ENVIRONMENTAL STATEMENT: 6.3 APPENDIX 6-4: UNDERWATER NOISE ASSESSMENT

DECARBONISATION

Cory Decarbonisation Project

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1. INTRODUCTION

1.1.1. This report comprises an assessment of the effects of underwater noise and vibration arising from the Proposed Scheme, specifically including dredging, piling (both impact piling and vibro-piling) and the associated vessel noise for the construction and operation of the Proposed Jetty; and the demolition of the Belvedere Power Station Jetty (disused) (if this option were taken forward), on the south bank of the River Thames in Belvedere, London.

1.1.2. This report has been structured as follows:

- **Section 1:** Introduction – a brief overview of the project and need for the assessment;
- **Section 2:** Underwater Acoustics Principles and Terminology – an overview of the fundamental underwater acoustics principles and the metrics considered within this assessment;
- **Section 3:** Underwater Noise Exposure on Marine Fauna – an overview of the potential impacts of noise exposure on marine fauna and acknowledgement of the marine fauna to be assessed within this assessment;
- **Section 4:** Underwater Noise Assessment Criteria – a review of the auditory thresholds and subsequent impact criteria associated with the marina fauna that occur within the zone of influence of the Proposed Scheme;
- **Section 5:** Underwater Noise Modelling Methodology - reviews the key factors influencing the propagation of underwater noise and presents the preferred underwater noise propagation model that has been applied in this assessment;
- **Section 6:** Project Related Noise Sources – a review of the proposed noise emitting activity and the corresponding specific acoustic characteristics of each activity;
- **Section 7:** Underwater Noise Modelling Results and Potential Effects – reviews the outputs of the modelling and the potential effects on the assessed marine fauna; and
- **Section 8:** Summary and Conclusions – presents an overview of the underwater noise assessment and conclusions and recommended mitigation considerations.

2. UNDERWATER ACOUSTICS PRINCIPLES & TERMINOLOGY

2.1.1. The following section comprises an overview of key underwater acoustics principles, and how it is described, classified and quantified.

2.1.2. Underwater sound is generated by the movement or vibration of any immersed object in water. The sound travels through the water as vibrations of the fluid particles in a series of pressure waves. The waves comprise a series of alternating compressions (positive pressure variations) and rarefactions (negative pressure fluctuations).

2.1.3. As sound consists of variations in pressure, the unit for measuring sound is usually referenced to a unit of pressure, the Pascal (Pa). The unit usually used to describe sound is the decibel (dB) and, in the case of underwater sound, the reference unit is taken as 1 micro pascal µPa (equal to 10^{-6} Pa), whereas airborne sound is usually referenced to a pressure of 20µPa. To convert from a sound pressure level reference to 20µPa to one referenced 1µPa, a factor of 20 log (20/1) (i.e. 26 dB) has to be added to the former quantity. Therefore, 60 dB re 20µPa is the same as 86 dB re 1µPa, although the difference in sound speed and densities mean that the difference in sound intensity is much greater from in-air compared to water.

2.1.4. All underwater sound pressure levels in this report are described in dB re 1µPa.

2.1.5. In water, the ‘strength’ of a sound source is usually described by its sound pressure level in dB re 1µPa, referenced back to a representative distance of 1 m from an assumed (infinitesimally small) point source. This allows for the calculation of sound levels in the far-field. For large, distributed sources, the actual sound pressure level in the near-field will be lower than predicted.

2.1.6. There are several different metrics that may be used as measures of underwater sound pressure (NPL, 2014). The key metrics that are used to characterise underwater sound pressure are as follows:

- **Peak sound pressure level (or zero-peak sound pressure), SPL_{pk}:** The maximum sound pressure during a stated time interval. A peak sound pressure may arise from a positive or negative sound pressure. This quantity is typically useful as a metric for a pulsed waveform.
- **Peak-peak sound pressure level, $SPL_{pk\text{-}pk}$:** The sum of the peak compressional pressure and the peak rarefactional pressure during a stated time interval. This quantity is typically most useful as a metric for a pulsed waveform.
- **Root mean square (RMS) sound pressure level, SPL_{rms}:** The square root of the mean square pressure, where the mean square pressure is the time integral of squared sound pressure over a specified time interval divided by the duration of the time interval.

2.1.7. **Figure 2-1** below provides a graphical representation of the above sound pressure metrics for a pulsed sound and a periodic waveform.

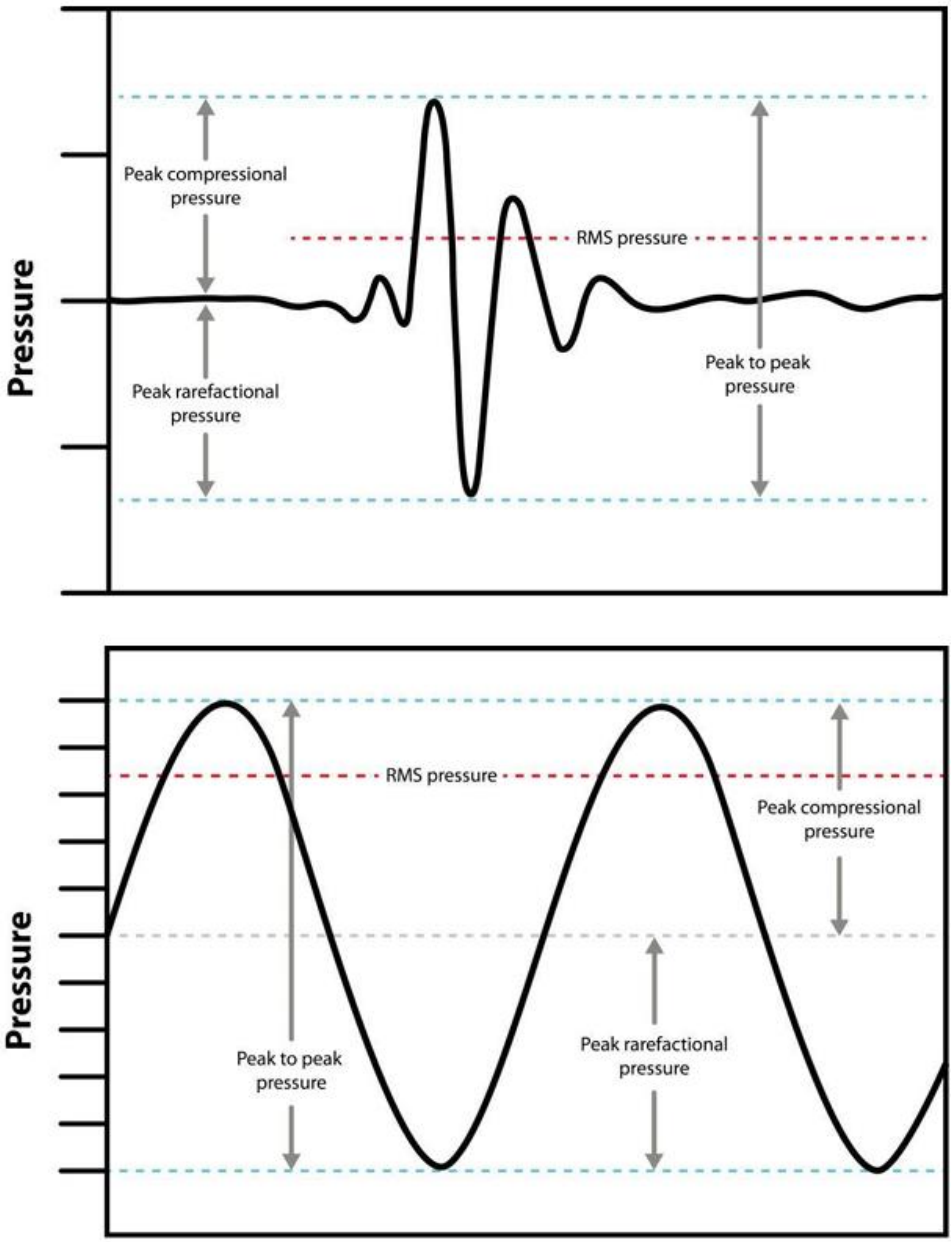

Figure 2-1: Graphical Representation of Sound Pressure Metrics for a Pulsed Sound (Upper Plot) and for a Periodic Waveform (LOWER plot) (NPL, 2014)

2.1.8. Another useful measure of sound used in underwater acoustics is the Sound Exposure Level (SEL). This metric is used as a measure of the total sound energy of an event or a number of events (e.g. over the course of a day) and is normalised to one second. This allows the total acoustic energy contained in events lasting a different amount of time to be compared on a like-for-like basis. It is defined as the integral of the square of the sound pressure over a stated time interval or event and is expressed in units of Pa^2s. In the context of this assessment, the SEL will be presented as either a cumulative SEL (SEL_{cum}) which is representative of the total acoustic energy of a noise source taking place across the course of a day, or a single strike SEL (SEL_{ss}) which is representative of a single event, in this case an impact pile strike.

