

Technical Appendix 7.1

Underwater Noise Modelling

Falmouth Docks Development

Underwater noise modelling

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Executive summary

The proposed development aims to restore and upgrade the existing facilities at Falmouth Docks, in order to reinstate and provide new alongside berth capacity, to facilitate the floating offshore wind (FLOW) renewable energy industry and accommodate cruise ships up to Excellence Class at the Docks.

The works will include construction of new suspended deck structures (Western Wharf, Northern Wharf and FLOW Deck) with a rock revetment under the suspended decks, an area of reclamation behind the Western Wharf, an extension of Queen's Wharf and demolition of the eastern and western parts of the existing Northern Arm. Dredging of the berths will also be carried out to accommodate cruise ships up to Excellence Class and FLOW devices.

The demolition and construction activities will generate underwater noise which may affect marine mammals and fish species. HR Wallingford was commissioned to carry out numerical modelling of the underwater noise generated by the activities and the potential effects on marine fauna in terms of thresholds for injury or behavioural response. An assessment of the potential increases to background vessel noise after completion of the dock development was also carried out in terms of effects on marine mammals.

Baseline background noise within the estuary was estimated using vessel position (AIS) data combined with empirical modelling. The modelled annual mean sound pressure level within the main shipping route is above the behavioural threshold for marine mammals. Disturbance to marine mammals is likely to occur frequently throughout the year in most parts of the deep estuary (>10m) when larger vessels move between the mouth of the Fal Estuary and the docks. Baseline timescales of disturbance by large vessels types (passenger, cargo, military and tanker) combined, is predicted to be approximately 120 – 140 hours/year. Following completion of the proposed development, an increase in disturbance of approximately 15 hours/year is predicted due to additional passenger and cargo vessels. Although less than a 10% increase, it is noted that the source level for the larger Excellence-class cruise ships is likely to be higher than other vessels, with distances of mammal disturbance of up to approximately 6 km (at 6 knots). Behavioural disturbance is therefore likely to be more pronounced for cruise ships, due to the additional Excellence Class vessels, but still below injury (TTS or PTS) thresholds.

Results for demolition and construction noise are presented in terms of distance to impact threshold for marine mammal hearing groups and fish. Demolition activity using a hydraulic hammer was predicted to cause temporary threshold shift (TTS) thresholds to be exceeded for most mammal groups, over distances of up to 3800 m, based on one hour of hammering with no pauses (considered to be worst case).

Dredging by backhoe dredger, due to its lower source levels and continuous sound, was predicted to result in TTS for both low frequency cetaceans and very high frequency cetaceans within a distance of approximately 500 m. Backhoe dredging has similar source levels to medium sized vessels and hence similar disturbance distances of the approximately 1 km.

In all cases, percussive piling was modelled with a 20 minute soft-start procedure. Percussive piling for the new suspended deck was predicted to cause TTS and permanent threshold shift (PTS) thresholds to be exceeded for all marine mammal hearing groups, sometimes over wide areas, reaching the eastern shoreline of the estuary (apart from during construction of the FLOW deck for which the sound is somewhat contained by the existing dock structures). Very high frequency cetaceans are particularly sensitive to pile driving noise with distances to TTS and PTS threshold of approximately 4 km and 2 km respectively. Disturbance during unmitigated pile driving and hammering (impulsive noise sources) is likely to extend over a considerably wider area, limited only by the shoreline, shallow areas and existing dock structures. Including a bubble curtain mitigation measure, the distances to threshold during percussive piling are reduced for all animals. For very high frequency cetaceans, the distances to TTS and PTS are reduced to approximately 3 km and 1 km. The bubble curtains also reduce the areas of modelled high level

disturbance (<160 dB), however large areas of low level disturbance (<140 dB) would remain (but limited to periods of pile driving).

In some cases, the agents within the model became trapped between the noise source and land or marine structures. This constrained the fleeing behaviour and resulted in higher a SEL_{cum} dose than would be accumulated if the agent was able to flee from the noise freely. In some of the modelled cases, SEL_{cum} thresholds were only exceeded for the animals in trapped locations. Whilst it is likely that real animals would exhibit more sophisticated fleeing behaviours than the model agents, it is still possible that real animals could become trapped with no direct escape route. Due to the identified potential for trapping of individuals, it is recommended that marine mammal observers (MMO) are used in combination with passive acoustic monitoring (PAM) to determine if marine mammals are present before piling commences.

Stationary fish were potentially impacted by the noise from the hydraulic hammer over an area of approximately 1.7 km², with the TTS threshold exceeded eastwards of the piling location and reaching the main channel through Carrick Roads. It was predicted that fleeing fish would only be impacted by the hydraulic hammer noise if they were between the noise source and the coastline/eastern breakwater when the noise began.

Fish were not predicted to be impacted by the dredging noise (considered a non-impulsive noise) at either the TTS or injury threshold level.

Stationary fish (i.e. worst case modelling assumption) were predicted to accumulate high SEL_{cum} doses, with injury and mortality thresholds exceeded over distances of up to 1700 m from the noise source. The SEL_{cum} TTS threshold was exceeded up to 4100 m from the noise source. For pile driving with a bubble curtain, impacted areas were predicted to be substantially smaller. Maximum distances to injury thresholds for stationary fish were reduced to 160 m (mortal injury), 290 m (injury) and up to 1700 m (TTS).

For pile driving with a soft start only, the distance to the SEL_{cum} TTS threshold for fleeing fish was up to 1500 m (worst case) depending on the location of the noise source. Injury thresholds were exceeded close to the piles in areas where fish could not escape easily because they were between the noise source and the coastline and, hence, would have had to swim through an area with higher sound levels to escape. With a bubble curtain, it was predicted that the injury and mortality SEL_{cum} thresholds would not be exceeded for fleeing fish and the TTS threshold would only be exceeded for fish between the noise source and the shoreline, where fleeing routes were obstructed.

Glossary

Term	Explanation
Ambient sound	The sound present in the marine environment due to wind, waves, surf, animal sound and other sources not related to the project.
Attenuation	The weakening or reducing of the amplitude of a sound caused by absorption in the water and sediment, spreading of the sound.
Bandwidth	The difference between upper and lower band edge frequencies ($\Delta f = f_{up} - f_{low}$).
Centre frequency	The geometric mean of the frequency band ($f_c = \sqrt{f_{low} * f_{up}}$).
dB re 1 µPa	The decibel scale used in underwater acoustics is referenced to 1 µPa (in air it is referenced to 20 µPa, the threshold of human hearing).
Octave bands	A series of adjacent bands that are one octave wide. Each band can be characterised by a central frequency, and upper and lower band edge frequencies and from one band to the next the frequency doubles ($f_{up} = 2f_{low}$).
Particle motion	Underwater sound is characterized by two different components, scalar pressure waves and directional particle motion. Mammals hear the pressure wave component using their ears. Fish on the other hand can also detect particle motion. At long distances from a source (greater

Term	Explanation
	than several wavelengths), the two components are directly related, whereas differences have been observed in the nearfield and near bed sediment interfaces.
Peak-to-peak	The amplitude of the sound pressure wave measured from the minimum to maximum values (i.e. negative peak to positive peak). This pressure value is double the zero-to-peak pressure or 6 dB greater than SPL_{peak} .
Peak SPL (SPL_{peak})	The peak sound pressure level based on the zero to peak-pressure.
Permanent threshold shift (PTS)	A permanent increase in the threshold at which a species can detect sound, often described as 'deafness'.
Power Spectral Density (PSD)	PSD the spectral density of the wave, when multiplied by an appropriate factor, will give the power carried by the wave, per unit frequency, known as the power spectral density (PSD) of the signal. Power spectral density is commonly expressed in watts per hertz (W/Hz).
Range-dependent Acoustic Model (RAM)	A model used to predict sound levels with distance from source taking into account bathymetry changes with range.
Received Level (RL)	The sound pressure level (SPL) received by a species for a given frequency and source level. Given as RMS dB re $1\mu Pa$.
Reflection	Sound waves may be reflected from a number of surfaces. Reflections from the seabed/sea surface are included in the model. Reflections from vertical structures may also occur, but are less important in terms of impact radius and are not included in the model.
Refraction	The process by which sounds waves curve as they pass through mediums of differing densities. This is most obvious where they pass from water to sediment/air, but also occurs due to continuous density changes within the water column (e.g. with depth, temperature and salinity).
Root Mean Square (RMS)	RMS of a time-varying quantity is obtained by squaring the amplitude at each instant, obtaining the average of the squared values over the interval of interest, and then taking the square root of this average. For a sine wave, multiplying the RMS value by the square root of 2 (1.414) gives the peak value of the wave. The RMS value, also called the effective value of the sound pressure, is the best measure of ordinary continuous sound.
Sound Exposure Level (SEL)	A measure of sound energy over a discrete time interval (usually a single pulse) by integrating the pressure over that interval. For pulses it should account for 90% of the energy within the pulse. If summed over numerous pulses (e.g. during pile driving), the metric is usually referred to as cumulative SEL (SEL_{cum}).
Sound Pressure Level (SPL)	The pressure of sound for a given frequency. For the purposes of this report, SPL is presented as an RMS value unless stated otherwise.
Source level (SL)	Source levels for underwater sound are usually quoted as the source level 1 m from the sound source, however this is not usually possible for pile driving due to the size of the source. Measuring the received level at a distance from the source and estimating the transmission loss over that distance can be used to calculate source level at 1 m, but only if measurements are available.
Temporary threshold shift (TTS)	A temporary increase in the threshold at which sound can be detected by a species i.e. a decrease in their sensitivity to sound. The period this lasts depends on the exposure of the individual to the sound.
Third-octave bands	Series of adjacent frequency bands that are one third of an octave wide.
Transmission Loss (TL)	The loss of sound pressure due to geometric spreading and attenuation with distance from a sound source.
Zero-to-peak pressure	The peak pressure measured from zero to peak amplitude.

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1 Introduction

1.1 Background

The Falmouth Docks is located in Carrick Roads in the Inner Harbour at Falmouth, Cornwall (see Figure 1.1).



Figure 1.1: Project location

The proposed development aims to restore and upgrade the existing facilities at Falmouth Docks, in order to reinstate and provide new alongside berth capacity, to facilitate the floating offshore wind (FLOW) renewable energy industry and accommodate cruise ships up to Excellence Class at the Docks (see Figure 1.2).

The works will include construction of new suspended deck structures (Western Wharf, Northern Wharf and FLOW Deck) with a rock revetment under the suspended decks, an area of reclamation behind the Western Wharf, an extension of Queen's Wharf and demolition of the eastern and western parts of the existing Northern Arm. Dredging of the berths will also be carried out to accommodate cruise ships up to Excellence Class and FLOW devices, as detailed in the Dredging Plan shown in Figure 1.3.

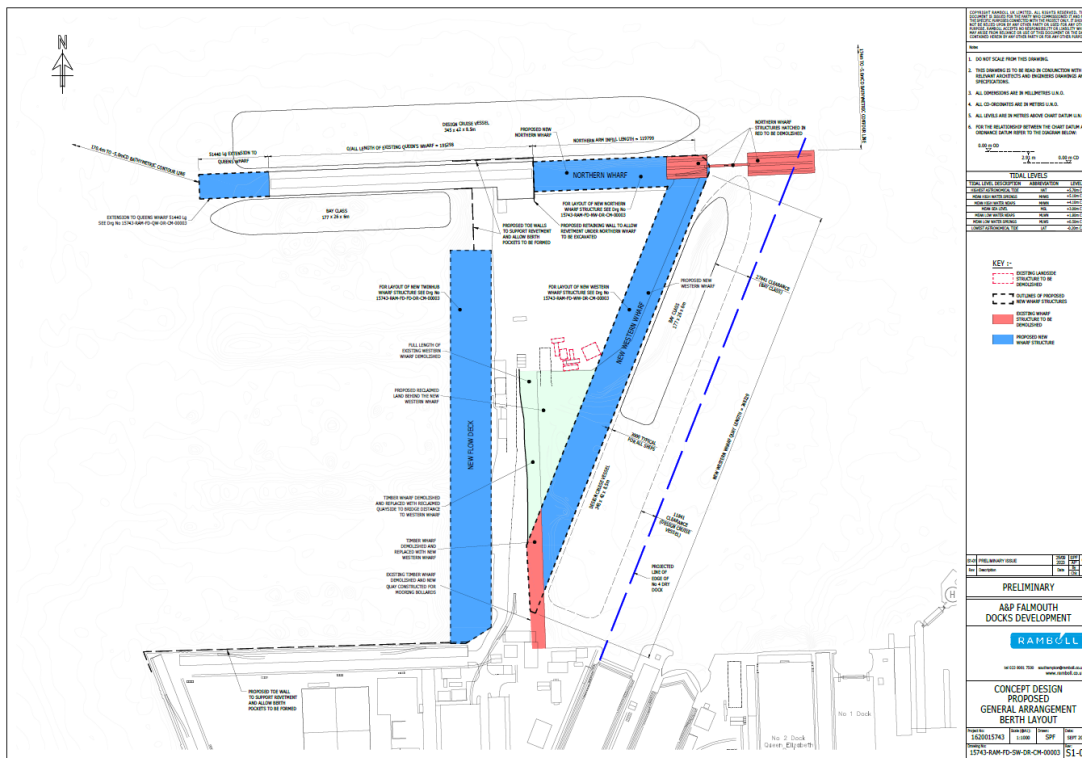


Figure 1.2: Proposed development works of Falmouth Docks

Source: Ramboll



Figure 1.3: Proposed Dredging Plan

Source: Ramboll

1.2 Objectives

This study is part of modelling studies (including hydrodynamics, sediment dynamics, under water noise) undertaken by HR Wallingford to support the Environmental Impact Assessment (EIA) for the proposed development.

This report presents the underwater noise modelling study carried out to model the effect of the demolition and construction activities on underwater noise and the distances over which secondary receptors (i.e. marine mammals and fish) may be impacted.

After the development of the docks there will be an increase in the number of passenger and cargo vessels using the estuary. An assessment of the potential increases to background vessel noise, and its effect on animals, following completion of the works will also be presented.

1.3 Report structure

The remainder of this report is arranged as follows:

- Section 2 presents a background to underwater noise and impact thresholds for marine animals.
- Section 3 describes the models used to predict underwater sound levels due to vessels and due to the demolition and construction activities, and for predicting the impacts on marine animals.
- Section 4 describes specifics of the data processing and modelling of baseline noise levels due to vessels in the Fal Estuary.
- Section 5 describes specifics of the model setup for determining the potential impacts due to the proposed demolition and construction works on marine fauna.
- Section 6 presents the results for the predicted baseline and future baseline vessel noise levels.
- Section 7 presents the results for the demolition and construction noise modelling.
- Section 7.5 summarises and interprets the results.
- Conclusions and recommendations are then provided in Section 9.

2 Background to underwater sound

2.1 Overview

Underwater sound propagates through water as a pressure wave and, due to the low impedance and absorption characteristics of water, travels further and faster than sound in air. The amount of sound generated by anthropogenic sources in the marine environment has been increasing due to 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, several countries 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 underwater sound 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 approximately 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 and hard rocky surfaces tending to reflect sound. 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.

Sound loses energy as it propagates away from a source and eventually drops to the same intensity as the ambient level, 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 (e.g. wind, waves, rain, animals) and common man-made sounds (e.g. shipping). In this report, the term 'baseline' is used to describe the ambient sound that is not associated with the construction activity being assessed. Following completion of the new dock facilities, the changes in number of vessels using the docks will lead to alterations in the ambient sound levels, and this is referred to as the 'future baseline'.

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 1 µPa'). 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 unit of frequency, measured as the number of pressure variations or cycles per second, is the hertz (Hz). The power spectral density (a measure of the power carried by the wave, per unit frequency) for different anthropogenic sources of sound can vary greatly. For example, seismic airguns generally have most energy in the lower frequency range (i.e. from the low tens of Hz up to a few hundred Hz), whereas the range of high frequency sonar is generally much higher (i.e. 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:

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

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 EIA 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, which allows received level to be calculated.

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 pile driving or seismic airguns. 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:

$$E_{90} = \int_{t_5}^{t_{95}} P^2(t) dt \quad (2)$$

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

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

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

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:

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

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:

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

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

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

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:

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

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

2.1.6 Particle motion

In addition to sound pressure, sound in water also has a particle motion component (e.g. Nedelec, et al., 2016). Hearing in marine mammals is based on the detection of sound pressure; however, fish and invertebrates may also be sensitive to particle motion (Nedelec, et al., 2016; Popper & Hawkins, 2019), particularly close to the sound source. Calculating particle motion from sound pressure can be achieved only when certain conditions are met and is not possible in complex, shallow water marine environments. Impact thresholds, such as temporary and permanent threshold shifts, are not available for particle motion.

2.2 Sound impact criteria for marine fauna

Marine fauna (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 are of concern, and national and international legislation asks for robust assessments of the potential impacts to be carried out for any new project or development. This requires an understanding of the sound detection capabilities of the receptor species, 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 adversely impact on fish, marine reptiles (sea turtles) and mammals. The potential impacts on these animals include causing discomfort by changing the acoustic environment, causing the animals to retreat from an area (i.e. behavioural response), and causing physical injury or potentially mortality. 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 (TTS) (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 (e.g. 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 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.

Behavioural disturbance and masking

At sound levels lower than those that can cause injury, impacts may also occur due to behavioural disturbance or masking of vocalisations. The area within which behavioural response occurs can be large and, hence, has potential to affect a large number of individuals. The effect of disturbance on animals over long periods of time may potentially affect the overall health of individuals and hence have a longer term effect on populations, but these impacts are generally difficult to quantify. The following subsections provide more details on the thresholds used in this study.

The thresholds presented below are based on research for a range of species; inclusion in the discussion of thresholds does not imply that a species will be present in the Fal Estuary. Baseline data on species present is given in the Marine Ecology Chapter of the ES (REF).

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 (e.g. 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 the largest range of frequencies.

The response of marine mammal species to underwater sound, and the potential physical impact of anthropogenic sound, have 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 the National Oceanic and Atmospheric Administration (NOAA) developed criteria for the impacts of underwater sound on marine mammals which allow an assessment of behavioural response to be made based on the best scientific knowledge at that 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 SPL_{peak} 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, 2016). It was also acknowledged that the Southall et al. (2007) 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). More recently, Southall, et al. (2019) carried out a review of the weightings and thresholds. They suggested an update to the naming conventions used for the mammal groups to better reflect hearing ranges. The threshold values were unchanged from NOAA 2016. These latest guidelines are used to carry out the marine mammals assessment required for this project. The Southall et al. (2019) naming convention is adopted.

The estimated functional hearing bandwidth for each of the marine mammal hearing groups under the Southall et al. (2019) guidelines are shown in Table 2.1.

Table 2.1: Marine mammal hearing groups and generalised hearing ranges

Hearing group	Mammals represented	Generalised hearing range (Hz)	
		Lower limit	Upper limit
Low-frequency (LF) cetaceans	Baleen whales	7	35,000
High-frequency (HF) cetaceans	Dolphins, toothed whales, beaked whales, bottlenose whales	150	160,000
Very high-frequency (VHF) cetaceans	True porpoises, Kogia, river dolphins, <i>cephalorhynchid</i> , <i>Lagenorhynchus cruciger</i> and <i>L. australis</i>	275	160,000
Phocid pinnipeds (PW)	True seals	50	86,000

Source: NOAA (2016) and (Southall, et al., 2019) Generalised 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 form of the updated auditory weighting functions for the hearing groups is written follows:

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

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 Southall et al. (2019) 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
High-Frequency (HF) Cetaceans	1.6	2	8,800	110,000	1.20
Very high-Frequency (VHF) Cetaceans	1.8	2	12,000	140,000	1.36
Phocid Pinnipeds in water (PW)	1.0	2	1,900	30,000	0.75

Source: Adapted from NOAA (2016) and Southall et al. (2019)

Similar to Southall et al. (2007), the NOAA guidelines also determine impact criteria based on SPL_{peak} 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 SPL_{peak} criteria for TTS and PTS for each mammal functional hearing group are given in Table 2.3 for impulsive sounds. In an assessment, both the SEL_{cum} and SPL_{peak} 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 for marine mammal injury from impulsive sounds

Hearing Group	TTS threshold		PTS threshold	
	SPL_{peak} (dB re 1 μPa)	SEL_{cum} (dB re 1 μPa^2s)	SPL_{peak} (dB re 1 μPa)	SEL_{cum} (dB re 1 μPa^2s)
Low-Frequency (LF) Cetaceans	213	168	219	183
High-Frequency (HF) Cetaceans	224	170	230	185
Very high-Frequency (VHF) Cetaceans	196	140	202	155
Phocid pinnipeds in water (PW)	212	170	218	185

Source: Adapted from NOAA (2016) and Southall et al. (2019). Peak pressure is RMS dB re 1 μPa unweighted values; SEL_{cum} units are dB re 1 μPa^2s , weighted for hearing range of the various categories and the SEL_{cum} accumulation period is 24 hours

Table 2.4: Weighted impact criteria for marine mammal injury from continuous sounds

Hearing Group	TTS threshold	PTS threshold
	SEL_{cum} (dB re 1 μPa^2s)	SEL_{cum} (dB re 1 μPa^2s)
Low-Frequency (LF) Cetaceans	179	199
High-Frequency (HF) Cetaceans	178	198
Very high-Frequency (VHF) Cetaceans	153	173
Phocid pinnipeds in water (PW)	181	201

Source: Adapted from NOAA (2016) and Southall et al. (2019) SEL_{cum} units are dB re 1 μPa^2s , weighted for hearing range of the various categories and the SEL_{cum} accumulation period is 24 hours

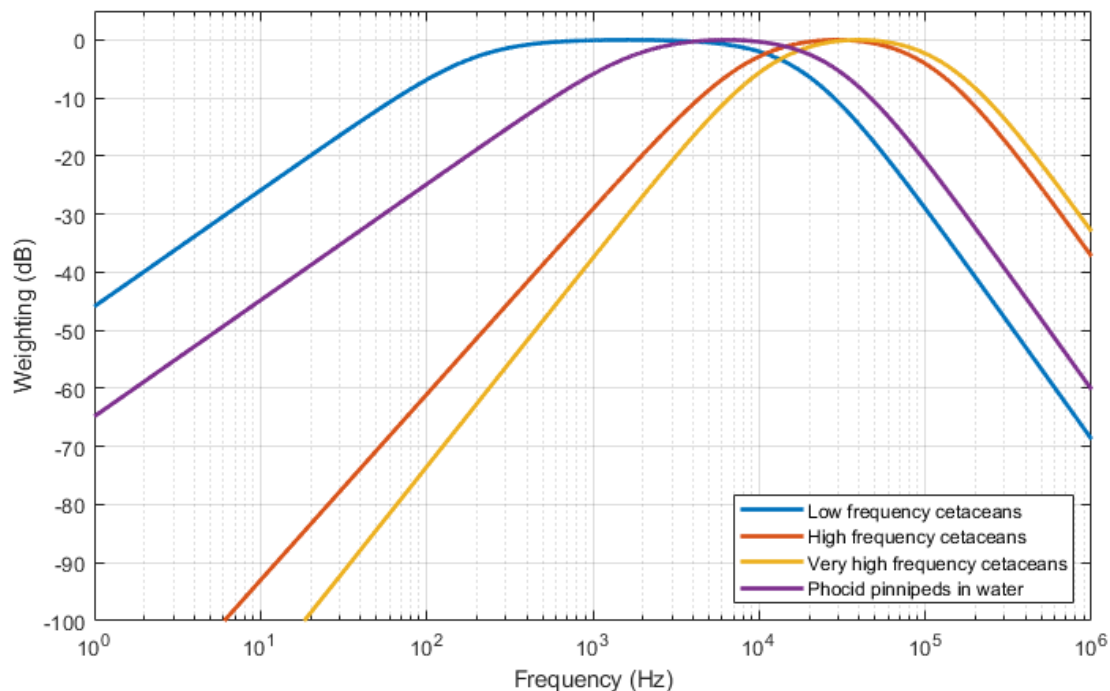


Figure 2.1: M-weightings for mammals using the assessment criteria of Southall et al. (2019)

Source: Adapted from Southall et al. (2019)

Behavioural Response Thresholds in Marine Mammals

Possible behavioural changes in marine mammals may include startle response, extended cessation or modification of vocal behaviour, brief cessation of reproductive behaviour or brief separation of females and dependent offspring. To assess the possibility of a disturbance resulting from the construction and demolition noise, it is necessary to consider the likelihood that the sound could cause significant disturbance.

Differences between location, noise source, species and even individuals within a species mean it is not yet possible to accurately quantify the sound level at which mammals will respond. Southall et al. (2007) states that “*behavioural reactions to acoustic exposure are generally more variable, context-dependent, and less predictable than effects of noise exposure on hearing or physiology*”. Furthermore, they suggest that the only feasible way to assess whether a particular sound might cause disturbance is to compare the circumstances of the situation with empirical studies using a ranking system to assess the severity of the behavioural response (from 0 to 9). The more severe the response (higher score), the lower the amount of time that the animals will tolerate the noise before they could be negatively impacted.

The JNCC guidance (JNCC, 2010) defines disturbance as when there is a risk of animals incurring sustained or chronic disruption of behaviour or when animals are displaced from an area, with subsequent redistribution being significantly different from that occurring due to natural variation. The JNCC guidance also indicates that a score of 5 or more on the Southall et al. (2007) behavioural response severity scale could be significant.

Southall et al. (2007) presents a summary of observed behavioural responses, with associated response score, due to multiple pulsed sound, although the data are primarily based on responses to seismic airgun noise and mainly for low-frequency cetaceans. Low frequency cetaceans, other than bow-head whales, were typically observed to respond significantly at a received level of 140 – 160 dB re 1 μ Pa (rms). It should be noted that the sound level spectrum generated by seismic airguns is generally concentrated below a frequency of about 1 kHz, and therefore low-frequency cetaceans are relatively sensitive to this type of noise source. Pile

driving noise tends to be spread across a much broader frequency range and so the energy at lower frequencies will be less for the same broadband SPL.

Southall et al. (2007) also states that there are few reliable studies available for pinnipeds, mid-frequency or high-frequency cetaceans. However, they refer to a study of mid-frequency cetaceans in which some significant response was observed at a sound pressure level of 120 – 130 dB re 1 μ Pa (rms), but the majority of the observed cetaceans did not display significant behavioural disturbance until exposed to an SPL of 170 – 180 dB re 1 μ Pa (rms). Even at these levels some mid-frequency cetaceans within the same study were observed to have no behavioural response.

For pinnipeds, a study using ringed, bearded and spotted seals (Harris et al., 2001) observed onset of a significant response at a received rms SPL of 160 – 170 dB re 1 μ Pa, although larger numbers of animals showed no response at noise levels of up to 180 dB re 1 μ Pa. Only at much higher sound pressure levels in the range of 190 – 200 dB re 1 μ Pa (rms) were significant numbers of seals found to exhibit a significant response. More recently, field studies investigating changes in seal densities during pile driving have suggested a single strike SEL threshold for behavioural avoidance of between 130 dB re 1 μ Pa²s and 155 dB re 1 μ Pa²s (Russell, 2016; Wyte, 2020). Assuming a pulse length of between 100 ms and 150 ms (typical for a wind farm monopile), this would equate to an rms range of approximately 138 dB re 1 μ Pa to 164 dB rms.

For high-frequency cetaceans there is a general lack of reliable behavioural response data (South et al., 2007). However, significant behavioural reactions have been observed for a single harbour porpoise to pulsed sound at received sound pressure levels above 174 dB re 1 μ Pa (peak-peak) or a SEL of 145 dB re 1 μ Pa²s, equivalent to an estimated rms sound pressure level of 166 dB re 1 μ Pa (Lucke et al., 2008).

The need to define threshold criteria for EIA purposes has meant that previous underwater noise studies have tended to take a precautionary approach to defining the thresholds for behavioural response. Two such studies (Kongsberg, 2010; Marine Scotland, 2015b) based the thresholds on the findings of the High Energy Seismic Survey workshop on the effects of seismic (i.e. pulsed) sound on marine mammals (HESS, 1997), which concluded that mild behavioural disturbance would most likely occur at rms sound levels greater than 140 dB re 1 μ Pa (rms), although acknowledged there was significant uncertainty. A second, higher threshold of 160 dB re 1 μ Pa (rms) is often used to define a higher level disturbance, based on the US National Marine Fisheries Service guidance (NMFS, 2005) for Level B harassment threshold for marine mammals.

Based on the above discussion, for the purposes of this study, a precautionary set of threshold levels for behavioural disturbance have been adopted for impulsive sounds. A threshold of 140 dB re 1 μ Pa (rms) is adopted to indicate the onset of low level marine mammal disturbance effects for all mammal groups for impulsive sound. In line with other assessments, a higher threshold of 160 dB re 1 μ Pa (rms) is used to define higher level disturbance for impulsive sound.

For continuous sounds, such as drilling, dredging or vessel noise, a lower threshold has been adopted based on a level at which baleen whales (low frequency cetaceans) have been observed to exhibit behavioural responses, which are particularly evident above received SPLs of 120 dB re 1 μ Pa (Southall et al., 2007).

2.2.3 Fish

Fish can detect sound through the use of otolith organs in their ears (Fay, 2011; Fay and Popper, 2012). 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 do not appear to use it to detect sound (Popper, 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 tens of Hz to a few thousands of 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 (Smith, Coffin, Miller, & Popper, 2006) (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). While 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 & Fay, Rethinking sound detection by fishes, 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

Standard guidance for assessing the impact of anthropogenic sound on fish from different sources is available (Popper, et al., 2014; Popper & Hawkins, 2019). 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 for the present study.

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

Category	Explanation
1. Fish without a swim bladder or other gas chamber	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
2. Fish with swim bladders, or other gas volume, which is not involved in the detection of sound	These species are susceptible to barotrauma although hearing only involves particle motion not sound pressure
3. Fish with a swim bladder or other gas volume which is involved in sound detection	These species are susceptible to barotrauma and detect sound pressure as well as particle motion
4. 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

impulsive noise sources are presented in Table 2.6. All 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

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

Notes: Adapted from Popper et al. (2014) and Popper and Hawkins (2019). Peak and RMS sound pressure level dB re 1 μ Pa; SEL dB re 1 μ Pa²s. SEL_{cum} = 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 1 μ Pa over a 48 hour period could cause recoverable injury in goldfish (*Carassius auratus*). Another study (Amoser & Ladich, 2003), in (Popper et al., 2014) suggested that 12 hours exposure to an RMS sound pressure level of 158 dB re 1 μ Pa could cause TTS in goldfish and catfish (*Pimelodus pictus*).

