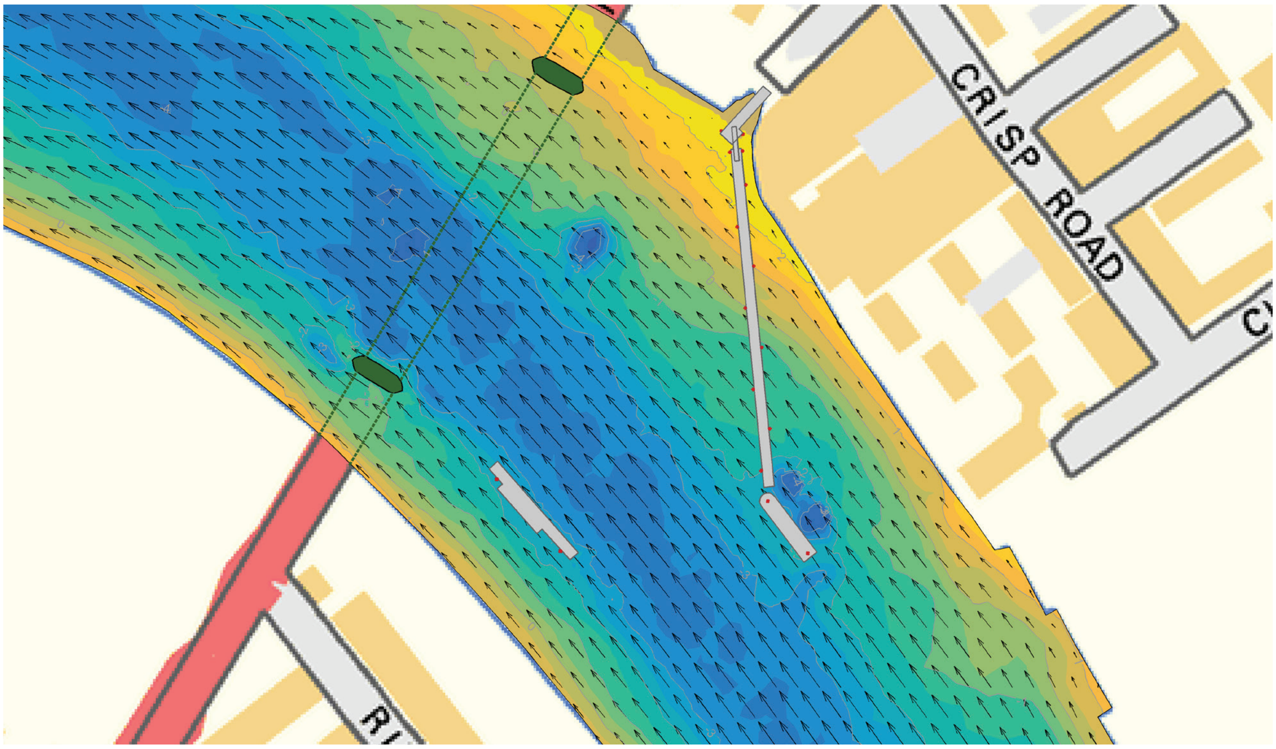
HR Wallingford
Working with water

Hammersmith Temporary Ferry

Underwater noise assessment



DER6480-RT002-R03-00 August 2021

Document information

Document permissions	Confidential - client
Project number	DER6480
Project name	Hammersmith Temporary Ferry
Report title	Underwater noise assessment
Report number	RT002
Release number	R03-00
Report date	August 2021
Client	Thames Clippers
Client representative	Ieva Sabone
Project manager	Kerry Marten
Project director	John Baugh

Document history

Date	Release	Prepared	Approved	Authorised	Notes
16 Aug 2021	03-00	JVB	JBL	JVB	
02 Aug 2021	02-00	KVM	TBE	KVB	
10 May 2021	01-00	KVM	TBE	JVB	

Document authorisation

Prepared	Approved	Authorised

Summary

Transport for London (TfL) are investigating an option of running a temporary ferry crossing alongside the existing Hammersmith Bridge during the bridge's refurbishment. Thames Clippers supported by Beckett Rankine recently won the tender to design and develop the ferry crossing and associated marine elements. HR Wallingford have been commissioned to support the consents process, including hydrodynamic, scour, underwater noise and ecological assessments.

On the Hammersmith side of the tidal River Thames, a floating walkway will be required to provide access to the temporary ferry pier for passengers for crossing a relatively wide area of intertidal. Construction of the walkway will require piles to be driven into the bed substrate. Sound may be introduced into the water column during piling and hence an assessment of the potential impacts of this sound on marine animals in the surrounding water is required. This report details the methods and results for the underwater noise assessment.

Based on the assumptions about the piling methodology, source level and duration for piling, modelling was undertaken to predict the underwater sound levels generated during construction of the floating walkway. The model results indicate that sound levels are unlikely to exceed temporary threshold shift (TTS) thresholds for marine mammals or fish, although there may be a localised behavioural impact on mammals and some fish species which may be excluded from the area while the piling activity is ongoing.

Contents

Summary

Figures

Tables

1. Introduction

An option for a temporary ferry crossing is being investigated by Transport for London (TfL) to run nearby to the existing Hammersmith Bridge during the bridge's refurbishment. Thames Clippers supported by Beckett Rankine recently won the tender to design and develop the ferry crossing and associated marine elements. HR Wallingford have been commissioned to support the consents process, including hydrodynamic, scour, underwater noise and ecological assessments.

The installation of two temporary piers, one on either side of the river, will be required to provide docking facilities for the ferry. On the north side, at Hammersmith, a floating walkway will be required to provide access for passengers to the temporary ferry pier across a relatively wide area of intertidal foreshore.

Construction of the walkway will require piles to be driven into the bed substrate. Installation of the piles may occur when the intertidal area is covered by the tide. Therefore sound may be introduced into the water column during piling and hence an assessment of the potential impacts of this sound on marine animals in the surrounding water is required. This report details the methods and results for the underwater noise assessment.

1.1. Project appreciation

Temporary piers to provide passenger access to the ferry will be located on either side of the river (Figure 1.1), immediately downstream of Hammersmith Bridge. Hammersmith Temporary Pier on the north bank will land at the end of Queen Caroline Street, while Barnes Temporary Pier will land on the Thames towpath on the south bank.

Both the Hammersmith Temporary Pier and Barnes Temporary Pier which make up the Hammersmith Ferry service are to be temporary installations for an intended period of 3 years with a maximum of 5 years. The design of each structure has therefore been completed with ease of removal as a key criterion.

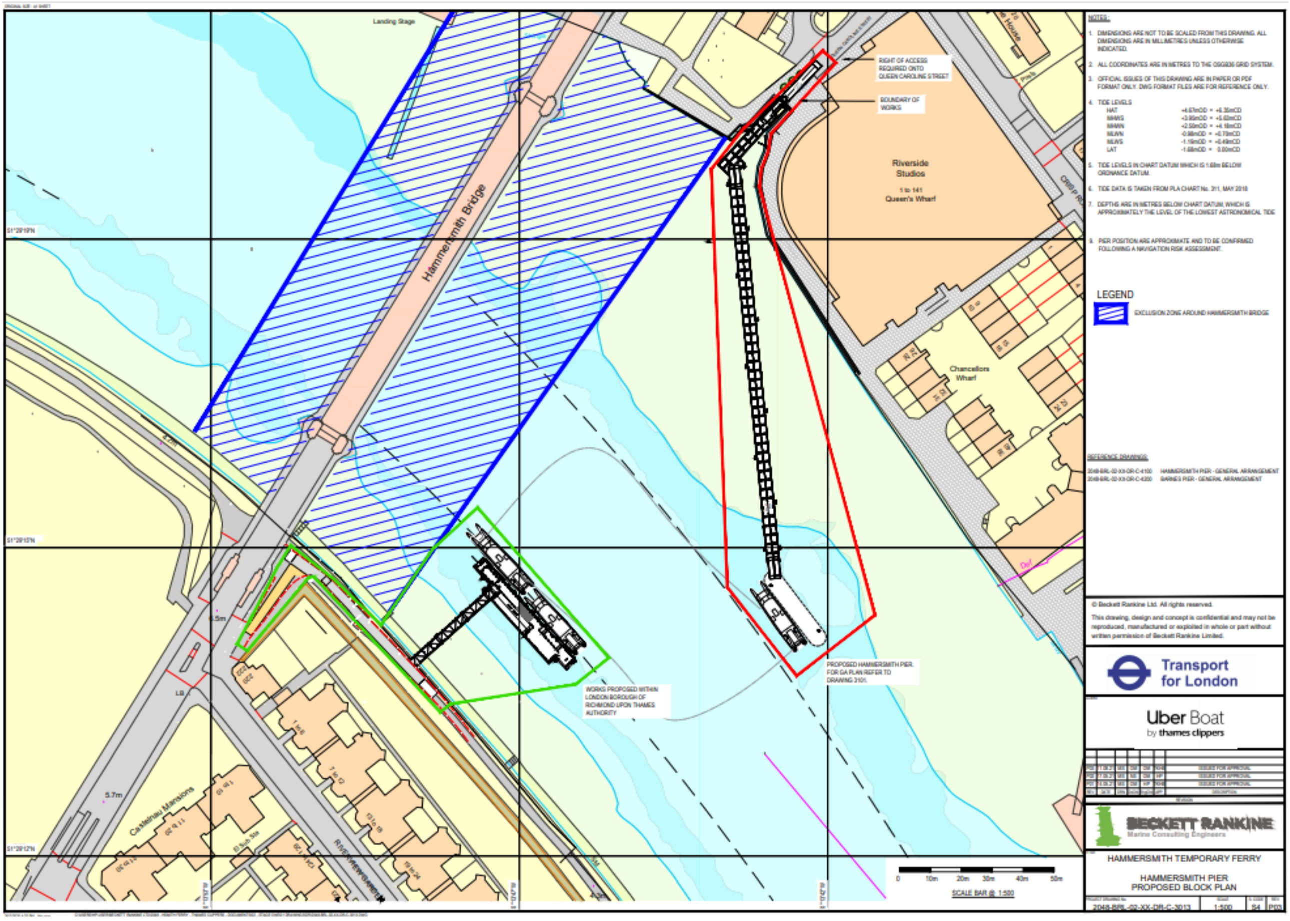


Figure 1.1: General arrangement of the temporary ferry project.

Source: Beckett Rankine, Drawing 2048-BRL-02-XX-DR-C-3013 P03

1.1.1. Hammersmith Temporary Pier

The proposed Hammersmith Temporary Pier (Figure 1.2 and Figure 1.3) is to land on the public slipway located at the end of Queen Caroline Street. The slipway is seldom used and is closed off with timber flood boards. Access to the pier is to be via a lightweight steel ramp that will span over the flood boards.

A modular floating walkway (using units by EZ Dock) will span between the flood defence wall and a second-hand barge, modified for use as a pier. The walkway will be restrained by tubular piles of up to 0.5m in diameter. The required piling is to be minimised to avoid major impacts and disturbance to the river environment. As identified in Figure 1.3, parts of the floating walkway will ground at low water.

The barge will be restrained by a pair of spud legs – these have been selected given their temporary nature and lesser impact when compared to piles. The pier is skewed downstream to facilitate passage of large vessels beneath Hammersmith Bridge (the bridge is open for occasional navigation when no works are in progress on the bridge). The position also makes use of the deeper water related to the nearby outfalls as shown in Figure 1.2.