2.1.9. The frequency, or pitch, of sound is the rate at which pressure oscillations occur and is measured in cycles per second, or Hertz (Hz). When sound is measured in a way which approximates how a human would perceive it using an A-weighting filter on a sound level meter, the resulting level is described in values of dBA. However, the auditory faculty of marine mammals is different to humans. Marine mammals perceive sound over a much wider range of frequencies and with a different sensitivity. It is therefore important to understand how an animal's hearing varies over the entire frequency range in order to assess the effects of sound on marine mammals. Consequently, hearing weighting functions have been developed to account for frequency-dependent sensitivities of pertinent marine mammal receptors (Southall *et al.* 2019). These hearing weighting functions have been used to inform the assessment.

3. UNDERWATER NOISE EXPOSURE ON MARINE FAUNA

3.1. POTENTIAL IMPACTS

3.1.1. Potential impacts on marine fauna from underwater noise are dependent upon: the noise source characteristics (frequency (Hz) and decibels (dB)); attenuation of the noise in the specific location; and the distance of the sound source from the receptor species. In addition to which, species and individual animals display variations in levels of sensitivity at different life stages and in different situations (e.g. presence of young).

3.1.2. Effects of underwater noise can be broadly classified as:

- **physical/physiological effects** (e.g. mortality, non-recoverable injury, permanent threshold shift (PTS) in hearing, temporary threshold shift (TTS) in hearing, recoverable injury); or
- **behavioural responses** (e.g. stress, changes in movements, migration, feeding, breeding, displacement, disturbance).

3.1.3. The biological significance of sound relates to how it interferes with an individual's capacity to undertake normal functional behaviours and activities, as well as their ability to grow, reproduce and survive. Behavioural effects of sound (e.g. communication, predator/prey detection) can result in both individual and population level consequences (e.g. alterations in abundance and diversity) and may affect the overall viability of a species (Popper *et al.* 2014). The greater magnitude and duration of a receptor having a response to noise the greater the likelihood of biological impacts arising from a behavioural disturbance (Popper *et al.* 2014).

3.2. SENSITIVE MARINE FAUNA ASSOCIATED WITH THE PROPOSED DEVELOPMENT

3.2.1. The Study Area is defined by the area at which underwater noise effects may take place. The following noise-sensitive marine species are known to be present in the Study Area or have been identified:

- **fish, eggs and larvae (species with and without swim bladders):** european seabass (*dicentrarchus labrax*), European flounder (*Platichthys flesus*), european smelt (*osmerus eperlanus*), pouting (*trisopterus luscus*), goby (*gobiidae*), various herring species; and
- **marine mammals:** harbour porpoise (*phocoena phocoena*), harbour seals (*phoca vitulina*), grey seals (*halichoerus grypus*).

4. UNDERWATER NOISE ASSESSMENT CRITERIA

4.1. INTRODUCTION

4.1.1. Sound propagation models can be constructed to allow the received noise level at different distances from the source to be calculated. To determine the consequences of these received levels on any marine fauna which might experience such noise emissions, it is necessary to relate the levels to known or estimated impact thresholds.

4.1.2. In order to determine the potential spatial range of injury and disturbance, a review has been undertaken of available evidence, including international guidance and scientific literature. The following sections summarise the relevant thresholds for the onset of effects and describe the evidence base used to derive them.

4.1.3. It is important to note that underwater sound has both a sound pressure and vibration (particle motion[a]) component. Whilst all marine mammals detect sound pressure in their auditory systems, all fish and many invertebrates also detect and use the particle motion component of underwater sound (Popper, Salmon & Horch 2001; Kaifu, Akamatsu & Segawa 2008). Invertebrates are understood to be mainly sensitive to particle motion rather than sound pressure, albeit more research is required to understand this (Hawkins *et al.,* 2021).

4.1.4. Despite it being widely known that fish are receptive to particle motion (e.g. Cahn, Siler & Wodinsky 1969), the major obstacle to scientific progress in this area has been the availability of appropriate equipment to apply in laboratory and field studies (Nedelec *et al.* 2016). Consequently, there are no widely used particle motion criteria to assess against. The criteria presented in the following sections are reflective of sound pressure metrics only. Invertebrates are not being considered as receptors within this assessment, as there are not any widely known particle motion and/or sound pressure criteria associated with them. Until further research is undertaken, this approach is typical of underwater noise assessments.

4.2. FISH, EGGS & LARVAE

4.2.1. Adult fish not in the immediate vicinity (i.e. the area around the noise source at which mortality or potential mortal injury is likely to take place, dependent on the characteristics of the noise source) of noise generating activity are generally able to vacate the area and avoid physical injury. However, larvae and spawn are not highly mobile and are therefore more likely to incur injuries from the sound energy in the immediate vicinity of the sound source, including damage to their hearing, kidneys, hearts and swim bladders. Such effects are unlikely to happen outside of the immediate vicinity of even the highest energy sound sources.

[a] Particle motion is the vibratory ‘back-and-forth’ motion in which particles move around an equilibrium point.

4.2.2. For fish, the most relevant criteria for injury are considered to be those contained in the *Sound Exposure for Fishes and Sea Turtles* (Popper *et al.,* 2014). Popper *et al.* (2014) sets out criteria for impacts due to different sources of noise. Those relevant to the Proposed Scheme are considered to be those for impacts due to impulsive noise (impact piling) and continuous noise (dredging, vessel noise, vibro-piling).

4.2.3. For both types of noise source (i.e. impulsive and continuous), where insufficient data exists to determine a quantitative guideline value, the risk is categorised in relative terms as “high”, “moderate” or “low” at three distances from the source: “near” (i.e. in the tens of metres), “intermediate” (i.e. in the hundreds of metres) or “far” (i.e. in the thousands of metres).

4.2.4. It should be noted that the qualitative criteria mentioned above cannot differentiate between exposures to different noise levels and therefore all sources of noise, no matter how noisy, would theoretically elicit the same assessment result. In the context of this assessment (i.e. the types of noise sources), and as shown in **Table 4-1**, the qualitative risks are generally qualified as “low”, with the exception of a moderate risk at “near” range (i.e. within tens of metres) for some types of animal and impairment effects. In line with the guidance provided in Popper *et al*., (2014), these relative risk ratings need to be considered with the source and received levels of the noise sources being assessed. The modelling inputs and outputs as presented in **Section 7** indicate that impacts ranges for instantaneous mortality and potential mortal injury, as well as recoverable injury are generally <15m where quantifiable peak sound pressure level criteria can be assessed against. As discussed in **Paragraph 4.2.1**, unless receptors are within this range, it is unlikely these effects will take place. Consequently, the qualitative relative risk ratings are not considered to provide a significant issue with respect to determining the potential effects of noise on fish.

4.2.5. **Table 4-1** below provides a summary of the assessment criteria applied in this assessment.

Table 4-1: Fish Auditory Threshold Criteria Applied in this Assessment

Fish Category	Impulsive Noise (Impact Piling)				Continuous Noise (Vibro-piling, Dredging, Vessel Noise)			
	Mortality and Potential Mortal Injury	Recoverable Injury	Temporary Threshold Shift (TTS)	Behavioural Response	Mortality and Potential Mortal Injury	Recoverable Injury	TTS	Behavioural Response
No swim bladder *(particle motion detection)*	>219 dB SEL_{cum} >213 dB SPL_{pk}	>216 dB SEL_{cum} >213 dB SPL_{pk}	>186 dB SEL_{cum}	**(N)** High **(I)** Moderate **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Moderate **(F)** Low
Swim bladder not involved in hearing *(particle motion detection)*	>210 dB SEL_{cum} >207 dB SPL_{pk}	>203 dB SEL_{cum} >207 dB SPL_{pk}	>186 dB SEL_{cum}	**(N)** High **(I)** Moderate **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Moderate **(F)** Low
Swim bladder involved in hearing *(primarily pressure detection)*	>207 dB SEL_{cum} >207 dB SPL_{pk}	>203 dB SEL_{cum} >207 dB SPL_{pk}	>186 dB SEL_{cum}	**(N)** High **(I)** High **(F)** Moderate	**(N)** Low **(I)** Low **(F)** Low	170 dB_{rms} 1µPa for 48hrs	158 dB_{rms} 1µPa for 12hrs	**(N)** High **(I)** Moderate **(F)** Low
Eggs and larvae	>210 dB SEL_{cum} >207 dB SPL_{pk}	**(N)** Moderate **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Low **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Moderate **(F)** Low

Fish Category	Impulsive Noise (Impact Piling)				Continuous Noise (Vibro-piling, Dredging, Vessel Noise)			
	Mortality and Potential Mortal Injury	Recoverable Injury	Temporary Threshold Shift (TTS)	Behavioural Response	Mortality and Potential Mortal Injury	Recoverable Injury	TTS	Behavioural Response

Notes:

SPL_{pk} and SPL_{rms} are referenced in dB re 1μPa, and SEL_{cum} is referenced in dB re $1μPa^2s$.