Table 2.7: Non-impulsive (continuous) noise impact criteria for fish

Category	Mortality or potential mortal injury	Recoverable injury	TTS	Masking	Behaviour
1. 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
2. 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
3. Fish: Swim bladder involved in hearing	(N) Low (I) Low (F) Low	170 dB RMS for 48 hours	158 dB RMS for 12 hours	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
4. 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

Notes: Adapted from Popper et al. (2014). RMS sound pressure levels dB re 1 μ Pa. 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 of sounds used by animals for behaviours such as communication and detection of predators or prey. 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 given in Table 2.8.

There is some debate over whether behavioural response is context specific; that is, for example, 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 (Kastelein, Wensveen, Hoek, Verboom, & Terhume, 2009) (Silve, 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

Notes: Adapted from Popper et al. (2014). Relative risk (high, moderate, and low) is given for animals at three distances from the source defined in relative terms as near (n), intermediate (I) or far (F).

Vibrations

Fish may also be sensitive to particle motion, as well as sound pressure (Popper et al., 2014), particularly close to a noise source. Species which are commonly found in contact with the sea bed (e.g. flat fish) may also be impacted by vibrations travelling through the substrate. These processes are not included in the underwater noise modelling presented below.

3 Model descriptions

3.1 Vessel background noise modelling

Ambient sound levels in the region will predominantly be caused by the presence of motorised vessels. The annual mean baseline noise levels were modelled using records of vessel movements in the region. To achieve this, the Ross method, obtained from the RANDI-3.1 model (Breeding et al., 1996), was used which estimates the source level (SL_s) for moving vessels at discrete frequencies (f_n) based on their hull length (l_s) and velocity (v_s), as in the following equation:

$$SL_s(f_n, v, l_s) = SL_{s0}(f_n) + c_v 10 \log_{10} \left(\frac{v_s}{v_0} \right) + c_l 10 \log_{10} \left(\frac{l_s}{l_0} \right) + df * dl + 3.0 \quad (9)$$

Where c_v and c_l are power law coefficients for speed and length with values of 6 and 2, respectively, and v_0 and l_0 are reference speed and lengths taken as 12 knots and 300 ft

respectively. Parameters df and dl are the frequency and length dependant corrections given by:

$$df = \begin{cases} 8.1, & 0.0 < f_n \leq 28.4 \\ 22.3 - 9.77 \log_{10}(f), & 28.4 < f_n \leq 191.6 \\ 0, & 191.6 < f_n \end{cases} \quad (10)$$

$$dl = l_s^{1.15} / 3643.0 \quad (11)$$

and for $f_n \leq 500$ Hz

$$SL_{s0}(f_n) = -10 \log_{10} (10^{-1.06 \log_{10} f_n - 14.34} + 10^{3.32 \log_{10} f_n - 21.425}) \quad (12)$$

and for $f_n > 500$ Hz

$$SL_{s0}(f_n) = 173.2 - 18.0 \log_{10} (f_n) \quad (13)$$

Examples of the sound spectra calculated using the above formulae for various sized vessels travelling at different speeds are shown in Figure 3.1. As can be seen, the sound levels from vessels are predominantly at low frequencies, below 100 Hz.

Using this method, time varying sound spectra were calculated for each segment of the AIS tracks, and then integrated with respect to frequency to provide a broadband source level. A spatial map of the annual averaged source level was then calculated by integrating the track source levels over the amount of time each vessel was within each grid cell and then dividing through by the number of seconds in a year. A spherical spreading model was then applied to the gridded source levels at each point to model the sound contribution from each cell added to all other cells in the grid. The spherical spreading model used in this approach had the following formulation:

$$RL(r) = SL_{ij} - 15.0 \log_{10} (r) \quad (14)$$

Where RL is the received level at radius r from the grid cell, and SL_{ij} is the source level calculated using Equation 9 at each grid cell. The resultant summed gridded values of total sound pressure level (SPL) then represented the annual mean SPL.

A final step in this study was to remove sound levels in shallow water below a depth of 10 m. The reasoning for this is that low frequency sound cannot be transmitted through shallow water (depth h), as defined by the cut-off frequency, f_0 , written as (Jensen et al., 2000):

$$f_0 = \frac{c_w}{4h\sqrt{1-(c_w/c_b)^2}} \quad (15)$$

Where c_w and c_b are the speed of sound in water and the bed sediment, respectively. A plot of the cut-off frequency with respect to water depth is shown in Figure 3.2 which shows that in water depths of less than 10 m, sound below around 100 Hz cannot propagate. Since vessel noise is predominantly at frequencies below about 100 Hz (Figure 3.1), the resultant sound field maps were masked in areas below this depth of water (taking the water level at high water mean spring tide as worst case).

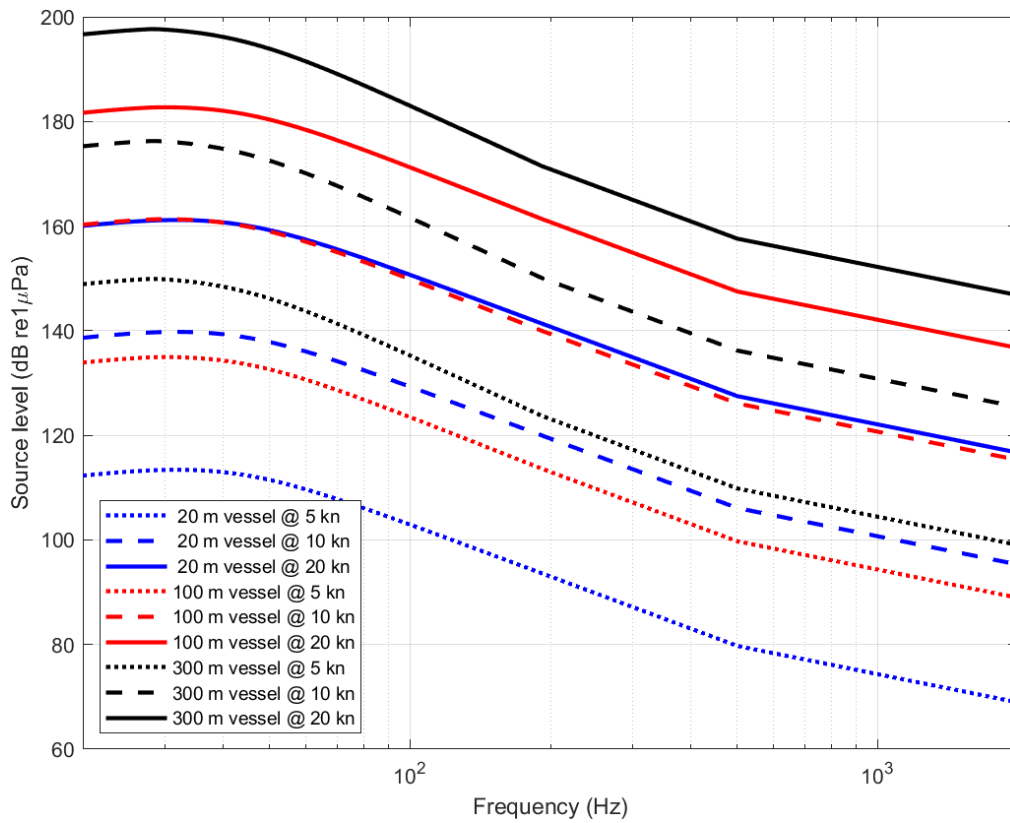


Figure 3.1: Synthetic source level sound spectra for three vessel lengths (20, 100 and 300 m), each travelling at three speeds (5, 10 and 20 knots)

Source: RANDI-3.1 model formulae

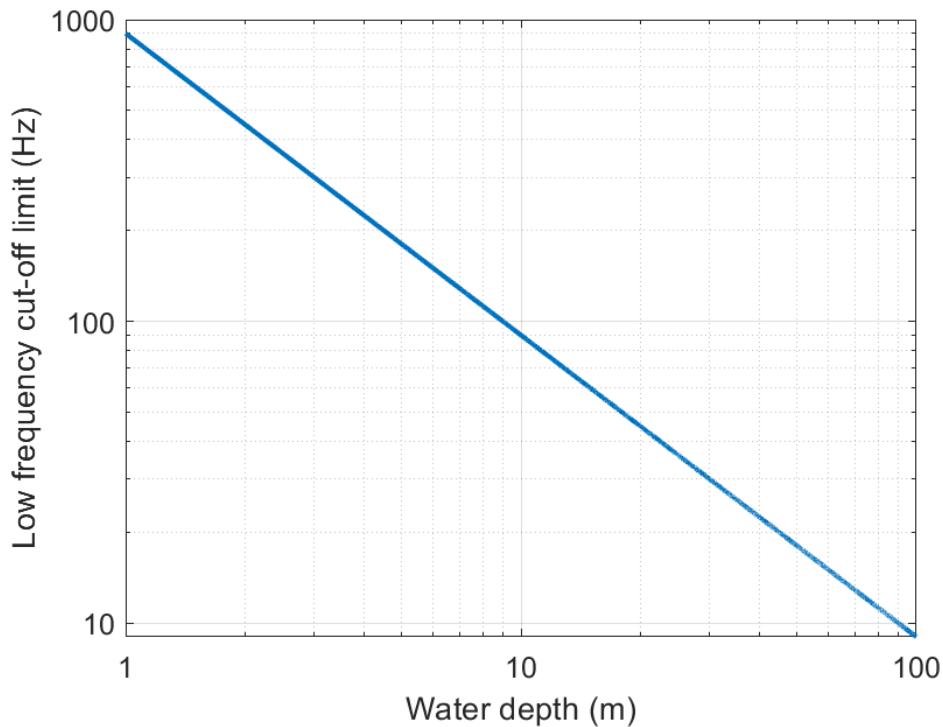


Figure 3.2: Low frequency cut-off limit for sound propagating in shallow water

Source: Adapted from Jensen et al. (2000)

3.2 Demolition and construction noise modelling

To account for the complexity of underwater sound propagation, the proprietary numerical modelling tool UnaCorda (HR Wallingford, 2012; 2013; Rossington, Benson, Lepper, & Jones, 2013) was used to predict sound propagation from the demolition and construction activities.

3.2.1 Underwater sound propagation model description

The UnaCorda model predicts the propagation of underwater sound from one or more point sources throughout the water column and for 360° around each sound source. Underwater sound is assessed for third-octave frequencies of sound across the spectrum from 10 Hz to 25 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 just results along a 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.

3.2.2 Model validation

UnaCorda has previously been validated by comparing modelled predictions against other models (HR Wallingford, 2012). A Lloyd Mirror test (see below) was carried out in which the model was compared against RAMGEO (a fully range dependent parabolic equation code for fluid seabeds, [cmst.curtin.edu.au/products/underwater/]) and also against a classical analytical solution to sound propagation in deep water. Two further, more rigorous, shallow water validation exercises were 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 (>2000 m). 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 3.3. 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 performs well in terms of propagation of sound through the water column with surface reflection.

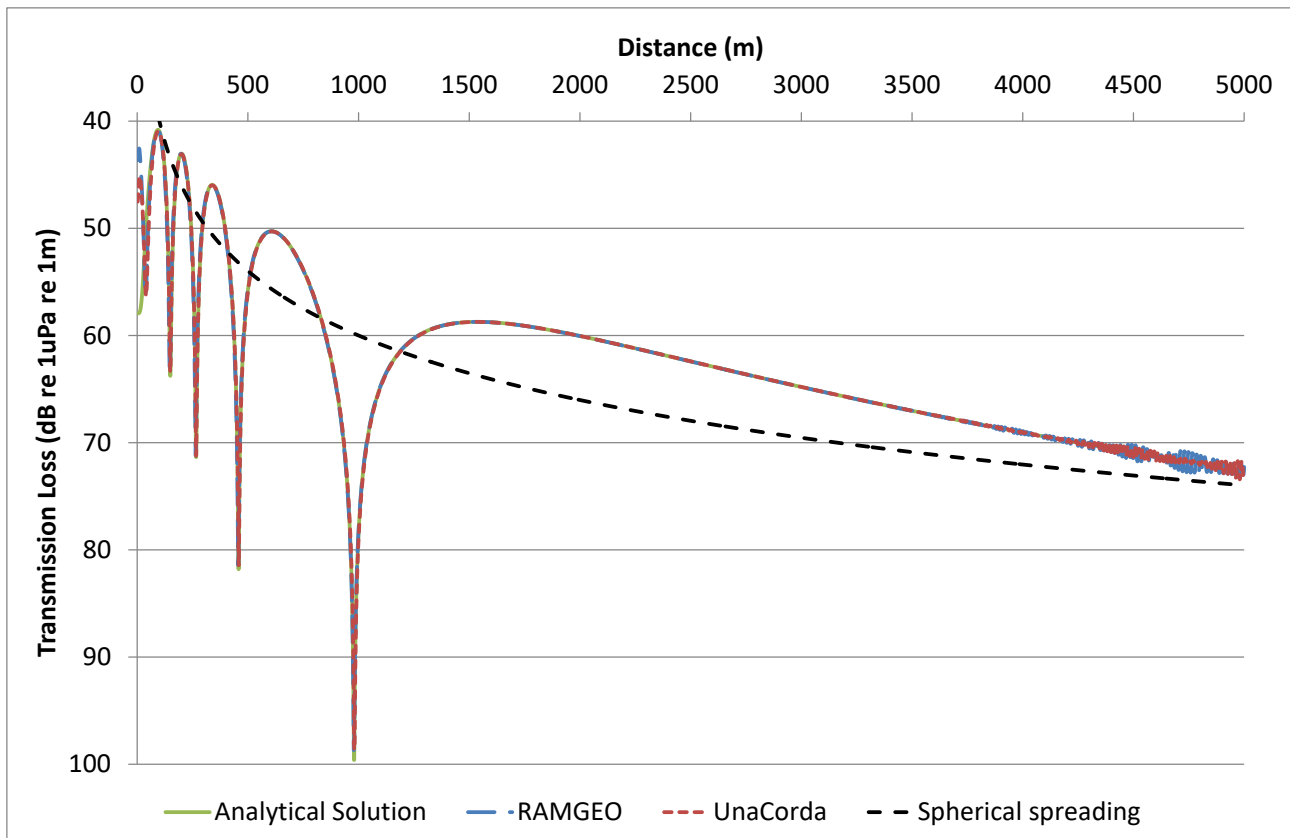


Figure 3.3: Comparison of noise module results for the Lloyd Mirror Test

Source: Collins (1990)

Field validations

In addition to the bench mark 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 3.4). Further validation of the model was carried out during the Rampion Offshore Wind Farm project in the UK (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.

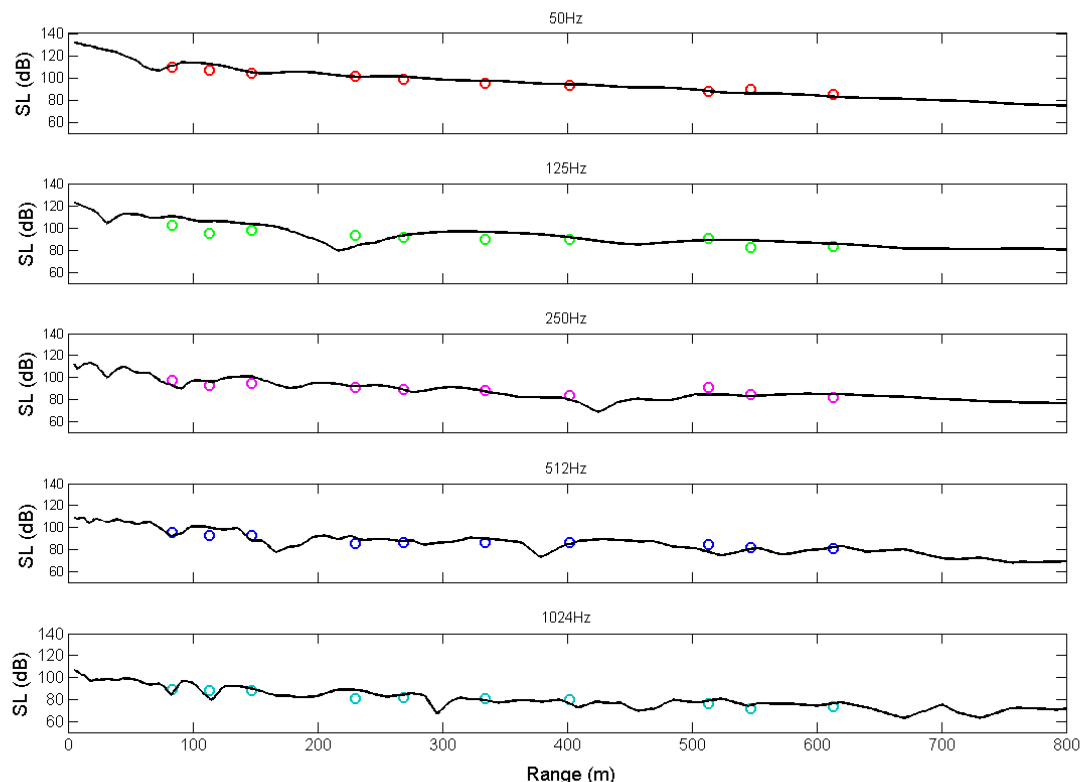


Figure 3.4: Comparison of predicted and measured sound levels during underwater drilling (lines are modelled, circles indicate observations)

Source: HR Wallingford (2013)

3.2.3 Modelling impacts on fleeing cetaceans

An important factor to consider when calculating a cumulative sound exposure level (SEL_{cum}) metric is that marine mammals have the ability (and cognitive skills) to swim away from an acoustic source if the sound levels are not tolerable. Hence it is now common practice (Lepper, Robinson, Ablitt, & Dible, 2007) to assume that, as soon as the sound generating activity is started, the animals affected by the sound swim in a straight line away from the source. As the individuals move away into quieter water, the instantaneous SEL generally reduces with range. The SEL_{cum} for each individual is therefore considerably less than if they were assumed to remain stationary.

A value for fleeing 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.

In order to accurately calculate the SEL_{cum} of fleeing mammals, HR Wallingford's agent-based model (HydroBoids) was used to predict the movement of fish and marine mammals away from the sound source, as described in the following section.

Agent-based model description (HydroBoids)

HydroBoids is an agent-based model (ABM) for predicting the movement of numerous marine animal individuals (agents) and consequences of behaviours in response to stimuli such as sound or properties of the water (Rossington & Benson, 2019). In the model, agents are represented as quasi-Lagrangian points in a three dimensional underwater space which, if required, can be advected by the Eulerian hydrodynamic flows calculated offline using the TELEMAC modelling system (www.opentelemac.org).

Each agent is assigned a swim speed and can be assigned multiple behaviours (e.g. avoidance of sound, light or predators). Of particular importance for the present study, a feature of the ABM is that the simulated agents are able to actively avoid 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).

Calculation of SEL_{cum} for fleeing cetaceans

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

In the agent-based model simulations, cumulative sound exposure levels (SEL_{cum}) 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 HydroBoids simulation for mammals to give the total SEL_{cum} for each animal.

Soft-start for pile driving

Using the fleeing animal method it is also possible to include a soft-start mitigation measure in the modelling. It is now part of standard guidance to start pile driving activities with a low hammer energy and gradually increase it over time. This allows animals some time to swim away from the area before sound levels become high enough to cause them harm. For all the modelled scenarios that assessed pile driving activity, a reduced source level was applied at the start of the simulation at 10 dB below the full source level. The source level was then ramped up in the model over a period of 20 minutes to the full source level.

3.2.4 Modelling impacts on fish

Fleeing models are less suitable for fish because the response of these animals is less certain as different species tend to react differently and the responses of many species have not been studied. Certain fish species can be highly territorial, for example when they are nesting, or may exhibit a 'freeze' reaction when subjected to high levels of noise (e.g. Mauro et al., 2020), and will therefore tend to maintain their position. There is also evidence that some fish species respond to noise by swimming to the seabed (e.g. European seabass: Neo et al., 2015; Fewtrell & McCauley, 2012). The assumption that the fish remain stationary is a conservative approach and considered a worst-case scenario for these animals. In the present study, results for both stationary and fleeing fish will be presented.

For continuous sound sources, such as from vessel movements and dredging activity, the guidance on thresholds for fish is limited to rms SPL metric (which is equal to the SEL over one second for continuous/non-impulsive sounds such as dredgers), under the assumption that the sound is experienced by stationary animals for 12 – 48 hours (refer back to Table 2.7). This metric has therefore been used to determine effects on fish using the output SPL sound field of the UnaCorda model.

4 Vessel data processing and model setup

4.1 Baseline vessel noise

Vessel AIS data were sourced from the UK government data service platform (environment.data.gov.uk, published by the Marine Management Organisation (MMO)) which holds anonymised AIS data for 2011 to 2019. The 2019 AIS data (referred to from here on as MMO, 2019), being the most recent, have been used in this assessment. The vessel types, along with their size range and annual number of vessels within the Fal Estuary for 2019, are listed in Table 4.1. The numbers of passenger and cargo vessels in Table 4.1 are 60 and 96, respectively. This corresponds approximately to the numbers calculated in the A&P assessment of 2023-24 AIS data, with recorded numbers scaled up from two blocks of data of two weeks duration, totalling 48 (passenger) and 108 (cargo) vessels. Considering the different years, measurement methods, and short time period of measurements for the A&P data, this is considered to be good agreement. There is a large discrepancy for non-port and port service craft vessel types (an order of magnitude lower in the MMO (2019) AIS data. This is possibly because the MMO (2019) dataset is less resolved and therefore may not pick up short vessel tracks around the docks where the A&P data were focussed. It is noted that these vessels are also relatively small in size so will not contribute to the sound levels to such an extent as the larger passenger and cargo vessels. The number of tankers and recreational craft was higher (almost double for both types) in the MMO (2019) AIS dataset compared to the A&P data, which is most likely because the data included vessels that were within areas of the estuary away from the docks, which may not be included in the A&P data.

There are likely to be many smaller craft that are not captured by the AIS data. In the A&P report, CCTV data were compared with the locally collected port AIS measurements and it was concluded that only between 4% and 50% of vessels (approximately 10% on average) were recorded using AIS during 2023 to 2024. In that report, a full breakdown of the numbers of vessels was not presented to identify which type of vessels had the largest discrepancy between AIS and visual observations, however it is very likely that smaller, non-commercial vessels accounted for the majority of the vessels with no AIS. Using this assumption, the underrepresentation of smaller vessels in the data means the estimates of background sound levels will be below the real levels, although larger vessels are likely to dominate the ambient sound levels. Assuming the number of smaller vessels stays fairly consistent with existing numbers following the dock development, the relative increases in sound levels caused by the larger commercial vessels will be more pronounced, and hence is considered a worst case in terms of predicted changes.

The anonymised MMO (2019) AIS dataset were processed for each vessel type using a cell-crossing algorithm to generate heat maps of annual averaged source level on a grid covering the Fal Estuary, with a grid resolution of 50x50 m. The MMO (2019) AIS data did not provide detailed information on the vessel speed, so an estimated speed of 6 knots was defined for all vessels within the estuary (which is the speed limit within the harbour). This assumption closely matched the average speed calculated across all of the tracks with respect to the start and finish times and distance travelled. Using a constant vessel speed is likely to overestimate the average sound levels in some regions, but should be an upper estimate due to the speed limit of 6 knots, so is considered a conservative estimate in terms of potential sound levels.

Using the AIS data (MMO, 2019), grids of the annual mean sound pressure levels were generated for each vessel type recorded in the AIS data using the method described in Section 3.1. Estimates of the source levels for the different types of vessel were calculated (described in the results, Section 6) and assessed in terms of the distance from the vessel that behavioural disturbance to marine mammals may occur.

4.2 Future baseline vessel noise

The expected increases in vessel type are shown in the last column in Table 4.1 (information taken from ES Chapter 4). It is expected there will be up to an additional 11 Excellence-class cruise ships docking at Falmouth per year, which are 345 m in length. There will also be up to an additional 12 cargo vessels docking at Falmouth per year, which typically are between 60 and 100 m in length. These numbers are multiplied by two to give the number of additional vessel movements through the estuary.

The additional amount of time per year that mammal disturbance may occur within the estuary due to the additional passenger and cargo vessels was calculated (presented in the results, Section 6).

Table 4.1: Vessel types recorded in the AIS data for 2019 (using data published by MMO, 2019) and expected change in number following the docks development

Vessel type	Length range (m)	Mean length (m)	Number of vessel movements inside the estuary	Number of 2023-24 movements close to docks (adapted from A&P assessment)	Expected change in number of vessel movements* after completion of development
Unknown	10 - 229	88	122	156	0
Non-Port service craft	14 - 28	18	8	286	0
Port service craft	15 - 42	19	293	3354	0
Dredging or underwater ops	15 - 130	61	9	0	0
High Speed Craft	15 - 102	50	16	26	0
Military or Law enforcement	23 - 201	105	35	52	0
Passenger	23 - 229	126	60	52	+22 (Excellence-class 345 m)
Cargo	24 - 292	122	96	117	+24 (60-100 m length)
Tankers	75 - 324	120	243	143	0
Fishing vessels	9 - 20	12	8	26	0
Recreational vessels	1 - 52	23	317	182	0

*the number of expected vessels visiting the dock per year was multiplied by two to give movements

5 Demolition and construction noise data processing and model setup

5.1 Activities modelled

The proposed Falmouth Docks development includes various activities which will generate noise underwater. These include:

- demolition of the existing Northern Arm, using wire saws and potentially a hydraulic hammer or other rock breaker. Of these, only the hydraulic hammer was modelled because this is expected to give the worst-case noise for this activity;
- capital dredging for the new berths using a backhoe excavator; and
- pile driving to install the new dock structures.

The underwater sound propagation for each of these activities has been modelled using HR Wallingford's underwater noise model, UnaCorda.

5.2 Model geometry and locations

The model domain covers the Fal Estuary, extending westwards to Penryn and northwards along Carrick Roads to Loe Beach. Eastward the model reaches to St Mawes and the seaward boundary is the mouth of the estuary, between Pendennis Point and St Anthony Head. The model domain and bathymetry are shown in Figure 5.1.

Figure 5.2 shows a schematic of the line of sight (underwater) from different points around the dock which provides an indication of how sound may either propagate freely or be blocked by the shoreline or dock structures. Based on this schematic, and the planned demolition and construction activities to be carried out, four locations (Figure 5.3) were chosen to model the main sources of sound. The choice of each location was decided primarily in terms of it being the worst case in terms of sound propagation (i.e. locations with least blocking from dock structures) and to give spatial coverage of different areas of the dock development.

The activities modelled at each of the four locations are shown in Table 5.1. Note that more than one activity was modelled at Locations 2 and 4 as shown. The worst case location in terms of potential spatial footprint of the noise overall is Location 2 (Western Wharf).

