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# Underwater noise modelling at the Teesside A offshore wind farm, Dogger Bank

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# 1 Introduction

Underwater noise propagation modelling was carried out by the National Physical Laboratory (NPL) (Theobald *et al*. 2013, hereafter the “NPL Report”) to assess the effects of noise from the construction of the Teesside A offshore wind farm, part of the Dogger Bank development area.

Since the NPL modelling was completed, new noise thresholds and criteria have been developed by Southall *et al*. (2019) for impacts on marine mammals and Popper *et al*. (2014) for impact on fish. To obtain impact ranges using these criteria at Teesside A, additional modelling has been carried out by Subacoustech Environmental.

The modelling undertaken by Subacoustech Environmental has sought to replicate the model of modelling by NPL as closely as possible, capable of providing equivalent results for given inputs and scenarios. Initially Subacoustech’s modelling was run to verify that results closely matched the NPL predicted ranges under the original scenarios. The results were then re-analysed to produce new ranges based on the up-to-date criteria.

In addition to these new criteria, additional modelling was carried out by Subacoustech Environmental to estimate noise levels produced by larger hammers using greater blow energies than those previously modelled. The noise from other related noise sources including cable laying, trenching, rock placement, vessel noise, and operational wind turbine generators (WTGs) have also been considered.

A map of the Teesside A site as part of the larger Dogger Bank development area, including the modelling locations, is shown in Figure 1-1.

This report assumes familiarity with basic underwater acoustical concepts and metrics.

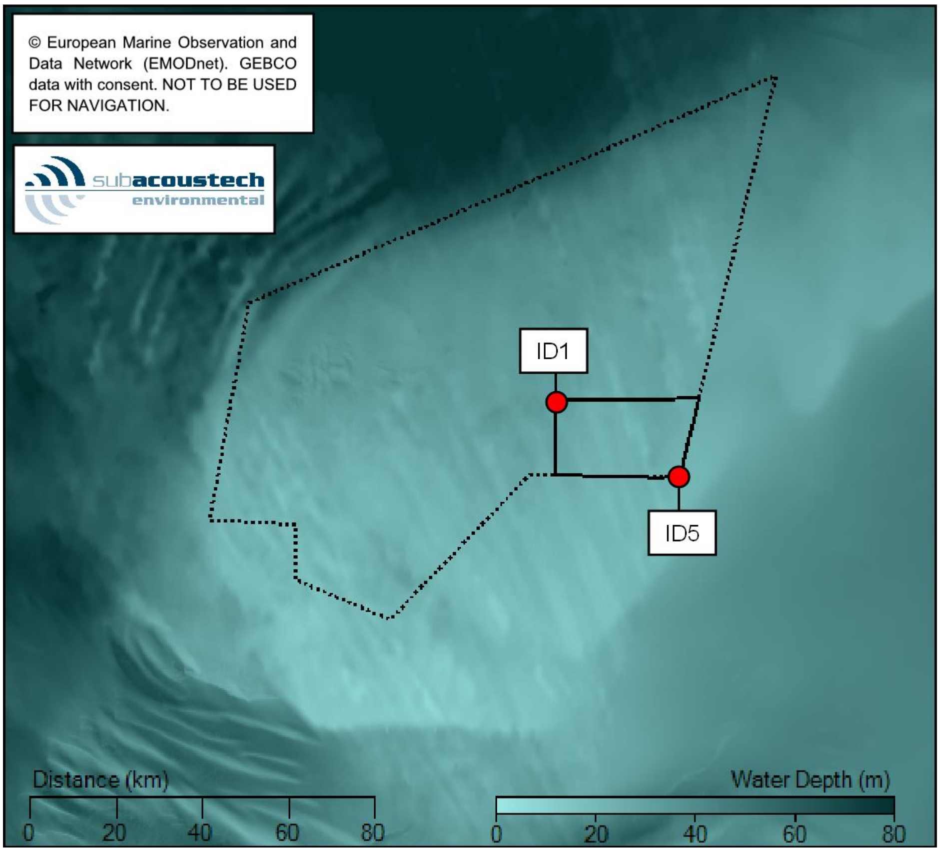


*Figure 1-1 Overview map showing the Teesside A windfarm boundary and the approximate locations used for the modelling*

# 2 Assessment criteria

## 2.1 Background

Over the past 20 years it has become increasingly evident that noise from human activities in and around underwater environments have the potential to cause adverse impacts on marine species in the area. The extent to which intense underwater sound might cause an adverse impact to a species is dependent upon the incident sound level, sound frequency, duration of exposure and/or repetition rate of an impulsive sound (Hastings and Popper, 2005), as well as the sensitivity of the species. As a result, scientific interest in the hearing abilities of aquatic animal species has increased. Studies are primarily based on evidence from high intensity sources of underwater noise such as blasting or impact piling, as these sources are likely to have the greatest environmental impact and the clearest observable effects, although there has been more interest in chronic noise exposure over the last ten years.

For this study, various criteria have been used, covering the values used in the NPL Report for comparison and the more up to date studies from Southall *et al*. (2019) for marine mammals and Popper *et al*. (2014) for fish.

## 2.2 Criteria from the NPL report

The following criteria were used in the NPL report and have been used to give a direct comparison between the NPL modelling and the INSPIRE modelling carried out for this study.

- Southall *et al*. (2007) for species of cetaceans and pinnipeds;
- Lucke *et al*. (2009) for harbour porpoises;
- Popper *et al*. (2006) and Carlson *et al*. (2007) for injury in fish using $SPL_{peak}$;
- Halvorsen *et al*. (2011) for injury in fish using $SEL_{cum}$; and
- McCauley *et al*. (2000) and Pearson *et al*. (1992) for behavioural response in fish.

These criteria are summarised in Table 2-1 to Table 2-5 as they appear in the NPL report.

| Effect | Criteria |
|---|---|
| Instantaneous injury / PTS | 200 dB re 1 µPa ($SPL_{peak}$) |
| | 179 dB re 1 µPa²s ($SEL_{ss}$) |
| TTS / fleeing response | 194 dB re 1 µPa ($SPL_{peak}$) |
| | 164 dB re 1 µPa²s ($SEL_{ss}$) |
| Possible avoidance from area | 168 dB re 1 µPa ($SPL_{peak}$) |
| | 145 dB re 1 µPa²s ($SEL_{ss}$) |

*Table 2-1 Criteria for assessing harbour porpoise impacts as presented in the NPL report. These have been derived from Lucke et al. (2009)*

| Effect | Criteria |
|---|---|
| Instantaneous injury / PTS | 230 dB re 1 µPa ($SPL_{peak}$) |
| | 198 dB re 1 µPa²s ($M_{mf}$-weighted $SEL_{ss}$) |
| TTS / fleeing response | 224 dB re 1 µPa ($SPL_{peak}$) |
| | 183 dB re 1 µPa²s ($M_{mf}$-weighted $SEL_{ss}$) |
| Likely avoidance from area | 170 dB re 1 µPa²s ($SEL_{ss}$) |
| Possible avoidance from area | 160 dB re 1 µPa²s ($SEL_{ss}$) |

*Table 2-2 Criteria for assessing mid-frequency (MF) cetacean impacts (including bottlenose dolphins) as presented in the NPL report. These have been derived from Southall et al. (2007)*

| Effect | Criteria |
|---|---|
| Instantaneous injury / PTS | 230 dB re 1 µPa ($SPL_{peak}$) |
| | 198 dB re 1 µPa$^2$s ($M_{lf}$-weighted $SEL_{ss}$) |
| TTS / fleeing response | 224 dB re 1 µPa ($SPL_{peak}$) |
| | 183 dB re 1 µPa$^2$s ($M_{lf}$-weighted $SEL_{ss}$) |
| Likely avoidance from area | 152 dB re 1 µPa$^2$s ($SEL_{ss}$) |
| Possible avoidance from area | 142 dB re 1 µPa$^2$s ($SEL_{ss}$) |

*Table 2-3 Criteria for assessing low-frequency (LF) cetacean impacts (including Minke whale) as presented in the NPL report. These have been derived from Southall et al. (2007)*

| Effect | Criteria |
|---|---|
| Instantaneous injury / PTS | 218 dB re 1 µPa ($SPL_{peak}$) |
| | 186 dB re 1 µPa$^2$s ($M_{pw}$-weighted $SEL_{ss}$) |
| TTS / fleeing response | 212 dB re 1 µPa ($SPL_{peak}$) |
| | 171 dB re 1 µPa$^2$s ($M_{pw}$-weighted $SEL_{ss}$) |

*Table 2-4 Criteria for assessing pinnipeds (in water) impacts as presented in the NPL report. These have been derived from Southall et al. (2007)*

| Effect | Criteria |
|---|---|
| Instantaneous injury / PTS | 206 dB re 1 µPa ($SPL_{peak}$) |
| | 211 dB re 1 µPa$^2$s ($SEL_{cum}$) |
| Possible moderate to strong avoidance | 168 – 173 dB re 1 µPa ($SPL_{peak}$) |
| Startle response or C-turn reaction | 200 dB re 1 µPa ($SPL_{peak}$) |

*Table 2-5 Criteria for assessing fish impacts as presented in the NPL report. These have been derived from Popper et al (2006), Carlson et al. (2007), Halvorsen et al. (2011), McCauley et al. (2000) and Pearson et al. (1992)*

## 2.3 Impacts on marine mammals

The Southall *et al*. (2019) paper on the effects of underwater noise on marine mammals is an update of the previous Southall *et al*. (2007) criteria, and was co-authored by many of the same authors. It gives identical thresholds to those from the NMFS (2018) guidance for marine mammals, although alters the category names (see below).

The Southall *et al.* (2019) guidance groups marine mammals into groups of similar species and applies filters to the unweighted noise to approximate the hearing sensitivity of the wider receptor group. The hearing groups given by Southall *et al.* (2019) are summarised in Table 2-6 and Figure 2-1. Further groups for sirenians and other marine carnivores in water are also given in the guidance but these have not been used in this study as those species are not commonly found in the areas surrounding Dogger Bank.

| Hearing group | Example species | Generalised hearing range |
|---|---|---|
| Low-frequency cetaceans (LF) | Baleen whales | 7 Hz to 35 kHz |
| High-frequency cetaceans (HF) | Dolphins, Toothed Whales, Beaked Whales, Bottlenose Whales (including Bottlenose Dolphin) | 150 Hz to 160 kHz |
| Very high-frequency cetaceans (VHF) | True Porpoises (including Harbour Porpoise) | 275 Hz to 160 kHz |
| Phocid Carnivores in Water (PCW) | True Seals (including Harbour Seal) | 50 Hz to 86 kHz |

*Table 2-6 Marine mammal hearing groups (from Southall et al. 2019)*

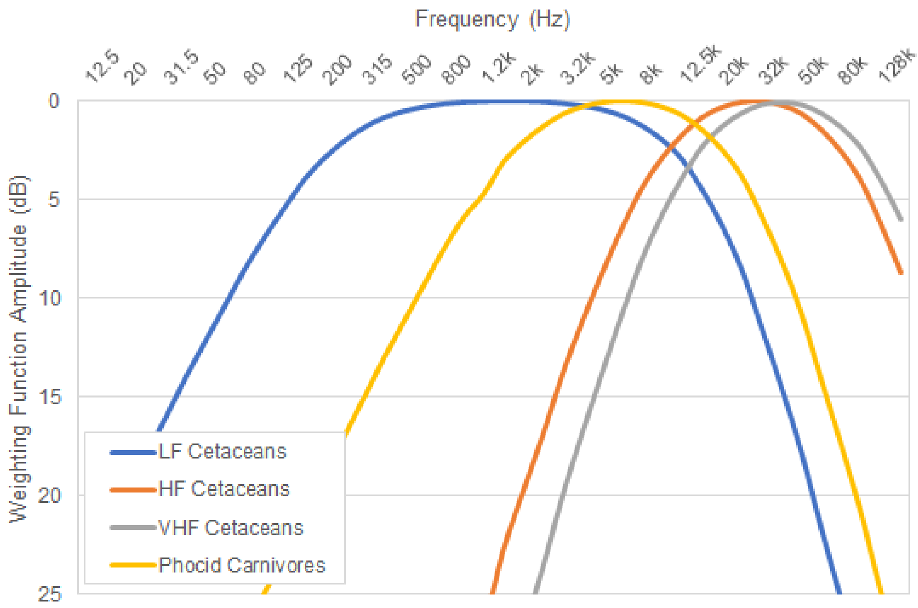


*Figure 2-1 Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al. 2019)*

It should also be noted that the criteria in NMFS (2018), although numerically identical to those in Southall *et al.* , apply different names to the marine mammal groupings and weightings. For example, the group Southall *et al.* (2019) refers to as high-frequency cetaceans (HF), is referred to in NMFS (2018) as mid-frequency cetaceans (MF), and the group Southall *et al*. (2019) refers to as very high-frequency cetaceans (VHF), is referred to as high-frequency cetaceans (HF) by NMFS (2018). As such, great care should be taken when comparing results using the Southall *et al*. (2019) and NMFS (2018), as well as Southall *et al.* (2007), criteria, especially as the “HF” groupings and criteria describe different species depending on which study is being used. The differences are summarised in Table 2-7.

| **Southall *et al*. (2019) hearing group** | **NMFS (2018) hearing group** |
|---|---|
| Low-frequency cetaceans (LF) | Low-frequency cetaceans (LF) |
| High-frequency cetaceans (HF) | Mid-frequency cetaceans (MF) |
| Very high-frequency cetaceans (VHF) | High-frequency cetaceans (HF) |
| Phocid carnivores in water (PCW) | Phocid pinnipeds in water (PW) |

*Table 2-7 Summary of the differences in weighting group names between the Southall et al. (2019) and NMFS (2018) criteria*

The Southall *et al* (2019) criteria has been used for this study as it is a peer-reviewed and published paper in a reputable journal, whereas NMFS (2018) is a guidance document from a government agency and, as such, could be subject to changes at any point.

Southall *et al*. (2019) gives individual criteria based on whether a noise source is considered impulsive or non-impulsive. The study categorises impulsive noises as having high peak sound pressure, short duration, fast rise-time, and broad frequency content at source, and non-impulsive sources as steady-state noise without the other above characteristics. Explosives, impact piling and seismic airguns are considered impulsive noise sources, sonars, vibropiling and other low-level continuous noises are considered non-impulsive. A non-impulsive sound does not necessarily have to have a long duration.

Southall *et al*. (2019) presents single strike, unweighted peak criteria ($SPL_{peak}$) and cumulative (i.e. more than a single sound impulse) weighted sound exposure criteria ($SEL_{cum}$) for both permanent threshold shift (PTS), where unrecoverable hearing damage may occur, and temporary threshold shift (TTS), where a temporary reduction in hearing sensitivity may occur in individual receptors.

As sound pulses, such as those from impact piling, propagate through the environment and dissipate, they also lose their most injurious characteristics (e.g. rapid pulse rise time, high peak sound pressure) and become more like a "non-pulse" at greater distances. This is briefly discussed in Southall *et al*. (2019). Active research is currently underway into identification of the distance at which the pulse can be considered effectively non-impulsive (Hastie *et al*. 2019). Although the situation is complex, the paper reported that most of the signals analysed (piling and seismic sources) crossed the threshold defined by Hastie *et al.* (2019) associated with impulsive noise for rapid rise time and high peak pressure at around 3.5 km. The signals beyond this point could be considered non-impulsive, and it is suggested that, beyond this point, signals will increasingly be better represented using the non-impulsive criteria.

Table 2-8 and Table 2-9 present the Southall *et al*. (2019) criteria for onset of risk of PTS and TTS for each of the key marine mammal hearing groups for impulsive and non-impulsive sources. In addition, single strike SEL values ($SEL_{ss}$) for each of the $SEL_{cum}$ criteria have been included to aid with the assessment. These are presented in Appendix A.

| Impulsive noise | PTS criteria | | TTS criteria | |
|---|---|---|---|---|
| **Group** | **$SEL_{cum}$ (weighted) dB re 1 µPa²s** | **$SPL_{peak}$ (unweighted) dB re 1 µPa** | **$SEL_{cum}$ (weighted) dB re 1 µPa²s** | **$SPL_{peak}$ (unweighted) dB re 1 µPa** |
| Low-frequency cetaceans (LF) | 183 | 219 | 168 | 213 |
| High-frequency cetaceans (HF) | 185 | 230 | 170 | 224 |
| Very high-frequency cetaceans (VHF) | 155 | 202 | 140 | 196 |
| Phocid carnivores in water (PCW) | 185 | 218 | 170 | 212 |

*Table 2-8 Assessment criteria for marine mammals from Southall et al. (2019) for impulsive noise*

| Non-impulsive noise | PTS criteria | TTS criteria |
|---|---|---|
| **Group** | **$SEL_{cum}$ (weighted) dB re 1 µPa²s** | **$SEL_{cum}$ (weighted) dB re 1 µPa²s** |
| Low-frequency cetaceans (LF) | 199 | 179 |
| High-frequency cetaceans (HF) | 198 | 178 |
| Very high-frequency cetaceans (VHF) | 173 | 153 |
| Phocid carnivores in water (PCW) | 201 | 181 |

*Table 2-9 Assessment criteria for marine mammals from Southall et al. (2019) for non-impulsive noise*

### *2.3.1 Weighted source levels*

To undertake the modelling for the Southall *et al*. (2019) criteria, with regards to the weighted $SEL_{cum}$ criteria, the $SEL_{ss}$ source levels were first adjusted using the auditory weighting functions shown in Figure 2-1. This significantly alters the source level for each functional group as shown in Figure 2-2. The equivalent 4000 kJ and 5400 kJ source spectra are not shown as they are visually identical to those for 3000 kJ (with an altered source level).