Where insufficient data exists to make a recommendation for guidelines a subjective approach is adopted in which the relative risk of an effect is placed in order of rank at three distances from the source – near (N), intermediate (I), and far (F) (top to bottom within each cell of the table, respectively). While it would not be appropriate to ascribe distances to effects because of the many variables in making such decisions, “near” might be considered to be in the tens of metres from the source, “intermediate” in the hundreds of metres, and “far” in the thousands of metres. The rating for effects in these tables is highly subjective and represents general consensus of the Popper *et al.* (2014) working group. These ratings are not hard and fast, and they are presented as the basis for discussion.

It is important to note, that the quantifiable criteria as set out for recoverable injury and TTS are reflective of the fish receptors being stationary for the 48 hour period or 12 hour period respectively. This is not reflective of real fish habitats, as the research is based on captive fish. However, it does provide a useful quantifiable threshold level at which conservative impact ranges can be calculated.

4.3. MARINE MAMMALS

4.3.1. The Joint Nature Conservation Committee (JNCC) guidance (JNCC, 2010) recommends using the injury criteria proposed by Southall *et al.* (2007). However, the guidance also suggests that criteria will need to be updated as and when more recent scientific studies become available.

4.3.2. These criteria were updated in 2016 (NOAA, 2018) and most recently in 2019 (Southall *et al.* 2019). They reflect the most comprehensive and up-to-date scientific knowledge relating to the risk of auditory injury to marine mammals.

4.3.3. Southall *et al.* (2019) divides marine mammals into various sensitivity groups, with the same impact thresholds used for all species within a group. The marine mammals that have been identified in the study area, and their correspondent groupings have been provided in **Table 4-2** below.

Table 4-2: Sensitivity Classification of Identified Marine Mammal Species

Marine Mammal Hearing Group	Generalised Hearing Range	Species
Very high-frequency cetaceans (VHF)	275 Hz to 160 kHz	Harbour porpoise (*phocoena phocoena*)
Phocid carnivores in water (PCW)	50 Hz to 86 kHz	Harbour seals (*phoca vitulina*), grey seals (*halichoerus grypus*)

4.3.4. JNCC requires the injury criteria and functional hearing groups presented in NOAA (2018) and Southall *et al.* (2019) to be used for any marine mammal noise assessment. It is worth noting that while the hearing groups and thresholds are the same in these two documents, the terminology used to identify the hearing groups does differ (e.g. harbour porpoise would be referred to as *high frequency* in NOAA 2018, but *very-high frequency* in Southall *et al.* 2019).

4.3.5. The injury criteria are based on a combination of linear (i.e. un-weighted) peak pressure levels and marine mammal hearing weighted sound exposure levels (SEL). The hearing weighting function is designed to represent the bandwidth for each group within which acoustic exposures can have auditory effects (Southall *et al.* 2019).

4.3.6. **Table 4-3** below provides the relevant criteria for the onset of PTS and TTS due to impulsive and continuous (i.e. non-impulsive) sound sources for the relevant marine mammal groups considered within this study.

Table 4-3: Marine Mammal Auditory Threshold Criteria Applied in this Assessment

Marine Mammal Hearing Group	Impulsive Noise (Impact Piling)		Continuous (i.e. Non-Impulsive) Noise (Vibro-piling, Dredging, Vessel Noise)	
	PTS Onset	TTS Onset	PTS Onset	TTS Onset
Very high-frequency cetaceans (VHF)	155 dB SEL_{cum} 202 dB SPL_{pk}	140 dB SEL_{cum} 196 dB SPL_{pk}	173 dB SEL_{cum}	153 dB SEL_{cum}
Phocid carnivores in water (PCW)	185 dB SEL_{cum} 218 dB SPL_{pk}	170 dB SEL_{cum} 212 dB SPL_{pk}	201 dB SEL_{cum}	181 dB SEL_{cum}
SPL_{pk} is referenced in dB re 1μPa, and SEL_{cum} is referenced in dB re 1μPa^{2}s.				

4.3.7. SPL_{pk} marine mammal auditory thresholds for impulsive noise sources provide an estimate of the instantaneous worst case potential effects on marine mammals. The SEL_{cum} is calculated from the energy in a representative single pile strike and the number of strikes over a 24 hour period. This metric assumes that all pile strikes have the same source level for each received SEL_{ss}. This is rarely the case as the receptor and/or source is likely to be moving relative to each other. It also assumes that the animal is stationary within the zone of potential effect for a 24 hour period which is highly unlikely to take place in reality. In addition to this, the metric does not take into consideration that potential physiological or physical recovery from any effects of a single impulse exposure into account. Consequently, the averaging associated with this measure may result in inaccurate conclusions on the effects of impulsive noise exposure and thus should be treated with caution (Hawkins and Popper, 2017).

4.3.8. Several field observations of harbour porpoise and pinnipeds to multiple pulse sounds have been made and are reviewed by Southall *et al.* (2007). The results of these studies are considered too variable and context-specific to allow single disturbance criteria for broad categories of taxa and of sounds to be developed. Consequently, there are no equivalent behavioural response criteria that would suitably represent the sources of underwater noise associated with the Proposed Scheme.

5. UNDERWATER NOISE MODELLING METHODOLOGY

5.1.1. As discussed in **Section 2**, underwater sound is generated by the movement or vibration of any immersed object in water. The sound propagates through the water as vibrations of the fluid particles in a series of pressure waves. The many complexities of underwater environments influence how the sound propagates and subsequently effects how acoustic energy is lost during the process (transmission loss). These factors broadly comprise the following (NPL, 2014):

- the reduction (or attenuation) of sound away from the source due to geometrical spreading;
- absorption of the sound by the sea-water and the sea-bed;
- the interaction with the sea-surface (reflection and scattering);
- the interaction with, and transmission through, the sea-bed;
- the refraction of the sound due to the sound speed gradient;
- the bathymetry (water depth) between sound and receiver positions; and
- source and receiver depth.

5.1.2. Underwater noise propagation is very complex. Consequently, predicting transmission loss in unique underwater environments, and therefore predicting received noise levels at a distance from the source, is computationally challenging. Use is generally made of theoretical models or empirical models based on field measurements.

5.1.3. In accordance with the *Underwater Noise Measurement Good Practice Guide* (NPL, 2014) , a simple practical spreading model has been utilised to approximate transmission loss and subsequent impact ranges from the underwater noise sources associated with the Proposed Scheme. Furthermore, several similar shallow water assessments have been undertaken with the same methodology accepted by the Marine Management Organisation (MMO) (URS Scott Wilson, 2011; ABPmer, 2015; Transport for London, 2016; ABPmer. 2022). The model is a logarithmic equation that incorporates geometric spreading and absorption loss factors that is simple and efficient to provide first order calculations of the received (unweighted) levels with distance from the source. The formula is represented as below (Ulrick, 1983; Xavier, 2002):

$$\mathbf{TL = L_2 - L_1 = N \log_{10} (R_1/R_2) + \alpha R}$$

Where:

TL: is the transmission loss in dB.

$\mathbf{L_1}$: sound pressure level at a given distance R1.

$\mathbf{L_2}$: measured sound pressure level at a given distance R2.

N: wave mode coefficient.

$\mathbf{R_1}$**:** is the impact range in metres from the noise source at which the relevant threshold is exceeded.

R_2: is the distance from the source of the initial measurement.

αR: linear absorption and scattering loss.

5.1.4. Solving for L_1 will provide the underwater sound pressure level at a given distance. To determine at what distance or range a known sound pressure level will occur, the equation must be solved for R_1:

$$R_1 = R_2 \times 10((L_2 - L_1) + \alpha R / N)$$

5.1.5. The nature of sound transmission in 'shallow' water is highly variable, site specific and strongly dependent on the acoustic properties of the sea surface and sea floor. In a worst case configuration, the transmitted sound field can be composed of many propagation paths by successive reflections on the sea surface and sea floor. In this configuration, the acoustic energy remains 'trapped' between the two boundaries of the sea surface and sea floor, and the sound propagation can be representative of cylindrical spreading (N=10). In 'deep' water, it is typical for spherical spreading to take place (N=20). Richardson *et al.* (1995) suggest that depths of 200m is commonly regarded as the boundary between 'shallow' and 'deep' regardless of source wavelength. Richardson *et al.* (1995) suggest using N=15 for underwater transmission in shallow water conditions where the depth is greater than five times the wavelength.

5.1.6. The absorption loss term within the transmission loss calculation considers attenuation of sound due to the source operating frequency, water depth, and a number of seawater physical properties. There are a number of empirical methods proposed that calculate this coefficient, of which four have been considered within the modelling (Francois and Garrison, 1982; Fisher and Simmons, 1977; Ainslie and McColm 1998; Thorp 1967).