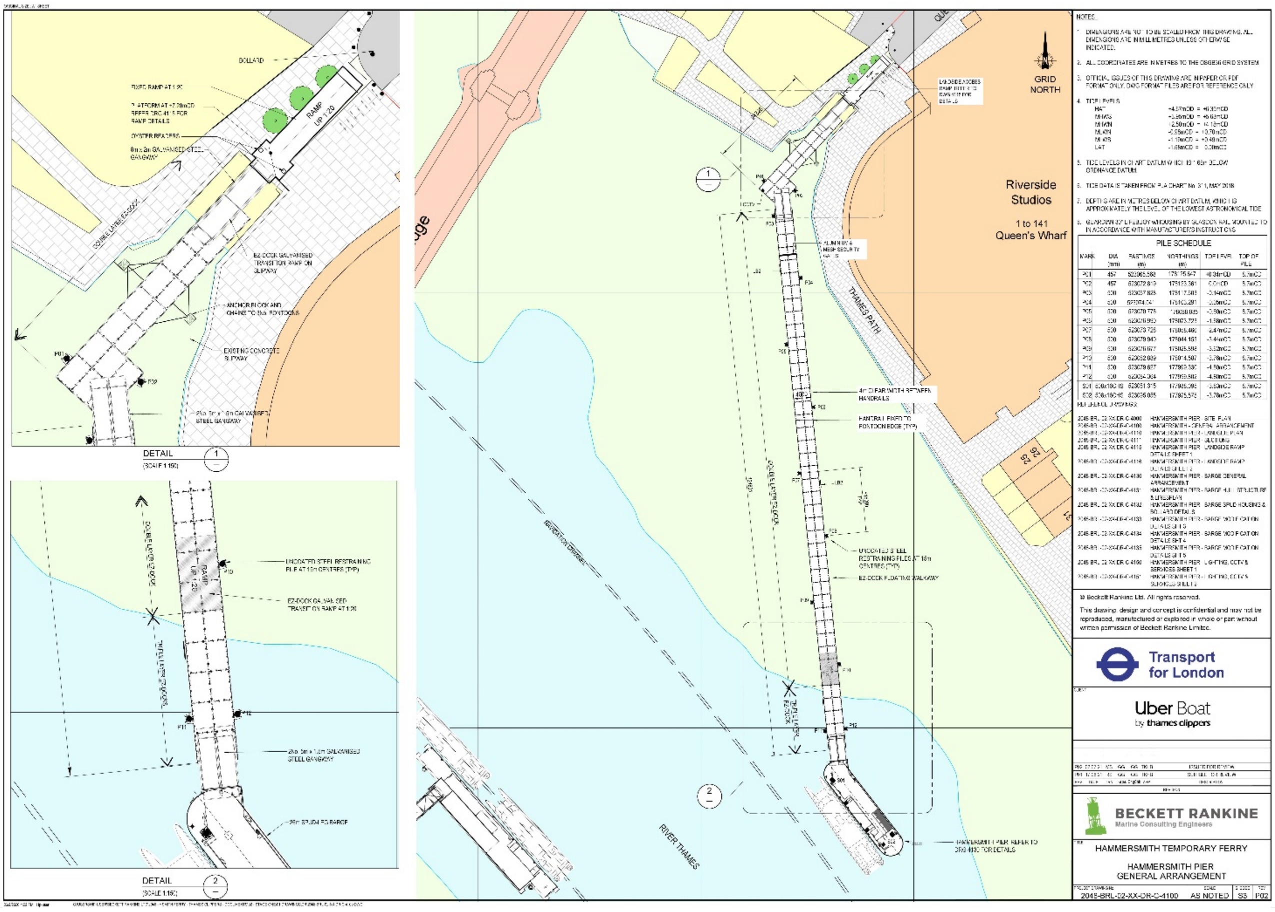


Figure 1.2: Hammersmith Temporary Pier general arrangement.

Source: Beckett Rankine, Drawing 2048-BRL-02-XX-DR-C-4100_P02 HSMTH BRG-GA

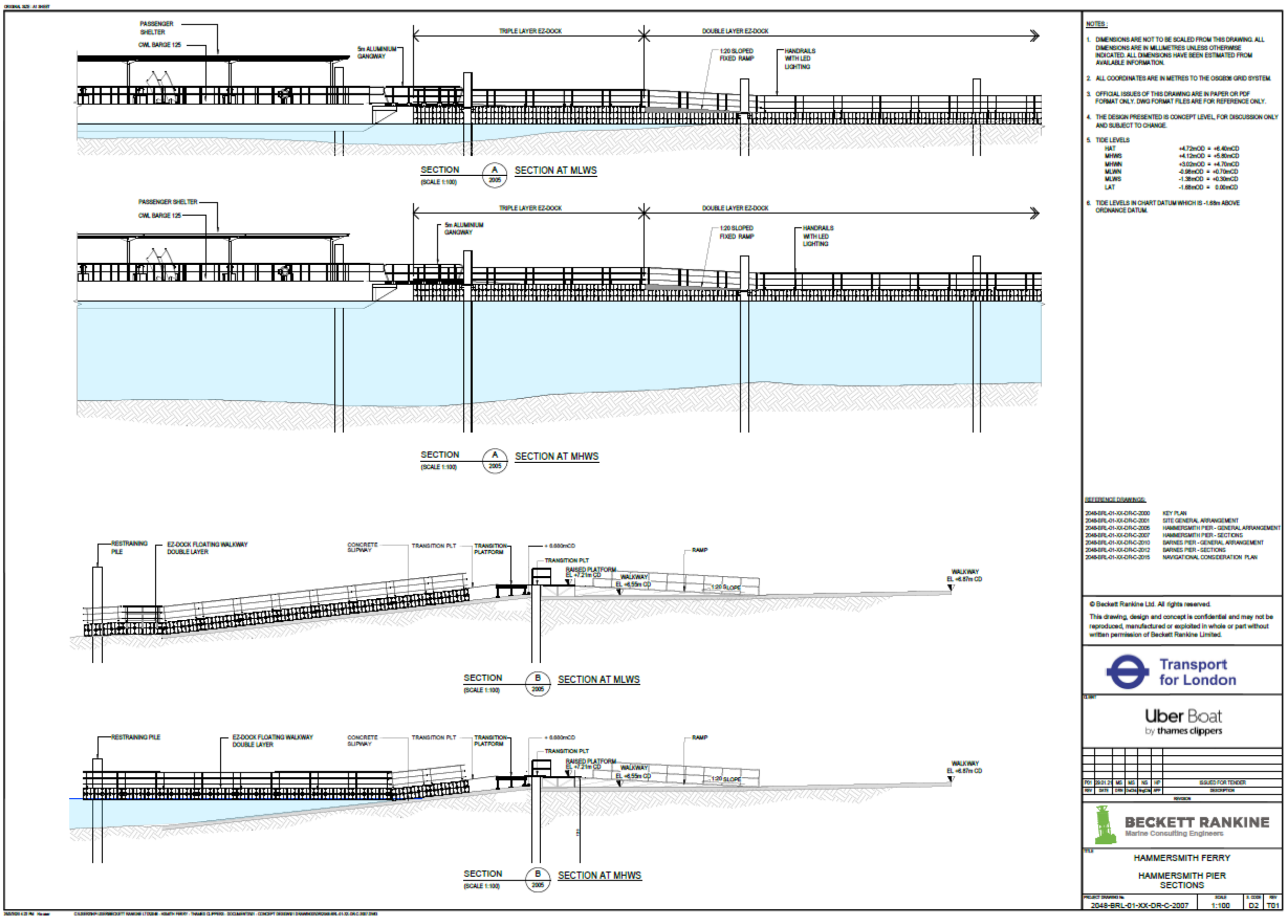


Figure 1.3: Cross-sections of the floating walkway proposed to access Hammersmith Temporary Pier

Source: Beckett Rankine, Drawing 2048-BRL-01-XX-DR-C-2007_T01

1.1.2. Barnes Temporary Pier

The proposed Barnes Temporary Pier (Figure 1.4) is formed from the old Savoy pier, itself a temporary structure, which will be repurposed for this development. The pier will be modified such that is restrained by a pair of spud legs rather than its current radial arms to minimise the impact on the foreshore.

Access to the pier is by an aluminium linkspan, connecting to the landside towpath. The towpath is located beneath Flood Defence Level and floods on some spring tides. As part of the works, a lightweight steel frame walkway will be installed to allow dry access to the pier.

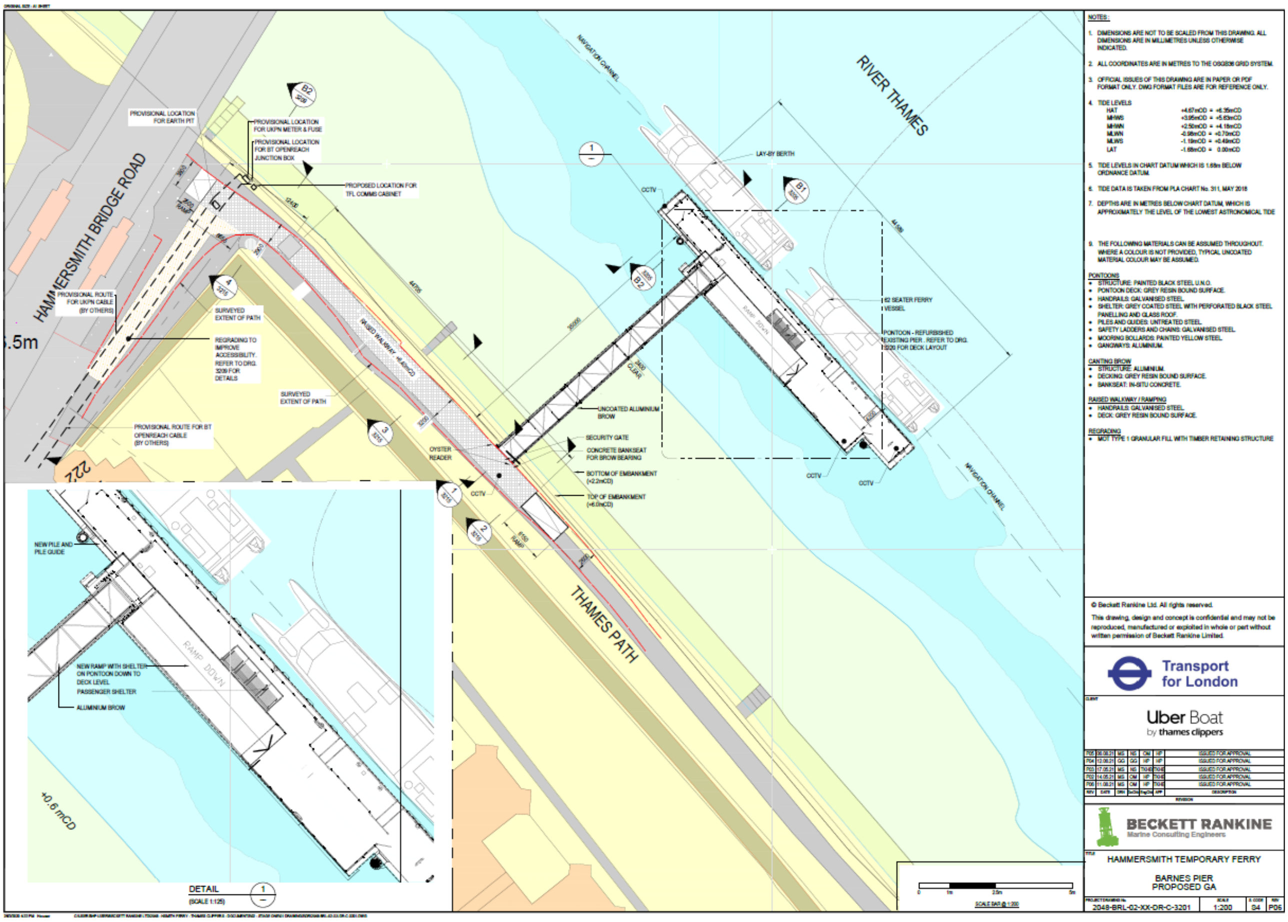


Figure 1.4: Barnes Temporary Pier general arrangement.

Source: Beckett Rankine, Drawing 2048-BRL-02-XX-DR-C-3201 P06 BARNES PIER PROPOSED GA (002)

1.1.3. Program

Offsite construction activities are underway. Works on site are due to start in early September and are to be completed by end of October. These dates continue to be subject to attaining the relevant licensing and consents for the works.