Table 5.1: Noise activities modelled at each location

Location	Name	Activities modelled
1	Northern Arm	Demolition with hydraulic hammer
2	Western Wharf	Backhoe dredging Percussive piling with soft start only Percussive piling with soft start and a bubble curtain
3	Queens Wharf	Percussive piling with soft start only Percussive piling with soft start and a bubble curtain
4	FLOW deck	Backhoe dredging Percussive piling with soft start only Percussive piling with soft start and a bubble curtain

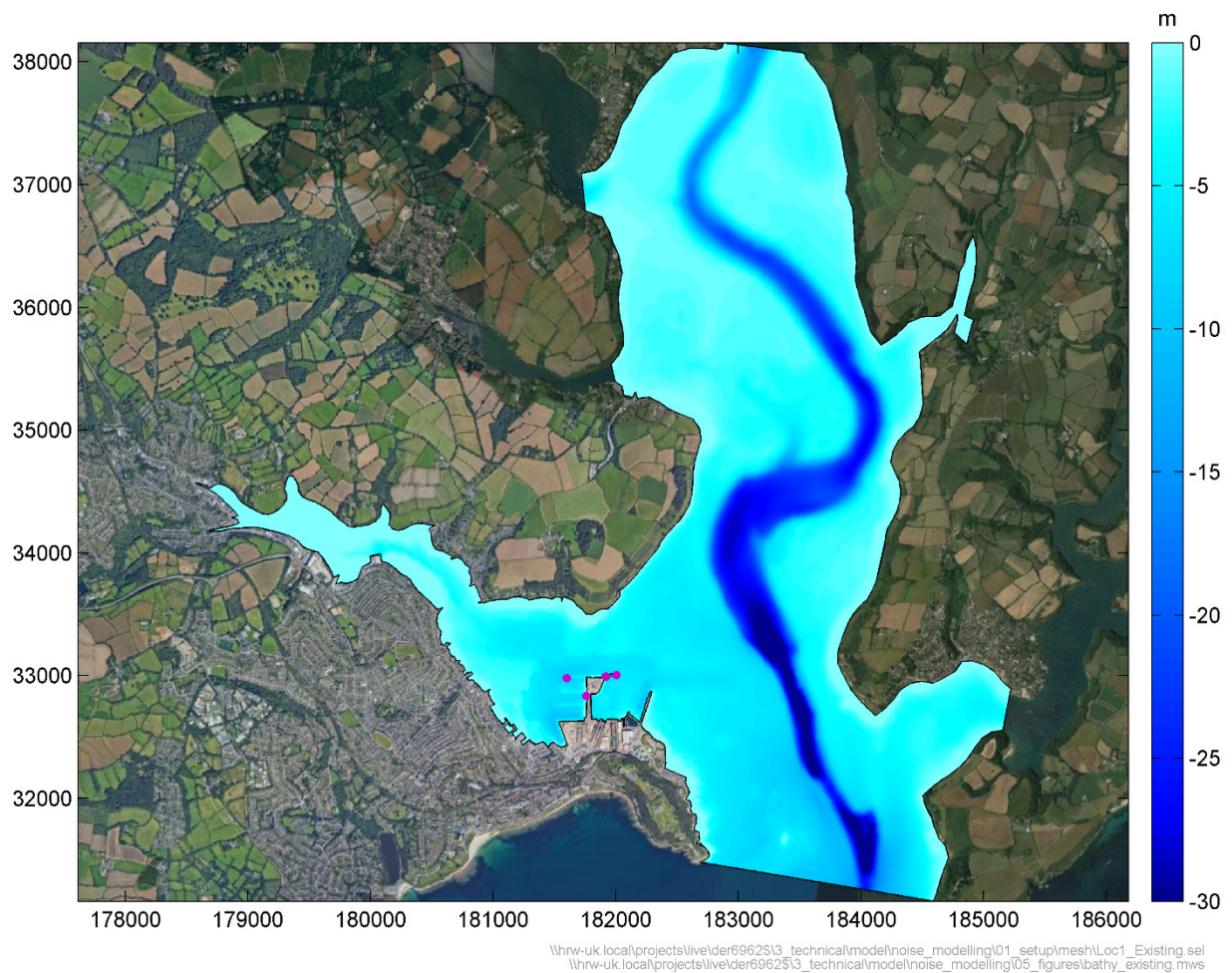


Figure 5.1: Model domain and bathymetry with the modelling locations plotted (magenta circles)

Source: Uses background imagery from Google Earth

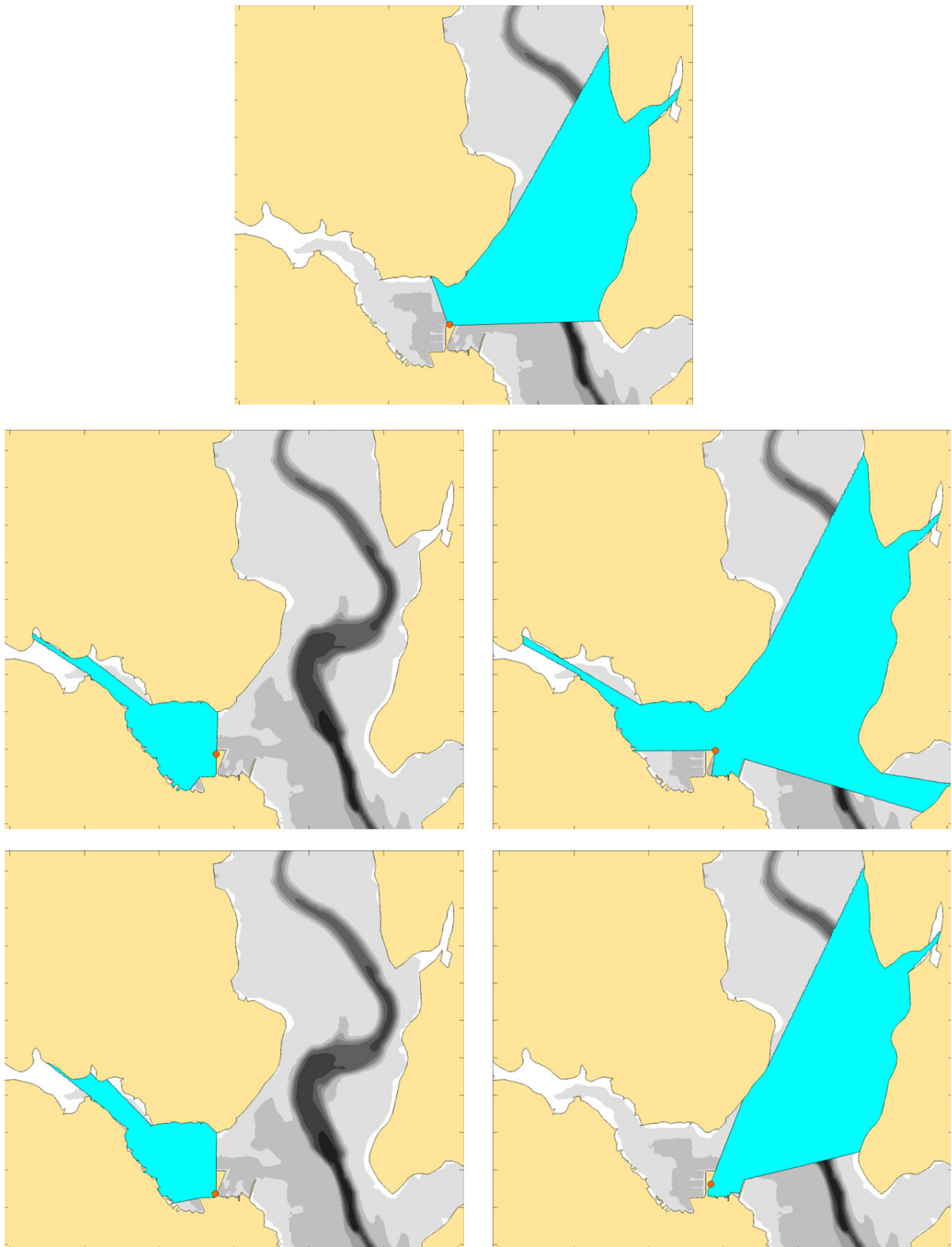


Figure 5.2: Line of sight (blue area) from different positions around the docks

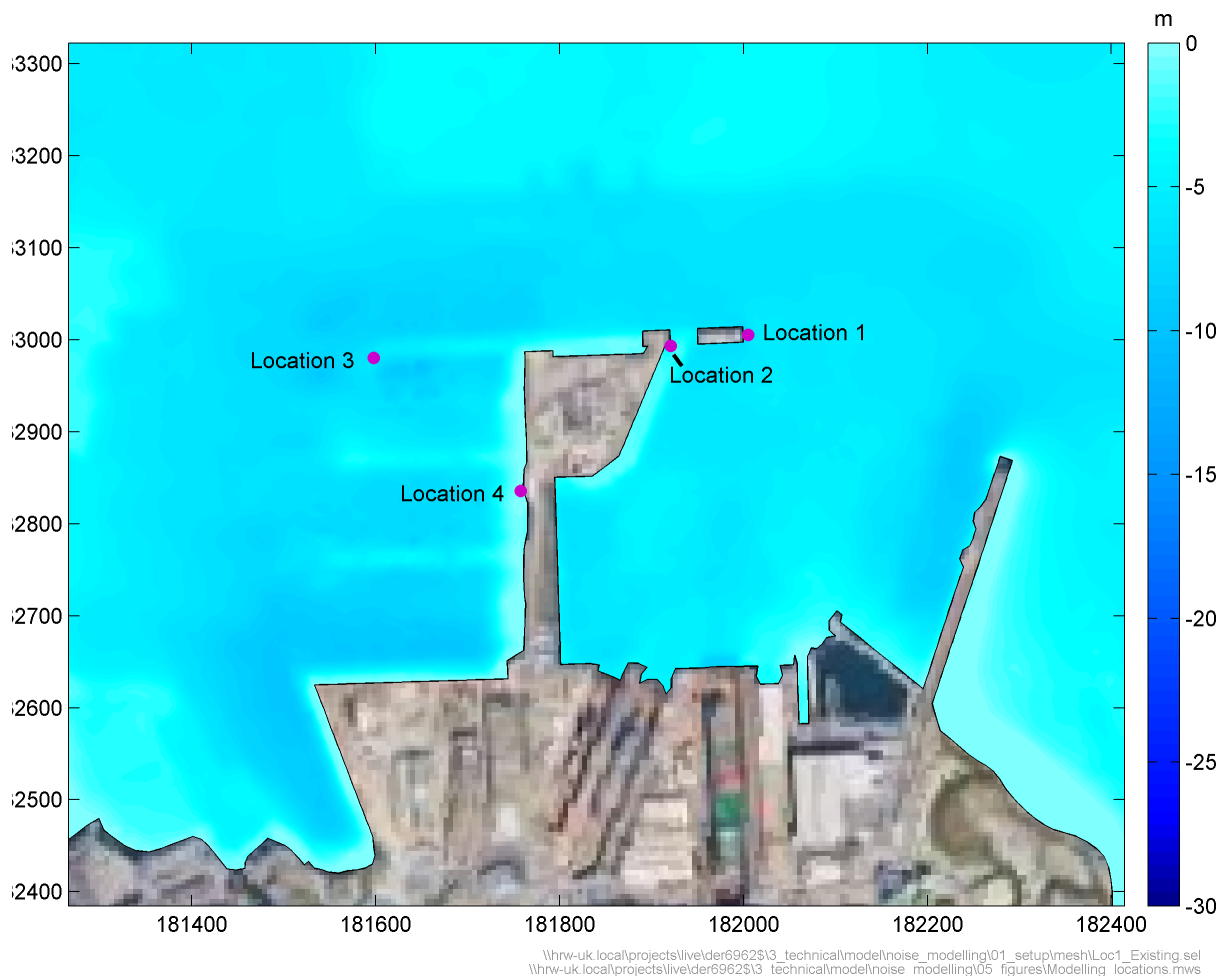


Figure 5.3: Close up of modelled sound source locations

Source: HR Wallingford model using CMAP bathymetry and ESRI background imagery

5.3 Source levels

The third-octave source level spectra used as input to the underwater sound propagation models are all plotted in Figure 5.4 and described in detail in the following subsections.

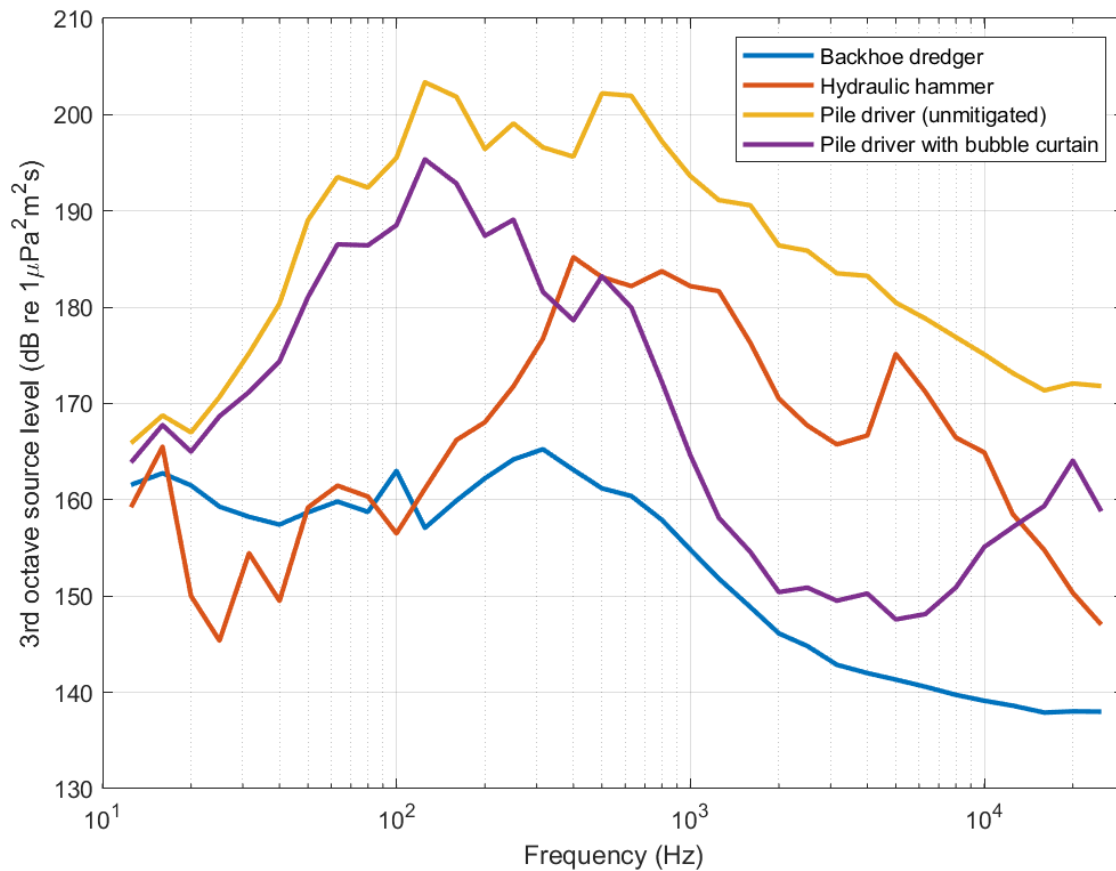


Figure 5.4: Third-octave source level sound spectra used for the various modelled demolition and construction activities

Note: Pile driving will use a soft start procedure which is taken into account in the animal modelling by decreasing the source levels shown here by 10 dB for the first 20 minutes of the simulation.

5.3.1 Pile driving source level (unmitigated)

The proposed development requires numerous piles to be installed as part of the new dock structures. Piles will be installed initially by vibro-piling, to reduce noise (Ramboll, 2023). However it is anticipated that percussive piling will also be necessary due to the nature of the rock in the area. Piles are up to 1.32 m in diameter. It is assumed that for percussive piling, a hammer energy of 300 kJ will be used, suitable for the pile size to be installed.

The source level of pile driving can be estimated based on the hammer energy. De Jong and Ainslie (2008) identified that the hammer energy (E) of the pile driver is a more reliable indicator of source level than the pile diameter. The following empirical relationship is used (de Jong & Ainslie, 2008):

$$E = \frac{4\pi}{\rho_0 c_0} 10^{(SL_E - 120)/10} \quad (16)$$

Where:

E = pile driver hammer energy (J);

ρ_0 = water density (1027 kg/m³ for seawater);

c_0 = speed of sound (~1500 m/s in seawater);

SL_E = energy related RMS source level (dB re 1 μPa²m²s).

Rearranging Equation 16 in terms of SL_E gives the following:

$$SL_E = 10 \cdot \log_{10} \left(\frac{E \rho_0 c_0}{4\pi} \right) + 120 \quad (17)$$

The maximum hammer energy of the piling equipment is 300 kJ. If it is assumed that this hammer energy is used and all of the energy is converted to underwater sound, the SL_E calculated from Equation 17 would be 225 dB re $1\mu\text{Pa}^2\text{m}^2\text{s}$. However, field measurements from other studies (de Jong & Ainslie, 2008) (Ainslie, de Jong, Robinson, & Lepper, 2012) have shown that only a small fraction of the total hammer energy is converted into underwater sound with values in the range of 0.3-10%, with an average of approximately 1%.

The variation of source level energy with hammer energy is plotted for different conversion efficiencies in Figure 5.5. For the present study, a slightly conservative sound conversion efficiency of 3% was used and this source level is 210 dB re $1\mu\text{Pa}^2\text{m}^2\text{s}$ (assuming no mitigation measures are used such as a bubble curtain).

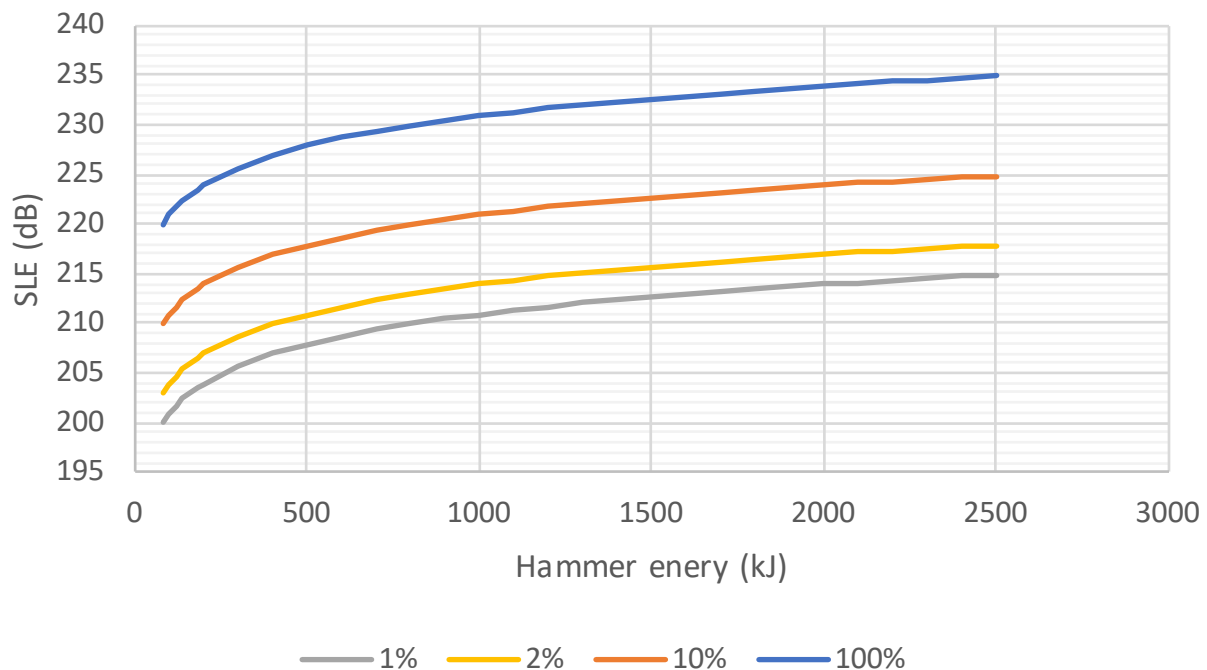


Figure 5.5: Theoretical source level energies for increasing hammer energy at different conversion efficiencies (i.e. percentage of hammer energy converted to underwater sound energy)

A suitable sound level spectrum for slightly larger pile diameter (2 m) was taken from the literature (Subacoustech, 2018) and scaled according to the calculated broadband source level obtained from Equation 17. The resultant spectrum for unmitigated pile driving is shown in Figure 5.4.

5.3.2 Pile driving source level with bubble curtain mitigation

Various forms of mitigation measure may be used to reduce the underwater sound levels generated during pile driving. Bubble curtains can be an effective method for reducing underwater noise. Compressed air is injected through a perforated ring laid on the seabed around the pile, creating a ring of air bubbles which rise to the surface. The difference in impedance between water and air results in sound being absorbed and scattered as it passes from the water into the air bubbles (Koschinski & Lüdderman, 2013).

Koschinski and Lüddermann (2013) reviews several studies which used bubble curtains to mitigate piling noise. Reductions of the broadband sound exposure level (SEL) resulting from the bubble

curtains were found to be between 11 dB re $1\mu\text{Pa}^2\text{s}$ and 12 dB re $1\mu\text{Pa}^2\text{s}$, but varied with distance from the pile.

To account for the presence of a bubble curtain, the reduction in sound pressure level (Figure 5.6), based on measurements taken during piling for the FINO3 research platform in the North Sea, were applied to the source spectrum and the broadband noise field recalculated (Figure 5.4). This is preferable to reducing the entire noise field by a fixed value because differences in propagation of each frequency are accounted for.

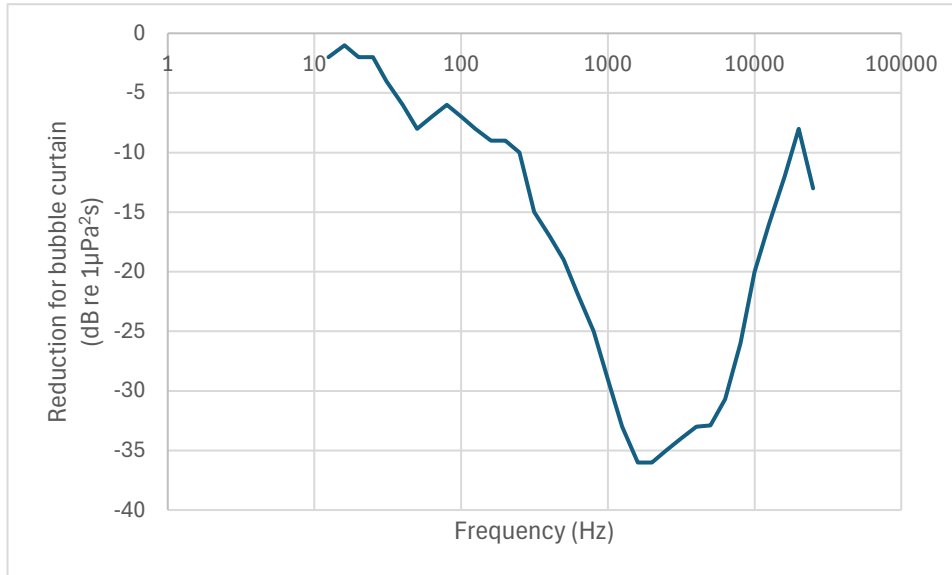


Figure 5.6: Bubble curtain reduction by frequency

Source: (Elmer & Savery, 2014)

The broadband reduction in source level due the bubble curtain was calculated to be 10 dB re $1\mu\text{Pa}^2\text{s}$. This does not reduce the noise field by 10 dB re $1\mu\text{Pa}^2\text{s}$ everywhere because the propagation loss differs for different frequencies.

Table 5.2: Input parameters for the percussive piling

Parameter	Value
Source level (SL)(no mitigation)	210 dB re $1\mu\text{Pa}^2\text{s}$
Source level (SL)(bubble curtain)	200 dB re $1\mu\text{Pa}^2\text{s}$
Duration (t)	4 hours
Type of sound	Impulsive
Strike rate	0.67 strikes per second

5.3.3 Demolition source level

Various demolition activities will be required, in particular around the existing Northern Arm of the docks, which is due to be removed. It is expected that the loudest of these will be the use of a hydraulic hammer to break up any of the structure remaining underwater after cutting and block removal has been completed. The source level (192 db re $1\mu\text{Pa}^2\text{s}$) and spectrum (Figure 5.4) for a hydraulic hammer was adapted from Connell et al. (2023). It is anticipated that the hydraulic hammer will only be needed for short periods, totalling up to one hour in any twenty-four hour period. Other demolition noises, such as wire cutting, will be quieter and have not been modelled.

Table 5.3: Input parameters for the Northern Arm demolition by hydraulic hammer

Parameter	Value
Source level (SL)	192 dB re 1µPa2s
Duration (t)	1 hour in 24 hours
Type of sound	Impulsive
Strike rate	5 strikes per second

5.3.4 Backhoe dredger sound source level

It is understood that a pontoon mounted backhoe dredger will be used for the capital dredging for the new berths. Measured sound levels for various activities performed by a backhoe dredger were summarised by Jones and Marten (2016). Source levels were predicted to vary between 154 and 179 dB re 1 µPa at 1 m from the source. Whilst dredging is considered here as a continuous noise, it will vary considerably through time. For the current study, results are presented for a source level of 175 dB re 1 µPa which is considered to be an upper (worst case) estimate for the average source level for the daily dredging activity. It is understood that dredging will potentially be carried out for 24 hours out of every day.

Table 5.4: Input parameters for the backhoe dredging

Parameter	Value
Source level (SL)	175 dB re 1µPa
Duration (t)	24 hours
Type of sound	Continuous

A suitable sound spectrum for a backhoe dredger was previously measured by Nedwell et al. (2008) at a distance of 7 m from the dredger. The broadband sound pressure level for spectrum extrapolated back to 1 m from the dredger, as calculated by Nedwell et al. (2008), was 163 dB 1µPa. For the present study, the spectrum was scaled equally across all frequencies to give a broadband source level of 175 dB 1µPa, and the resultant spectrum (Figure 5.4) was used in the sound modelling.

5.4 Bed parameters

The geo-acoustic properties of the sea bed sediment influence how sound is refracted and attenuated as it propagates underwater.

Particle size distributions provided by Ramboll¹ for the Falmouth Docks area, showed a mixture of mud, sand and gravel. The emitted sound will propagate over a large area and the sediment type will vary spatially across the region. Insufficient data were available to create a detailed map of the bed sediment stratigraphy across the region as a whole. The sediment was therefore approximated to be a uniform properties everywhere, with values representative of sand. Using the assumption of a homogeneous sandy bed type, the acoustic properties of the seabed within the region have been estimated based on data of Jensen et al. (2000), which describes empirical predictions of seafloor properties based on remotely measured sediment impedance in a variety of sediments. The sound propagation properties used are given in Table 5.5.

Table 5.5: Physical properties of the bed sediment (sand) as input into the UnaCorda model

Physical Property	Value
Density (kg/m³)	1900
Sound speed (m/s)	1650
Attenuation coefficient (dB/λ)	0.8

Source: HR Wallingford using information from Jensen et al. (2000)

¹ J0710_PSD_Analysis.csv provided by Ramboll on 15/01/2024

5.5 Estimation of Peak Sound Pressure Level

For underwater pile driving noise or other activities where there are multiple sound impulses over an extended period of time (e.g. seismic surveys or percussive piling), the SEL_{cum} metric is usually the greater of the two metrics in terms of distance to TTS or PTS for marine mammals. This is due to the cumulative effect of integrating the energy dosage over time using the SEL_{cum} metric. The potential impacts on marine mammals are, therefore, primarily assessed in this report in terms of the SEL_{cum} metric. However, following the guidance of Southall et al. (2007), SPL_{peak} should also be considered.

Sound propagation models generally are only able to predict the propagation of sound energy (i.e. SEL) and are not capable of resolving the time component of the sound impulse. They are, therefore, not capable of modelling the peak in the sound pressure. The SPL_{peak} is dependent on the type of pile driving equipment and also the peak reduces non-linearly relative to the sound energy due to spreading of the pulse as it travels away from the source of the sound. Previous research has shown that there is a relationship, albeit an empirical one, between the SEL and SPL_{peak} (Lippert et al., 2015). Whilst the empirical relationship between SEL and SPL_{peak} is site specific and therefore, to be accurate, would require in-situ sound measurements from the development site to be recorded whilst the piling equipment is in use, as the impacts resulting from SEL_{cum} are greater than those envisaged from the SPL_{peak}, an estimation of the SPL_{peak} is considered suitable for this assessment. An estimate of the SPL_{peak} was calculated for the present study assuming that the empirical constants are similar to those calculated by Lippert et al. (2015) for a study of pile driving during construction of three offshore wind farms. The three cases showed similar linear relationships between SEL and SPL_{peak}, with the worst case used for the present study, written as:

$$\text{SPL}_{\text{peak}} = 1.43 \text{ SEL}_{\text{ss}} - 44.0 \text{ (18)}$$

where SEL_{ss} is the modelled single strike SEL.

This approach is considered to be a practical option for assessing the impact due to SPL_{peak} in this instance.

5.6 Fleeing animal model inputs

Modelling for fleeing animals was undertaken using agent-based modelling. At the start of the agent-based model simulations, agents (mammals) were initialised at the positions of the noise model mesh nodes across the whole model domain. At the onset of the noise, it was assumed the animals swam away from the sound source at a swim speed of 1.5 m/s. The modelled duration was specific for each activity modelled and the animal model time step interval was one second.

Since it is not known what water depth the animals will be swimming at, the maximum SEL through the water column was used in the calculations to be conservative. A summary of the main parameters used in the fleeing animal modelling is given in Table 5.6.

Table 5.6: Parameters used in fleeing animal model

Parameter	Value used
Animal swim speed	1.5 m/s
3D sound levels used	Through-depth maximum
Mammal weightings used	Southall et al. (2019)

Source: HR Wallingford

It is noted that the agents in the model have a simplistic fleeing behaviour, they swim directly away from the noise and do not have sophisticated behaviours to avoid obstacles (e.g. marine structures). This means that agents can become trapped between the noise and an obstacle and may therefore accumulate a higher SEL_{cum} dose than if the fleeing behaviour was unconstrained. Where this is seen in the model predictions it has been noted.

6 Vessel noise results

As described in Section 3.1, noise generated by vessels is generally low frequency (<100 Hz). The fact that the vessels are generally moving also means the highest sound levels occur over a relatively short duration at any one location as the vessel passes close to any sensitive receptors, leading to lower cumulative levels than for a stationary sound source and stationary receptors. The cumulative sound exposure level from vessels is therefore predicted to be well below the sensitivity thresholds (Table 2.4) for marine mammals and is unlikely to cause temporary or permanent threshold shift. However, the Fal is a busy estuary in terms of commercial, military and recreational vessels, many of which are of a large size with potentially high source levels. It is therefore necessary to assess the potential for behavioural disturbance for the existing baseline and how this might change following the completion of the dock development.

The DEFRA AIS cell-crossings data (described in Section 4) were used to generate a map of the total residence time of vessels of different types within each 50x50 m grid cell (Figure 6.1). In total across all vessel types, the amount of time a vessel lies within each grid cell is maximum within the main approach channel of the estuary, with up to approximately half an hour per year. The resultant annual mean sound pressure levels due to the vessels is shown in Figure 6.2. Within the main shipping route, the annual mean SPL due to vessels in the modelled output (see last subfigure in Figure 6.2) exceeds the threshold for behavioural disturbance (120 dB for continuous noise, see Section 2.2.2).

Port service craft and recreational craft have the highest numbers of vessels recorded in terms of time visiting the area (Figure 6.1). Tankers also spend similar amounts of time in and around the estuary, but are less present close to the docks, presumably because they do not tend to moor at the berths. In terms of sound pressure level (Figure 6.2), the larger commercial and military vessels contribute the most (i.e. Passenger, tankers, cargo and military vessels). The passenger vessels are present in relatively high numbers and tend to follow a well defined course along the channel, resulting in the highest annual mean source levels out of all vessel types concentrated along the shipping channel.

Planned increases in vessels in the future baseline are only envisaged for cargo (i.e. commercial freight) and passenger vessels. Some reduction in tender vessels is anticipated due to the ability of the large passenger vessels to moor at the berths, but the reduction in numbers is not known, so the effects are not considered here.

Source levels for the different vessel types, with the assumption of 6 knot cruising speed, were calculated using the Ross formulae (Section 3.1) as shown in Table 6.1. Using these source levels, the approximate distances from the vessel to the 120 dB marine mammal behavioural threshold for continuous sounds were calculated (also shown in the table). These distances were calculated using a simple spreading transmission loss method (Equation 14) and represent the maximum distance to low level disturbance threshold for marine mammals. For the larger commercial vessels, the distances in most cases extend beyond the limits of the deep water channel which indicates that minor disturbances of marine mammals will occur throughout most of the estuary width during the passage of the larger vessels. The amount of time for a vessel to travel from the estuary mouth to the dock (a distance of 3-4 km), at an assumed speed of 6 knots, is approximately 15-20 minutes. The amount of additional time per year that animals may be disturbed within the deeper areas of the estuary, assuming 11 passenger and 12 cargo vessels visits (i.e. 46 transits through the estuary in total) is therefore of the order of 15 hours/year combined. This is in addition to the current levels of vessel activity, which for combined passenger and cargo vessels is estimated to be approximately 50 - 60 hours (based on measured numbers of vessels). It is noted also that the predicted source levels for the Excellence-class cruise ships are higher than the other (smaller) vessels, with distances of disturbance of up to approximately 6 km from the vessel at 6 knots (in deep water). The behavioural disturbance effects are therefore likely to be more pronounced for the larger vessels, but below injury thresholds.