5.1.7. It is understood that the Environment Agency has compiled measured data to derive a more appropriate empirically informed wave mode coefficient (N) and absorption coefficient (α) for shallow water environments. These data were presented at the Institute of Fisheries Management (IFM) Conference on 23 May 2013, and were collected from the following construction projects undertaken in shallow water estuarine and coastal locations:

- Russian River New Bridge in Geyserville, California (Illinworth and Rodkin, 2007);
- San Rafael Sea Wall in San Francisco Bay, California (Illinworth and Rodkin, 2007);
- Scroby Sands Offshore Wind Farm located off the coast of Great Yarmouth (Nedwell et al., 2007a);
- North Hoyle Offshore Wind Farm in Liverpool Bay (Nedwell et al., 2007a);
- Kentish Flats Offshore Wind Farm located off the coast of Kent (Nedwell et al., 2007a);
- Burbo Bank Offshore Wind Farm in Liverpool Bay (Nedwell et al., 2007a);
- Barrow Offshore Wind Farm located south west of Walney Island (Nedwell *et al.,* 2007a); and

- Belvedere Energy-from-Waste Plant on Thames Estuary (measurements collected by Subacoustech Ltd on behalf of the Environment Agency and Costain).

5.1.8. These provide a mean N coefficient of 17.91 (Standard Deviation (SD) 3.05) and α coefficient of 0.00523 dB m-1 (SD 0.00377 dB m^{-1}) based on 11 and 9 observations respectively. It is understood that the Environment Agency has recommended the application of these model input values in underwater noise assessments undertaken in shallow water environments (e.g. URS Scott Wilson, 2011; ABPmer, 2015; Transport for London, 2016; ABPmer, 2022). These values are, therefore considered appropriate to include as constants within the proposed modelling approach.

5.1.9. As discussed, underwater noise transmission loss through the marine environment can be complicated and depend on a multitude of factors, which can vary temporally and spatially (see reviews in Urick 1979, 1983; Richardson *et al.* 1995). Many of these factors that affect underwater noise transmission loss can be site specific. This is particularly the case for shallow water (Richardson *et al.* 1995). It is important to recognise that the practical spreading model is a simplistic approach to the calculation of transmission loss. Such models do not account for several of the factors that influence underwater noise propagation. This includes, not accounting for changes in bathymetry, and hence not being able to predict the influence from complex changes in water depth; not explicitly including frequency dependence, hence not predicting transmission loss at different frequencies due to the varying sound absorption properties of water.

5.1.10. Farcas *et al.* (2016) also demonstrated how use of these simple models in complex environments typical of coastal and inland waters can underestimate noise levels close to the source and substantially overestimate noise levels further from the source. In other words, they can underestimate the risk of injury or disturbance to marine fauna close to the source whilst giving the impression that a larger area would be affected.

5.1.11. Despite this modelling methodology representing a simplistic approach to predicting transmission loss, it is a well-established approach in Environmental Impact Assessments (EIAs) that have been widely accepted by UK regulators for recent port and waterfront developments.

5.1.12. NOAA in the United States recommends the use of practical spreading model solutions to developers and has subsequently incorporated this into two separate calculation tools (NMFS, 2021; NOAA, 2021) to calculate impact ranges for fish and marine mammals for impulsive and continuous (i.e. non-impulsive) underwater noise. These calculation tools have been utilised accordingly within this assessment. Further details of assumptions, input values, and amendments[b] to the tools are provided in **Section 7**.

[b] The NMFS Multi Species Pile Driving Calculator Tool (NMFS, 2021) utilises legacy impact thresholds for fish from the Fisheries Hydroacoustics Working Group (FHWG) (2008) which has since been superseded by Popper et al. (2014) and other more up-to-date research.

5.1.13. As the Proposed Scheme takes place in shallow water, the propagation of noise will be limited. Shallow water channels do not allow the propagation of low frequency signals due to the 'wave-guide' effect[c] of the channel (Urick, 1983; Clay and Medwin, 1977; Jensen *et al.,* 2000; Ainslie, 2011). In other words, shallow water acts as a high pass filter that only allows signals to pass with a frequency higher than a certain cut-off frequency and attenuates signals with frequencies lower than this cut-off frequency. The cut-off frequency gets higher as the water gets shallower (Harland *et al.,* 2005). In this way, the propagation of low frequency underwater noise such as piling will be reduced in very shallow water locations compared to in the deep oceanic waters. At high frequencies (>10 kHz), increasing absorption also prevents high frequency sound propagating over great distances in shallow water.

5.1.14. Consequently, it is considered that a simple logarithmic spreading model is considered appropriate on the basis of the available information for use in this underwater acoustic assessment.

[c] A wave guide is a structure that guides waves by restricting energy transmission to one direction. In shallow water, the interaction with the seabed and sea surface becomes very important. The surface and seabed act as boundaries which 'channel' the sound between them with the action of a waveguide (NPL, 2014).

6. NOISE SOURCES FROM THE PROPOSED SCHEME

6.1. UNDERWATER NOISE GENERATING ACTIVITIES

6.1.1. The Proposed Jetty construction will feature three main stages:

- **Dredging:** for the creation of the berth pocket (construction phase), as well as maintenance dredging throughout the operational phase of the Proposed Scheme;
- **Vibro-piling:** for the retaining sheet pile wall installation for the construction of the Proposed Jetty, and pile removal for the demolition of the Belvedere Power Station Jetty (disused);
- **Impact piling:** for the installation of piles to construct the Proposed Jetty; and
- **Vessel movements:** associated vessel noise emissions associated with each of the above activities.

6.2. DREDGING (CONSTRUCTION AND OPERATION)

6.2.1. The dredging requirements for the Proposed Scheme will involve backhoe dredging. Dredging will be undertaken to create the berth pocket associated with the Proposed Jetty construction (capital dredging), and for maintenance throughout the operation phase of the Proposed Scheme.

6.2.2. Backhoe dredging This method of dredging utilises an excavator mounted on the edge of a pontoon or barge, which reaches into the water and scoops bed material out. A separate vessel or barge will be moored alongside, which the material is deposited directly into. Once this vessel is at capacity it will depart and deposit its cargo at the designated area. This method of dredging allows for continuous operations if there is a vessel to deposit material into.

6.2.3. Dredging involves a variety of sound generating activities which can be generally divided into sediment excavation, transport, and placement of the dredged material at the disposal site (CEDA, 2011; WODA, 2013; Jones and Marten, 2016). The main source of sound generally emitted from dredging activity relates to the vessel engine noise. Dredging activities produce broadband and continuous sound, mainly at lower frequencies of less than 500 Hz and moderate SPL_{rms} levels from around 150 to 188 dB re 1µPa m (Thomsen *et al.,* 2009; CEDA, 2011; Robinson *et al.,* 2011; WODA, 2013; MMO, 2015; Jones and Marten, 2016).

6.2.4. Backhoe dredgers have been measured to generate SPL_{rms} levels in the range of 154 to 179 dB re 1µPa m (Reine *et al.,* 2012; Nedwell *et al.,* 2008). Measurements of underwater sound from backhoe dredging operations indicate that the highest levels of underwater sound occur when the excavator is in contact with the seabed. This type of dredging is generally considered to be quieter compared to other types of dredging, with recorded sound levels just above the background sound at approximately 1km from the source (CEDA, 2011).

6.2.5. SPL_{rms} levels of TSHDs are variable but have been measured to generally range from 160 to above 180 dB re 1µPa for large TSHDs (Robinson *et al.* 2011). The most onerous sound emissions from the TSHDs comprise frequencies up to and including 1,000 Hz in most cases (Robinson *et al.* 2011; De Jong *et al.* 2010). Differences in sound levels are mainly a result of the difference in size between the dredging vessels observed rather than the materials dredged. High frequency components of the broadband sound are generated by sand and gravel movement through the suction pipes, the movement of the draghead on the seabed, splashing from the spillways, cavitation, and use of positioning thrusters. Also, gravelly sand extraction resulted in higher levels of this sound than sandy gravel when comparing the same dredging vessel (Robinson *et al.* 2011).

6.2.6. Following a literature review, SPL_{rms} levels for water injection dredging are not available.

6.2.7. Despite backhoe dredging being utilised, the highest measured noise source level data available in the literature is for trail suction hopper dredging (TSHD) where on two separate occasions broadband source level of 188 dB re 1µPa was measured, presented in Ainslie *et al.,* (2009) and Nedwell *et al.,* (2008). Consequently, the assessment assumes that the dredging activity will generate a worst case unweighted SPL_{rms} of up to 188 dB re 1µPa (representative of TSHD (i.e. the worst case)). By utilising the worst case measured noise levels for the most onerous potential dredging source, the assessment is considered robust.