1.1.4. Construction

The first activity on site will be the bathymetric and UXO surveys. A proof dig at the pile line will also be carried out. Following this, the temporary piers will be installed following Red7 Marine’s method statement. All piles will be driven by the crawler crane mounted on a jack-up barge. In the case of the 4 most northern piles, a landside excavator will act as the piling gate. For the remainder of the piles the excavator will be mounted on the jack-up barge where it will also act as a piling gate. A supply barge will operate adjacent to the jack-up barge to store the piles. Where necessary for the spud leg piles at Barnes Pier, the excavator will be mounted on the supply barge.

Non-percussive piling methods will be used to install the tubular piles. Soft-start vibratory piling methods (high-frequency, variable moment resonant free vibratory hammer) will be used instead to embed the piles ~4 m into the riverbed, therefore, the noise and vibratory effects will be significantly reduced and less harmful to the surroundings. Piles will be driven dry where possible, and in the minimum water level possible where not possible. The plant requires a minimum water depth of 2 m to safely carry out the works. The methodology utilises low water piling techniques to reduce noise and vibration effects throughout the works.

2. Background to underwater sound

Underwater sound is detected as a pressure wave that propagates through the marine environment and, due to the low absorption characteristics of water, it can travel further and faster than sound in air. The amount of sound generated by anthropogenic sources in the marine environment has been increasing due to the growth in a number of areas e.g. shipping activity and construction of more offshore and coastal facilities. There is a concern that the increased levels of underwater sound will adversely impact on marine life and, to address this, the European Union have identified underwater sound as a form of energy which cannot be introduced into the marine environment at levels which will be detrimental (Van der Graaf et al., 2012).

The propagation of sound underwater is affected by the frequency of sound emitted and the physical properties of the water and seabed. Water depth is a key factor altering the propagation of underwater sound. In shallow water (less than about 200 m deep) propagated sound will dissipate more quickly than in deeper water due to numerous interactions with the surface and the bed, although this is also frequency dependant. The seabed type will alter the rate of transmission loss (TL) of propagated sound, with softer, muddy sediments tending to absorb sound whereas hard rocky surfaces will cause reflection and hence less absorption. The vertical profiles of temperature and salinity through the water column are also important, particularly in deep water, because these affect the speed of sound and thus the degree to which the sound is refracted up or down as it propagates horizontally away from the source.

As the sound propagates from a source it will lose energy and so eventually the sound levels drop to the same intensity as the ambient sound at which point it becomes indistinguishable from the background and can no longer effectively be heard. The ambient sound is a combination of all natural sounds such as wind, waves, rain, animals and other common sources of man-made sound in the area such as shipping. The term ‘ambient sound’ can be used to describe all sound not associated with the development or activity being assessed in the present study.

2.1.1. Acoustic metrics and units

The unit of sound pressure is the pascal (Pa) and is most commonly described in terms of decibels (dB) relative to a reference pressure, which for underwater sound is 1 μPa (expressed as ‘dB re 1μPa’). The use of a logarithmic scale means that a 6 dB increase in the underwater sound level represents equates to a doubling of the intensity.

The frequency spectrum of underwater sound is also important in terms of potential impacts. The power spectral density for different anthropogenic sources of sound can vary greatly. For example seismic airguns generally have most energy in the lower frequency range, from the low tens of Hertz (Hz) up to a few hundred Hz, whereas the range of high frequency sonar, for example, is generally much higher, in the thousands to millions of Hz. Knowing the frequency range of the acoustic source being assessed means that the potential adverse impacts on marine life can be assessed realistically, as hearing ranges of different species can be taken into account.

2.1.2. Sound Pressure Level (SPL)

Most commonly, underwater sound is expressed as the root mean square (RMS) of the sound pressure level (SPL) over a stated interval. This is a time-averaged value for the pressure, which is most useful for assessing continuous sound sources such as drilling or shipping sounds, rather than impulsive sounds such as pile driving or seismic surveying. This is calculated from the following:

$$SPL = 20\log_{10}\frac{P}{P_{ref}} \qquad (1)$$

Where P is the sound pressure and P_{ref} is the reference pressure (1 μPa).

The SPL is described as the received level (RL) which is the sound pressure level at a distance from a source with a source level (SL) minus the transmission loss (TL). For ESHIA purposes the RL is the more useful metric as this will provide the sound level a receptor is being exposed to. Models are usually required to simulate both the source level and the transmission loss.

2.1.3. Sound Exposure Level (SEL)

The sound exposure level (SEL) is a measure of sound energy in a pulse that takes into account both the peak and the duration of the sound and is therefore useful for describing impulsive sounds, such as those emitted by seismic airguns or by pile driving. SEL is calculated by integrating the square of the pressure waveform over the duration of the pulse. The duration of the pulse is defined as the region of the waveform containing the central 90% of the energy (E_{90}) of the pulse. The calculation is given by:

$$E_{90} = \int_{t5}^{t95} P^2(t)dt \qquad (2)$$

This is usually expressed as dB re 1 $\mu Pa^2 s$ and is calculated as follows:

$$SEL = 10\log_{10}\left[\frac{E_{90}}{E_0}\right] \qquad (3)$$

where E_0 is the reference value of 1 $Pa^2 s$.

Since the SEL is the time integral of the sound , it can also be related to the RMS SPL by the time duration T over which the RMS was calculated, as:

$$SEL = SPL + 10\log_{10}(\mathrm{T}) \qquad (4)$$

2.1.4. Cumulative Sound Exposure Level (SEL_{cum})

SEL is also used to express the amount of sound over time to which a receptor is exposed, this can be called the SEL ‘dose’ or the cumulative SEL (SEL_{cum}).

For a sequence of pulses, the cumulative SEL is calculated as:

$$SEL_{cum} = 10\log_{10}\left(\sum_{p=1}^{N_p} 10^{\frac{SEL_p}{10}}\right) \qquad (5)$$

For a sequence of equal intensity SEL exposures, this simplifies to:

$$SEL_{cum} = SEL + 10\log_{10}(\mathrm{N_p}) \qquad (6)$$

Where N_p is the number of pulses.

2.1.5. Power spectral density and third-octaves

It is important to model the frequency spectrum emanating from a source because different marine species are more sensitive to certain portions of the sound spectrum. Modelling of the full range of frequencies is usually carried out by modelling discrete frequencies at third-octave intervals. The broadband sound is then calculated by integrating the sound energy across the bandwidth (Δb_f) for each third-octave frequency and then summing across all the bands, written as:

$$SEL_{bb} = \sum_{f=1}^{N_f} SEL_f + 10\log_{10}(\Delta b_f) \qquad (7)$$

Where SEL_{bb} is the broadband sound exposure level, and SEL_f is the sound exposure level at each discrete frequency, f.

2.2. Sound impact criteria for marine and estuarine species

Marine mammals, fish and reptiles are acoustically sensitive and use sound to communicate, navigate and to find prey. The potential effects of increasing anthropogenic sound in the marine environment is of concern, and national and international legislation is asking for robust assessments of the potential impacts to be carried out for any new project or development. To carry out these assessments an understanding of the sound detection capabilities of the species of interest is required, along with knowledge of the sound field which will be generated.

2.2.1. Potential effects of underwater sound

Underwater sound from anthropogenic activities has the potential to have adverse impacts on fish, marine reptiles (sea turtles) and mammals.

The potential impacts on these animals range from causing discomfort by changing the acoustic environment, causing the animals to retreat from an area (i.e. behavioural response), to causing physical injury. Generally physical injury is caused by either a large and sudden change in pressure causing barotrauma e.g. bursting of swim-bladder or blood vessels, or by the cumulative amount of sound that an animal is exposed to. The latter is usually associated with temporary threshold shift i.e. a temporary increase in the threshold at which an animal can hear. For all of the available impact criteria, assessment of the effects is related to the sound pressure levels in the far-field rather than to the associated particle motion in the near-field area of the sound source.

Lethal effects

Mortality from underwater sound is usually associated with being very close to the acoustic source due to the high peak pressure levels, particularly from pulsed sounds such as seismic sources or pile driving. Severe injury which leads to death of the individual is also possible within a certain distance from the acoustic source. These injuries are associated with the rapid and large changes in pressure that an animal is exposed to rather than whether they can hear the sound.

Threshold shift

Exposure to high levels of underwater sound can also cause impairment in sound detection capabilities of marine species. The impairment can be a temporary threshold shift (TTS) where normal detection would return after a length of time dependant on the intensity of the sound and the duration for which an animal was exposed, or the impairment can be a permanent threshold shift (PTS) where no recovery is possible.

2.2.2. Marine mammals

The hearing frequency range of marine mammals is wide, and each species will differ slightly in the frequency of greatest sensitivity. In general, baleen whales such as the blue, humpback and southern right whale hear the lowest frequencies; dolphins and toothed whales hear mid-high frequencies; and porpoises and their relatives hear the highest frequencies and have the largest range. Pinnipeds have different hearing abilities dependent on whether they are underwater or not, with a greater hearing range underwater than in air (Babushina et al, 1991; Kastak and Schusterman, 1999; Reichmuth, et al, 2013). Pinnipeds can also be split into otariids, such as sea lions and fur seals, and phocids which are the true seals (e.g. grey or harbour seal), as recent research has shown that they have markedly different hearing ranges (Hemilä et al, 2006; Kastelein et al, 2009; Reichmuth et al, 2013).

The response of marine mammal species to underwater sound, and the potential physical impact of anthropogenic sound, has been the subject of scientific study for several decades, although the results are often uncertain due to the difficulties of identifying behavioural responses to sound in the open sea (Weilgart, 2007; Boyd et al, 2011). The US Marine Mammal Criteria Group within NOAA developed criteria for the impacts of underwater sound on marine mammals which allows an assessment of behavioural response to be made based on the best scientific knowledge at the time (Southall et al, 2007).

Southall et al (2007) divided marine mammals into four distinct groups based on their known, or assumed, auditory ranges – low-frequency cetaceans, mid-frequency cetaceans, high frequency cetaceans and pinnipeds (in air and in water). For each mammal group, the hearing range of the animals was accounted for using weighting factors (or M-weightings) to the received level sound at each centre frequency (f) of the third-octave sound spectrum.

For impulsive sound sources such as seismic survey airguns or pile drivers, the zero-to-peak (referred to as peak) sound pressure levels close to the source may be high enough to cause injury or mortality for marine animals. The work of Southall et al (2007) therefore also determined impact criteria based on peak SPL of impulsive sound using unweighted broadband values.

The criteria of Southall et al (2007) were not originally meant to become guidance for carrying out acoustic impact assessments for estuarine or offshore developments but they became accepted as industry standard for doing so (NOAA, 2013). It was also acknowledged that the Southall work was limited to the few marine mammal species which had been studied up to that point. As such, NOAA developed new impact criteria into a guidance document which is designed to be used for assessing impacts of anthropogenic sound on marine mammals (NOAA, 2016). These latest NOAA guidelines will be used to carry out the marine mammals assessment required for this project.

Table 2.1: Marine mammal hearing groups and generalised hearing ranges

		Generalised hearing range (Hz)	
Hearing group	Mammals represented	Lower limit	Upper limit
Low-frequency (LF) cetaceans	Baleen whales	7	35,000
Mid-frequency (MF) cetaceans	Dolphins, toothed whales, beaked whales, bottlenose whales	150	160,000
High-frequency (HF) cetaceans	True porpoises, Kogia, river dolphins, cephalorhynchid, Lagenorhynchus cruciger and L. australis	275	160,000
Phocid pinnipeds (PW)	True seals	50	86,000
Otariid pinnipeds (OW)	Sea lions and fur seals	60	39,000

Source: NOAA (2016). Generalized hearing ranges for the entire group are a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad.

The recent NOAA guidance for assessing the impact of underwater acoustics on marine mammals updated the auditory weighting functions defined by Southall et al (2007) and split the pinnipeds into phocids and otariids rather than accounting for different hearing in air and water (NOAA, 2016). The estimated functional hearing bandwidth for each of the hearing groups under the NOAA (2016) guidelines are shown in Table 2.1.