Table 6.1: Approximate vessel source levels at assumed speed of 6 knots and potential marine mammal disturbance radii during transit

Vessel type	Length range (m)	Mean length (m)	Calculated source level min-max (and mean) (dB)	Potential distance to 120 dB* (m)
Unknown	10 – 229	88	141 – 171 (160)	23 – 2497 (490)
Non-Port service craft	14 – 28	18	143 – 150 (146)	36 – 94 (51)
Port service craft	15 – 42	19	144 – 153 (146)	40 – 166 (55)
Dredging or underwater ops	15 – 130	61	144 – 164 (157)	40 – 910 (284)
High Speed Craft	15 – 102	50	144 – 162 (155)	40 – 616 (213)
Military or Law enforcement	23 – 201	105	148 – 169 (162)	72 – 1947 (645)
Passenger	23 – 229	126	148 – 171 (164)	72 – 2497 (864)
Cargo	24 – 292	122	148 – 174 (164)	76 – 4120 (820)
Tankers	75 – 324	120	159 – 176 (164)	385 – 5195 (798)
Fishing vessels	9 – 20	12	140 – 147 (142)	20 – 59 (30)
Recreational vessels	1 – 52	23	120 – 155 (148)	1 – 225 (72)
<i>Excellence-class cruise ship**</i>	–	345	177	6013

*range calculated assume spherical spreading formula with the for $RL=SL-15\log_{10}(\text{range})$

**Excellence-class cruise ships are planned

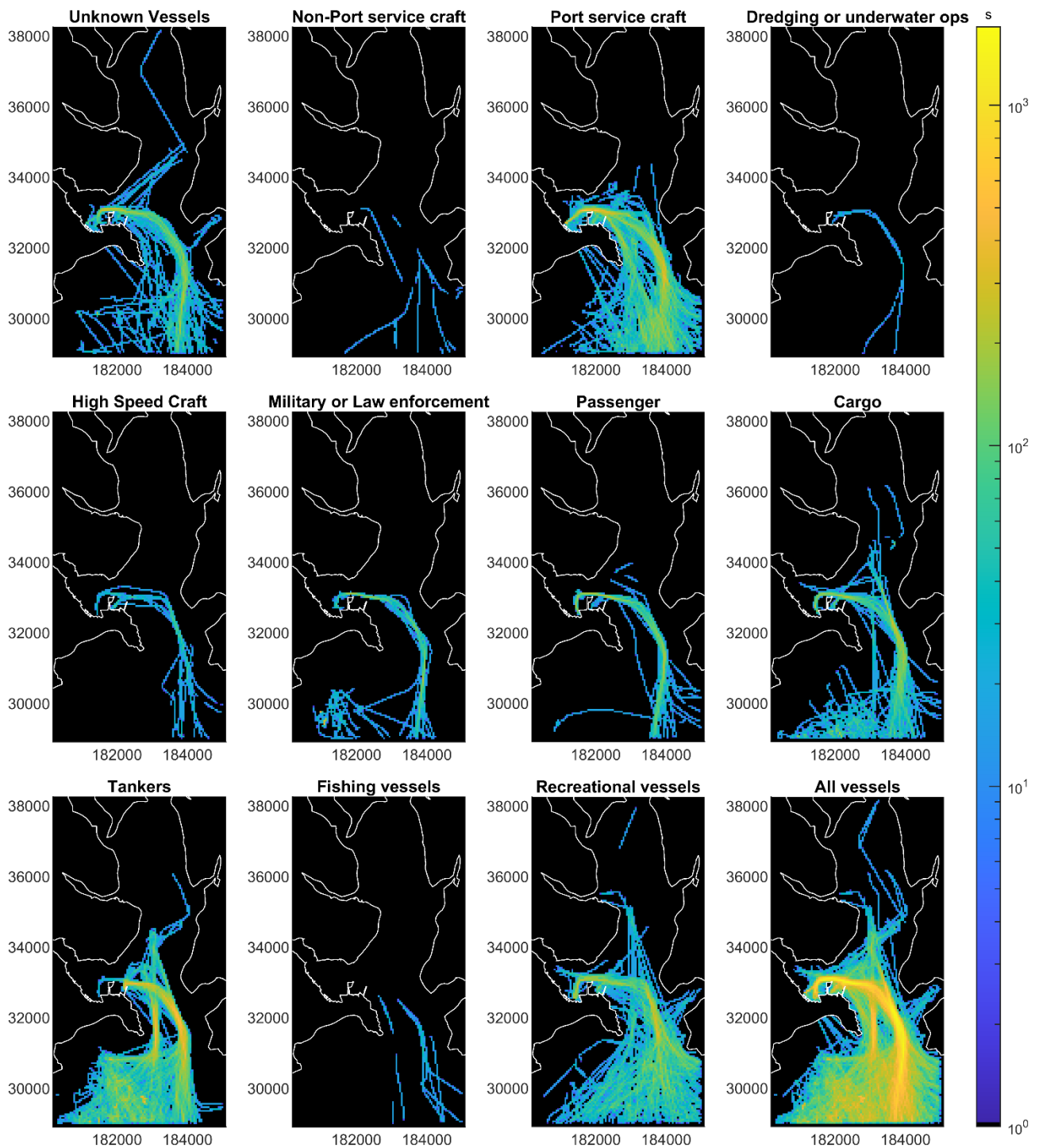


Figure 6.1: Annual residence time within each 50x50m cell for each vessel type (note logarithmic colour scale for time)

Source: DEFRA AIS data for 2019

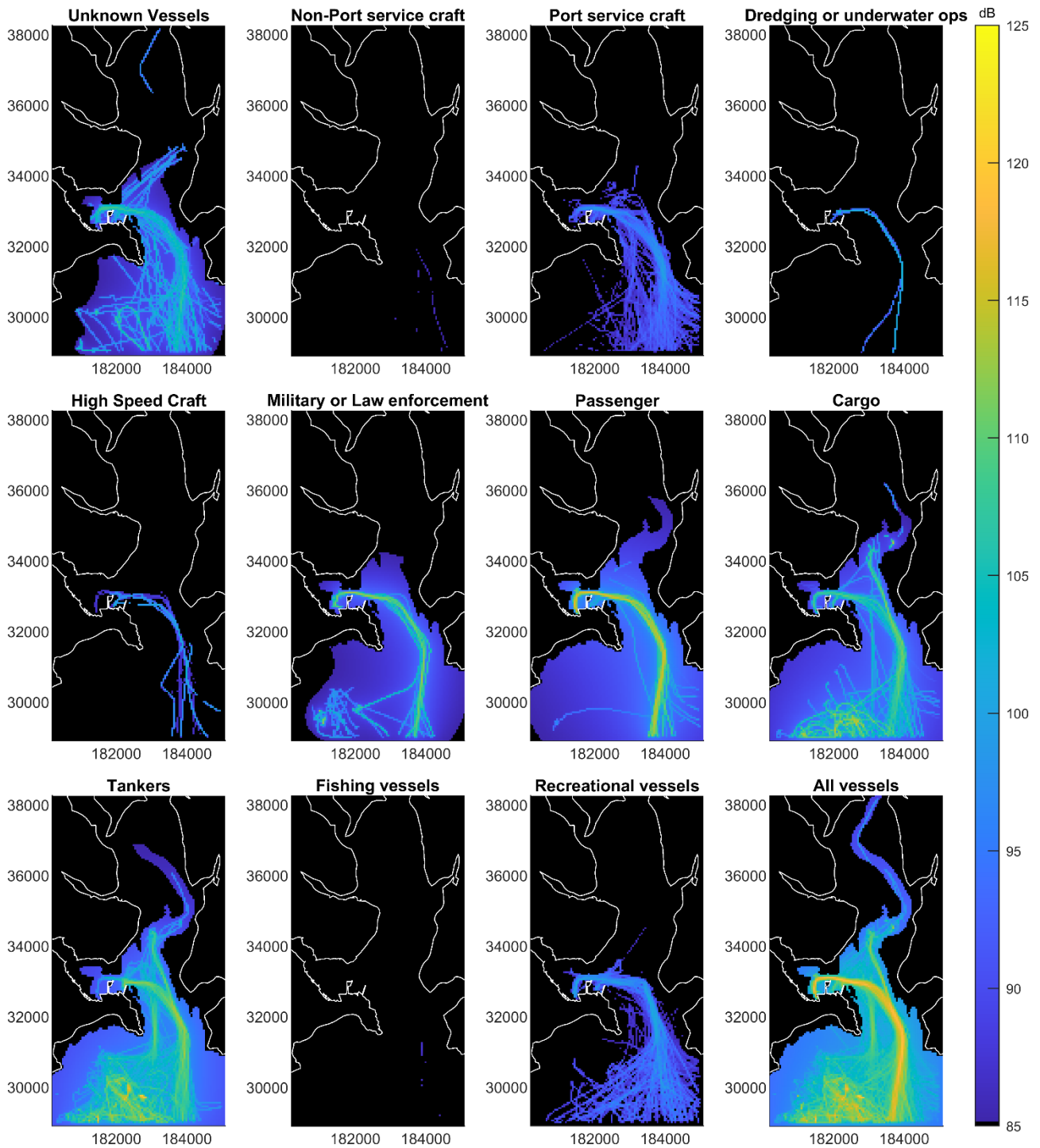


Figure 6.2: Modelled annual mean sound pressure level for each vessel type (sound levels are cropped in water depths under 10 m mean high water springs)

Source: Modelled sound levels using DEFRA AIS data

7 Demolition and construction noise impact modelling results

In this section, the results for the predicted sound fields and potential impacts of noise of marine mammals and fish are presented for each modelled activity.

For each mammal hearing group, the thresholds for temporary threshold shift (TTS) and permanent threshold shift (PTS) have been used as set out in Table 2.3 (for impulsive noises of pile driving and hydraulic hammering) and Table 2.4 (for the continuous noise associated with backhoe dredging).

For fish, thresholds for mortal or recoverable injury and TTS for impulsive noises are used as shown in Table 2.6. The results for fish, both fleeing and stationary, are presented for the two most sensitive fish groups (i.e. those with swim bladders that are associated with auditory functions and those with swim bladders not associated with auditory functions). The first group represent the likely worse case of fish sensitivities to underwater noise. For continuous noise, fish are assessed for recoverable injury and TTS using the SPL criteria, as defined in Table 2.7.

The model results for both marine mammals and fish were analysed to predict the distance to the relevant impact thresholds, reported as:

- $R_{\max}$ – the maximum distance from the pile within which the threshold is exceeded;
- R_{95} – the distance within which the threshold is exceeded 95% of the time;
- R_{mean} – the mean distance within which the threshold is exceeded.

Figures illustrating the predicted impact footprint are also presented in the following subsections for selected scenarios that show the most significant potential impact. The contours in the figures for fleeing animals indicate the starting locations for which animals inside the contour are predicted to experience cumulative sound exposure levels exceeding the impact contours.

7.1 Location 1 – Northern Arm

7.1.1 Demolition with a hydraulic hammer

Demolition of the existing Northern Arm of the Falmouth Docks may require a hydraulic breaker attached to an excavator to break up the concrete structure for removal. Other demolition methods, such as wire cutting and removal of sections by backhoe are expected to be quieter than the hydraulic hammer and therefore not modelled. Modelling assumes that the hydraulic hammer will be used for up to one hour in any twenty-four hours.

Broadband sound field

Figure 7.1 shows the predicted broadband sound field for the demolition activity noise source. Sound levels decrease with distance from the source, with the broadband SEL dropping below 150 dB re 1 μ Pa²s approximately 1 km away.

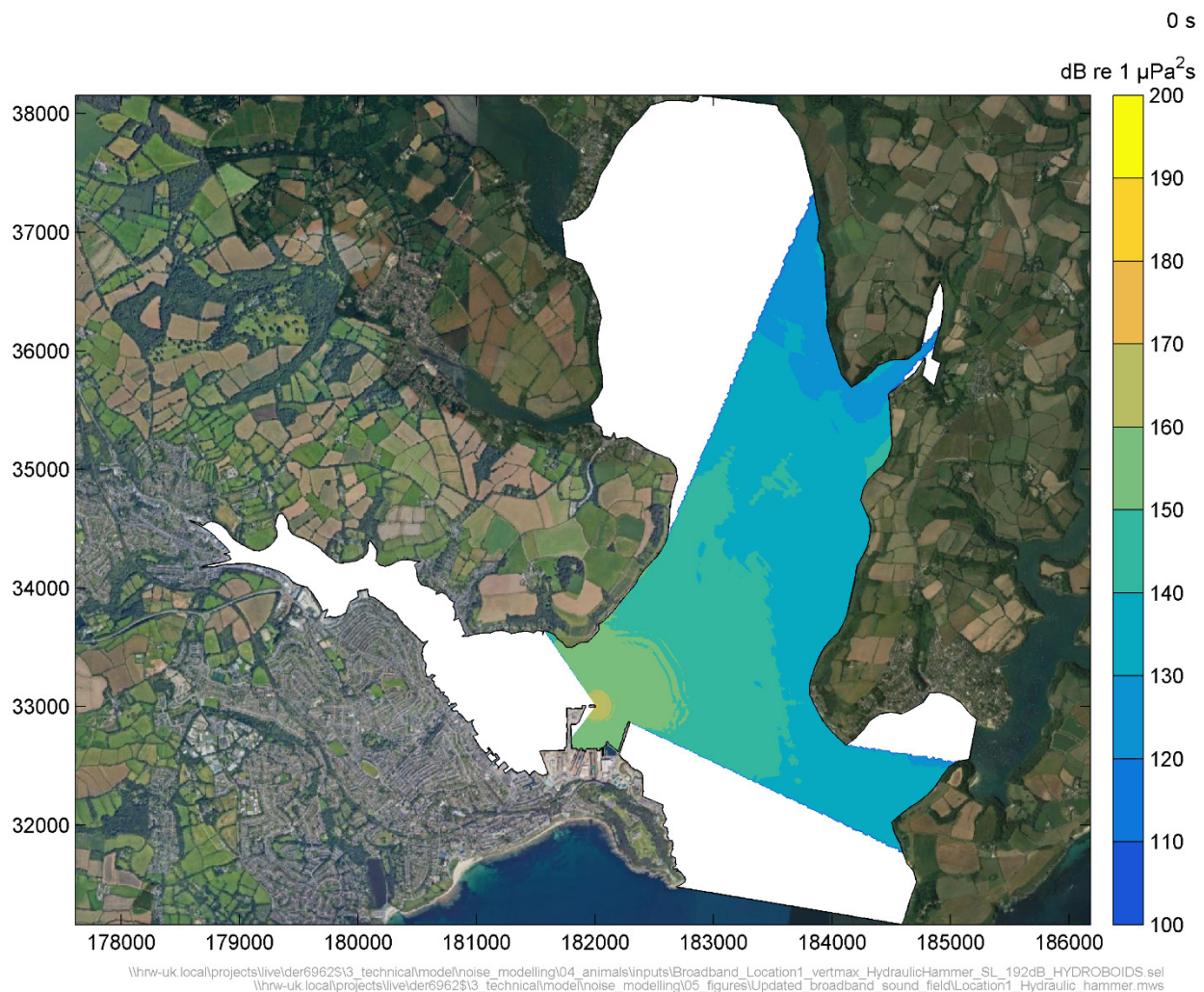


Figure 7.1: Predicted single strike SEL sound field for demolition at Location 1 using a hydraulic hammer

Source: Uses Google Earth imagery

Mammals

Table 7.1 shows the predicted distances to the impact thresholds for the mammal groups. This was based on using the hydraulic hammer for one hour without pausing, and is likely to be worst case.

In most cases it is predicted that the areas predicted to exceed the SEL_{cum} PTS thresholds are within 400 m of the noise source and would mostly apply to any animals between the noise source and the shoreline (or Eastern Breakwater). The exception is for the very high frequency cetacean hearing group, for which the area above the PTS threshold extends northward and eastward across almost the whole width of the estuary (Figure 7.4). TTS thresholds were predicted to cover wider areas for all hearing groups.

For this activity, it was predicted that:

- For low frequency cetaceans (LF):
 - The TTS threshold for SEL_{cum} was predicted to be exceeded within 3000 m of the demolition (Figure 7.2);
 - The PTS threshold for SEL_{cum} was predicted to be exceeded within 400 m.
- For high frequency cetaceans (HF):

- The maximum distance to the TTS threshold was 400 m. The threshold was exceeded only for animals between the Falmouth Dock and the Eastern Breakwater (Figure 7.3);
- No PTS exceedance is predicted to occur in relation to the demolition activity at the Northern Arm for this hearing group.
- For very high frequency cetaceans (VHF) (Figure 7.4):
 - The maximum distance to the SEL_{cum} TTS threshold was 3800 m;
 - The PTS threshold for SEL_{cum} was predicted to be exceeded within 1700 m.
- For pinnipeds:
 - The maximum distance to the TTS threshold was 2400 m;
 - The maximum distance to the PTS threshold was 400 m. The threshold was exceeded only for animals between the Falmouth Dock and the Eastern Breakwater (Figure 7.5).
- Using the SPL_{peak} metric, the TTS thresholds were exceeded for all groups within 40 m of the noise source.
- Distances to impact threshold were much smaller with SPL_{peak} compared to the SEL_{cum}.

Table 7.1: Distances to impact threshold for different mammal hearing groups (demolition of the Northern Arm, Location 1)

	TTS			PTS		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
LF cetaceans (SEL _{cum})	3000 m	2500 m	1100 m	400 m*	360 m	150 m
HF cetaceans (SEL _{cum})	400 m	370 m	140 m	0 m	0 m	0 m
VHF cetaceans (SEL _{cum})	3800 m	3400 m	1400 m	1700 m	1600 m	550 m
Pinnipeds (SEL _{cum})	2400 m	2200 m	770 m	400 m*	370 m	130 m
LF cetaceans (SPL _{peak})	4 m	4 m	4 m	2 m	2 m	2 m
HF cetaceans (SPL _{peak})	1 m	1 m	1 m	0 m	0 m	0 m
VHF cetaceans (SPL _{peak})	40 m	30 m	30 m	20 m	20 m	20 m
Pinnipeds (SPL _{peak})	4 m	4 m	4 m	2 m	2 m	2 m

* Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted



Figure 7.2: Predicted SEL_{cum} impact footprint for the low frequency cetacean hearing group for demolition with a hydraulic hammer at the Northern Arm (Location 1)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery



Figure 7.3: Predicted SEL_{cum} impact footprint for the high frequency cetacean hearing group for demolition with a hydraulic hammer at the Northern Arm (Location 1)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery



Figure 7.4: Predicted SEL_{cum} impact footprint for the very high frequency cetacean hearing group for demolition with a hydraulic hammer at the Northern Arm (Location 1)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery



Figure 7.5: Predicted SEL_{cum} impact footprint for pinnipeds for demolition with a hydraulic hammer at the Northern Arm (Location 1)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery

Behavioural disturbance

Areas of potential behavioural disturbance to marine mammals are shown in Figure 7.6, based on the criteria discussed in Section 2.2.2. A higher level of behavioural disturbance was predicted within approximately 1 km of the noise source. The potential for low level disturbance was predicted across the estuary, except in areas shadowed by headlands and jetties. The potential for behavioural disturbances does not account for hearing and sensitivity differences between the mammal groups because insufficient information is available regarding sound levels causing behavioural disturbance.

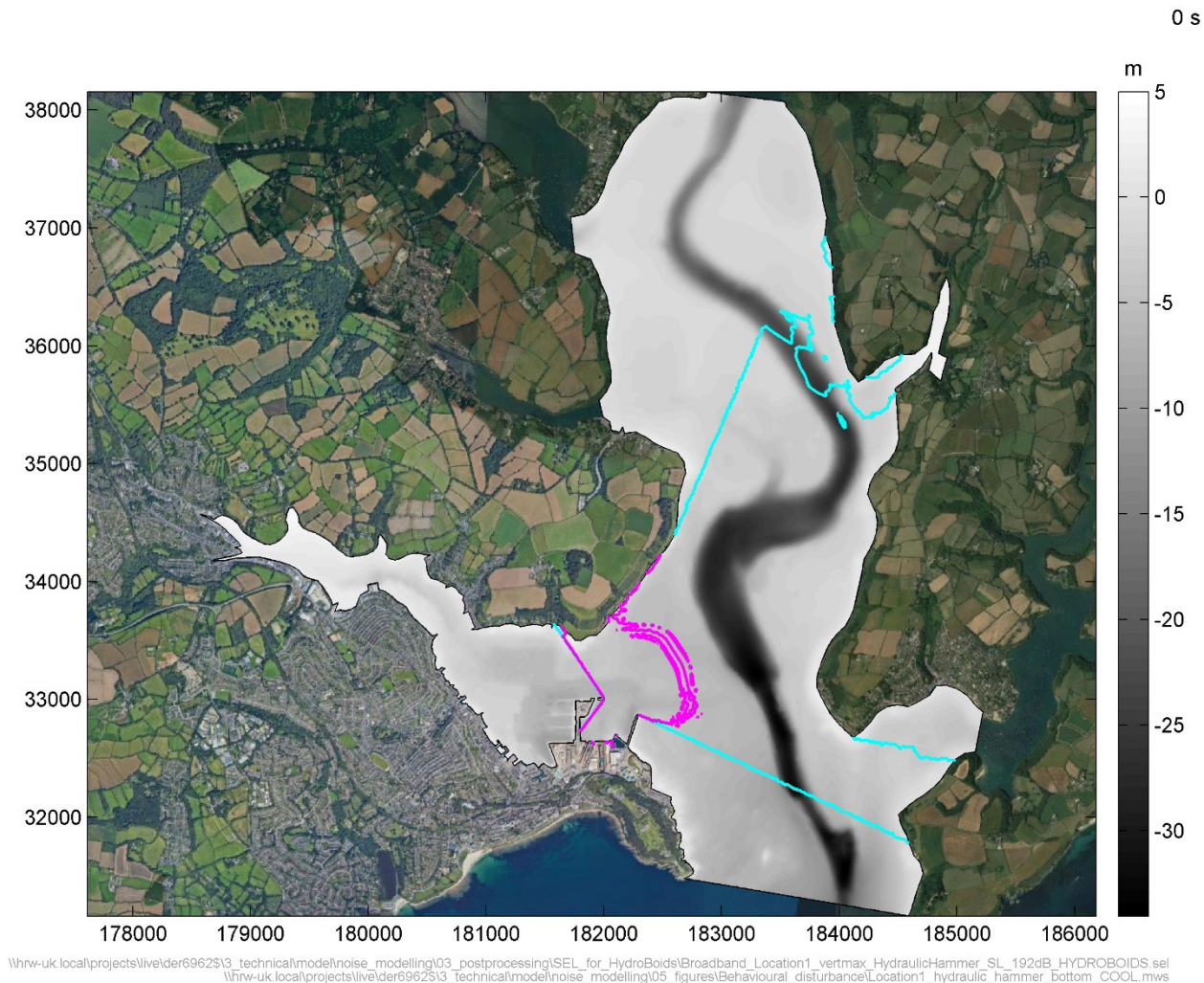


Figure 7.6: Impact contours for potential behavioural disturbance to marine mammals for demolition activities using the hydraulic hammer

Notes: Low level disturbance threshold (140 dB re 1µPa) – turquoise; higher level of disturbance (160 dB re 1µPa) – magenta

Source: Uses Google Earth imagery

Fish

Impact distances are given for the most sensitive hearing groups, fish with swim bladders involved in hearing (Category 3) and fish with swim bladders not involved in hearing (Category 2). Fish may flee on exposure to noise, or may display other behaviours, such as swimming to the seabed. To cover the range of potential behaviours, fish are modelled as fleeing or stationary. The distances to impact thresholds for the demolition activity are shown in Table 7.2:

- For fleeing fish (Figure 7.7), the TTS threshold was exceeded within 400 m of the noise source and represents fish between the dock and the Eastern Breakwater, for which routes to flee the noise were restricted. Recoverable injury and mortality thresholds were not exceeded.
- Distances to threshold were the same for Category 3 and Category 2 fish when fleeing.
- For stationary fish (Figure 7.8), the maximum distance to the TTS threshold was 3300 m, to injury threshold was 160 m and to mortality threshold was 60 m for Category 3 fish.
- The mortality R_{max} threshold was predicted to be 40 m for the Category 2 fish.
- SPL_{peak} thresholds for injury and mortality were only exceeded within 8 m of the noise source.

Table 7.2: Distances from the pile to impact radii for fish (demolition of the Northern Arm, Location 1)

	TTS			Recoverable Injury			Mortality		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
Fleeing (SEL _{cum}) (swim bladder involved in hearing)	400 m *	370 m	120 m	0 m	0 m	0 m	0 m	0 m	0 m
Fleeing (SEL _{cum}) (swim bladder not involved in hearing)	400 m*	370 m	120 m	0 m	0 m	0 m	0 m	0 m	0 m
Stationary (SEL _{cum}) (swim bladder involved in hearing)	3300 m	1700 m	980 m	160 m	150 m	110 m	60 m	60 m	50 m
Stationary (SEL _{cum}) (swim bladder not involved in hearing)	3300 m	1700 m	980 m	160 m	150 m	110 m	40 m	40 m	30 m
SPL _{peak}	-	-	-	8 m	8 m	7 m	8 m	8 m	7 m

*Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted

**For SPL_{peak} only mortality and injury thresholds are available, and are equal



Figure 7.7: Predicted SEL_{cum} impact footprint for fleeing fish for demolition with a hydraulic hammer at the Northern Arm (Location 1)

Notes: TTS – yellow; PTS – orange; mortal injury – red

Source: Uses Google Earth imagery

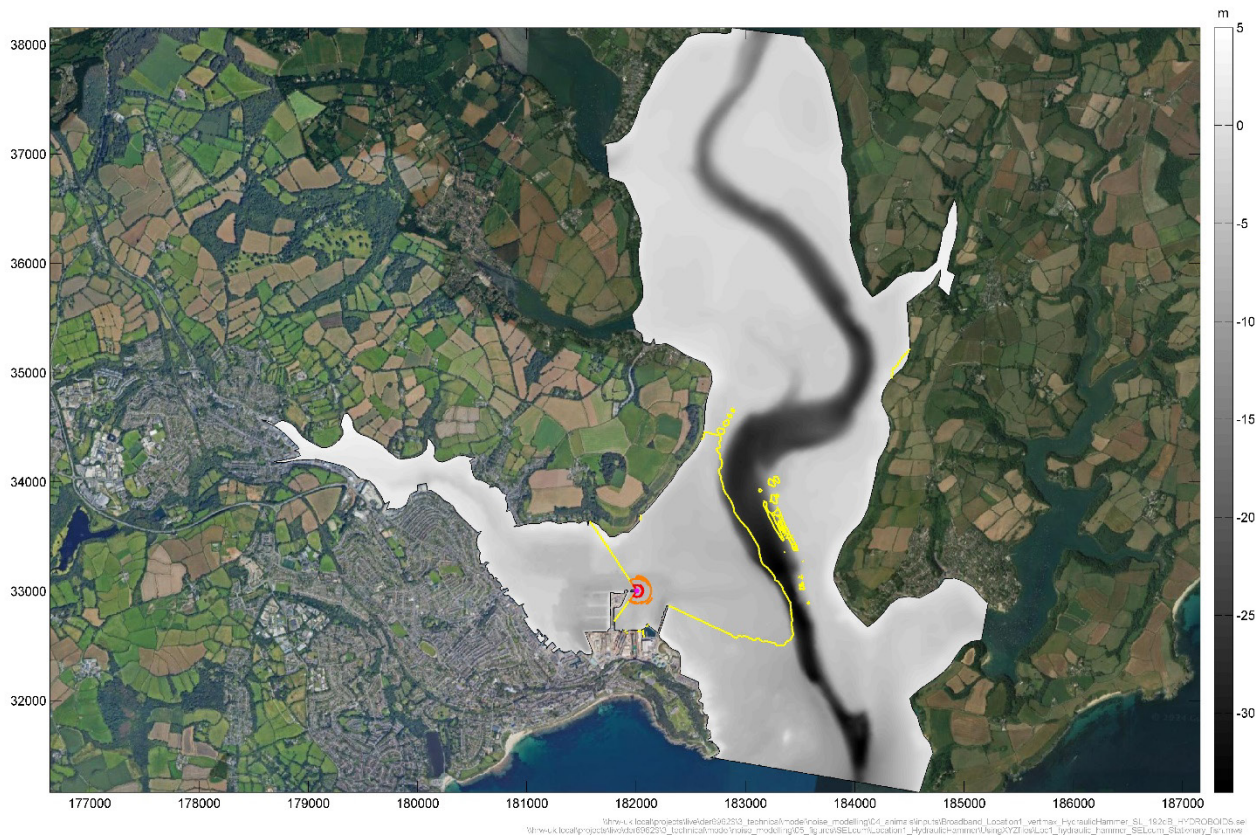


Figure 7.8: Predicted SEL_{cum} impact footprint for stationary fish for demolition with a hydraulic hammer at the Northern Arm (Location 1)

Notes: TTS – yellow; PTS – orange; mortal injury – red

Source: Uses Google Earth imagery

7.2 Location 2 – Western Wharf

7.2.1 Dredging with a backhoe

Backhoe dredging to create the deeper berths for the proposed Falmouth Dock Development was modelled for the north corner of the Western Wharf because this location is worst case in terms of spatial impact, with “lines of sight” extending past the Eastern Breakwater into the Percuil River, as well as to the north east and north west. Backhoe dredging is assumed to be continuous, with the cumulative sound exposure calculated over 24 hours.

Broadband sound field

Figure 7.9 shows the predicted sound pressure levels for the demolition activity noise source. Sound levels decrease with distance from the source, with the sound pressure levels sound dropping below 130 dB re 1µPa approximately 1 km away.