6.3. VIBRO-PILING (CONSTRUCTION AND DEMOLITION)

6.3.1. To eliminate the need for extensive dredging to the rear of the Proposed Jetty, in order to satisfy an appropriate slope angle, a sheet pile retaining wall will be installed to the rear of the loading platform, in front of all but the outermost mooring dolphins. This will hold material in place behind the pocket and allow it to function as intended. This wall will be installed using barges and cranes (more detail of which can be found in the piling section below), which will lift the sections from their delivery barges into position, then vibrate, push or hammer them into their final position depending on particular ground conditions. Installation of the wall will be undertaken prior to dredging works being completed. The two operations can be phased and planned to be undertaken in turns[d].

6.3.2. Vibratory pile driving will also be utilised to ‘pull out’ tubular piles associated with the decommissioned Belvedere Power Station Jetty (disused) if this option is taken forward via an appropriate capacity crane.

[d] The rate of the sheet pile wall installation will be approximately 5-10m of wall length per day.

6.3.3. Vibratory pile driving is commonly used to install small piles and/or may be used to initially drive a larger pile. Here, vibratory hammers sit on top of the pile, and a series of oscillating weights continuously transfer vertical vibrations into the pile at a specific frequency. These vertical vibrations cause the sediment surrounding the pile to liquefy, allowing the pile to penetrate the substrate (ICF Jones & Stokes and Illingworth & Rodkin, 2007).

6.3.4. Vibratory pile driving produces a continuous sound with peak pressures lower than those observed in pulses generated by impact pile driving. Sound signals generated by vibratory pile driving usually consist of a low fundamental frequency, from 20-40 Hz. Average, near source, peak sound pressure levels range from 165-185 dB re 1μPa.

6.3.5. Information on the proposed pile size or vibratory duration are unknown at this stage. On this basis, the SPL_{rms} for the vibratory piling of sheet piles as part of the Proposed Scheme is assumed based on the loudest near-source (10m from the source) measured data available in the NMFS calculation tool database for vibratory piling of sheet piles in a shallow water environment (NMFS, 2021; Caltrans, 2015). The measured data provides an SPL_{pk} of 182 dB re 1μPa, an SPL_{rms} of 165 dB re 1μPa, and a SEL for one second of continuous driving of 165 dB re $1μPa^2s$. It is assumed that 15 piles per day will be installed, with each taking 20 minutes of continuous vibratory piling to install until refusal.

6.4. IMPACT PILING (CONSTRUCTION)

6.4.1. There are several methods which could be utilised for the construction of the Proposed Jetty. However, impact piling is considered to the quickest and most economical.

6.4.2. Piling for the loading platform, berthing and mooring dolphins, access trestle, and tug mooring pontoon will likely be undertaken first. This is due to the cost of piling plant, meaning a contractor would undertake all piling at once, to keep time and therefore costs to a minimum.

6.4.3. Piling for the loading platform, vertical berthing dolphin piles, and tug mooring platform could be installed using a 50m crane barge, which would be capable of supporting a 300t crawler crane. This would be used to lift piles from a support barge into positions where they will be installed. The largest lifts will be for the six vertical berthing dolphins. Piling would be undertaken, to begin with, closest to the shore moving further into the river as the process progresses, and support and supply barges would be moored riverward of the crane barge. The marine plant footprint would be largely within the area of the dredge pocket or slightly riverward and would be moved via an anchor spread.

6.4.4. Alternatively, this process could be undertaken using by spud or jack-up barges. Piling for the mooring dolphins would be done using a jack-up barge, as these are raked piles. Piling would be done from the long edge, and for the dolphin closest to Middleton Jetty, the barge could be located to the east of the dolphin to avoid conflict with Cory barge manoeuvres.

6.4.5. It is likely that the rate of piling would be on average 1 per day, allowing for delivery, movement, founding etc. This would result in an overall time of 4 months, not accounting for any undue delays.

6.4.6. The most onerous underwater noise levels generated during the proposed marine works will take place due to impact piling. Impact piling involves a large weight or 'ram' being dropped or driven onto the top of the pile, driving it into the seabed. The hammering action results in radiation of noise from the pile into the surrounding water and seabed.

6.4.7. At each strike of the hammer, in addition to the whole displacement of the pile further into the seabed, the pile bends elastically and then returns to its original shape. This bending takes the form of flexural waves in the pile which propagate along the length of the pile and into the seafloor[e]. The transverse component of the wave creates compression waves in the water which will propagate out from the pile as noise. The compressional component of the flexural wave will propagate into the seabed. The dominant underwater noise source from the piling activity is the compression wave generated from the surface of the pile in the water column.

6.4.8. Impulsive sources such as pile driving should have sound levels expressed for a single pulse as either SEL with units of dB re 1μPa² s, or as a SPL_{pk-pk} or SPL_{pk}, with units of dB re 1μPa (Farcas *et al.,* 2016). Typical SPL_{pk} levels for impact piling range from 190 to 245 dB re 1 μPa (DPTI, 2012). Most of the sound energy usually occurs at lower frequencies between 100 Hz and 1 kHz. The magnitude of the noise emanating from a pile during piling is a function of the piling method (i.e. impact hammer or vibration), the pile material type (i.e. steel or concrete), the force applied to the pile (usually described by the hammer energy or hammer size), the pile size, and to lesser extent the characteristics of the substrate into which it is being driven.

6.4.9. Information on the proposed pile diameter and/or hammer energy is unknown at this stage. Consequently, the SPL_{pk} and SEL_{ss} for the impact piling of piles as part of the Proposed Scheme is assumed based on the loudest near-source (10m from the source) measured data available in the NMFS calculation tool database for impact piling of steel tubular piles in a shallow water environment (NMFS, 2021; Caltrans, 2020). The measured data provides an SPL_{pk} of 210 dB re 1μPa, an SPL_{rms} of 190 dB re 1μPa, and an SEL_{ss} of 185 dB re 1μPa^{2}s.

[e] Note: depending on the resistivity of the soil, some of the energy will be reflected back up the length of the pile.

6.5. VESSEL MOVEMENTS (CONSTRUCTION, DEMOLITION AND OPERATION)

6.5.1. Vessels involved during the construction of the Proposed Scheme will primarily be the crane barge(s), flat top barge(s), tugs, safety boat/crew transfer vessel, dredger with associated attendant split barges.

6.5.2. During operation, the Proposed Jetty will be used to transfer liquid CO_2 from the associated Carbon Capture Facility onto vessels to then be shipped for permanent sequestration underground.

6.5.3. The demolition of the Belvedere Power Station Jetty (disused) will involve a waste removal vessel and a jack-up barge.

6.5.4. The dredgers and barges are anticipated to generate sound pressure levels of up to 188 dB re 1µPa (UKMMAS, 2010; CEDA, 2011).

6.5.5. Overall, the vessels' movements involved in the construction, operation and demolition of the Proposed Scheme are anticipated to generate worst case SPL_{rms} levels of up to 188 dB re 1 µPa. Continuous (24 hours a day, 7 days a week) noise generation from vessel activities has been assumed and as such, provides a precautionary assessment.

7. UNDERWATER NOISE MODELLING RESULTS & POTENTIAL EFFECTS

7.1. FISH

DREDGING AND VESSEL MOVEMENTS (CONSTRUCTION, DEMOLITION AND OPERATION)

7.1.1. The NMFS Optional Multi-species Pile Driving Calculator tool (NMFS, 2021) was utilised to predict underwater noise levels and the subsequent fish species impact ranges and relative risk due to the proposed dredging activity and associated vessel movements for both construction (capital dredging) and operational maintenance phases. The tool was manually updated to account for the most up-to-date impact thresholds which are considered in this assessment as provided by Popper *et al.* (2014). The tool was also updated to include the relevant absorption coefficient as expressed in **Section 5.** The model input values and associated assumptions for the dredging activity and associated vessel movements are provided in **Table 7-1** below.

Table 7-1: NMFS Calculator Tool Input Values For Dredging and Vessel Noise

Model Inputs	Value	Assumptions
SPL_{rms} dB re 1µPa	188	Loudest near-source SPL_{rms} (1m from the source) measured data available (UKMMAS, 2010; CEDA, 2011).
Distance from source, *m*	1	Distance from the dredging barge source at which the data was measured.
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient from several construction projects undertaken in shallow water environments (see **Section 5**).
Absorption coefficient, *dB* m^{-1}	0.00523	Derived from 9 observations of transmission loss coefficient from several construction projects undertaken in shallow water environments (see **Section 5**).

7.1.2. **Table 7-2** below provides the distances at which recoverable injury and TTS impact thresholds are reached, as well as the Popper *et al.* (2014) defined relative risk of impact.