The form of the updated auditory weighting functions for the hearing groups is written follows:

$$M(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a[1+(f/f_2)^2]^b}\right\} \qquad (8)$$

Where M(f) is the weighted frequency. The constants for the above auditory weighting function for each mammal hearing group are given in Table 2.2 and the resultant weighting curves are plotted in Figure 2.1.

Table 2.2: Summary of NOAA (2016) weighting and exposure function parameters

Hearing Group	a	b	f1 (Hz)	f2 (Hz)	C (dB)
Low-Frequency (LF) Cetaceans	1.0	2	200	19,000	0.13
Mid-Frequency (MF) Cetaceans	1.6	2	8,800	110,000	1.20
High-Frequency (HF) Cetaceans	1.8	2	12,000	140,000	1.36
Phocid Pinnipeds in water (PW)	1.0	2	1,900	30,000	0.75
Otariid Pinnipeds in water (OW)	2.0	2	940	25,000	0.64

Source: Adapted from NOAA (2016)

Similarly to Southall et al (2007), the NOAA guidelines also determines impact criteria based on peak SPL for impulsive sound using unweighted broadband values for both TTS and PTS thresholds (with PTS calculated as 6 dB greater than TTS for each mammal hearing group).

The SEL_{cum} and peak SPL criteria for TTS and PTS for each mammal functional hearing group are given in Table 2.3 for impulsive sounds and Table 2.4 for non-impulsive sounds. In an assessment, both the SEL_{cum} and peak SPL should be assessed, and whichever is the greater in terms of impact for each mammal hearing group should be used.

Table 2.3: Weighted impact criteria of NOAA (2016) for marine mammal injury from impulsive sounds

	TTS threshold		**PTS threshold**	
Hearing Group	**Peak SPL (dB re 1 µPa)**	**SEL_{cum} (dB re 1 µPa^{2}s)**	**Peak SPL (dB re 1 µPa)**	**SEL_{cum} (dB re 1 µPa^{2}s)**
Low-Frequency (LF) Cetaceans	213	168	219	183
Mid-Frequency (MF) Cetaceans	224	170	230	185
High-Frequency (HF) Cetaceans	195	140	202	155
Phocid Pinnipeds in water (PW)	212	170	218	185
Otariid Pinnipeds in water (OW)	226	188	232	203

Source: Adapted from NOAA (2016). Peak pressure is rms dB re 1 µPa un-weighted values; SELcum units are dB re 1 µPa^{2}s, weighted for hearing range of the various categories and the SELcum accumulation period is 24 hours.

Table 2.4: Weighted impact criteria of NOAA (2016) for marine mammal injury from non- impulsive sounds

Hearing Group	**TTS threshold**	**PTS threshold**
Low-Frequency (LF) Cetaceans	179	199
Mid-Frequency (MF) Cetaceans	178	198
High-Frequency (HF) Cetaceans	153	173
Phocid Pinnipeds in water (PW)	181	201
Otariid Pinnipeds in water (OW)	199	219

Source: Adapted from NOAA (2016). SELcum units are dB re 1 µPa^{2}s, weighted for hearing range of the various categories and the SELcum accumulation period is 24 hours.

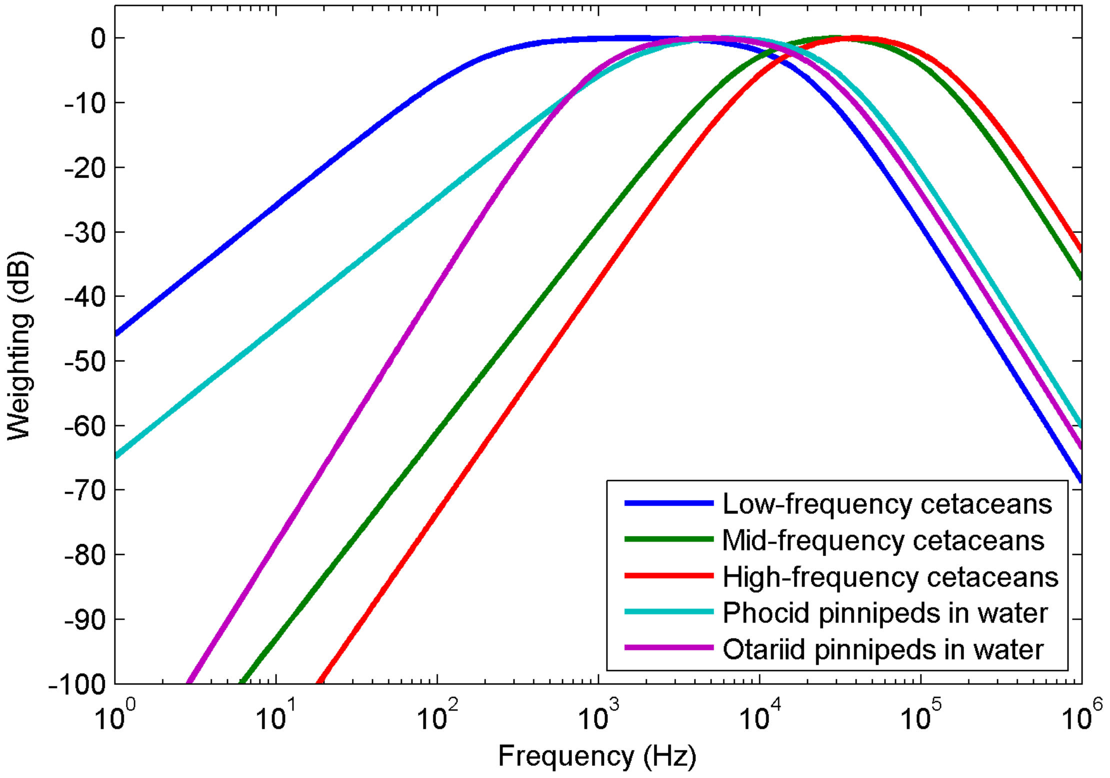


Figure 2.1: M-weighting using the NOAA (2016) assessment criteria

Source: Adapted from NOAA (2016)

2.2.3. Fish

Fish are known to be able to detect sound through the use of otolith organs in their ears (Fay, 2011; Popper and Fay, 2011). There are also species that can detect the pressure of a sound wave through gas filled structures e.g. the swim-bladder (Fay, 2011). This is a very simplified way of understanding how fish detect sound, as in reality most fish are somewhere on a scale between detecting particle motion caused by a sound wave and detecting the pressure of the sound wave (Popper and Fay, 2011; Fay and Popper, 2012). Flatfish, for example, are at one end of the scale as they do not have a swim bladder and are more likely to detect the particle motion, whereas catfish, goldfish and their relatives are at the other end of the scale with a swim-bladder connected to their otolith organs, and pressure will be the primary detection method for underwater sound (Fay and Popper, 2012). Some fish which do have swim-bladders are less sensitive to underwater sound than would be expected e.g. Atlantic salmon, as they don’t appear to use it to detect sound (see Popper, A.N. et al., 2014 and references therein).

Studies of the ability of fish to detect sound have been limited to very few of the species present in the marine environment, and have often been focussed on those of a commercial importance or those that are easy to keep in laboratory conditions. Nevertheless, these studies have shown that fish in general detect sound in the lower frequency range, from a few 10s of Hz to a few thousand Hz, although for the majority of marine species the lowest thresholds of sound detection i.e. where they are most sensitive, are below 1 kHz.

The assessment of underwater sound impacts on fish has been developed based on the hearing thresholds of individual species (Popper et al, 2003; Smith et al, 2004; Nedwell et al, 2007; Popper et al, 2014). This involves weighting the received level (RL) of sound so that the perceived sound according to the hearing abilities of the fish were taken into account, meaning that frequencies outside of the fish detection range were given lower weight than those which the fish could hear (Nedwell et al, 2007). Whilst this principle works well for mammalian hearing, due to the way in which fish detect sound using a combination of particle motion and sound pressure the method is not applicable for fish (Popper and Fay, 2011; Popper, et al, 2014). There is also a problem associated with the number of audiograms available for fish species, as this is highly limited and proxy species are often employed in acoustic impact assessments. The methods for collecting the audiograms have been called into question as artefacts negatively influencing the data may have been introduced during the studies (Popper et al, 2014).

Injury

Guidance for assessing the impact of anthropogenic sound on fish from different sources is available (Popper et al., 2014). The guidance is based on whether fish primarily detect the sound pressure component of a noise, the particle motion component or a combination of both, which is particularly relevant to behavioural responses rather than physical injury (see Table 2.5). The guidance also offers sound levels where impulsive sound may cause permanent or temporary injury and TTS. As the guidance is becoming ‘industry standard’ for use in assessing impacts of impulsive sound on marine fish, it has therefore been used to carry out the assessment required by this project.

Table 2.5: Fish categories for use in assessments of underwater sound impacts

Category	Explanation
Fish without a swim bladder or other gas chamber e.g. dab and other flatfish	These species are more likely to only detect particle motion rather than sound pressure. As they have no gas chambers, they are less likely to suffer significant barotrauma
Fish with swim bladders, or other gas volume, which is not involved in the detection of sound e.g. Atlantic salmon	These species are susceptible to barotrauma although hearing only involves particle motion not sound pressure
Fish with a swim bladder or other gas volume which is involved in sound detection e.g. Atlantic cod, herring and relatives	These species are susceptible to barotrauma and detect sound pressure as well as particle motion
Fish eggs and larvae	Fish eggs and larvae may contain gas bubbles/developing swim bladders, rendering them susceptible to barotrauma

Source: Adapted from Popper et al. (2014)

Using the categories defined in Table 2.5, and the most up to date scientific studies, the guidance identifies impact criteria (i.e. levels of underwater sound which could adversely affect fish), via mortal and recoverable injuries for a range of anthropogenic acoustic sources. The guidance also provides some data and impact criteria for the potential effects of underwater sound on fish eggs and larvae, but these are not included in the current study. The criteria for seismic sources are presented in Table 2.6. All impact criteria are based on sound pressure levels as no information for the particle motion proportion of the potential impact exists.

Table 2.6: Impact pile driving criteria for fish as defined by Popper et al (2014)

Category	Mortality or potential mortal injury	Recoverable injury	TTS
Fish: No swim bladder	>219 dB SEL_{cum} OR >213 dB peak SPL	>216 dB SEL_{cum} OR >213 dB peak SPL	>>186 dB SEL_{cum}
Fish: Swim bladder not involved in hearing	210 dB SEL_{cum} OR >207 dB peak SPL	203 dB SEL_{cum} OR >207 dB peak SPL	>186 dB SEL_{cum}
Fish: Swim bladder involved in hearing	207 dB SEL_{cum} OR >207 dB peak SPL	203 dB SEL_{cum} OR >207 dB peak SPL	186 dB SEL_{cum}
Eggs and larvae	210 dB SEL_{cum} OR >207 dB peak SPL	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

Notes: *Adapted from Popper et al. (2014). Peak and rms sound pressure level dB re 1 μPa; SEL dB re 1 μPa2·s. SELcum = Cumulative sound exposure level accumulated over a 24 hour period assuming stationary animals.*

For non-impulsive (continuous) noise, such as shipping noise and drilling, sound exposure thresholds are less well defined, largely being categorised as high, moderate or low potential impact (Popper et al 2014), as shown in Table 2.7.

For fish with a swim bladder, Smith et al (2006) (in Popper et al, 2014) found that exposure to a continuous noise with an RMS of 170 dB re 1μPa over a 48 hour period could cause recoverable injury in goldfish (*Carassius auratus*). Another study (Amoser and Ladich, 2003, in Popper et al 2014) suggested that 12 hours exposure to an RMS sound pressure level of 158 dB re 1μPa could cause a temporary threshold shift (TTS) in goldfish and catfish (*Pimelodus pictus*).