Noise from impact piling is predominantly low frequency in nature and reduces significantly at frequencies above 1 kHz. The impact piling source levels for monopiles using a 3000 kJ hammer blow energy given as 1/3 octave spectra in Figure 2-2 show that the weighting only makes a modest difference to source levels for LF cetaceans when weightings are applied and a significant reduction for other hearing groups.

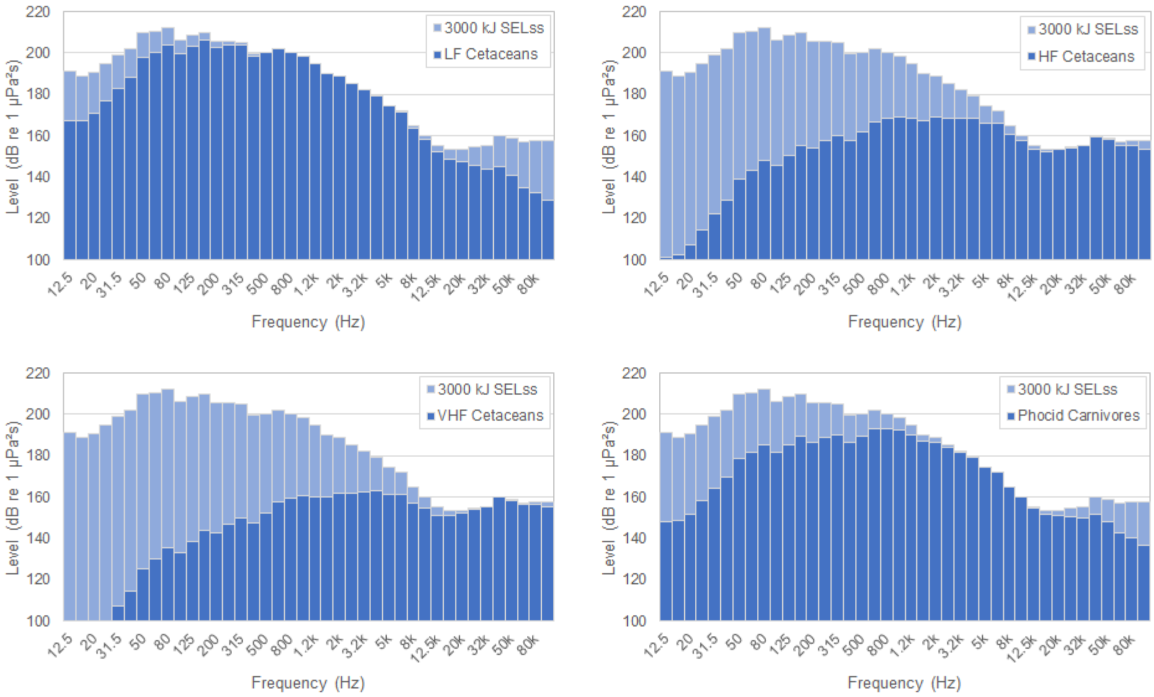


*Figure 2-2 Unweighted and Southall et al. (2019) weighted SEL monopile impact piling source level third octave values for LF, HF, VHF and PCW hearing groups for a 3000 kJ hammer*

## 2.4 Impacts on fish

The effects of noise on fish have been assessed using criteria from Popper *et al*. (2014), which gives specific criteria for mortality and potential mortal injury, recoverable injury and TTS, masking and behaviour from various stimuli, including impact piling. Species of fish are grouped by whether they have a swim bladder and whether that swim bladder is involved in its hearing. The criteria are given as unweighted $SPL_{peak}$, and $SEL_{cum}$ values and are summarised in Table 2-10 for impact piling and Table 2-11 for continuous noise sources.

| Impact piling | Mortality & potential mortal injury | Impairment | |
|---|---|---|---|
| | | Recoverable injury | TTS |
| Fish: no swim bladder | > 219 dB $SEL_{cum}$<br>> 213 dB $SPL_{peak}$ | > 216 dB $SEL_{cum}$<br>> 213 dB $SPL_{peak}$ | >> 186 dB $SEL_{cum}$ |
| Fish: swim bladder not involved in hearing | 210 dB $SEL_{cum}$<br>> 207 dB $SPL_{peak}$ | 203 dB $SEL_{cum}$<br>> 207 dB $SPL_{peak}$ | > 186 dB $SEL_{cum}$ |
| Fish: swim bladder involved in hearing | 207 dB $SEL_{cum}$<br>> 207 dB $SPL_{peak}$ | 203 dB $SEL_{cum}$<br>> 207 dB $SPL_{peak}$ | 186 dB $SEL_{cum}$ |

*Table 2-10 Assessment criteria for species of fish from Popper et al. (2014) for impact piling noise*

| Shipping and continuous sounds | Impairment | |
|---|---|---|
| | Recoverable injury | TTS |
| Fish: swim bladder involved in hearing | 170 dB RMS for 48h | 158 dB RMS for 12h |

*Table 2-11 Assessment criteria for species of fish from Popper et al. (2014) for shipping and continuous sounds*

Where insufficient data is available (which is the case for masking and behavioural effects from impact piling), qualitative criteria have been given, summarising the effect of the noise as having either a high, moderate or low effect on an individual in either the near-field (tens of metres), intermediate-field (hundreds of metres) or far-field (thousands of metres). This also includes information for masking and behavioural effect. These qualitative effects are reproduced in Table 2-12 and Table 2-13.

| Impact piling | **Mortality and potential mortal injury** | **Recoverable injury** | **TTS** | **Masking** | **Behaviour** |
|---|---|---|---|---|---|
| Fish: no Swim bladder | See Table 2-10 | See Table 2-10 | See Table 2-10 | (N) Moderate<br>(I) Low<br>(F) Low | (N) High<br>(I) Moderate<br>(F) Low |
| Fish: swim bladder not involved in hearing | See Table 2-10 | See Table 2-10 | See Table 2-10 | (N) Moderate<br>(I) Low<br>(F) Low | (N) High<br>(I) Moderate<br>(F) Low |
| Fish: swim bladder involved in hearing | See Table 2-10 | See Table 2-10 | See Table 2-10 | (N) High<br>(I) High<br>(F) Moderate | (N) High<br>(I) High<br>(F) Moderate |

*Table 2-12 Summary of the qualitative effects on fish from impact piling noise from Popper et al. (2014) (N=Near field, I=Intermediate field, F=Far field)*

| Shipping and continuous sounds | **Mortality and potential mortal injury** | **Recoverable injury** | **TTS** | **Masking** | **Behaviour** |
|---|---|---|---|---|---|
| Fish: no Swim bladder | (N) Low<br>(I) Low<br>(F) Low | (N) Low<br>(I) Low<br>(F) Low | (N) Moderate<br>(I) Low<br>(F) Low | (N) High<br>(I) High<br>(F) Moderate | (N) Moderate<br>(I) Moderate<br>(F) Low |
| Fish: swim bladder not involved in hearing | (N) Low<br>(I) Low<br>(F) Low | (N) Low<br>(I) Low<br>(F) Low | (N) Moderate<br>(I) Low<br>(F) Low | (N) High<br>(I) High<br>(F) Moderate | (N) Moderate<br>(I) Moderate<br>(F) Low |
| Fish: swim bladder involved in hearing | (N) Low<br>(I) Low<br>(F) Low | See Table 2-11 | See Table 2-11 | (N) High<br>(I) High<br>(F) High | (N) High<br>(I) Moderate<br>(F) Low |

*Table 2-13 Summary of the qualitative effects on fish from impact piling noise from Popper et al. (2014) (N=Near field, I=Intermediate field, F=Far field)*

Both a fleeing animal and stationary animal model have been used for assessing the $SEL_{cum}$ criteria for fish. It is recognised that there is limited evidence for fish fleeing from high noise sources in the wild and it would reasonably be expected that the reaction would differ between species. Most species are likely to move away from a sound that is loud enough to cause harm (Dahl *et al.,* 2015; Popper *et al*., 2014), some may seek protection in the sediment and others may dive deeper in the water column. The flee speed chosen for this study of 1.5 $ms^{-1}$ is relatively slow in relation to the data in Hirata (1999) and thus is considered somewhat conservative.

Although it is feasible that some species will not flee, those that are likely to remain are thought more likely to be benthic species or species without a swim bladder; these are the least sensitive species. For example, from Popper *et al*. (2014): "There is evidence (e.g. Goertner *et al*., 1994; Stephenson *et al.*, 2010; Halvorsen *et al.*, 2012) that little or no damage occurs to fishes without a swim bladder except at very short ranges from an in-water explosive event. Goertner (1978) showed that the range from an explosive event over which damage may occur to a non-swim bladder fish is in the order of 100 times less than that for swim bladder fish."

Stationary animal modelling has been included in this study, based on research from Hawkins *et al.* (2014). However, basing the assessment on a stationary (zero flee speed) receptor is likely to greatly overestimate the potential risk to fish species, especially when considering the precautionary nature of the parameters already built into the cumulative exposure model.

# 3 Modelling methodology

## 3.1 NPL modelling

The original modelling for Teesside A was undertaken by NPL. The modelling utilised an energy flux solution by Weston (1976), capable of calculation of underwater noise propagation over large distances while accounting for range-dependent bathymetry and frequency-dependent absorption.

21 locations were modelled by NPL, covering the extents of the Teesside A site, and for each location pile driving noise was modelled for a hammer operating at up to 3000 kJ.

The model used by NPL is not openly available. As such, Subacoustech Environmental have used a different but comparable modelling method.

## 3.2 Subacoustech Environmental modelling

The primary goal in respect to the first stage of underwater noise propagation modelling presented in this report was to replicate the results from the NPL modelling as closely as possible, to ensure that the new modelling was consistent with that undertaken previously. Results using the Southall *et al*. (2019) and Popper *et al*. (2014) criteria could then be calculated with confidence.

For the modelling in this study, Subacoustech Environmental have used the INSPIRE modelling software to predict noise levels and impact ranges from piling at Teesside A.

The INSPIRE model (currently version 3.5) is a semi-empirical, depth-dependent, underwater noise propagation model based around a combination of numerical modelling and actual measured data from over 50 datasets of noise propagation from impact piling, mostly surrounding the UK. It is designed to calculate the propagation of noise in shallow, mixed, coastal waters, typical of the conditions around the UK, and is well suited to the Dogger Bank, and Teesside A, region.

The model can provide estimates of unweighted $SPL_{peak}$ (peak sound pressure level), $SEL_{ss}$ (single strike sound exposure level) and $SEL_{cum}$ (cumulative sound exposure level) noise levels as well as various other weighted noise metrics. Calculations are made along 180 equally spaced radial transects, i.e. one every 2°. For each modelling run, a criterion level is specified, allowing a noise contour to be drawn, within which a given effect may occur. These results are then plotted over digital bathymetry data so that impact ranges can be clearly visualised and assessed as necessary.

The methods used within this report meet the requirements set by the NPL Good Practice Guide 133 for underwater noise measurement (Robinson *et al.* 2014).

The approach used considers a wide range of input parameters to ensure as detailed results as possible. The resulting transmission losses have then been compared to (and in some cases extrapolated from) the results given in the NPL report to ensure compatibility. This is discussed further in section 3.3.

### *3.2.1 Modelling locations*

Modelling has been undertaken at two locations over the Teesside A site identified in the NPL Report (locations ID1 and ID5 in Table 4.1). These locations have been chosen as they are used for detailed analysis within the NPL Report. The locations encompass the worst-case scenario and include a wide area of the Teesside A site including both deep and shallow water areas.

The approximate location is given in Figure 1-1 and the coordinates are summarised in Table 3-1.

| | ID1 | ID5 |
|---|---|---|
| Latitude | 55.11789°N | 54.95484°N |
| Longitude | 2.57523°E | 3.03186°E |
| Depth (m) | 30 | 21 |

*Table 3-1 Summary of the modelling locations used for this study*

### 3.2.2 Modelling input parameters

The following environmental and noise source parameters have been assumed in the modelling.

*Impact piling*

The original modelling by NPL considered four blow energy scenarios: foundations installed using hammers with blow energies of 300, 1900, 2300, and 3000 kJ, covering various soft start and full power scenarios.

The initial (comparative) scenarios have been modelled using the Subacoustech Environmental approach described above for these four blow energies. In addition, two higher maximum blow energies for monopiles, 4000 kJ and 5400 kJ, could potentially be used for installation and the effects of these have been modelled.

*Source levels*

Underwater noise modelling requires knowledge of the source level, which is the noise level at 1 m from the noise source. The source levels used by NPL for their modelling were not presented in their report. For this study, the source level has been derived by taking the modelled transmission loss of the noise over distance and fitting it to the impact ranges presented previously in the NPL Report. The resulting source levels have been used for calculating the impact ranges for the Southall *et al*. (2019) and Popper *et al*. (2014) criteria. A description for the process of fitting of the data and comparisons to NPL modelling are presented in section 3.3.

The unweighted source levels used for the modelling are provided in Table 3-2 for the maximum blow energies, which are in line with those seen at other, similar scale projects.

| | $SPL_{peak}$ source level | $SEL_{ss}$ source level |
|---|---|---|
| 300 kJ blow energy | 233.2 dB re 1 µPa @ 1 m | 208.0 dB re 1 µPa²s @ 1 m |
| 400 kJ blow energy | 234.8 dB re 1 µPa @ 1 m | 209.4 dB re 1 µPa²s @ 1 m |
| 540 kJ blow energy | 236.4 dB re 1 µPa @ 1 m | 210.8 dB re 1 µPa²s @ 1 m |
| 1900 kJ blow energy | 243.2 dB re 1 µPa @ 1 m | 217.0 dB re 1 µPa²s @ 1 m |
| 2300 kJ blow energy | 244.1 dB re 1 µPa @ 1 m | 217.8 dB re 1 µPa²s @ 1 m |
| 3000 kJ blow energy | 245.2 dB re 1 µPa @ 1 m | 219.0 dB re 1 µPa²s @ 1 m |
| 4000 kJ blow energy | 247.0 dB re 1 µPa @ 1 m | 220.5 dB re 1 µPa²s @ 1 m |
| 5400 kJ blow energy | 248.5 dB re 1 µPa @ 1 m | 221.9 dB re 1 µPa²s @ 1 m |

*Table 3-2 Summary of the unweighted, single strike, source levels used for modelling in this study*

It is important to note that the source level value is theoretical and does not necessarily, nor is intended to, represent the actual noise level at 1 m from the piling operation, which is highly complex close to a large distributed source such as a foundation pile. Its purpose is for the accurate calculation of noise levels at greater distances from the source, to correspond with relevant thresholds, and crucially in this case, to agree with the original NPL modelling.

*Frequency content*

The size of the pile being installed has been applied to the modelling to estimate the frequency content of the noise. Frequency data was not given in the NPL report. As such, frequency data has been derived using Subacoustech Environmental's noise measurement database. Representative third-octave noise levels dependent on the size of the monopiles for Teesside A have been used for this modelling. The SEL third-octave frequency spectrum levels used for modelling are illustrated in Figure 3-1. The shape of each spectrum is the same for all blow energies at source, with the overall source levels adjusted to account for the changing blow energy.

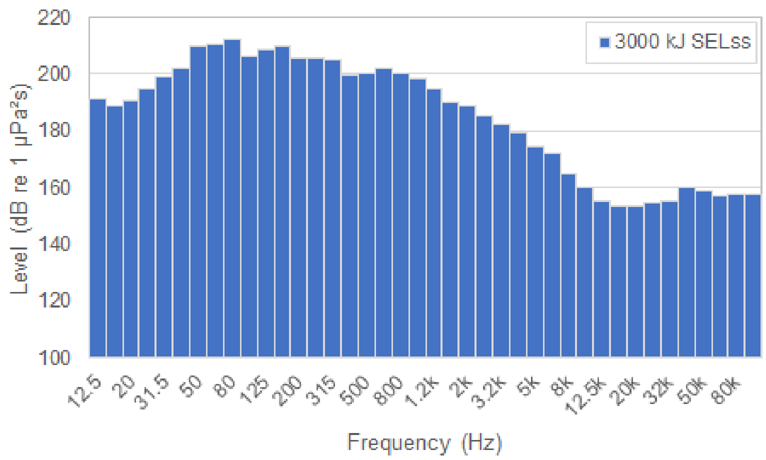


*Figure 3-1 $SEL_{ss}$ third-octave source level frequency spectra used for modelling*

*Soft start, strike rate, and piling duration*

For cumulative SELs ($SEL_{cum}$), which accounts for the total exposure of a receptor to the noise of the complete piling period, the soft start, strike rate and duration of the piling events have also been considered. Table 4.4 in the NPL Report gives a summary of the parameters used for cumulative strike modelling; the two worst case of these sequences have been considered for this modelling. The parameters used for this modelling, based on those given in the NPL report, are summarised in Table 3-3 below. Sequence 2 assumes 5,000 strikes over 140 minutes and sequence 3 assumes 12,600 strikes over 330 minutes. Sequence 1 is not used in this assessment.