Table 7-2: Predicted Approximate Impact Ranges in Metres at which Fish Hearing Response Thresholds are Reached During Dredging and Vessel Movement Activity

Fish Category	Mortality and Potential Mortal Injury	Recoverable Injury	TTS	Behavioural Response
No swim bladder *(particle motion detection)*	**(N)** Low **(I)** Low **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Moderate **(F)** Low
Swim bladder not involved in hearing *(particle motion detection)*	**(N)** Low **(I)** Low **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Moderate **(F)** Low
Swim bladder involved in hearing *(primarily pressure detection)*	**(N)** Low **(I)** Low **(F)** Low	10	47	**(N)** High **(I)** Moderate **(F)** Low
Eggs and larvae	**(N)** Low **(I)** Low **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Moderate **(F)** Low

7.1.3. The onset of recoverable injury in fish where swim bladders are primarily used as a pressure detection mechanism, would take place if the fish were within 10m from dredging or vessel movements for a 48 hour period. The onset of TTS in fish where swim bladders are primarily used as a pressure detection mechanism, would take place if the fish were within 47m from dredging or vessel movements for a 12 hour working day period.

7.1.4. Overall, there is considered to be a low risk of any injury in fish as a result of the underwater noise generated by dredging and vessel movements. The level of exposure will depend on the position of the fish with respect to the source, the propagation conditions, and the individual's behaviour over time. However, it is unlikely that a fish would remain in the vicinity of a dredger for extended periods. Behavioural responses are anticipated to be spatially negligible in scale and fish will be able to move away and avoid the source of the noise as required.

7.1.5. The noise emissions from vessels associated with the operational phase of the Proposed Scheme, and the demolition of the Belvedere Power Station Jetty (disused) are likely to be less onerous than the source noise level used for this assessment. This is due to the dredging component of the noise not being present. Consequently, it considered there is an even lesser risk of injury to fish as a result of the underwater noise generated by vessels associated with these phases.

VIBRO-PILING (CONSTRUCTION AND DEMOLITION)

7.1.6. The NMFS Optional Multi-species Pile Driving Calculator tool (NMFS, 2021) was utilised to predict underwater noise levels and the subsequent fish species impact ranges and relative risk due to the proposed vibro-piling activity. The tool was manually updated to account for the most up-to-date impact thresholds which are considered in this assessment as provided by Popper *et al.* (2014). The tool was also updated to include the relevant absorption coefficient as expressed in **Section 5.** The model input values and associated assumptions for the vibro-piling are provided in **Table 7-3** below.

Table 7-3: NMFS Calculator Tool Input Values for Vibro-piling

Model Inputs	Value	Assumptions
Duration of vibro-piling per pile, *minutes*	20	Worst case maximum vibro-piling duration used in similar shallow water piling scenarios.
Number of piles per day	15	The maximum vibro-piling scenario is for the proposed sheet piled wall construction to comprise up to 10m of installation length per day (see **Section 6**), based on a 24" width sheet pile.
SPL_{rms} dB re 1µPa	165	Loudest near-source SPL_{rms} (10m from the source) measured data available in the NMFS calculation tool database for impact piling of steel sheet piles in a shallow water environment (NMFS, 2021; Caltrans, 2020).
Distance from source, *m*	10	Distance from the vibro-piling source at which the data was measured.
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient from several construction projects undertaken in shallow water environments (see **Section 5**).
Absorption coefficient, *dB m^{-1}*	0.00523	Derived from 9 observations of transmission loss coefficient from several construction projects undertaken in shallow water environments (see **Section 5**).

7.1.7. **Table 7-4** below provides the distances at which recoverable injury and TTS impact thresholds are reached, as well as the Popper *et al.* (2014) defined relative risk of impact.

Table 7-4: Predicted Approximate Impact Ranges in Metres at which Fish Hearing Response Thresholds are Reached during Vibro-piling Activity

Fish Category	Mortality and Potential Mortal Injury	Recoverable Injury	TTS	Behavioural Response
No swim bladder *(particle motion detection)*	**(N)** Low **(I)** Low **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Moderate **(F)** Low
Swim bladder not involved in hearing *(particle motion detection)*	**(N)** Low **(I)** Low **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Moderate **(F)** Low
Swim bladder involved in hearing *(primarily pressure detection)*	**(N)** Low **(I)** Low **(F)** Low	Not reached	24	**(N)** High **(I)** Moderate **(F)** Low
Eggs and larvae	**(N)** Low **(I)** Low **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Low **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Moderate **(F)** Low

7.1.8. The onset of TTS in fish where swim bladders are primarily used as a pressure detection mechanism, would take place if the fish were within 24m from the vibro-piling activity for a full 12 hour working day. Given the mobility of fish, any individuals that might be present within this impact range would be expected to easily move away and avoid impacts.

7.1.9. It is also worth considering the existing ambient noise context. The area in which the construction will take place already experiences regular vessel operations and maintenance dredging. Consequently, fish are likely to be habituated to a certain level of anthropogenic background noise.

7.1.10. It is considered that vibro-piling associated with the demolition of the Belvedere Power Station Jetty (disused) where the piles are to be ‘pulled out’ will generate similar underwater noise levels. Consequently, as discussed above, given the mobility of fish, any individuals that might be present within the above impact range would be expected to easily move away and avoid impacts.

IMPACT PILING (CONSTRUCTION)

7.1.11. As discussed in **Section 5**, underwater noise levels and the subsequent fish species impact ranges were calculated using the NMFS Optional Multi-species Pile Driving Calculator tool (NMFS, 2021). The tool was manually updated to account for the most up-to-date impact thresholds which are considered in this assessment as provided by Popper *et al.* (2014). The tool was also updated to include the relevant absorption coefficient as expressed in **Section 5.** The model input values and associated assumptions for the impact piling are provided in **Table 7-5** below.

Table 7-5: NMFS Calculator Tool Input Values for Impact Piling

Model Inputs	Value	Assumptions
Number of strikes per pile	900	Worst case maximum number of strikes used in similar shallow water piling scenarios.
Number of piles per day	1	The maximum impact piling scenario is for the Proposed Jetty construction to comprise 1no. pile installation per day (see **Section 6**).
SPL_{pk} dB re 1µPa	210	Loudest near-source SPL_{pk} (10m from the source) measured data available in the NMFS calculation tool database for impact piling of steel tubular piles in a shallow water environment (NMFS, 2021; Caltrans, 2020). Representative of a 30” diameter pile.
SEL_{ss} dB re 1µPa^{2}s	185	Loudest near-source SEL_{ss} (10m from the source) measured data available in the NMFS calculation tool database for impact piling of steel tubular piles in a shallow water environment (NMFS, 2021; Caltrans, 2020). Representative of a 30” diameter pile.
SEL_{cum} dB re 1µPa^{2}s	215	$SEL_{cum} = SEL_{ss} + 10\log_{10}$ (No. *of strikes per pile)*
Distance from source, *m*	10	Distance from the impact piling source at which the data was measured.
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient from several construction projects undertaken in shallow water environments (see **Section 5**).
Absorption coefficient, *dB m^{-1}*	0.00523	Derived from 9 observations of transmission loss coefficient from several construction projects undertaken in shallow water environments (see **Section 5**).

7.1.12. The distances at which potential mortal injury, recoverable injury, and behavioural effects are predicted to take place in fish during impact piling activity associated with the Proposed Scheme are provided in **Table 7-6** below.

Table 7-6: Predicted Approximate Impact Ranges in Metres at which Fish Hearing Response Thresholds are Reached during Impact Piling Activity

Fish Category	Mortality and Potential Mortal Injury*		Recoverable Injury*		TTS	Behavioural Response
	SPL_{pk}	*SEL_{cum}*	*SPL_{pk}*	*SEL_{cum}*	*SEL_{cum}*	
No swim bladder *(particle motion detection)*	7	6	7	8	390	**(N)** High **(I)** Moderate **(F)** Low
Swim bladder not involved in hearing *(particle motion detection)*	15	18	15	44	390	**(N)** High **(I)** Moderate **(F)** Low
Swim bladder involved in hearing *(primarily pressure detection)*	15	26	15	44	390	**(N)** High **(I)** High **(F)** Moderate
Eggs and larvae	15	18	**(N)** Moderate **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Low **(F)** Low	**(N)** Moderate **(I)** Low **(F)** Low

7.1.13. As discussed in **Section 4**, adult fish not in the immediate vicinity of instantaneous noise generating activity are generally able to vacate the area and avoid physical injury and recoverable injury. In this case, the peak sound pressure level criteria physical injury and recoverable injury is only exceeded within 15m from the impact piling source. For the sound exposure level criteria to be exceeded for physical injury, fish will need to be within 44m from the impact piling source for a 24 hour period. Both of these scenarios are considered unlikely due to the relative proximity to the source. However, larvae, spawn and smaller fish are not highly mobile and are therefore more likely to incur injuries from the sound energy in the immediate vicinity of the sound source.

