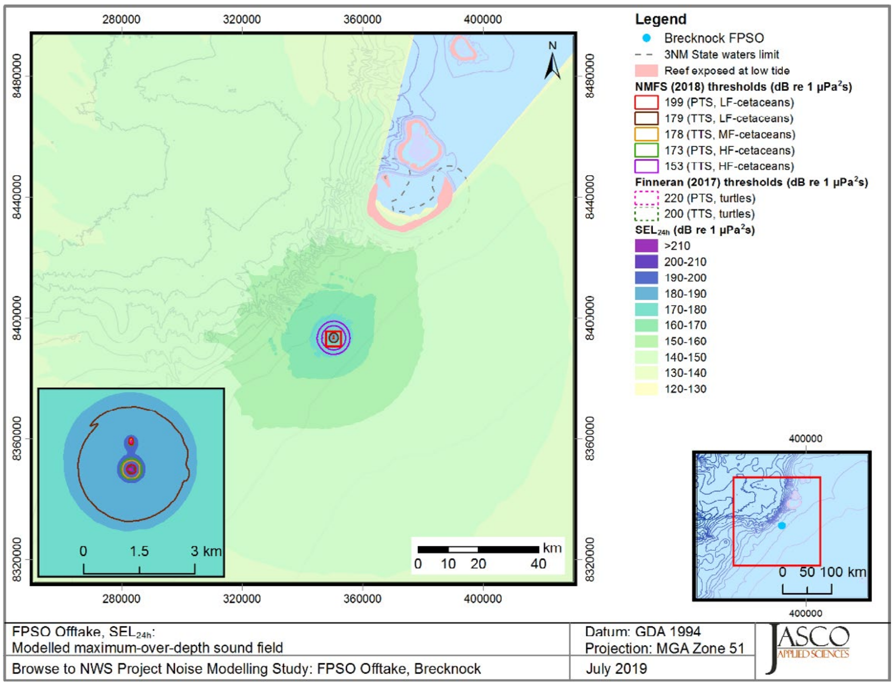

Figure 85. *Brecknock, FPSO offtake, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles. Threshold for mid-frequency cetacean PTS was not reached.

4.4.2.2. Aggregate scenarios

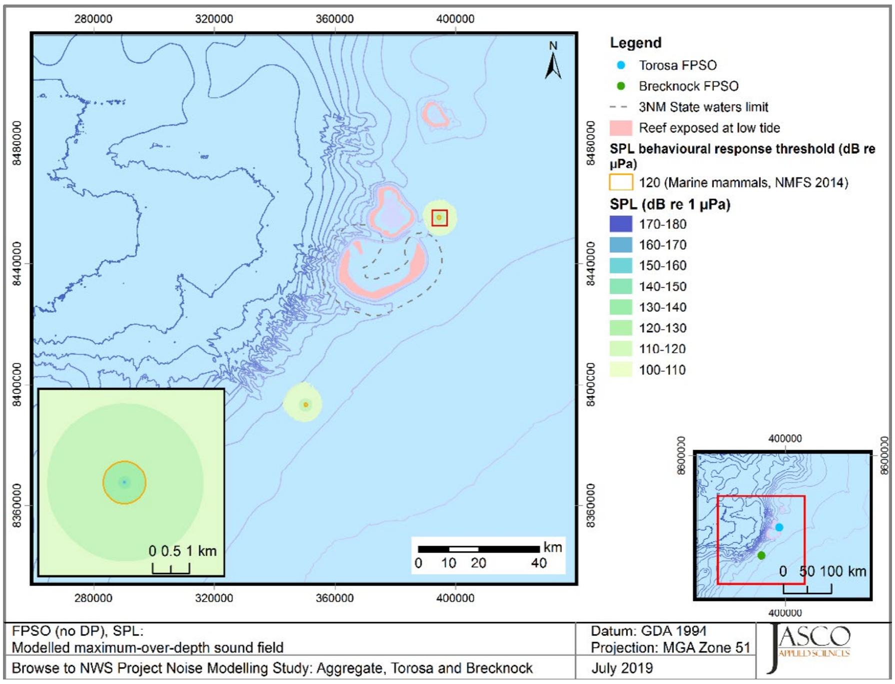

Figure 86. *Torosa and Brecknock, Aggregate FPSOs without DP, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

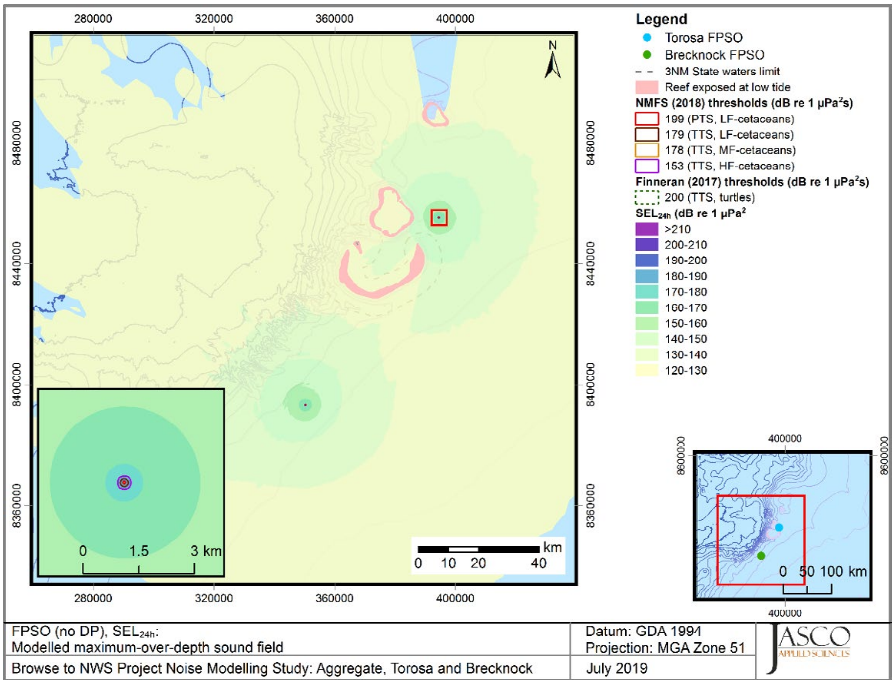

Figure 87. *Torosa and Brecknock, Aggregate FPSOs without DP, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles. Thresholds for mid- and high- frequency cetacean PTS was not reached.

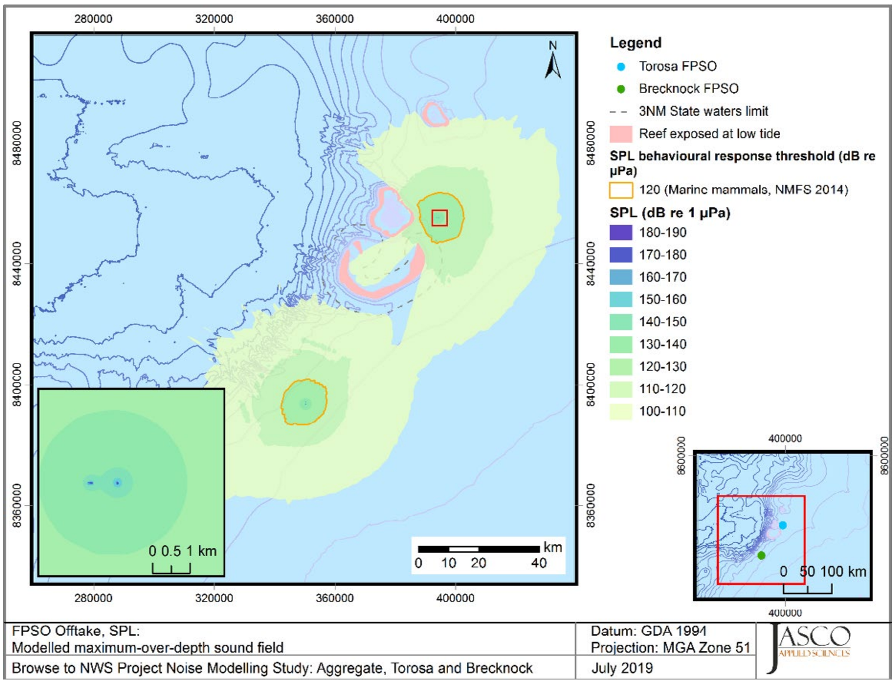

Figure 88. *Torosa and Brecknock, Aggregate FPSO offtake, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

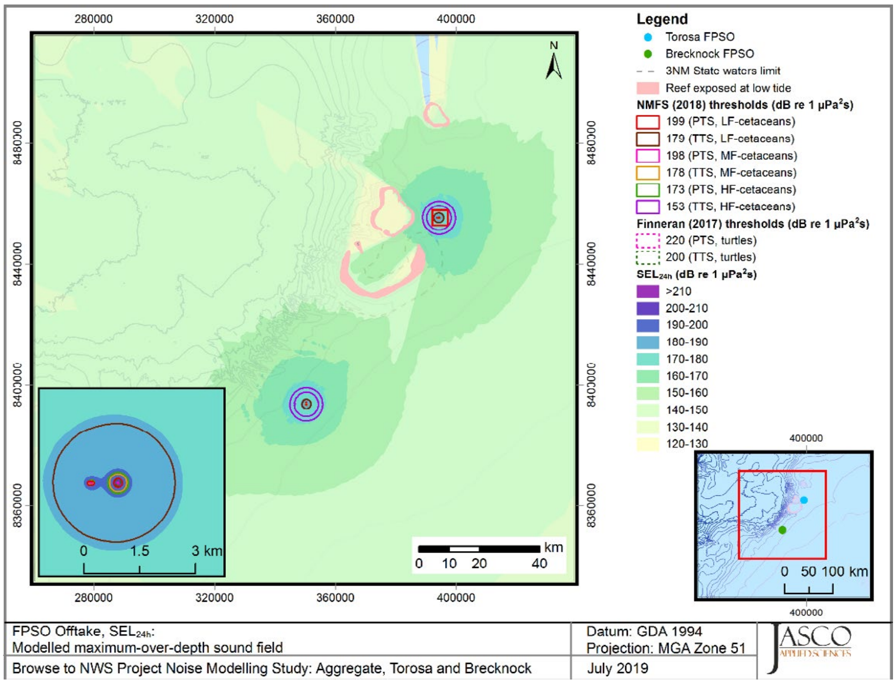

Figure 89. *Torosa and Brecknock, Aggregate FPSO offtake, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles.

5. Discussion and Summary

5.1. Pile Driving

5.1.1. Acoustic propagation

This study predicted underwater sound levels associated with impact driving of subsea piles to anchor the Torosa FPSO facility turret. The underwater sound field was modelled for 53.25 m long piles with a 5.5 m diameter with 60 mm wall thickness; The piles will be driven a total of 51.5 m into the seabed. The modelling applied a sound speed profile derived from a public database (Appendix F.3.2), and also accounted for bathymetric variations (Appendix F.3.1) and local geoacoustic properties (Appendix F.3.3). The broadband sound energy at 10 m for each penetration depth ranged from 184.6–199.4 dB re 1 µPa^2·s with the peak sound energy concentrated in the frequency range 70 to 300 Hz (Figure 16), with levels from the pile at the 17 m penetration depth having the highest energy.

Noise emissions from pile driving were considered here to be cylindrically isotropic (i.e., omnidirectional in the horizontal plane). As such, variations in noise that propagates across azimuths are attributed to the bathymetry alone, with this accounted for in the modelling methodology. When the hammer strikes the pile, noise propagates into the water as a downward Mach cone (see Appendix B). A portion of the energy from the strike is also reflected at the pile bottom, generating an upward Mach cone. This cycle of downward propagation, reflection, and upward propagation occurs multiple times per strike. At close range from the pile, noise levels are determined by the summation of Mach cones, which might add constructively (i.e., their summation results in a total wave with higher amplitude than the original ones) or destructively (i.e., wavefronts can cancel each other, resulting in low amplitudes). The way in which Mach cones combine with each other is strongly dependent on their frequency content, which is determined by the hammer forcing function and the pile dimensions.

Due to the relation between the speed of sound in steel (~5000 m/s) relative to the speed of sound in the water (~1490 m/s at the depth of the pile), the Mach cone propagates away from the pile and impinges the seabed at an angle of ~17°. The first bottom bounce occurs within 16 m from the pile, and the first surface bounce occurs within 1.5 from the pile. As shown in Figure 25, the Mach cone corresponding to the shallowest pile penetration introduces substantial energy that propagates through the water column, compared to the 45 m pile penetration scenario in Figure 27, for which underground sound propagation tends to dominate near the pile.

The modelling of the three penetration depths for each pile provides a detailed quantification of the associated sound levels for each penetration. The distances to all per-strike isopleths are farthest at the start of piling when most of the pile is in the water column, and distances are shortest at the end of piling when most of the pile is buried in the sediment. This is despite the per-strike pile penetration being less during the final stages of driving, and the increased resistance generating stronger stress-wave reflections at the pile toe. Therefore, the amount of pile in the water has greatest influence on the in-water sound levels. The isopleths for unweighted marine mammal behavioural thresholds for each penetration are presented on the same map for each hammer to assist with comparison (Figures 23 and 24 for Torosa and Figures 46 and 47 for Brecknock). The highest peak pressure levels are predicted to occur at the shallowest penetration (17 m) and for the IHC S-1200.

5.1.1.1. Propagation at Torosa

As evidenced in Figures 23 and 24, sound propagation around the pile is mostly isotropic, except along transects toward the North Scott Reef in the eastern direction. Along these transects, the following phenomena take place:

- Sound is significantly blocked when it reaches the exposed reefs, as the acoustic wavefront hits the limestone interface and reflects. This is due to the high impedance contrast between water and limestone. Note that the results presented here do not account for backpropagated sound.
- At azimuth 240° from the pile, sound propagates within the channel between the two reefs as far as the bathymetry allows (see Figures 25–30). Between 3–17 km from the pile, propagation takes place along a sand/gravel seabed, which enhances energy contributions from seabed reflections

in this direction (compared to those in directions away from the reef). At a range of approximately 17 km from the pile, the bathymetry abruptly reduces from ~440 m depth to 50 m depth.

- Beyond 17 km range from the pile, sound propagates along a shallow (50 m depth) waveguide, up to 30 km, where it reaches the shallow reef and sound is blocked. At ranges >17 km, despite bottom reflections being strong (due to the high acoustic contrast between water and limestone), sound propagation is not significant, as very small amount of energy enters the shallow waveguide (see Figures 25–30).

The enhanced propagation along sandy/gravel seabed is observed as “sound islands” in maps of SPL and SEL_{24h} criteria. The R_{max} radius is more representative of the effective extent of the footprint because the source is stationary and is more conservative, however, when determining potential impacts, the azimuthal distribution of sound should be considered, particularly at Torosa. Given the likely soil resistance, the modelling scenarios represent the maximum noise footprint from pile driving activities as a conservative estimate.

The maximum received level at the Scott Reef state waters limit (Table 9) is 160.8 or 165.2 dB re 1 µPa, depending upon the hammer used (Table 26).

5.1.1.2. Propagation at Brecknock

For Brecknock, sound interaction with the reefs only takes place at ranges of at least 30 km from the pile (in the northeast direction). Therefore, the different seabed types around the reefs have no influence on distances to the thresholds presented in this study (which when reached, occur at shorter ranges). At this location, sound propagation is mostly affected by bathymetry features. At ranges less than 13 km from the pile, the bathymetry varies smoothly from 400 m to 800 m from southeast–northwest direction. This smooth variation has little impact on sound propagation, resulting in mostly isotropic sound propagation (i.e. Figures 46 and 47). Beyond 13 km range from the pile, transects northwest from the pile encounter slightly rougher bathymetry features and steeper bathymetry decay, reaching water depths as deep as ~2.4 km 80 km from the pile. Contrary to this, transects southeast from the pile encounter a sharp decrease in water depth at ranges 50 km–60 km, reaching water depths ~100 m at 80 km from the pile. The influence of this asymmetry on sound propagation can be observed in the sound field maps in Section 4.2.2.2, for which sound propagates farther along downslope bathymetry lines.

5.1.2. Ranges to exposure thresholds

For criteria based on SEL_{24h} metrics, the ranges must be considered in context of the duration of operations. For the purposes of modelling, one pile will be driven per day; therefore, the corresponding sound level is denoted as SEL_{24h}; however, the estimated times for driving piles are 78.5 or 45.5 minutes (Torosa) and 80.1 or 47.4 minutes (Brecknock) for medium and high-power hammers, respectively (Table 16 for Torosa and Table 17 for Brecknock). SEL_{24h} is a cumulative metric that reflects the dosimetric impact of noise levels within the driving period, assuming that an animal is consistently exposed to such noise levels at a fixed position. The radii that correspond to SEL_{24h} typically represent an unlikely worst-case scenario for SEL-based exposure because, more realistically, marine fauna (mammals or fish) would not stay in the same location or at the same distance from a sound source for an extended period. Therefore, a reported radius for SEL_{24h} criteria does not mean that any animal travelling within this radius from the source *will* be exposed to PTS or TTS, but rather that it *could* be exposed if it remained within that range for the entire duration of the pile driving

For each sound level threshold, the maximum range (R_{max}) and the 95% range ($R_{95\%}$) were calculated. R_{max} is the distance to the farthest occurrence of the threshold level, at any depth. $R_{95\%}$ for a sound level is the radius of a circle, centred on the source, encompassing 95% of the sound at levels above threshold. Using $R_{95\%}$ reduces the sensitivity to extreme outlying values (the farthest 5% of ranges).

5.1.2.1. Marine mammals

The results for the NMFS (2018) criteria applied for marine mammal PTS and TTS consider both metrics within the criteria (PK and SEL), with SEL assessed here for a single pile within a 24 h period, i.e., a single pile per day. The metric with the longest distance must be applied, and these maximum distances along with the relevant metric are summarised in Table 56.

The maximum distances to the NMFS (2014) marine mammal behavioural response criterion of 160 dB re 1 µPa (SPL) are associated with the shallowest penetration of 17 m for both hammers, with the maximum distances summarised in Table 57.

Table 56. *Marine mammal injury and hearing sensitivity changes*: Maximum-over-depth distances (in km) from the pile to PTS and TTS thresholds (NMFS 2018). PK results are in Table 24 for Torosa and Table 35 for Brecknock and results for SEL_{24h} are in Table 27 for Torosa and Table 37 for Brecknock.

Hearing group	PTS				TTS			
	IHC S-600		IHC S-1200		IHC S-600		IHC S-1200	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Torosa								
LF cetaceans	5.15#	5.00#	5.35#	5.12#	26.10#	20.79#	29.46#	22.60#
MF cetaceans	<0.02†		<0.02†		0.03#		0.06#	0.06#
HF cetaceans	0.21†		0.26†		0.35†	0.30#	2.20#	2.06#
Brecknock								
LF cetaceans	4.58#	4.05#	4.62#	4.40#	23.11#	20.04#	24.75#	20.80#
MF cetaceans	<0.02†		<0.02†		<0.02†		0.05#	0.05#
HF cetaceans	0.19†		0.26†		0.36†	0.31#	2.33#	2.20#

† PK (L_{pk}; dB re 1 µPa)
# Frequency weighted SEL_{24h} ($L_{E,24h}$). For the SEL_{24h} criteria, the model does not account for shutdowns.

Table 57. *Marine mammal behaviour*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the piles to modelled maximum-over-depth isopleths for behavioural response thresholds, maximum across all three penetration depths. Results are in Tables 23 and 34.

SPL (L_p; dB re 1 µPa)	IHC S-600		IHC S-1200	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Torosa				
160†	10.48	6.74	17.15	11.63
Brecknock				
160†	7.06	6.40	13.97	11.87

† Threshold for marine mammal behavioural response (NMFS 2014).

5.1.2.2. Turtles

The results for the Finneran et al. (2017) criteria applied for turtle PTS and TTS consider both metrics within the criteria (PK and SEL), with SEL assessed here for a single pile within a 24 h period, i.e., a single pile per day. The metric with the longest distance must be applied, and these maximum distances along with the relevant metric are summarised in Table 58.

The maximum distances to the two criteria considered, the NMFS criterion for behavioural response (SPL of 166 dB re 1 µPa) and a criterion for behavioural disturbance (SPL of 175 dB re 1 µPa)

(McCauley et al. 2000a, 2000b), are associated with the shallowest penetration of 17 m for both hammers, with the maximum distances summarised in Table 59.

Table 58. *Turtle injury and hearing sensitivity changes*: Maximum-over-depth distances (in km) to PTS and TTS thresholds from Finneran et al. (2017). PK results are in Table 24 for Torosa and Table 35 for Brecknock. Results for SEL_{24h} are in Table 27 for Torosa and Table 37 for Brecknock.

Hearing group	PTS				TTS			
	IHC S-600		IHC S-1200		IHC S-600		IHC S-1200	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Torosa								
Turtles	0.24	0.23	0.25	0.25	4.79	2.36	5.07	4.94
Brecknock								
Turtles	0.24	0.23	0.25	0.24	2.58	2.44	2.60	2.47

All distances are associated with frequency weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s), not PK (L_{pk}; dB re 1 µPa). For the SEL_{24h} criteria, the model does not account for shutdowns.

Table 59. *Turtle behaviour*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile to modelled maximum-over-depth behavioural response thresholds, maximum across all three penetration depths. Results are in Tables 23 and 34.

SPL (L_p; dB re 1 µPa)	IHC S-600		IHC S-1200	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Torosa				
175†	0.68	0.64	1.87	1.79
166‡	5.11	4.99	9.11	5.66
Brecknock				
175†	0.67	0.63	1.87	1.77
166‡	2.87	2.70	6.38	5.92

† Threshold for turtle behavioural response to impulsive noise (McCauley et al. 2000a, 2000b).
‡ Threshold for turtle behavioural response to impulsive noise (NSF 2011).

5.1.2.3. Fish, fish eggs, and fish larvae

The modelling study assessed the ranges for quantitative criteria from Popper et al. (2014) associated with mortality and potential mortal injury and impairment in the following:

- Fish without a swim bladder (also appropriate for sharks in the absence of other information)
- Fish with a swim bladder not used for hearing
- Fish that use their swim bladders for hearing
- Fish eggs, and fish larvae

Considering both per-strike modelled penetrations and associated SEL_{24h} scenario, along with both PK and SEL_{24h} metrics, in line with the conditions of the criteria, the maximum distances are summarised in Table 60 for Torosa and Table 61 for Brecknock.

Table 60. *Torosa fish effect thresholds:* Summary of maximum fish, fish eggs, and larvae injury and TTS onset distances for single impulse and SEL_{24h} modelled scenarios (PK values from Table 25, SEL_{24h} values from Table 28).

Relevant hearing group	Effect criteria	IHC S-600		IHC S-1200	
		Metric associated with longest distance to criteria	R_{max} (km)	Metric associated with longest distance to criteria	R_{max} (km)
Fish: No swim bladder	Injury	PK	0.08	PK	0.1
	TTS	SEL_{24h}	9.05	SEL_{24h}	9.15
Fish: Swim bladder not involved in hearing	Injury	SEL_{24h}	0.15	PK	0.17
	TTS	SEL_{24h}	9.05	SEL_{24h}	9.15
Fish: Swim bladder involved in hearing	Injury	SEL_{24h}	0.21	SEL_{24h}	0.22
	TTS	SEL_{24h}	9.05	SEL_{24h}	9.15
Fish eggs, and larvae	Injury	SEL_{24h}	0.15	PK	0.17

Table 61. *Brecknock fish effect thresholds*: Summary of maximum fish, fish eggs, and larvae injury and TTS onset distances for single impulse and SEL_{24h} modelled scenarios (PK values from Table 36, SEL_{24h} values from Table 38).

Relevant hearing group	Effect criteria	IHC S-600		IHC S-1200	
		Metric associated with longest distance to criteria	R_{max} (km)	Metric associated with longest distance to criteria	R_{max} (km)
Fish: No swim bladder	Injury	PK	0.04	PK	0.07
	TTS	SEL_{24h}	6.12	SEL_{24h}	6.27
Fish: Swim bladder not involved in hearing	Injury	SEL_{24h}	0.14	PK	0.16
	TTS	SEL_{24h}	6.12	SEL_{24h}	6.27
Fish: Swim bladder involved in hearing	Injury	SEL_{24h}	0.20	SEL_{24h}	0.22
	TTS	SEL_{24h}	6.12	SEL_{24h}	6.27
Fish eggs, and larvae	Injury	SEL_{24h}	0.14	PK	0.16

5.2. Animal movement and exposure modelling

The estimated sound fields produced by source and propagation models for the driving of a single pile were incorporated into the JASMINE sound exposure model to estimate the number of animals potentially exposed to levels above the defined thresholds. The range within which 95% of the exposure exceedances occur was also reported (95th percentile ranges, P_{95}, which could also be referred to as Exposure Range 95%, or $ER_{95\%}$). No density data were available for migratory green turtles (Section 3.7.3.2) therefore results are presented in terms of the 95th percentile ranges only. Mitigation of potential impacts through exclusion zones for turtles and pygmy blue whales (500 and 2000 m, respectively) were considered in the modelling.