The soft start, or the use of lower hammer energy for an initial period, takes place over the first half-hour of piling, with a blow energy of 10% of maximum, then for the remaining number of strikes the blow energy is 100%. This is a worst-case scenario, as it is likely that the blow energy will ramp up gradually from 10% to 100% after the soft start and for engineering reasons piling would not be at 100% for this extended period. However, information on a ramp-up was unavailable in the NPL report, and thus these worst-case assumptions have been made.

| Maximum hammer blow energy | **Percent of maximum blow energy** | |
|---|---|---|
| | **10% (soft start)** | **100%** |
| 3000 kJ blow energy | 300 kJ | 3000 kJ |
| 4000 kJ blow energy | 400 kJ | 4000 kJ |
| 5400 kJ blow energy | 540 kJ | 5400 kJ |
| Strike rate | 1 strike every 3 seconds | 1 strike every 1.5 seconds |
| Duration | 30 minutes | 110 minutes (sequence 2)<br>300 minutes (sequence 3) |
| Number of strikes | 600 strikes | 4,400 strikes (sequence 2)<br>12,000 strikes (sequence 3) |

*Table 3-3 Summary of the multiple pulse scenarios used for cumulative SEL modelling*

*Fleeing receptors*

Where the $SEL_{cum}$ results are required, a fleeing animal model has been used. This assumes that the animal exposed to the noise levels will swim away from the source as it occurs. For this, a constant speed of 3.25 $ms^{-1}$ has been assumed for the low-frequency cetaceans (LF) group (Blix and Folkow, 1995) based on data for Minke whale. All other receptors are assumed to swim at a constant speed of 1.5 $ms^{-1}$ (Otani *et al*. 2000; Hirata, 1999). These are considered worst-case (i.e. relatively slow, leading to greater calculated exposures) as marine mammals are expected to swim much faster under stress conditions. The modelling assumes that when a fleeing receptor reaches the coast it receives no more noise, as it is likely that it will flee along the coast (rather than staying in a single location at the shore).

*Environmental conditions*

By inclusion of measured data from similar offshore impact piling events, the INSPIRE model intrinsically accounts for various environmental conditions. Data from the British Geological Survey (BGS) presented as part of the Marine Environmental Mapping Programme (MAREMAP) show that the areas around Teesside A and the Dogger Bank region generally are made up of sand or gravelly sand.

Bathymetry from the European Marine Observation and Data Network (EMODnet) was used for this modelling. Mean tidal depth was used throughout for the bathymetry to match conditions used in the NPL report.

## 3.3 Results of original and revised modelling comparison

### *3.3.1 Model comparison*

In order to obtain modelling results representative of those produced for the NPL Report, modelling was carried out using the INSPIRE model, using the parameters detailed in the previous section to acquire a transmission loss over multiple transects. These transmission losses were then compared against the results given in the NPL Report. Location ID1 at Teesside A was chosen as a representative modelling location due to its location in the deeper water to the north west of the site.

There was good correlation between the two resultant data sets. Figure 3-2 and Figure 3-3 compare the unweighted noise level plots from the NPL Report and the new Subacoustech modelling at the same scale. It should be noted that although the noise levels do not line up perfectly, the figures do show many of the same features, such as a largely uniform distribution in all directions for the highest noise levels, with larger ranges into the deeper water to the north and northwest and some effects of shallower areas and sandbanks to the south, which reduce noise transmission.

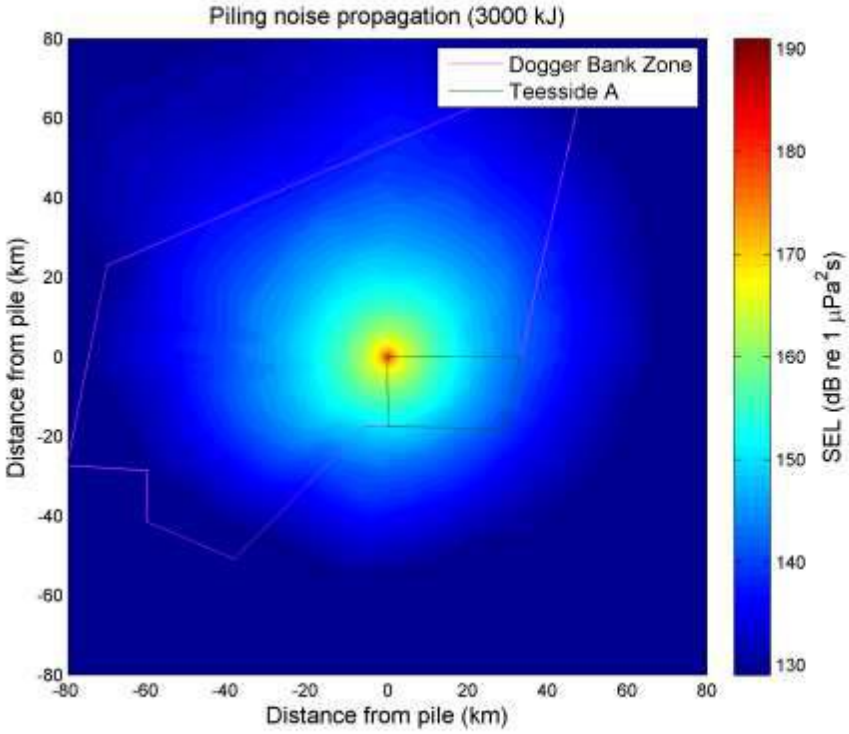


*Figure 3-2 $SEL_{ss}$ impact piling noise propagation map for Teesside A location ID1 for a 3000 kJ hammer from the NPL modelling (Figure 4.2 in the NPL report)*

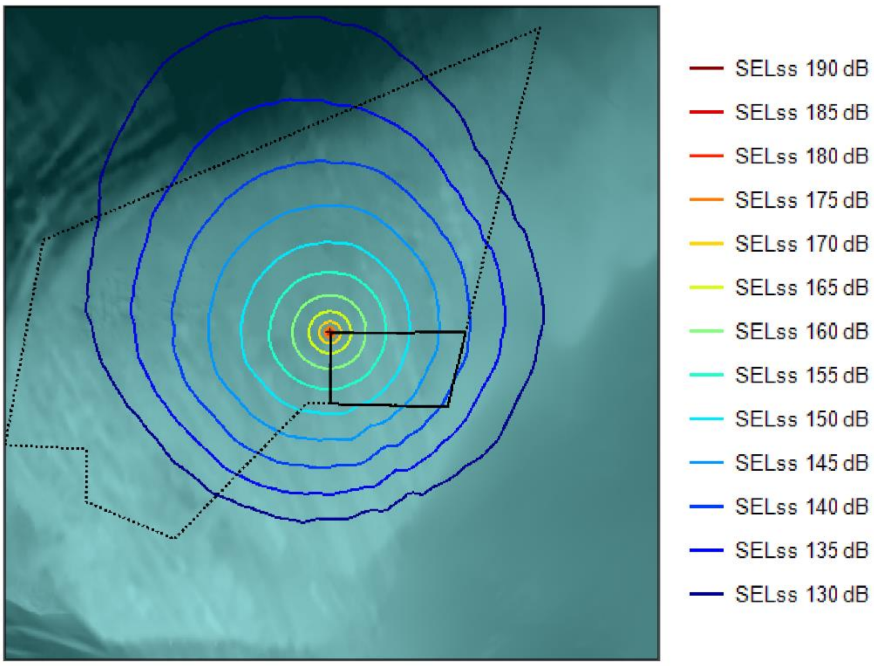


*Figure 3-3 $SEL_{ss}$ impact piling noise propagation map for Teesside A location ID1 for a 3000 kJ hammer showing the transmission losses predicted for the INSPIRE modelling, the same colour scale from Figure 3-2 has been used to aid comparison*

The source level was ascertained by fitting the modelled transmission loss to the impact ranges given in the NPL Report. Figure 3-4 and Figure 3-5 show how the worst-case transect lines up with the higher $SPL_{peak}$ and $SEL_{ss}$ impact ranges given in the NPL Report.. A conservative fit to the data has been used so that levels predicted along the worst-case transect intersect with the highest levels reported by NPL. This data is summarised in Table 3-4 and Table 3-5.

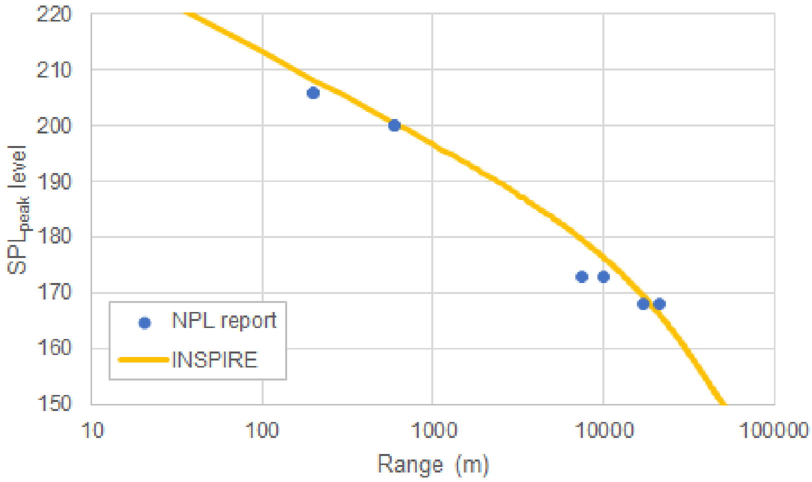


*Figure 3-4 Level versus range plots showing a comparison between the reported NPL impact ranges and the new modelling fitted to the data (unweighted $SPL_{peak}$)*

The idiosyncrasies of any model mean that another model emulating it will have variations, as can be seen in the surrounding figures. Overall the modelled ranges have a good fit, although for safety the model is designed to generally overestimate rather than underestimate.

| $SPL_{peak}$ | Criteria | NPL modelling | INSPIRE worst case |
|---|---|---|---|
| 3000 kJ | 206 dB re 1 µPa | 200 m | 280 m |
| | 200 dB re 1 µPa | 600 m | 640 m |
| | 173 dB re 1 µPa | 7.5 to 10.0 km | 13 km |
| | 168 dB re 1 µPa | 17 to 21.0 km | 19 km |

*Table 3-4 Summary of the maximum modelled $SPL_{peak}$ values compared in Figure 3-4*

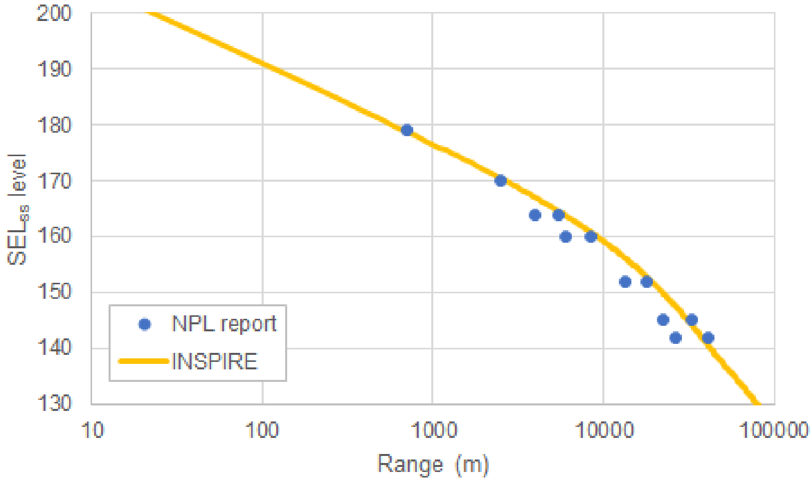


*Figure 3-5 Level versus range plots showing a comparison between the reported NPL impact ranges and the new modelling parameters fitted to the data (unweighted $SEL_{ss}$)*

| $SEL_{ss}$ | Criteria | NPL modelling | INSPIRE worst case |
|---|---|---|---|
| 3000 kJ | 179 dB re 1 µPa²s | 700 m | 690 m |
| | 164 dB re 1 µPa²s | 4.0 to 5.5 km | 5.8 km |
| | 145 dB re 1 µPa²s | 22 to 33 km | 31 km |
| | 170 dB re 1 µPa²s | 2.5 km | 2.7 km |
| | 160 dB re 1 µPa²s | 6.0 to 8.5 km | 9.2 km |
| | 152 dB re 1 µPa²s | 13.5 to 18.0 km | 19 km |
| | 142 dB re 1 µPa²s | 26.5 to 41.0 km | 38 km |

*Table 3-5 Summary of the maximum modelled $SEL_{ss}$ values compared in Figure 3-5*

### 3.3.2 Comparison with data from the NPL report

Expanding on the data from the previous section, Table 3-6 and Table 3-7 give summaries of direct comparisons between the modelled impact ranges for all blow energies presented by NPL, and the modelling undertaken by Subacoustech Environmental ("Sub-E") for this report. All the values are either unweighted $SPL_{peak}$ values or unweighted single strike $SEL_{ss}$ values. As stated earlier, where a range of distances are given in the NPL report, the greatest distances have been used to ensure a conservative fit to the data.

It should be noted that the ranges given in the NPL report, and presented below in Table 3-6 and Table 3-7, consider all modelling locations at Teesside A, whereas the Subacoustech Environmental comparison modelling has only considered the a single location (ID1).

Overall, there is a good level of correlation between the two datasets and the results from the INSPIRE model, with the NPL model having a greater variability along the transect than INSPIRE, which produces a smoother curve. This does lead to larger calculated effect ranges in some locations for INSPIRE's worst case. Small ranges of the order of hundreds of metres or less, will always produce significant variability as all models are designed for long-range accuracy, as this is where the majority of thresholds are reached and where receptors are present. The chosen approach provides a good substitute for the NPL modelling in calculating the Southall *et al*. (2019) and Popper *et al*. (2014) criteria.

| Unwtd $SPL_{peak}$ | 300 kJ hammer energy | | 1900 kJ hammer energy | | 2300 kJ hammer energy | | 3000 kJ hammer energy | |
|---|---|---|---|---|---|---|---|---|
| | NPL | INSPIRE | NPL | INSPIRE | NPL | INSPIRE | NPL | INSPIRE |
| 206 dB | 100 m | 50 m | 200 m | 210 m | 200 m | 240 m | 200 m | 280 m |
| 200 dB | 100 m | 120 m | 500 m | 490 m | 500 m | 550 m | 600 m | 640 m |
| 173 dB | 3.0 to 3.8 km | 4.3 km | 6.5 to 8.0 km | 11 km | 7.0 to 10.0 km | 12 km | 7.5 to 10.0 km | 13 km |
| 168 dB | 6.6 to 8.5 km | 7.2 km | 14.0 to 17.5 km | 16 km | 15.5 to 19.0 km | 17 km | 17.0 to 21.0 km | 19 km |

*Table 3-6 Comparison between ranges to unweighted $SPL_{peak}$ values given in the NPL Report and the comparative modelling undertaken by Subacoustech Environmental (INSPIRE) for location ID1 at Teesside A*

The chosen approach provides a good substitute for the NPL modelling in calculating the Southall *et al*. (2019) and Popper *et al*. (2014) criteria. The greatest variations are in the $SPL_{peak}$ modelled ranges but the SEL ranges are more important to the assessment. For the SEL, the majority of INSPIRE calculated ranges are within 10% of the NPL model.

| Unwtd $SEL_{ss}$ | **300 kJ hammer energy** | | **1900 kJ hammer energy** | | **2300 kJ hammer energy** | | **3000 kJ hammer energy** | |
|---|---|---|---|---|---|---|---|---|
| | NPL | INSPIRE | NPL | INSPIRE | NPL | INSPIRE | NPL | INSPIRE |
| 179 dB | 100 m | 120 m | 500 m | 510 m | 600 m | 580 m | 700 m | 690 m |
| 164 dB | 1.5 km | 1.3 km | 3.2 to 4.2 km | 4.6 km | 3.5 to 4.6 km | 5.1 km | 4.0 to 5.5 km | 5.8 km |
| 145 dB | 10.0 to 13.5 km | 14 km | 20.0 to 28.0 km | 27 km | 21.0 to 30.0 km | 29 km | 22.0 to 33.0 km | 31 km |
| 170 dB | 600 m | 500 m | 2.0 km | 2.0 km | 2.0 km | 2.3 km | 2.5 km | 2.7 km |
| 160 dB | 2.5 km | 2.3 km | 5.0 to 7.0 km | 7.4 km | 5.0 to 7.2 km | 8.1 km | 6.0 to 8.5 km | 9.2 km |
| 152 dB | 4.8 to 6.8 km | 6.6 km | 11.0 to 15.5 km | 16 km | 12.0 to 17.0 km | 17 km | 13.5 to 18.0 km | 19 km |
| 142 dB | 13.5 to 18.0 km | 18 km | 23.0 to 35.5 km | 33 km | 24.0 to 37.5 km | 35 km | 26.5 to 41.0 km | 38 km |

*Table 3-7 Comparison between ranges to unweighted $SEL_{ss}$ values given in the NPL Report and the comparable modelling undertaken by Subacoustech Environmental (INSPIRE) for location ID1 at Teesside A*

# 4 Modelling results

The following sections present the modelling impact ranges for the criteria discussed in section 2 at Teesside A.