7.1.14. TTS effects are anticipated to occur across most of the width of the River Thames during low tide. This therefore potentially creates a partial temporary barrier to fish movements. However, as discussed in **Paragraph 7.1.16** below, this partial temporary barrier will only be apparent for a small percentage of a working day.

7.1.15. The effects of piling noise on fish also need to be considered in terms of the duration of exposure. Impact piling activity will take place over a 4 month period. However, piling will not take place continuously as there will be periods of downtime, pile positioning, and associated set up.

7.1.16. Based on one pile installation per day, and assuming 900 strikes per pile, at a rate of 30 strikes per minute[f], piling activity will be taking place for 30 minutes per day. This is approximately 4% of the duration of a 12 hour working day. In other words, any fish that remain within the predicted TTS effects zone at the time of percussive piling will be exposed to impact piling noise 4% of the time during any 12 hour working day.

7.1.17. It is also worth considering the existing ambient noise context. The area in which the construction will take place already experiences regular vessel operations and maintenance dredging. Consequently, fish are likely to be habituated to a certain level of anthropogenic background noise.

7.2. MARINE MAMMALS

DREDGING AND VESSEL MOVEMENTS (CONSTRUCTION, DEMOLITION AND OPERATION)

7.2.1. The NMFS Companion User Spreadsheet Tool (NOAA, 2021) has been utilised to predict the range at which the weighted SEL_{cum} impact thresholds (Southall, 2019) for the onset of PTS and TTS are reached during the proposed dredging activity as well as the associated vessel movements for both construction (capital dredging) and operational maintenance phases.

7.2.2. In accordance with the guidance provided in NOAA's user manual and the spreadsheet tool instructions, *Tab C: Mobile source, non-impulsive, continuous ('safe distance' methodology),* was selected as the most appropriate method to apply for the dredging activity and associated vessel movements. The tool was also updated to include the relevant absorption coefficient as expressed in **Section 5.** The model input values and associated assumptions for the dredging activity and associated vessel movements are provided in **Table 7-7** below.

Table 7-7: NOAA companion User Spreadsheet Tool Input Values (*Tab C*)

Model Inputs	Value	Assumptions
Weighting factor adjustment	2.5	Default value for vibratory pile driving sources provided in the NOAA guidance (NOAA, 2021). No default value for dredging and/or

[f] Worst case assumption of strikes per pile from experience on other similar shallow water environments and associated impact piling activity.

Model Inputs	Value	Assumptions
		vessel noise. This value chosen as it generates the worst case predicted ranges for PTS and TTS impacts.
SPL_{rms} dB re 1μPa	188	Loudest near-source SPL_{rms} (1m from the source) measured data for all forms of dredging and vessel movements assumed for the Proposed Scheme (See **Section 6**).
Distance from source, *m*	1	Distance from the dredging barge source at which the data was measured.
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient from several construction projects undertaken in shallow water environments (see **Section 5**).
Absorption coefficient, *dB m^{-1}*	0.00523	Derived from 9 observations of transmission loss coefficient from several construction projects undertaken in shallow water environments (see **Section 5**).

7.2.3. The impact ranges at which PTS and TTS in marine mammals are predicted to take place during the proposed dredging and associated vessel movement activities are provided in **Table 7-8** below.

Table 7-8: Approximate Distances (Metres) Marine Mammal Impact Thresholds are Reached during Dredging and Vessel Activity

Marine Mammal Hearing Group	PTS Onset Isopleths (m)	TTS Onset Isopleths (m)
Very high-frequency cetaceans (VHF) *(Harbour Porpoise)*	<1	44
Phocid carnivores in water (PCW) *(Harbour Seal, Grey Seal)*	<1	12

7.2.4. There is predicted to be no risk of PTS in harbour porpoise and the risk of TTS is limited to within less than 44m from the dredging or vessel activity. There is predicted to be no risk of PTS in seals and the risk of TTS is limited to within 12m from the source.

7.2.5. Overall, there is not considered to be any risk of injury or significant disturbance to marine mammals from the proposed dredging and vessel activities even if they were to take place continuously 24 hours a day, 7 days a week.

7.2.6. The noise emissions from vessels associated with the operational phase of the project, and the demolition of the Belvedere Power Station Jetty (disused) are likely to be less onerous than the source noise level used for this assessment. This is due to the dredging component of the noise not being present. Consequently, there is not considered to be any risk of injury or significant disturbance to marine mammals from the proposed vessel activities during the operational and demolition phase of the Proposed Scheme, even if they were to take place continuously 24 hours a day, 7 days a week.

VIBRO-PILING (CONSTRUCTION AND DEMOLITION)

7.2.7. The NMFS Companion User Spreadsheet Tool (NOAA, 2021) has been utilised to predict the range at which the weighted SEL_{cum} impact thresholds (Southall, 2019) for the onset of PTS and TTS are reached during the proposed vibro-piling activity.

7.2.8. In accordance with the guidance provided in NOAA's user manual and the spreadsheet tool instructions, *Tab A.1: Vibratory pile driving (Stationary Source: non-impulsive, continuous)*, was selected as the most appropriate method to apply for the vibro-piling activity. The tool was also updated to include the relevant absorption coefficient as expressed in **Section 5**. The model input values and associated assumptions for the impact piling are provided in **Table 7-9** below.

Table 7-9: NOAA Companion User Spreadsheet Tool Input Values (*Tab A.1*)

Model Inputs	Value	Assumptions
Weighting factor adjustment	2.5	Default value for vibratory pile driving sources provided in the NOAA guidance (NOAA, 2021).
Duration of vibro-piling per pile, *minutes*	20	Worst case maximum vibro-piling duration used in similar shallow water piling scenarios.
Number of piles per day	15	The maximum vibro-piling scenario is for the proposed retaining wall construction to comprise up to 10m of installation length per day (see **Section 6**), based on a 24" width sheet pile.
$10Log_{10}$ (duration of sound production), *dB*	42.55	Duration of sound production within a day is 18000 seconds based on 15no. 20 minute vibro-piling durations. This is then multiplied by $10Log_{10}$ to obtain the source level offset that is representative of the SEL_{cum} for the duration of the piling activity.
SPL_{rms} dB re 1µPa	165	Loudest near-source SPL_{rms} (10m from the source) measured data available in the NMFS calculation tool database for impact piling of steel sheet piles in a shallow water environment (NMFS, 2021; Caltrans, 2020).
Distance from source, *m*	10	Distance from the vibro-piling source at which the data was measured.

Model Inputs	Value	Assumptions
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient from several construction projects undertaken in shallow water environments (see **Section 5**).
Absorption coefficient, *dB m^{-1}*	0.00523	Derived from 9 observations of transmission loss coefficient from several construction projects undertaken in shallow water environments (see **Section 5**).

7.2.9. The impact ranges at which PTS and TTS in marine mammals are predicted to take place during the proposed vibro-piling activities are provided in **Table 7-10** below.

Table 7-10: Approximate Distances (Metres) Marine Mammal Impact Thresholds are Reached during Vibro-piling

Marine Mammal Hearing Group	PTS Onset Isopleths (m)	TTS Onset Isopleths (m)
Very high-frequency cetaceans (VHF) *(Harbour Porpoise)*	41	538
Phocid carnivores in water (PCW) *(Harbour Seal, Grey Seal)*	20	256

7.2.10. If the propagation of underwater noise from piling was unconstrained by any boundaries, the maximum theoretical distance at which the predicted SEL_{cum} weighted levels of underwater noise during vibro-piling is within the limits of PTS and TTS in harbour porpoise is 41m and 538m respectively. The maximum distance for PTS and TTS in seals is 20m and 256m respectively.

7.2.11. Assuming a lower worst case swimming speed of 1.5m/s for all marine mammal species (including both adults and juveniles), the maximum time that would take harbour porpoise to leave the centre of the SEL_{cum} weighted PTS and TTS injury zones during vibro-piling is estimated to be 30 seconds and 6 minutes respectively. This is less than 0.5% of the time that would be required for an injury to occur, and therefore, assuming harbour porpoise evade the injury effects zone, they are not considered to be at risk of any PTS or TTS impacts during the proposed vibro-piling activity.

7.2.12. The maximum time that would take seals to leave the PTS and TTS zones is estimated to be 20 seconds and 3 minutes respectively. This is less than 0.2% of the time that would be required for an injury to occur and, therefore, assuming seals evade the injury effects zone, they are not considered to be at risk of any PTS or TTS impacts during the proposed vibro-piling activity.

7.2.13. The results indicate that if any marine mammals present in the River Thames were to remain stationary within the cumulative SEL distances from the source of piling over a 24 hour period, it could result in temporary and/or permanent hearing injury. However, it is considered highly unlikely that any individual marine mammal will stay within this 'injury zone' during the vibro-piling operations.