5.2.1. Torosa FPSO anchor piles

Animal movement modelling simulation results predict that inter-nesting turtles are unlikely to be exposed above TTS, PTS, or behavioural thresholds for either of the two hammers at the Torosa location. Real-world densities are unavailable for migrating green turtles, so the true number of animals are not calculated in that case. However, there were no PTS PK, PTS SEL_{24h}, or TTS PK exposures above threshold for either hammer. Prior to considering exclusion zones, the 95th percentile range to TTS SEL_{24h} was 1.65 km and 1.79 km for the S-600 and S-1200 hammers, respectively. After considering a 500 m exclusion zone, the number of animals impacted was reduced by 20.7% for the S-600 hammer and 11.5% for the S-1200 hammer.

A number of migrating green turtles were exposed above both behavioural thresholds. The 95th percentile range to animats exceeding the behavioural disturbance threshold (175 dB re 1 µPa) was 50 m for the S-600 hammer and 1.77 km for the S-1200 hammer. Whilst the range to animats exceeding the behavioural response threshold (166 dB re 1 µPa) was 2.54 or 4.64 km for the S-600 or S-1200 hammer. The effectiveness of the exclusion zone in reducing exposures was moderate (less than 11%) in most cases. The exception being the exposures over the behavioural disturbance threshold for the S-600 hammer, in which the application of the exclusion zone reduced the number of animats exposed above threshold by 100%, or to zero.

Without considering the 2000 m exclusion zone, neither the migrating nor foraging pygmy blue whales are expected to be exposed above TTS PK or PTS PK thresholds for either of the two hammers. Regardless of hammer type, a total of 0.02 migrating pygmy blue whales are expected to be exposed above the PTS SEL_{24h} threshold, and a total of 0.06 foraging pygmy blue whales are expected to be exposed above the PTS SEL_{24h} threshold. The number of animats exposed above TTS SEL_{24h} was similar for between hammer types for migrating blue whales, with 1.28 or 1.30 individuals exposed for the S-600 and S-1200 hammer, respectively. The number of individual foraging blue whales exposed above TTS SEL_{24h} was slightly higher, but also similar between the two hammers, with 1.65 and 1.75 individuals for the S-600 and S-1200 hammers. After applying the 2000 m exclusion zone, the number of pygmy blue whales exposed above PTS SEL_{24h} threshold dropped to zero for both hammers.

The number of animals expected to be exposed above the 160 dB re 1 µPa (SPL) behavioural threshold ranges ranged from 0.58 for the foraging pygmy blue whale with the S-600 hammer, to 1.41 for the migrating pygmy blue whale with the S-1200 hammer.

For the thresholds which occur at a greater distance from the pile (TTS SEL_{24h}, and behavioural thresholds), more animats for both species and both hammers were exposed above threshold at larger ranges. Consequently, the effect of the exclusion zone wasn't significant for those metrics. Most of the ranges computed after the application of exclusion zones either increased or stayed the same, due to the influence on the statistical distribution of exposure ranges. In the cases where the exclusion zone encompassed all the exposures above threshold, there were no exposures remaining and the 95th percentile range therefore dropped to zero. Figure 90 shows the distribution of 95th percentile ranges before and after the application of the 2000 m exclusion zone for migrating pygmy blue whales above the behavioural threshold. After applying the exclusion zone, all of the close-range exposures were removed, which effectively shifted the entire distribution to longer ranges. This shift is reflected in the 0.58 km increase in 95th percentile range. Figure 91 shows the case where all the exposures above threshold occur within the exclusion zone range. Once the exposures below that range are excluded, the 95th percentile range defaults to zero.

The migratory behavioural profile includes migratory dives with a mean depth of 14 m ± 4 m (24 m maximum), and exploratory dives with a mean maximum depth of 107 ± 81 m (320 m maximum) (Section 3.7.2.1). These are included in the behavioural profile (Table G-2) as gaussian distributions. Due to the low sample size (a single animal), the variability across the population is unknown. To provide context if the distribution centres (means) are different, focused slice plots were produced (Figures 31–34). Within one standard deviation for the migratory dives, 4 m, there is minimal difference between the sound field distribution within the water column, and only a slight difference between the mean and maximum. For the exploratory dives, the levels are louder shallower than the mean or deeper than the mean depending upon the distance from the source. However, as the whales are moving up and down within the water column during their dives, they are exposed to a range of sound levels, including the quieter levels close to the surface.

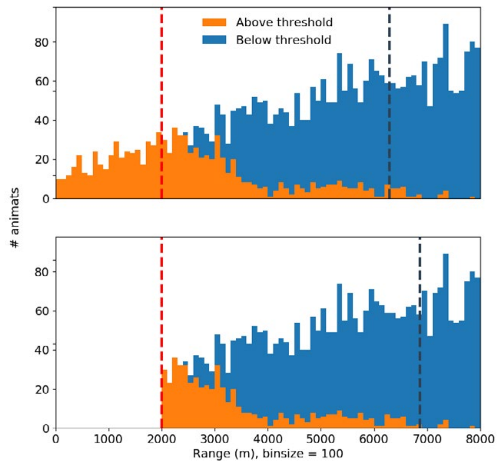

Figure 90. *Pygmy blue whale behavioural threshold*: Histograms of the distribution ranges for pygmy blue whale animat exposures for the S-600 hammer, showing (upper panel) exposures without and (lower panel) with an exclusion zone. Black dashed line: 95th percentile ranges. Red dashed line: 2000 m exclusion zone boundary.

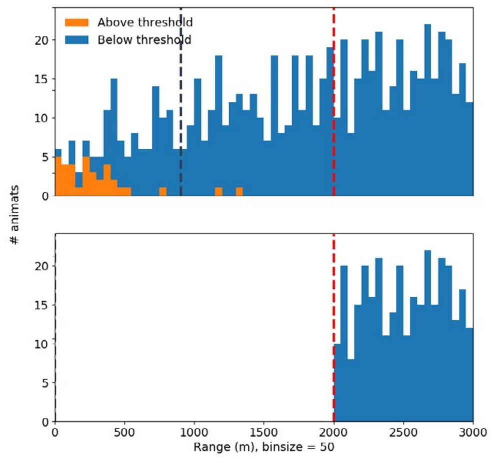

Figure 91. *Pygmy blue whale PTS threshold*: Histograms of the distribution ranges for pygmy blue whale animat exposures for the S-600 hammer, showing (upper panel) exposures without and (lower panel) with an exclusion zone. Black dashed line: 95th percentile ranges. Red dashed line: 2000 m exclusion zone boundary.

Implementing an exclusion zone of 500 m for green turtles and 2000 m for pygmy blue whales reduced all exposures above TTS and PTS threshold criteria to zero for both hammers, except for the TTS SEL_{24h} thresholds, where estimated exposures were only slightly reduced.

Interpretation of the 95th percentile ranges is nuanced and is the result of specific acoustic propagation characteristics as well as the probabilistic nature of the animal movement modelling simulation. As an example, Figure 92 shows vertical slices of SPL as a function of range and depth in the upper water column at a single azimuth (270°) for all three penetration depths for the IHC S-1200 hammer. The histograms in Figure 93 show how the probability of migrating green turtle exposures above threshold within the 95th percentile range varies as a function of the specific exposure threshold being applied (either 166 or 175 dB re 1 µPa in this case). A lower threshold level means that turtle animats further from the source will reach that threshold, therefore the computed 95th percentile range of all exposed turtle animats will be larger. Depending on the nature of the sound field as a function of range and depth, larger ranges may encompass different numbers of animats that are above and below sound threshold levels.

The example in Figure 93 demonstrates a case where, due to the nature of the acoustic propagation in the area, a lower proportion of the turtle animats within the higher threshold range are exposed above that threshold. For the S-1200 hammer, 45% of turtle animats within 4.64 km are exposed above the 166 dB SPL behavioural response threshold. For the same hammer, 58% of turtle animats within 1.77 km are above the 175 dB SPL increased behavioural disturbance threshold.

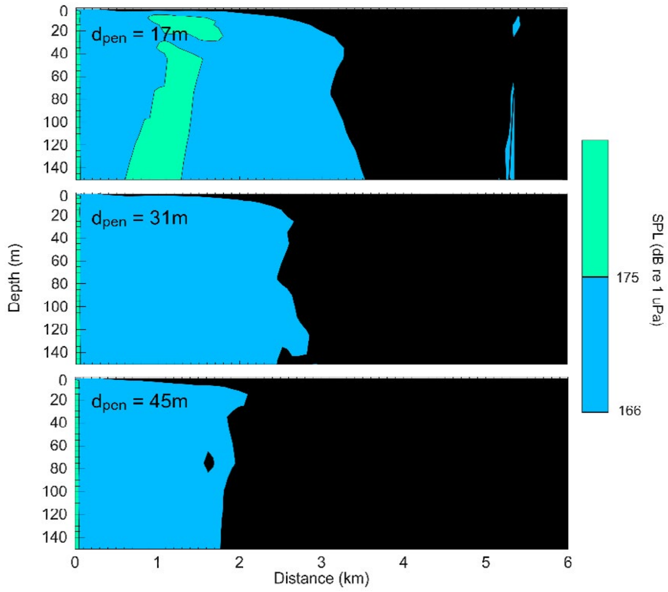

Figure 92. SPL (dB re 1µPa) for each of the modelled pile penetration depths (d_{pen}) as a function of distance from the piling location and depth in the upper 150 m of the water column for the IHC S-1200 hammer. Profiles are at an azimuth of 270°. Specific contours show the behavioural thresholds for green turtles.

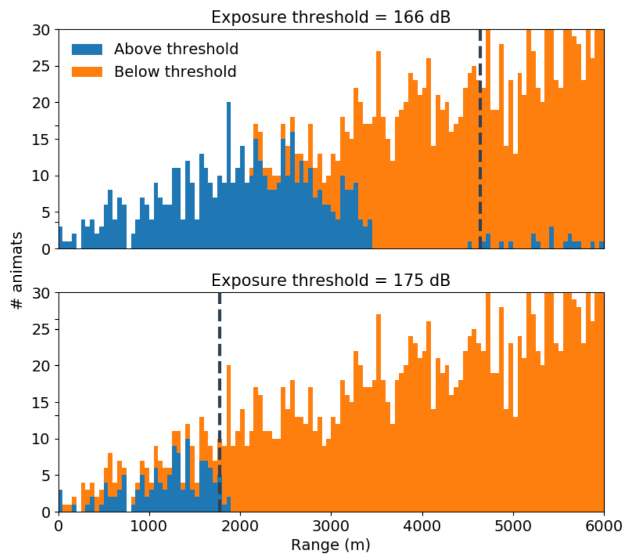

Figure 93. *Turtle behavioural threshold*: Histograms of the distribution ranges migrating green turtle animat exposures for the S-1200 hammer, showing (upper panel) exposures without and (lower panel) with an exclusion zone. Black dashed line: 95th percentile ranges. Red dashed line: 2000 m exclusion zone boundary.

5.2.2. Brecknock FPSO anchor piles

Animal movement modelling simulation results showed that green turtles were not exposed above threshold for PTS, TTS, or behaviour thresholds, even without applying the exclusion zone. This is because the Brecknock pile location is more than 40 km from either the modified inter-nesting or migration area BIAs.

Without consideration of the exclusion zone, pygmy blue whales have no exposures above PTS PK or TTS PK for either hammer. There were 0.02 exposures above PTS SEL_{24h} for the S-600 hammer, and 0.04 exposures above PTS SEL_{24h} for the S-1200 hammer. TTS SEL_{24h} exposures for migrating blue whales ranged from 1.56–1.67 for the S-600 and S-1200 hammers. The number of expected exposures above TTS_{24h} threshold for foraging pygmy blue whales was much lower since the Brecknock piling location is 10.3 km from the BIA: 0.02 individuals for the S-600 hammer and 0.08 individuals for the S-1200 hammer.

With the exclusion zone in place, the PTS SEL_{24h} exposures reduced to zero. The number of predicted exposures for foraging pygmy blue whales did not change as a result of applying an exclusion zone because of the large distance to the BIA.

The distribution of sound within the water column at depths relevant to the migratory behavioural profile, shown in Figures 58–61, follows a similar trend to that observed at Torosa, although the sound fields are quieter at greater ranges. Changes to migratory dive behaviour that result in a mean dive depth of a few metres deeper or shallower are, based on the presented results, unlikely to change the exposure ranges significantly.

5.3. VSP

5.3.1. Acoustic propagation

This study predicted underwater sound levels associated with VSP sources at Torosa TRD Well and Brecknock. The underwater sound field was modelled for a 750 in^3 seismic source array deployed at depth 6 m (Appendix C). Since the VSP source is mostly isotropic (vertically and horizontally), sound propagation for this source is driven by bathymetry features. For the Brecknock location, sound propagates larger distances towards the northwest, along downslope bathymetries. Similarly, for the Torosa TRD Well location sound from the VSP propagates mostly towards the north, passing along the west side of North Scott Reef. At both locations, sound is effectively blocked by the shallow reefs, which is more evident at the Torosa location due to its close proximity to the VSP source.

The overall broadband (10–25000 Hz) unweighted per-pulse SEL source level was 214.0 dB 1 μPa^2m^2s and 214.1 dB 1 μPa^2m^2s in the broadside and endfire directions, respectively. Additional results are presented in Table 40.

5.3.2. Ranges to exposure thresholds

The findings for the VSP operations pertaining each of the metrics and criteria for various marine species of interest are summarised below.

Marine mammals

- The maximum distance where the NMFS (2014) marine mammal behavioural response criterion of 160 dB re 1 µPa (SPL) could be exceeded varied between 1.6 and 1.7 km, provided in Table 42, with the distance being longer at Brecknock.
- The results for the criteria applied for marine mammal Permanent Threshold Shift (PTS), NMFS (2018), consider both metrics within the criteria (PK and SEL_{24h}), with results presented in Tables 43, 45 and 46.. The SEL_{24h} considers a range of impulses within 24 h, from 1 to 150. The applicable metric from the criteria, associated with the longest distance associated with either metric, depends upon the number of impulses with the 24 h. The ranges presented are based upon no more than 150 impulses within 24 h. A reported radius for SEL_{24h} criteria does not mean that marine mammals travelling within this radius of the source will be impacted, but rather that an

animal could be exposed to the sound level associated with auditory impairment (either PTS or TTS) if it remained in that location for either the duration of the activity or 24 hours.

PTS and TTS are not predicted to occur in mid-frequency cetaceans. For PTS in high-frequency cetaceans, the PK metric is always associated with the longest range (68 m), while for PTS in low-frequency cetaceans, for less than 10 impulses the range is greater due to the PK metric (12 m), but otherwise the range is determined by SEL_{24h}, with the maximum distance of 200 m being associated with 150 impulses at either Torosa TRD Well or Brecknock.

For TTS in high-frequency cetaceans the PK metric is always associated with the longest range (141 m), while for TTS in low-frequency cetaceans the range is determined by SEL_{24h}, with the maximum distance of 1 1.69 km for 150 impulses at Torosa TRD Well or Brecknock.

Turtles

- The VSP source is not predicted to cause PTS in turtles, as it doesn't cause either the PK or SEL_{24h} criteria from Finneran et al. (2017) to be exceeded at a distance greater than the horizontal modelling resolution (20 m) from the source (Tables 43 and 45).

  As with marine mammals, the SEL_{24h} considers a range of impulses within 24 h, from 1 to 150. While the TTS criteria due to the PK metric isn't exceeded, depending upon the number of impulses, the TTS SEL_{24h} criteria can be exceeded at up to 160 m for 150 impulses at Torosa TRD Well or Brecknock.
- Similarly to marine mammals, a reported radius for SEL_{24h} criteria does not mean that turtles travelling within this radius of the source will be impacted, but rather that an animal could be exposed to the sound level associated with auditory impairment (TTS) if it remained in that location for either the duration of the activity or 24 hours.
- The distances at where the two criteria considered in relation to turtle behaviour, behavioural response and disturbance, could be exceeded are summarised in Table 62.

Table 62. Distances to turtle behavioural response criteria (from Table 42).

SPL (L_p; dB re 1 µPa)	Distance	
	R_{max} (km)	$R_{95\%}$ (km)
Torosa TRD Well		
175†	0.23	0.23
166‡	0.81	0.77
Brecknock		
175†	0.23	0.23
166‡	0.72	0.69

† Threshold for turtle behavioural response to impulsive noise (McCauley et al. 2000a, McCauley et al. 2000b).
‡ Threshold for turtle behavioural response to impulsive noise (NSF 2011).

Fish, fish eggs, and fish larvae

- This modelling study assessed the ranges for quantitative criteria based on Popper et al. (2014) and considered both PK (seafloor and water column) and SEL_{24h} metrics associated with mortality and potential mortal injury and impairment (as defined in the criteria) in the following groups:
  - Fish without a swim bladder (also appropriate for sharks in the absence of other information)
  - Fish with a swim bladder that do not use it for hearing
  - Fish that use their swim bladders for hearing
  - Fish eggs and fish larvae
- Sound levels at the seafloor do not exceed any of the criteria.

- Based on PK metrics, acoustic injury could be sustained within a maximum horizontal distance of 21 m of the source for fish without a swim bladder, and within a maximum horizontal distance of 40 m for fish with a swim bladder, fish eggs, and fish larvae (Table 43). SEL_{24h} metrics for injury were not exceeded.

Sponges and Coral

- To assist with assessing the potential effects on sponges and coral receptors, the PK sound level at the seafloor directly underneath the VSP source was estimated at both modelling sites. It was found that the sound level of 226 dB re 1 µPa PK, a sound level associated with no effect (Heyward et al. 2018) was not reached.

5.4. Vessel Noise (MODU, OSV, and FPSO)

5.4.1. Acoustic propagation

This study predicted underwater sound levels associated with the operations of a Mobile Offshore Drilling Unit (MODU), FPSOs with and without DP operating, an OSV near each FPSO, and Offtake operations including an FPSO under DP, a noiseless condensate tanker and an OSV for locations at Torosa and Brecknock (Section 3.6). This includes aggregate scenarios which include FPSOs under normal operating conditions (without DP), as well as offtake operations, at both locations simultaneously.

Despite the different vessels having different source depths and either no thrusters or different thruster locations, sound propagation for these sources is driven by bathymetry features. The Torosa TRD Well location, where the MODU is located, is closer to the reef than the FPSO location, and thus the reef has an increased influence on the sound field. Sound propagates into South Scott Reef Lagoon, but the higher levels are restricted to the channel. The SPL sound field for sources located at Torosa (FPSO and OSV) above 120 dB are less influenced by the reef, although they are slightly attenuated in the direction of the reef for considering the FPSO under DP.

For the Brecknock location, sound propagates larger distances towards the northwest, along downslope bathymetries, with the influence apparent for all modelled sources.

Due to the distance of ~70 km between the Torosa and the Brecknock sites, as well as the blockage in line-of-sight due to the reef, contours for the criteria thresholds considered in this study do not combine between sites. Therefore, radii to criteria thresholds presented for FPSOs under normal operating conditions (without DP) and for offtake operations are still valid even in the case of simultaneous activity at Torosa and Brecknock. The only isopleths affected by simultaneous activities at both locations are those corresponding to the lower levels, below either 110 dB re 1 µPa or 170 dB re 1 $\mu Pa^2 \cdot s$ (unweighted) (Figures 87–89), which are not associated to any criteria.

5.4.2. Ranges to exposure thresholds

Marine mammals

The results for the NMFS (2018) criteria applied for marine mammal PTS and TTS for vessels are assessed here for a 24 h period. The maximum distances to PTS are summarised in Table 63, with complete results for PTS and TTS at the Torosa and Brecknock locations presented in Tables 50 and 51. The maximum distances to the NMFS (2014) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) are summarised in Table 64, with complete results presented in Tables 47 and 48.

For aggregate scenarios considering both FPSO’s, it was found that due to the separation between the sites, distances to PTS, TTS, and behavioural thresholds remained unaltered compared to the individual operations (Tables 52–55). This was quantified by verifying that the total aggregate area within threshold isopleth for marine mammal behavioural response to continuous noise (NMFS 2014) equals the sum of the areas for the individual operations.

Table 63. *Marine mammal injury*: Maximum (R_{max}) horizontal distances (km) to modelled maximum-over-depth PTS threshold from NMFS (2018) for vessel-based scenarios.

Hearing group	Threshold for PTS, SEL_{24h} (dB re 1 µPa²·s) #	Distance R_{max} (km)				
		MODU	OSV	FPSO on DP	FPSO without DP	FPSO offtake
Torosa						
LF cetaceans	199	0.11	0.05	0.12	-	0.12
MF cetaceans	198	-	-	<0.02	-	<0.02
HF cetaceans	173	0.15	0.07	0.28	-	0.28
Brecknock						
LF cetaceans	199	0.11	0.06	0.12	<0.02	0.12
MF cetaceans	198	-	-	<0.02	-	<0.02
HF cetaceans	173	0.15	0.07	0.28	<0.02	0.28

Frequency weighted.
A dash indicates the level was not reached.
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Table 64. *Marine mammal behaviour*: Summary of maximum behavioural disturbance distances for vessel-based scenarios, derived from Tables 47 and 48.

SPL (L_p; dB re 1 µPa)	Distance R_{max} (km)				
	MODU	OSV	FPSO on DP	FPSO without DP	FPSO Offtake
Torosa					
120†	10.50	2.25	8.77	0.57	8.89
Brecknock					
120†	8.84	2.39	8.78	0.54	8.89

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Turtles

Results for the Finneran et al. (2017) criteria applied for turtle PTS and TTS for vessels are assessed here for a 24 h period. The maximum distances to PTS are summarised in Table 65, with complete results for PTS and TTS at the Torosa and Brecknock locations presented in Tables 50 and 51.

Table 65. *Turtle SEL_{24h} thresholds*: Maximum-over-depth distances (in km) to turtle PTS threshold (Finneran et al. 2017).

SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Distance R_{max} (km)				
	MODU	OSV	FPSO on DP	FPSO without DP	FPSO Offtake
Torosa					
220†	0.06	0.06	<0.02	-	<0.02
Brecknock					
220†	0.06	0.06	<0.02	-	<0.02

† Threshold for turtle-weighted SEL_{24h} (Finneran et al. 2017).
A dash indicates the level was not reached.
FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Fish

Sound produced by the vessel operations could cause physiological effects, and recoverable injury, to some fish species, but only if the animals are in very close proximity to the sound sources–within a planar distance of 60 m, for 48 h. Temporary impairment due to TTS could occur at similar short distances if fish remain at the same point within the sound field for long periods of time (12 h). The distances are farther for the MODU, and smallest for the FPSO without DP (Table 49).

For offtake operations, recoverable injury and temporary impairment could happen if fish remain within planar distances of <20 m and 40 m, respectively, from the FPSO or the OSV thrusters. There is no increased risk to fish from aggregate scenarios, with ranges to thresholds from the individual sources unchanged.

6. Glossary

1/3-octave
One third of an octave. Note: A one-third octave is approximately equal to one decidecade (1/3 oct ≈ 1.003 ddec; ISO 2017).

1/3-octave-band
Frequency band whose bandwidth is one one-third octave. Note: The bandwidth of a one-third octave-band increases with increasing centre frequency.

absorption
The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

acoustic impedance
The ratio of the sound pressure in a medium to the rate of alternating flow of the medium through a specified surface due to the sound wave.

ambient noise
All-encompassing sound at a given place, usually a composite of sound from many sources near and far (ANSI S1.1-1994 R2004), e.g., shipping vessels, seismic activity, precipitation, sea ice movement, wave action, and biological activity.

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

Auditory frequency weighting (auditory weighting function, frequency-weighting function)
The process of band-pass filtering sounds to reduce the importance of inaudible or less-audible frequencies for individual species or groups of species of aquatic mammals (ISO 2017). One example is M-weighting introduced by Southall et al. (2007) to describe "Generalized frequency weightings for various functional hearing groups of marine mammals, allowing for their functional bandwidths and appropriate in characterizing auditory effects of strong sounds".

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

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

bar
Unit of pressure equal to 100 kPa, which is approximately equal to the atmospheric pressure on Earth at sea level. 1 bar is equal to 10^5 Pa or 10^{11} μPa.

broadband sound level
The total sound pressure level measured over a specified frequency range. If the frequency range is unspecified, it refers to the entire measured frequency range.

broadside direction
Perpendicular to the travel direction of a source. Compare with endfire direction.

cavitation
A rapid formation and collapse of vapor cavities (i.e., bubbles or voids) in water, most often caused by a rapid change in pressure. Fast-spinning vessel propellers typically cause cavitation, which creates a lot of noise.

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

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

continuous sound
A sound whose sound pressure level remains above ambient sound during the observation period (ANSI/ASA S1.13-2005 R2010). A sound that gradually varies in intensity with time, for example, sound from a marine vessel.

decade
Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 2006).

decidecade
One tenth of a decade (ISO 2017). Note: An alternative name for decidecade (symbol ddec) is "one-tenth decade". A decidecade is approximately equal to one third of an octave (1 ddec ≈ 0.3322 oct) and for this reason is sometimes referred to as a "one-third octave".

decidecade band
Frequency band whose bandwidth is one decidecade. Note: The bandwidth of a decidecade band increases with increasing centre frequency.