Table 2.7: Continuous sound criteria for fish as defined by Popper et al (2014)

Category	Mortality or potential mortal injury	Recoverable injury	TTS	Masking	Behaviour
Fish: No swim bladder	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder not involved in hearing	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder	(N) Low (I) Low	170 dB RMS for 48 hours	158 dB RMS for 12 hours	(N) High (I) High	(N) High (I) Moderate

Category	Mortality or potential mortal injury	Recoverable injury	TTS	Masking	Behaviour
involved in hearing	(F) Low			(F) High	(F) Low
Eggs and larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

Source: *After Popper et al. (2014)*

Notes: *Adapted from Popper et al. (2014). RMS sound pressure levels dB re 1 µPa. All criteria are presented as sound pressure even for fish without swim bladders since no data for particle motion exist. Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I) and far (F).*

Behavioural response and masking

Behavioural response to noise will vary between species and between individuals of the same species. The 2014 guidance for assessing injuries to fish from anthropogenic noise do not provide definitive levels of sound which would cause a behavioural response or lead to masking. Instead a subjective approach has been adopted due to the lack of evidence for behavioural response in the majority of fish species of interest and the sometimes contradictory information which is available for others. The relative risks for each of the fish categories at each distance are presented in Table 2.8.

There is some debate over whether behavioural response is context specific i.e. if a fish is currently engaged in another activity which is of biological importance such as spawning, it may ignore noise levels that it would normally react to when not engaged in spawning activity or similar (e.g. see Kastelein, et al., 2008; Sivle. et al., 2012).

Table 2.8: Masking and behavioural response impact criteria for fish from pile driving

Category	Masking	Behavioural response
No swim bladder	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Swim bladder not involved in hearing	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Swim bladder involved in hearing	(N) High (I) High (F) Moderate	(N) High (I) Moderate (F) Low
Eggs and larvae	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

Source: *After Popper et al. (2014)*

2.3. Key species of concern in the region

The marine mammal species that have previously been observed around the project site include grey seals (*Halichoerus grypus)* and harbour seals (*Phoca vitulina),* both of which are phocid pinnipeds, as well as harbour porpoise (*Phocoena phocoena*) which are high frequency cetaceans.

Several fish species have been identified as spending all or part of their lifecycle in the tidal Thames Estuary and therefore have the potential to be impacted by the development (Table 2.9). Four of the species listed are also known to spawn between Teddington Lock and Wandsworth Bridge, where the project is located and the periods when spawning occurs are shown.

Table 2.9: Common and protected species between Teddington Lock to Wandsworth Bridge (Table derived from ZSL Guidance document, 2016)

Common Name	**Scientific Name**	**Type of fish**	**Time period near site**	**Local spawning event***
Atlantic Salmon	*Salmo salar*	4	A,B,C,D	
Barbel	*Barbus barbus*	2	A,B,C,D	
Brown/Sea Trout	*Salmo trutta*	4	A,B,C,D	
Bullhead	*Cottus gobio*	2	A,B,C,D	
Common Dace	*Leuciscus*	2	A,B,C,D	During B
Common Goby	*Pomatoschistus microps*	1	A,B,C,D	During A & B
European Eel	*Anguilla anguilla*	4	A,B,C,D	
European Seabass	*Dicentrarchus labrax*	3	B,C	
European Smelt	*Osmerus eperlanus*	4	B,C,D	During A & B
Flounder	*Platichthys flesus*	3	B,C,D	
River Lamprey	*Lampetra fluviatilis*	4	B,C,D	
Roach	*Rutilus*	2	B,C,D	During B

Notes: Type of fish: (1) Spend entire life in Tidal Thames; (2) Mainly present in freshwater dominated Tidal Thames; (3) Use the Tidal Thames to spawn or grow whilst juveniles; (4) Migrate through the Tidal Thames to freshwater or saltwater.

Timing Key: (A) Jan-March; (B) April-June; (C) July-Sept; (D) Oct-Dec

Spawning events: The listed spawning events are known to occur at the specified time periods between Teddington Lock to Wandsworth Bridge where the project is located.*

3. Methods

3.1. Underwater sound propagation model description

To account for the complexity of underwater sound propagation, the proprietary numerical modelling tool UnaCorda (HR Wallingford, 2012; 2013; Rossington et al, 2013) was used to predict sound propagation from the installation of the bridge piles. This model is used to predict the propagation of underwater sound from one or more point sources throughout the water column and for 360º around each sound source. Underwater sound is assessed for third-octave frequencies of sound across the spectrum from 10 Hz to 20 kHz and the outputs from the model are presented as ‘sound maps’ for each frequency showing the transmission loss (TL) or received level (RL) from the source in decibels (dB).

The underwater acoustic propagation model uses a parabolic equation approach based on the Range dependent Acoustic Model (RAM) which has been modified to be computationally efficient and to produce 3D sound maps, rather than give results for single line. Being a range dependent model, it takes into account changes in bathymetry, sediment type and speed of sound profile with distance from the source. The model is used to predict the TL for discrete frequencies, allowing differences in attenuation that come with different wavelengths to be included in the model. The seabed sediment type is taken into account using known absorption coefficients for different sediment types and, if required, a variable seabed which differing absorptions can be used as a base over which the sound is propagated in the model.

3.1.1. Model validation

The UnaCorda underwater sound propagation module (part of the HAMMER tool box) has previously been validated by comparing modelled predictions against other models (HR Wallingford 2012). First, a Lloyd Mirror test was carried out in which the model was compared against RAMGEO and also against a classical analytical solution to sound propagation in deep water. Two further, more rigorous, shallow water validation exercises were then carried using test results from a journal article for a wedge shaped bed profile (Collins 1993), first with sediment and then with a reflecting bed. The results of the Lloyd mirror test are presented below; details of the wedge tests can be found in HR Wallingford (2013).

Lloyd mirror test

The ability to accurately reproduce a deep water Lloyd Mirror interference pattern is a classic test for assessing sound propagation models. In this test the water depth is set to be very large (>2000m). Assuming the water is homogenous (i.e. there are no temperature or salinity gradients), then the sound speed profile caused by pressure alone results in an upward refraction of sound waves. Consequently, in the near-field, sound waves from a source located near to the surface are not able to reach the seabed, but may reflect from the surface (Jensen et al. 2000).

The Lloyd mirror comparison is presented in Figure 3.1. Beyond a distance of about 50 m (the analytical solution does not represent near-field attenuation correctly) it can be seen that the three solutions are virtually identical. This shows that UnaCorda is performing well in terms of propagation of sound through the water column with surface reflection.

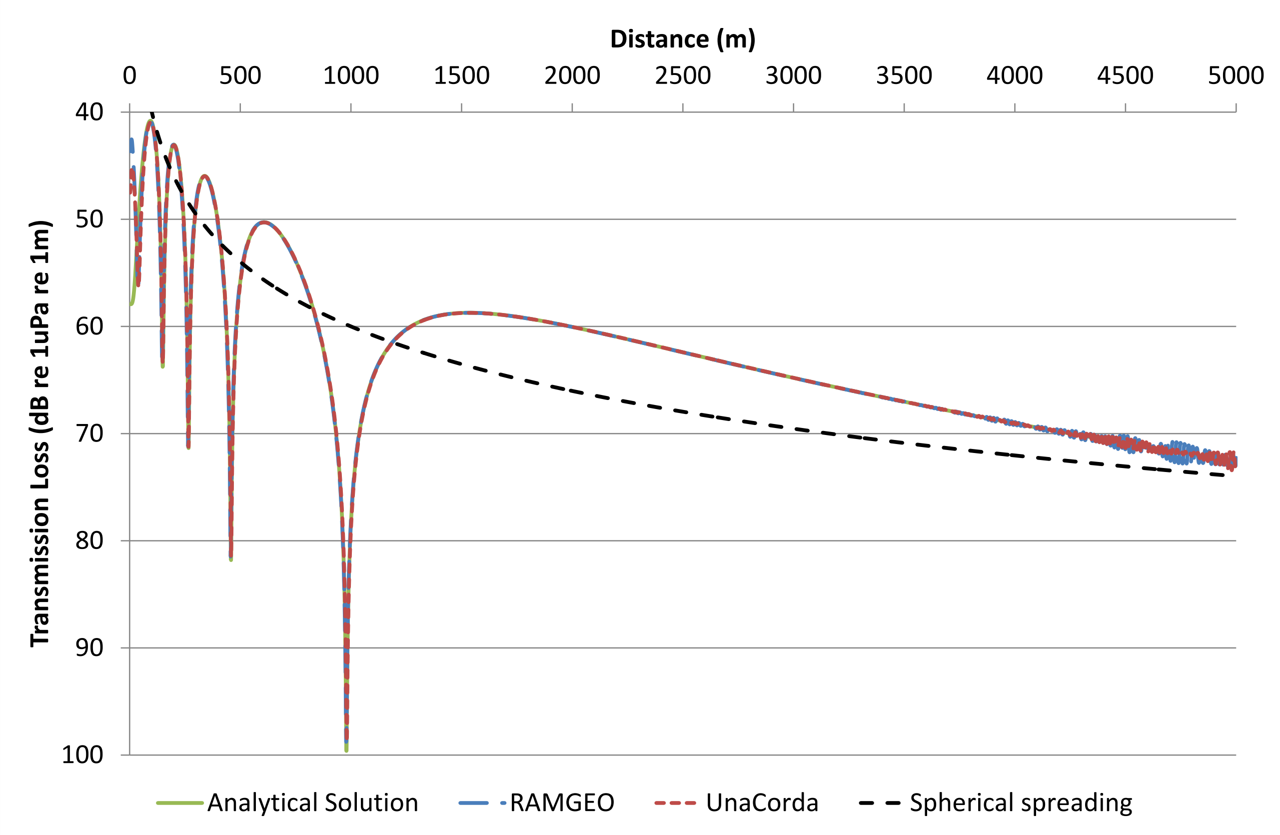


Figure 3.1: Comparison of noise module results for the Lloyd Mirror Test

Source: Collins (1990)

Field validations

In addition to the benchmark test, UnaCorda has been validated against field measurements of underwater sound. HR Wallingford (2013) found good agreement between predicted and measured sound levels for underwater drilling (Figure 3.2). Further validation of the model was carried out during the Rampion Offshore Wind Farm project (HR Wallingford, 2016) during which the predicted underwater sound levels were compared with measurements taken during impact pile driving for an offshore windfarm. Again, good agreement between the model and the measurements were found.

3.2. Fleeing animals

An important factor to consider when calculating a cumulative SEL metric is that mammals have the ability to swim away from an acoustic source if the sound levels are not tolerable. Hence it is now common practice (Lepper et al, 2007) to assume that as soon as surveying is initiated, the mammals affected by the sound swim in a straight line away from the source. As the individuals move away into quieter water, the SEL generally reduces with range. The cumulative SEL for each individual is therefore considerably less than if they were assumed to remain stationary. A value of swim speed for the mammals is usually taken to be 1.5 m/s (e.g. Lepper et al, 2007; RSK Environmental, 2012) and this value has been assumed in this study.

Fleeing models are not generally used for fish since different species tend to react differently and the responses of many species have not been studied. Furthermore, certain fish species can be highly territorial, for example when they are nesting, and so will tend to maintain their position. Therefore, in the case of fish species it is initially assumed that they remain stationary. This is a conservative approach and considered worst case scenario for these animals.

In order to accurate calculate the $\mathrm{SEL}_{\mathrm{cum}}$ of fleeing animals in the Thames Estuary, assuming animals swim in a straight line away from the sound is not appropriate because the Thames curves and they would reach the bank if they had swum in a straight line. Instead, HR Wallingford's agent-based model (Hydroboids) was used to predict the movement of marine mammals and fish away from sound source.

3.2.1. Agent-based model description (Hydroboids)

HydroBoids is an agent-based model (ABM) for predicting the movement of fish (or other mobile marine animals) and consequences of behaviours in response to stimuli such as sound or chemical tracers (Rossington and Benson, 2019). In the model, individuals are represented as quasi-Lagrangian points, or *agents*, in a three dimensional underwater space which are advected by the Eulerian hydrodynamic flows calculated offline using the TELEMAC modelling system (www.opentelemac.org).