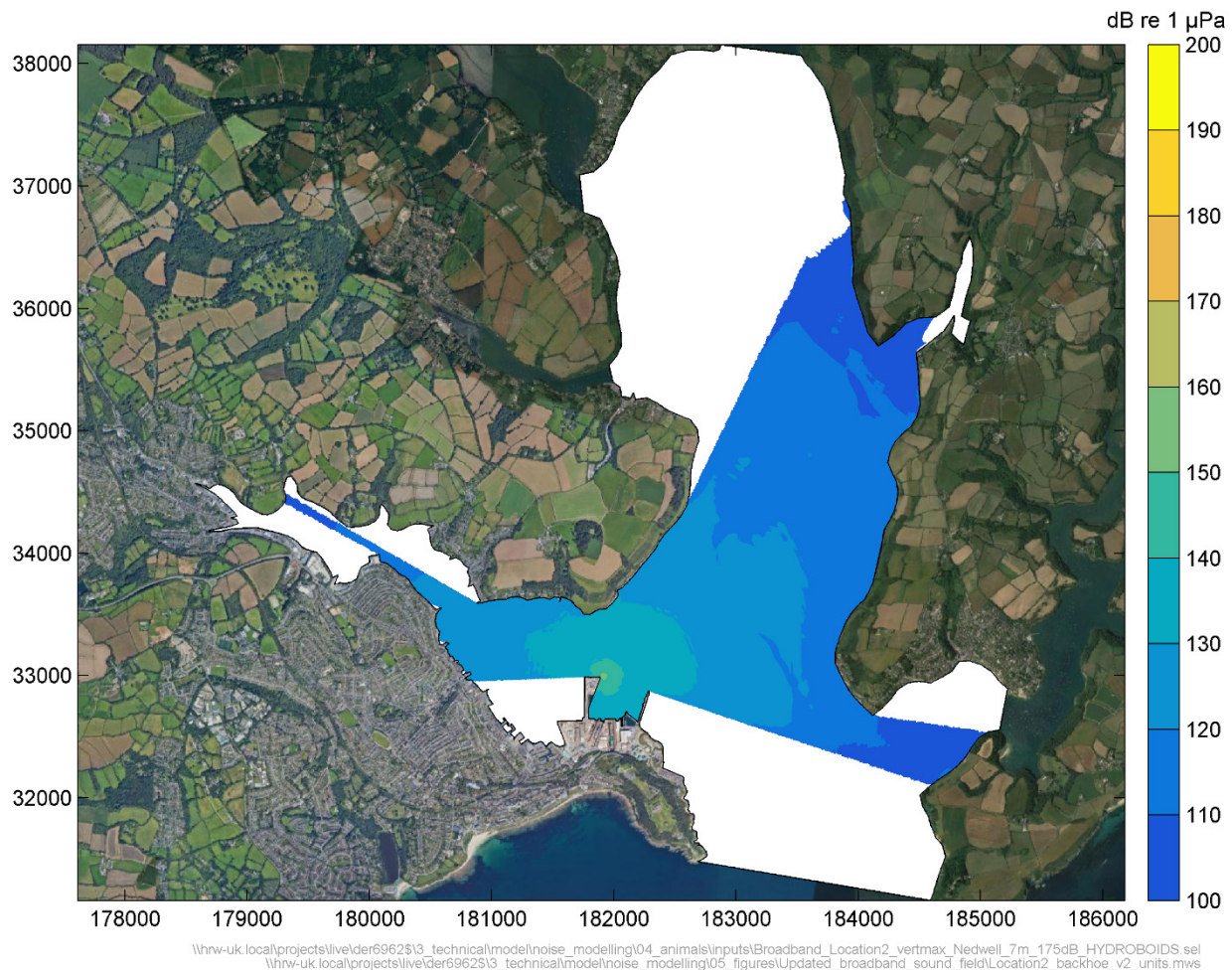


Figure 7.9: Predicted SPL sound field for backhoe dredging at Location 2

Source: Uses Google Earth imagery

Mammals

Table 7.3 shows the predicted distances to the impact thresholds for the mammal groups. SEL_{cum} PTS thresholds were not exceeded. TTS thresholds were exceeded for low frequency cetaceans and very high frequency cetaceans, within 460 m of the noise source and applying to animals between the noise source and the shoreline.

For this activity, it was predicted that:

- For low frequency cetaceans (LF) (Figure 7.10 and very high frequency cetaceans (VHF) (Figure 7.10):
 - The TTS threshold for SEL_{cum} was predicted to be exceeded only within 460 m of the dredging. The threshold was exceeded only for animals between the Falmouth Docks and the Eastern Breakwater;
 - The PTS threshold for SEL_{cum} was predicted not to be exceeded.
- For high frequency cetaceans (HF) and pinniped, no thresholds were predicted to be exceeded.

Table 7.3: Distances to impact threshold for different mammal hearing groups (backhoe dredging at the Western Wharf (Location 2))

	TTS			PTS		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
LF cetaceans (SEL _{cum})	460 m *	390 m	190 m	0 m	0 m	0 m
HF cetaceans (SEL _{cum})	0 m	0 m	0 m	0 m	0 m	0 m
VHF cetaceans (SEL _{cum})	460 m *	390 m	170 m	0 m	0 m	0 m
Pinnipeds (SEL _{cum})	0 m	0 m	0 m	0 m	0 m	0 m

*Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted



Figure 7.10: Predicted SEL_{cum} impact footprint for the very high frequency cetacean hearing group for dredging with a backhoe at the Western Wharf (Location 2)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery

Behavioural disturbance

Areas of potential behavioural disturbance to marine mammals are shown in Figure 7.11, based on the criteria discussed in Section 2.2.2. A low level of behavioural disturbance was predicted within approximately 2.5 km of the noise source. The potential for behavioural disturbances does not account for hearing and sensitivity differences between the mammal groups because insufficient information is available regarding sound levels causing behavioural disturbance.

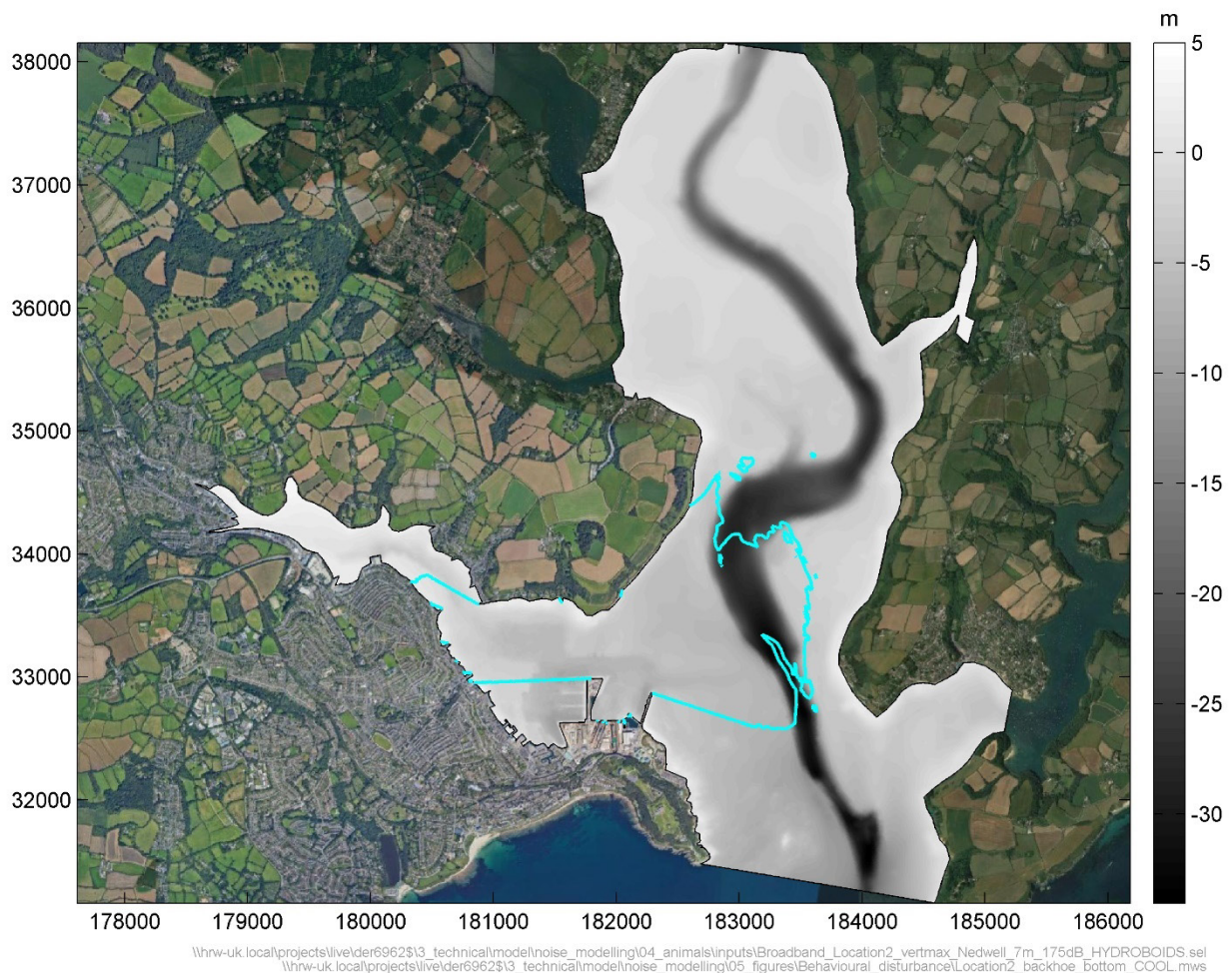


Figure 7.11: Impact contours for potential behavioural disturbance to marine mammals for dredging activities using the backhoe dredger

Notes: Low level disturbance threshold (140 dB re 1µPa) – turquoise; higher level of disturbance (160 dB re 1µPa) – magenta

Source: Uses Google Earth imagery

Fish

Fish impacts for continuous noises, such as the backhoe dredging are based on the RMS sound pressure level, for which the following criteria are defined:

- TTS occurs if the RMS SPL exceeds 158 dB re 1 µPa for 12 hours;
- Injury occurs if the RMS SPL exceeds 170 dB re 1 µPa for 48 hours.

Neither threshold is exceeded in this case.

7.2.2 Percussive piling with soft start only

Percussive piling will be required to install piles supporting the proposed suspended decks. Percussive piling is assumed to be used for a maximum of four hours in 24 hours.

Broadband sound field

Figure 7.12 shows the predicted single strike SEL sound field for the percussive piling noise source at the Western Wharf location. Sound levels decrease with distance from the source,

with the single strike SEL sound dropping below 170 dB re 1 μ Pa²s approximately 600 m away and below 160 dB re 1 μ Pa²s approximately 1750 m away.

It is noted that the location selected for modelling this activity (the northern-most point of Western Wharf/eastern-most point of Northern Wharf) is the worst case in terms of spatial extent, because the “lines of sight” are longest from this point in all directions. Piling further south along Western Wharf will impact smaller areas as the structures themselves (i.e. the existing causeway and Eastern Breakwater, provide a sheltering effect. An indicative area for piling at the south of the Western Wharf is given in Figure 7.13. This figure shows only the indicative areas that would be expected to have noise related to the activity, and has not been modelled at this location.

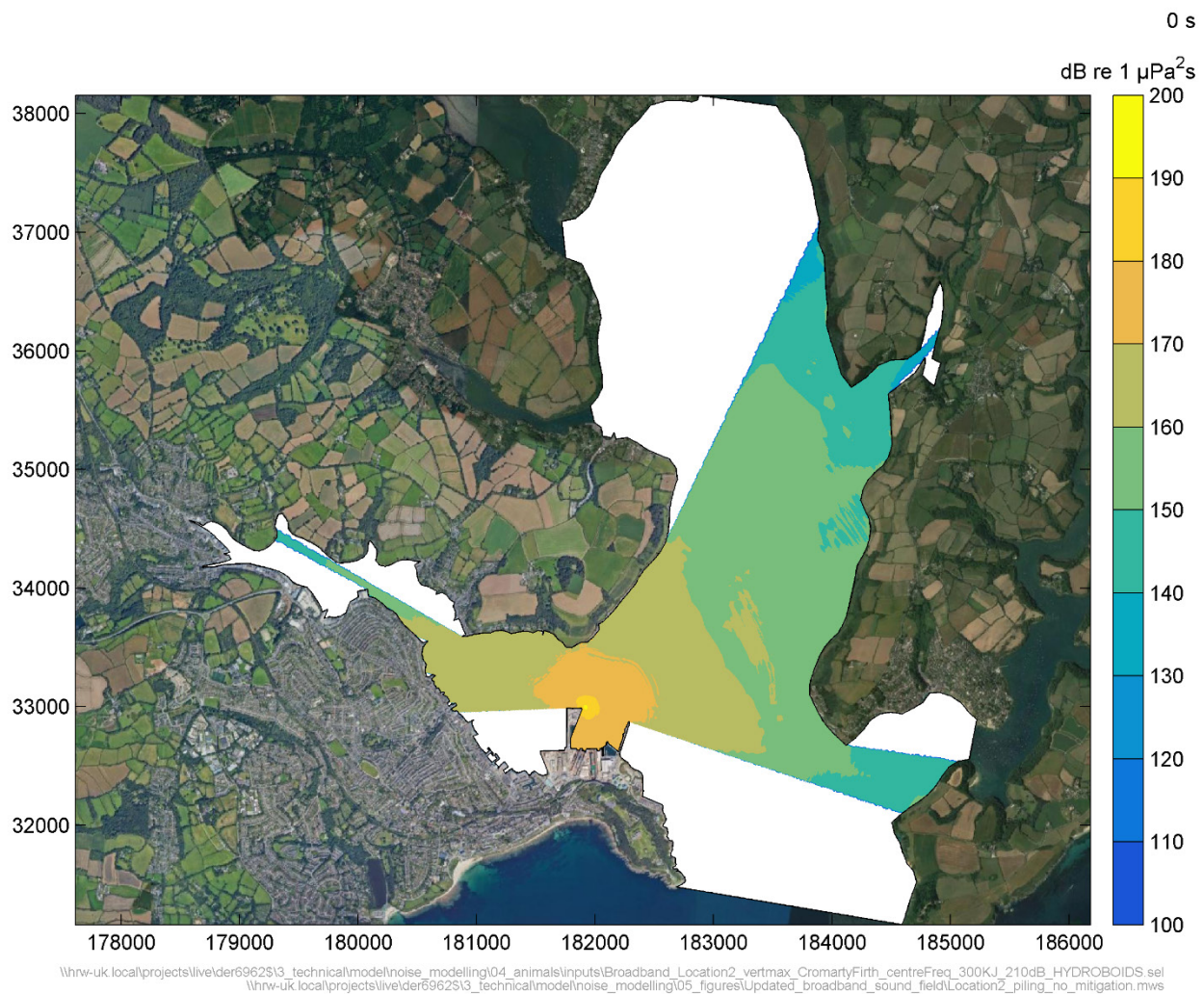


Figure 7.12: Predicted single strike SEL sound field for percussive piling at Location 2

Source: Uses Google Earth imagery

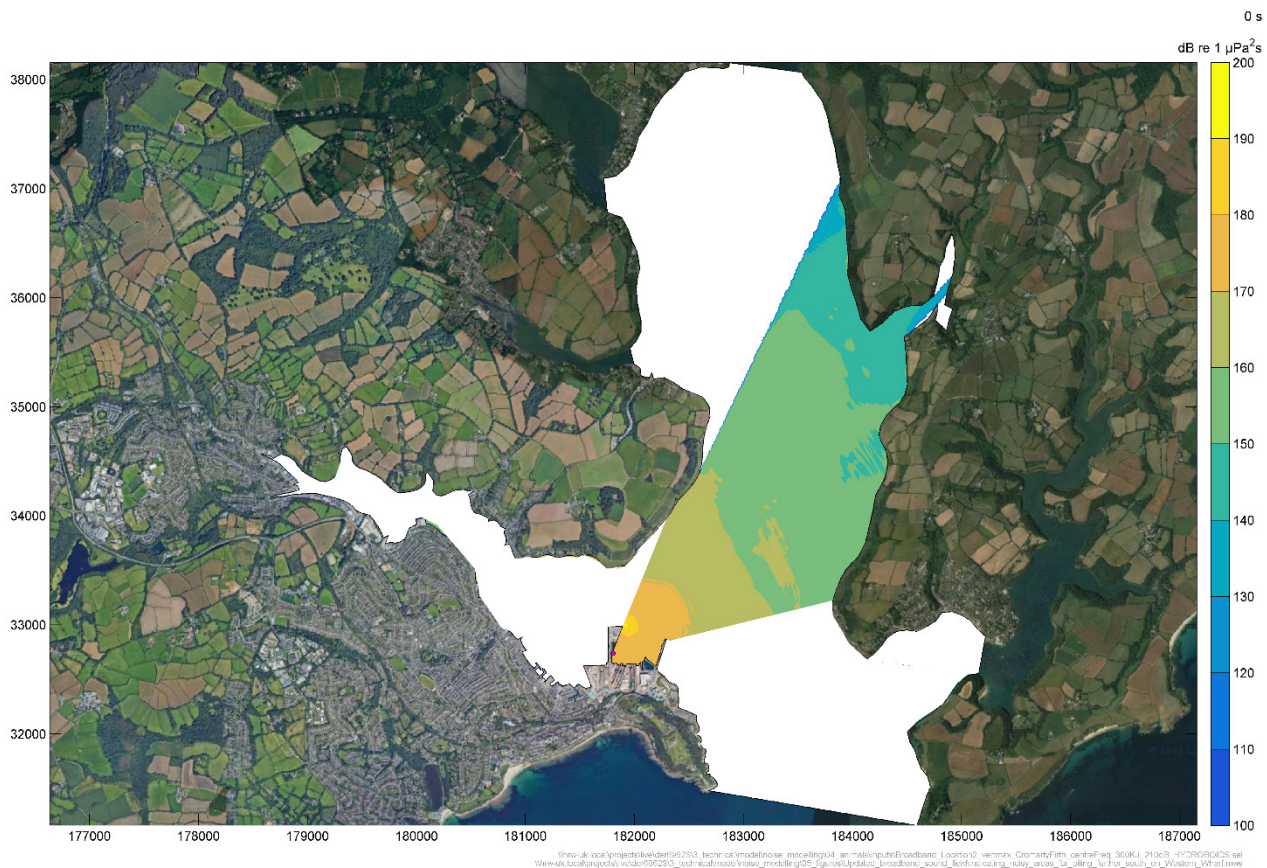


Figure 7.13: Indicating how the spatial extent of the noise field would change with piling further to the south on the Western Wharf (note indicative only, modelling not undertaken for this location)

Source: Uses Google Earth imagery

Mammals

Table 7.4 shows the predicted distances to the impact thresholds for the mammal groups. For this activity, PTS and TTS thresholds for low frequency cetaceans and very high frequency cetaceans were predicted to be exceeded over the width of the estuary.

For this activity, it was predicted that:

- For low frequency cetaceans (LF):
 - The TTS threshold for SEL_{cum} was predicted to be exceeded within 3500 m of the piling (Figure 7.14);
 - The PTS threshold for SEL_{cum} was predicted to be exceeded within 1500 m.
- For high frequency cetaceans (HF):
 - The maximum distance to the TTS threshold was 1300 m;
 - The PTS threshold for SEL_{cum} was predicted to be exceeded within 460 m. Threshold exceedance in this case occurred only for animals between the noise source and the shoreline, where fleeing is restricted.
- For very high frequency cetaceans (VHF) (Figure 7.15):
 - The maximum distance to the SEL_{cum} TTS threshold was 4100 m;
 - The PTS threshold for SEL_{cum} was predicted to be exceeded within 2000 m.
- For pinnipeds:
 - The maximum distance to the TTS threshold was 2300 m;

- The maximum distance to the PTS threshold was 1100 m.
- Distances to impact threshold were much smaller with SPL_{peak} compared to the SEL_{cum} :
 - Very high frequency cetaceans were predicted to experience peak SPL above their TTS threshold up to 1300 m from the piling activity, and PTS up to 630 m;
 - Distances to peak SPL thresholds were less than 140 m for the other mammal groups.

Table 7.4: Distances to impact threshold for different mammal hearing groups (percussive piling with soft start procedure at the Western Wharf, Location 2)

	TTS			PTS		
	R_{max}	R_{95}	R_{mean}	R_{max}	R_{95}	R_{mean}
LF cetaceans (SEL_{cum})	3500 m	2900 m	1200 m	1500 m	1200 m	700 m
HF cetaceans (SEL_{cum})	1300 m	1000 m	360 m	460 m *	370 m	210 m
VHF cetaceans (SEL_{cum})	4100 m	3300 m	1400 m	2000 m	1700 m	850 m
Pinnipeds (SEL_{cum})	2300 m	2100 m	970 m	1100 m	840 m	270 m
LF cetaceans (SPL_{peak})	130 m	130 m	100 m	120 m	100 m	60 m
HF cetaceans (SPL_{peak})	30 m	30 m	30 m	20 m	20 m	10 m
VHF cetaceans (SPL_{peak})	1300 m	760 m	570 m	630 m	440 m	340 m
Pinnipeds (SPL_{peak})	140 m	130 m	110 m	120 m	100 m	60 m

*Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted



Figure 7.14: Predicted SEL_{cum} impact footprint for the low frequency cetacean hearing group percussive piling, with a soft start procedure, at the Western Wharf (Location 2)

Notes: TTS - yellow; PTS - red

Source: Uses Google Earth imagery

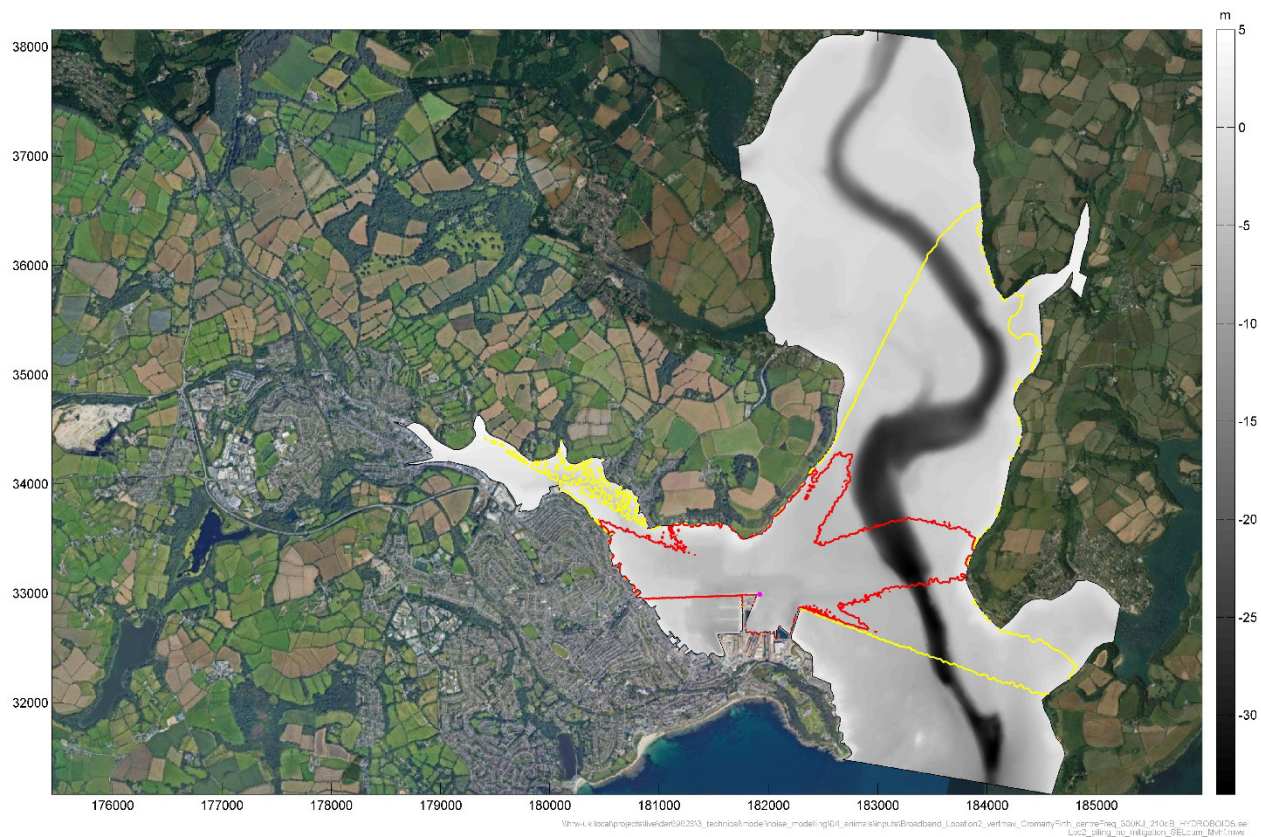


Figure 7.15: Predicted SEL_{cum} impact footprint for the very high frequency cetacean hearing group percussive piling, with a soft start procedure, at the Western Wharf (Location 2)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery

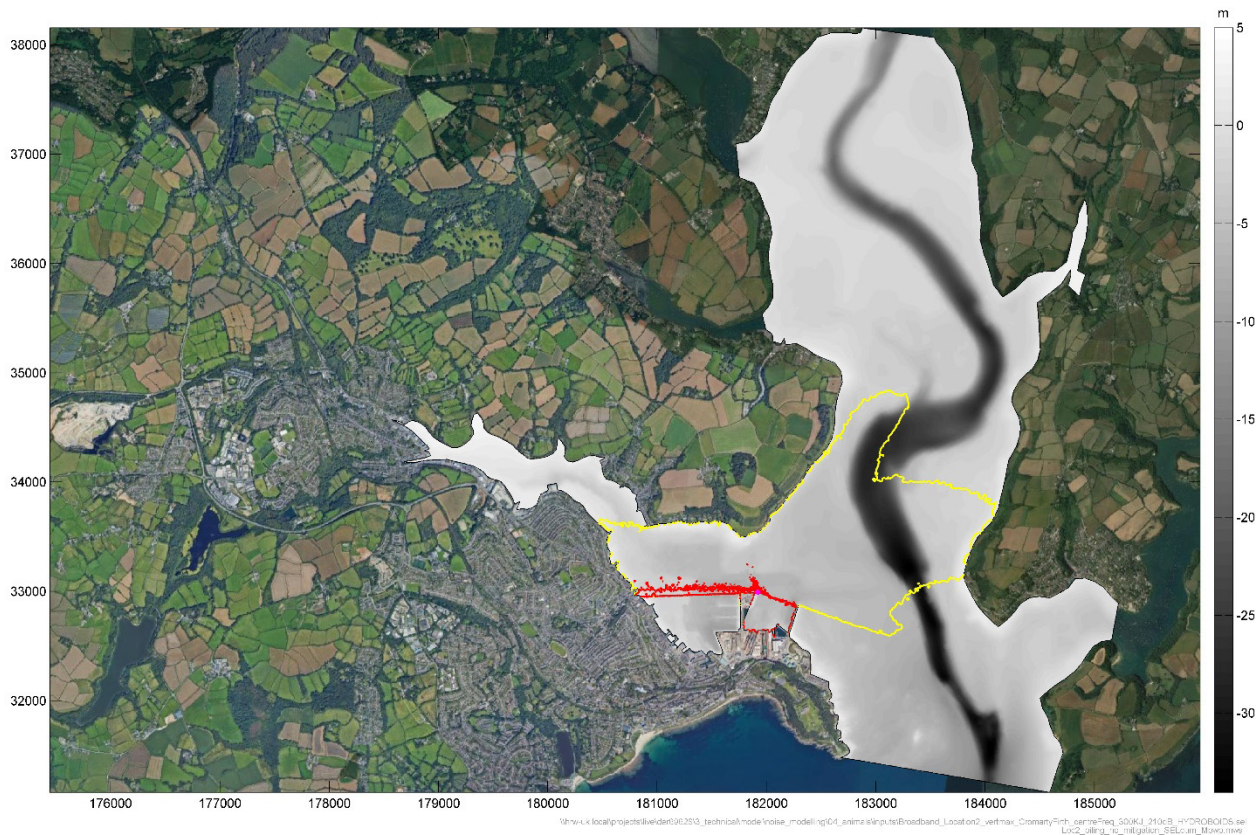


Figure 7.16: Predicted SEL_{cum} impact footprint for pinniped for percussive piling, with a soft start procedure, at the Western Wharf (Location 2)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery

Behavioural disturbance

Worst-case areas of potential behavioural disturbance to marine mammals are shown in Figure 7.17, based on the criteria discussed in Section 2.2.2. The potential for low and higher level disturbance was predicted across the estuary (in areas not shadowed by headlands or jetties). The potential for behavioural disturbances does not account for hearing and sensitivity differences between the mammal groups because insufficient information is available regarding sound levels causing behavioural disturbance.