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

endfire direction
Parallel to the travel direction of a source. See also broadside direction.

ensonified
Exposed to sound.

far-field
The zone where, to an observer, sound originating from an array of sources (or a spatially distributed source) appears to radiate from a single point. The distance to the acoustic far-field increases with frequency.

fast-average sound pressure level
The time-averaged sound pressure levels calculated over the duration of a pulse (e.g., 90%-energy time window), using the leaky time integrator from Plomp and Bouman (1959) and a time constant of 125 ms. Typically used only for pulsed sounds.

fast Fourier transform (FFT)
A computationally efficiently algorithm for computing the discrete Fourier transform.

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

hearing group
Groups of marine mammal species with similar hearing ranges. Commonly defined functional hearing groups include low-, mid-, and high-frequency cetaceans, pinnipeds in water, and pinnipeds in air.

geoacoustic
Relating to the acoustic properties of the seabed.

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

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

high-frequency (HF) cetacean
The functional cetacean hearing group that represents those odontocetes (toothed whales) specialized for hearing high frequencies.

intermittent sound
A level of sound that abruptly drops to the background noise level several times during the observation period.

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

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

masking
Obscuring of sounds of interest by sounds at similar frequencies.

median
The 50th percentile of a statistical distribution.

mid-frequency (MF) cetacean
The functional cetacean hearing group that represents those odontocetes (toothed whales) specialized for mid-frequency hearing.

Monte Carlo simulation
The method of investigating the distribution of a non-linear multi-variate function by random sampling of all of its input variable distributions.

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

non-impulsive sound
Sound that is broadband, narrowband or tonal, brief or prolonged, continuous or intermittent, and typically does not have a high peak pressure with rapid rise time (typically only small fluctuations in decibel level) that impulsive signals have (ANSI/ASA S3.20-1995 R2008). For example, marine vessels, aircraft, machinery, construction, and vibratory pile driving (NIOSH 1998, NOAA 2015).

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

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

otariid
A common term used to describe members of the Otariidae, eared seals, commonly called sea lions and fur seals. Otariids are adapted to a semi-aquatic life; they use their large fore flippers for propulsion. Their ears distinguish them from phocids. Otariids are one of the three main groups in the superfamily Pinnipedia; the other two groups are phocids and walrus.

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

particle velocity
The physical speed of a particle in a material moving back and forth in the direction of the pressure wave. Unit: metre per second (m/s). Symbol: v.

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

peak-to-peak pressure level (PK-PK)
The difference between the maximum and minimum instantaneous pressure levels. Unit: decibel (dB).

percentile level, exceedance
The sound level exceeded n% of the time during a measurement.

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

phocid
A common term used to describe all members of the family Phocidae. These true/earless seals are more adapted to in-water life than are otariids, which have more terrestrial adaptations. Phocids use their hind flippers to propel themselves. Phocids are one of the three main groups in the superfamily Pinnipedia; the other two groups are otariids and walrus.

phocid pinnipeds in water (PPW)
The functional pinniped hearing group that represents true/earless seals under water.

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

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

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

pressure, hydrostatic
The pressure at any given depth in a static liquid that is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid. Unit: pascal (Pa).

received level (RL)
The sound level measured (or that would be measured) at a defined location.

rms
root-mean-square.

signature
Pressure signal generated by a source.

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

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

sound exposure level (SEL)
A cumulative measure related to the sound energy in one or more pulses. Unit: dB re 1 $\mu Pa^2 \cdot s$. SEL is expressed over the summation period (e.g., per-pulse SEL [for airguns], single-strike SEL [for pile drivers], 24-hour SEL).

sound exposure spectral density
Distribution as a function of frequency of the time-integrated squared sound pressure per unit bandwidth of a sound having a continuous spectrum (ANSI S1.1-1994 R2004). Unit: $\mu Pa^2 \cdot s/Hz$.

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

sound intensity
Sound energy flowing through a unit area perpendicular to the direction of propagation per unit time.

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

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 μPa) and the unit for SPL is dB re 1 μPa^2:

$$L_p = 10 \log_{10}(p^2/p_0^2) = 20 \log_{10}(p/p_0)$$

Unless otherwise stated, SPL refers to the root-mean-square (rms) pressure level. See also 90% sound pressure level and fast-average sound pressure level. Non-rectangular time window functions may be applied during calculation of the rms value, in which case the SPL unit should identify the window type.

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

source level (SL)
The sound level measured in the far-field and scaled back to a standard reference distance of 1 metre from the acoustic centre of the source. Unit: dB re 1 μPa·m (pressure level) or dB re 1 $\mu Pa^2 \cdot s \cdot m$ (exposure level).

spectrogram
A visual representation of acoustic amplitude compared with time and frequency.

spectrum
An acoustic signal represented in terms of its power, energy, mean-square sound pressure, or sound exposure distribution with frequency.

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

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

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

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Appendix A. Acoustic Metrics

A.1. Pressure Related Acoustic Metrics

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa. Because the perceived loudness of sound, especially impulsive noise such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate noise and its effects on marine life. We provide specific definitions of relevant metrics used in the accompanying report. Where possible we follow the ANSI and ISO standard definitions and symbols for sound metrics, but these standards are not always consistent.

The zero-to-peak sound pressure level (PK; L_{pk}; $L_{p,pk}$; dB re 1 μPa), is the maximum instantaneous sound pressure level in a stated frequency band attained by an acoustic pressure signal, $p(t)$:

$$L_{p,pk} = 20\log_{10}\left[\frac{\max(|p(t)|)}{p_0}\right] \tag{A-1}$$

PK is often included as a criterion for assessing whether a sound is potentially injurious; however, because it does not account for the duration of a noise event, it is generally a poor indicator of perceived loudness.

The peak-to-peak sound pressure level (PK-PK; $L_{pk\text{-}pk}$; $L_{p,pk\text{-}pk}$; dB re 1 μPa) is the difference between the maximum and minimum instantaneous sound pressure levels in a stated frequency band attained by an impulsive sound, $p(t)$:

$$L_{p,pk-pk} = 10\log_{10}\left\{\frac{[\max(p(t)) - \min(p(t))]^2}{p_0^2}\right\} \tag{A-2}$$

The sound pressure level (SPL; L_p; dB re 1 μPa) is the rms pressure level in a stated frequency band over a specified time window (T, s) containing the acoustic event of interest. It is important to note that SPL always refers to a rms pressure level and therefore not instantaneous pressure:

$$L_p = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_0^2\right) \tag{A-3}$$

The SPL represents a nominal effective continuous sound over the duration of an acoustic event, such as the emission of one acoustic pulse, a marine mammal vocalization, the passage of a vessel, or over a fixed duration. Because the window length, T, is the divisor, events with similar sound exposure level (SEL) but more spread out in time have a lower SPL. A fixed window length of 0.125 s (critical duration defined by Tougaard et al. (2015)) is used in this study for impulsive sounds.

The sound exposure level (SEL; L_E; $L_{E,p}$; dB re 1 μPa^2·s) is a measure related to the acoustic energy contained in one or more acoustic events (N). The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (T):

$$L_E = 10\log_{10}\left(\int_T p^2(t)dt \Big/ T_0 p_0^2\right) \tag{A-4}$$

where T_0 is a reference time interval of 1 s. The SEL continues to increase with time when non-zero pressure signals are present. It therefore can be construed as a dose-type measurement, so the integration time used must be carefully considered in terms of relevance for impact to the exposed recipients.

SEL can be calculated over periods with multiple acoustic events or over a fixed duration. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, SEL can be computed by summing (in linear units) SEL of the *N* individual events:

$$L_{E,N} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right). \quad \text{(A-5)}$$

If applied, the frequency weighting of an acoustic event should be specified, as in the case of weighted SEL (e.g., $L_{E,LFC,24h}$; Appendix A.3). The use of fast, slow, or impulse exponential-time-averaging or other time-related characteristics should else be specified.

A.2. Marine Mammal Impact Criteria

It has been long recognised that marine mammals can be adversely affected by underwater anthropogenic noise. For example, Payne and Webb (1971) suggested that communication distances of fin whales are reduced by shipping sounds. Subsequently, similar concerns arose regarding effects of other underwater noise sources and the possibility that impulsive sources—primarily airguns used in seismic surveys—could cause auditory injury. This led to a series of workshops held in the late 1990s, conducted to address acoustic mitigation requirements for seismic surveys and other underwater noise sources (NMFS 1998, ONR 1998, Nedwell and Turnpenny 1998, HESS 1999, Ellison and Stein 1999). In the years since these early workshops, a variety of thresholds have been proposed for both injury and disturbance. The following sections summarize the recent development of thresholds; however, this field remains an active research topic.

A.2.1. Injury

In recognition of shortcomings of the SPL-only based injury criteria, in 2005 NMFS sponsored the Noise Criteria Group to review literature on marine mammal hearing to propose new noise exposure criteria. Some members of this expert group published a landmark paper (Southall et al. 2007) that suggested assessment methods similar to those applied for humans. The resulting recommendations introduced dual acoustic injury criteria for impulsive sounds that included peak pressure level thresholds and SEL_{24h} thresholds, where the subscripted 24h refers to the accumulation period for calculating SEL. The peak pressure level criterion is not frequency weighted whereas SEL_{24h} is frequency weighted according to one of four marine mammal species hearing groups: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively) and Pinnipeds in Water (PINN). These weighting functions are referred to as M-weighting filters (analogous to the A-weighting filter for human; Appendix A.3). The SEL_{24h} thresholds were obtained by extrapolating measurements of onset levels of Temporary Threshold Shift (TTS) in belugas by the amount of TTS required to produce Permanent Threshold Shift (PTS) in chinchillas. The Southall et al. (2007) recommendations do not specify an exchange rate, which suggests that the thresholds are the same regardless of the duration of exposure (i.e., it implies a 3 dB exchange rate).

Wood et al. (2012) refined Southall et al.'s (2007) thresholds, suggesting lower injury values for LF and HF cetaceans while retaining the filter shapes. Their revised thresholds were based on TTS-onset levels in harbour porpoises from Lucke et al. (2009), which led to a revised impulsive sound PTS threshold for HF cetaceans of 179 dB re 1 µPa^2·s. Because there were no data available for baleen whales, Wood et al. (2012) based their recommendations for LF cetaceans on results obtained from MF cetacean studies. In particular they referenced Finneran and Schlundt (2010) research, which found mid-frequency cetaceans are more sensitive to non-impulsive sound exposure than Southall et al. (2007) assumed. Wood et al. (2012) thus recommended a more conservative TTS-onset level for LF cetaceans of 192 dB re 1 µPa^2·s.

As of 2017, an optimal approach is not apparent. There is consensus in the research community that an SEL-based method is preferable either separately or in addition to an SPL-based approach to assess the potential for injuries. In August 2016, after substantial public and expert input into three draft versions and based largely on the above-mentioned literature (NOAA 2013, 2015, 2016), NMFS finalised technical guidance for assessing the effect of anthropogenic sound on marine mammal hearing (NMFS 2016). The guidance describes injury criteria with new thresholds and frequency weighting functions for the five hearing groups described by Finneran and Jenkins (2012). The latest revision to this work was published in 2018 (NMFS 2018). Southall et al. (2019) revisited the interim criteria published in 2007; all noise exposure criteria in NMFS (2018) and Southall et al. (2019) are identical (for impulsive and non-impulsive sounds), however the mid-frequency cetaceans from NMFS (2018) are classified as high-frequency cetaceans in Southall et al. (2019), and high-frequency cetaceans from NMFS (2018) are classified as very-high-frequency cetaceans in Southall et al. (2019). This report continues to apply the terminology from NMFS (2018) for consistency with other projects.

A.3. Marine Mammal Frequency Weighting

The potential for noise to affect animals depends on how well the animals can hear it. Noises are less likely to disturb or injure an animal if they are at frequencies that the animal cannot hear well. An exception occurs when the sound pressure is so high that it can physically injure an animal by non-auditory means (i.e., barotrauma). For sound levels below such extremes, the importance of sound components at particular frequencies can be scaled by frequency weighting relevant to an animal's sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

A.3.1. Marine mammal frequency weighting functions

In 2015, a U.S. Navy technical report by Finneran (2015) recommended new auditory weighting functions. The overall shape of the auditory weighting functions is similar to human A-weighting functions, which follows the sensitivity of the human ear at low sound levels. The new frequency-weighting function is expressed as:

$$G(f) = K + 10\log_{10}\left[\left(\frac{(f/f_{lo})^{2a}}{\left[1+(f/f_{lo})^2\right]^a\left[1+(f/f_{hi})^2\right]^b}\right)\right] \tag{A-6}$$

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid-, and high-frequency cetaceans, phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA's technical guidance that assesses noise impacts on marine mammals (NMFS 2016, NMFS 2018). Table A-1 lists the frequency-weighting parameters for each hearing group; Figure A-1 shows the resulting frequency-weighting curves.

Table A-1. Parameters for the auditory weighting functions used in this project as recommended by NMFS (2018).

Hearing group	a	b	f_{lo} (Hz)	f_{hi} (kHz)	K (dB)
LF cetaceans (baleen whales)	1.0	2	200	19,000	0.13
MF cetaceans (dolphins, plus toothed, beaked, and bottlenose whales)	1.6	2	8,800	110,000	1.20
HF cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* and *L. australis*)	1.8	2	12,000	140,000	1.36

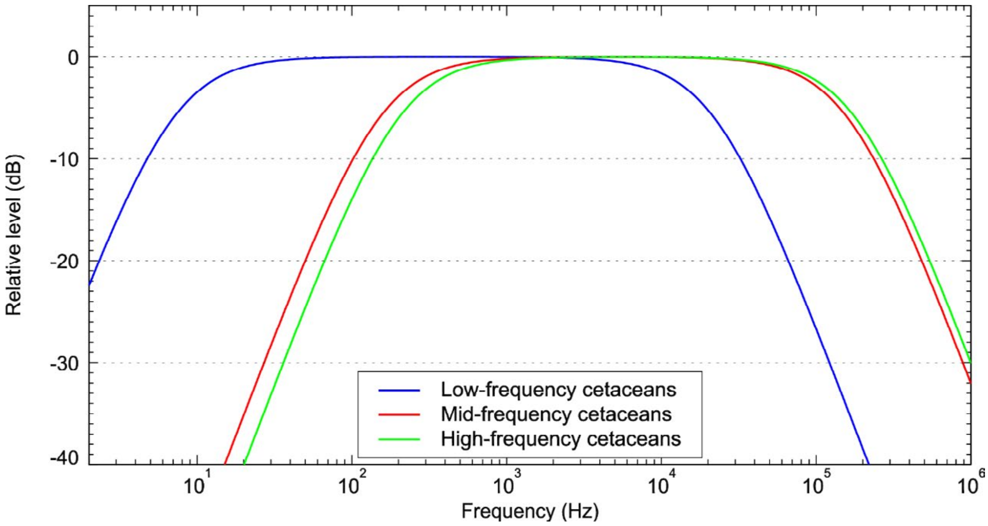


Figure A-1. Auditory weighting functions for functional marine mammal hearing groups as recommended by NMFS (2018).

Appendix B. Pile Driving Acoustic Source Model

A physical model of pile vibration and near-field sound radiation is used to calculate source levels of piles. The physical model employed in this study computes the underwater vibration and sound radiation of a pile by solving the theoretical equations of motion for axial and radial vibrations of a cylindrical shell. These equations of motion are solved subject to boundary conditions, which describe the forcing function of the hammer at the top of the pile and the soil resistance at the base of the pile (Figure B-1). Damping of the pile vibration due to radiation loading is computed for Mach waves emanating from the pile wall. The equations of motion are discretised using the finite difference (FD) method and are solved on a discrete time and depth mesh.

To model the sound emissions from the piles, the force of the pile driving hammers also had to be modelled. The force at the top of each pile was computed using the GRLWEAP 2010 wave equation model (GRLWEAP, Pile Dynamics 2010), which includes a large database of simulated hammers—both impact and vibratory—based on the manufacturer's specifications. The forcing functions from GRLWEAP were used as inputs to the FD model to compute the resulting pile vibrations.

The sound radiating from the pile itself is simulated using a vertical VSP array of discrete point sources. The point sources are centred on the pile axis. Their amplitudes are derived using an inverse technique, such that their collective particle velocity—calculated using a near-field wave-number integration model—matches the particle velocity in the water at the pile wall. The sound field propagating away from the vertical source VSP array is then calculated using a time-domain acoustic propagation model (FWRAM, Appendix E.2). MacGillivray (2014) describes the theory behind the physical model in more detail. The accuracy of JASCO's pile driving model has been verified by comparing its output against benchmark scenarios (Lippert et al. 2016) and detailed measurement programs (Austin et al. 2016, Denes et al. 2016, MacGillivray 2018).

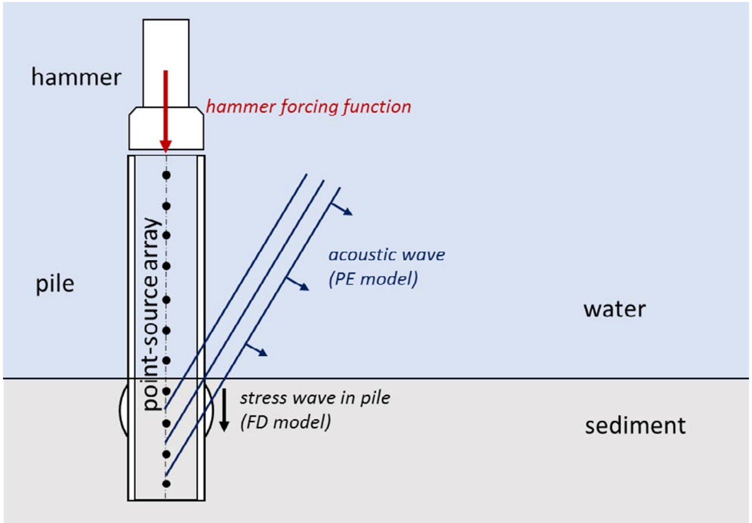


Figure B-1. Physical model geometry for impact driving of a cylindrical pile (vertical cross-section). The hammer forcing function is used with the finite difference (FD) model to compute the stress wave vibration in the pile. A vertical VSP array of point sources is used with the parabolic equation (PE) model to compute the acoustic waves that the pile wall radiates.

Appendix C. VSP Source

C.1. Airgun Array Source Model

The source levels and directivity of the seismic source were predicted with JASCO's Airgun Array Source Model (AASM). AASM includes low- and high-frequency modules for predicting different components of the seismic source spectrum. The low-frequency module is based on the physics of oscillation and radiation of airgun bubbles, as originally described by Ziolkowski (1970), that solves the set of parallel differential equations that govern bubble oscillations. Physical effects accounted for in the simulation include pressure interactions between airguns, port throttling, bubble damping, and generator-injector (GI) gun behaviour discussed by Dragoset (1984), Laws et al. (1990), and Landro (1992). A global optimisation algorithm tunes free parameters in the model to a large library of airgun source signatures.

While airgun signatures are highly repeatable at the low frequencies, which are used for seismic imaging, their sound emissions have a large random component at higher frequencies that cannot be predicted using a deterministic model. Therefore, AASM uses a stochastic simulation to predict the high-frequency (800−25,000 Hz) sound emissions of individual airguns, using a data-driven multiple-regression model. The multiple-regression model is based on a statistical analysis of a large collection of high quality seismic source signature data recently obtained from the Joint Industry Program (JIP) on Sound and Marine Life (Mattsson and Jenkerson 2008). The stochastic model uses a Monte-Carlo simulation to simulate the random component of the high-frequency spectrum of each airgun in an array. The mean high-frequency spectra from the stochastic model augment the low-frequency signatures from the physical model, allowing AASM to predict airgun source levels at frequencies up to 25,000 Hz.

AASM produces a set of "notional" signatures for each array element based on:

- Array layout
- Volume, operating depth, and firing pressure of each airgun
- Interactions between different airguns in the array

These notional signatures are the pressure waveforms of the individual airguns at a standard reference distance of 1 m; they account for the interactions with the other airguns in the array. The signatures are summed with the appropriate phase delays to obtain the far-field source signature of the entire array in all directions. This far-field array signature is filtered into 1/3-octave-bands to compute the source levels of the array as a function of frequency band and azimuthal angle in the horizontal plane (at the source depth), after which it is considered a directional point source in the far field.

A seismic array consists of many sources and the point source assumption is invalid in the near field where the array elements add incoherently. The maximum extent of the near field of an array (R_{nf}) is:

$$R_{\mathrm{nf}} < \frac{l^2}{4\lambda} \quad \text{(C-1)}$$

where λ is the sound wavelength and l is the longest dimension of the array (Lurton 2002, §5.2.4). For example, a seismic source length of l = 21 m yields a near-field range of 147 m at 2 kHz and 7 m at 100 Hz. Beyond this R_{nf} range, the array is assumed to radiate like a directional point source and is treated as such for propagation modelling.

The interactions between individual elements of the array create directionality in the overall acoustic emission. Generally, this directionality is prominent mainly at frequencies in the mid-range between tens of hertz to several hundred hertz. At lower frequencies, with acoustic wavelengths much larger than the inter-airgun separation distances, the directionality is small. At higher frequencies, the pattern of lobes is too finely spaced to be resolved and the effective directivity is less.

C.2. VSP Source Parameters

The layout of the seismic source is provided in Figure F-1. Details of the airgun parameters are provided in Table C-1.

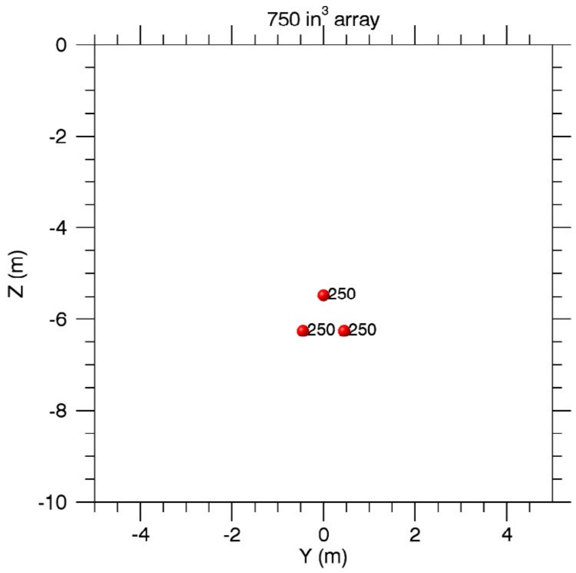


Figure C-1. Layout of the modelled 750 in^3 seismic source array. Operational depth is 6 m. The labels indicate the firing volume (in cubic inches) for each airgun. Also see Table C-1.

Table C-1. Layout of the modelled 750 in^3 seismic source array. Operational depth is 6 m. Firing pressure for all guns is 1800 psi. Also see Figure C-1.

Gun	x (m)	y (m)	z (m)	Volume (in^3)
1	0	0	5.48	250
2	0	-0.45	6.26	250
3	0	0.45	6.26	250

C.3. Array Source Levels and Directivity

Figure C-2 shows the broadside (perpendicular to the tow direction), endfire (parallel to the operational direction), and vertical overpressure signature and corresponding power spectrum levels for the 750 in^3 array (Appendix C.2). Horizontal 1/3-octave-band source levels shown as a function of band centre frequency and azimuth (Figure C-3) indicate that this array is mainly isotropic.

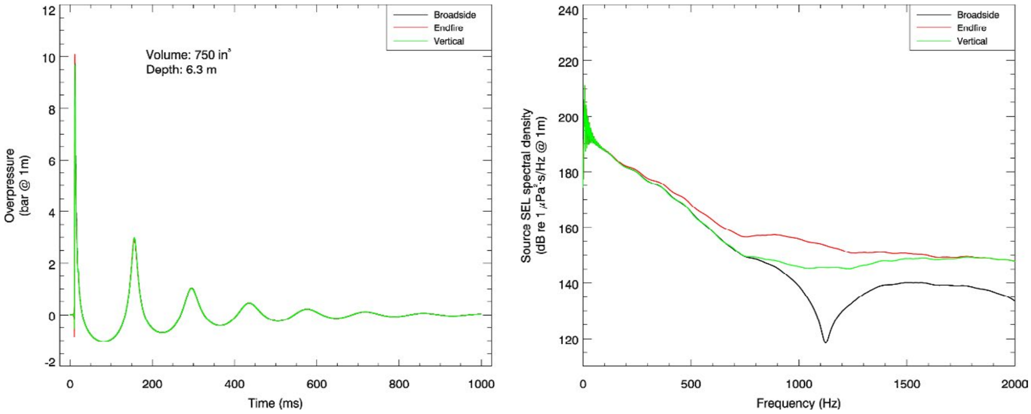


Figure C-2. Predicted source level details for the 750 in^3 array at a 6 m operational depth.(Left) the overpressure signature and (right) the power spectrum for in-plane horizontal (broadside), perpendicular (endfire), and vertical directions.