7.2.14. The effects of vibro-piling noise on marine mammals also need to be considered in terms of the duration of exposure. The duration of proposed vibro-piling activity is unknown at this stage. However, piling will not take place continuously as there will be periods of downtime, pile positioning, and associated set up.

7.2.15. It is also worth considering the existing ambient noise context. The area in which the construction will take place already experiences regular vessel operations and maintenance dredging. Consequently, marine mammals are likely to be habituated to a certain level of anthropogenic background noise.

7.2.16. It is considered that vibro-piling associated with the demolition of the Belvedere Power Station Jetty (disused) where the piles are to be 'pulled out' will generate similar underwater noise levels. As discussed above, it is considered highly unlikely that any individual marine mammal will stay within the stated 'injury zone' during the vibro-piling operations.

IMPACT PILING (CONSTRUCTION)

7.2.17. Underwater noise levels and the subsequent marine mammal species impact ranges were calculated using the NMFS Companion User Spreadsheet Tool (NOAA, 2021) to the NOAA (2018) technical guidance for assessing the effects of anthropogenic noise on marine mammal hearing. The tool predicts the range at which the weighted SEL_{cum} and instantaneous SPL_{pk} acoustic thresholds (Southall *et al.* 2019) for the onset of PTS and TTS are reaching during the proposed impact piling activity.

7.2.18. In accordance with the guidance provided in NOAA's user manual and the spreadsheet tool instructions, *Tab E.1: Impact pile driving (Stationary Source: Impulsive, Intermittent)*, was selected as the most appropriate method to apply for the impact piling activity. The tool was also updated to include the relevant absorption coefficient as expressed in **Section 5**. The model input values and associated assumptions for the impact piling are provided in **Table 7-11** below.

Table 7-11: NOAA Companion User Spreadsheet Tool Input Values (*Tab E.1*)

Model Inputs	Value	Assumptions
Weighting factor adjustment	2	Default value for impact pile driving sources provided in the NOAA guidance (NOAA, 2021).
Number of strikes per pile	900	Worst case maximum number of strikes used in similar shallow water piling scenarios.

Model Inputs	Value	Assumptions
Number of piles per day	1	The maximum impact piling scenario is for the Proposed Jetty construction to comprise 1no. pile installation per day (see **Section 6**)
SPL_{pk} dB re 1µPa	210	Loudest near-source SPL_{pk} (10m from the source) measured data available in the NMFS calculation tool database for impact piling of steel tubular piles in a shallow water environment (NMFS, 2021; Caltrans, 2020). Representative of a 30" diameter pile.
SEL_{ss} dB re 1µPa²s	185	Loudest near-source SEL_{ss} (10m from the source) measured data available in the NMFS calculation tool database for impact piling of steel tubular piles in a shallow water environment (NMFS, 2021; Caltrans, 2020). Representative of a 30" diameter pile.
SEL_{cum} dB re 1µPa²s	215	$SEL_{cum} = SEL_{ss} + 10\log_{10}$ (No. *of strikes per pile)*
Distance from source, *m*	10	Distance from the impact piling source at which the data was measured.
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient from several construction projects undertaken in shallow water environments (see **Section 5**).
Absorption coefficient, *dB m⁻¹*	0.00523	Derived from 9 observations of transmission loss coefficient from several construction projects undertaken in shallow water environments (see **Section 5**).

7.2.19. The impact ranges at which PTS and TTS in marine mammals are predicted to take place during the proposed impact piling activities are provided in **Table 7-12**.

Table 7-12: Approximate Distances (Metres) Marine Mammal Impact Thresholds are Reached During Impact Piling

Marine Mammal Hearing Group	PTS Onset Isopleths (m)		TTS Onset Isopleths (m)	
	SPL_{pk} (Unweighted)	*SEL_{cum} (Weighted)*	*SPL_{pk} (Unweighted)*	*SEL_{cum} (Weighted)*
Very high-frequency cetaceans (VHF) *(Harbour Porpoise)*	28	663	60	4559
Phocid carnivores in water (PCW) *(Harbour Seal, Grey Seal)*	4	626	8	2333

7.2.20. There is predicted to be a risk of instantaneous (SPL_{pk}) PTS onset and TTS onset in harbour porpoise within 28m and 60m respectively from the source of the impact piling. The risk of instantaneous (SPL_{pk}) PTS onset and TTS onset in seals is within 4m and 8m from the source of the impact piling.

7.2.21. If the propagation of underwater noise from piling was unconstrained by any boundaries, the maximum theoretical distance at which the predicted SEL_{cum} weighted levels of underwater noise during impact piling is within the limits of PTS and TTS in harbour porpoise is 663m and 4.5km respectively. The maximum distance for PTS and TTS in seals is 626m and 2.3km respectively.

7.2.22. Assuming a lower worst-case swimming speed of 1.5m/s for all marine mammal species (including both adults and juveniles), the maximum time that a harbour porpoise would take to leave the centre of the SEL_{cum} weighted PTS and TTS injury zones during impact piling is estimated to be 7 minutes and 51 minutes respectively. This is less than 4% of the time that would be required for an injury to occur, and therefore, assuming harbour porpoise evade the injury effects zone, they are not considered to be at risk of any PTS or TTS impacts during the proposed impact piling activity.

7.2.23. The maximum time that seals would take to leave the PTS and TTS zones is estimated to be 7 minutes and 26 minutes respectively. This is less than 2% of the time that would be required for an injury to occur and, therefore, assuming seals evade the injury effects zone, they are not considered to be at risk of any PTS or TTS impacts during the proposed impact piling activity.

7.2.24. The results indicate that if any marine mammals present in the River Thames were to remain stationary within the cumulative SEL distances from the source of piling over a

24 hour period, it could result in temporary and/or permanent hearing injury. However, it is considered highly unlikely that any individual marine mammal will stay within this ‘injury zone’ during the piling operations.

7.2.25. The effects of piling noise on marine mammals also needs to be considered in terms of the duration of exposure. Impact piling activity will take place over a 4 month period. However, piling will not take place continuously as there will be periods of downtime, pile positioning, and associated set up.

7.2.26. Based on one pile installation per day, and assuming 900 strikes per pile, at a rate of 30 strikes per minute[g], piling activity will be taking place for 30 minutes per day. This is approximately 4% of the duration of a 12 hour working day. In other words, any marine mammal that remains within the predicted TTS effects zone at the time of piling will be exposed to impact piling noise 4% of the time during any 12 hour working day.

7.2.27. It is also worth considering the existing ambient noise context. The area in which the construction will take place already experiences regular vessel operations and maintenance dredging. Consequently, marine mammals are likely to be habituated to a certain level of anthropogenic background noise.

[g] Worst case assumption of strikes per pile from experience on other similar shallow water environments and associated impact piling activity.

8. SUMMARY AND CONCLUSIONS

8.1.1. An assessment of the effects of underwater noise arising from dredging, piling (both impact piling and vibro-piling) and the associated vessel noise for the construction and operation of the Proposed Jetty, and the demolition of the Belvedere Power Station Jetty (disused), on the south bank of the River Thames, in Belvedere, London.

8.1.2. This report presents the results of the underwater noise modelling and subsequent analysis of the impacts on the relevant marine fauna within the zone of influence of the Proposed Scheme.

8.1.3. In accordance with available guidance (NPL, 2014; Farcas *et al.,* 2016), and following reviews of assessments for similar projects accepted by the MMO, a simple logarithmic spreading model has been selected to predict the propagation of underwater sound.

8.1.4. The predicted levels of underwater noise have been compared against peer-reviewed noise exposure criteria to determine the potential risk of impact on marine fauna (Popper *et al.,* 2014; NOAA, 2018; Southall *et al.,* 2019).

8.1.5. Several mitigation measures have been provided below for consideration to reduce or minimise the risk of potential adverse impacts on marine fauna during the construction of the Proposed Scheme:

- follow the protocol provided in the JNCC (2010) statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise. Despite this document being specific for offshore windfarm piling, it states that *“this protocol may also be useful to other industries in the marine environment which use pile-driving”*. Key mitigation measures in this document include (non-exhaustive):
  - Best Available Techniques (BAT): demonstrate BAT are being implemented and considered where feasible;
  - Marine Mammal Observers (MMO): utilise marine mammal observers during the construction of the proposed development;
  - Passive Acoustic Monitoring (PAM): Utilise passive acoustic monitoring (PAM) and associated PAM operatives;
  - Soft-Start Procedure: Ensure there is a gradual ramping up of piling power incrementally over a set time period until full operational power is achieved. The soft start duration should be a period of not less than 20 minutes; and
  - Acoustic Deterrent Devices (ADDs): The use of devices that have the potential to exclude animals from the piling area should be considered.
- utilise vibro-piling over impact piling where feasible as this produces lower peak source noise levels than impact piling;
- undertake piling operations during low tide wherever practicable, in particular piles which are located in the intertidal area as this will result in no direct noise emissions in the underwater environment from piling noise.

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