## 4.1 Previously considered criteria

Table 4-1 to Table 4-10 present the impact ranges from the INSPIRE modelling considering the single pulse noise criteria used in the NPL report, including the metrics and criteria described in section 2.2. Also included are the results for the 4000 and 5400 kJ hammer energies.

Predicted ranges smaller than 50 m, and areas less than 0.1 km$^2$ for single strike criteria and smaller than 100 m for cumulative criteria, have not been presented as the modelling processes are unable to specify that level of accuracy with confidence due to acoustic effects near the source and other noise processes at close range.

Cells marked with a hyphen (300 kJ and 1900 kJ, fish impact ranges) are only used for single strike hammer energies within the soft start period. As such cumulative SELs are not intended to be calculated for them. Also, in certain cases the predicted ranges for 2300 kJ hammer energy are higher than those predicted for 3000 kJ hammer energy, this is due to the assumption that the 2300 kJ hammer is installing pin piles and the 3000 kJ hammer is installing monopiles, which have different frequency components that affect the weighted criteria.

| Location ID1 Harbour porpoise Impact criterion | | **300 kJ hammer energy** | **1900 kJ hammer energy** | **2300 kJ hammer energy** | **3000 kJ hammer energy** | **4000 kJ hammer energy** | **5400 kJ hammer energy** |
|---|---|---|---|---|---|---|---|
| Instantaneous injury/PTS ($SPL_{peak}$ 200 dB re 1 µPa) | Area (km$^2$) | 0.05 | 0.77 | 0.96 | 1.3 | 2.1 | 3.2 |
| | Max (m) | 130 | 500 | 560 | 650 | 820 | 1000 |
| | Min (m) | 120 | 490 | 550 | 640 | 810 | 1000 |
| | Mean (m) | 130 | 500 | 560 | 650 | 820 | 1000 |
| Instantaneous injury/PTS ($SEL_{ss}$ 179 dB re 1 µPa$^2$s) | Area (km$^2$) | 0.05 | 0.83 | 1.1 | 1.5 | 2.4 | 3.8 |
| | Max (m) | 130 | 520 | 590 | 700 | 880 | 1100 |
| | Min (m) | 120 | 510 | 580 | 690 | 870 | 1100 |
| | Mean (m) | 130 | 520 | 590 | 700 | 880 | 1100 |
| TTS/fleeing response ($SPL_{peak}$ 194 dB re 1 µPa) | Area (km$^2$) | 0.25 | 3.8 | 4.8 | 6.4 | 10 | 15 |
| | Max (m) | 290 | 1100 | 1200 | 1400 | 1800 | 2200 |
| | Min (m) | 280 | 1100 | 1200 | 1400 | 1800 | 2200 |
| | Mean (m) | 290 | 1100 | 1200 | 1400 | 1800 | 2200 |
| TTS/fleeing response ($SEL_{ss}$ 164 dB re 1 µPa$^2$s) | Area (km$^2$) | 5.2 | 65 | 80 | 110 | 150 | 200 |
| | Max (m) | 1300 | 4600 | 5100 | 5900 | 7000 | 8300 |
| | Min (m) | 1300 | 4500 | 5000 | 5700 | 6800 | 7900 |
| | Mean (m) | 1300 | 4600 | 5000 | 5800 | 6900 | 8100 |
| Possible avoidance of area ($SPL_{peak}$ 168 re 1 µPa$^2$s) | Area (km$^2$) | 160 | 780 | 860 | 1000 | 1200 | 1500 |
| | Max (m) | 7300 | 17000 | 18000 | 19000 | 21000 | 23000 |
| | Min (m) | 6900 | 15000 | 15000 | 17000 | 18000 | 20000 |
| | Mean (m) | 7100 | 16000 | 17000 | 18000 | 20000 | 22000 |
| Possible avoidance of area ($SEL_{ss}$ 145 re 1 µPa$^2$s) | Area (km$^2$) | 540 | 2000 | 2200 | 250 | 3000 | 3500 |
| | Max (m) | 14000 | 28000 | 29000 | 9300 | 34000 | 38000 |
| | Min (m) | 12000 | 23000 | 24000 | 8800 | 27000 | 29000 |
| | Mean (m) | 13000 | 25000 | 27000 | 9000 | 31000 | 33000 |

*Table 4-1 Predicted harbour porpoise impact ranges using criteria derived from Lucke et al. (2009) at location ID1*

| Location ID5<br>Harbour porpoise<br>Impact criterion | | **300 kJ hammer energy** | **1900 kJ hammer energy** | **2300 kJ hammer energy** | **3000 kJ hammer energy** | **4000 kJ hammer energy** | **5400 kJ hammer energy** |
|---|---|---|---|---|---|---|---|
| Instantaneous injury/PTS ($SPL_{peak}$ 200 dB re 1 µPa) | Area (km²) | 0.05 | 0.68 | 0.86 | 1.2 | 1.8 | 2.8 |
| | Max (m) | 130 | 470 | 530 | 620 | 770 | 950 |
| | Min (m) | 120 | 460 | 520 | 610 | 760 | 940 |
| | Mean (m) | 130 | 470 | 530 | 620 | 770 | 950 |
| Instantaneous injury/PTS ($SEL_{ss}$ 179 dB re 1 µPa²s) | Area (km²) | 0.05 | 0.8 | 1.0 | 1.4 | 2.3 | 3.5 |
| | Max (m) | 130 | 510 | 570 | 680 | 860 | 1100 |
| | Min (m) | 120 | 500 | 560 | 670 | 840 | 1100 |
| | Mean (m) | 130 | 510 | 570 | 680 | 850 | 1100 |
| TTS/fleeing response ($SPL_{peak}$ 194 dB re 1 µPa) | Area (km²) | 0.24 | 3.4 | 4.1 | 5.5 | 8.5 | 12 |
| | Max (m) | 280 | 1000 | 1200 | 1300 | 1700 | 2000 |
| | Min (m) | 270 | 1000 | 1100 | 1300 | 1600 | 2000 |
| | Mean (m) | 280 | 1000 | 1100 | 1300 | 1600 | 2000 |
| TTS/fleeing response ($SEL_{ss}$ 164 dB re 1 µPa²s) | Area (km²) | 4.8 | 53 | 65 | 85 | 120 | 160 |
| | Max (m) | 1200 | 4200 | 4600 | 5300 | 6200 | 7300 |
| | Min (m) | 1200 | 4100 | 4500 | 5200 | 6000 | 7000 |
| | Mean (m) | 1200 | 4100 | 4600 | 5200 | 6100 | 7100 |
| Possible avoidance of area ($SPL_{peak}$ 168 re 1 µPa²s) | Area (km²) | 120 | 570 | 630 | 730 | 910 | 1100 |
| | Max (m) | 6200 | 14000 | 15000 | 17000 | 19000 | 21000 |
| | Min (m) | 6000 | 12000 | 13000 | 14000 | 16000 | 17000 |
| | Mean (m) | 6100 | 13000 | 14000 | 15000 | 17000 | 19000 |
| Possible avoidance of area ($SEL_{ss}$ 145 re 1 µPa²s) | Area (km²) | 410 | 1600 | 1800 | 2000 | 2400 | 2900 |
| | Max (m) | 12000 | 26000 | 27000 | 30000 | 33000 | 36000 |
| | Min (m) | 14000 | 20000 | 21000 | 22000 | 24000 | 26000 |
| | Mean (m) | 15000 | 23000 | 24000 | 25000 | 28000 | 30000 |

*Table 4-2 Predicted harbour porpoise impact ranges using criteria derived from Lucke et al. (2009) at location ID5*

| Location ID1<br>Mid-frequency cetaceans<br>Impact criterion | | **300 kJ hammer energy** | **1900 kJ hammer energy** | **2300 kJ hammer energy** | **3000 kJ hammer energy** | **4000 kJ hammer energy** | **5400 kJ hammer energy** |
|---|---|---|---|---|---|---|---|
| Instantaneous injury/PTS ($SPL_{peak}$ 230 dB re 1 µPa) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| Instantaneous injury/PTS ($M_{mf}$ $SEL_{ss}$ 198 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS/fleeing response ($SPL_{peak}$ 224 dB re 1 µPa) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS/fleeing response ($M_{mf}$ $SEL_{ss}$ 183 dB re 1 µPa²s) | Area (km²) | < 0.01 | 0.03 | 0.06 | 0.06 | 0.09 | 0.13 |
| | Max (m) | < 50 | 100 | 140 | 140 | 170 | 210 |
| | Min (m) | < 50 | 90 | 130 | 130 | 160 | 200 |
| | Mean (m) | < 50 | 90 | 140 | 140 | 170 | 210 |
| Likely avoidance of area ($SEL_{ss}$ 170 re 1 µPa²s) | Area (km²) | 0.8 | 13 | 16 | 22 | 33 | 49 |
| | Max (m) | 510 | 2000 | 2300 | 2700 | 3300 | 4000 |
| | Min (m) | 500 | 2000 | 2300 | 2700 | 3300 | 3900 |
| | Mean (m) | 510 | 2000 | 2300 | 2700 | 3300 | 4000 |
| Possible avoidance of area ($SEL_{ss}$ 160 re 1 µPa²s) | Area (km²) | 17 | 170 | 200 | 250 | 340 | 450 |
| | Max (m) | 2300 | 7500 | 8200 | 9300 | 11000 | 12000 |
| | Min (m) | 2300 | 7200 | 7800 | 8800 | 10000 | 11000 |
| | Mean (m) | 2300 | 7300 | 8000 | 9000 | 10000 | 12000 |

*Table 4-3 Predicted mid-frequency cetacean impact ranges using criteria derived from Southall et al. (2007) at location ID1*

| Location ID5 Mid-frequency cetaceans Impact criterion | | **300 kJ hammer energy** | **1900 kJ hammer energy** | **2300 kJ hammer energy** | **3000 kJ hammer energy** | **4000 kJ hammer energy** | **5400 kJ hammer energy** |
|---|---|---|---|---|---|---|---|
| Instantaneous injury/PTS ($SPL_{peak}$ 230 dB re 1 µPa) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| Instantaneous injury/PTS ($M_{mf}$ $SEL_{ss}$ 198 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS/fleeing response ($SPL_{peak}$ 224 dB re 1 µPa) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS/fleeing response ($M_{mf}$ $SEL_{ss}$ 183 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | 0.03 | 0.06 | 0.05 | 0.09 | 0.13 |
| | Max (m) | < 50 | 100 | 140 | 130 | 170 | 210 |
| | Min (m) | < 50 | 90 | 130 | 120 | 160 | 200 |
| | Mean (m) | < 50 | 100 | 140 | 130 | 170 | 210 |
| Likely avoidance of area ($SEL_{ss}$ 170 re 1 µPa$^2$s) | Area (km$^2$) | 0.77 | 11 | 14 | 19 | 29 | 41 |
| | Max (m) | 500 | 1900 | 2100 | 2500 | 3000 | 3700 |
| | Min (m) | 490 | 1900 | 2100 | 2500 | 3000 | 3600 |
| | Mean (m) | 500 | 1900 | 2100 | 2500 | 3000 | 3600 |
| Possible avoidance of area ($SEL_{ss}$ 160 re 1 µPa$^2$s) | Area (km$^2$) | 15 | 130 | 160 | 200 | 260 | 340 |
| | Max (m) | 2200 | 6600 | 7200 | 8200 | 9500 | 11000 |
| | Min (m) | 2200 | 6400 | 6900 | 7700 | 8800 | 9900 |
| | Mean (m) | 2200 | 6500 | 7100 | 7900 | 9200 | 10000 |

*Table 4-4 Predicted mid-frequency cetacean impact ranges using criteria derived from Southall et al. (2007) at location ID5*

| Location ID1 Low-frequency cetaceans Impact criterion | | **300 kJ hammer energy** | **1900 kJ hammer energy** | **2300 kJ hammer energy** | **3000 kJ hammer energy** | **4000 kJ hammer energy** | **5400 kJ hammer energy** |
|---|---|---|---|---|---|---|---|
| Instantaneous injury/PTS ($SPL_{peak}$ 230 dB re 1 µPa) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| Instantaneous injury/PTS ($M_{lf}$ $SEL_{ss}$ 198 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | 0.01 | 0.01 | 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | 50 | 60 | 70 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | 50 | 60 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | 60 | 70 |
| TTS/fleeing response ($SPL_{peak}$ 224 dB re 1 µPa) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS/fleeing response ($M_{lf}$ $SEL_{ss}$ 183 dB re 1 µPa$^2$s) | Area (km$^2$) | 0.02 | 0.24 | 0.31 | 0.44 | 0.7 | 1.1 |
| | Max (m) | 80 | 280 | 320 | 380 | 480 | 590 |
| | Min (m) | 70 | 270 | 310 | 370 | 470 | 580 |
| | Mean (m) | 80 | 280 | 320 | 380 | 480 | 590 |
| Likely avoidance of area ($SEL_{ss}$ 152 re 1 µPa$^2$s) | Area (km$^2$) | 130 | 760 | 860 | 1000 | 1300 | 1500 |
| | Max (m) | 6600 | 16000 | 18000 | 19000 | 21000 | 24000 |
| | Min (m) | 6400 | 15000 | 16000 | 17000 | 19000 | 20000 |
| | Mean (m) | 6500 | 16000 | 17000 | 18000 | 20000 | 22000 |
| Possible avoidance of area ($SEL_{ss}$ 142 re 1 µPa$^2$s) | Area (km$^2$) | 880 | 2800 | 3100 | 3500 | 4000 | 4600 |
| | Max (m) | 18000 | 33000 | 35000 | 38000 | 41000 | 45000 |
| | Min (m) | 16000 | 26000 | 27000 | 29000 | 31000 | 32000 |
| | Mean (m) | 17000 | 30000 | 31000 | 33000 | 36000 | 38000 |

*Table 4-5 Predicted low-frequency cetacean impact ranges using criteria derived from Southall et al. (2007) at location ID1*

| Location ID5<br>Low-frequency cetaceans<br>Impact criterion | | 300 kJ hammer energy | 1900 kJ hammer energy | 2300 kJ hammer energy | 3000 kJ hammer energy | 4000 kJ hammer energy | 5400 kJ hammer energy |
|---|---|---|---|---|---|---|---|
| Instantaneous injury/PTS ($SPL_{peak}$ 230 dB re 1 µPa) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| Instantaneous injury/PTS ($M_{lf}$ $SEL_{ss}$ 198 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | 0.01 | 0.01 | 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | 50 | 50 | 70 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | 60 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | 70 |
| TTS/fleeing response ($SPL_{peak}$ 224 dB re 1 µPa) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS/fleeing response ($M_{lf}$ $SEL_{ss}$ 183 dB re 1 µPa²s) | Area (km²) | 0.02 | 0.22 | 0.29 | 0.42 | 0.68 | 1.0 |
| | Max (m) | 80 | 270 | 310 | 370 | 470 | 580 |
| | Min (m) | 70 | 260 | 300 | 360 | 460 | 470 |
| | Mean (m) | 80 | 270 | 310 | 370 | 470 | 580 |
| Likely avoidance of area ($SEL_{ss}$ 152 re 1 µPa²s) | Area (km²) | 110 | 580 | 660 | 790 | 990 | 1200 |
| | Max (m) | 5900 | 15000 | 16000 | 17000 | 20000 | 22000 |
| | Min (m) | 5700 | 13000 | 13000 | 15000 | 16000 | 18000 |
| | Mean (m) | 5800 | 14000 | 15000 | 16000 | 18000 | 20000 |
| Possible avoidance of area ($SEL_{ss}$ 142 re 1 µPa²s) | Area (km²) | 680 | 2300 | 2600 | 2900 | 3400 | 4000 |
| | Max (m) | 16000 | 32000 | 33000 | 36000 | 39000 | 43000 |
| | Min (m) | 14000 | 23000 | 24000 | 26000 | 27000 | 29000 |
| | Mean (m) | 15000 | 27000 | 28000 | 30000 | 33000 | 35000 |