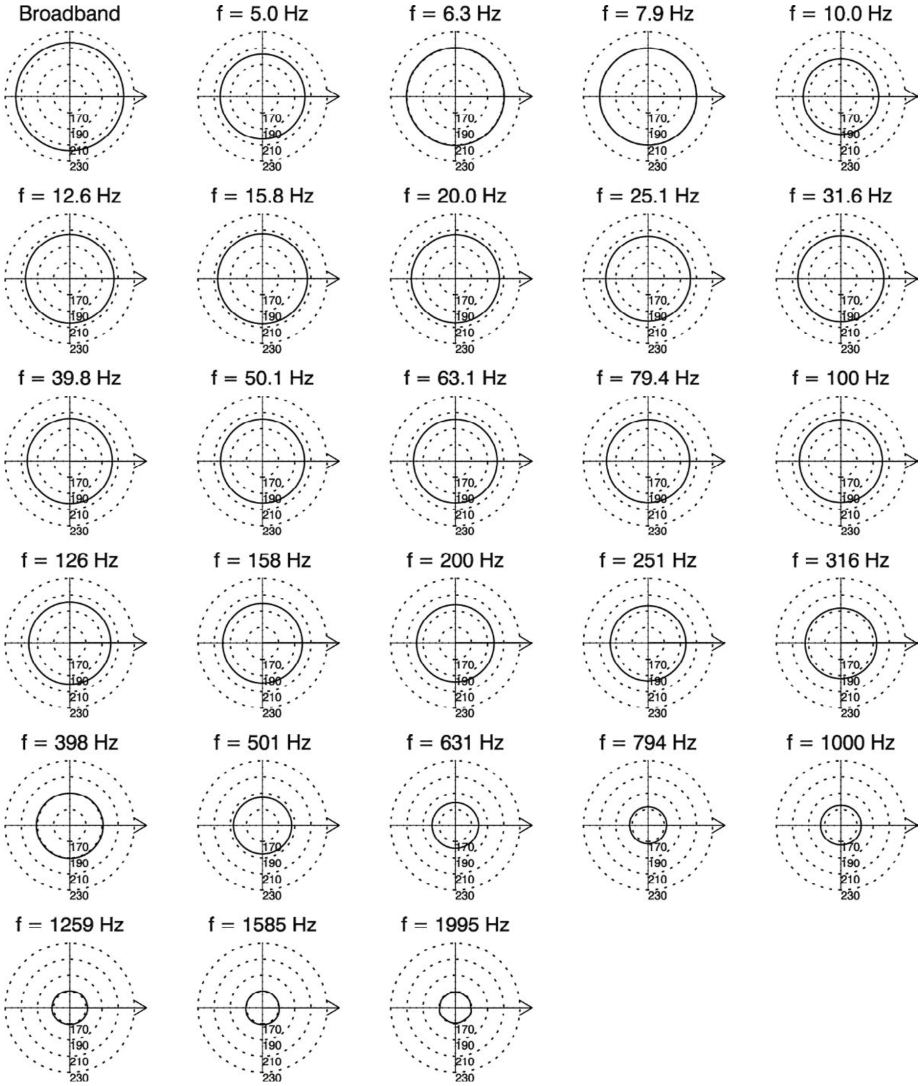


Figure C-3. Directionality of the predicted horizontal source levels for the 750 in^3 seismic source array, 10 Hz to 2 kHz. Source levels (in dB re 1 $\mu Pa^2 \cdot s\ m^2$) are shown as a function of azimuth for the centre frequencies of the 1/3-octave-bands modelled; frequencies are shown above the plots. The perpendicular direction to the frame is to the right. Operational depth is 6 m.

Appendix D. Thruster Source Level Estimation

Underwater sound that radiates from vessels is produced mainly by propeller and thruster cavitation, with a smaller fraction of sound produced by sound transmitted through the hull, such as by engines, gearing, and other mechanical systems. Sound levels tend to be the highest when thrusters are used to position the vessel and when the vessel is transiting at high speeds. A vessel's sound signature depends on the vessel's size, power output, propulsion system, and the design characteristics of the given system (e.g., blade shape and size). A vessel produces broadband acoustic energy with most of the energy emitted below a few kilohertz. Sound from onboard machinery, particularly sound below 200 Hz, dominates the sound spectrum before cavitation begins—normally around 8–12 knots on many commercial vessels (Spence et al. 2007). Under higher speeds and higher propulsion system load, the acoustic output from the cavitation processes on the propeller blades dominates other sources of sound on the vessel such as machinery or hull vibration (Leggat et al. 1981).

A vessel equipped with propellers/thrusters has two primary sources of sound that propagate from the unit: the machinery and the propellers. For thrusters operating in the heavily loaded conditions, the acoustic energy generated by the cavitation processes on the propeller blades dominates (Leggat et al. 1981). The sound power from the propellers is proportional to the number of blades, the propeller diameter, and the propeller tip speed.

Based on an analysis of acoustic data, Ross (1976) provided the following formula for the sound levels from a vessel's propeller, operating in calm, open ocean conditions:

$$L_{100} = 155 + 60\log(u/25) + 10\log(B/4)\ , \qquad \text{(D-1)}$$

where L_{100} is the spectrum level at 100 Hz, u is the propeller tip speed (m/s), and B is the number of propeller blades. Equation D-1 gives the total energy produced by the propeller cavitation at frequencies between 100 Hz and 10 kHz. This equation is valid for a propeller tip speed between 15 and 50 m/s. The spectrum is assumed to be flat below 100 Hz. Its level is assumed to fall off at a rate of −6 dB per octave above 100 Hz (Figure D-1).

Another method of predicting the source level of a propeller was suggested by Brown (1977). For propellers operating in heavily loaded conditions, the formula for the sound spectrum level is:

$$\mathrm{SL}_B = 163 + 40\log D + 30\log N + 10\log B + 20\log f + 10\log(A_c/A_D)\ , \qquad \text{(D-2)}$$

where D is the propeller diameter (m), N is the propeller revolution rate per second, B is the number of blades, A_C is the area of the blades covered by cavitation, and A_D is the total propeller disc area. Similar to Ross's approach, the spectrum below 100 Hz is assumed to be flat. The tests with a naval propeller operating at off-design heavily loaded conditions showed that Equation D-2 should be used with a value of $(A_c/A_D) = 1$ (Leggat et al. 1981).

The combined source level for multiple thrusters operating together can be estimated using the formula:

$$\mathrm{SL}_{\mathrm{total}} = 10\log_{10}\sum_i 10^{\frac{SL_i}{10}}, \qquad \text{(D-3)}$$

where $\mathrm{SL}_{1,\ldots,N}$ are the source levels of individual thrusters. If the vessel is equipped with the same type of thrusters, the combined source level can be estimated using the formula:

$$\mathrm{SL}_N = \mathrm{SL} + 10\log N \qquad \text{(D-4)}$$

where N is the total number of thrusters of the same type.

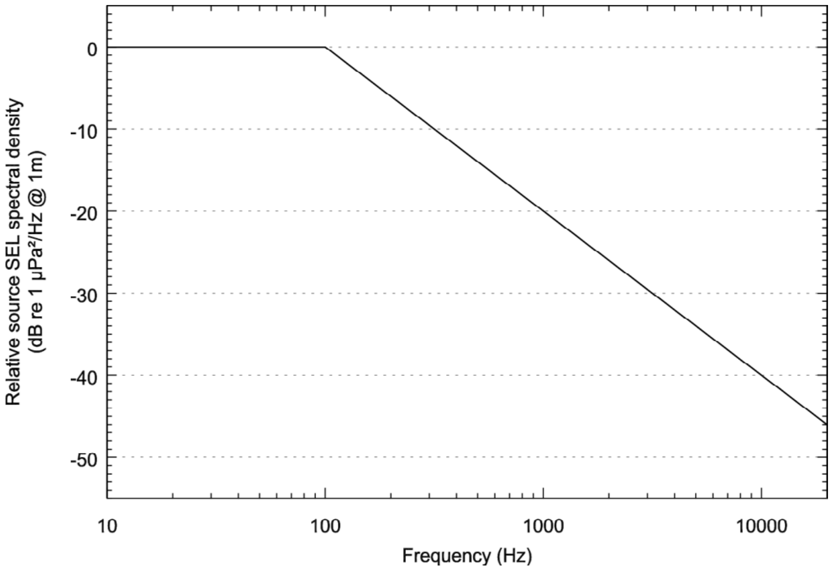


Figure D-1. Estimated sound spectrum from cavitating propeller (Leggat et al. 1981).

Appendix E. Sound Propagation Models

E.1. Transmission Loss

The propagation of sound through the environment was modelled by predicting the acoustic transmission loss—a measure, in decibels, of the decrease in sound level between a source and a receiver some distance away. Geometric spreading of acoustic waves is the predominant way by which transmission loss occurs. Transmission loss also happens when the sound is absorbed and scattered by the seawater, and absorbed scattered, and reflected at the water surface and within the seabed. Transmission loss depends on the acoustic properties of the ocean and seabed; its value changes with frequency.

If the acoustic source level (SL), expressed in dB re 1 μPa^{2}m^2, and transmission loss (TL), in units of dB, at a given frequency are known, then the received level (RL) at a receiver location can be calculated in dB re 1 μPa by:

$$\mathrm{RL} = \mathrm{SL} - \mathrm{TL} \quad \text{(E-1)}$$

E.2. Noise Propagation with FWRAM

For impulsive sounds from impact pile driving, time-domain representations of the pressure waves generated in the water are required to calculate SPL and peak pressure level. Furthermore, the pile must be represented as a distributed source to accurately characterise vertical directivity effects in the near-field zone. For this study, synthetic pressure waveforms were computed using JASCO's Full Waveform Range-dependent Acoustic Model (FWRAM). FWRAM computes acoustic propagation via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for an elastic seabed (Zhang and Tindle 1995). The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). FWRAM accounts for the additional reflection loss at the seabed due to partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. FWRAM incorporates the following site-specific environmental properties: a modelled area bathymetric grid, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

FWRAM computes pressure waveforms via Fourier synthesis of the modelled acoustic transfer function in closely spaced frequency bands. FWRAM employs the VSP array starter method to accurately model sound propagation from a spatially distributed source (MacGillivray and Chapman 2012).

Synthetic pressure waveforms from pile driving strikes were modelled and post-processed, after applying a travel time correction, to calculate standard SPL, SEL and PK metrics versus range and depth from the source.

E.3. MONM-BELLHOP

Long-range sound fields were computed using JASCO's Marine Operations Noise Model (MONM). Compared to VSTACK, MONM less accurately predicts steep-angle propagation for environments with higher shear speed but is well suited for effective longer-range estimation. This model computes sound propagation at frequencies of 10 Hz to 1.6 kHz via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed (Zhang and Tindle 1995). MONM computes sound propagation at frequencies > 1.6 kHz via the BELLHOP Gaussian beam acoustic ray-trace model (Porter and Liu 1994).

The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). MONM accounts for the additional reflection loss at the seabed, which results from partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. MONM incorporates the following site-specific environmental properties: a bathymetric grid of the modelled area, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

This version of MONM accounts for sound attenuation due to energy absorption through ion relaxation and viscosity of water in addition to acoustic attenuation due to reflection at the medium boundaries and internal layers (Fisher and Simmons 1977). The former type of sound attenuation is significant for frequencies higher than 5 kHz and cannot be neglected without noticeably affecting the model results.

MONM computes acoustic fields in three dimensions by modelling transmission loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as N×2-D. These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding N = 360°/$\Delta\theta$ number of planes (Figure E-1).

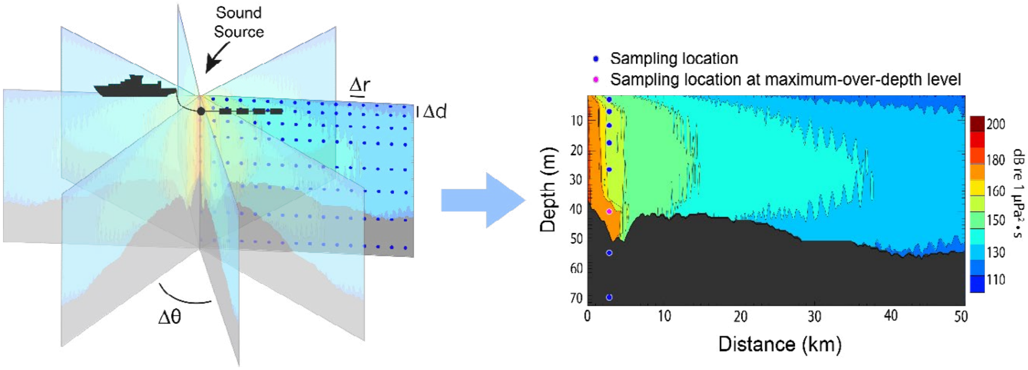


Figure E-1. The N×2-D and maximum-over-depth modelling approach used by MONM.

MONM treats frequency dependence by computing acoustic transmission loss at the centre frequencies of 1/3-octave-bands. Sufficiently many 1/3-octave-bands, starting at 10 Hz, are modelled to include most of the acoustic energy emitted by the source. At each centre frequency, the transmission loss is modelled within each of the N vertical planes as a function of depth and range from the source. The 1/3-octave-band received per-pulse SEL are computed by subtracting the band transmission loss values from the directional source level in that frequency band. Composite broadband received per-pulse SEL are then computed by summing the received 1/3-octave-band levels.

The received per-pulse (VSP source) or per-second vessel (MODU, FPSO, and OSV sources) SEL sound field within each vertical radial plane is sampled at various ranges from the source, generally with a fixed radial step size. At each sampling range along the surface, the sound field is sampled at various depths, with the step size between samples increasing with depth below the surface. The step sizes are chosen to provide increased coverage near the depth of the source and at depths of interest in terms of the sound speed profile. For areas with deep water, sampling is not performed at depths beyond those reachable by marine mammals. The received per-pulse or per-second SEL at a surface sampling location is taken as the maximum value that occurs over all samples within the water column, i.e., the maximum-over-depth received per-pulse SEL. These maximum-over-depth per-pulse SEL are presented as colour contours around the source.

An inherent variability in measured sound levels is caused by temporal variability in the environment and the variability in the signature of repeated acoustic impulses (sample sound source verification results is presented in Figure E-2). While MONM’s predictions correspond to the averaged received levels, cautionary estimates of the threshold radii are obtained by shifting the best fit line (solid line, Figure E-2) upward so that the trend line encompasses 90% of all the data (dashed line, Figure E-2).

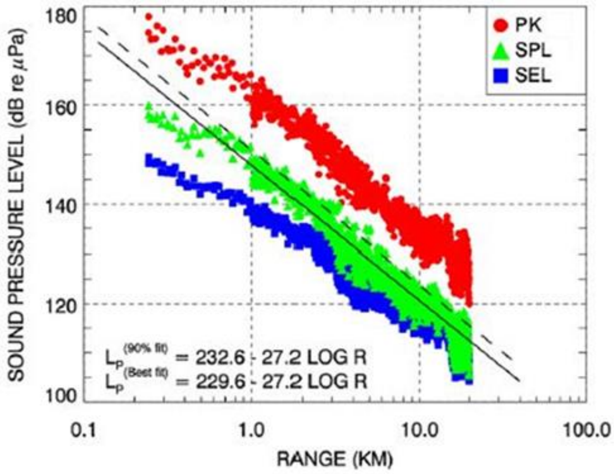


Figure E-2. PK and SPL and per-pulse SEL versus range from a 20 in^3 seismic source. Solid line is the least squares best fit to SPL. Dashed line is the best fit line increased by 3.0 dB to exceed 90% of all SPL values (90th percentile fit) (Ireland et al. 2009, Figure 10).

E.4. Wavenumber Integration Model

Sound pressure levels near the seismic source were modelled using JASCO's VSTACK wavenumber integration model. VSTACK computes synthetic pressure waveforms versus depth and range for arbitrarily layered, range-independent acoustic environments using the wavenumber integration approach to solve the exact (range-independent) acoustic wave equation. This model is valid over the full angular range of the wave equation and can fully account for the elasto-acoustic properties of the sub-bottom. Wavenumber integration methods are extensively used in the field of underwater acoustics and seismology where they are often referred to as reflectivity methods or discrete wavenumber methods. VSTACK computes sound propagation in arbitrarily stratified water and seabed layers by decomposing the outgoing field into a continuum of outward-propagating plane cylindrical waves. Seabed reflectivity in the model is dependent on the seabed layer properties: compressional and shear wave speeds, attenuation coefficients, and layer densities. The output of the model can be post-processed to yield estimates of the SEL, SPL, and PK.

VSTACK accurately predicts steep-angle propagation in the proximity of the source, but it is computationally slow at predicting sound pressures at large distances due to the need for smaller wavenumber steps with increasing distance. Additionally, VSTACK assumes range-invariant bathymetry with a horizontally stratified medium (i.e., a range-independent environment) which is azimuthally symmetric about the source. VSTACK is thus best suited to modelling the sound field near the source.

Appendix F. Methods and Parameters

This section describes the specifications of the seismic source that was used at all sites and the environmental parameters used in the propagation models.

F.1. Estimating Range to Thresholds Levels

Sound level contours were calculated based on the underwater sound fields predicted by the propagation models, sampled by taking the maximum value over all modelled depths above the sea floor for each location in the modelled region. The predicted distances to specific levels were computed from these contours. Two distances relative to the source are reported for each sound level: 1) R_{max}, the maximum range to the given sound level over all azimuths, and 2) $R_{95\%}$, the range to the given sound level after the 5% farthest points were excluded (see examples in Figure F-1).

The $R_{95\%}$ is used because sound field footprints are often irregular in shape. In some cases, a sound level contour might have small protrusions or anomalous isolated fringes. This is demonstrated in the image in Figure F-1(a). In cases such as this, where relatively few points are excluded in any given direction, R_{max} can misrepresent the area of the region exposed to such effects, and $R_{95\%}$ is considered more representative. In strongly asymmetric cases such as shown in Figure F-1(b), on the other hand, $R_{95\%}$ neglects to account for significant protrusions in the footprint. In such cases R_{max} might better represent the region of effect in specific directions. Cases such as this are usually associated with bathymetric features affecting propagation. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the non-uniformity of the acoustic environment.

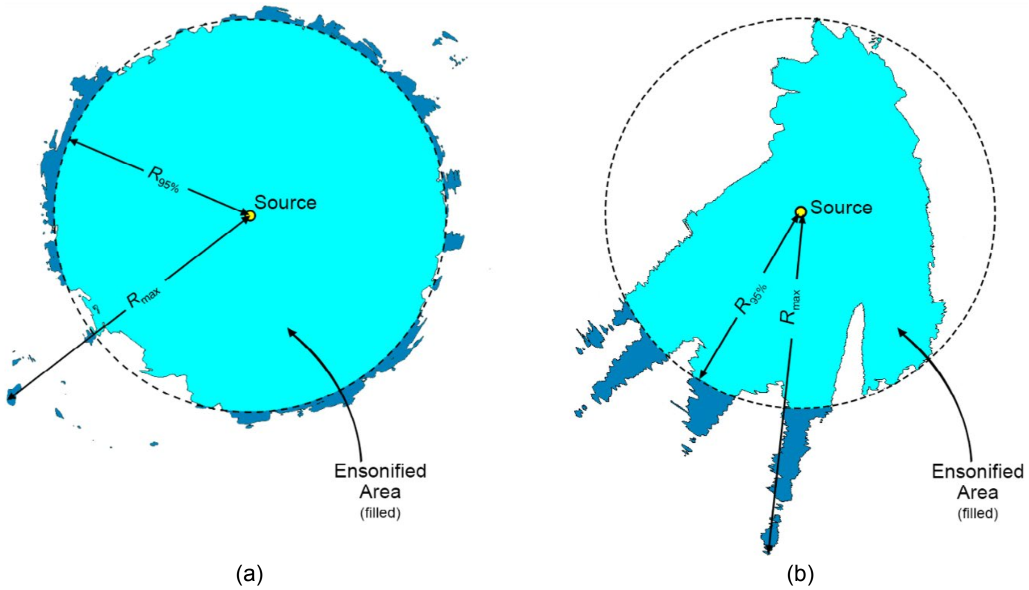
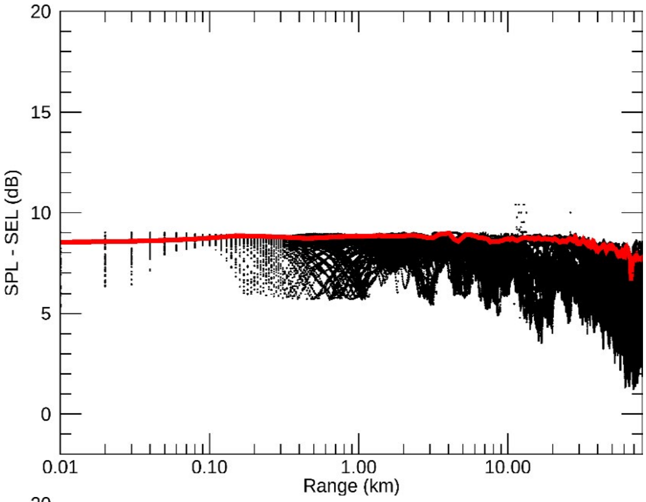


Figure F-1. Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ ranges shown for two different scenarios. (a) Largely symmetric sound level contour with small protrusions. (b) Strongly asymmetric sound level contour with long protrusions. Light blue indicates the ensonified areas bounded by $R_{95\%}$; darker blue indicates the areas outside this boundary which determine R_{max}.

F.2. Estimating SPL from Modelled SEL Results

The per-pulse SEL of sound pulses is an energy-like metric related to the dose of sound received over a pulse's entire duration. The pulse SPL on the other hand, is related to its intensity over a specified time interval. Seismic pulses typically lengthen in duration as they propagate away from their source, due to seafloor and surface reflections, and other waveguide dispersion effects. The changes in pulse length, and therefore the time window considered, affect the numeric relationship between SPL and SEL. This study has applied a fixed window duration to calculate SPL (T_{fix} = 125 ms; see Appendix A.1), as implemented in Martin et al. (2017b). Full-waveform modelling was used to estimate SPL, but this type of modelling is computationally intensive, and can be prohibitively time consuming when run at high spatial resolution over large areas.

For the current study, FWRAM (Appendix E.2) was used to model synthetic seismic pulses over the frequency range 5–1024 Hz. This was performed along all broadside and endfire radials at two sites. FWRAM uses Fourier synthesis to recreate the signal in the time domain so that both the SEL and SPL from the source can be calculated. The differences between the SEL and SPL were extracted for all ranges and depths that corresponded to those generated from the high spatial-resolution results from MONM. A 125 ms fixed time window positioned to maximise the SPL over the pulse duration was applied. The resulting SEL -to-SPL offsets were averaged in 0.3 km range bins along each modelled radial and depth, and the 90th percentile was selected at each range to generate a generalised range-dependent conversion function for each site. The range- dependent conversion function was averaged between the two sites and applied to predicted per-pulse SEL results from MONM to model SPL values. Figure F-2 shows the conversion offsets for each site; the spatial variation is caused by changes in the received airgun pulse as it propagates from the source.



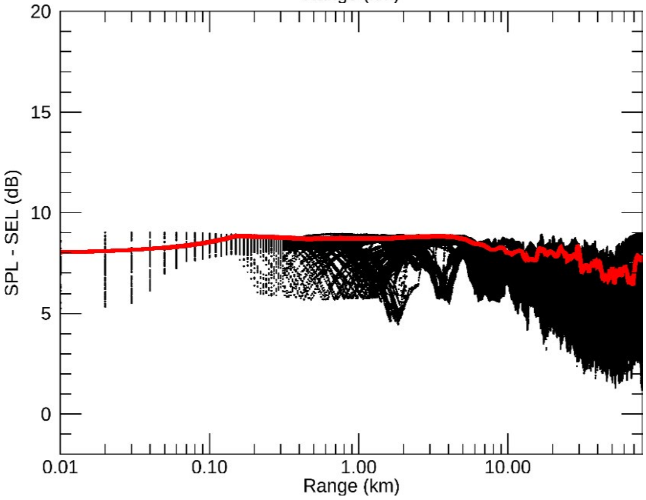


Figure F-2. Range-and-depth-dependent conversion offsets for converting SEL to SPL for seismic pulses for Torosa (top) and Brecknock (bottom) sites. Black dots are the modelled differences between SEL and SPL across different radials and receiver depths; the solid red line is the 90th percentile of the modelled differences at each range.

F.3. Environmental Parameters

F.3.1. Bathymetry

Water depths (Mean Sea Level) at close- and mid-range from the pile were provided by Woodside: within ~5–7 km from the pile, the data has a grid resolution of 2 m× 2 m, while data at the passage between Scott Reef South and Scott Reef Central has a grid resolution of 1 m× 1 m. Bathymetry data with grid resolution of 10 × 10 m was provided as far as 33 km northeast of the pile, and as far as 85 km southwest of the pile. Modelling was conducted along 80 km long radials emanating from the pile in all directions. For this reason, the high-resolution data was complemented using the Australian Bathymetry and Topography Grid, a 9 arc-second grid rendered for Australian waters (Whiteway 2009). The data were adjusted for an increase of 1.7 m in depth (Bureau of Meterology 2019), so the modelling results correspond to the most conservative propagation conditions at maximum tide at Scott Reef. Bathymetry data were re-gridded onto a Map Grid of Australia (MGA) coordinate projection (Zone 51) with a regular grid spacing of 50 × 50 m.