Agents are assigned characteristics or traits that are both *physiological* (e.g. swim speed), which are assigned to each individual in the population from a normal distribution, and also *behavioural* (e.g. schooling). The ability to model intra-population variability is a key reason why the ABM approach is useful for modelling ecological impacts since not all individuals of the same species will respond in the same way (Castro-Santos and Haro, 2013).

Of particular importance for the present study, a feature of the ABM is that the simulated agents are able to actively avoid very shallow water and land boundaries. In the event of an agent finding itself stranded at the end of a particular model time step, they iteratively reattempt the movement for that step, each time modifying their heading in small increments, until they successfully remain in the water column and within the model domain at the end of the step. This simulates avoidance behaviour and allows the animals to swim away from the noise source without getting stuck on the river margins.

The model is described in more detail by Rossington and Benson (2019).

3.2.2. Calculation of SELcum for fleeing mammals

For each mammal hearing group, the specific M-weighting function was applied to the source spectrum (see Section 2.2.2) and the weighted spectrum model results from UnaCorda were used to calculate the instantaneous spatial SEL for that hearing group.

In the agent-based model simulations, cumulative sound exposure levels were calculated for fleeing mammal individuals of each hearing group as they swam away from the noise source. At each model time interval, the instantaneous M-weighted SEL at each animal's position was added cumulatively (see Section 2.1.4). This procedure was carried out for the duration of the ABM simulation for mammals to give the total $\mathrm{SEL}_{\mathrm{cum}}$ for each animal.

4. Model set up

This section describes the inputs used for the underwater sound propagation model (UnaCorda). The underwater sound model requires various input data, listed as:

- A source level spectrum for the activity undertaken;
- Source locations and bathymetry to take into account the spatially varying water depth; and,
- Geophysical bed parameters to simulate absorption by the seabed sediments.

4.1. Vibro-piling source level

Sound is likely to be generated by several activities required for the installation of piles for the floating walkway at Hammersmith Temporary Pier. These include:

- Vessel engines;
- Repositioning of the jack-up rig;
- Vibro-piling to install the piles for the temporary floating walkway.

Of these, it is expected that the vibro-piling will introduce the highest levels of sound into the surrounding water.

Pile driving will be carried out to install the floating walkway for the Hammersmith Temporary Pier using vibro-hammer with variable moment (PVE 20VM), which has a maximum centrifugal force of 1100 kN and vibration frequency of 2300 rpm (38 Hz).

Relatively little information for vibro-hammer source levels could be found in the literature. Two potentially suitable sources of literature were identified (Blackwell, 2005; Dahl et al, 2015), each with distinctly different source level spectra which are plotted in Figure 4.1.

Blackwell (2005) recorded sound pressure levels during Port MacKenzie dock modifications in Cook Inlet, Alaska in which two 0.91 m steel pipes of length 46 m were driven approximately 15 m into the seabed in water depths of 10-17m. The recorded RMS sound pressure levels at 56 m from the pile during vibro-piling were between 162-164 dB re 1μPa.

Dahl et al (2015) recorded sound pressure levels emitted during the installation of a 17 m long pile, with a diameter of 0.76 m, in 8 m water depth, which was being installed as part of the construction of a ferry dock in Port Townsend, Washington. The measured RMS sound pressure level at 16 m was approximately 165-168 dB re1μPa.

Both of the reported frequency spectra were reported to show peaks low frequencies associated with the vibration frequency of the vibro-hammer (approximately 15 Hz and multiples thereof). However, the spectra of Blackwell (2005) shows a greater proportion of the total energy between 400 and 2000 Hz than the other spectrum. Because of the larger amount of energy in the higher frequencies, this spectrum was chosen as a worst case in terms of impacts. The reasons why this is considered worst case are twofold:

1. Lower frequencies (below a 1000 Hz) tend to be attenuated by the bed sediment more readily as the sound propagates away from the pile. Therefore, if the two spectra had equal broadband source levels,

the higher frequency spectrum would generally result in higher RMS sound levels further from the pile than the lower frequency spectrum, and hence greater impacts.

2. The marine mammal species of concern in the area (i.e. harbour porpoise and seals) are more sensitive to frequencies at and above 1000 Hz (as shown in Figure 2.1). Therefore the spectrum with more energy at higher frequencies will result in greater predicted impacts.

Both of the plotted spectra have been corrected to give the same combined broadband source level of 175 dB re 1µPa. The source level value has been estimated based on the various stated source levels derived from the literature.

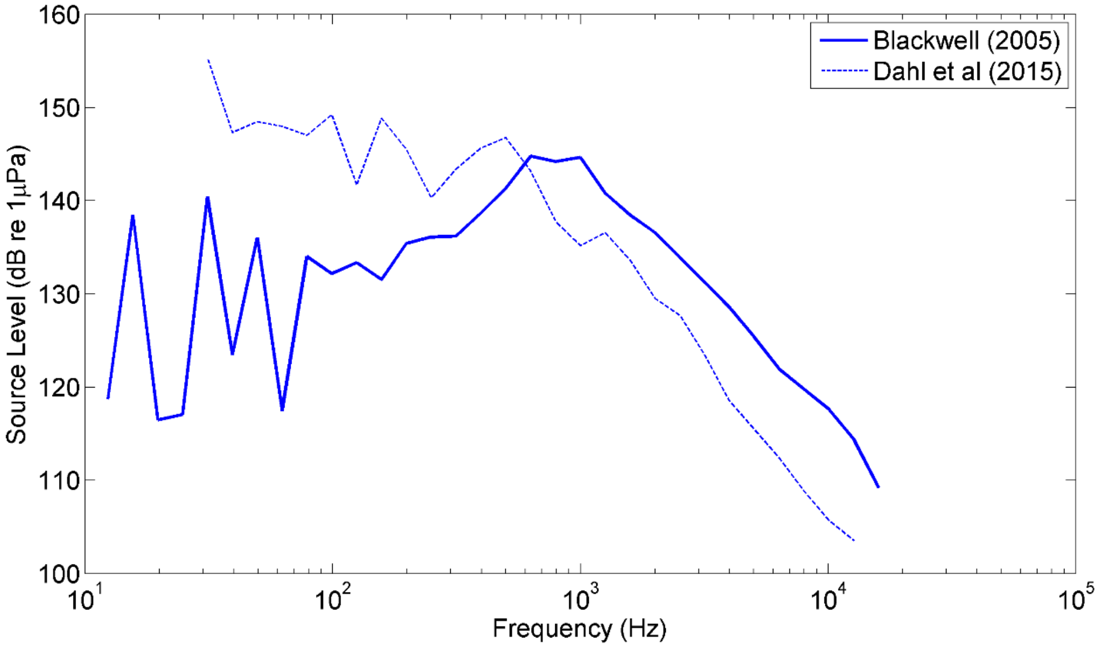


Figure 4.1: Source level spectrum for vibro-piling (solid line used in the model)

Source: The solid line shows the worst case spectrum adapted from Blackwell (2005) used for the modelling. For comparison, the dashed line shows another spectrum adapted from Dahl et al (2015) which would result in lower impacts if used in the present study,

4.2. Modelled pile location and bathymetry

The UnaCorda model requires a detailed bathymetry interpolated onto an unstructured mesh (with triangular elements) as an input. One location was modelled, the position of which is given in Table 4.1. The triangular elements, which are of irregular size and shape, allows a spatially non-uniform mesh resolution to be defined. The highest resolution (smaller mesh size, minimum 0.5 m) was defined at the sound source, with decreasing resolution (larger mesh size, max ~25 m) moving away from the source, with an element size growth rate of around 0.2%. The water level was set to +4 m OD(N), representing high water on a spring tide.

Table 4.1: Coordinates of the modelled pile location

Location	Easting (m)	Northing (m)
Deepest water depth pile	523081	178000

The 3D model set up includes a vertical resolution of 10 horizontal sigma planes spaced uniformly between the seabed and the sea surface. The individual planes do not represent a constant depth, but rather a proportion of the water column position across the whole model domain.

4.3. Bed parameters

The geo-acoustic properties of the seabed sediment influence how sound is refracted and attenuated as it propagates away from the sound source. In the absence of local geotechnical data, the acoustic properties of the seabed within the near-field area have been estimated based on Richardson and Briggs (2004), which describes empirical predictions of seafloor properties based on remotely measured sediment impedance in both siliclastic and carbonate sediments. It was assumed that the sediments are best described as CLAY and parameters selected accordingly. The values of the various properties derived from measurements of sediment within this large dataset are summarised in Table 4.2.

Table 4.2: Physical properties of the bed sediment type as input into the UnaCorda modelling tool.

Physical Property	Value
Density (kg/m^3)	1500
Sound speed (m/s)	1500
Attenuation coefficient (dB/λ)	0.2

Source: HR Wallingford using information from Richardson and Briggs (2004)

4.4. Fleeing animal model inputs

At the start of the ABM simulations, animals (mammals or fish) were initialised at the positions of the noise model mesh nodes. At the onset of piling it was assumed the animals swam away from the sound source at a swim speed of 1.5 m/s. Each animal's cumulative SEL dosage was calculated over the estimated time for installation of a single pile (40 minutes). In fact, this period was found to be sufficient for all animals to swim around the bend in the estuary, out of the insonified area.

Since the depth of the animals is not known, the maximum SEL through the water column is used in the calculations to be conservative.

A summary of the main parameters used in the fleeing animal modelling is given in Table 4.3.

Table 4.3: Parameters used in fleeing animal model

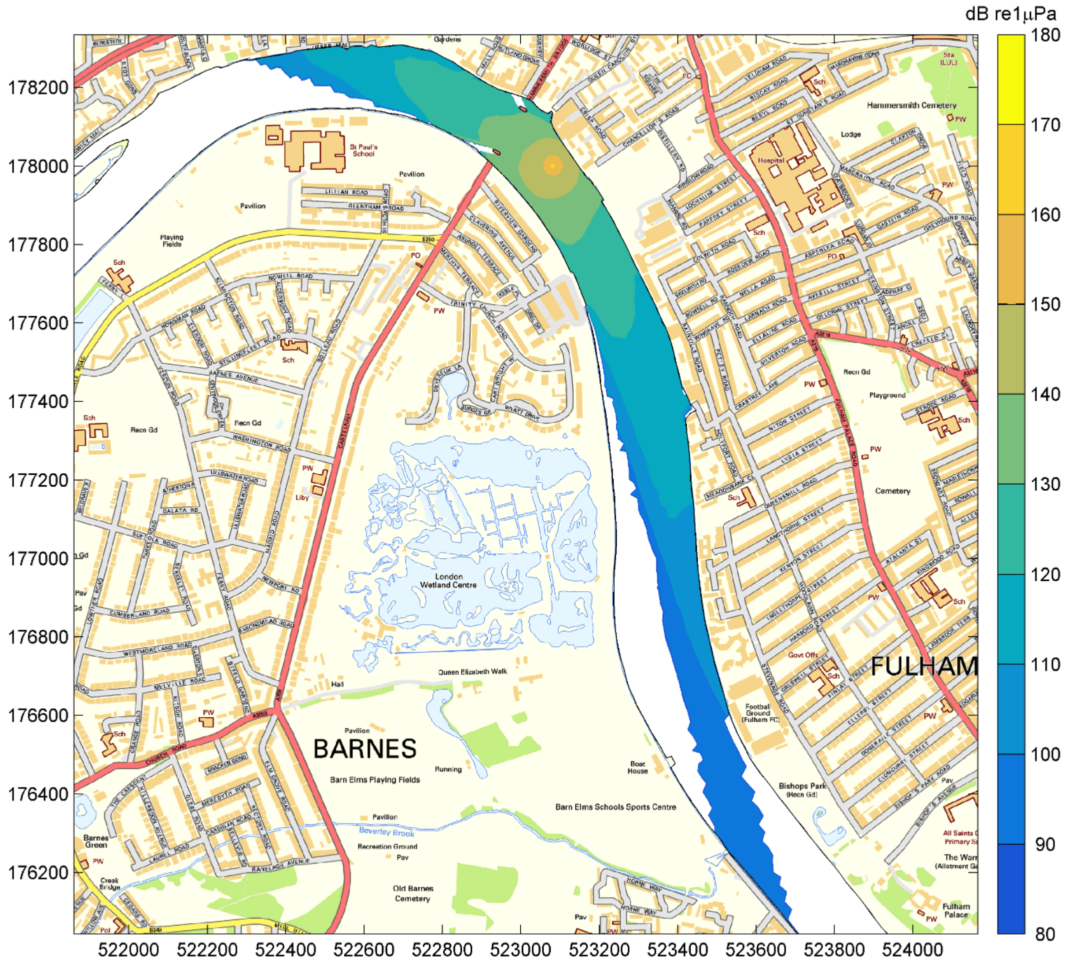
Parameter	Value used
Animal swim speed	1.5 m/s
Duration of cumulative sound exposure	40 minutes (estimated period for installation of a single pile)
3D sound levels used	Vertical maximum
Mammal weightings used	NOAA (2016)

Source: HR Wallingford

5. Results

5.1. Modelled broadband sound propagation

The modelled RMS sound pressure levels (broadband) emitted into the water during vibro-piling are plotted in Figure 5.1. The plotted values are the maximum RMS sound pressure level that occurs vertically in the water column. The modelled received levels for vibro-piling are up to 175 dB re 1µPa at the pile. Generally, sound from the pile location propagates through the water until it reaches the estuary bank or shallow area. The extent of the sound is therefore limited due to the bends in the estuary channel.