*Table 4-6 Predicted low-frequency cetacean impact ranges using criteria derived from Southall et al. (2007) at location ID5*

| Location ID1<br>Pinnipeds (in water)<br>Impact criterion | | 300 kJ hammer energy | 1900 kJ hammer energy | 2300 kJ hammer energy | 3000 kJ hammer energy | 4000 kJ hammer energy | 5400 kJ hammer energy |
|---|---|---|---|---|---|---|---|
| Instantaneous injury/PTS ($SPL_{peak}$ 218 dB re 1 µPa) | Area (km²) | < 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.03 |
| | Max (m) | < 50 | 50 | 60 | 60 | 80 | 100 |
| | Min (m) | < 50 | < 50 | 50 | 50 | 70 | 90 |
| | Mean (m) | < 50 | < 50 | 60 | 60 | 80 | 100 |
| Instantaneous injury/PTS ($M_{pw}$ $SEL_{ss}$ 186 dB re 1 µPa²s) | Area (km²) | < 0.01 | 0.03 | 0.07 | 0.06 | 0.1 | 0.14 |
| | Max (m) | < 50 | 110 | 150 | 140 | 180 | 220 |
| | Min (m) | < 50 | 100 | 140 | 130 | 170 | 210 |
| | Mean (m) | < 50 | 110 | 150 | 140 | 180 | 220 |
| TTS/fleeing response ($SPL_{peak}$ 212 dB re 1 µPa) | Area (km²) | 0.01 | 0.03 | 0.03 | 0.05 | 0.09 | 0.12 |
| | Max (m) | 50 | 100 | 110 | 130 | 170 | 200 |
| | Min (m) | < 50 | 90 | 100 | 120 | 160 | 190 |
| | Mean (m) | < 50 | 100 | 110 | 130 | 170 | 200 |
| TTS/fleeing response ($M_{pw}$ $SEL_{ss}$ 171 dB re 1 µPa²s) | Area (km²) | 0.2 | 3.3 | 6.4 | 6.0 | 9.3 | 14 |
| | Max (m) | 260 | 1000 | 1400 | 1400 | 1700 | 2100 |
| | Min (m) | 250 | 1000 | 1400 | 1400 | 1700 | 2100 |
| | Mean (m) | 260 | 1000 | 1400 | 1400 | 1700 | 2100 |

*Table 4-7 Predicted pinniped (in water) impact ranges using criteria derived from Southall et al. (2007) at location ID1*

| Location ID5<br>Pinnipeds (in water)<br>Impact criterion | | **300 kJ hammer energy** | **1900 kJ hammer energy** | **2300 kJ hammer energy** | **3000 kJ hammer energy** | **4000 kJ hammer energy** | **5400 kJ hammer energy** |
|---|---|---|---|---|---|---|---|
| Instantaneous injury/PTS ($SPL_{peak}$ 218 dB re 1 µPa) | Area ($km^2$) | < 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 |
| | Max (m) | < 50 | 50 | 60 | 60 | 80 | 90 |
| | Min (m) | < 50 | < 50 | 50 | 50 | 70 | 80 |
| | Mean (m) | < 50 | < 50 | 60 | 60 | 80 | 90 |
| Instantaneous injury/PTS ($M_{pw}$ $SEL_{ss}$ 186 dB re 1 µ$Pa^2$s) | Area ($km^2$) | < 0.01 | 0.03 | 0.07 | 0.06 | 0.09 | 0.14 |
| | Max (m) | < 50 | 110 | 150 | 140 | 170 | 220 |
| | Min (m) | < 50 | 100 | 140 | 130 | 160 | 210 |
| | Mean (m) | < 50 | 110 | 150 | 140 | 170 | 220 |
| TTS/fleeing response ($SPL_{peak}$ 212 dB re 1 µPa) | Area ($km^2$) | 0.01 | 0.03 | 0.03 | 0.05 | 0.08 | 0.12 |
| | Max (m) | 50 | 100 | 110 | 130 | 160 | 200 |
| | Min (m) | < 50 | 90 | 100 | 120 | 150 | 190 |
| | Mean (m) | < 50 | 100 | 110 | 130 | 160 | 200 |
| TTS/fleeing response ($M_{pw}$ $SEL_{ss}$ 171 dB re 1 µ$Pa^2$s) | Area ($km^2$) | 0.19 | 3.1 | 5.9 | 5.5 | 8.5 | 13 |
| | Max (m) | 250 | 1000 | 1400 | 1300 | 1700 | 2000 |
| | Min (m) | 240 | 990 | 1400 | 1300 | 1600 | 2000 |
| | Mean (m) | 250 | 990 | 1400 | 1300 | 1600 | 2000 |

*Table 4-8 Predicted pinniped (in water) impact ranges using criteria derived from Southall et al. (2007) at location ID5*

| Location ID1<br>Fish<br>Impact criterion | | **300 kJ hammer energy** | **1900 kJ hammer energy** | **2300 kJ hammer energy** | **3000 kJ hammer energy** | **4000 kJ hammer energy** | **5400 kJ hammer energy** |
|---|---|---|---|---|---|---|---|
| Instantaneous injury/PTS ($SPL_{peak}$ 206 dB re 1 µPa) | Area ($km^2$) | 0.01 | 0.14 | 0.19 | 0.25 | 0.42 | 0.62 |
| | Max (m) | 60 | 220 | 250 | 290 | 370 | 450 |
| | Min (m) | 50 | 210 | 240 | 280 | 360 | 440 |
| | Mean (m) | 60 | 220 | 250 | 290 | 370 | 450 |
| PTS ($SEL_{cum}$ 211 dB re 1 µ$Pa^2$s) – Sequence 2 | Area ($km^2$) | - | - | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | - | - | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | - | - | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | - | - | < 100 | < 100 | < 100 | < 100 |
| PTS ($SEL_{cum}$ 211 dB re 1 µ$Pa^2$s) – Sequence 3 | Area ($km^2$) | - | - | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | - | - | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | - | - | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | - | - | < 100 | < 100 | < 100 | < 100 |
| Possible moderate to strong avoidance (upper $SPL_{peak}$ 173 dB re 1 µPa) | Area ($km^2$) | 56 | 380 | 430 | 510 | 650 | 810 |
| | Max (m) | 4300 | 11000 | 12000 | 13000 | 15000 | 1700 |
| | Min (m) | 4200 | 10000 | 11000 | 12000 | 14000 | 1500 |
| | Mean (m) | 4200 | 11000 | 12000 | 13000 | 14000 | 16000 |
| Possible moderate to strong avoidance (lower $SPL_{peak}$ 168 dB re 1 µPa) | Area ($km^2$) | 160 | 780 | 860 | 1000 | 1200 | 1500 |
| | Max (m) | 7300 | 17000 | 18000 | 19000 | 21000 | 23000 |
| | Min (m) | 6900 | 15000 | 15000 | 17000 | 18000 | 20000 |
| | Mean (m) | 7100 | 16000 | 17000 | 18000 | 20000 | 22000 |
| Startle response or C-turn reaction ($SPL_{peak}$ 200 dB re 1 µPa) | Area ($km^2$) | 0.05 | 0.77 | 0.96 | 1.3 | 2.1 | 3.2 |
| | Max (m) | 130 | 500 | 560 | 650 | 820 | 1000 |
| | Min (m) | 120 | 490 | 550 | 640 | 810 | 1000 |
| | Mean (m) | 130 | 500 | 560 | 650 | 820 | 1000 |

*Table 4-9 Predicted fish impact ranges using criteria derived from Popper et al. (2006), Carlson et al. (2007), Halvorsen et al (2011), McCauley et al. (2000), and Pearson et al (1992) at location ID1*

| Location ID5<br>Fish<br>Impact criterion | | **300 kJ hammer energy** | **1900 kJ hammer energy** | **2300 kJ hammer energy** | **3000 kJ hammer energy** | **4000 kJ hammer energy** | **5400 kJ hammer energy** |
|---|---|---|---|---|---|---|---|
| Instantaneous injury/PTS ($SPL_{peak}$ 206 dB re 1 µPa) | Area ($km^2$) | 0.01 | 0.14 | 0.17 | 0.24 | 0.37 | 0.56 |
| | Max (m) | 60 | 220 | 240 | 280 | 350 | 430 |
| | Min (m) | 50 | 210 | 230 | 270 | 340 | 420 |
| | Mean (m) | 60 | 220 | 240 | 280 | 350 | 430 |
| PTS ($SEL_{cum}$ 211 dB re 1 µ$Pa^2$s) – Sequence 2 | Area ($km^2$) | - | - | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | - | - | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | - | - | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | - | - | < 100 | < 100 | < 100 | < 100 |
| PTS ($SEL_{cum}$ 211 dB re 1 µ$Pa^2$s) – Sequence 3 | Area ($km^2$) | - | - | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | - | - | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | - | - | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | - | - | < 100 | < 100 | < 100 | < 100 |
| Possible moderate to strong avoidance (upper $SPL_{peak}$ 173 dB re 1 µPa) | Area ($km^2$) | 44 | 270 | 310 | 370 | 470 | 590 |
| | Max (m) | 3800 | 9700 | 10000 | 11000 | 13000 | 15000 |
| | Min (m) | 3700 | 8900 | 9500 | 10000 | 11000 | 13000 |
| | Mean (m) | 3800 | 9300 | 10000 | 11000 | 12000 | 14000 |
| Possible moderate to strong avoidance (lower $SPL_{peak}$ 168 dB re 1 µPa) | Area ($km^2$) | 120 | 570 | 630 | 730 | 910 | 1100 |
| | Max (m) | 6200 | 14000 | 15000 | 17000 | 19000 | 21000 |
| | Min (m) | 6000 | 12000 | 13000 | 14000 | 16000 | 17000 |
| | Mean (m) | 6100 | 13000 | 14000 | 15000 | 17000 | 19000 |
| Startle response or C-turn reaction ($SPL_{peak}$ 200 dB re 1 µPa) | Area ($km^2$) | 0.05 | 0.68 | 0.86 | 1.2 | 1.8 | 2.8 |
| | Max (m) | 130 | 470 | 530 | 620 | 770 | 950 |
| | Min (m) | 120 | 460 | 520 | 610 | 760 | 940 |
| | Mean (m) | 130 | 470 | 530 | 620 | 770 | 950 |

*Table 4-10 Predicted fish impact ranges using criteria derived from Popper et al. (2006), Carlson et al. (2007), Halvorsen et al (2011), McCauley et al. (2000), and Pearson et al (1992) at location ID5*

## 4.2 Marine mammals

### *4.2.1 Southall et al. (2019) impact ranges*

Table 4-11 to Table 4-26 present the impact ranges for the Southall *et al*. (2019) criteria for marine mammals. Predicted ranges smaller than 50 m, and area less than 0.01 $km^2$ for single strike criteria, and smaller than 100 m for cumulative criteria, have not been presented as the modelling processes are unable to specify that level of accuracy with confidence due to acoustic effects near the source and other noise processes at close ranges.

The results show that, using the Southall *et al*. (2019) $SPL_{peak}$ criteria, ranges are largely within a few hundred metres, with only the TTS ranges for high-frequency cetaceans extending over 1 km. For the $SEL_{cum}$ criteria, larger ranges are predicted, with PTS for LF cetaceans reaching 8.4 km and TTS for LF cetaceans reaching a maximum range of 32 km for the largest hammer blow energies (5400 kJ) and worst-case ramp-up sequence 3.

In some cases, the increases for some smaller ranges between the 4000 kJ to 5400 kJ hammer are quite significant (see for example Table 4-21). Exposures of this sort will increase rapidly beyond the point that a threshold is reached. For example, where the 4000 kJ hammer does not quite, or only just, reaches the SEL noise threshold, the cumulative SEL range will remain negligible. However, once the SEL noise level is exceeded, the receptor will receive multiple noise exposures from this higher-level pulse and so the exposure increases rapidly.

Additional modelling was carried out for $SEL_{ss}$ noise levels using the Southall *et al*. (2019) weightings and criteria, these are presented in Appendix A.

| Low-frequency cetaceans (LF) (maximum energy) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| PTS (Impulsive) Unwtd $SPL_{peak}$ (219 dB re 1 µPa) | Area ($km^2$) | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 |
| | Max (m) | < 50 | 60 | 70 | < 50 | 60 | 70 |
| | Min (m) | < 50 | 60 | 70 | < 50 | 50 | 70 |
| | Mean (m) | < 50 | 60 | 70 | < 50 | 60 | 70 |
| TTS (Impulsive) Unwtd $SPL_{peak}$ (213 dB re 1 µPa) | Area ($km^2$) | 0.03 | 0.05 | 0.08 | 0.03 | 0.05 | 0.08 |
| | Max (m) | 100 | 130 | 170 | 100 | 130 | 160 |
| | Min (m) | 100 | 130 | 160 | 100 | 130 | 160 |
| | Mean (m) | 100 | 130 | 170 | 100 | 130 | 160 |

*Table 4-11 Predicted unweighted $SPL_{peak}$ impact ranges for low-frequency cetaceans using criteria from Southall et al. (2019) for maximum hammer blow energies*

| Low-frequency cetaceans (LF) (soft start) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 300 kJ | 400 kJ | 540 kJ | 300 kJ | 400 kJ | 540 kJ |
| PTS (Impulsive) Unwtd $SPL_{peak}$ (219 dB re 1 µPa) | Area ($km^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Impulsive) Unwtd $SPL_{peak}$ (213 dB re 1 µPa) | Area ($km^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |

*Table 4-12 Predicted unweighted $SPL_{peak}$ impact ranges for low-frequency cetaceans using criteria from Southall et al. (2019) for soft start hammer blow energies*

| Low-frequency cetaceans (LF) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Sequence 2 - PTS (Impulsive) Weighted $SEL_{cum}$ (183 dB re 1 µ$Pa^2$s) | Area ($km^2$) | 35 | 80 | 150 | 12 | 34 | 74 |
| | Max (m) | 3900 | 5800 | 7800 | 2500 | 4200 | 6100 |
| | Min (m) | 2700 | 4100 | 5700 | 1400 | 2500 | 3700 |
| | Mean (m) | 3300 | 5000 | 6800 | 1900 | 3300 | 4800 |
| Sequence 2 - TTS (Impulsive) Weighted $SEL_{cum}$ (168 dB re 1 µ$Pa^2$s) | Area ($km^2$) | 2000 | 2500 | 3000 | 1600 | 2000 | 2500 |
| | Max (m) | 32000 | 36000 | 41000 | 29000 | 33000 | 37000 |
| | Min (m) | 20000 | 22000 | 23000 | 17000 | 18000 | 20000 |
| | Mean (m) | 25000 | 28000 | 31000 | 22000 | 25000 | 28000 |
| Sequence 3 - PTS (Impulsive) Weighted $SEL_{cum}$ (183 dB re 1 µ$Pa^2$s) | Area ($km^2$) | 39 | 87 | 160 | 13 | 38 | 81 |
| | Max (m) | 4200 | 6200 | 8400 | 2700 | 4600 | 6600 |
| | Min (m) | 2800 | 4200 | 5800 | 1400 | 2500 | 3700 |
| | Mean (m) | 3500 | 5200 | 7100 | 2000 | 3500 | 5000 |
| Sequence 3 - TTS (Impulsive) Weighted $SEL_{cum}$ (168 dB re 1 µ$Pa^2$s) | Area ($km^2$) | 2200 | 2800 | 3400 | 1700 | 2200 | 2700 |
| | Max (m) | 35000 | 41000 | 46000 | 31000 | 35000 | 39000 |
| | Min (m) | 20000 | 22000 | 24000 | 17000 | 18000 | 20000 |
| | Mean (m) | 26000 | 29000 | 32000 | 23000 | 26000 | 29000 |

*Table 4-13 Predicted low-frequency cetacean weighted $SEL_{cum}$ impact ranges (impulsive) using criteria from Southall et al. (2019) assuming a fleeing speed of 3.25 $ms^{-1}$ for the two piling sequences*

| Low-frequency cetaceans (LF) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Sequence 2 - PTS (Non-impulsive) Weighted $SEL_{cum}$ (199 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 2 - TTS (Non-impulsive) Weighted $SEL_{cum}$ (179 dB re 1 µPa²s) | Area (km²) | 210 | 330 | 480 | 120 | 200 | 300 |
| | Max (m) | 9400 | 12000 | 14000 | 7600 | 8200 | 12000 |
| | Min (m) | 6900 | 8500 | 10000 | 4600 | 4700 | 7600 |
| | Mean (m) | 8200 | 10000 | 12000 | 6000 | 6300 | 9800 |
| Sequence 3 - PTS (Non-impulsive) Weighted $SEL_{cum}$ (199 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 3 - TTS (Non-impulsive) Weighted $SEL_{cum}$ (179 dB re 1 µPa²s) | Area (km²) | 230 | 350 | 510 | 130 | 200 | 330 |
| | Max (m) | 10000 | 13000 | 15000 | 8200 | 10000 | 13000 |
| | Min (m) | 6900 | 8600 | 10000 | 4700 | 6100 | 7700 |
| | Mean (m) | 8400 | 11000 | 13000 | 6300 | 7900 | 10000 |