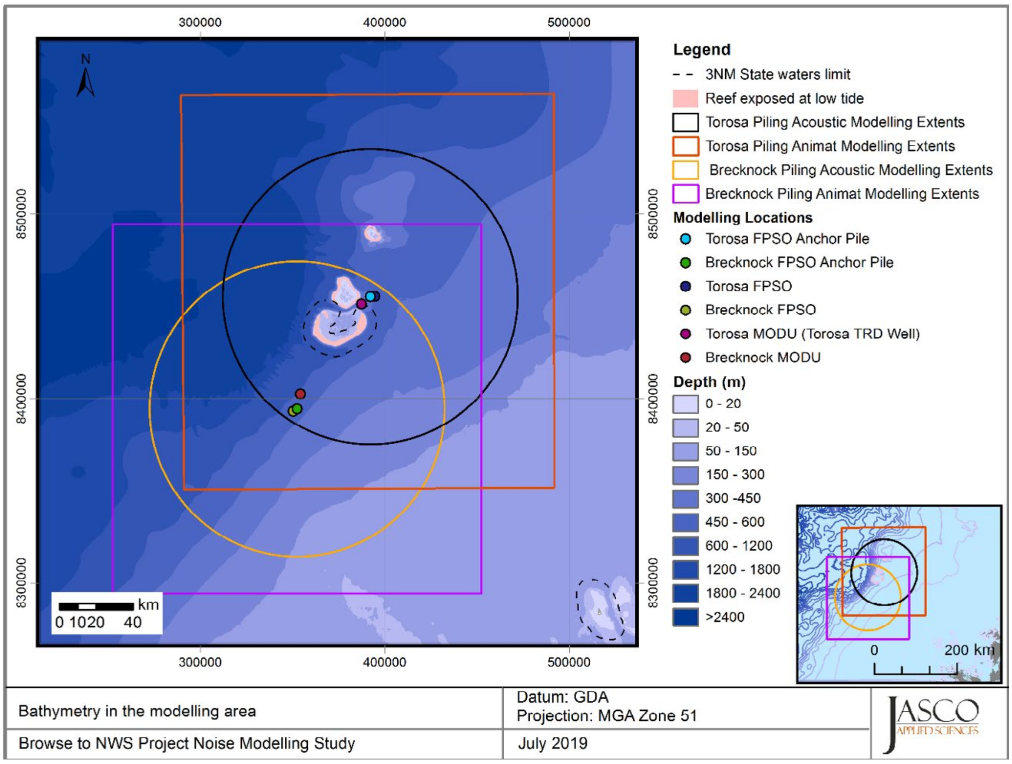


Figure F-3. Bathymetry in the modelled area.

F.3.2. Sound speed profile

The sound speed profile in the area was derived from temperature and salinity profiles from the U.S. Naval Oceanographic Office's *Generalized Digital Environmental Model V 3.0* (GDEM; Teague et al. 1990, Carnes 2009). GDEM provides an ocean climatology of temperature and salinity for the world's oceans on a latitude-longitude grid with 0.25° resolution, with a temporal resolution of one month, based on global historical observations from the U.S. Navy's Master Oceanographic Observational Data Set (MOODS). The climatology profiles include 78 fixed depth points to a maximum depth of 6800 m (where the ocean is that deep). The GDEM temperature-salinity profiles were converted to sound speed profiles according to Coppens (1981).

Mean monthly sound speed profiles were derived from the GDEM profiles at distances less than 76 km around the modelled site. The June sound speed profile is expected to be most favourable to longer-range sound propagation across the entire year. As such, June was selected for sound propagation modelling to ensure precautionary estimates of distances to received sound level thresholds. Figure F-4 shows the resulting profile, which was used as input to the sound propagation modelling.

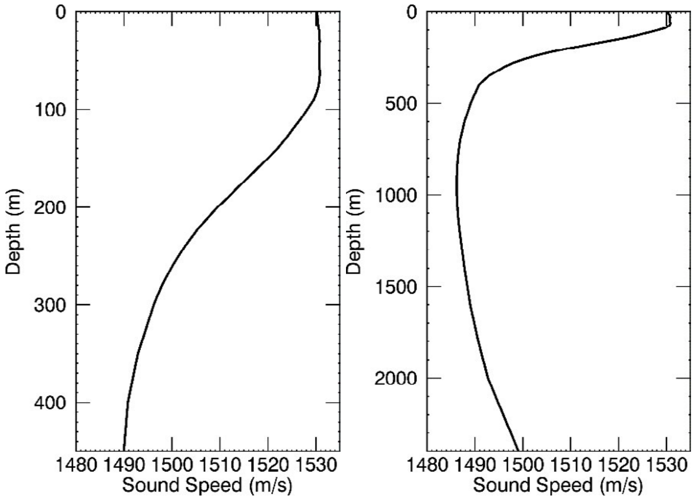


Figure F-4. The modelling sound speed profile corresponding to June: top 450 m (left) and full profile (right) Profiles are calculated from temperature and salinity profiles from *Generalized Digital Environmental Model* V 3.0 (GDEM; Teague et al. 1990, Carnes 2009).

F.3.3. Geoacoustics

As in previous acoustic studies in the area (Duncan 2014), the modelling area was divided into three seabed types (Figure F-5). A silt seabed typical of the continental slope was considered for the majority of the modelling area (Table F-1). A seabed consisting of coarse sand/gravel was used for areas in the vicinity of the reefs (Table F-2). Finally, the reefs were modelled as limestone (Table F-3), using the same equivalent fluid geoacoustic model as in Duncan et al (2014).

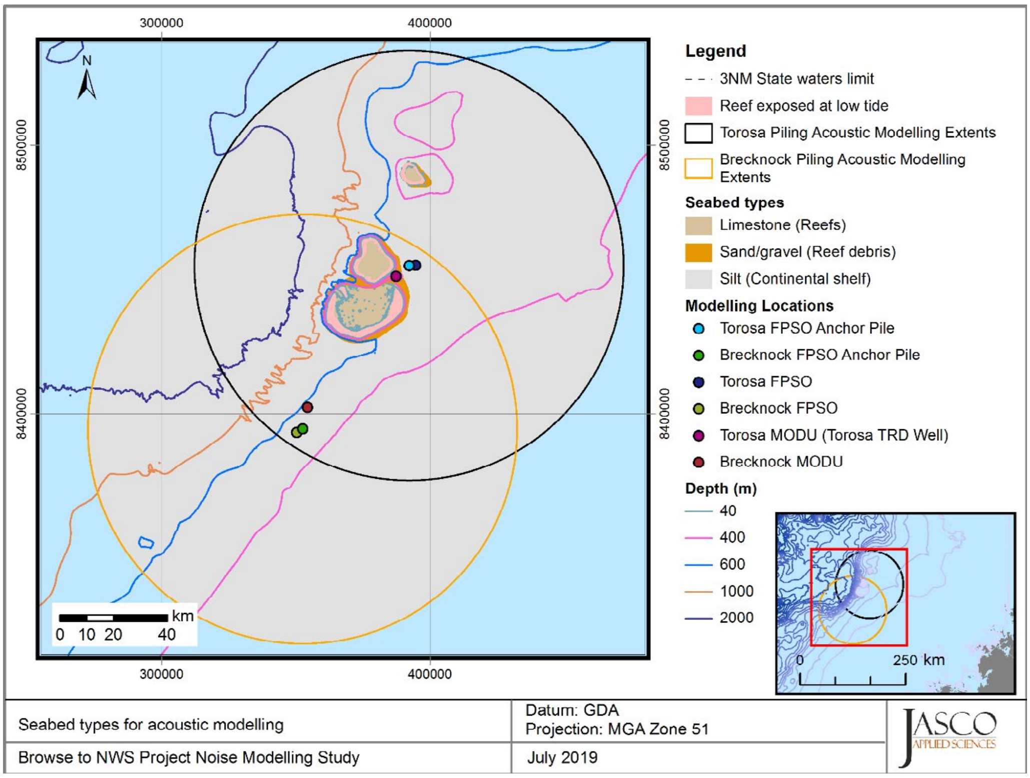


Figure F-5. Geographic boundaries of the seabed types considered in this study , following Duncan et al. (2014).

Table F-1. Continental slope geoacoustic profile. Within each depth range, each parameter varies linearly within the stated range. The compressional wave is the primary wave and the shear wave is the secondary wave.

Depth below seafloor (m)	Material	Density (g/cm³)	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0–50		1.70–1.75	1566–1627			
50–100		1.75–1.80	1627–1686			
100–150	Silt	1.80–1.85	1686–1742	1.0	210	1.5
150–200		1.85–1.90	1742–1795			
>200		1.90	1795			

Table F-2. Reef debris geoacoustic profile Within each depth range, each parameter varies linearly within the stated range. The compressional wave is the primary wave and the shear wave is the secondary wave.

Depth below seafloor (m)	Material	Density (g/cm³)	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0–50	Sand/gravel	1.80–1.85	1714–1782	0.6	300	2.0
50–100		1.85–1.90	1782–1847			
100–150		1.90–1.95	1847–1908			
150–200		1.95–2.00	1908–1967			
>200		2.00	1967			

Table F-3. Reef geoacoustic profile and equivalent fluid modelThe compressional wave is the primary wave and the shear wave is the secondary wave.

Depth below seafloor (m)	Material	Elastic model					Fluid equivalent		
		Density (g/cm³)	Compressional wave		Shear wave		Density (g/cm³)	Compressional wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)		Speed (m/s)	Attenuation (dB/λ)
>0	Limestone	2.4	3000	0.1	1500	0.2	2.4	1350	14

F.4. Model Validation Information

Predictions from JASCO's propagation models (MONM, FWRAM, and VSTACK) have been validated against experimental data from a number of underwater acoustic measurement programs conducted by JASCO globally, including the United States and Canadian Artic, Canadian and southern United States waters, Greenland, Russia and Australia (Hannay and Racca 2005, Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010, Racca et al. 2012a, Racca et al. 2012b, Matthews and MacGillivray 2013, Martin et al. 2015, Racca et al. 2015, Martin et al. 2017a, Martin et al. 2017b, Warner et al. 2017, MacGillivray 2018, McPherson et al. 2018, McPherson and Martin 2018).

In addition, JASCO has conducted measurement programs associated with a significant number of anthropogenic activities which have included internal validation of the modelling (including McCrodan et al. 2011, Austin and Warner 2012, McPherson and Warner 2012, Austin and Bailey 2013, Austin et al. 2013, Zykov and MacDonnell 2013, Austin 2014, Austin et al. 2015, Austin and Li 2016, Martin and Popper 2016).

Appendix G. Animal Movement and Exposure Modelling

To assess the risk of impacts from exposure, an estimate of received sound levels for the animals in the area during pile driving is required. The sound field may be complex, and the sound received by a moving animal is a function of where the animal is at any given time. The sound source is stationary, and acoustic modelling can be used to predict the 3-D sound field. The location and movement of animals within the sound field, however, is unknown. Realistic animal movement within the sound field can be simulated. Repeated random sampling (Monte Carlo method simulating many animals within the operations area) is used to estimate the sound exposure history of the population of simulated animals during the operation.

Monte Carlo methods provide a heuristic approach for determining the probability distribution function (PDF) of complex situations, such as animals moving in a sound field. The probability of an event's occurrence is determined by the frequency with which it occurs in the simulation. The greater the number of random samples, in this case the more simulated animals (animats), the better the approximation of the PDF. Animats are randomly placed, or seeded, within the simulation boundary at a specified density (animats/km^2). Higher densities provide a finer PDF estimate resolution but require more computational resources. To ensure good representation of the PDF, the animat density is set as high as practical allowing for computation time. The animat density is much higher than the real-world density to ensure good representation of the PDF. The resulting PDF is scaled using the real-world density.

Several models for marine mammal movement have been developed (Ellison et al. 1987, Frankel et al. 2002, Houser 2006). These models use an underlying Markov chain to transition from one state to another based on probabilities determined from measured swimming behaviour. The parameters may represent simple states, such as the speed or heading of the animal, or complex states, such as likelihood of participating in foraging, play, rest, or travel. Attractions and aversions to variables like anthropogenic sounds and different depth ranges can be included in the models.

The JASCO Animal Simulation Model Including Noise Exposure (JASMINE) was based on the open-source Marine Mammal Movement and Behaviour Model (3MB; Houser 2006). JASMINE was used in this study to predict the exposure of virtual animals ('animats') to sound arising from the pile driving activities. Animats were programmed to behave like the species of interest likely to be present in the area of interest. The parameters used for forecasting realistic behaviours (e.g., diving, foraging, aversion, surface times, etc.) were determined and interpreted from marine species studies (e.g., tagging studies) where available, or reasonably extrapolated from related species. An individual animat's modelled sound exposure levels are summed over the total simulation duration, such as 24 h for the current simulation, to determine its total received energy, and then compared to the assumed threshold criteria.

JASMINE uses the same animal movement algorithms as the 3MB model (Houser 2006), but has been extended to be directly compatible with MONM and FWRAM acoustic field predictions, for inclusion of source tracks, and importantly for animats to change behavioural states based on time and space dependent modelled variables such as received levels for aversion behaviour, although aversion was not considered in this study.

G.1. Animal Movement Parameters

JASMINE uses previously measured behaviour to forecast behaviour in new situations and locations. The parameters used for forecasting realistic behaviour are determined (and interpreted) from marine species studies (e.g., tagging studies). Each parameter in the model is described as a probability distribution. When limited or no information is available for a species parameter, a Gaussian or uniform distribution may be chosen for that parameter. For the Gaussian distribution, the user determines the mean and standard deviation of the distribution from which parameter values are drawn. For the uniform distribution, the user determines the maximum and minimum distribution from which parameter values are drawn. When detailed information about the movement and behaviour of a species are available, a user-created distribution vector, including cumulative transition probabilities, may be used (referred to here as a vector model; Houser 2006). Different sets of parameters can be defined for different behaviour states. The probability of an animat starting out in or transitioning into a given behaviour state can in turn be defined in terms of the animat's current behavioural state, depth, and the time of day. In addition, each travel parameter and behavioural state has a termination function that governs how long the parameter value or overall behavioural state persists in simulation.

The parameters used in JASMINE describe animal movement in both the vertical and horizontal planes. The parameters relating to travel in these two planes are briefly described below.

Travel sub-models

- **Direction**– determines an animat's choice of direction in the horizontal plane. Sub-models are available for determining the heading of animats, allowing for movement to range from strongly biased to undirected. A random walk model can be used for behaviours with no directional preference, such as feeding and playing. In a random walk, all bearings are equally likely at each parameter transition time step. A correlated random walk can be used to smooth the changes in bearing by using the current heading as the mean of the distribution from which to draw the next heading. An additional variant of the correlated random walk is available that includes a directional bias for use in situations where animals have a preferred absolute direction, such as migration. A user-defined vector of directional probabilities can also be input to control animat heading. For more detailed discussion of these parameters, see Houser (2006) and Houser and Cross (1999).
- **Travel rate**–defines an animat's rate of travel in the horizontal plane. When combined with vertical speed and dive depth, the dive profile of the animat is produced.

Dive sub-models

- **Ascent rate**–defines an animat's rate of travel in the vertical plane during the ascent portion of a dive.
- **Descent rate**–defines an animat's rate of travel in the vertical plane during the descent portion of a dive.
- **Depth**–defines an animat's maximum dive depth.
- **Reversals**–determines whether multiple vertical excursions occur once an animat reaches the maximum dive depth. This behaviour is used to emulate the foraging behaviour of some marine mammal species at depth. Reversal-specific ascent and descent rates may be specified.
- **Surface interval**–determines the duration an animat spends at, or near, the surface before diving again.

G.1.1. Exposure integration time

The interval over which acoustic exposure (L_E) should be integrated and maximal exposure (L_p) determined is not well defined. Both Southall et al. (2007) and the NMFS (2018) recommend a 24 h baseline accumulation period, but state that there may be situations where this is not appropriate (e.g., a high-level source and confined population). Resetting the integration after 24 h can lead to overestimating the number of individual animals exposed because individuals can be counted multiple times during an operation. The type of animal movement engine used in this study simulates realistic movement using swimming behaviour collected over relatively short periods (hours to days) and does not include large-scale movement such as migratory circulation patterns. For this study, a single day was modelled.

Ideally, a simulation area is large enough to encompass the entire range of a population so that any animal that could approach the pile driving site during an operation is included. However, there are limits to the simulation area, and computational overhead increases with area. For practical reasons, the simulation area is limited in this analysis to a maximum distance from the piling operation. In the simulation, every animat that reaches a border is replaced by another animat entering at the opposing border—e.g., an animat crossing the northern border of the simulation is replaced by one entering the southern border at the same longitude. When this action places the animat in an inappropriate water depth, the animat is randomly placed on the map at a depth suited to its species definition. The exposures of all animats (including those leaving the simulation and those entering) are kept for analysis. This approach maintains a consistent animat density and allows for longer integration periods with finite simulation areas.

G.1.2. Seeding density and scaling

The exposure criteria for impulsive sounds were used to determine the number of animats exceeding exposure thresholds. To generate statistically reliable probability density functions, all simulations were seeded with a specific animat density over the entire simulation area. To evaluate potential injury (PTS), TTS, or behavioural disturbance, threshold exceedance was determined in a 24 h time window. From the numbers of animats exceeding threshold, the numbers of individual pygmy blue whales and green turtles predicted to exceed threshold were determined by scaling the animat results by the ratio of local real-world density to modelling density.

G.2. Pygmy Blue Whale Species-Specific Details

Table G-1. *Foraging pygmy blue whales*: Data values and references input in JASMINE to create diving behaviour (number values represent means [standard deviations] unless otherwise indicated).

Behaviour	Variable	Value	Reference
Deep foraging dive	Travel direction	Correlated random walk	Houser (2006), D. Houser, pers.comm.
	Perturbation value	10	Houser (2006), D. Houser, pers.comm.
	Termination coefficient	0.2	Houser (2006), D. Houser, pers.comm.
	Travel rate (m/s)	Gaussian 1.25 (0.42)	Sears and Perrin (2009)
	Ascent rate (m/s)	Gaussian 1.6 (0.5)	Goldbogen et al. (2011)
	Descent rate (m/s)	Gaussian 2.6 (0.5)	Goldbogen et al. (2011)
	Dive depth (m)	Gaussian 129.0 (183.0)	Owen et al. (2016)
	Reversals	3.5 (1.1)	Goldbogen et al. (2011)
	Probability of reversal	0.7	Approximated
	Reversal ascent dive rate (m/s)	Random 1.7–0.37	Goldbogen et al. (2011)
	Reversal descent dive rate (m/s)	Random 1.4–0.46	Goldbogen et al. (2011)
	Time in reversal (s)	Random 26.3–52.5	Approximated
	Surface interval (s)	Gaussian 162.0 (66.0)	Goldbogen et al. (2011)
	Bout duration (s)	Gaussian 12600 (1800)	Owen et al. (2016)
General	Shore following (m)	30	Approximated
	Depth limit on seeding (m)	100.0 (minimum), 110000.0 (maximum)	Approximated

Table G-2. *Migrating pygmy blue whales*: Data values and references input in JASMINE to create diving behaviour (number values represent means [standard deviations] unless otherwise indicated).

Behaviour	Variable	Value	
Migratory dive	Travel direction	Correlated random walk	Houser (2006), D. Houser, pers.comm.
	Perturbation value	10	Houser (2006), D. Houser, pers.comm.
	Termination coefficient	0.2	Houser (2006), D. Houser, pers.comm.
	Travel rate (m/s)	Gaussian 0.78 (0.61)	Sears and Perrin (2009)
	Ascent rate (m/s)	Gaussian 0.7 (0.2)	Goldbogen et al. (2011)
	Descent rate (m/s)	Gaussian 1.5 (0.1)	Goldbogen et al. (2011)
	Dive depth (m)	Gaussian 14.0 (4.0)	Owen et al. (2016)
	Reversals	No	Owen et al. (2016)
	Surface interval (s)	Gaussian 60.0 (66.0)	Owen et al. (2016), approximated
	Bout duration (s)	Gaussian 12060 (1800)	Owen et al. (2016)
Exploratory dive	Travel direction	Correlated random walk	Houser (2006), D. Houser, pers.comm.
	Perturbation value	10	Houser (2006), D. Houser, pers.comm.
	Termination coefficient	0.2	Houser (2006), D. Houser, pers.comm.
	Travel rate (m/s)	Gaussian 1.25 (0.42)	Sears and Perrin (2009)
	Ascent rate (m/s)	Gaussian 1.6 (0.5)	Goldbogen et al. (2011)
	Descent rate (m/s)	Gaussian 2.6 (0.5)	Goldbogen et al. (2011)
	Dive depth (m)	Gaussian 107.0 (81.0)	Owen et al. (2016)
	Reversals	No	Owen et al. (2016)
	Surface interval (s)	Gaussian 162.0 (66.0)	Goldbogen et al. (2011)
	Bout duration (s)	Gaussian 516 (120)	Owen et al. (2016)
General	Shore following (m)	30	Approximated
	Depth limit on seeding (m)	100.0 (minimum), 110000.0 (maximum)	Approximated

G.3. Green Turtle Species-Specific Details

Table G-3. *Inter-nesting green turtles*: Data values input in JASMINE to create diving behaviour (number values represent means [standard deviations] unless otherwise indicated). The references associated with the data values include Pendoley (2005), and Guinea (2011) (Section 3.7.3.1).

Behaviour	Variable	Value
Shallow diving	Travel direction	Correlated random walk
	Perturbation value	10
	Termination coefficient	0.2
	Travel rate (m/s)	Gaussian 0.69 (0.17)
	Ascent rate (m/s)	Gaussian 0.085 (0.021)
	Descent rate (m/s)	Gaussian 0.125 (0.049)
	Dive depth (m)	Random 0.0–2.0
	Bottom following	No
	Reversals	No
	Surface interval (s)	Gaussian 150.0 (15.0)
	Bout duration (s)	Gaussian 7800.0 (1200.0)
Feeding	Travel direction	Correlated random walk
	Perturbation value	10
	Termination coefficient	0.2
	Travel rate (m/s)	Gaussian 0.69 (0.17)
	Ascent rate (m/s)	Gaussian 0.045 (0.014)
	Descent rate (m/s)	Gaussian 0.02 (0.07)
	Dive depth (m)	Random 1.0–45.0
	Bottom following	Yes
	Reversals	Gaussian 1.0 (0.0)
	Probability of reversal	1
	Reversal ascent dive rate (m/s)	Gaussian 0.001 (0.001)
	Reversal descent dive rate (m/s)	Gaussian 0.0 (0.0)
	Time in reversal (s)	Gaussian 1694.0 (481.0)
	Surface interval (s)	Gaussian 300.0 (30.0)
	Bout duration (s)	Gaussian 14400.0 (400.0)
General	Shore following (m)	2
	Depth limit on seeding (m)	2.0 (minimum), 10000.0 (maximum)

Table G-4. *Migrating green turtles*: Data values input in JASMINE to create diving behaviour (number values represent means [standard deviations] unless otherwise indicated).

Behaviour	Variable	Value
Migration	Travel direction	Correlated random walk
	Perturbation value	10
	Termination coefficient	0.2
	Travel rate (m/s)	Gaussian 0.57 (0.03)
	Ascent rate (m/s)	Gaussian 0.15 (0.04)
	Descent rate (m/s)	Gaussian 0.34 (0.08)
	Dive depth (m)	Random 0.0–80.0
	Bottom following	No
	Reversals	No
	Surface interval (s)	Gaussian 30.0 (60.0)
General	Shore following (m)	0
	Depth limit on seeding (m)	0.0 (minimum), 10000.0 (maximum)

Appendix H. Additional Results

H.1. Torosa Piling SEL Contour Maps

Maps of the per-strike SEL results associated with the three modelled penetration depths are shown in Figures H-1, H-2 and H-3 for the IHC S-600, and in Figures H-4, H-5 and H-6 for the IHC S-1200.

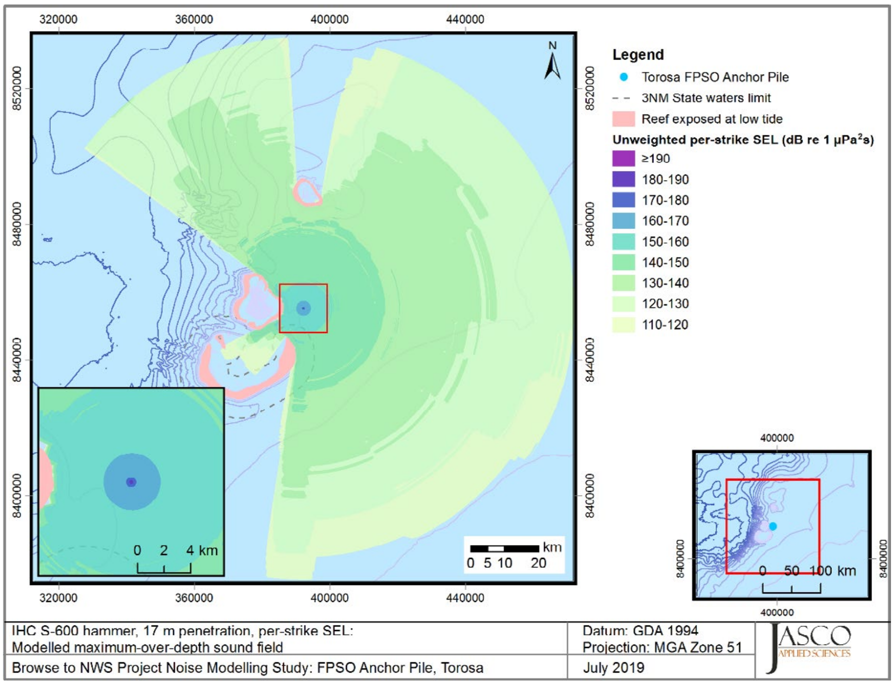


Figure H-1. *Torosa, IHC S-600, per-strike SEL, 17 m penetration depth*: Sound level contour map showing maximum-over-depth results.