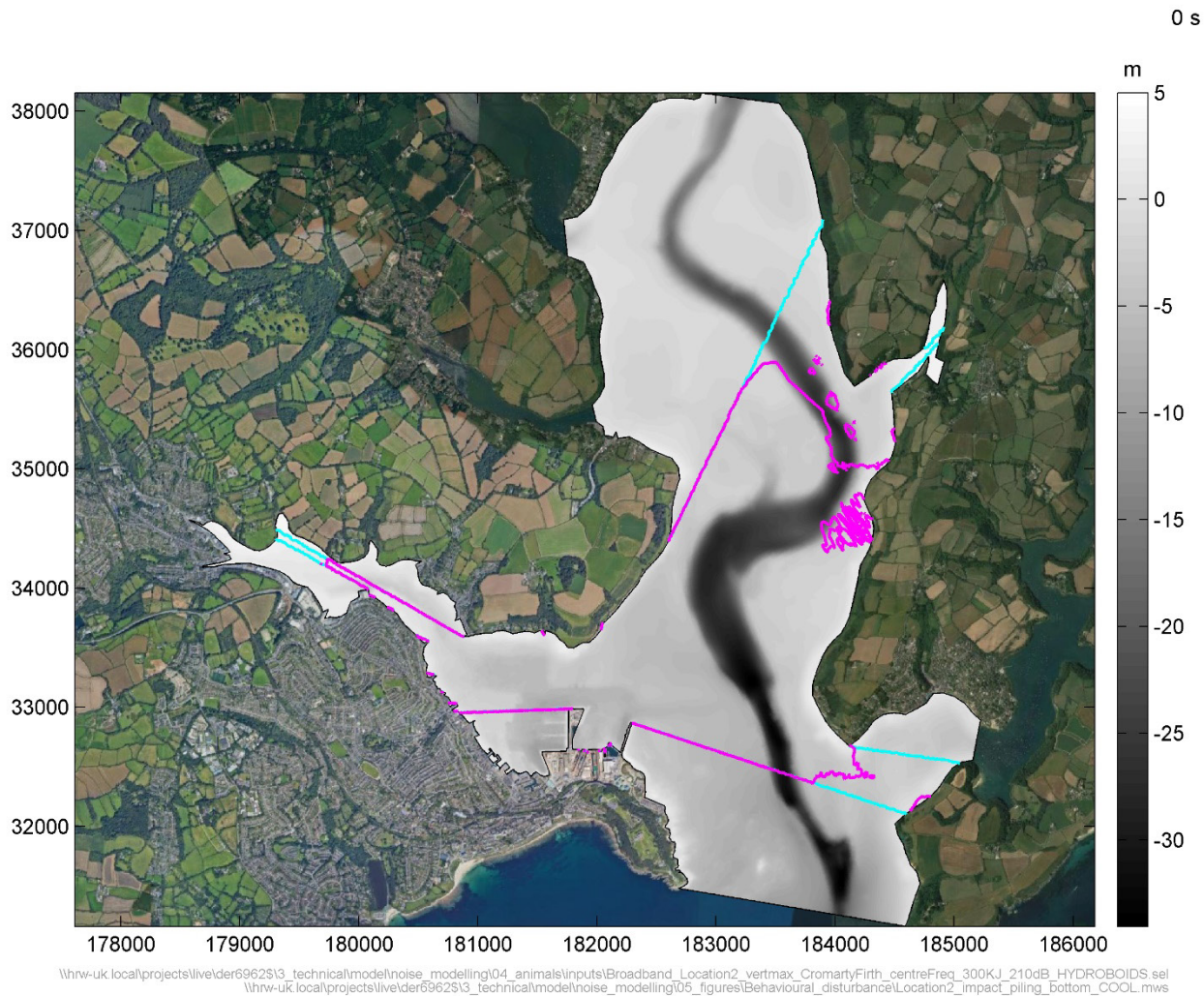


Figure 7.17: Impact contours for potential behavioural disturbance to marine mammals for piling activities using percussive piling (Location 2)

Notes: Low level disturbance threshold (140 dB re 1µPa) – turquoise; higher level of disturbance (160 dB re 1µPa) – magenta

Source: Uses Google Earth imagery

Fish

Impact distances are given for the most sensitive hearing groups, fish with swim bladders involved in hearing (category 3) and fish with swim bladders not involved in hearing (Category 2). Fish may flee on exposure to noise, or may display other behaviours, such as swimming to the seabed. To cover the range of potential behaviours, fish are modelled as fleeing or stationary. The distances to impact thresholds for the piling activity (with soft start) are shown in Table 7.5:

- For fleeing fish (Figure 7.18):
 - The TTS threshold was exceeded within 1500 m of the noise;
 - Recoverable injury and mortality thresholds were exceeded within 460 m of the piling, representing fish trapped between the noise and the Eastern Breakwater;
 - R_{max} values were the same for both hearing groups, although the R_{95} and R_{mean} values for the mortality threshold differed.

- For stationary fish (Figure 7.19), the maximum distance to the TTS threshold was 4100 m, to injury threshold was 1700 m and to mortality threshold was 1100 m for Category 3 fish and 940 m for Category 2 fish.
- SPL_{peak} thresholds for injury and mortality were exceeded within 460 m of the noise source.

Table 7.5: Distances from the pile to impact radii for fish for percussive piling with soft-start at Location 2

	TTS			Recoverable Injury			Mortality		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
Fleeing (SEL _{cum}) (swim bladder involved in hearing)	1500 m	1300 m	650 m	460 m *	400 m	210 m	460 m*	390 m	170 m
Fleeing (SEL _{cum}) (swim bladder not involved in hearing)	1500 m	1300 m	650 m	460 m *	400 m	210 m	460 m*	360 m	210 m
Stationary (SEL _{cum}) (swim bladder involved in hearing)	4100 m	3600 m	1700 m	1700 m	1300 m	880 m	1300 m	860 m	630 m
Stationary (SEL _{cum}) (swim bladder not involved in hearing)	4100 m	3600 m	1700 m	1700 m	1300 m	880 m	940 m	580 m	450 m
SPL _{peak}				460 m	270 m	230 m	460 m	270 m	230 m

*Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted

**For SPL_{peak} only mortality and injury thresholds are available, and are equal



Figure 7.18: Predicted SEL_{cum} impact footprint for fleeing fish for percussive piling, with a soft start procedure, at the Western Wharf (Location 2)

Notes: TTS – yellow; PTS – orange; mortal injury – red

Source: Uses Google Earth imagery

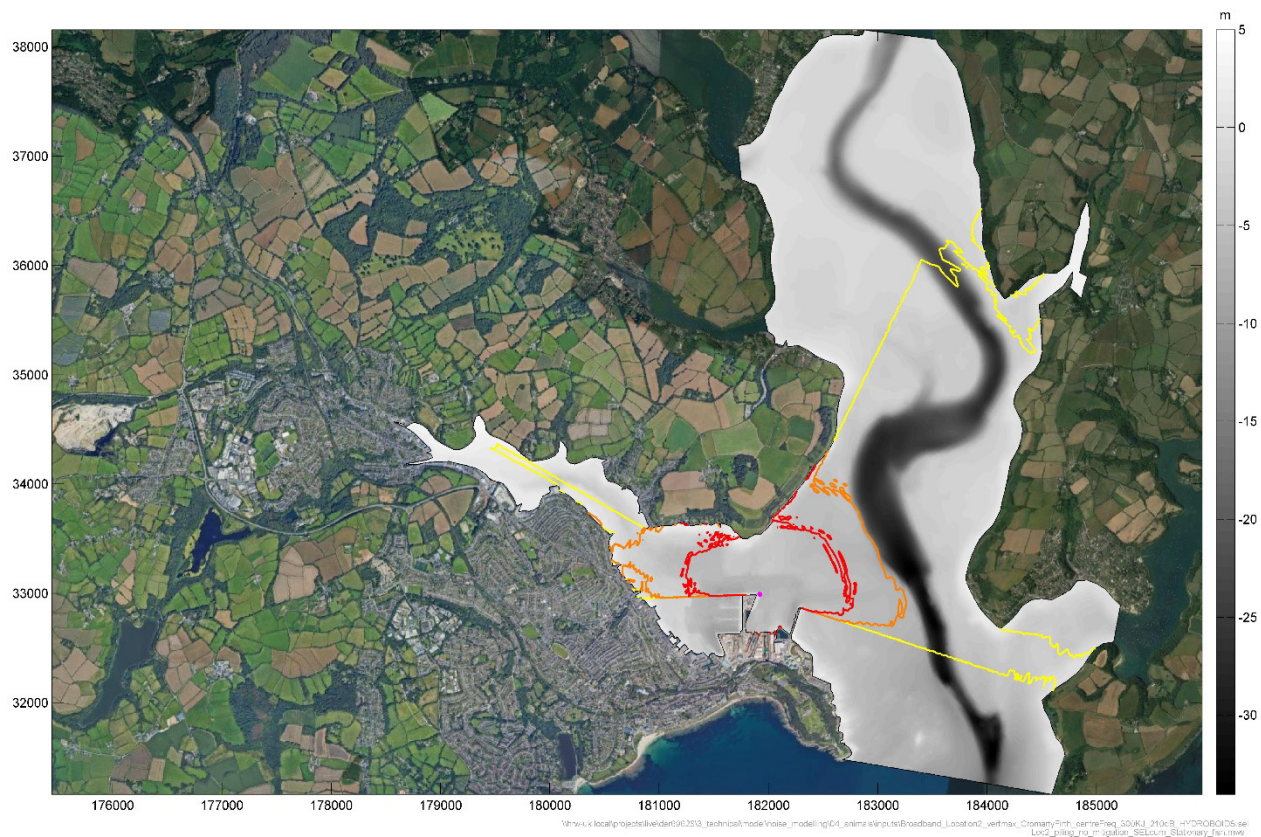


Figure 7.19: Predicted SEL_{cum} impact footprint for Category 3 stationary fish for percussive piling, with a soft start procedure, at the Western Wharf (Location 2)

Notes: TTS – yellow; PTS – orange; mortal injury – red

Source: Uses Google Earth imagery

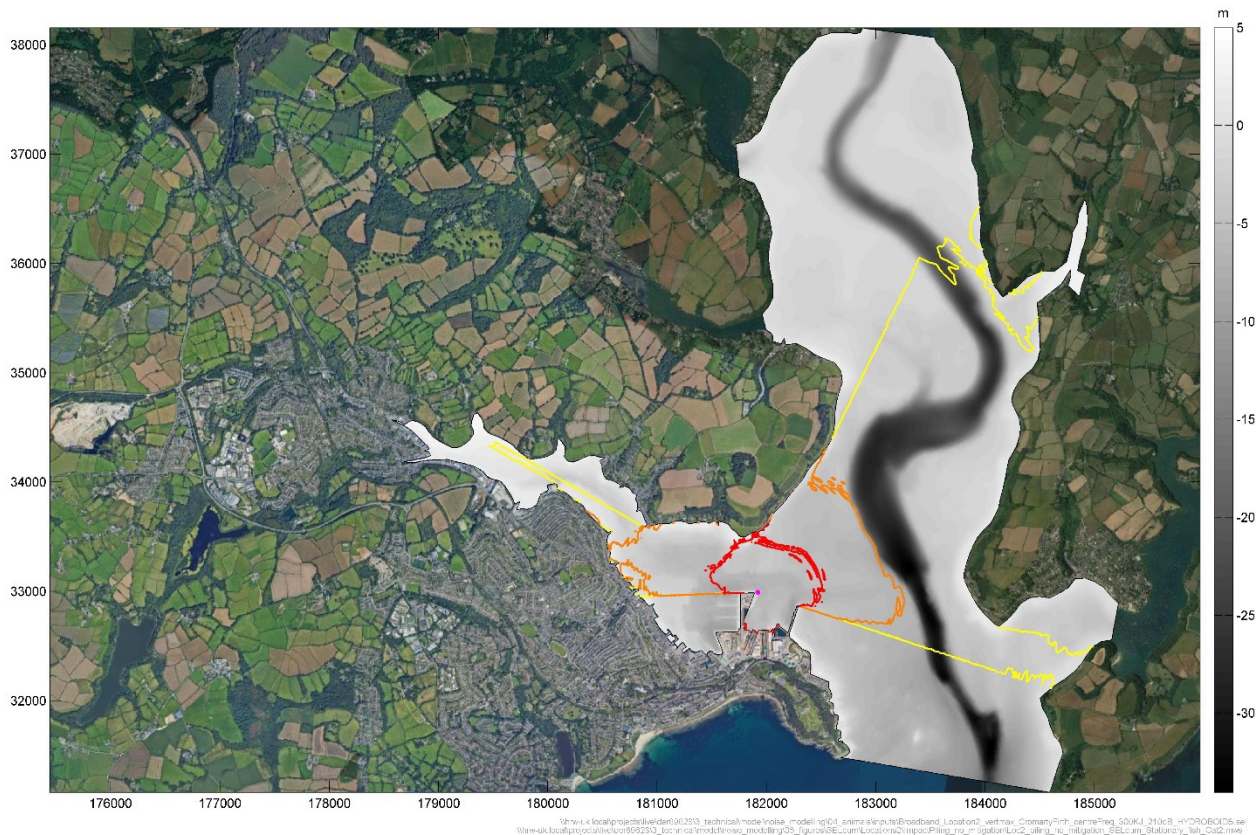


Figure 7.20: Predicted SEL_{cum} impact footprint for Category 2 stationary fish for percussive piling, with a soft start procedure, at the Western Wharf (Location 2)

Notes: TTS – yellow; PTS – orange; mortal injury – red

Source: Uses Google Earth imagery

7.2.3 Percussive piling with soft start and bubble curtain

Percussive piling will be required to install piles supporting the proposed suspended deck. Percussive piling is assumed to be used for a maximum of four hours in 24 hours. In this case, the source level is reduced to replicate the effect of a bubble curtain on the noise field, as described in Section 5.3.2.

Broadband sound field

Figure 7.21 shows the predicted single strike SEL sound field for the percussive piling noise source at the Western Wharf location. Sound levels decrease with distance from the source, with the single strike SEL sound dropping below 160 dB re 1μPa²s approximately 400 m away and below 150 dB re 1μPa²s approximately 1150 m away.

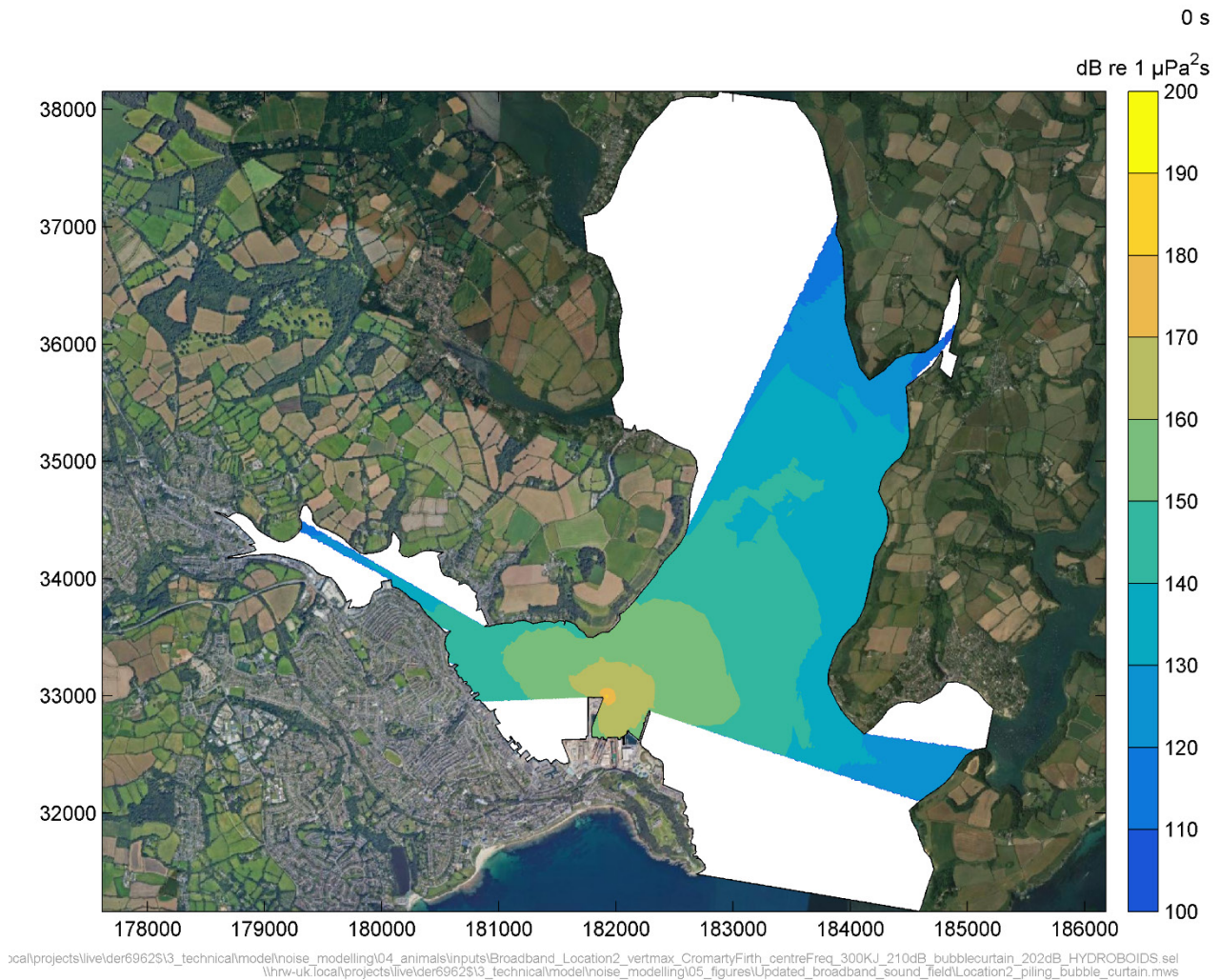


Figure 7.21: Predicted single strike SEL sound field for percussive piling at Location 2, with a bubble curtain

Source: Uses Google Earth imagery

Mammals

Table 7.6 shows the predicted distances to the impact thresholds for the mammal groups for piling at Location 2 with a bubble curtain. The areas exceeding the SEL_{cum} impact threshold are much reduced compared with piling without a bubble curtain.

For this activity, it was predicted that:

- For low frequency cetaceans (LF):
 - The TTS threshold for SEL_{cum} was predicted to be exceeded within 1300 m of the piling (Figure 7.22);
 - The PTS threshold for SEL_{cum} was predicted to be exceeded within 460 m.
- For high frequency cetaceans (HF):
 - The maximum distance to the TTS threshold was 460 m, representing any animals trapped between the noise source and the Eastern Breakwater;
 - The PTS threshold for SEL_{cum} was predicted to not be exceeded.
- For very high frequency cetaceans (VHF) (Figure 7.23):
 - The maximum distance to the SEL_{cum} TTS threshold was 2300 m;

- The PTS threshold for SEL_{cum} was predicted to be exceeded within 1500 m.
- For pinnipeds:
 - The maximum distance to the TTS threshold was 460 m, representing any animals trapped between the noise source and the Eastern Breakwater;
 - The PTS threshold for SEL_{cum} was predicted to not be exceeded.
- Distances to impact threshold were much smaller with SPL_{peak} compared to the SEL_{cum}:
 - Very high frequency cetaceans were predicted to experience peak SPL above their TTS threshold up to 130 m from the piling activity, and PTS up to 60 m;
 - Distances to peak SPL thresholds were less than 20 m for the other mammal groups.

Table 7.6: Distances to impact threshold for different mammal hearing groups (percussive piling with soft start procedure and bubble curtain at the Western Wharf, Location 2)

	TTS			PTS		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
LF cetaceans (SEL _{cum})	1300 m	1200 m	600 m	460 m *	410 m	220 m
HF cetaceans (SEL _{cum})	460 m *	350 m	200 m	0 m	0 m	0 m
VHF cetaceans (SEL _{cum})	2300 m	2000 m	1000 m	1500 m	1200 m	460 m
Pinnipeds (SEL _{cum})	460 m *	410 m	210 m	0 m	0 m	0 m
LF cetaceans (SPL _{peak})	20 m	20 m	10 m	7 m	7 m	6 m
HF cetaceans (SPL _{peak})	4 m	4 m	3 m	2 m	2 m	2 m
VHF cetaceans (SPL _{peak})	130 m	130 m	100 m	60 m	60 m	50 m
Pinnipeds (SPL _{peak})	20 m	20 m	20 m	10 m	10 m	7 m

*Threshold exceedance occurs only for animals between the noise source and the shoreline, where fleeing is restricted

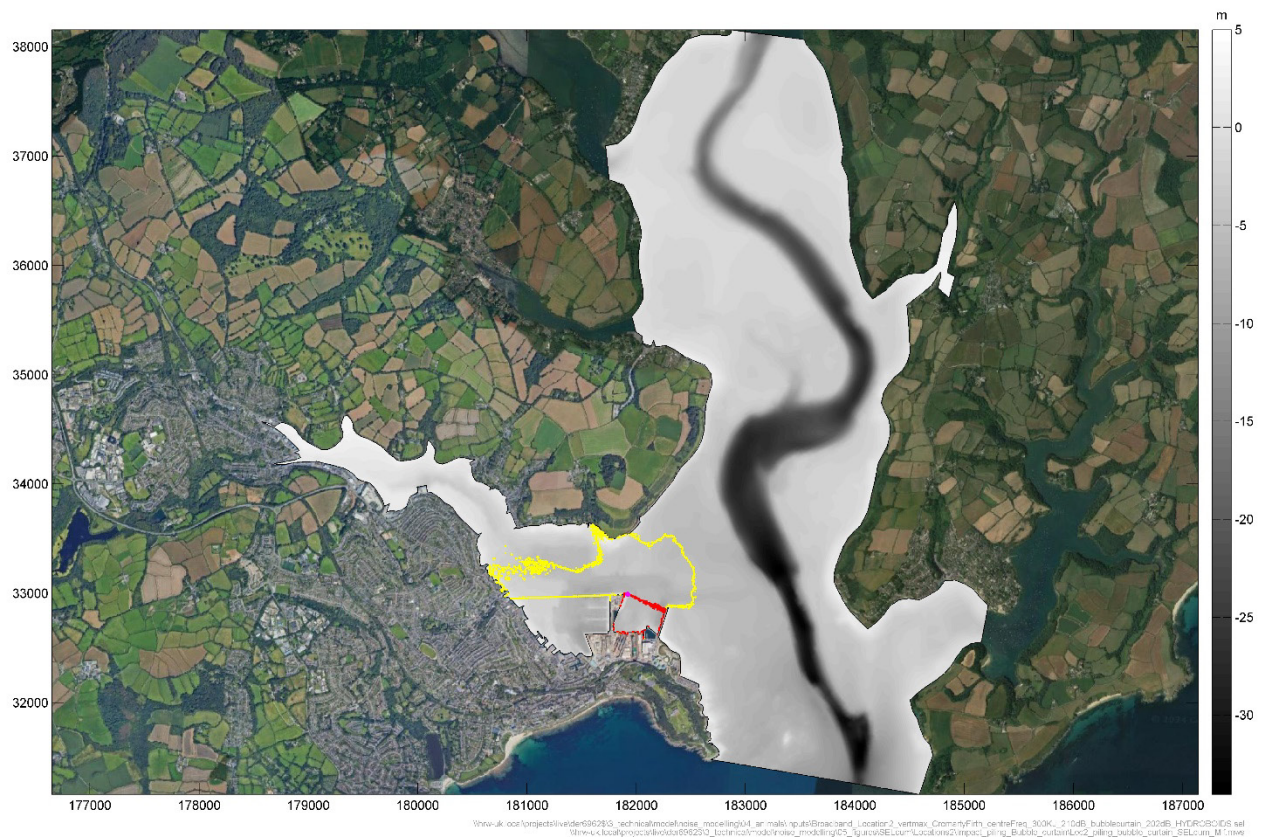


Figure 7.22: Predicted SEL_{cum} impact footprint for the low frequency cetacean hearing group percussive piling, with a soft start procedure and a bubble curtain, at the Western Wharf (Location 2)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery

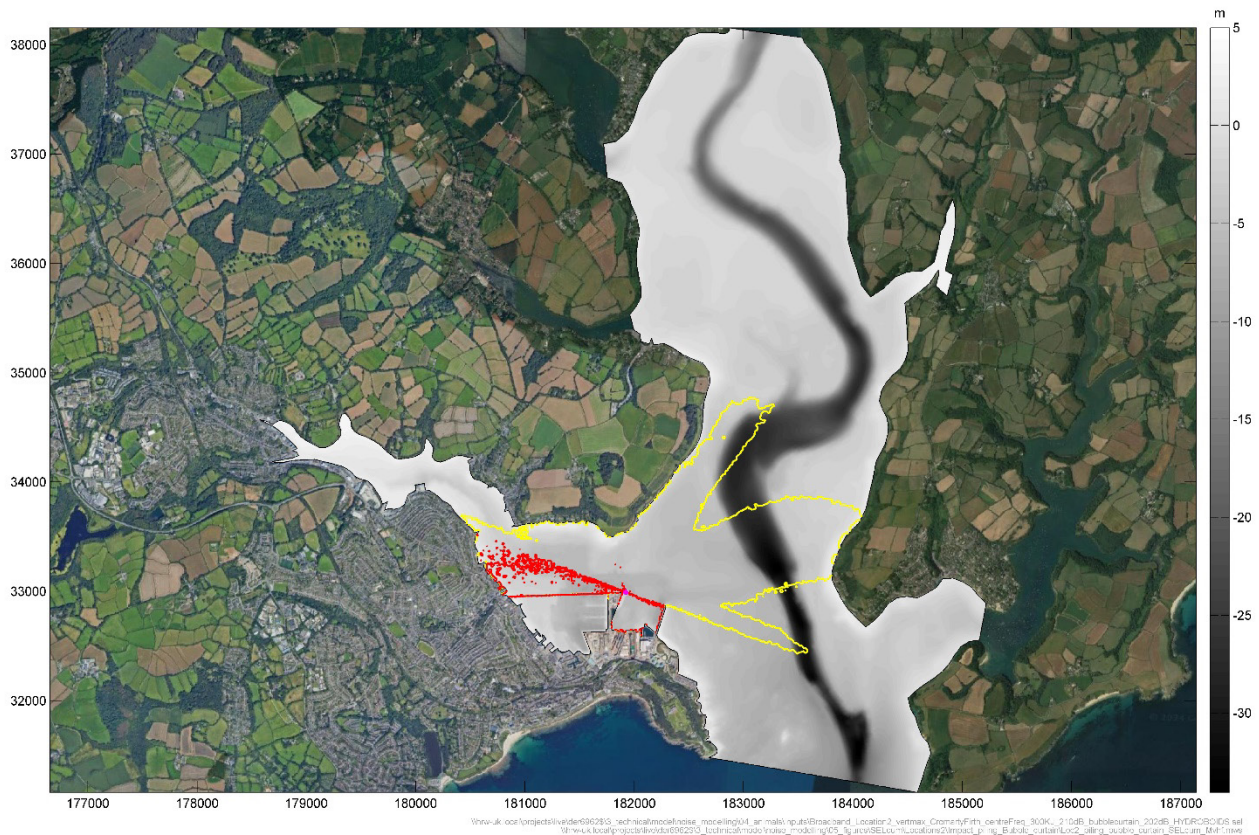


Figure 7.23: Predicted SEL_{cum} impact footprint for the very high frequency cetacean hearing group percussive piling, with a soft start procedure and a bubble curtain, at the Western Wharf (Location 2)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery

Behavioural disturbances

Areas of potential behavioural disturbance to marine mammals are shown in Figure 7.24, based on the criteria discussed in Section 2.2.2. A higher level of behavioural disturbance was predicted within approximately 2 km of the noise source. The potential for low level disturbance was predicted across the estuary. The potential for behavioural disturbances does not account for hearing and sensitivity differences between the mammal groups because insufficient information is available regarding sound levels causing behavioural disturbance.

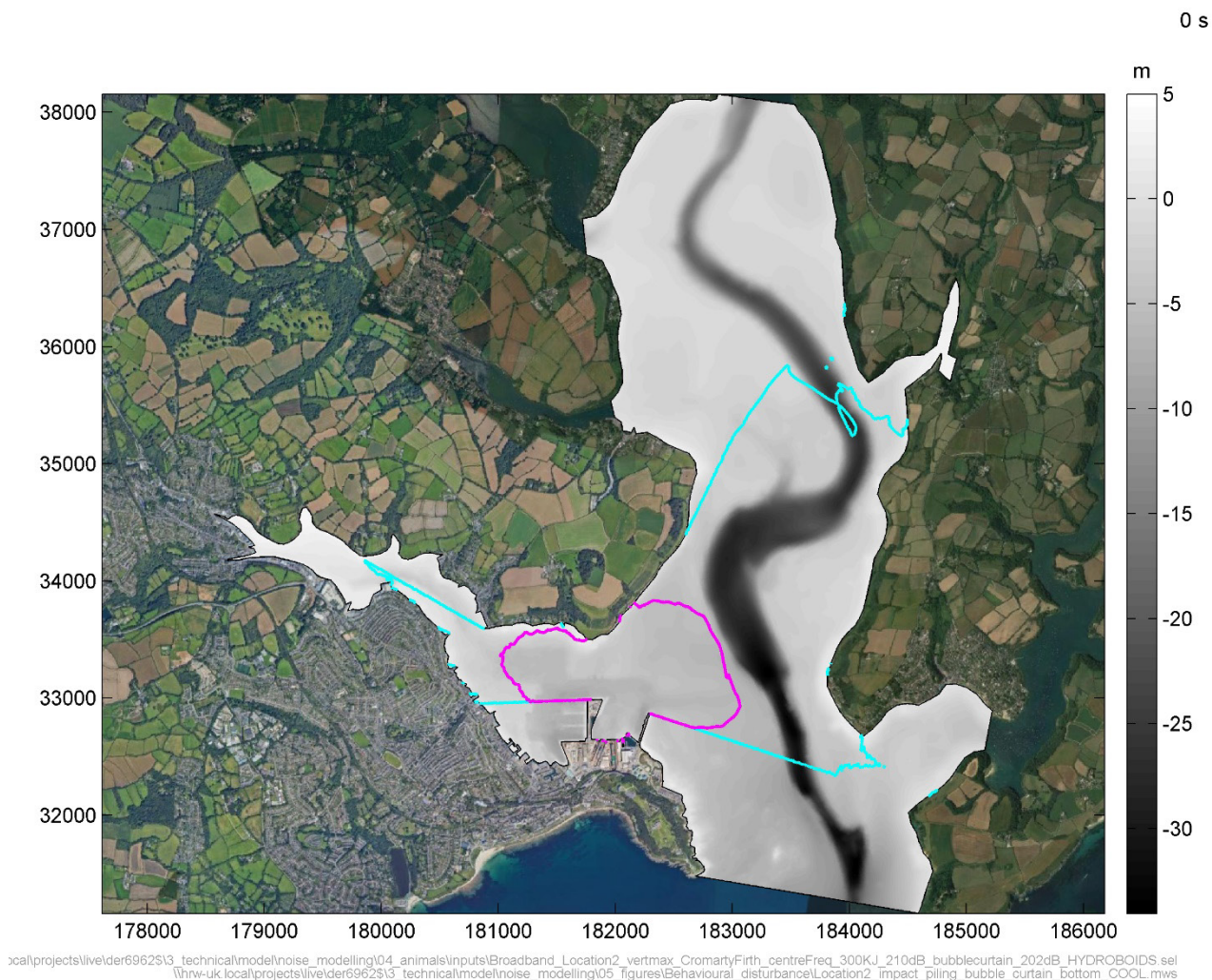


Figure 7.24: Impact contours for potential behavioural disturbance to marine mammals for piling activities using percussive piling with a bubble curtain (Location 2)

Notes: Low level disturbance threshold (140 dB re 1µPa) – turquoise; higher level of disturbance (160 dB re 1µPa) – magenta

Source: Uses Google Earth imagery

Fish

Impact distances are given for the most sensitive hearing groups, fish with swim bladders involved in hearing (category 3) and fish with swim bladders not involved in hearing (category 2). Fish may flee on exposure to noise, or may display other behaviours, such as swimming to the seabed. To cover the range of potential behaviours, fish are modelled as fleeing or stationary. The distances to impact thresholds for the piling activity with soft-start and bubble curtain in place are shown in Table 7.7:

- For Category 2 and 3 fleeing fish:
 - The TTS threshold was exceeded within 460 m of the noise;
 - Recoverable injury and mortality thresholds were not predicted to be exceeded.
- For stationary fish (Figure 7.25), the maximum distance to the TTS threshold was 1700 m, to injury threshold was 280 m and to mortality threshold was 140 m for category 3 fish and 80 m for category 2 fish.
- SPL_{peak} thresholds for injury and mortality were exceeded within 30 m of the noise source.