*Table 4-14 Predicted low-frequency cetacean weighted $SEL_{cum}$ impact ranges (non-impulsive) using criteria from Southall et al. (2019) assuming a fleeing speed of 3.25 $ms^{-1}$ for the two piling sequences*

| High-frequency cetaceans (HF) (maximum energy) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| PTS (Impulsive) Unwtd $SPL_{peak}$ (230 dB re 1 µPa) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Impulsive) Unwtd $SPL_{peak}$ (224 dB re 1 µPa) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |

*Table 4-15 Predicted unweighted $SPL_{peak}$ impact ranges for high-frequency cetaceans using criteria from Southall et al. (2019) for maximum hammer blow energies*

| High-frequency cetaceans (HF) (soft start) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 300 kJ | 400 kJ | 540 kJ | 300 kJ | 400 kJ | 540 kJ |
| PTS (Impulsive) Unwtd $SPL_{peak}$ (230 dB re 1 µPa) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Impulsive) Unwtd $SPL_{peak}$ (224 dB re 1 µPa) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |

*Table 4-16 Predicted unweighted $SPL_{peak}$ impact ranges for high-frequency cetaceans using criteria from Southall et al. (2019) for soft start hammer blow energies*

| High-frequency cetaceans (HF) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Sequence 2 - PTS (Impulsive) Weighted $SEL_{cum}$ (185 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 2 - TTS (Impulsive) Weighted $SEL_{cum}$ (170 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 3 - PTS (Impulsive) Weighted $SEL_{cum}$ (185 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 3 - TTS (Impulsive) Weighted $SEL_{cum}$ (170 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |

*Table 4-17 Predicted high-frequency cetacean weighted $SEL_{cum}$ impact ranges (impulsive) using criteria from Southall et al. (2019) assuming a fleeing speed of 1.5 $ms^{-1}$ for the two piling sequences*

| High-frequency cetaceans (HF) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Sequence 2 - PTS (Non-impulsive) Weighted $SEL_{cum}$ (198 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 2 - TTS (Non-impulsive) Weighted $SEL_{cum}$ (178 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 3 - PTS (Non-impulsive) Weighted $SEL_{cum}$ (198 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 3 - TTS (Non-impulsive) Weighted $SEL_{cum}$ (178 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |

*Table 4-18 Predicted high-frequency cetacean weighted $SEL_{cum}$ impact ranges (non-impulsive) using criteria from Southall et al. (2019) assuming a fleeing speed of 1.5 $ms^{-1}$ for the two piling sequences*

| Very high-frequency cetaceans (VHF) (maximum energy) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| PTS (Impulsive) Unwtd $SPL_{peak}$ (202 dB re 1 µPa) | Area (km$^2$) | 0.73 | 1.2 | 1.8 | 0.66 | 1.1 | 1.6 |
| | Max (m) | 480 | 610 | 760 | 460 | 580 | 720 |
| | Min (m) | 480 | 610 | 760 | 460 | 580 | 720 |
| | Mean (m) | 480 | 610 | 760 | 460 | 580 | 720 |
| TTS (Impulsive) Unwtd $SPL_{peak}$ (196 dB re 1 µPa) | Area (km$^2$) | 3.7 | 5.9 | 8.9 | 3.3 | 5.1 | 7.6 |
| | Max (m) | 1100 | 1400 | 1700 | 1000 | 1300 | 1600 |
| | Min (m) | 1100 | 1400 | 1700 | 1000 | 1300 | 1600 |
| | Mean (m) | 1100 | 1400 | 1700 | 1000 | 1300 | 1600 |

*Table 4-19 Predicted unweighted $SPL_{peak}$ impact ranges for very high-frequency cetaceans using criteria from Southall et al. (2019) for maximum hammer blow energies*

| Very high-frequency cetaceans (VHF) (soft start) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 300 kJ | 400 kJ | 540 kJ | 300 kJ | 400 kJ | 540 kJ |
| PTS (Impulsive) Unwtd $SPL_{peak}$ (202 dB re 1 µPa) | Area ($km^2$) | 0.03 | 0.04 | 0.06 | 0.02 | 0.04 | 0.06 |
| | Max (m) | 90 | 110 | 140 | 90 | 110 | 140 |
| | Min (m) | 90 | 110 | 140 | 90 | 110 | 130 |
| | Mean (m) | 90 | 110 | 140 | 90 | 110 | 140 |
| TTS (Impulsive) Unwtd $SPL_{peak}$ (196 dB re 1 µPa) | Area ($km^2$) | 0.14 | 0.21 | 0.33 | 0.13 | 0.19 | 0.3 |
| | Max (m) | 210 | 260 | 330 | 200 | 250 | 310 |
| | Min (m) | 210 | 260 | 320 | 200 | 250 | 310 |
| | Mean (m) | 210 | 260 | 330 | 200 | 250 | 310 |

*Table 4-20 Predicted unweighted $SPL_{peak}$ impact ranges for very high-frequency cetaceans using criteria from Southall et al. (2019) for soft start hammer blow energies*

| Very high-frequency cetaceans (VHF) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Sequence 2 - PTS (Impulsive) Weighted $SEL_{cum}$ (155 dB re 1 µ$Pa^2$s) | Area ($km^2$) | < 0.01 | < 0.01 | 0.4 | < 0.01 | < 0.01 | 0.04 |
| | Max (m) | < 100 | < 100 | 410 | < 100 | < 100 | 130 |
| | Min (m) | < 100 | < 100 | 310 | < 100 | < 100 | 100 |
| | Mean (m) | < 100 | < 100 | 360 | < 100 | < 100 | 110 |
| Sequence 2 - TTS (Impulsive) Weighted $SEL_{cum}$ (140 dB re 1 µ$Pa^2$s) | Area ($km^2$) | 460 | 620 | 820 | 310 | 430 | 580 |
| | Max (m) | 13000 | 15000 | 18000 | 11000 | 14000 | 16000 |
| | Min (m) | 11000 | 13000 | 14000 | 8600 | 10000 | 12000 |
| | Mean (m) | 12000 | 14000 | 16000 | 9900 | 12000 | 14000 |
| Sequence 3 - PTS (Impulsive) Weighted $SEL_{cum}$ (155 dB re 1 µ$Pa^2$s) | Area ($km^2$) | < 0.01 | < 0.01 | 1.0 | < 0.01 | < 0.01 | 0.1 |
| | Max (m) | < 100 | < 100 | 670 | < 100 | < 100 | 210 |
| | Min (m) | < 100 | < 100 | 460 | < 100 | < 100 | 140 |
| | Mean (m) | < 100 | < 100 | 570 | < 100 | < 100 | 180 |
| Sequence 3 - TTS (Impulsive) Weighted $SEL_{cum}$ (140 dB re 1 µ$Pa^2$s) | Area ($km^2$) | 570 | 770 | 1000 | 390 | 540 | 730 |
| | Max (m) | 15000 | 18000 | 21000 | 13000 | 16000 | 19000 |
| | Min (m) | 12000 | 13000 | 15000 | 9100 | 11000 | 12000 |
| | Mean (m) | 13000 | 16000 | 18000 | 11000 | 13000 | 15000 |

*Table 4-21 Predicted very high-frequency cetacean weighted $SEL_{cum}$ impact ranges (impulsive) using criteria from Southall et al. (2019) assuming a fleeing speed of 1.5 $ms^{-1}$ for the two piling sequences*

| Very high-frequency cetaceans (VHF) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Sequence 2 - PTS (Non-impulsive) Weighted $SEL_{cum}$ (173 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 2 - TTS (Non-impulsive) Weighted $SEL_{cum}$ (153 dB re 1 µPa$^2$s) | Area (km$^2$) | 0.02 | 1.3 | 7.6 | < 0.01 | 0.19 | 2.6 |
| | Max (m) | 110 | 710 | 1700 | < 100 | 290 | 1000 |
| | Min (m) | < 100 | 560 | 1400 | < 100 | 210 | 810 |
| | Mean (m) | < 100 | 630 | 1600 | < 100 | 240 | 900 |
| Sequence 3 - PTS (Non-impulsive) Weighted $SEL_{cum}$ (173 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 3 - TTS (Non-impulsive) Weighted $SEL_{cum}$ (153 dB re 1 µPa$^2$s) | Area (km$^2$) | 0.08 | 2.6 | 12 | 0.01 | 0.42 | 4.1 |
| | Max (m) | 210 | 1000 | 2200 | < 100 | 430 | 1300 |
| | Min (m) | 120 | 770 | 1700 | < 100 | 290 | 970 |
| | Mean (m) | 160 | 910 | 2000 | < 100 | 370 | 1100 |

*Table 4-22 Predicted very high-frequency cetacean weighted $SEL_{cum}$ impact ranges (non-impulsive) using criteria from Southall et al. (2019) assuming a fleeing speed of 1.5 ms$^{-1}$ for the two piling sequences*

| Phocid carnivores in water (PCW) (maximum energy) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| PTS (Impulsive) Unwtd $SPL_{peak}$ (218 dB re 1 µPa) | Area (km$^2$) | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 |
| | Max (m) | 50 | 70 | 80 | 50 | 60 | 80 |
| | Min (m) | 50 | 60 | 80 | < 50 | 60 | 80 |
| | Mean (m) | 50 | 70 | 80 | 50 | 60 | 80 |
| TTS (Impulsive) Unwtd $SPL_{peak}$ (212 dB re 1 µPa) | Area (km$^2$) | 0.04 | 0.07 | 0.11 | 0.04 | 0.07 | 0.1 |
| | Max (m) | 120 | 150 | 190 | 120 | 150 | 180 |
| | Min (m) | 120 | 150 | 190 | 110 | 150 | 180 |
| | Mean (m) | 120 | 150 | 190 | 120 | 150 | 180 |

*Table 4-23 Predicted unweighted $SPL_{peak}$ impact ranges for phocid carnivores in water using criteria from Southall et al. (2019) for maximum hammer blow energies*

| Phocid carnivores in water (PCW) (soft start) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 300 kJ | 400 kJ | 540 kJ | 300 kJ | 400 kJ | 540 kJ |
| PTS (Impulsive) Unwtd $SPL_{peak}$ (218 dB re 1 µPa) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Impulsive) Unwtd $SPL_{peak}$ (212 dB re 1 µPa) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |

*Table 4-24 Predicted unweighted $SPL_{peak}$ impact ranges for phocid carnivores in water using criteria from Southall et al. (2019) for soft start hammer blow energies*

| Phocid carnivores in water (PCW) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Sequence 2 - PTS (Impulsive) Weighted $SEL_{cum}$ (185 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 2 - TTS (Impulsive) Weighted $SEL_{cum}$ (170 dB re 1 µPa²s) | Area (km²) | 330 | 470 | 630 | 220 | 310 | 440 |
| | Max (m) | 11000 | 13000 | 16000 | 9400 | 11000 | 14000 |
| | Min (m) | 9300 | 11000 | 13000 | 7200 | 8700 | 10000 |
| | Mean (m) | 10000 | 12000 | 14000 | 8300 | 10000 | 12000 |
| Sequence 3 - PTS (Impulsive) Weighted $SEL_{cum}$ (185 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | 0.02 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 3 - TTS (Impulsive) Weighted $SEL_{cum}$ (170 dB re 1 µPa²s) | Area (km²) | 420 | 580 | 775 | 270 | 400 | 550 |
| | Max (m) | 13000 | 15000 | 18000 | 11000 | 14000 | 16000 |
| | Min (m) | 10000 | 12000 | 13000 | 7700 | 9200 | 11000 |
| | Mean (m) | 12000 | 14000 | 16000 | 9300 | 11000 | 13000 |

*Table 4-25 Predicted phocid carnivores in water weighted $SEL_{cum}$ impact ranges (impulsive) using criteria from Southall et al. (2019) assuming a fleeing speed of 1.5 $ms^{-1}$ for the two piling sequences*

| Phocid carnivores in water (PCW) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Sequence 2 - PTS (Non-impulsive) Weighted $SEL_{cum}$ (201 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 2 - TTS (Non-impulsive) Weighted $SEL_{cum}$ (181 dB re 1 µPa²s) | Area (km²) | 0.16 | 3.1 | 12 | 0.02 | 0.71 | 4.9 |
| | Max (m) | 270 | 1100 | 2200 | < 100 | 540 | 1400 |
| | Min (m) | 200 | 890 | 1800 | < 100 | 420 | 1100 |
| | Mean (m) | 230 | 990 | 2000 | < 100 | 480 | 1300 |
| Sequence 3 - PTS (Non-impulsive) Weighted $SEL_{cum}$ (201 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Sequence 3 - TTS (Non-impulsive) Weighted $SEL_{cum}$ (181 dB re 1 µPa²s) | Area (km²) | 0.5 | 5.5 | 19 | 0.04 | 1.3 | 7.4 |
| | Max (m) | 480 | 1500 | 2700 | 130 | 750 | 1700 |
| | Min (m) | 310 | 1100 | 2200 | < 100 | 530 | 1300 |
| | Mean (m) | 400 | 1300 | 2500 | 110 | 650 | 1500 |

*Table 4-26 Predicted phocid carnivores in water weighted $SEL_{cum}$ impact ranges (non-impulsive) using criteria from Southall et al. (2019) assuming a fleeing speed of 1.5 $ms^{-1}$ for the two piling sequences*

## 4.3 Fish

### *4.3.1 Popper et al. (2014) impact ranges*

Table 4-27 to Table 4-32 present the impact ranges for fish for the Popper *et al*. (2014) criteria, covering unweighted $SPL_{peak}$ and $SEL_{cum}$ metrics for all both piling sequences (Table 3-3). All fleeing calculations have assumed both a receptor fleeing at a constant rate of 1.5 $ms^{-1}$ and a stationary receptor. As before ranges smaller than 50 m for $SPL_{peak}$ and 100 m for $SEL_{cum}$ have not been presented.

The ranges calculated for the Popper *et al*. (2014) criteria are no greater than 400 m, with many, especially the $SEL_{cum}$ criteria, being less than 100 m. The exceptions were ranges modelled for TTS, where the largest values predicted were when considering the largest blow energy, with impact ranges of between 16 and 18 km depending on the piling ramp up scenario. Stationary animal $SEL_{cum}$ calculations see the TTS impact ranges increase to 33 km.

Also, additional modelling was carried out for $SEL_{ss}$ noise levels for the unweighted, cumulative Popper *et al*. (2014) criteria, these are presented in Appendix A.

| Fish - $SPL_{peak}$ (maximum energy) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Injury (fish: no swim bladder) unweighted $SPL_{peak}$ (213 dB re 1 µPa) | Area (km²) | 0.03 | 0.05 | 0.08 | 0.03 | 0.05 | 0.08 |
| | Max (m) | 100 | 130 | 170 | 100 | 130 | 160 |
| | Min (m) | 100 | 130 | 160 | 100 | 130 | 160 |
| | Mean (m) | 100 | 130 | 170 | 100 | 130 | 160 |
| Injury (fish: with swim bladder) unweighted $SPL_{peak}$ (207 dB re 1 µPa) | Area (km²) | 0.18 | 0.29 | 0.45 | 0.17 | 0.27 | 0.42 |
| | Max (m) | 240 | 310 | 380 | 230 | 290 | 370 |
| | Min (m) | 240 | 310 | 380 | 230 | 290 | 370 |
| | Mean (m) | 240 | 310 | 380 | 230 | 290 | 370 |

*Table 4-27 Predicted unweighted $SPL_{peak}$ impact ranges for fish using criteria from Popper et al. (2014) for maximum hammer blow energies*

| Fish - $SPL_{peak}$ (soft start) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 300 kJ | 400 kJ | 540 kJ | 300 kJ | 400 kJ | 540 kJ |
| Injury (fish: no swim bladder) unweighted $SPL_{peak}$ (213 dB re 1 µPa) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| Injury (fish: with swim bladder) unweighted $SPL_{peak}$ (207 dB re 1 µPa) | Area (km²) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| | Max (m) | 50 | 60 | 70 | < 50 | 50 | 70 |
| | Min (m) | < 50 | 60 | 70 | < 50 | 50 | 70 |
| | Mean (m) | 50 | 60 | 70 | < 50 | 50 | 70 |

*Table 4-28 Predicted unweighted $SPL_{peak}$ impact ranges for fish using criteria from Popper et al. (2014) for soft start hammer blow energies*

| Fish - Fleeing - $SEL_{cum}$ (Sequence 2) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Mortality (fish: no swim bladder) $SEL_{cum}$ (> 219 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Recoverable injury (fish: no swim bladder) $SEL_{cum}$ (> 216 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Mortality (fish: swim bladder not involved in hearing) $SEL_{cum}$ (210 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Mortality (fish: swim bladder involved in hearing) $SEL_{cum}$ (207 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Recoverable injury (fish: with swim bladder) $SEL_{cum}$ (203 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| TTS (all fish) $SEL_{cum}$ (186 re 1 µPa²s) | Area (km²) | 470 | 640 | 830 | 320 | 440 | 600 |
| | Max (m) | 13000 | 16000 | 18000 | 11000 | 14000 | 16000 |
| | Min (m) | 11000 | 13000 | 14000 | 8700 | 10000 | 12000 |
| | Mean (m) | 12000 | 14000 | 16000 | 10000 | 12000 | 14000 |