\\hrw-uk.local\projects\live\der6480$\3_technical\model\Animals\3_Analysis\Set1\Vibropiling_RMS_2.mws

Figure 5.1: Modelled broadband sound propagation during vibro-piling

5.2. Potential impacts

5.2.1. Potential impacts on fleeing mammals

Sounds maps of cumulative sound exposure levels over 30 minutes are given in Figure 5.2 and Figure 5.3 for high frequency cetaceans and phocid pinnipeds, respectively. The SEL_{cum} values are plotted at the start locations of each animal to show the distance from the pile that an animal would need to be at the start of drilling in order to receive a particular dosage of sound, i.e. based on Figure 5.2, a high frequency cetacean situated in the centre of the channel under Hammersmith Bridge at the start of drilling would receive a maximum SEL_{cum} dose of 130 dB re1μPa^{2}s.

Vibro-piling noise is assumed to be non-impulsive and therefore the appropriate thresholds are those given in Table 2.4. In all cases, the PTS and TTS thresholds for mammals are not exceeded.

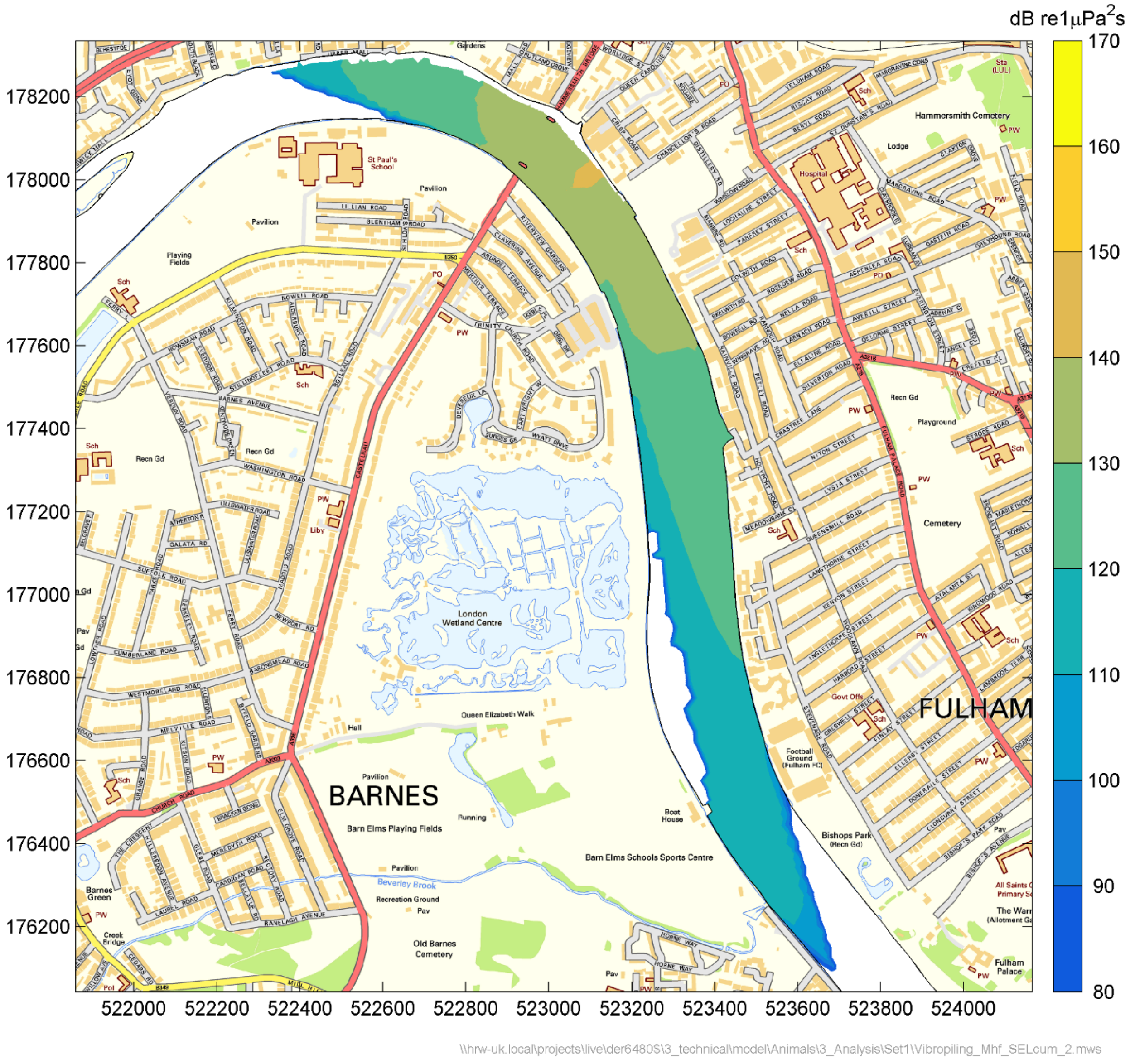
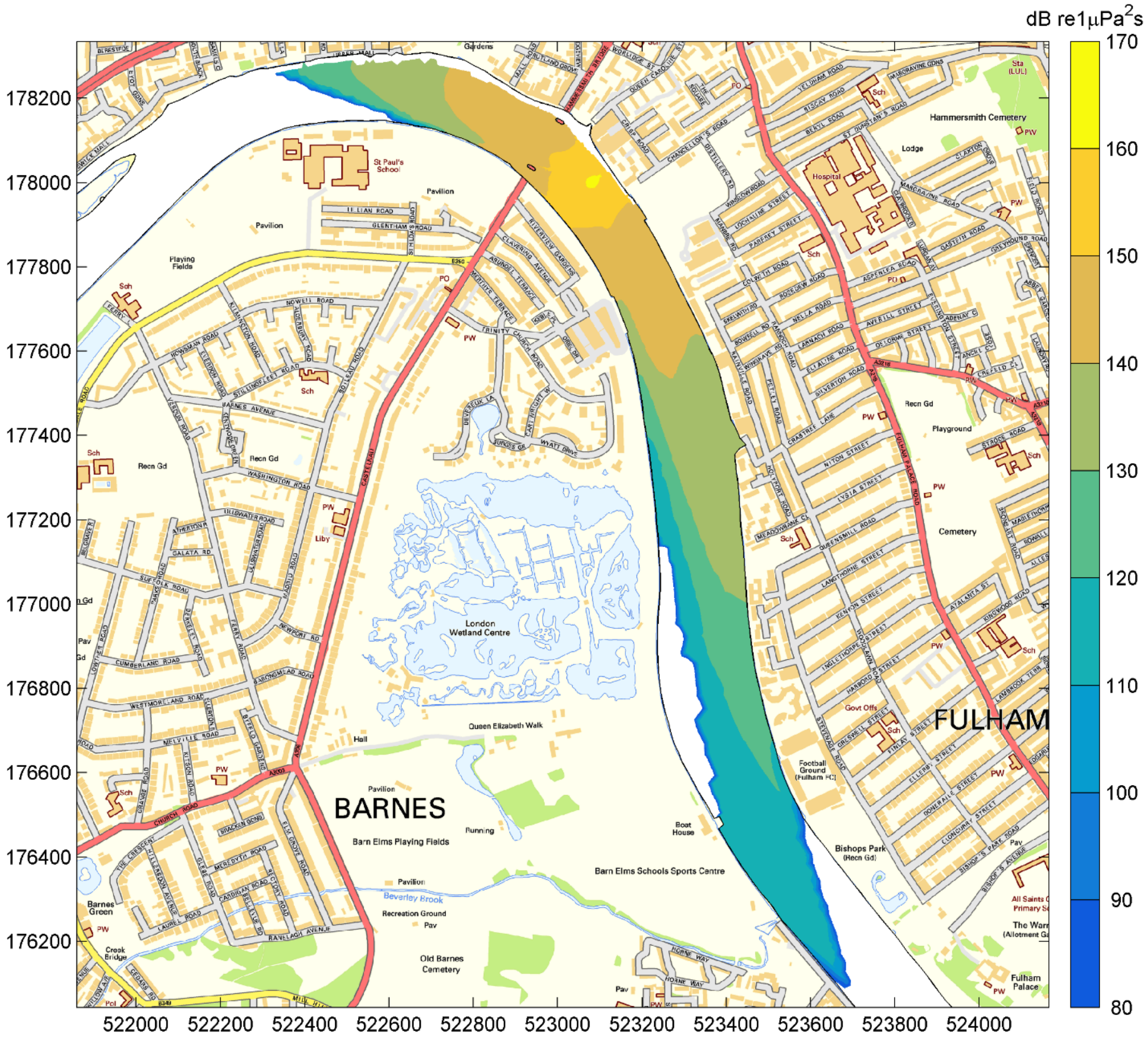


Figure 5.2: Cumulative sound exposure level for high frequency cetaceans (e.g. harbour porpoise) during vibro-piling



\\hrw-uk.local\projects\live\der6480S\3_technical\model\Animals\3_Analysis\Set1\Vibropiling_Mpwp_SELcum_2.mws

Figure 5.3: Cumulative sound exposure level for phocid pinnipeds (e.g. grey seal, harbour seal) during vibro-piling

5.2.2. Potential impacts on fish

The threshold levels for PTS and TTS in fish caused by continuous/non-impulsive sounds are given in Table 2.7. In this case the fish are assumed to be stationary because the available thresholds are RMS sound pressure levels rather than cumulative sound exposure levels. There is a lack of data for defining these thresholds, but thresholds of 158 dB re 1μPa RMS for TTS and 170 dB re 1μPa RMS for recoverable damage have been reported for fish with swim bladders used in hearing for periods of 12 hours and 48 hours respectively (Popper et al, 2014).

The 170 dB re 1μPa threshold is not exceeded for the modelled vibro-piling (Figure 5.1) and the 158 dB re 1μPa TTS threshold is exceeded only within 10 m of the pile. It should be emphasised that the threshold value of 158 dB re 1μPa assumes that the fish are subjected to the sound for 12 hours continuously whereas the estimated piling installation time is 40 minutes per pile. Therefore it is highly unlikely that the piling activity will cause hearing damage to any fish.

For fish eggs and larvae, the risk of TTS or damage is expected to be low (see Table 2.7) (Popper et al, 2014).

6. Conclusions

Based on the current assumptions about the source level and duration for the vibro-piling, it is predicted that the underwater sound levels generated during construction of the floating walkway are unlikely to exceed TTS thresholds for marine mammals or fish. There may still be a localised behavioural impact on mammals and some fish species which may be excluded from the area while the vibro-piling activity is ongoing. Behavioural impacts on fish species may be particularly important during periods when species are known to spawn in the area (Table 2.9).