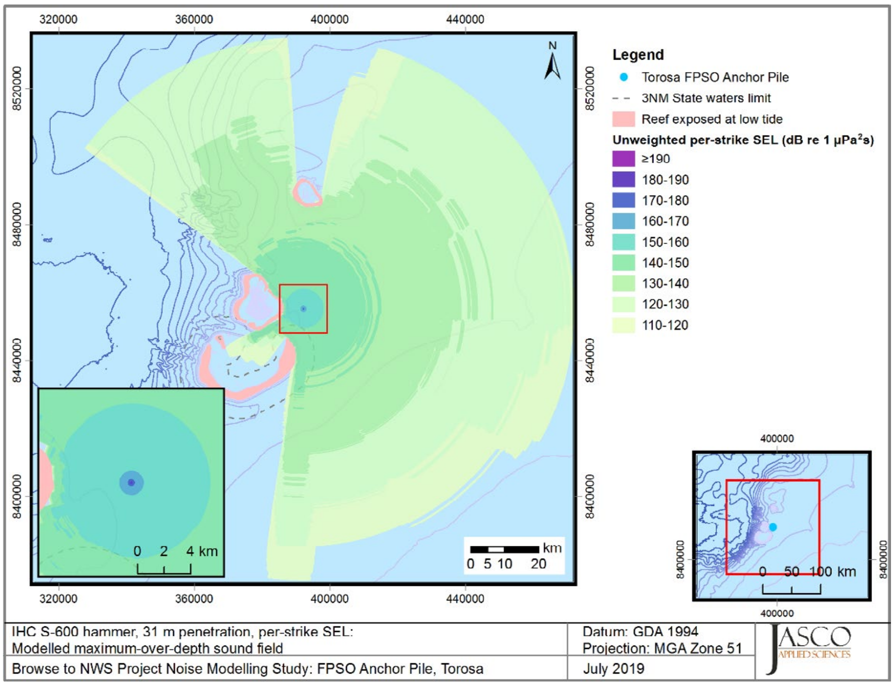


Figure H-2. *Torosa, IHC S-600, per-strike SEL, 31 m penetration depth*: Sound level contour map showing maximum-over-depth results.

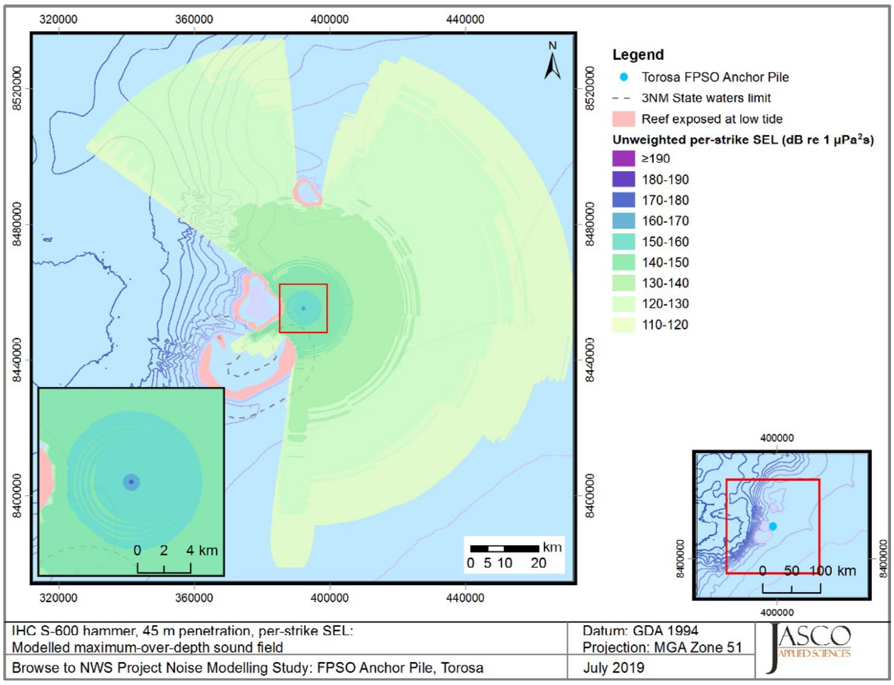


Figure H-3. *Torosa, IHC S-600, per-strike SEL, 45 m penetration depth*: Sound level contour map showing maximum-over-depth results.

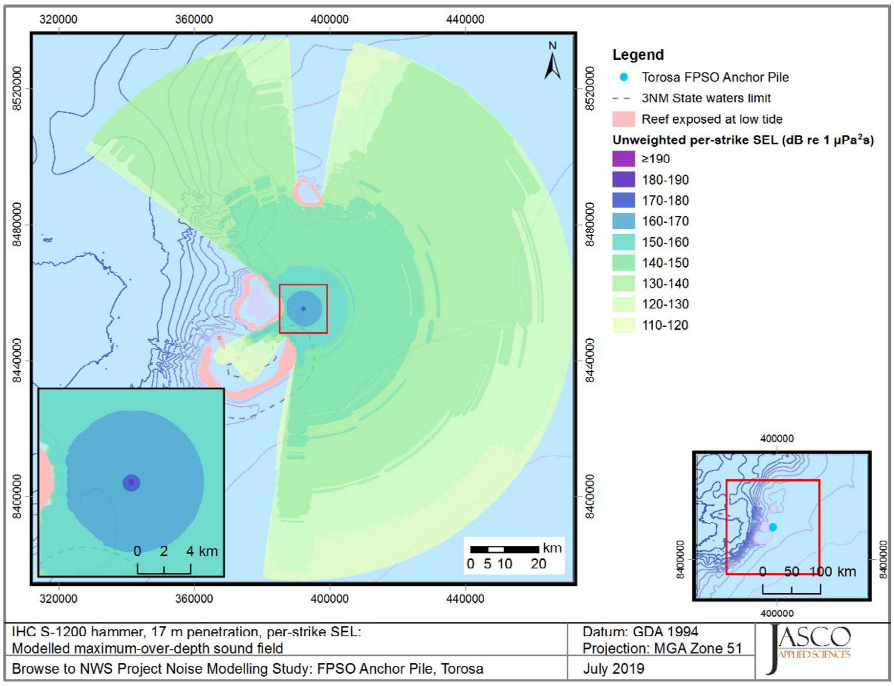


Figure H-4. *Torosa, IHC S-1200, per-strike SEL, 17 m penetration depth*: Sound level contour map showing maximum-over-depth results.

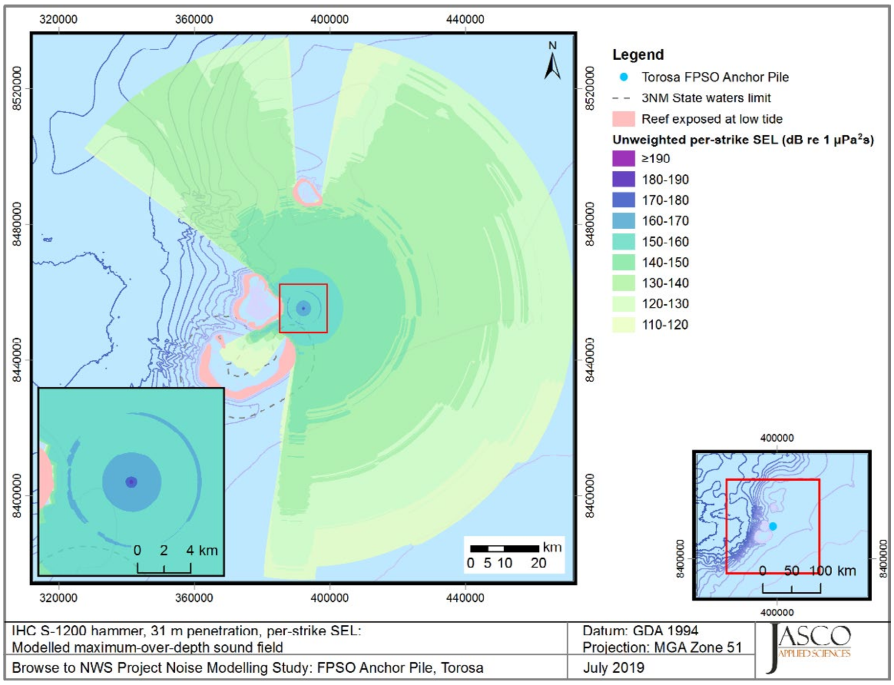


Figure H-5. *Torosa, IHC S-1200, per-strike SEL, 31 m penetration depth*: Sound level contour map showing maximum-over-depth results.

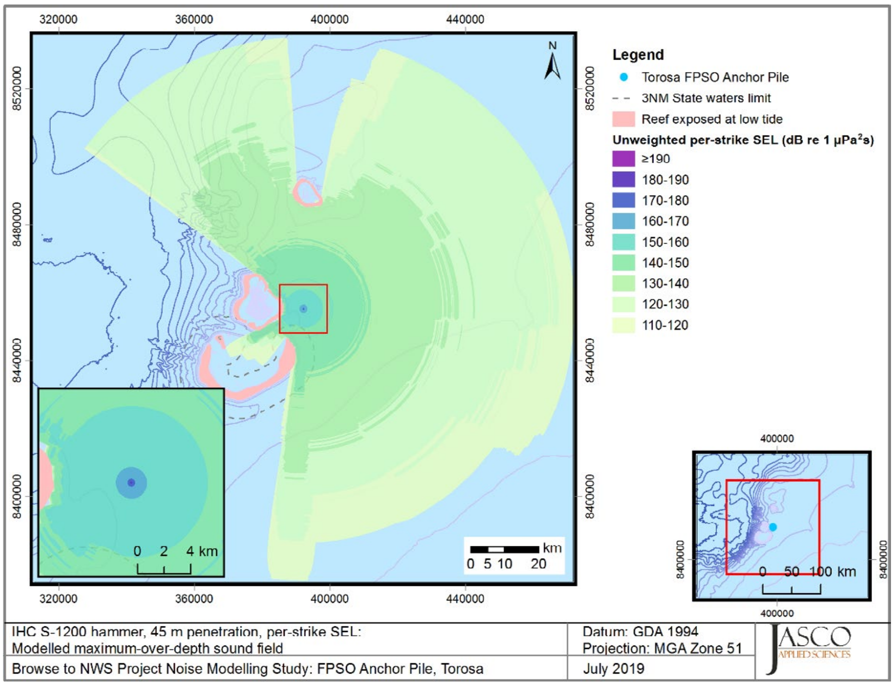


Figure H-6. *Torosa, IHC S-1200, per-strike SEL, 45 m penetration depth*: Sound level contour map showing maximum-over-depth results.

H.2. Brecknock Piling SEL Contour Maps

Maps of the per-strike SEL results associated with the three modelled penetration depths are shown in Figures H-7, H-8 and H-9 for the IHC S-600, and in Figures H-10, H-11 and H-12 for the IHC S-1200.

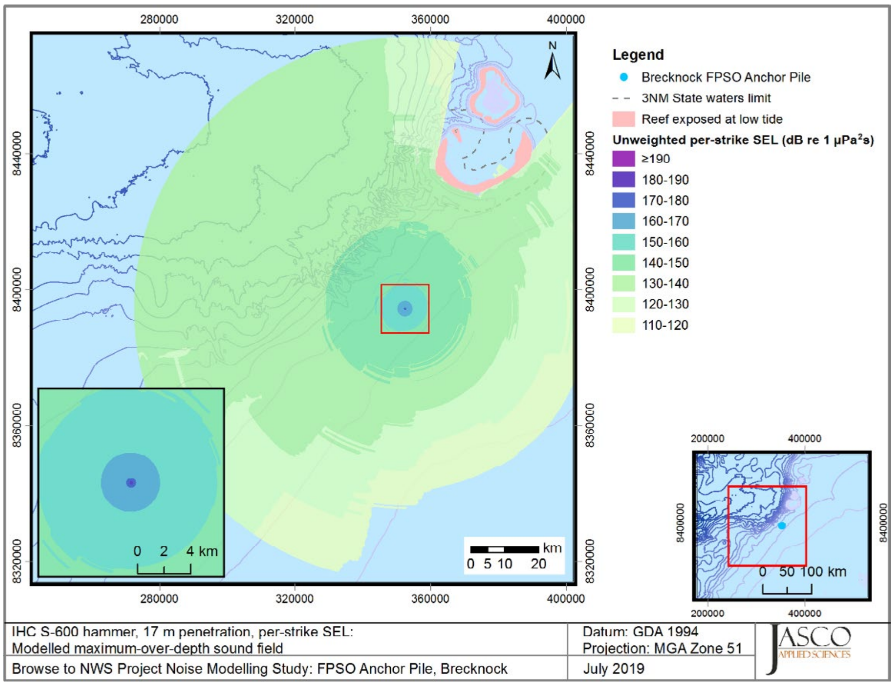


Figure H-7. *Brecknock, IHC S-600, per-strike SEL, 17 m penetration depth*: Sound level contour map showing maximum-over-depth results.

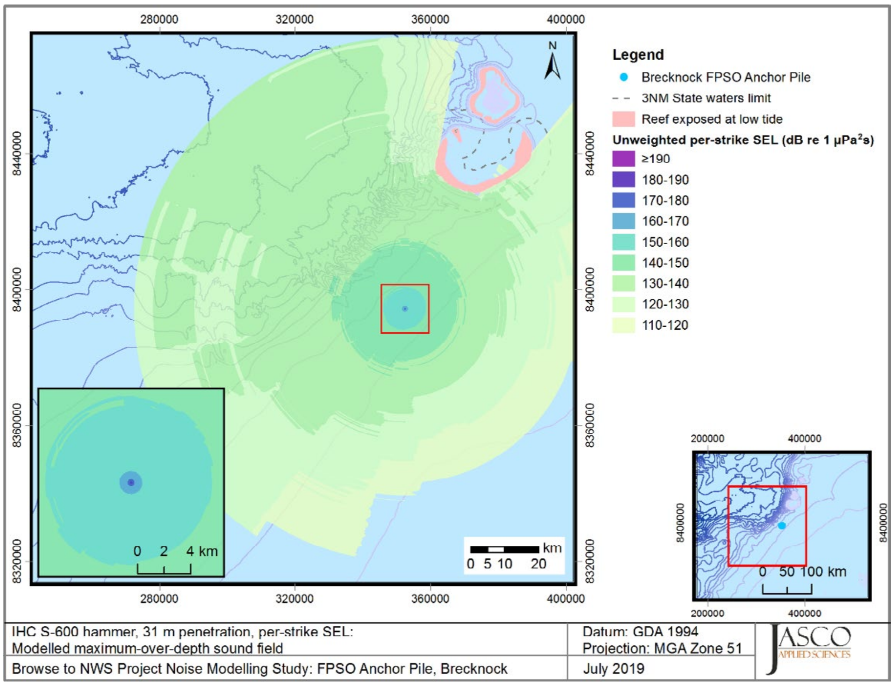


Figure H-8. *Brecknock, IHC S-600, per-strike SEL, 31 m penetration depth*: Sound level contour map showing maximum-over-depth results.

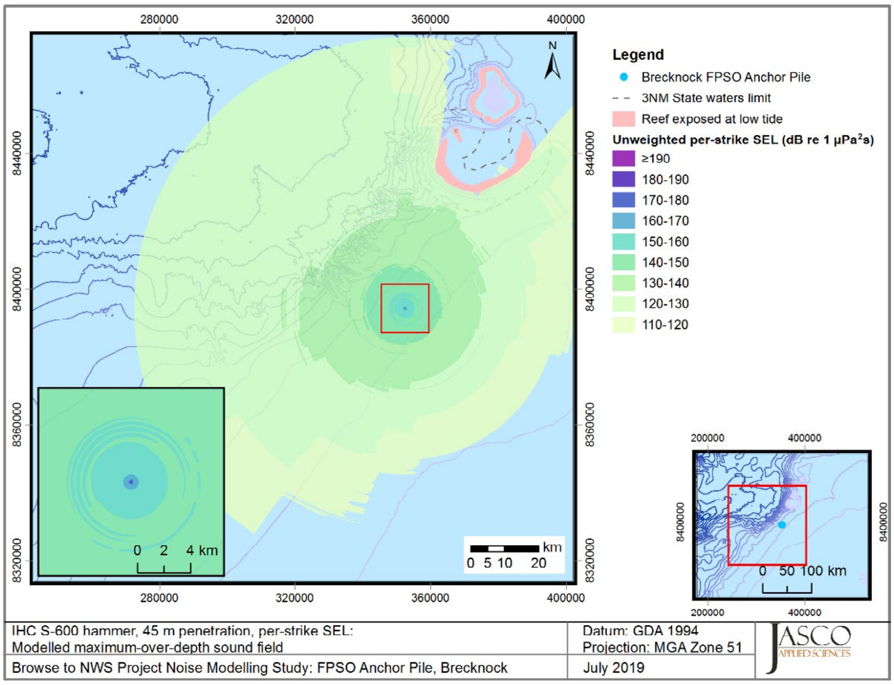


Figure H-9. *Brecknock, IHC S-600, per-strike SEL, 45 m penetration depth*: Sound level contour map showing maximum-over-depth results.

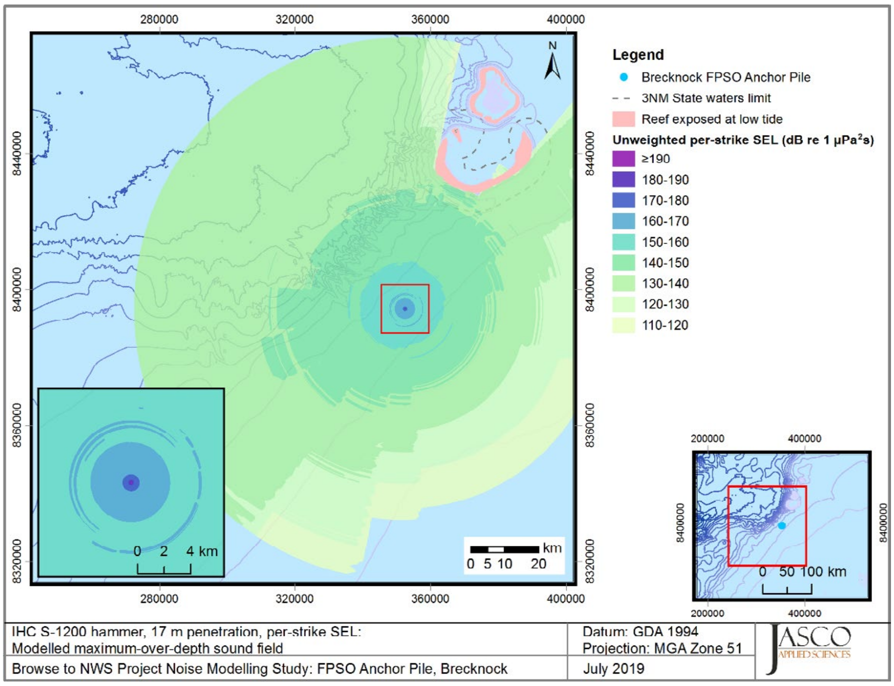


Figure H-10. *Brecknock, IHC S-1200, per-strike SEL, 17 m penetration depth*: Sound level contour map showing maximum-over-depth results.

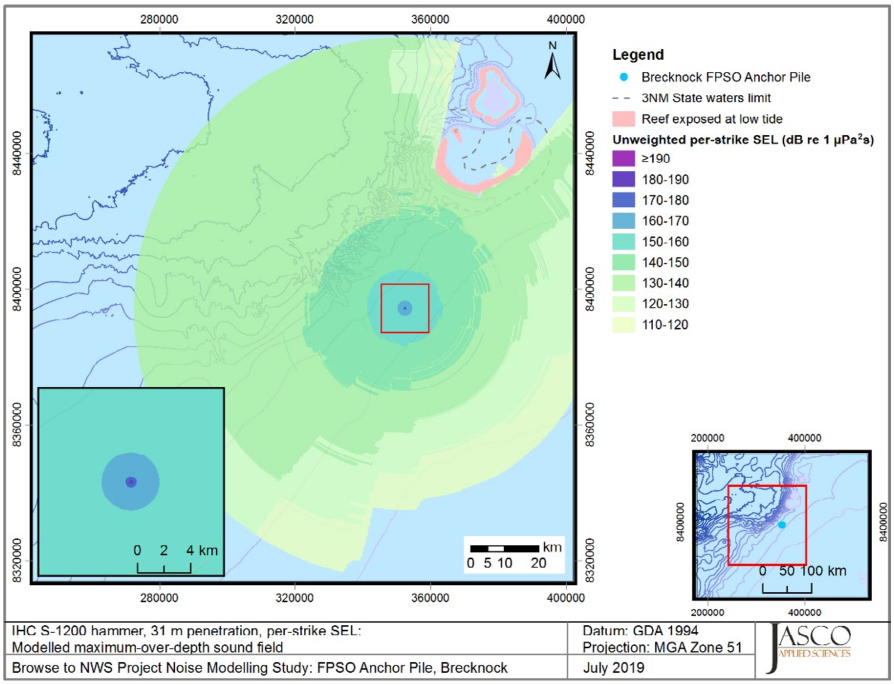


Figure H-11. *Brecknock, IHC S-1200, per-strike SEL, 31 m penetration depth*: Sound level contour map showing maximum-over-depth results.

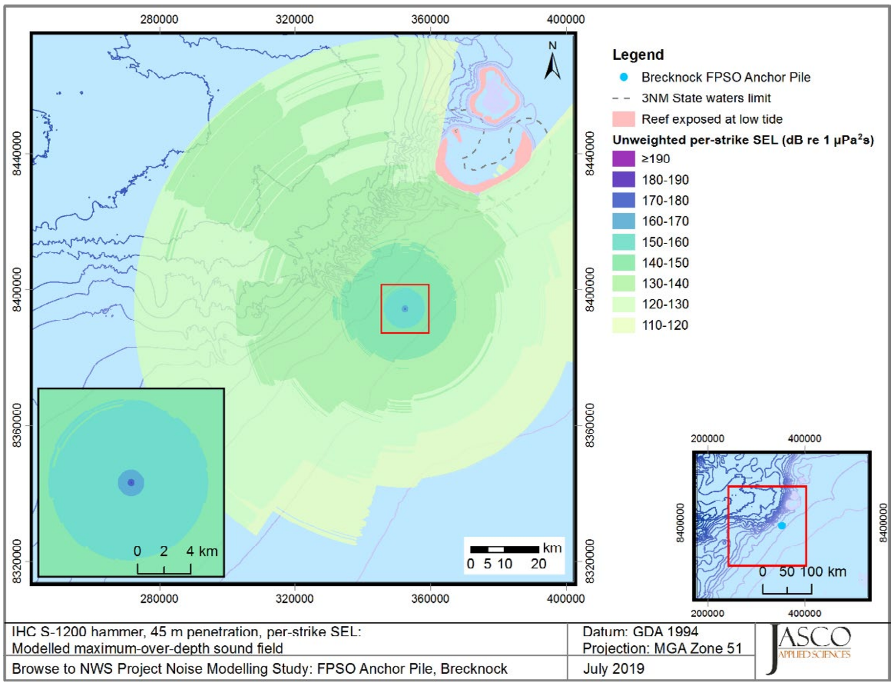


Figure H-12. *Brecknock, IHC S-1200, per-strike SEL, 45 m penetration depth*: Sound level contour map showing maximum-over-depth results.

H.3. VSP SEL Contour Maps

Maps of the per-pulse SEL results for the two VSP locations are shown in Figures H-13 and H-14.