*Table 4-29 Predicted unweighted $SEL_{cum}$ impact ranges for fish using criteria from Popper et al. (2014) assuming a fleeing speed of 1.5 $ms^{-1}$ for piling sequence 2*

| Fish - Fleeing - $SEL_{cum}$ (Sequence 3) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Mortality (fish: no swim bladder) $SEL_{cum}$ (> 219 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Recoverable injury (fish: no swim bladder) $SEL_{cum}$ (> 216 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Mortality (fish: swim bladder not involved in hearing) $SEL_{cum}$ (210 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Mortality (fish: swim bladder involved in hearing) $SEL_{cum}$ (207 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| Recoverable injury (fish: with swim bladder) $SEL_{cum}$ (203 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Min (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| | Mean (m) | < 100 | < 100 | < 100 | < 100 | < 100 | < 100 |
| TTS (all fish) $SEL_{cum}$ (186 re 1 µPa²s) | Area (km²) | 580 | 780 | 1000 | 400 | 550 | 740 |
| | Max (m) | 15000 | 18000 | 21000 | 14000 | 16000 | 19000 |
| | Min (m) | 12000 | 13000 | 15000 | 9200 | 11000 | 12000 |
| | Mean (m) | 14000 | 16000 | 18000 | 11000 | 13000 | 15000 |

*Table 4-30 Predicted unweighted $SEL_{cum}$ impact ranges for fish using criteria from Popper et al. (2014) assuming a fleeing speed of 1.5 $ms^{-1}$ for piling sequence 3*

| Fish - Stationary - $SEL_{cum}$ (Sequence 2) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Mortality (fish: no swim bladder) $SEL_{cum}$ (> 219 dB re 1 µPa²s) | Area (km²) | 0.29 | 0.46 | 0.73 | 0.27 | 0.44 | 0.7 |
| | Max (m) | 310 | 390 | 490 | 300 | 380 | 480 |
| | Min (m) | 300 | 380 | 480 | 290 | 370 | 470 |
| | Mean (m) | 310 | 390 | 490 | 300 | 380 | 480 |
| Recoverable injury (fish: no swim bladder) $SEL_{cum}$ (> 216 dB re 1 µPa²s) | Area (km²) | 0.73 | 1.2 | 1.8 | 0.7 | 1.1 | 1.7 |
| | Max (m) | 490 | 620 | 770 | 480 | 600 | 750 |
| | Min (m) | 480 | 610 | 760 | 470 | 590 | 740 |
| | Mean (m) | 490 | 620 | 770 | 480 | 600 | 750 |
| Mortality (fish: swim bladder not involved in hearing) $SEL_{cum}$ (210 dB re 1 µPa²s) | Area (km²) | 4.7 | 7.4 | 11 | 4.3 | 6.7 | 10 |
| | Max (m) | 1200 | 1500 | 1900 | 1200 | 1500 | 1800 |
| | Min (m) | 1200 | 1500 | 1900 | 1200 | 1500 | 1800 |
| | Mean (m) | 1200 | 1500 | 1900 | 1200 | 1500 | 1800 |
| Mortality (fish: swim bladder involved in hearing) $SEL_{cum}$ (207 dB re 1 µPa²s) | Area (km²) | 11 | 18 | 26 | 10 | 16 | 23 |
| | Max (m) | 1900 | 2400 | 2900 | 1800 | 2200 | 2700 |
| | Min (m) | 1900 | 2400 | 2900 | 1800 | 2200 | 2700 |
| | Mean (m) | 1900 | 2400 | 2900 | 1800 | 2200 | 2700 |
| Recoverable injury (fish: with swim bladder) $SEL_{cum}$ (203 dB re 1 µPa²s) | Area (km²) | 35 | 52 | 75 | 30 | 44 | 62 |
| | Max (m) | 3400 | 4100 | 5000 | 3100 | 3800 | 4500 |
| | Min (m) | 3300 | 4100 | 4900 | 3100 | 3700 | 4400 |
| | Mean (m) | 3400 | 4100 | 4900 | 3100 | 3700 | 4400 |
| TTS (all fish) $SEL_{cum}$ (186 re 1 µPa²s) | Area (km²) | 1100 | 1400 | 1700 | 880 | 1100 | 1300 |
| | Max (m) | 20000 | 23000 | 25000 | 18000 | 21000 | 23000 |
| | Min (m) | 18000 | 19000 | 21000 | 15000 | 17000 | 18000 |
| | Mean (m) | 19000 | 21000 | 23000 | 17000 | 19000 | 21000 |

*Table 4-31 Predicted unweighted $SEL_{cum}$ impact ranges for fish using criteria from Popper et al. (2014) assuming a stationary receptor for piling sequence 2*

| Fish - Stationary - $SEL_{cum}$ (Sequence 3) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Mortality (fish: no swim bladder) $SEL_{cum}$ (> 219 dB re 1 µPa$^2$s) | Area (km$^2$) | 1.1 | 1.8 | 2.8 | 1.1 | 1.7 | 2.6 |
| | Max (m) | 600 | 760 | 950 | 590 | 740 | 920 |
| | Min (m) | 590 | 750 | 940 | 580 | 730 | 910 |
| | Mean (m) | 600 | 760 | 950 | 590 | 740 | 920 |
| Recoverable injury (fish: no swim bladder) $SEL_{cum}$ (> 216 dB re 1 µPa$^2$s) | Area (km$^2$) | 2.9 | 4.5 | 6.9 | 2.7 | 4.2 | 6.3 |
| | Max (m) | 960 | 1200 | 1500 | 930 | 1200 | 1400 |
| | Min (m) | 950 | 1200 | 1500 | 920 | 1200 | 1400 |
| | Mean (m) | 960 | 1200 | 1500 | 930 | 1200 | 1400 |
| Mortality (fish: swim bladder not involved in hearing) $SEL_{cum}$ (210 dB re 1 µPa$^2$s) | Area (km$^2$) | 17 | 26 | 38 | 15 | 22 | 32 |
| | Max (m) | 2300 | 2900 | 3500 | 2200 | 2700 | 3200 |
| | Min (m) | 2300 | 2900 | 3500 | 2200 | 2700 | 3200 |
| | Mean (m) | 2300 | 2900 | 3500 | 2200 | 2700 | 3200 |
| Mortality (fish: swim bladder involved in hearing) $SEL_{cum}$ (207 dB re 1 µPa$^2$s) | Area (km$^2$) | 39 | 57 | 82 | 33 | 47 | 67 |
| | Max (m) | 3500 | 4300 | 5200 | 3300 | 3900 | 4700 |
| | Min (m) | 3500 | 4200 | 5100 | 3200 | 3900 | 4600 |
| | Mean (m) | 3500 | 4300 | 5100 | 3200 | 3900 | 4600 |
| Recoverable injury (fish: with swim bladder) $SEL_{cum}$ (203 dB re 1 µPa$^2$s) | Area (km$^2$) | 110 | 150 | 510 | 85 | 120 | 160 |
| | Max (m) | 5900 | 7100 | 8300 | 5300 | 6300 | 7300 |
| | Min (m) | 5700 | 6800 | 8000 | 5200 | 6100 | 7000 |
| | Mean (m) | 5800 | 6900 | 8100 | 5200 | 6200 | 7200 |
| TTS (all fish) $SEL_{cum}$ (186 re 1 µPa$^2$s) | Area (km$^2$) | 2000 | 2400 | 2800 | 1600 | 1900 | 2300 |
| | Max (m) | 28000 | 30000 | 33000 | 26000 | 29000 | 32000 |
| | Min (m) | 23000 | 25000 | 26000 | 20000 | 22000 | 23000 |
| | Mean (m) | 25000 | 28000 | 30000 | 23000 | 25000 | 27000 |

*Table 4-32 Predicted unweighted $SEL_{cum}$ impact ranges for fish using criteria from Popper et al. (2014) assuming a stationary receptor for piling sequence 3*

# 5 Other noise sources

Although impact piling is expected to be the primary noise source during offshore wind farm construction and development (Bailey et al., 2014), several other anthropogenic noise sources may be present. Each of these has been considered, and its impact assessed, in this section.

Table 5-1 provides a summary of the various noise producing sources, aside from impact piling, that are expected to be present during the construction and operation of Teesside A.

| Activity | Description |
|---|---|
| Cable laying | Noise from the cable laying vessel and any other associated noise during the offshore cable installation. |
| Rock placement | Potentially required on site for installation of offshore cables (Cable crossings and cable protection) and scour protection around foundation structures. |
| Trenching | Plough trenching may be required during offshore cable installation. |
| Vessel noise | Jack-up barges for piling substructure and WTG installation. Other large and medium sized vessels on site to carry out other construction tasks, and anchor handling. Other small vessels for crew transport and maintenance on site. |
| Operational WTG | Noise transmitted through the water from operational WTG. The project design envelope gives turbines with rotor diameters of up to 280 m. |

*Table 5-1 Summary of the possible noise making activities at Teesside A other than impact piling*

The NPL Good Practice Guide 133 for underwater noise measurements (Robinson *et al*., 2014) indicates that under certain circumstances, a simple modelling approach may be considered acceptable. Such an approach has been used for these noise sources, which are variously either quiet compared to impact piling (e.g. cable laying, rock placement) or where detailed modelling would imply an unwarranted accuracy (e.g. where data is limited such as with large operational WTG noise). The high-level overview of modelling that has been presented here is considered sufficient and it is considered that there would be little benefit in using a more detailed model at this stage. The limitations of this approach are noted, including the lack of frequency or bathymetry dependence.

## 5.1 Noise making activities

For the purposes of identifying the greatest noise impacts, approximate subsea noise levels have been predicted using a simple modelling approach based on measured data from Subacoustech Environmental's own underwater noise measurement database, scaled to relevant parameters for the site and specific noise source. Predicted source levels for the construction activities are presented in Table 5-2 along with a summary of the number of datasets used in each case. As previously, all $SEL_{cum}$ criteria use the same assumptions as presented in section 3.2.2 and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. It should be noted that this modelling approach does not take bathymetry or other environmental conditions into account, and as such can be applied to any location in the Teesside A project area. Operational WTGs have been assessed separately in section 5.2.

| Source | Estimated unweighted source level | Comments |
|---|---|---|
| Cable laying | 171 dB re 1 µPa @ 1 m (RMS) | Based on 11 datasets from a pipe laying vessel measuring 300 m in length; this is considered a worst-case noise source for cable laying operations |
| Rock placement | 172 dB re 1 µPa @ 1 m (RMS) | Based on four datasets from rock placement vessel 'Rollingstone.' |
| Trenching | 172 dB re 1 µPa @ 1 m (RMS) | Based on three datasets of measurements from trenching vessels more than 100 m in length |
| Vessel noise (large) | 171 dB re 1 µPa @ 1 m (RMS) | Based on five datasets of large vessels including container ships, FPSOs and other vessels more than 100 m in length. Vessel speed assumed as 12 knots. |
| Vessel noise (medium) | 164 dB re 1 µPa @ 1 m (RMS) | Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 12 knots. |

*Table 5-2 Summary of the estimated unweighted source levels for the different construction noise sources considered*

Table 5-3 and Table 5-4 summarise the predicted impact ranges for these noise sources. It is worth noting that the Southall *et al*. (2019) and Popper *et al*. (2014) criteria give different criteria for non-impulsive or continuous noise sources compared to impulsive noise (see sections 2.2 and 2.4); all sources in this section are considered non-pulse or continuous-type.

Given the modelled impact ranges, any marine mammal would have to remain in close proximity (in most cases less than 50 m) from the source continuously for 24 hours to be exposed to levels sufficient to induce PTS as per Southall *et al*. (2019); in most hearing groups, the noise levels are low enough that there is negligible risk. For fish, there is a low to negligible risk of any injury or TTS, in line with guidance for continuous noise sources in Popper *et al*. (2014) as presented in Table 2-11. All sources presented here are much quieter than those presented for impact piling in section 4.

| Southall *et al*. (2019) | | Cable laying | Rock placement | Trenching | Vessels (large) | Vessels (medium) |
|---|---|---|---|---|---|---|
| PTS | 199 dB (LF $SEL_{cum}$) | < 100 m | < 100 m | < 100 m | < 100 m | < 100 m |
| | 198 dB (HF $SEL_{cum}$) | < 100 m | < 100 m | < 100 m | < 100 m | < 100 m |
| | 173 dB (VHF $SEL_{cum}$) | < 100 m | < 100 m | < 100 m | < 100 m | < 100 m |
| | 201 dB (PCW $SEL_{cum}$) | < 100 m | < 100 m | < 100 m | < 100 m | < 100 m |
| TTS | 179 dB (LF $SEL_{cum}$) | < 100 m | < 100 m | < 100 m | < 100 m | < 100 m |
| | 178 dB (HF $SEL_{cum}$) | < 100 m | < 100 m | < 100 m | < 100 m | < 100 m |
| | 153 dB (VHF $SEL_{cum}$) | < 100 m | 990 m | < 100 m | < 100 m | < 100 m |
| | 181 dB (PCW $SEL_{cum}$) | < 100 m | < 100 m | < 100 m | < 100 m | < 100 m |

*Table 5-3 Summary of the impact ranges for the different noise sources related to construction using the non-impulsive criteria from Southall et al. (2019) for marine mammals*

| Popper *et al*. (2014) | Cable laying | Rock placement | Trenching | Vessels (large) | Vessels (medium) |
|---|---|---|---|---|---|
| **Recoverable injury** 170 dB (48 hours) Unweighted $SPL_{RMS}$ | < 50 m | < 50 m | < 50 m | < 50 m | < 50 m |
| **TTS** 158 dB (12 hours) Unweighted $SPL_{RMS}$ | < 50 m | < 50 m | < 50 m | < 50 m | < 50 m |

*Table 5-4 Summary of the impact ranges from Popper et al. (2014) for shipping and continuous noise, covering the different noise sources related to construction for species of fish (swim bladder involved in hearing)*

## 5.2 Operational WTG noise

It is believed that the main source of underwater noise from operational WTGs will be mechanically generated vibration from the rotating machinery in the turbines, which is transmitted into the sea through the structure of the turbine tower, pile and foundations (Nedwell *et al.*, 2003). Noise levels generated above the water surface are low enough that no significant airborne sound will pass from the air to the water.

The project design envelope for Teesside A gives the maximum potential WTG rotor diameter as 280 m. A summary of operational WTG where measurements have been collected is given in Table 5-5.

| Wind farm | Lynn | Inner Dowsing | Gunfleet Sands 1 & 2 | Gunfleet Sands 3 |
|---|---|---|---|---|
| Type of turbine used | Siemens SWT-3.6-107 | Siemens SWT-3.6-107 | Siemens SWT-3.6-107 | Siemens SWT-6.0-120 |
| Number of turbines | 27 | 27 | 48 | 2 |
| Rotor diameter | 107 m | 107 m | 107 m | 120 m |
| Water depths | 6 to 8 m | 6 to 14 m | 0 to 15 m | 5 to 12 m |
| Representative sediment type | Sandy gravel / muddy sandy gravel | Sandy gravel / muddy sandy gravel | Sand / muddy sand / muddy sandy gravel | Sand / muddy sand / muddy sandy gravel |
| Turbine separation (representative) | 500 m | 500 m | 890 m | 435 m |

*Table 5-5 Characteristics of measured operational wind farms used as a basis for modelling*

The estimation of the effects of operational noise in these situations has two features that make it harder to assess compared with noise sources such as impact piling. Primarily, the problem is one of level; noise measurements made at many wind farms have demonstrated that the operational noise produced was at such a low level that it was difficult to measure relative to background noise (Cheesman, 2016) at distances of a few hundred metres. Also, the multiple turbines of an offshore wind farm could be considered as an extended, distributed noise source, as opposed to a “point source” as would be appropriate for pile driving at a single location, for example. The measurement techniques used at the sites above have dealt with these issues by considering the operational noise spectra in terms of levels within and on the edge of the wind farm (but relatively close to the turbines, so that some noise above background could be detected).

The considered turbine size for Teesside A is larger than those for which data is available, and as such, estimations of a scaling factor must be conservative to minimise the risk of underestimating the noise. However, it is recognised that the available data on which to base the scaling factor is limited and the extrapolation that must be made is significant.