There are a number of reasons why predicted impacts are somewhat mitigated. The position of the proposed temporary ferry is on a bend in the tidal River Thames, meaning that the extent of the underwater sound propagation is limited by the estuary geometry. The methodology for installing the piles has also been chosen specifically to minimise disturbance to both ecology and the surrounding human inhabitants.

7. References

Amoser S, Ladich F (2003). Diversity in noise-induced temporary hearing loss in otophysine fishes. Journal of the Acoustics Society of America, 113:2170–2179.

Ainslie, M.A., de Jong, C.A., Robinson, S.P. and Lepper, P.A., (2012). What is the source level of pile-driving noise in water? Advances in experimental medicine and biology, 730, pp:445-448.

Babushina, Y.S., Zaslavskii, G.L. and Yurkevich, L.I., (1991). Air and underwater hearing characteristics of the northern fur seal: Audiograms, frequency and differential thresholds. Biophysics, 36, pp:909-913.

Bailey, H., Senior, B., Simmons, D. , Rusin, J., Picken, G., Thompson, P.M. (2010). Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals, Marine Pollution Bulletin 60 (2010) 888–897. doi:10.1016/j.marpolbul.2010.01.003.

Blackwell, S.B., 2005. Underwater Measurements of Pile Driving Sounds during the Port MacKenzie Dock Modifications 13-16 August 2004. Greenridge Report 328-1. Prepared by Greenridge Sciences, Inc. for Knik Arm Bridge and Toll Authority, AK DOT&PF, and FHA. Goleta, California.

BC Ministry of Transportation and Infrastructure. (2016). George Massey Tunnel Replacement Project: Technical Volume - Underwater Noise Modelling Study.

Boyd IL, Frisk G, Urban E, Tyack P, Ausubel J, Seeyave S, Cato D, Southal B, Weise M, Andrew R, Akamatsu T, Ling RD, Erbe C, Farmer D, Gentry R, Gross T, Hawkins A, Li F, Metcalf K, Miller JH, Moretti D, Rodrigo C, Shinke T (2011) An international quiet ocean experiment. Oceanography 24:174-181.

Castro-Santos, T., & Haro, A. (2013). Survival and Behavioral Effects of Exposure to a Hydrokinetic Turbine on Juvenile Atlantic Salmon and Adult American Shad. *Estuaries and Coasts*, *38*(1), 203–214. https://doi.org/10.1007/s12237-013-9680-6.

Collins, M. D., (1993). A split-step Pade solution for the parabolic equation method, J. Acoust. Soc. Am. 93 (1736–1742. doi:10.1121/1.406739.

Dahl, P.H., Dall'Osto, D.R., Farrell, D.M. (2015). The underwater sound field from vibratory pile driving. The Journal of the Acoustical Society of America, 137, 3544-3554, https://doi.org/10.1121/1.4921288.

Fay, R.R., (2011). Hearing and lateral line | Psychoacoustics: What fish hear. In: Encyclopedia of Fish Physiology, Vol 1, pp 276-282.

Fay, R.R. and Popper, A.N., (2012). Fish hearing: New perspectives from two 'senior' bioacousticians. Brain, Behavior and Evolution, 79, pp:215-217.

HR Wallingford (2012). Eco-hydro-acoustic modelling: Proof of concept. HR Wallingford report DHY0446-RT001-R01-00.

HR Wallingford (2013). Eco-Hydro acoustic modelling: HAMMER noise module development phase 2. HR Wallingford report DHY0446-RT004-R01-00.

HR Wallingford (2013b). Eco-Hydro-Acoustic Modelling: Acoustic Model Test Case, SeaGen Tidal Turbine, Strangford Lough. HR Wallingford report DHY0446-RT05-R02-00.

HR Wallingford (2016). Rampion Windfarm: Kingmere MCZ additional seasonal restrictions review. HR Wallingford report DDM7600-RT006-R03-00.

Jasco, 2016. Hydroacoustic pile driving noise study – comprehensive report. http://www.dot.alaska.gov/stwddes/research/assets/pdf/4000-135.pdf.

Jensen F, Kuperman W, MB P, Schmidt H (2000) Computational Ocean Acoustics. Springer-Verlag, New York.

Kastak, D. and Schusterman, R.J., (1999). In-air and underwater hearing sensitivity of a northern elephant seal (Mirounga angustirostris). Canadian Journal of Zoology, 77, pp:1751-1758.

Kastelein, R.A., Wensveen, P.J., Hoek, L., Verboom, W.C. and Terhune, J.M., (2009). Underwater detection of tonal signals between 0.125 and 100 kHz by harbor seals (Phoca vitulina). Journal of the Acoustical Society of America, 125, pp:1222-1229.

Lepper, P., Robinson, S., Ablitt, J., Dible, S., 2007. Temporal and Spectral Characteristics of a Marine Piling Operation in Shallow Water, in: Proceedings of the NAG/DAGA 2009 International Conference on Acoustics Including the 35th German Annual Conference. pp. 266 – 268.

Nedwell, J.R., Parvin, S.J., Edwards, B., Workman, R., Brooker, A G., Kynoch, J.E. (2005). Measurement and interpretation of underwater noise during construction and operation of offshore windfarms in UK waters, 2007. http://www.vattenfall.com/en/file/Kentish_Flats_Underwater_nois_8459864.pdf.

Nedwell, J.R., Turnpenny, A.W.H., Lovell, J., Parvin, S.J., Workman, R., et al. (2007). A validation of the dBht as a measure of the behavioural and auditory effects of underwater noise, SubAcoustech Report No. 534R1231.

Nedwell, J. R. & Brooker, A. G. (2008). Measurement and assessment of background underwater noise and its comparison with noise from pin pile drilling operations during installation of the SeaGen tidal turbine device, Strangford Lough.

NOAA (2013). Draft Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammals: Acoustic Threshold Levels for Onset of Permanent and Temporary Threshold Shifts, National Oceanic and Atmospheric Administration.

NOAA (2016). Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts, National Oceanic and Atmospheric Administration, Technical Memorandum NMFS-OPR-55, July 2016, http://www.nmfs.noaa.gov/pr/publications/techmemos.htm.

Popper, A.N., Fewtrell, J., Smith, M.E. and McCauley, R.D., (2003). Anthropogenic sound: Effects on the behavior and physiology of fishes. Marine Technology Society Journal, 37, pp:35-40.

Popper AN, Smith ME, Cott PA, Hanna BW, MacGillivray AO, Austin ME, Mann DA.(2005) Effects of exposure to seismic airgun use on hearing of three fish species. J Acoust Soc Am. 2005 Jun;117(6): 3958-71.

Popper, A.N. and Fay, R.R., (2011). Rethinking sound detection by fishes. Hearing Research, 273, pp:25-36.

Popper AN, Hawkins AD, Fay RR, Mann DA, Bartol S, Carlson TJ, Coombs S, Ellison WT, Gentry RL, Halvorsen MB, Løkkeborg S, Rogers PH, Southall BL, Zeddies DG, Tavolga WN (2014) ASA S3/SC1.4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. Springer and ASA Press.

Reichmuth, C., Holt, M.M., Mulsow, J., Sills, J.M. and Southall, B.L., (2013). Comparative assessment of amphibious hearing in pinnipeds. Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology, 199, pp:491-507.

Richardson, M.D. and Briggs, K.B. (2004). Empirical predictions of seafloor properties based on remotely measured sediment impedance, proceedings of the High Frequency Ocean Acoustics Conference, La Jolla, California, 1-5 March 2004.

Rossington, K., Benson, T., Lepper, P. & Jones, D. (2013). Eco-hydro-acoustic modelling and its use as an EIA tool. *Marine Pollution Bulletin*, 75, 235-243.

Rossington, K., and Benson, T., 2019. An Agent-Based Model to predict fish collisions with tidal stream turbines. Renewable Energy, in press. https://doi.org/10.1016/j.renene.2019.11.127.

RSK Environmental Ltd, 2012. Rampion Offshore Windfarm: ES Section 10 - Marine Mammals. Document 6.1.10. Prepared for E.ON Climate and Renewables UK Rampion Offshore Wind Limited.

Sivle, L.D., Kvadsheim, P.H., Ainslie, M.A., Solow, A., Handegard, N.O., Nordlund, N., Lam, F.P.A. (2012). Impact of naval sonar signals on Atlantic herring (Clupea harengus) during summer feeding, ICES Journal of Marine Science, 69 p1078–1085. doi:10.1093/icesjms/fss080.

Smith ME, Coffin AB, Miller DL, Popper AN (2006) Anatomical and functional recovery of the goldfish (*Carassius auratus*) ear following noise exposure. Journal of Experimental Biology, 209:4193–4202.

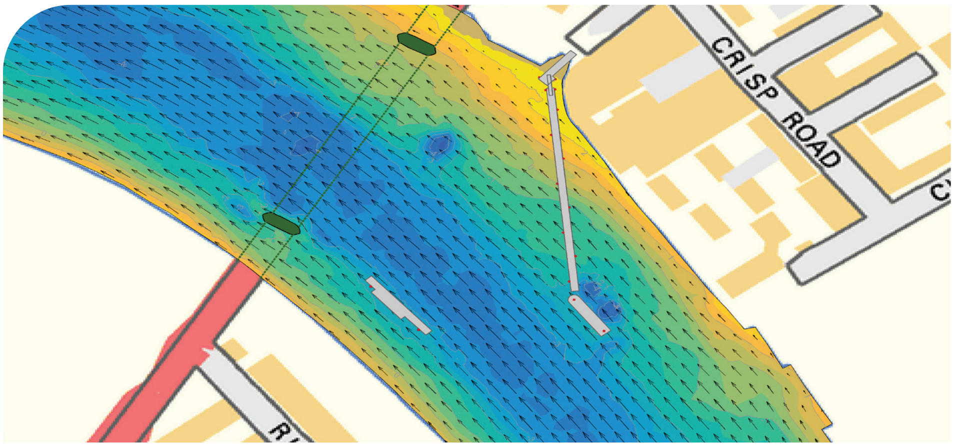
Southall BL, Bowles AE, Ellison WT, Finneran JJ, Gentry RL, Greene Jr CR, Kastak D, Ketten DR, Miller JH, Nachtigall PE, Richardson WJ, Thomas JA, Tyack PL (2007) Marine mammal noise exposure criteria: Initial scientific recommendations. Aquatic Mammals 33:pp 521.

Subacoustech, 2018. Wylfa Newydd Project: underwater noise baseline and modelling. Subacoustech Environmental Report no E522R0704.

Van der Graaf, A.J., Ainslie, M.A., André, M., Brensing, K., Dalen, J., et al. (2012). European Marine Strategy Framework Directive - Good Environmental Status (MSFD GES): Report of the Technical Subgroup on Underwater noise and other forms of energy, European Union.

Weilgart LS (2007) The impacts of anthropogenic ocean noise on cetaceans and implications for management. Canadian Journal of Zoology-Revue Canadienne De Zoologie 85:1091-1116.

HR Wallingford
Working with water



PAS 99
Integrated
Management
Systems
CERTIFIED

IMR 719286

ISO 9001
Quality
Management
Systems
CERTIFIED

FS 516431

ISO 45001
Occupational
Health and Safety
Management
CERTIFIED

OHS 595357

ISO 14001
Environmental
Management
CERTIFIED

EMS 558310

HR Wallingford is an independent engineering and environmental hydraulics organisation. We deliver practical solutions to the complex water-related challenges faced by our international clients. A dynamic research programme underpins all that we do and keeps us at the leading edge. Our unique mix of know-how, assets and facilities includes state of the art physical modelling laboratories, a full range of numerical modelling tools and, above all, enthusiastic people with world-renowned skills and expertise.

HR Wallingford, Howbery Park, Wallingford, Oxfordshire OX10 8BA, United Kingdom
tel +44 (0)1491 835381 fax +44 (0)1491 832233 email info@hrwallingford.com
www.hrwallingford.com