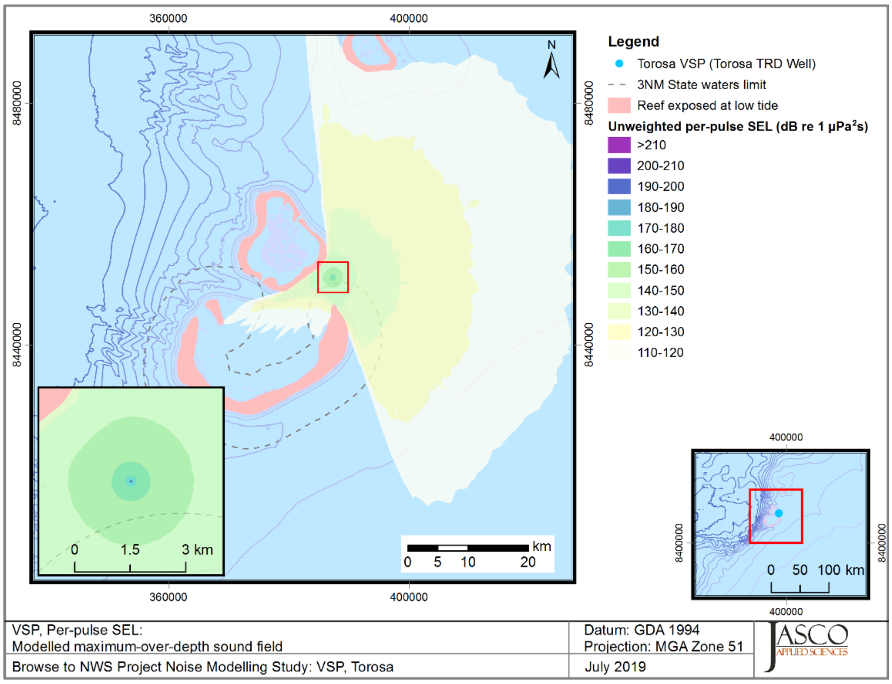
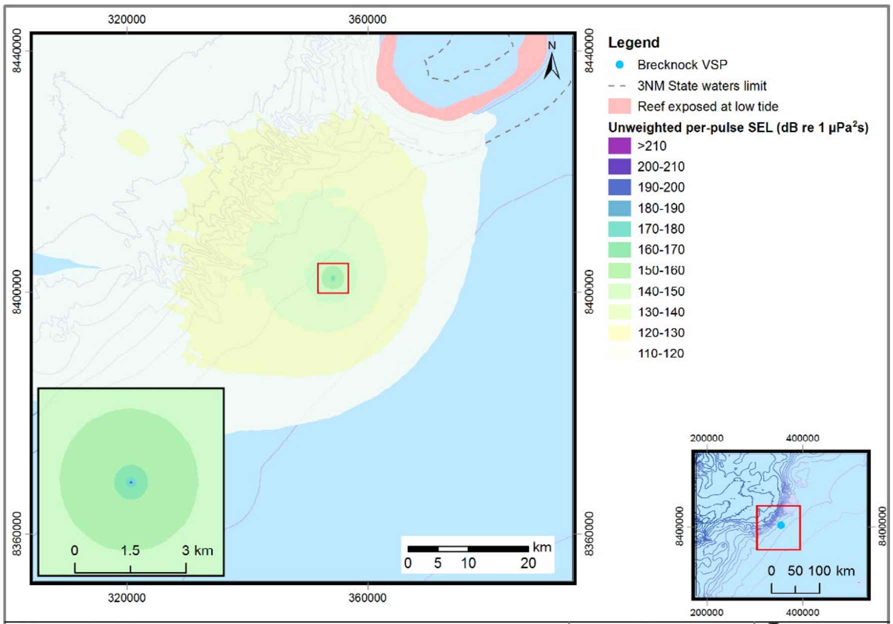


Figure H-13. *Torosa TRD Well VSP, per-pulse SEL:* Sound level contour map showing unweighted maximum-over-depth results.



VSP, Per-pulse SEL: Modelled maximum-over-depth sound field	Datum: GDA 1994 Projection: MGA Zone 51	JASCO APPLIED SCIENCES
Browse to NWS Project Noise Modelling Study: VSP, Brecknock	July 2019	

Figure H-14. *Brecknock VSP, per-pulse SEL:* Sound level contour map showing unweighted maximum-over-depth results.

Browse to North West Shelf Project Noise Modelling Study - Addendum

Additional Information

Submitted to:

Arne De Vos
Jacobs
PO: 538, 28 May 2019

Authors:

Craig McPherson
Matthew Koessler
Michelle Weirathmueller

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JASCO Applied Sciences (Australia) Pty Ltd.
Unit 1, 14 Hook Street
Capalaba, Queensland, 4157
Tel: +61 7 3823 2620
www.jasco.com

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Disclaimer:

The results presented herein are relevant within the specific context described in this report. They could be misinterpreted if not considered in the light of all the information contained in this report. Accordingly, if information from this report is used in documents released to the public or to regulatory bodies, such documents must clearly cite the original report, which shall be made readily available to the recipients in integral and unedited form.

Contents

Figures

Tables

1. Introduction

This report is an addendum to McPherson et al. (2019), and presents:

- Additional modelling scenarios:
    - The additional modelled scenarios consider both Floating Production Storage and Offloading (FPSO) facilities during offtake along with operations of a Mobile Offshore Drilling Unit (MODU) under dynamic positioning at either the Torosa TRD well or Brecknock. The FPSO operational noise during offtake, includes the FPSO under DP, an Offshore Support Vessel (OSV) near each FPSO (presented in isolation also) and a noiseless condensate tanker.
- Discussion of the interaction between impulsive and continuous sources from an acoustic modelling for impact assessment perspective.
- Calculations of the areas within relevant threshold isopleths for the static acoustic modelling sound fields were calculated from the area encompassed by the shape file representing the isopleths.
- Areas within specific threshold isopleths from the static sound field modelling results presented in McPherson et al. (2019) and this addendum. Additionally, the area of the overlap between considered Biologically Important Areas (BIAs) and the relevant isopleths is also calculated.
- For the assessment of turtle exposure through animal movement and exposure modelling, considering an additional BIA, that for the Department of Environment and Energy (DoEE) Green Turtle Inter-nesting Buffer located at Scott Reef – Sandy Islet.

The geographic coordinates for the modelled sites are provided in Table 1 and an overview of the modelling area is shown in Figure 1.

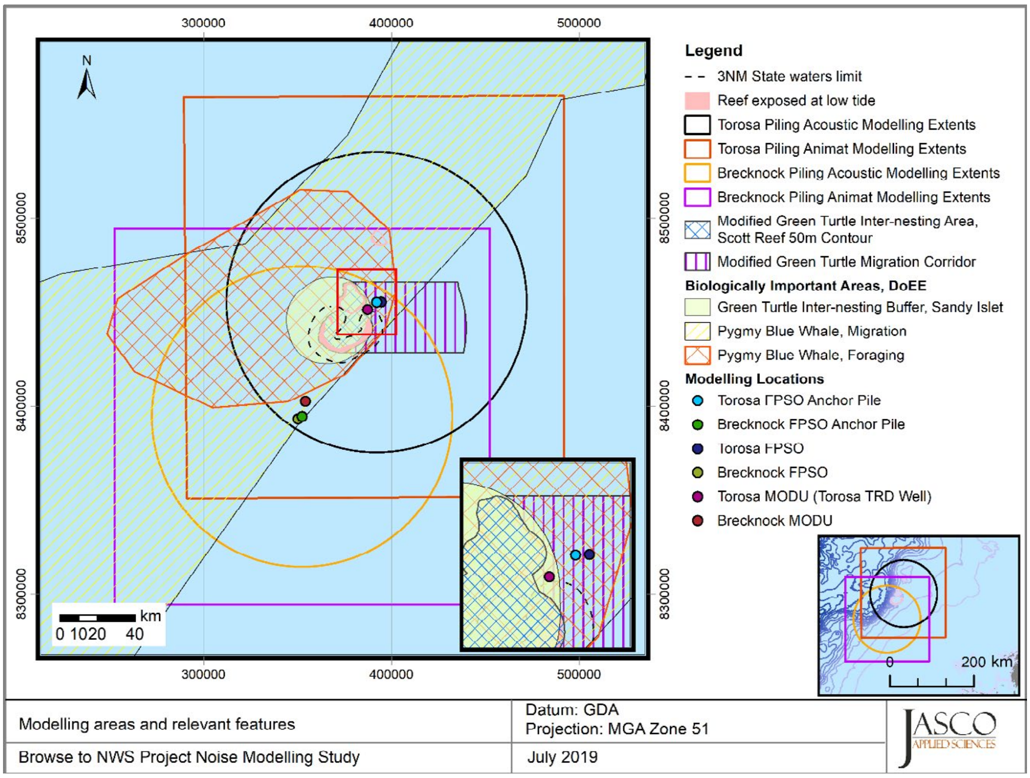

Figure 1. Overview of the modelled area and local features.

Table 1. Location details for the modelled sites.

Site	Source	Latitude (S)	Longitude (E)	MGA (GDA94), Zone 51		Water depth (m)
				X (m)	*Y* (m)	
Torosa	FPSO Anchor Pile	13° 58' 16.97"	122° 00' 05.23"	392148	8455212	448
	FPSO (turret)	13° 58' 15.06"	122° 01' 28.53"	394647	8455281	463
	OSV (bow)	13° 58' 15.06"	122° 00' 50.38"	393502.3	8455276	463
Torosa TRD Well	MODU (centre)	14° 00' 26.64"	121° 57' 23.58"	387315	8451207	391
	VSP (MODU centre)					
Brecknock	FPSO Anchor Pile	14° 31' 10.31"	121° 37' 50.58"	352456	8394373	506
	FPSO (turret)	14° 31' 51.44"	121° 36' 38.47"	350305	8393096	515
	OSV (bow)	14° 31' 14.19"	121° 36' 38.55"	350300.3	8394241	515
	MODU (centre)	14° 26' 49.45"	121° 38' 52.09"	354250	8402400	467
	VSP (MODU centre)					

2. Methods

In addition to the methods presented in McPherson et al. (2019), the methodology for the calculations of ensonified and exposed areas, both in their own right and overlapping relevant BIA's, and the consideration of an additional green turtle BIA and an alternative number of individuals, is outlined in this addendum report.

2.1. Exposed Areas

The areas within relevant threshold isopleths for the static acoustic modelling sound fields were calculated from the area encompassed by the shape file representing the isopleths. These areas can be combined to create a simplistic representation of the area within which a threshold is exceeded to assist with the impact assessment.

For the animal movement and exposure modelling, a key output was the 95th percentile ranges (P_{95}), or the range within which 95% of the exposure exceedances. This range was converted into an area ($\pi*(P_{95})^2$).

To calculate the overlap between the area within a threshold isopleth or P_{95} area of a pygmy blue whale or green turtle relevant BIA, the two features were mapped in Global Mapper (Global Mapper 2019) and the overlapping area calculated.

2.2. Animal Movement and Exposure Modelling

2.2.1. Assessment areas

Two areas of interest are defined for inter-nesting green turtles:(1) a modified Biologically Important Area (BIA) defined by the 50 m contour around North and South Scott Reef, including a corridor connecting the two reefs, and (2) the DoEE-defined inter-nesting BIA boundary around Scott Reef.

Figures 2 and 3 show maps of both of the BIAs for inter-nesting green turtles in relation to both the Torosa and Brecknock piling locations. Both maps also show the extents of the modelling and animat simulation area. To account for the difference between the animat simulation area and the BIAs, the final exposure estimates are scaled by the ratio of the clipped BIA relative to the simulation area.

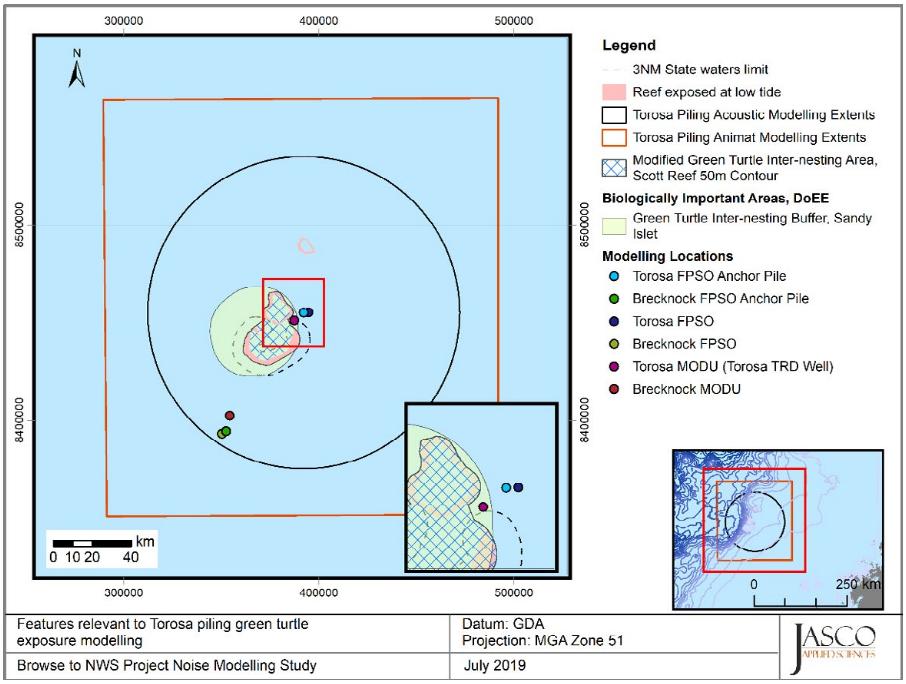

Figure 2. *Torosa:* Map of green turtle exposure modelling features, including modified BIAs for inter-nesting and migrating green turtles, along with extents for acoustic propagation modelling and animat modelling.

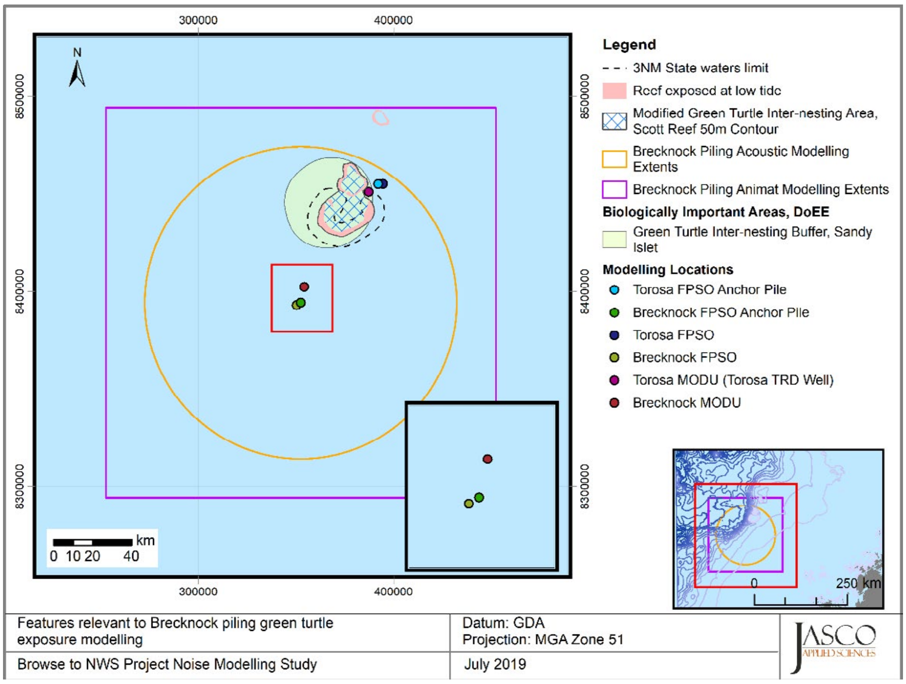

Figure 3. *Brecknock:* Map of green turtle exposure modelling features, including modified BIAs for inter-nesting and migrating green turtles, along with extents for acoustic propagation modelling and animat modelling.

2.2.2. Methodology

The exposure criteria for impulsive sounds (described in Section 2, McPherson et al. (2019)) were used to determine the number of animats exceeding thresholds. To evaluate potential injury (PTS), TTS, and behavioural disturbance, exposure results were summed over the driving of a single pile, which represents the exposure over 24 h, as only one pile will be driven per day.

Model simulations were run with animat seeding densities of 15 animats/km^2 for pygmy blue whales and 15 animats/km^2 green turtles to generate a statistically reliable probability density function (PDF) for each species. Seeding densities need to be high enough to adequately sample the underlying sound exposure PDF. Typically, for longer duration simulations (7-14 days), a seeding density of 0.5 animats/km^2 is sufficient. However, in this case, where the active duration of the pile driving is less than 80 minutes within 24 hours (78.5 or 80 minutes, IH S-600 hammer, Tables 16 and 17, McPherson et al. (2019)), the simulated density must be increased substantially to provide a comparably reliable sampling of the underlying PDF. A statistically equivalent result could also be accomplished by running several independent simulations at a lower seeding density; however, this is computationally less efficient. The number of simulated animats exposed above relevant thresholds can then be scaled by the ratio of the real-world density to the seeded animat density to convert to an estimate of the number of individual animals impacted.

The distribution of ranges of exposed animats was used to estimate the 95th percentile ranges at which the animats were exposed above threshold. Within the 95th percentile range, there are generally some proportion of animats that did not exceed threshold criteria.

The proposed number of individual green turtles in McPherson et al. (2019) was 1162, or a density of 1.79 turtles/km^2 within an inter-nesting area defined by the 50 m bathymetry around North and South Scott Reef, referred to as the ‘Modified Green Turtle Inter-nesting Area, Scott Reef 50 m Contour’. This addendum considers the possibility of 5000 individuals within this modified inter-nesting area.

Table 2. Exposure modelling scenarios and associated areas of concern for green turtle simulations, along with estimated animal densities.

Animat scenario	Full area (km^2)	R_{min} (km)	Adjusted A_{full} (km^2)	$BIA_{clipped}$ (km^2)	Area-based scaling, S_A	Number of turtles	Animal density (# per km^2)
Torosa							
DoEE Green Turtle Inter-nesting Buffer located at Scott Reef – Sandy Islet	40000.0	3.8	39954.6	1666.8	0.04	1162	0.70
						5000	3.00
Modified Green turtle inter-nesting buffer, Scott Reef 50 m contour	40000.0	7.9	39804.1	658.2	0.02	1162	1.79
						5000	7.70
Brecknock							
DoEE Green Turtle Inter-nesting Buffer located at Scott Reef – Sandy Islet	40000.0	29.7	37228.8	1666.8	0.04	1162	0.70
						5000	3.00
Modified Green turtle inter-nesting buffer, Scott Reef 50 m contour	40000.0	40.4	34872.4	658.2	0.02	1162	1.79
						5000	7.70

3. Results

3.1. Pile Driving: Torosa FPSO Anchor Piles

3.1.1. Areas within threshold isopleths

The area within threshold isopleths for low-frequency marine mammals and turtles for the Torosa FPSO pile driving scenarios are shown in Tables 3 and 4.

Table 3. *Torosa*: Areas (km^2) within isopleths corresponding to maximum-over-depth low-frequency cetacean PTS and TTS thresholds (NMFS 2018) and marine mammal behavioural response to continuous noise (NMFS 2014).

Threshold	Area (km^2)	Area within PBW migratory BIA (km^2)	Area within PBW foraging BIA (km^2)
IHC S-600 hammer			
LF cetacean PTS†	39.70	39.70	39.70
LF cetacean TTS†	943.80	803.40	623.70
Marine mammal behavioural response#	123.53	123.53	123.53
IHC S-1200 hammer			
LF cetacean PTS†	54.10	54.10	54.10
LF cetacean TTS†	1091.90	875.50	646.20
Marine mammal behavioural response#‡	376.75	376.75	333.82

† Frequency-weighted SEL_{24h} based marine mammal PTS and TTS thresholds (NMFS 2018)
#160 dB re 1 µPa (SPL) (NMFS 2014)

Table 4. *Torosa*: Areas (km^2) within isopleths corresponding to maximum-over-depth turtle PTS and TTS (Finneran et al. 2017), behavioural response (NSF 2011) and disturbance (McCauley et al. 2000a, 2000b).

Threshold	Area (km^2)	Area within Modified Migratory Corridor (km^2)	Area within Modified Turtle BIA (km^2)	Area within DoEE Green Turtle BIA (km^2)
IHC S-600 hammer				
Turtle PTS†	0.20	0.00	0.20	0.00
Turtle TTS†	18.40	0.00	18.40	0.00
Turtle behavioural response#	52.85	0.00	26.46	0.66
Turtle behavioural disturbance‡	2.70	0.00	1.35	0.00
IHC S-1200 hammer				
Turtle PTS†	0.20	0.00	0.20	0.00
Turtle TTS†	23.00	0.00	23.00	1.18
Turtle behavioural response#	202.06	0.00	100.87	6.92
Turtle behavioural disturbance‡	21.12	0.16	10.56	0.00

† Frequency-weighted SEL_{24h} based turtle PTS and TTS thresholds (Finneran et al. 2017)
#166 dB re 1 µPa (SPL) (NSF 2011)
‡175 dB re 1 µPa (SPL) (McCauley et al. 2000a, 2000b)

3.1.2. Area within 95th percentile ranges (P_{95})

The area within P_{95} ranges for pygmy blue whales and turtles for the Torosa FPSO pile driving scenarios are shown in Tables 5–8.

Table 5. *Torosa*: Area (km²) within the 95th percentile exposure ranges, P_{95} (km), for pygmy blue whale animat simulation scenarios without an exclusion zone implemented.

Threshold	Migrating		Foraging	
	Area within P_{95} (km²)	Area of PBW migratory BIA within P_{95} (km²)	Area within P_{95} (km²)	Area of PBW foraging BIA within P_{95} (km²)
IHC S-600 hammer				
LF cetacean PTS†	2.60	2.6	6.61	6.6
LF cetacean TTS†	166.04	165.95	363.05	338.35
Marine mammal behavioural response#	124.29	124.23	141.87	141.79
IHC S-1200 hammer				
LF cetacean PTS†	5.39	5.387	7.74	7.739
LF cetacean TTS†	218.52	218.4	446.38	401.39
Marine mammal behavioural response#‡	262.45	262.31	361.03	336.78

† Frequency-weighted SEL_{24h} based marine mammal PTS and TTS thresholds (NMFS 2018)
#160 dB re 1 µPa (SPL) (NMFS 2014)

Table 6. *Torosa*: Area (km²) within the 95th percentile exposure ranges, P_{95} (km), for pygmy blue whale animat simulation scenarios with a 2000 m exclusion zone implemented.

Threshold	Migrating		Foraging	
	Area within P_{95} (km²)	Area of PBW migratory BIA within P_{95} (km²)	Area within P_{95} (km²)	Area of PBW foraging BIA within P_{95} (km²)
IHC S-600 hammer				
LF cetacean PTS†	0.00	0.00	0.00	0.00
LF cetacean TTS†	187.23	187.13	369.15	343.07
Marine mammal behavioural response#	148.27	148.19	150.01	149.93
IHC S-1200 hammer				
LF cetacean PTS†	0.00	0.00	13.72	0.00
LF cetacean TTS†	231.27	231.15	454.65	407.5
Marine mammal behavioural response#‡	297.42	297.27	368.47	342.55

† Frequency-weighted SEL_{24h} based marine mammal PTS and TTS thresholds (NMFS 2018)
#160 dB re 1 µPa (SPL) (NMFS 2014)

Table 7. *Torosa*: Area (km^2) within the 95th percentile exposure ranges, P_{95} (km), for green turtle animat simulation scenarios without an exclusion zone implemented.

Threshold	Migratory		Inter-nesting			
	Area within P_{95} (km^2)	Area of Modified Migratory Corridor within P_{95} (km^2)	Modified Inter-nesting turtle BIA		DoEE Green Turtle BIA	
			Area within P_{95} (km^2)	Area of BIA within P_{95} (km^2)	Area within P_{95} (km^2)	Area of BIA within P_{95} (km^2)
IHC S-600 hammer						
Turtle PTS†	0.00	0.00	0.00	0.00	0.00	0.00
Turtle TTS†	8.55	8.55	0.00	0.00	0.00	0.00
Turtle behavioural response#	20.27	20.27	0.00	0.00	0.00	0.00
Turtle behavioural disturbance‡	0.01	0.00	0.00	0.00	0.00	0.00
IHC S-1200 hammer						
Turtle PTS†	0.00	0.00	0.00	0.00	0.00	0.00
Turtle TTS†	10.07	10.07	0.00	0.00	0.00	0.00
Turtle behavioural response#	67.64	67.64	0.00	0.00	128.68	18.13
Turtle behavioural disturbance‡	9.84	9.84	0.00	0.00	0.00	0.00

† Frequency-weighted SEL_{24h} based turtle PTS and TTS thresholds (Finneran et al. 2017)
#166 dB re 1 µPa (SPL) (NSF 2011)
‡175 dB re 1 µPa (SPL) (McCauley et al. 2000a, 2000b)

Table 8. *Torosa*: Area (km^2) within the 95th percentile exposure ranges, P_{95} (km), for green turtle animat simulation scenarios with a 500 m exclusion zone implemented.

Threshold	Migratory		Inter-nesting			
	Area within P_{95} (km^2)	Area of Modified Migratory Corridor within P_{95} (km^2)	Modified Inter-nesting turtle BIA		DoEE Green Turtle BIA	
			Area within P_{95} (km^2)	Area of BIA within P_{95} (km^2)	Area within P_{95} (km^2)	Area of BIA within P_{95} (km^2)
IHC S-600 hammer						
Turtle PTS†	0.00	0.00	0.00	0.00	0.00	0.00
Turtle TTS†	8.97	8.97	0.00	0.00	0.00	0.00
Turtle behavioural response#	20.59	20.59	0.00	0.00	0.00	0.00
Turtle behavioural disturbance‡	0.00	0.00	0.00	0.00	0.00	0.00
IHC S-1200 hammer						
Turtle PTS†	0.00	0.00	0.00	0.00	0.00	0.00
Turtle TTS†	10.29	10.29	0.00	0.00	0.00	0.00
Turtle behavioural response#	69.69	69.69	0.00	0.00	128.68	18.13
Turtle behavioural disturbance‡	9.95	9.95	0.00	0.00	0.00	0.00

† Frequency-weighted SEL_{24h} based turtle PTS and TTS thresholds (Finneran et al. 2017)
#166 dB re 1 µPa (SPL) (NSF 2011)
‡175 dB re 1 µPa (SPL) (McCauley et al. 2000a, 2000b)

3.1.3. Animal Movement and Exposure Modelling

Summaries of the animat modelling results at Torosa for inter-nesting green turtles with 1162 or 5000 individuals are provided in Table 9.

Table 9. *Torosa*: Summary of animat simulation results for inter-nesting turtles. Includes the distances to acoustic modelling thresholds (km), the 95th percentile exposure ranges (km), and the number of real-world individuals exposed above threshold. Acoustic modelling results are presented in McPherson et al. (2019).