The operational source levels (as $SPL_{RMS}$) for the measured sites are given in Table 5-6 (Cheesman, 2016), with an estimated source level for Teesside A in the bottom row. To predict operational WTG noise levels, the measured levels at each of the sites have been taken and then a linear correction factor has been included to scale up the source levels. A linear fit was applied to the data as this is the most conservative extrapolation, leading to the highest, and thus worst-case, estimation of source level noise from the larger 280 m diameter rotor WTGs. This results in an estimated source level of 162.7 dB SPL$_{RMS}$ @ 1 m, 16.7 dB higher than the 120 m diameter rotor WTG, the largest for which noise data was available.

| **Site** | **Unweighted source level** |
|---|---|
| Lynn (107 m) | 141 dB re 1 µPa (RMS) @ 1 m |
| Inner Dowsing (107 m) | 142 dB re 1 µPa (RMS) @ 1 m |
| Gunfleet Sands 1 & 2 (107 m) | 145 dB re 1 µPa (RMS) @ 1 m |
| Gunfleet Sands 3 (120 m) | 146 dB re 1 µPa (RMS) @ 1 m |
| Teesside A (280 m) | 162.7 dB re 1 µPa (RMS) @ 1 m |

*Table 5-6 Measured operational WTG noise taken at operational wind farms, and the predicted source level for the maximum turbine size considered at Teesside A*

A summary of the predicted impact ranges is given in Table 5-7 and Table 5-8. The SEL$_{cum}$ criteria use the same assumptions as presented in section 3.2.2m and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. The operational WTG source is considered a non-impulsive sound by Southall *et al*. (2019) and a continuous source by Popper *et al*. (2014).

| Southall *et al*. (2019) | | **Operational WTG (280 m)** |
|---|---|---|
| **PTS** | 199 dB (LF SEL$_{cum}$) | < 100 m |
| | 198 dB (HF SEL$_{cum}$) | < 100 m |
| | 173 dB (VHF SEL$_{cum}$) | < 100 m |
| | 201 dB (PCW SEL$_{cum}$) | < 100 m |
| **TTS** | 179 dB (LF SEL$_{cum}$) | < 100 m |
| | 178 dB (HF SEL$_{cum}$) | < 100 m |
| | 153 dB (VHF SEL$_{cum}$) | < 100 m |
| | 181 dB (PCW SEL$_{cum}$) | < 100 m |

*Table 5-7 Summary of the impact ranges for operational WTGs using the non-impulsive noise criteria from Southall et al. (2019) for marine mammals*

| Popper *et al*. (2014) | **Operational WTG (280 m)** |
|---|---|
| **Recoverable injury**<br>170 dB (48 hours) Unweighted SPL$_{RMS}$ | < 50 m |
| **TTS**<br>158 dB (12 hours) Unweighted SPL$_{RMS}$ | < 50 m |

*Table 5-8 Summary of the impact ranges for shipping and continuous noise from Popper et al. (2014) for operational WTGs for species of fish (swim bladder involved in hearing)*

The results show that, for operational WTGs, any injury risk is minimal. Taking both sets of results into account (operational WTG noise and other noise sources related to construction, see section 5.1), and comparing them to the impact piling results in section 4, it is clear that noise from impact piling results in much greater levels and impact ranges, and hence should be considered the activity which has the potential to have the greatest effect during the construction and lifecycle of Teesside A.

# 6 Summary and conclusions

Underwater noise modelling was carried out by NPL in 2013 to assess the effects of impact piling noise on fish and marine mammals from the construction of the Teesside A offshore wind farm, in the Dogger Bank development area. In the time since the original modelling was completed, new noise thresholds and criteria have been developed by Southall *et al*. (2019) for marine mammals and Popper *et al*. (2014) for fish. To obtain impact ranges for these new criteria, additional modelling has been carried out by Subacoustech Environmental.

The modelling undertaken by NPL utilised an energy flux solution, and the model used is not openly available. Subacoustech have used a different but comparable method using the semi-empirical INSPIRE model. This additional modelling has sought to be compatible with and provide equivalent results to the original modelling. A conservative fit to the data was used so that levels predicted along the worst-case transect match with the highest levels reported originally, especially at the greatest distances. Overall, there was a good level of correlation between the two modelling result datasets.

In addition to modelling to the new criteria, the effects of two piling hammer blow energies greater than that considered originally have been assessed (4000 kJ and 5400 kJ).

The modelling results using the new metrics showed that, using the Southall *et al*. (2019) $SPL_{peak}$ criteria, ranges are largely within a few hundred metres, with only the TTS ranges for high-frequency cetaceans extending over 1 km. For the $SEL_{cum}$ criteria, larger ranges are predicted, with PTS for LF cetaceans reaching 8.4 km and TTS for LF cetaceans reaching a maximum range of 32 km for the largest hammer blow energies (5400 kJ) and worst-case ramp-up sequence 3. Also, predicted impact ranges for ramp-up sequence 3 (with 12,600 pile strikes) resulted in larger ranges than those predicted for ramp-up sequence 2 (with 5,000 pile strikes).

When considering the Popper *et al*. (2014) criteria, the ranges calculated are no greater than 400 m, with many, especially the $SEL_{cum}$ criteria, being less than 100 m. The exceptions were ranges modelled for TTS, where the largest values predicted were when considering the largest blow energy, with impact ranges of between 16 and 18 km depending on the piling ramp up scenario.

All modelled scenarios using the increased maximum blow energies result in larger impact ranges than with the largest blow energy used in the original report.

Noise sources other than piling have been considered using a high-level, simple modelling approach, including cable laying, rock placement, trenching, vessel noise and operational WTG noise. The predicted noise levels for the other construction noise sources and during WTG operation are well below those predicted for impact piling noise. The risk of any potential injurious effects to fish or marine mammals from these sources are expected to be negligible as the noise emissions from these are very close to, or below, the appropriate injury criteria at the source of the noise.

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# Appendix A Additional impact ranges

The following tables collect single strike SEL impact ranges for Southall *et al*. (2019) (Table A 1 to Table A 8) and Popper *et al*. (2014) (Table A 9 and Table A 10) criteria.

| Low-frequency cetaceans (LF) (maximum energy) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| PTS (Impulsive) Weighted $SEL_{ss}$ (183 dB re 1 $\mu Pa^2 s$) | Area (km$^2$) | 0.07 | 0.12 | 0.19 | 0.07 | 0.12 | 0.19 |
| | Max (m) | 160 | 200 | 250 | 150 | 200 | 250 |
| | Min (m) | 150 | 200 | 250 | 150 | 190 | 250 |
| | Mean (m) | 160 | 200 | 250 | 150 | 200 | 250 |
| TTS (Impulsive) Weighted $SEL_{ss}$ (168 dB re 1 $\mu Pa^2 s$) | Area (km$^2$) | 8.5 | 13 | 20 | 7.7 | 12 | 17 |
| | Max (m) | 1700 | 2100 | 2500 | 1600 | 1900 | 2400 |
| | Min (m) | 1600 | 2000 | 2500 | 1600 | 1900 | 2400 |
| | Mean (m) | 1700 | 2100 | 2500 | 1600 | 1900 | 2400 |
| PTS (Non-impulsive) Weighted $SEL_{ss}$ (199 dB re 1 $\mu Pa^2 s$) | Area (km$^2$) | < 0.01 | 0.01 | 0.01 | < 0.01 | < 0.01 | 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Non-impulsive) Weighted $SEL_{ss}$ (179 dB re 1 $\mu Pa^2 s$) | Area (km$^2$) | 0.27 | 0.44 | 0.7 | 0.26 | 0.42 | 0.67 |
| | Max (m) | 300 | 380 | 470 | 290 | 370 | 460 |
| | Min (m) | 300 | 380 | 470 | 290 | 370 | 460 |
| | Mean (m) | 300 | 380 | 470 | 290 | 370 | 460 |

*Table A 1 Predicted low-frequency cetacean weighted $SEL_{ss}$ impact ranges using criteria from Southall et al. (2019) for maximum blow energies*

| Low-frequency cetaceans (LF) (soft start) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 300 kJ | 400 kJ | 540 kJ | 300 kJ | 400 kJ | 540 kJ |
| PTS (Impulsive) Weighted $SEL_{ss}$ (183 dB re 1 $\mu Pa^2 s$) | Area (km$^2$) | < 0.01 | < 0.01 | 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Impulsive) Weighted $SEL_{ss}$ (168 dB re 1 $\mu Pa^2 s$) | Area (km$^2$) | 0.27 | 0.43 | 0.68 | 0.26 | 0.41 | 0.65 |
| | Max (m) | 300 | 370 | 470 | 290 | 360 | 460 |
| | Min (m) | 300 | 370 | 470 | 290 | 360 | 460 |
| | Mean (m) | 300 | 370 | 470 | 290 | 360 | 460 |
| PTS (Non-impulsive) Weighted $SEL_{ss}$ (199 dB re 1 $\mu Pa^2 s$) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Non-impulsive) Weighted $SEL_{ss}$ (179 dB re 1 $\mu Pa^2 s$) | Area (km$^2$) | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 |
| | Max (m) | 50 | 60 | 80 | 50 | 60 | 80 |
| | Min (m) | < 50 | 60 | 80 | < 50 | 60 | 80 |
| | Mean (m) | 50 | 60 | 80 | 50 | 60 | 80 |

*Table A 2 Predicted low-frequency cetacean weighted $SEL_{ss}$ impact ranges using criteria from Southall et al. (2019) for soft start blow energies*

| High-frequency cetaceans (HF) (maximum energy) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| PTS (Impulsive) Weighted $SEL_{ss}$ (185 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Impulsive) Weighted $SEL_{ss}$ (170 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| PTS (Non-impulsive) Weighted $SEL_{ss}$ (198 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Non-impulsive) Weighted $SEL_{ss}$ (178 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |

*Table A 3 Predicted high-frequency cetacean weighted $SEL_{ss}$ impact ranges using criteria from Southall et al. (2019) for maximum blow energies*

| High-frequency cetaceans (HF) (soft start) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 300 kJ | 400 kJ | 540 kJ | 300 kJ | 400 kJ | 540 kJ |
| PTS (Impulsive) Weighted $SEL_{ss}$ (185 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Impulsive) Weighted $SEL_{ss}$ (170 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| PTS (Non-impulsive) Weighted $SEL_{ss}$ (198 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Non-impulsive) Weighted $SEL_{ss}$ (178 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |

*Table A 4 Predicted high-frequency cetacean weighted $SEL_{ss}$ impact ranges using criteria from Southall et al. (2019) for soft start blow energies*

| Very high-frequency cetaceans (VHF) (maximum energy) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| PTS (Impulsive) Weighted $SEL_{ss}$ (155 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Impulsive) Weighted $SEL_{ss}$ (140 dB re 1 µPa²s) | Area (km²) | 0.15 | 0.25 | 0.39 | 0.15 | 0.24 | 0.38 |
| | Max (m) | 220 | 280 | 360 | 220 | 280 | 350 |
| | Min (m) | 220 | 280 | 350 | 220 | 280 | 350 |
| | Mean (m) | 220 | 280 | 360 | 220 | 280 | 350 |
| PTS (Non-impulsive) Weighted $SEL_{ss}$ (173 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Non-impulsive) Weighted $SEL_{ss}$ (153 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | 0.01 | < 0.01 | < 0.01 | 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |

*Table A 5 Predicted very high-frequency cetacean weighted $SEL_{ss}$ impact ranges using criteria from Southall et al. (2019) for maximum blow energies*

| Very high-frequency cetaceans (VHF) (soft start) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 300 kJ | 400 kJ | 540 kJ | 300 kJ | 400 kJ | 540 kJ |
| PTS (Impulsive) Weighted $SEL_{ss}$ (155 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Impulsive) Weighted $SEL_{ss}$ (140 dB re 1 µPa²s) | Area (km²) | < 0.01 | 0.01 | 0.01 | < 0.01 | 0.01 | 0.01 |
| | Max (m) | < 50 | < 50 | 60 | < 50 | < 50 | 60 |
| | Min (m) | < 50 | < 50 | 60 | < 50 | < 50 | 60 |
| | Mean (m) | < 50 | < 50 | 60 | < 50 | < 50 | 60 |
| PTS (Non-impulsive) Weighted $SEL_{ss}$ (173 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Non-impulsive) Weighted $SEL_{ss}$ (153 dB re 1 µPa²s) | Area (km²) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |

*Table A 6 Predicted very high-frequency cetacean weighted $SEL_{ss}$ impact ranges using criteria from Southall et al. (2019) for soft start blow energies*

| Phocid carnivores in water (PCW) (maximum energy) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| PTS (Impulsive) Weighted $SEL_{ss}$ (185 dB re 1 µ$Pa^2$s) | Area ($km^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Impulsive) Weighted $SEL_{ss}$ (170 dB re 1 µ$Pa^2$s) | Area ($km^2$) | 0.1 | 0.16 | 0.25 | 0.1 | 0.15 | 0.24 |
| | Max (m) | 180 | 230 | 280 | 180 | 220 | 280 |
| | Min (m) | 180 | 220 | 280 | 170 | 220 | 280 |
| | Mean (m) | 180 | 230 | 280 | 180 | 220 | 280 |
| PTS (Non-impulsive) Weighted $SEL_{ss}$ (201 dB re 1 µ$Pa^2$s) | Area ($km^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Non-impulsive) Weighted $SEL_{ss}$ (181 dB re 1 µ$Pa^2$s) | Area ($km^2$) | < 0.01 | < 0.01 | 0.01 | < 0.01 | < 0.01 | 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |

*Table A 7 Predicted phocid carnivores in water weighted $SEL_{ss}$ impact ranges using criteria from Southall et al. (2019) for maximum blow energies*

| Phocid carnivores in water (PCW) (soft start) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 300 kJ | 400 kJ | 540 kJ | 300 kJ | 400 kJ | 540 kJ |
| PTS (Impulsive) Weighted $SEL_{ss}$ (185 dB re 1 µ$Pa^2$s) | Area ($km^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Impulsive) Weighted $SEL_{ss}$ (170 dB re 1 µ$Pa^2$s) | Area ($km^2$) | < 0.01 | < 0.01 | 0.01 | < 0.01 | < 0.01 | 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| PTS (Non-impulsive) Weighted $SEL_{ss}$ (201 dB re 1 µ$Pa^2$s) | Area ($km^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (Non-impulsive) Weighted $SEL_{ss}$ (181 dB re 1 µ$Pa^2$s) | Area ($km^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |

*Table A 8 Predicted phocid carnivores in water weighted $SEL_{ss}$ impact ranges using criteria from Southall et al. (2019) for soft start blow energies*

| Fish - $SEL_{cum}$ (maximum energy) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 3000 kJ | 4000 kJ | 5400 kJ | 3000 kJ | 4000 kJ | 5400 kJ |
| Mortality (fish: no swim bladder) $SEL_{ss}$ (> 219 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| Recoverable injury (fish: no swim bladder) $SEL_{ss}$ (> 216 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| Mortality (fish: swim bladder not involved in hearing) $SEL_{ss}$ (210 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| Mortality (fish: swim bladder involved in hearing) $SEL_{ss}$ (207 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| Recoverable injury (fish: with swim bladder) $SEL_{ss}$ (203 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (all fish) $SEL_{ss}$ (186 re 1 µPa$^2$s) | Area (km$^2$) | 0.16 | 0.25 | 0.41 | 0.15 | 0.25 | 0.39 |
| | Max (m) | 230 | 290 | 360 | 220 | 280 | 350 |
| | Min (m) | 220 | 290 | 360 | 220 | 280 | 350 |
| | Mean (m) | 230 | 290 | 360 | 220 | 280 | 350 |

*Table A 9 Predicted unweighted fish $SEL_{ss}$ impact ranges using criteria from Popper et al. (2014) for maximum blow energies*

| Fish - $SEL_{cum}$ (soft start) | | Location ID1 | | | Location ID5 | | |
|---|---|---|---|---|---|---|---|
| | | 300 kJ | 400 kJ | 540 kJ | 300 kJ | 400 kJ | 540 kJ |
| Mortality (fish: no swim bladder) $SEL_{ss}$ (> 219 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| Recoverable injury (fish: no swim bladder) $SEL_{ss}$ (> 216 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| Mortality (fish: swim bladder not involved in hearing) $SEL_{ss}$ (210 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| Mortality (fish: swim bladder involved in hearing) $SEL_{ss}$ (207 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| Recoverable injury (fish: with swim bladder) $SEL_{ss}$ (203 dB re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Max (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Min (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| | Mean (m) | < 50 | < 50 | < 50 | < 50 | < 50 | < 50 |
| TTS (all fish) $SEL_{ss}$ (186 re 1 µPa$^2$s) | Area (km$^2$) | < 0.01 | 0.01 | 0.01 | < 0.01 | 0.01 | 0.01 |
| | Max (m) | < 50 | < 50 | 60 | < 50 | < 50 | 60 |
| | Min (m) | < 50 | < 50 | 60 | < 50 | < 50 | 60 |
| | Mean (m) | < 50 | < 50 | 60 | < 50 | < 50 | 60 |

*Table A 10 Predicted unweighted fish $SEL_{ss}$ impact ranges using criteria from Popper et al. (2014) for soft start blow energies*

# Report documentation page

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