Table 7.7: Distances from the pile to impact radii for fish (percussive piling with soft start and bubble curtain at Location 2)

	TTS			Recoverable Injury			Mortality		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
Fleeing (SEL _{cum}) (swim bladder involved in hearing)	460 m *	410 m	220 m	0 m	0 m	0 m	0 m	0 m	0 m
Fleeing (SEL _{cum}) (swim bladder not involved in hearing)	460 m *	410 m	220 m	0 m	0 m	0 m	0 m	0 m	0 m
Stationary (SEL _{cum}) (swim bladder involved in hearing)	1700 m	1600 m	820 m	280 m	270 m	210 m	140 m	140 m	120 m
Stationary (SEL _{cum}) (swim bladder not involved in hearing)	1700 m	1600 m	820 m	280 m	270 m	210 m	80 m	80 m	70 m
SPL _{peak} **				30 m	30 m	30 m	30 m	30 m	30 m

*Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted

**For SPL_{peak} only mortality and injury thresholds are available, and are equal

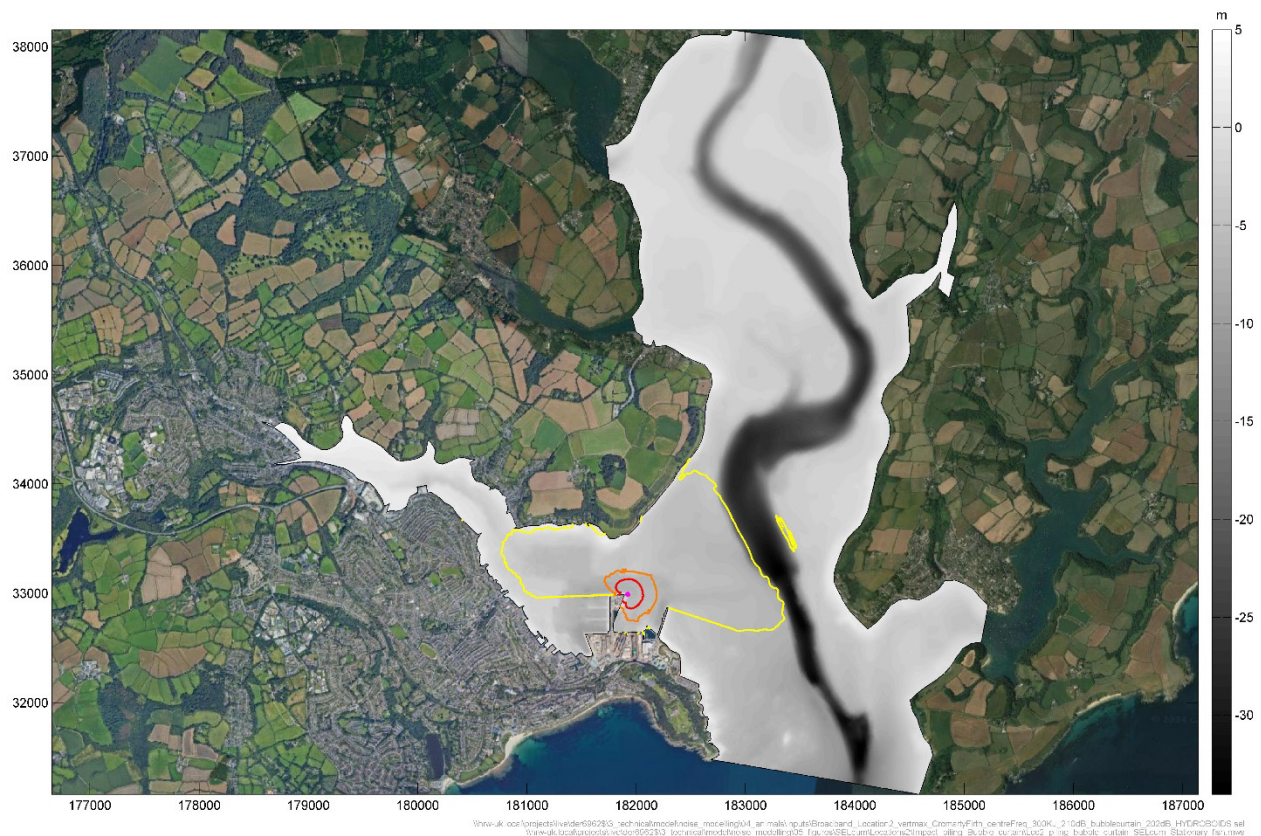


Figure 7.25: Predicted SEL_{cum} impact footprint for the stationary fish (category 3) for percussive piling, with a soft start procedure and a bubble curtain, at the Western Wharf (Location 2)

Notes: TTS – yellow; PTS – orange; mortal injury – red

Source: Uses Google Earth imagery

7.3 Location 3 – Queen’s Wharf

7.3.1 Percussive piling with soft start only

Percussive piling will be required to install piles supporting the proposed suspended deck. Percussive piling is assumed to be used for a maximum of four hours in 24 hours.

Broadband sound field

Figure 7.26 shows the predicted broadband single strike SEL sound field for the percussive piling noise source at the Western Wharf location. Sound levels decrease with distance from the source, with the single strike SEL sound dropping below 170 dB re 1 μ Pa²s approximately 500 m away and below 160 dB re 1 μ Pa²s approximately 1500 m away.

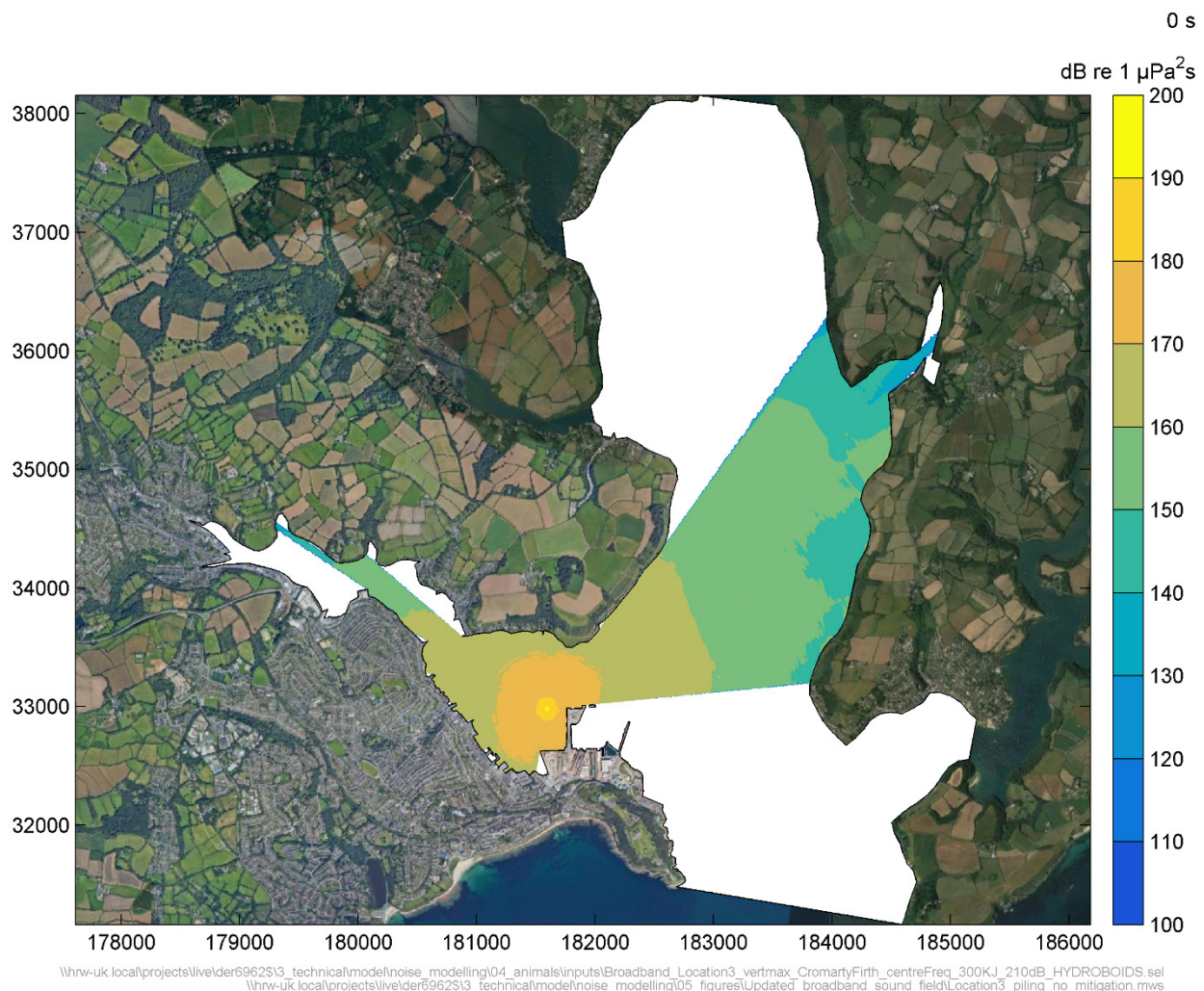


Figure 7.26: Predicted single strike SEL sound field for percussive piling at Location 3

Source: Uses Google Earth imagery

Mammals

Table 7.8 shows the predicted distances to the impact thresholds for the mammal groups. For this activity, PTS and TTS thresholds for low frequency cetaceans and very high frequency cetaceans were predicted to be exceeded over the width of the estuary.

For this activity, it was predicted that:

- For low frequency cetaceans (LF):

- The TTS threshold for SEL_{cum} was predicted to be exceeded within 3600 m of the piling (Figure 7.27);
- The PTS threshold for SEL_{cum} was predicted to be exceeded within 2000 m, extending to the main channel through Carrick Roads.
- For high frequency cetaceans (HF):
 - The maximum distance to the TTS threshold was 860 m;
 - The PTS threshold for SEL_{cum} was predicted to not be exceeded.
- For very high frequency cetaceans (VHF) (Figure 7.28):
 - The maximum distance to the SEL_{cum} TTS threshold was 3800 m;
 - The PTS threshold for SEL_{cum} was predicted to be exceeded within 2600 m, extending eastward to the far side of the estuary.
- For pinnipeds (Figure 7.29):
 - The maximum distance to the TTS threshold was 3100 m;
 - The maximum distance to the PTS threshold was 800 m.
- Distances to impact threshold were much smaller with SPL_{peak} compared to the SEL_{cum} :
 - Very high frequency cetaceans were predicted to experience peak SPL above their TTS threshold up to 1100 m from the piling activity, and PTS up to 440 m;
 - Distances to peak SPL thresholds were less than 140 m for the other mammal groups.

Table 7.8: Distances to impact threshold for different mammal hearing groups (percussive piling with soft start at the Queen's Wharf, Location 3)

	TTS			PTS		
	R_{max}	R_{95}	R_{mean}	R_{max}	R_{95}	R_{mean}
LF cetaceans (SEL_{cum})	3600 m	2900 m	1200 m	2000 m	1800 m	880 m
HF cetaceans (SEL_{cum})	860 m	640 m	310 m	0 m	0 m	0 m
VHF cetaceans (SEL_{cum})	3800 m	3300 m	1300 m	2600 m	2200 m	930 m
Pinnipeds (SEL_{cum})	3100 m	2500 m	1000 m	810 m	650 m	310 m
LF cetaceans (SPL_{peak})	120 m	110 m	100 m	60 m	60 m	50 m
HF cetaceans (SPL_{peak})	30 m	30 m	30 m	20 m	20 m	10 m
VHF cetaceans (SPL_{peak})	1100 m	690 m	580 m	440 m	410 m	340 m
Pinnipeds (SPL_{peak})	140 m	130 m	120 m	70 m	60 m	50 m

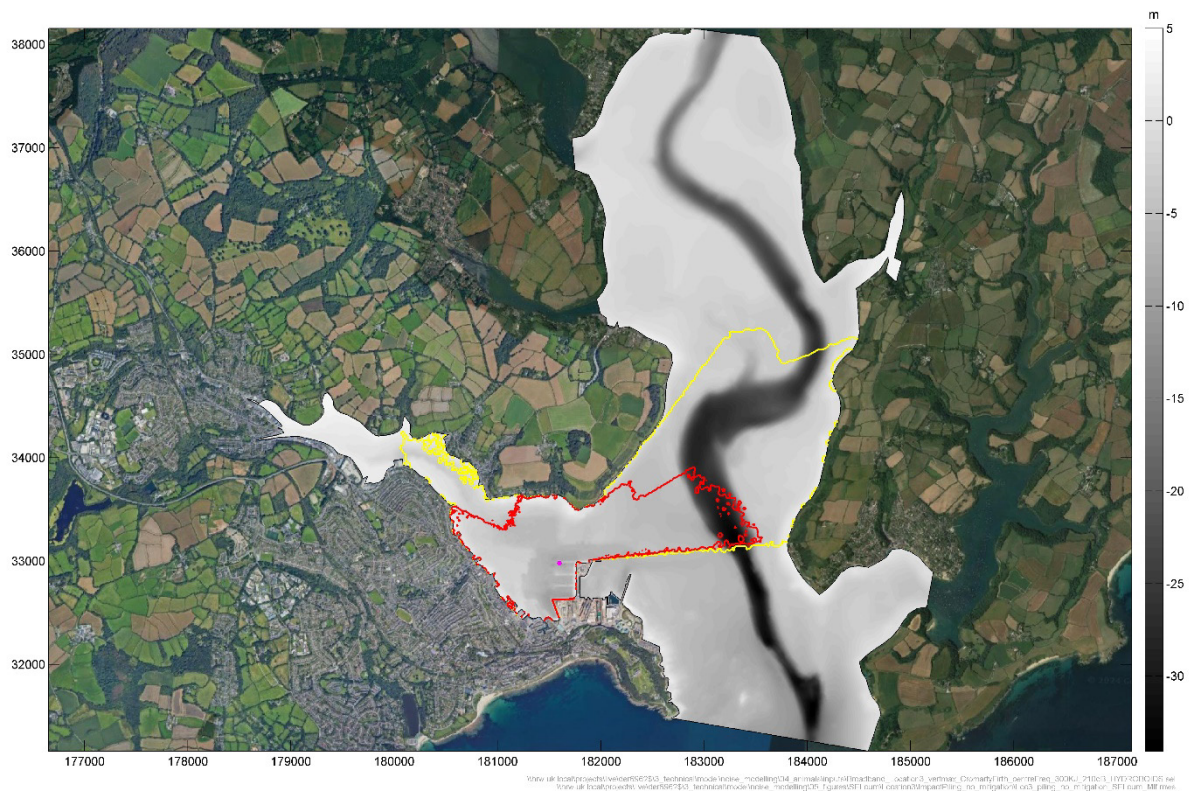


Figure 7.27: Predicted SEL_{cum} impact footprint for the low frequency cetacean hearing group percussive piling, with a soft start procedure, at the Queen's Wharf (Location 3)

Notes: TTS - yellow; PTS - red

Source: Uses Google Earth imagery

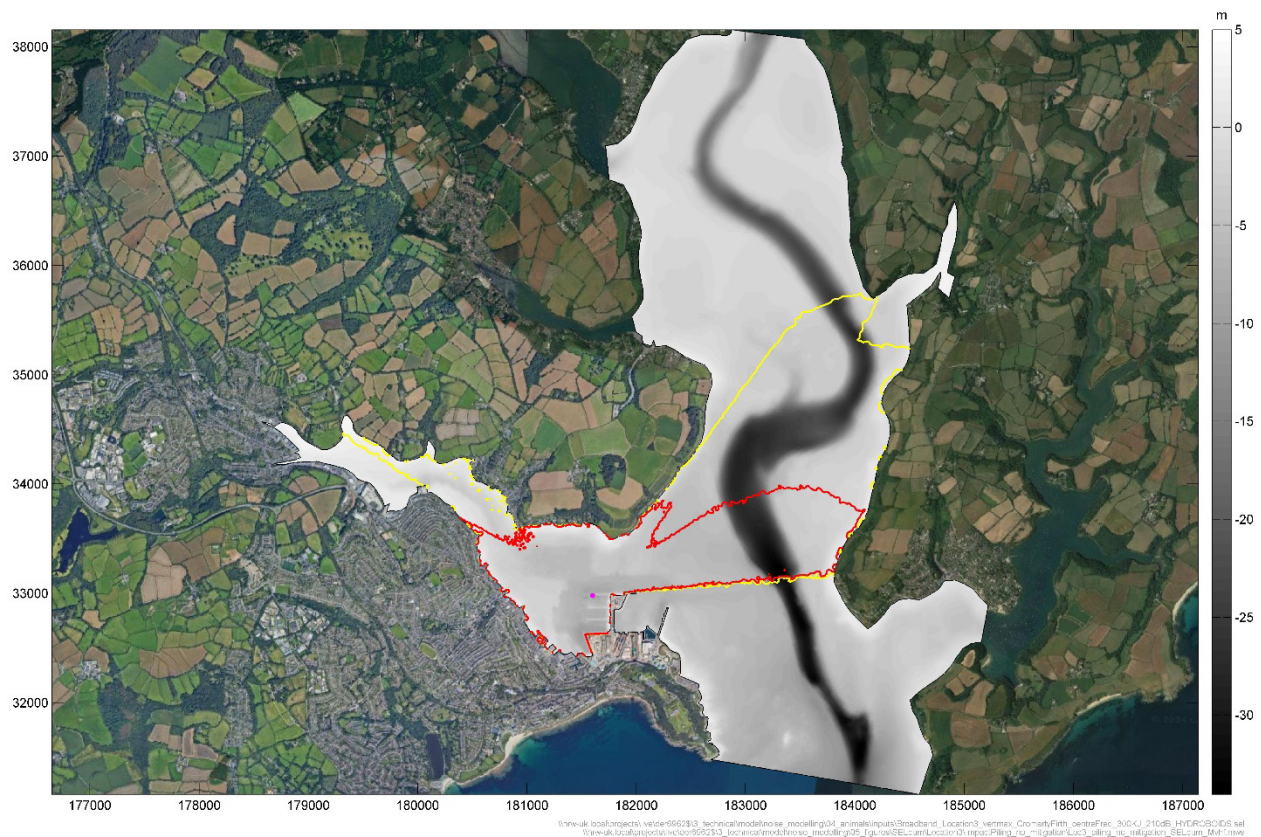


Figure 7.28: Predicted SEL_{cum} impact footprint for the very high frequency cetacean hearing group percussive piling, with a soft start procedure, at the Queen's Wharf (Location 3)

Notes: TTS - yellow; PTS - red

Source: Uses Google Earth imagery

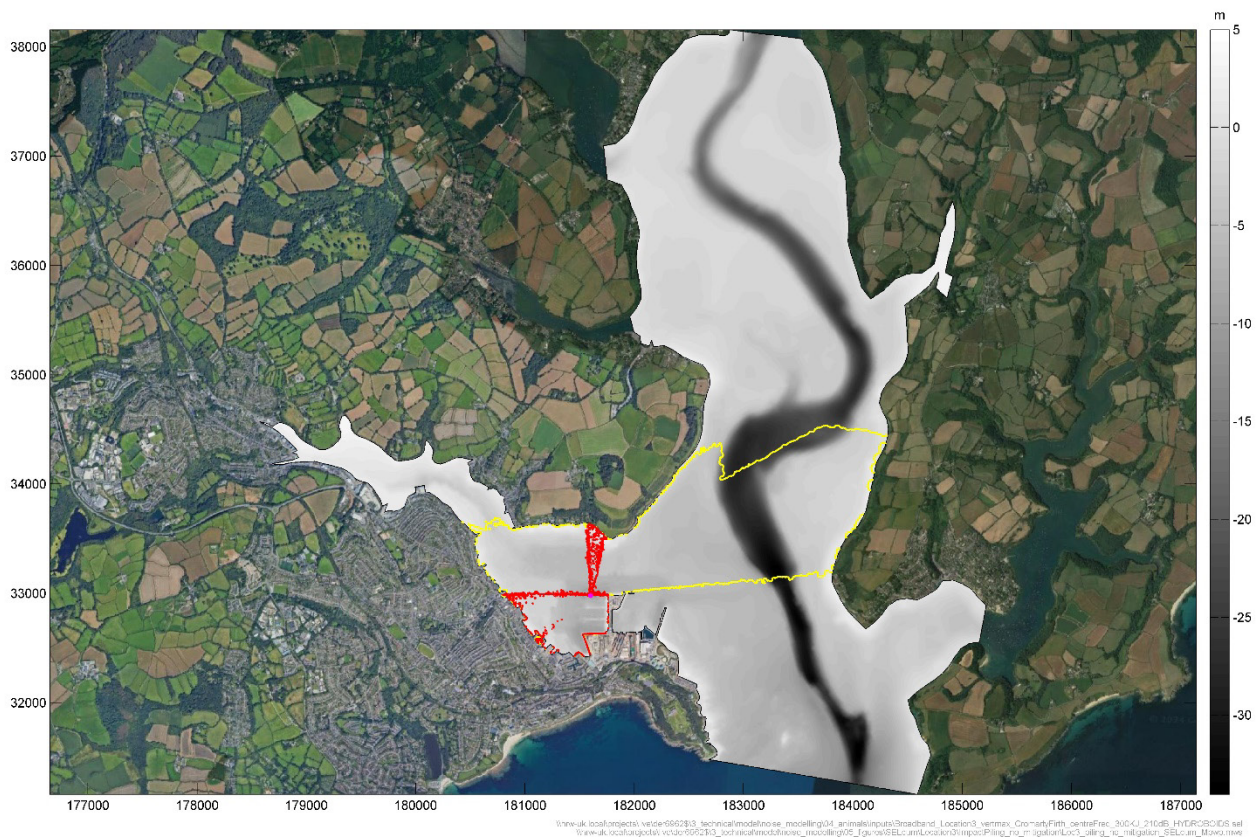


Figure 7.29: Predicted SEL_{cum} impact footprint for pinnipeds for percussive piling, with a soft start procedure, at the Queen's Wharf (Location 3)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery

Behavioural disturbances

Areas of potential behavioural disturbance to marine mammals are shown in Figure 7.17, based on the criteria discussed in Section 2.2.2. The potential for low and higher level disturbance was predicted across the estuary. The potential for behavioural disturbances does not account for hearing and sensitivity differences between the mammal groups because insufficient information is available regarding sound levels causing behavioural disturbance.

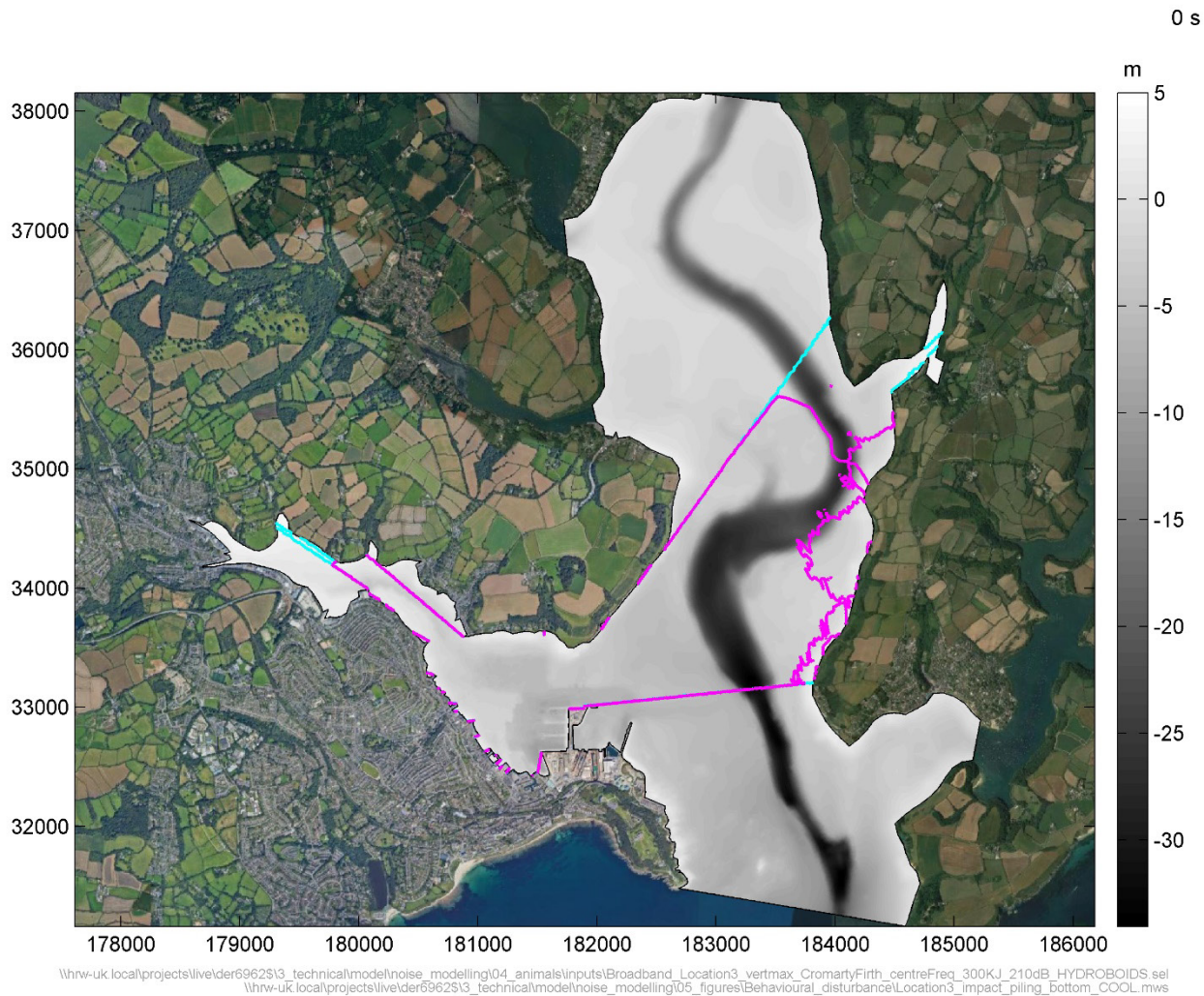


Figure 7.30: Impact contours for potential behavioural disturbance to marine mammals for piling activities using percussive piling (Location 3)

Notes: Low level disturbance threshold (140 dB re 1µPa) – turquoise; higher level of disturbance (160 dB re 1µPa) – magenta

Source: Uses Google Earth imagery

Fish

Impact distances are given for the most sensitive hearing groups, fish with swim bladders involved in hearing (Category 3) and fish with swim bladders not involved in hearing (Category 2). Fish may flee on exposure to noise, or may display other behaviours, such as swimming to the seabed. To cover the range of potential behaviours, fish are modelled as fleeing or stationary. The distances to impact thresholds for the piling activity (with soft-start) are shown in Table 7.9:

- For fleeing fish (Figure 7.31):
 - The TTS threshold was exceeded within 1200 m of the noise;
 - Recoverable injury and mortality thresholds were exceeded within 670 m of the piling for Category 3 fish, representing fish trapped between the noise and shoreline;
 - For Category 2 fish, mortality thresholds were not exceeded.
- For stationary fish (Figure 7.32), the maximum distance to the TTS threshold was 3900 m, to injury threshold was 1500 m and to mortality threshold was 1100 m for Category 3 fish. The maximum distance to mortality threshold for Category 2 fish was predicted to be 560 m.

- SPL_{peak} thresholds for injury and mortality were exceeded within 270 m of the noise source.