Threshold		Distance to threshold from acoustic modelling		Modified Inter-nesting BIA						DoEE Sandy Islet 20km BIA					
				Inter-nesting turtles			Inter-nesting turtles with 500 m exclusion zone			Inter-nesting turtles			Inter-nesting turtles with 500 m exclusion zone		
Threshold description	Sound level (dB)	R_{max} (km)	$R_{95\%}$ (km)	Range, P_{95} (km)	Number of individuals (1162 total)	Number of individuals (5000 total)	Range, P_{95} (km)	Number of individuals (1162 total)	Number of individuals (5000 total)	Range, P_{95} (km)	Number of individuals (1162 total)	Number of individuals (5000 total)	Range, P_{95} (km)	Number of individuals (1162 total)	Number of individuals (5000 total)
IHC S600 Hammer															
TTS, PK	226†	<0.02*		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TTS, SEL_{24h}	189‡	4.79	2.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PTS, PK	232†	<0.02*		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PTS, SEL_{24h}	204‡	0.24	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Behavioural response	166#	5.11	4.99	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	175#	0.68	0.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IHC S1200 Hammer															
TTS, PK	226†	<0.02*		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TTS, SEL_{24h}	189‡	5.07	4.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PTS, PK	232†	<0.02*		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PTS, SEL_{24h}	204‡	0.25	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Behavioural response	166#	9.11	5.66	0.00	0.00	0.00	0.00	0.00	0.00	**6.40**	**0.03**	**0.15**	**6.40**	**0.03**	**0.15**
	175#	1.87	1.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

† PK (L_{pk}; dB re 1 µPa)
‡ Turtle weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s)
# SPL (L_p; dB re 1 µPa)
* R_{max} reported for TTS PK and PTS PK from acoustic modelling

3.2. Pile Driving: Brecknock FPSO Anchor Piles

3.2.1. Areas within threshold isopleths

The area within threshold isopleths for low-frequency marine mammals and turtles for the Brecknock FPSO pile driving scenarios are shown in Tables 10 and 11.

Table 10. *Brecknock*: Areas (km^2) within isopleths corresponding to maximum-over-depth low-frequency cetacean PTS and TTS thresholds NMFS (2018) and marine mammal behavioural response to continuous noise (NMFS 2014).

Threshold	Area (km^2)	Area within PBW migratory BIA (km^2)	Area within PBW foraging BIA (km^2)
IHC S-600 hammer			
LF cetacean PTS†	27.90	21.80	0.00
LF cetacean TTS†	1048.20	695.20	224.50
Marine mammal behavioural response#	130.98	85.37	0.00
IHC S-1200 hammer			
LF cetacean PTS†	32.40	25.80	0.00
LF cetacean TTS†	1156.30	759.30	252.00
Marine mammal behavioural response#‡	431.09	289.47	20.44

† Frequency-weighted SEL_{24h} based marine mammal PTS and TTS thresholds (NMFS 2018)
#160 dB re 1 µPa (SPL) (NMFS 2014)

Table 11. *Brecknock*: Areas (km^2) within isopleths corresponding to maximum-over-depth turtle PTS and TTS (Finneran et al. 2017), behavioural response (NSF 2011) and disturbance (McCauley et al. 2000a, 2000b).

Threshold	Area (km^2)	Area within Modified Migratory Corridor (km^2)	Area within Modified Turtle BIA (km^2)	Area within DoEE Green Turtle BIA (km^2)
IHC S-600 hammer				
Turtle PTS†	0.20	0.00	0.00	0.00
Turtle TTS†	19.60	0.00	0.00	0.00
Turtle behavioural response#	47.70	0.00	0.00	0.00
Turtle behavioural disturbance‡	2.57	0.00	0.00	0.00
IHC S-1200 hammer				
Turtle PTS†	0.20	0.00	0.00	0.00
Turtle TTS†	20.20	0.00	0.00	0.00
Turtle behavioural response#	230.18	0.00	0.00	0.00
Turtle behavioural disturbance‡	18.41	0.00	0.00	0.00

† Frequency-weighted SEL_{24h} based turtle PTS and TTS thresholds (Finneran et al. 2017)
#166 dB re 1 µPa (SPL) (NSF 2011)
‡175 dB re 1 µPa (SPL) (McCauley et al. 2000a, 2000b)

3.2.2. Area within 95th percentile ranges (P_{95})

At Brecknock, no exposures were recorded for migratory or inter-nesting turtles due to the distance from the FPSO pile of any defined turtle BIAs, therefore no animat simulation results are presented for turtles at Brecknock.

Table 12. *Brecknock*: Area (km^2) within the 95th percentile exposure ranges, P_{95} (km), for pygmy blue whale animat simulation scenarios without an exclusion zone implemented.

Threshold	Migrating		Foraging	
	Area within P_{95} (km^2)	Area of PBW migratory BIA within P_{95} (km^2)	Area within P_{95} (km^2)	Area of PBW foraging BIA within P_{95} (km^2)
IHC S-600 hammer				
LF cetacean PTS†	4.08	4.07	0.00	0.00
LF cetacean TTS†	176.71	117.71	393.38	1.81
Marine mammal behavioural response#	44.18	35.51	0.00	0.00
IHC S-1200 hammer				
LF cetacean PTS†	4.99	4.97	0.00	0.00
LF cetacean TTS†	204.60	134.19	490.87	0.00
Marine mammal behavioural response#‡	235.06	152.04	454.65	7.91

† Frequency-weighted SEL_{24h} based marine mammal PTS and TTS thresholds (NMFS 2018)
#160 dB re 1 µPa (SPL) (NMFS 2014)

Table 13. *Brecknock*: Area (km^2) within the 95th percentile exposure ranges, P_{95} (km), for pygmy blue whale animat simulation scenarios with a 2000 m exclusion zone implemented.

Threshold	Migrating		Foraging	
	Area within P_{95} (km^2)	Area of PBW migratory BIA within P_{95} (km^2)	Area within P_{95} (km^2)	Area of PBW foraging BIA within P_{95} (km^2)
IHC S-600 hammer				
LF cetacean PTS†	0.00	0.00	0.00	0
LF cetacean TTS†	184.82	122.51	393.38	1.81
Marine mammal behavioural response#	48.03	38.09	0.00	0
IHC S-1200 hammer				
LF cetacean PTS†	0.00	0.00	0.00	0.00
LF cetacean TTS†	210.21	137.49	456.17	8.10
Marine mammal behavioural response#‡	239.43	154.59	454.65	7.91

† Frequency-weighted SEL_{24h} based marine mammal PTS and TTS thresholds (NMFS 2018)
#160 dB re 1 µPa (SPL) (NMFS 2014)

3.2.3. Animal Movement and Exposure Modelling

At Brecknock, no exposures were recorded for migratory or inter-nesting turtles due to the distance from the pile of any defined turtle BIAs, therefore no results are presented.

3.3. Vessel noise

3.3.1. Additional modelling results

3.3.1.1. Tabulated results

Modelling results for additional modelled scenarios considering both Floating Production Storage and Offloading (FPSO) facilities during offtake along with operations of a Mobile Offshore Drilling Unit (MODU) under dynamic positioning at either the Torosa TRD well or Brecknock are presented in Tables 14 and 15.

Table 14. *Vessels, SPL*: Areas (km^2, WGS84, geographic) for combined FPSO offtake and MODU operations within isopleths corresponding to the threshold for marine mammal behavioural response to continuous noise (NMFS 2014).

SPL (*L_p*; dB re 1 µPa)	**Both FPSO's offloading with MODU at Torosa TRD well**	**Both FPSO's offloading with MODU at Brecknock**
	Area (km^2)	Area (km^2)
120†	481.9	551.2

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).
FPSO offtake (offloading) includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Table 15. *Vessels, SEL$_{24}$*: Areas (km^2, WGS84, geographic) for combined FPSO offtake and MODU operations within isopleths corresponding to the thresholds for maximum-over-depth PTS and TTS thresholds for cetaceans (NMFS 2018) and turtles (Finneran et al. 2017).

Hearing group	**Threshold for SEL$_{24h}$ ($L_{E,24h}$ dB re 1 µPa²·s) #**	**Both FPSO's offloading with MODU at Torosa TRD well**	**Both FPSO's offloading with MODU at Brecknock**
		Area (km^2)	Area (km^2)
PTS			
LF cetaceans	199	0.16	0.16
MF cetaceans	198	0.001	0.001
HF cetaceans	173	0.62	0.62
Turtles	220	0.017	0.016
TTS			
LF cetaceans	179	30.05	18.95
MF cetaceans	178	0.41	0.41
HF cetaceans	153	201.5	211.7
Turtles	200	0.13	0.13

A dash indicates the level was not reached.
Frequency weighted.
Only areas > 0.001 km^2 are resolved.
FPSO offtake (offloading) includes an FPSO under DP, a noiseless condensate tanker and an OSV.

3.3.1.2. Sound field maps

Maps of the estimated sound fields, threshold contours, and isopleths of interest for SPL and SEL_{24h} sound fields have been presented for the aggregate FPSO and MODU modelling scenarios (Table 1 details source locations) in Figures 4–7.

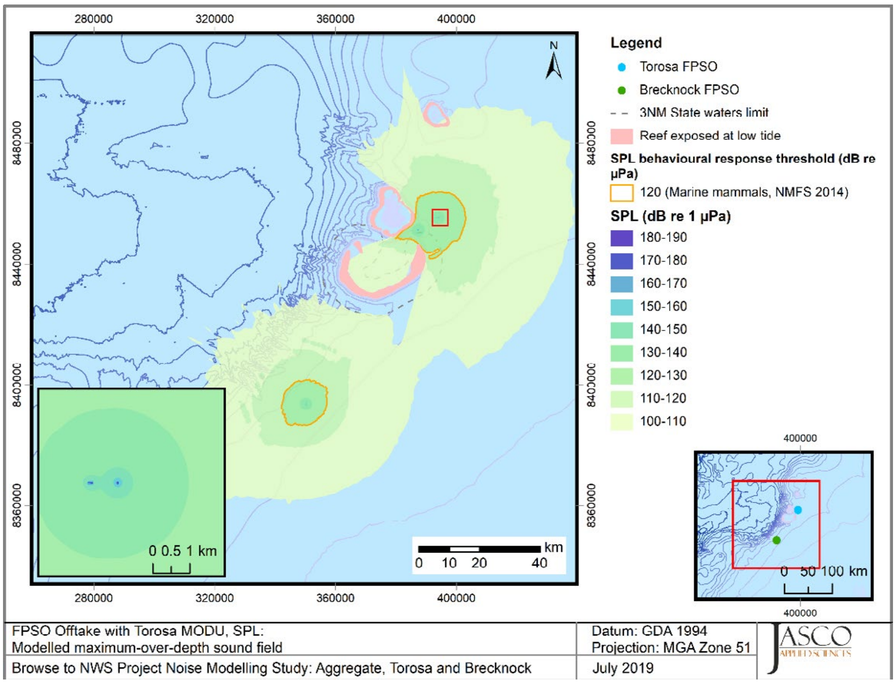

Figure 4. *Torosa and Brecknock, Aggregate FPSO offtake and MODU at Torosa TRD well, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal (120 dB re 1 µPa) behavioural criteria is shown.

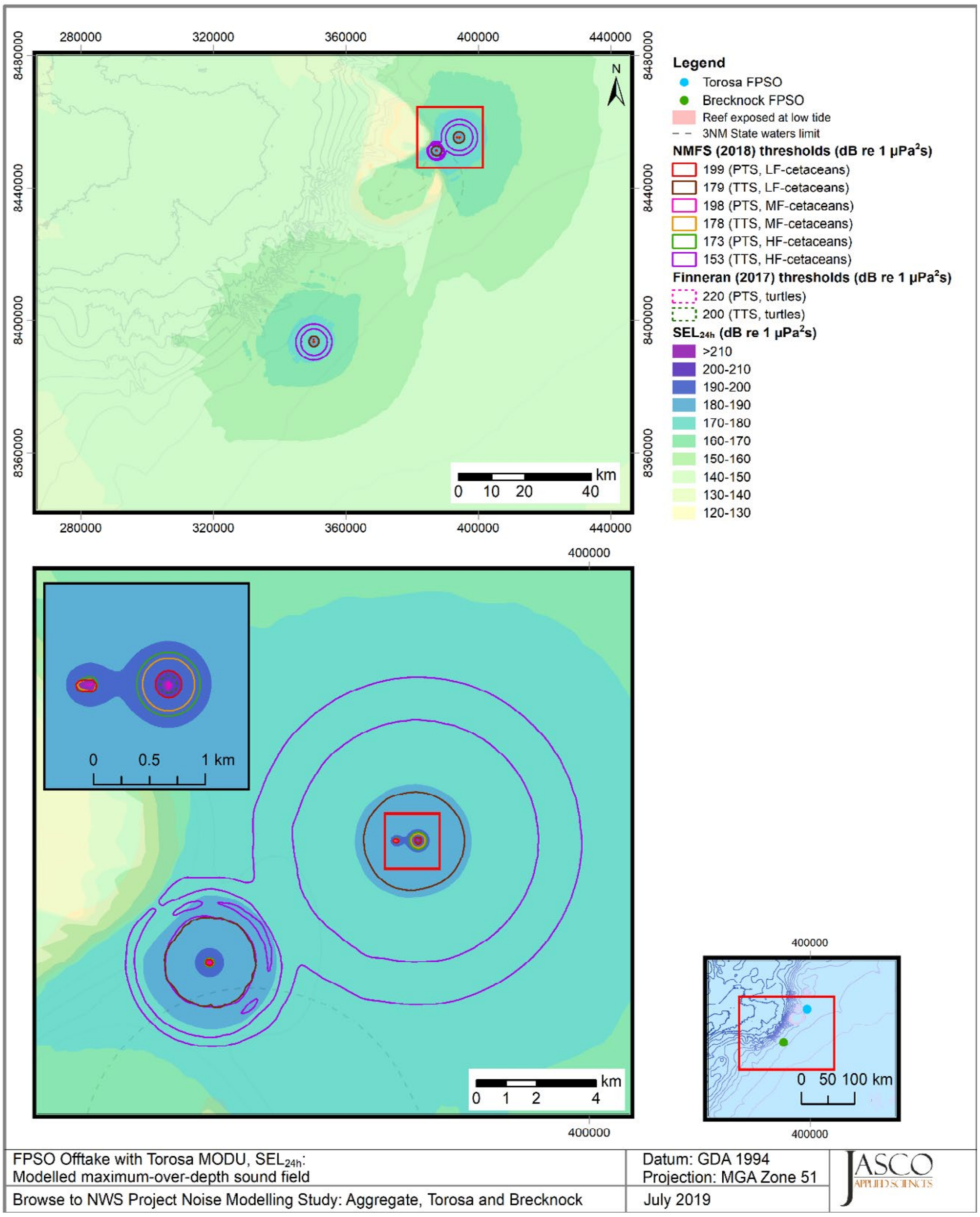

Figure 5. *Torosa and Brecknock, Aggregate FPSO offtake and MODU at Torosa TRD well, SEL24h*: Sound level contour map showing unweighted maximum-over-depth SEL24h results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles.

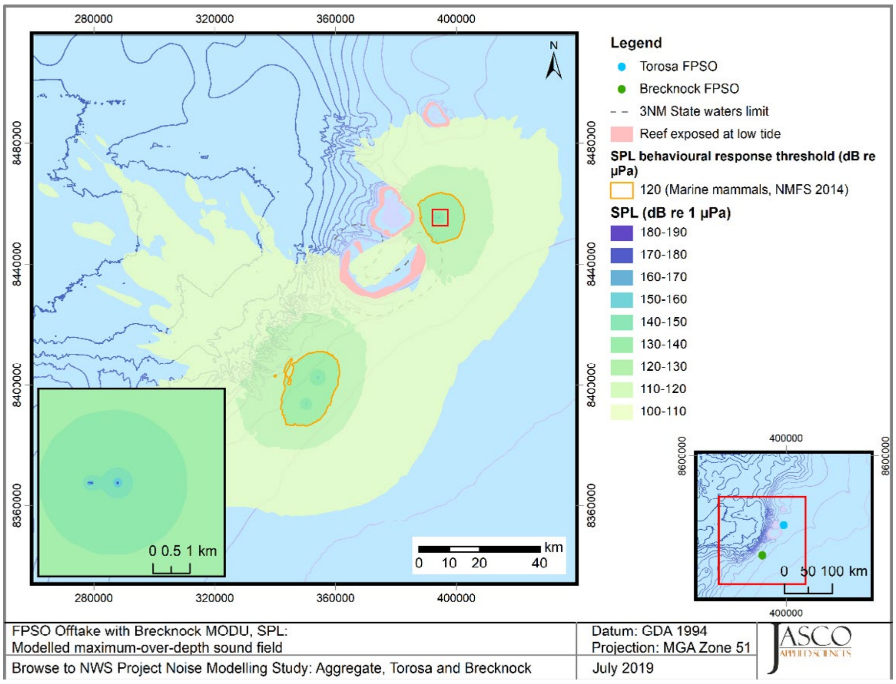

Figure 6. *Torosa and Brecknock, Aggregate FPSO offtake and MODU at Brecknock, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal (120 dB re 1 µPa) behavioural criteria is shown.

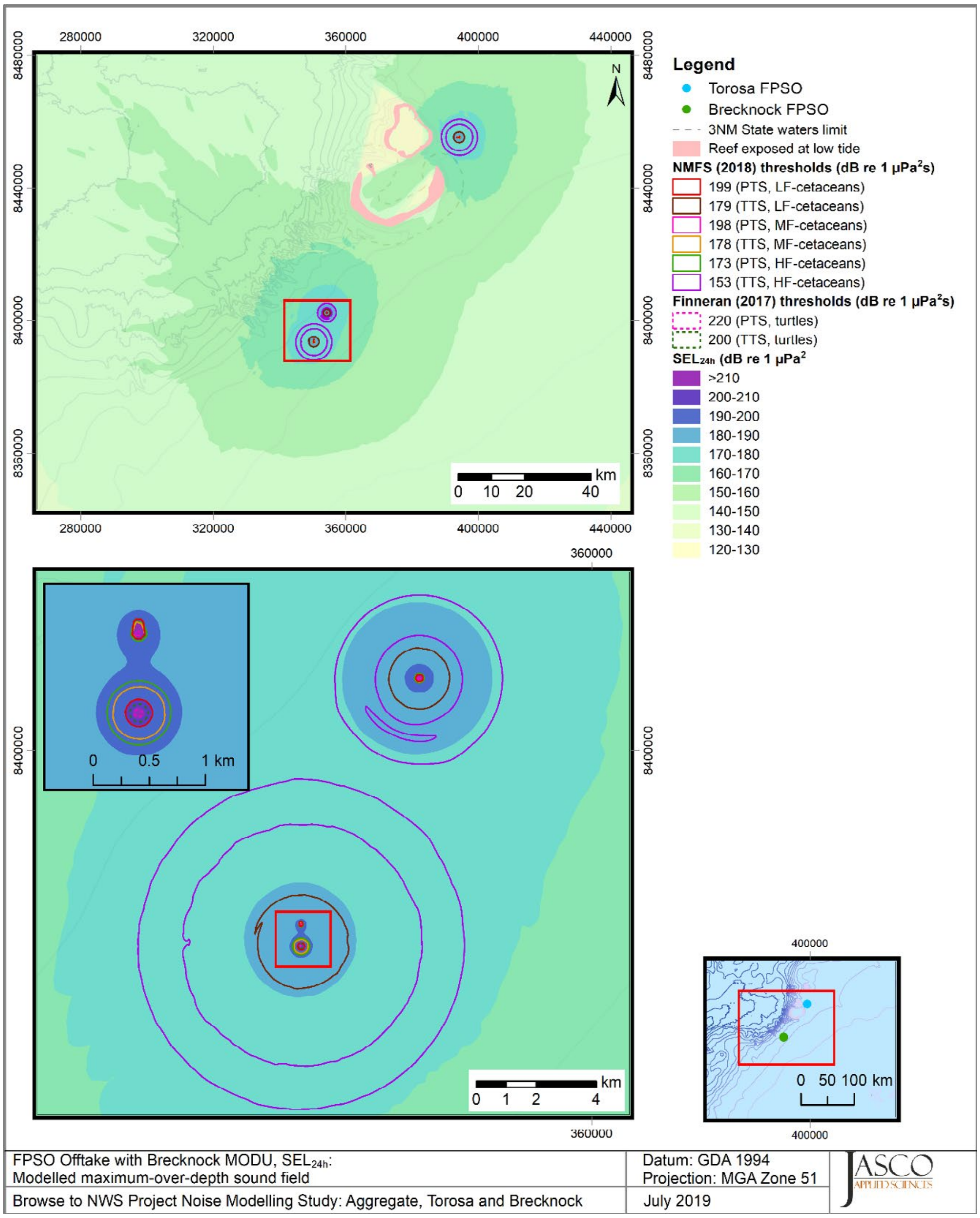

Figure 7. *Torosa and Brecknock, Aggregate FPSO offtake and MODU at Brecknock, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL24h results, along with isopleths for low-, mid-, and high-frequency cetaceans and turtles.

3.3.2. Exposed Areas

The area within threshold isopleth for marine mammal behavioural response to continuous noise (NMFS 2014) from the vessel scenarios considered in McPherson et al. (2019) and Section 3.3.1.1 are presented in Table 16, along with the area of each pygmy blue whale BIA in which the threshold is exceeded.

Table 16. Ensonified areas within 120 dB re 1 µPa (SPL) isopleth, and the ensonified area of the pygmy blue whale (PBW) migratory and foraging BIA's.

Scenario Name	Area within 120 dB re 1 µPa (SPL) isopleth† (km^2)	Area within PBW migratory BIA (km^2)	Area within PBW foraging BIA (km^2)
Torosa			
MODU	111.2	111.2	111.2
FPSO on DP	183.4	183.4	164.8
FPSO without DP	1.0	1.0	1.0
Offtake Support Vessel on DP	15.3	15.3	15.3
FPSO Offtake	192.9	192.9	174.2
Brecknock			
MODU	185.7	180.7	47.6
FPSO on DP	173.3	134.3	0.0
FPSO without DP	1.1	1.1	0.0
Offtake Support Vessel on DP	17.1	17.0	0.0
FPSO Offtake	181.5	139.9	0.0
Aggregate			
FPSO without DP at both Torosa and Brecknock	1.9	1.9	1.0
FPSO Offtake at both Torosa and Brecknock	374.5	332.8	174.2
FPSO Offtake at both Torosa and Brecknock, and MODU at Torosa	481.9	440.2	274.6
FPSO Offtake at both Torosa and Brecknock, and MODU at Brecknock	551.2	491.2	232.3

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).

4. Discussion

This addendum presents exposure areas for isopleths representing specific thresholds from the static sound field modelling results and scenarios originally presented in McPherson et al. (2019). Two additional aggregate scenarios are presented in this addendum. The presented areas are associated with noise exposures and thresholds both continuous and impulsive noise sources respectively.

This study presents areas of exposure associated with continuous noise source underwater sound levels from scenarios that include the operations of a Mobile Offshore Drilling Unit (MODU), FPSOs with and without DP operating, an OSV near each FPSO, and Offtake operations including an FPSO under DP, a noiseless condensate tanker and an OSV for locations at Torosa and Brecknock.

Areas of exposure associated with impulsive noise sources from scenarios that include impact driving of subsea piles to anchor the Torosa and Brecknock FPSO facility turret are also presented.

The areas presented in both this addendum and McPherson et al. (2019) represent the areas from the considered modelling scenarios and specific sources. Depending upon the metric and threshold, these areas can be combined to create a simplistic representation of the area within which a threshold is exceeded to assist with the impact assessment.

4.1. Cumulative Scenarios from Impulsive and Continuous Sources

4.1.1. Areas associated with PTS and TTS thresholds

Considering the different characterises of continuous versus impulsive sources, the adopted noise exposure criteria NMFS (2018) considers several received level thresholds and two metrics to assess the effect of noise on marine mammals of the considered sources. One set of metrics and thresholds apply to continuous (non-pulsed) noise sources and a different set apply to impulsive sources. Considering this, it is not possible to present distances to thresholds for cumulative scenarios that contain both pile driving and vessel noise (impulsive and continuous sources). The total exposed area for marine mammal PTS or TTS could be calculated considering the individual exposure areas to determine the maximum exposed area for a cumulative scenario with both continuous and impulsive sources; however this is likely an unduly simplistic and un-assessable given the NMFS (2018) exposure criteria. It also depends upon the time period the different sources under consideration are operational.

Furthermore, the NMFS (2018) criteria were developed considering impulsive source and continuous sources separately, it is therefore appropriate to assess impulsive and continuous (pile driving and vessel noise) separately. No criteria exist for received levels with impulsive and continuous character and it is not currently known what the effect of a received levels with impulsive and continuous character would have on marine mammal PTS and TTS thresholds and spatial extent, if any.

4.1.2. Behavioural Areas

Similar to the points above in regard to PTS and TTS thresholds, an aggregate area considering the behavioural response to sound could be calculated from pile driving and vessel operations. However, ability to assess the source specific spatial extent of behavioural thresholds would be lost in an aggregate impulsive and continuous scenario because the threshold is associated with different sound levels.

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