Table 7.9: Distances from the pile to impact radii for fish with Location 3 (percussive piling with soft start at Queens Wharf, Location 3)

	TTS			Recoverable Injury			Mortality		
	R_{max}	R_{95}	R_{mean}	R_{max}	R_{95}	R_{mean}	R_{max}	R_{95}	R_{mean}
Fleeing (SEL_{cum}) (swim bladder involved in hearing)	1200 m	1000 m	630 m	670 m *	590 m	270 m	650 m*	540 m	270 m
Fleeing (SEL_{cum}) (swim bladder not involved in hearing)	1200 m	1000 m	630 m	670 m *	590 m	270 m	0 m	0 m	0 m
Stationary (SEL_{cum}) (swim bladder involved in hearing)	3900 m	3600 m	1500 m	1500 m	1200 m	830 m	1100 m	770 m	620 m
Stationary (SEL_{cum}) (swim bladder not involved in hearing)	3900 m	3600 m	1500 m	1500 m	1200 m	830 m	560 m	520 m	440 m
SPL_{peak}^{**}				270 m	250 m	200 m	270 m	250 m	200 m

*Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted

**For SPL_{peak} only mortality and injury thresholds are available, and are equal



Figure 7.31: Predicted SEL_{cum} impact footprint for fleeing fish for percussive piling, with a soft start procedure, at the Queen's Wharf (Location 3)

Notes: TTS – yellow; PTS – orange; mortal injury – red

Source: Uses Google Earth imagery

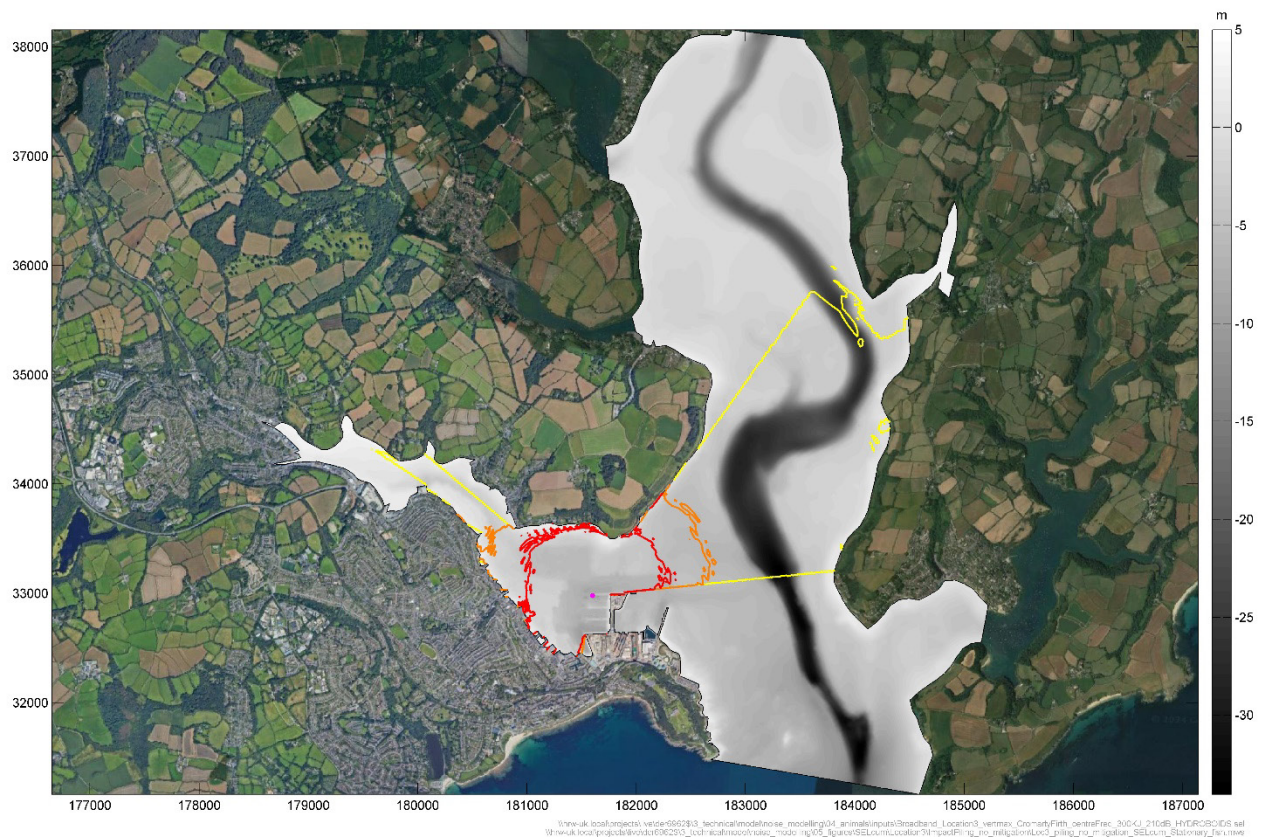


Figure 7.32: Predicted SEL_{cum} impact footprint for the for Category 3 stationary fish for percussive piling, with a soft start procedure, at the Queen's Wharf (Location 3)

Notes: TTS - yellow; PTS - orange; mortal injury - red

Source: Uses Google Earth imagery

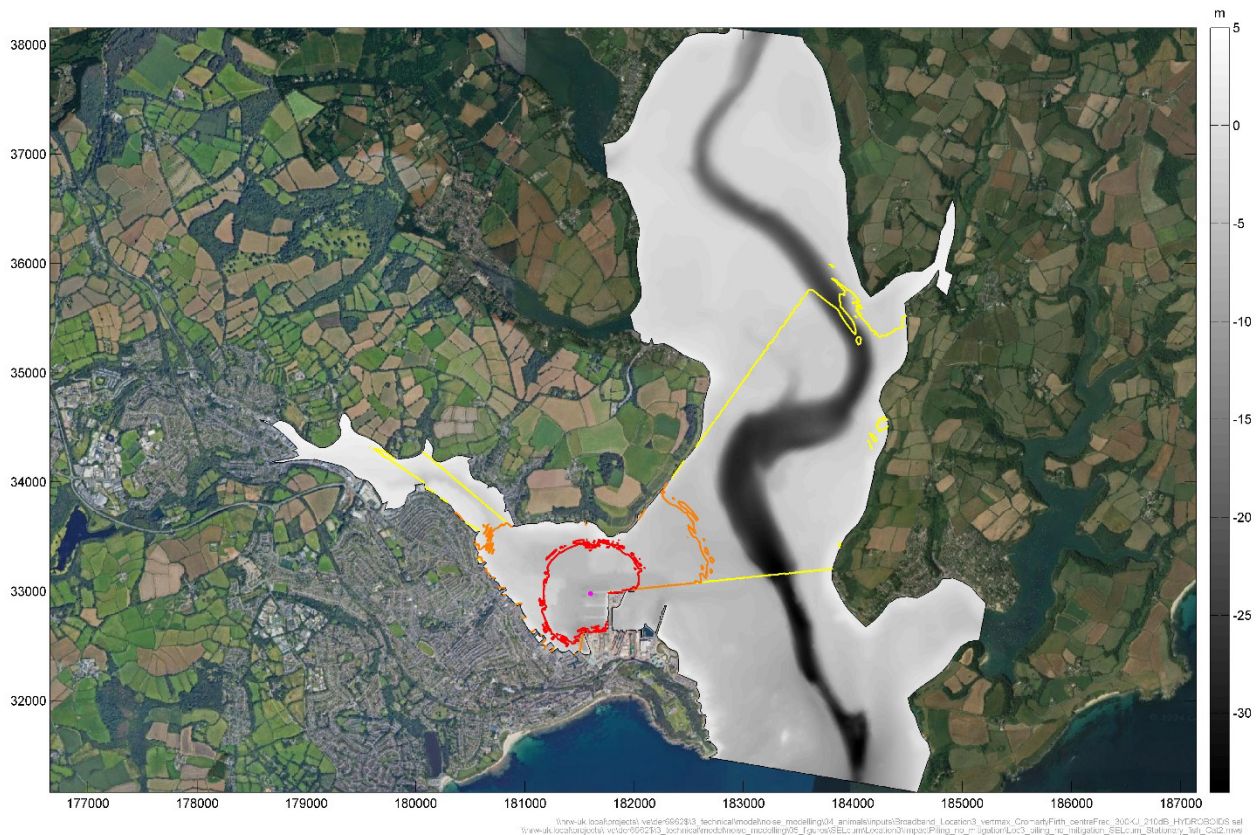


Figure 7.33: Predicted SELcum impact footprint for the for category 2 stationary fish for percussive piling, with a soft start procedure, at the Queen's Wharf (Location 3)

Notes: TTS - yellow; PTS - orange; mortal injury - red

Source: Uses Google Earth imagery

7.3.2 Percussive piling with soft start and bubble curtain

Percussive piling will be required to install piles supporting the proposed suspended deck. Percussive piling is assumed to be used for a maximum of four hours in 24 hours. In this case, the source level is reduced to replicate the effect of a bubble curtain on the noise field, as described in Section 5.3.2.

Broadband sound field

Figure 7.26 shows the predicted broadband single strike SEL sound field for the percussive piling noise source at the Western Wharf location. Sound levels decrease with distance from the source, with the single strike SEL sound dropping below 160 dB re 1 μ Pa²s approximately 400 m away and below 150 dB re 1 μ Pa²s approximately 1000 m away.

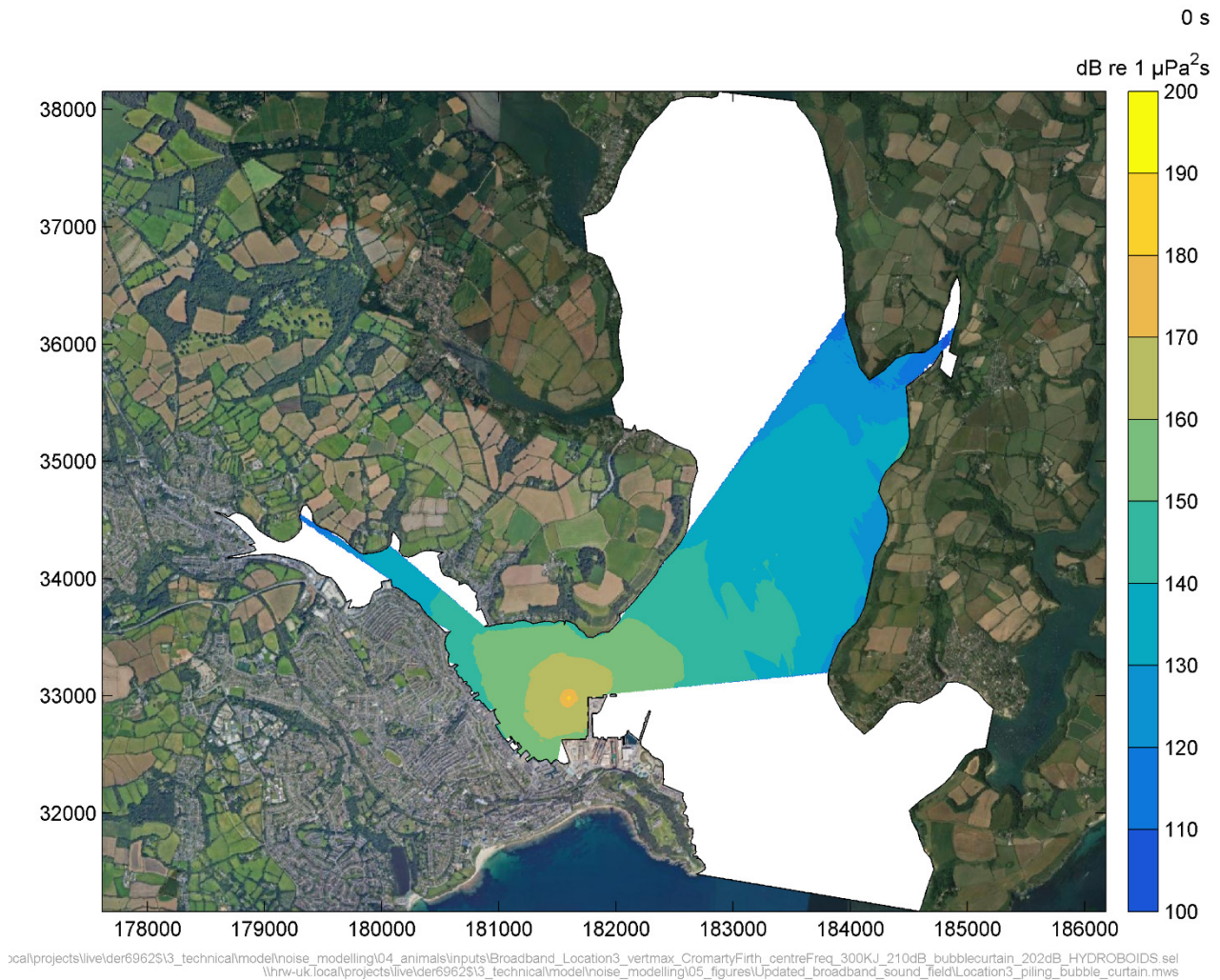


Figure 7.34: Predicted single strike SEL sound field for percussive piling at Location 3 with bubble curtain mitigation

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery

Mammals

Table 7.10 shows the predicted distances to the impact thresholds for the mammal groups. For piling using a bubble curtain the impacted areas were reduced compared to piling without a bubble curtain.

For this activity, it was predicted that:

- For low frequency cetaceans (LF):
 - The TTS threshold for SEL_{cum} was predicted to be exceeded within 990 m of the piling (Figure 7.35);
 - The PTS threshold for SEL_{cum} was predicted to be exceeded within 660 m. Threshold exceedance in this case occurs only for animals between the noise source and the shoreline, where fleeing is restricted in the model.
- For high frequency cetaceans (HF):
 - Neither TTS nor PTS thresholds were predicted to be exceeded for high frequency cetaceans.

- For very high frequency cetaceans (VHF) (Figure 7.36):
 - The maximum distance to the SEL_{cum} TTS threshold was 2800 m;
 - The PTS threshold for SEL_{cum} was predicted to be exceeded within 810 m, extending eastward to the far side of the estuary.
- For pinnipeds:
 - The maximum distance to the TTS threshold was 660 m;
 - The PTS threshold for SEL_{cum} was not exceeded.
- Distances to impact threshold were much smaller with SPL_{peak} compared to the SEL_{cum}.
 - Very high frequency cetaceans were predicted to experience peak SPL above their TTS threshold up to 130 m from the piling activity, and PTS up to 60 m;
 - Distances to peak SPL thresholds were less than 20 m for the other mammal groups.

Table 7.10: Distances to impact threshold for different mammal hearing groups (percussive piling with soft start and bubble curtain at Queen's Wharf, Location 3)

	TTS			PTS		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
LF cetaceans (SEL _{cum})	990 m	860 m	570 m	670 m *	600 m	280 m
HF cetaceans (SEL _{cum})	0 m	0 m	0 m	0 m	0 m	0 m
VHF cetaceans (SEL _{cum})	2800 m	2200 m	1100 m	810 m	680 m	330 m
Pinnipeds (SEL _{cum})	670 m *	620 m	290 m	0 m	0 m	0 m
LF cetaceans (SPL _{peak})	20 m	20 m	20 m	8 m	7 m	7 m
HF cetaceans (SPL _{peak})	4 m	4 m	4 m	2 m	2 m	2 m
VHF cetaceans (SPL _{peak})	130 m	120 m	120 m	60 m	60 m	50 m
Pinnipeds (SPL _{peak})	20 m	20 m	20 m	10 m	10 m	9 m

*Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted

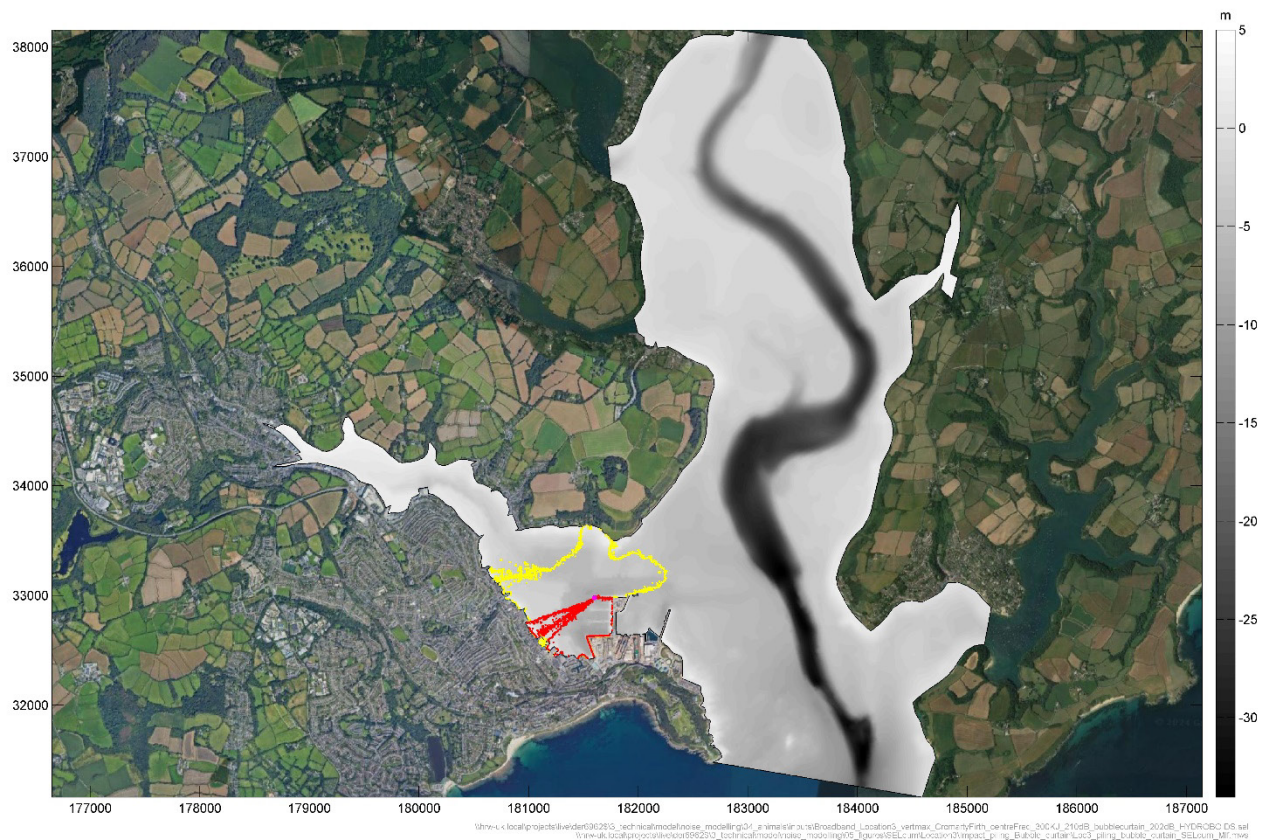


Figure 7.35: Predicted SEL_{cum} impact footprint for the low frequency cetacean hearing group percussive piling, with a soft start procedure and bubble curtain, at the Queen's Wharf (Location 3)

Notes: TTS - yellow; PTS - red

Source: Uses Google Earth imagery

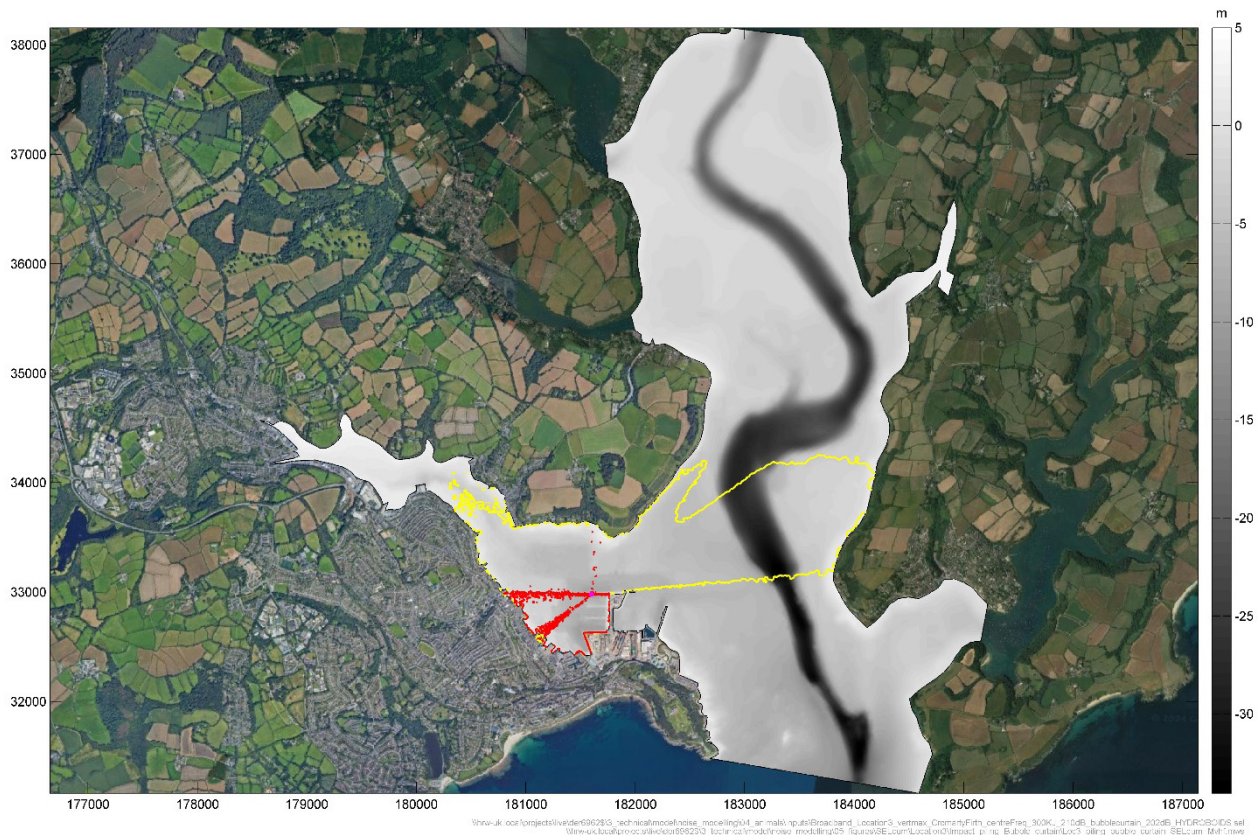


Figure 7.36: Predicted SEL_{cum} impact footprint for the very high frequency cetacean hearing group percussive piling, with a soft start procedure and bubble curtain, at the Queen's Wharf (Location 3)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery

Behavioural disturbances

Areas of potential behavioural disturbance to marine mammals are shown in Figure 7.46, based on the criteria discussed in Section 2.2.2. A higher level of behavioural disturbance was predicted within approximately 1.5 km of the noise source. The potential for low level disturbance was predicted across the estuary, in areas predicted to be reached by piling sounds. The areas with potential for higher levels of behavioural disturbance were smaller compared to without the bubble curtain.

The potential for behavioural disturbances does not account for hearing and sensitivity differences between the mammal groups because insufficient information is available regarding sound levels causing behavioural disturbance.

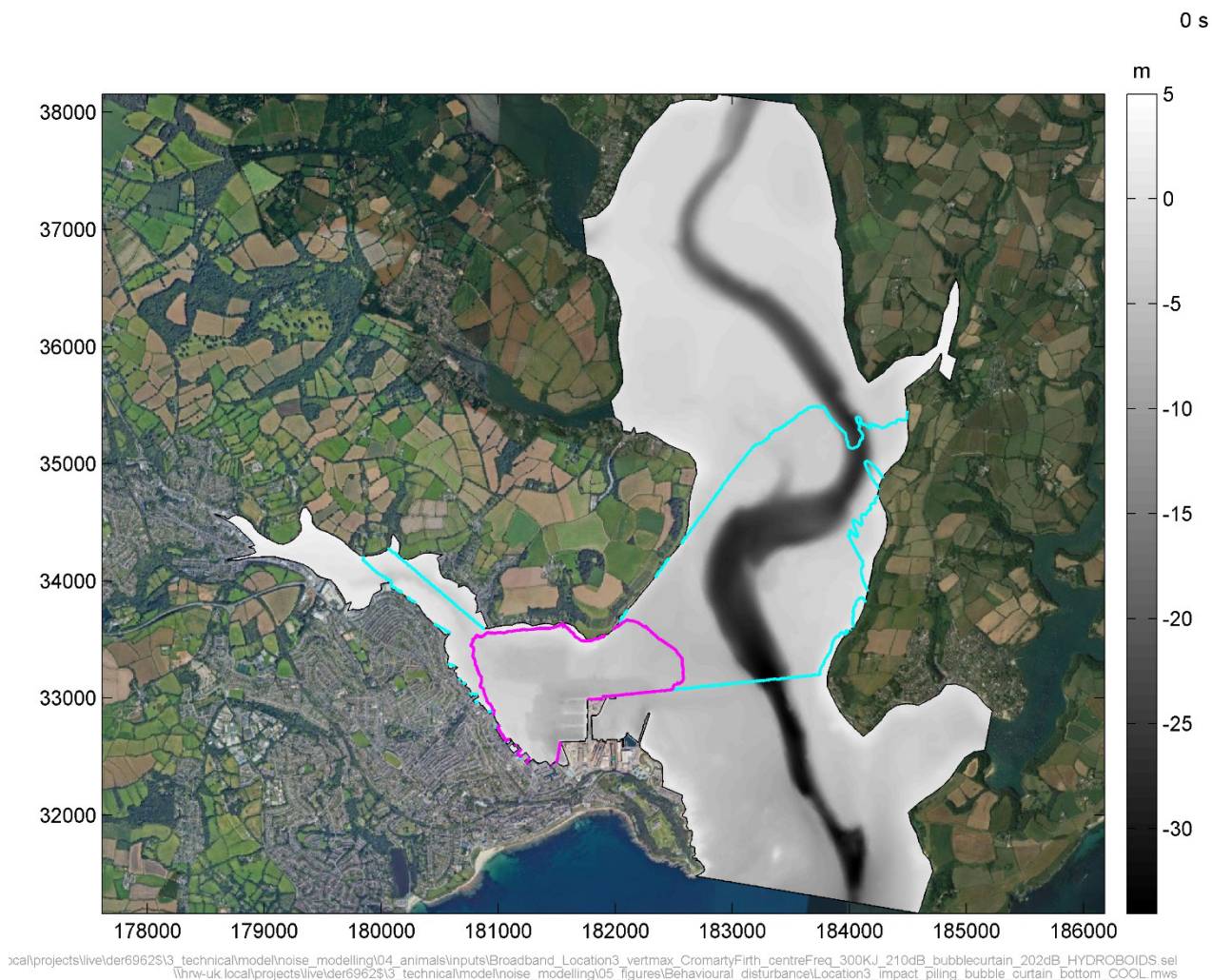


Figure 7.37: Impact contours for potential behavioural disturbance to marine mammals for piling activities using percussive piling with a bubble curtain (Location 3)

Notes: Low level disturbance threshold (140 dB re 1µPa) – turquoise; higher level of disturbance (160 dB re 1µPa) – magenta

Source: Uses Google Earth imagery

Fish

Impact distances are given for the most sensitive hearing groups, fish with swim bladders involved in hearing (category 3) and fish with swim bladders not involved in hearing (category 2). Fish may flee on exposure to noise, or may display other behaviours, such as swimming to the seabed. To cover the range of potential behaviours, fish are modelled as fleeing or stationary. The distances to impact thresholds for the piling activity (with soft-start and bubble curtain) are shown in Table 7.11:

- For both category 2 and 3 fleeing fish (Figure 7.38):
 - The TTS threshold was exceeded within 660 m of the noise;
 - Recoverable injury and mortality thresholds were not exceeded.
- For stationary fish (Figure 7.39), the maximum distance to the TTS threshold was 1400 m, to injury threshold was 290 m and to mortality threshold was 160 m (category 3 fish) and 80 m (category 2 fish).
- SPL_{peak} thresholds for injury and mortality were exceeded within 40 m of the noise source.

Table 7.11: Distances from the pile to impact radii for fish with Location 3 with soft start and bubble curtain use

	TTS			Recoverable Injury			Mortality		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
Fleeing (SEL _{cum}) (swim bladder involved in hearing)	670 m *	600 m	290 m	0 m	0 m	0 m	0 m	0 m	0 m
Fleeing (SEL _{cum}) (swim bladder not involved in hearing)	670 m *	600 m	290 m	0 m	0 m	0 m	0 m	0 m	0 m
Stationary (SEL _{cum}) (swim bladder involved in hearing)	1400 m	1300 m	750 m	290 m	280 m	240 m	160 m	150 m	130 m
Stationary (SEL _{cum}) (swim bladder not involved in hearing)	1400 m	1300 m	750 m	290 m	280 m	240 m	80 m	80 m	70 m
SPL _{peak} **				40 m	40 m	30 m	40 m	40 m	30 m

**Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted*

***For SPL_{peak} only mortality and injury thresholds are available, and are equal*



Figure 7.38: Predicted SEL_{cum} impact footprint for fleeing fish for percussive piling, with a soft start procedure and a bubble curtain, at the Queen's Wharf (Location 3)

Notes: TTS – yellow; PTS – orange; mortal injury – red

Source: Uses Google Earth imagery

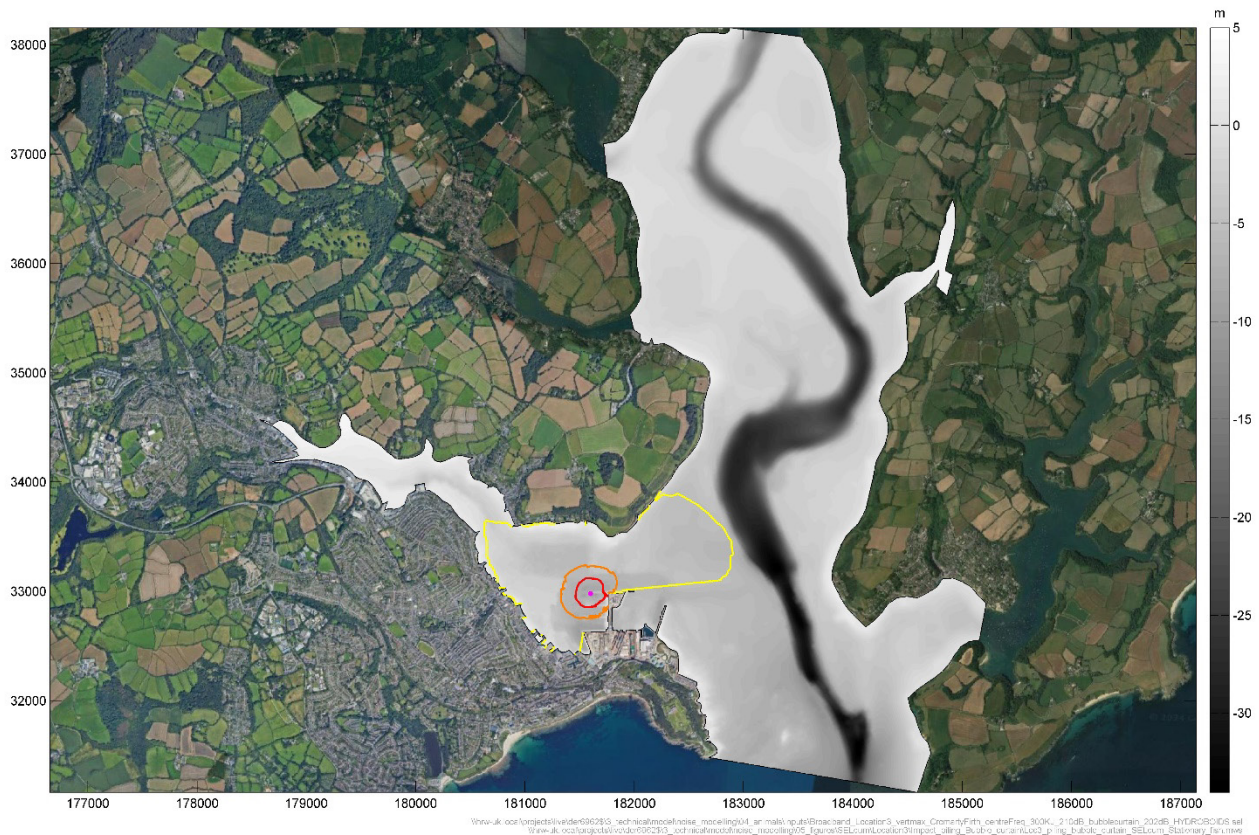


Figure 7.39: Predicted SEL_{cum} impact footprint for the for stationary fish for percussive piling, with a soft start procedure and a bubble curtain, at the Queen's Wharf (Location 3)

Notes: TTS – yellow; PTS – orange; mortal injury – red

Source: Uses Google Earth imagery

7.4 Location 4 – FLOW deck

7.4.1 Dredging with a backhoe

Backhoe dredging is assumed to be continuous, with the cumulative sound exposure calculated over 24 hours.

Broadband sound field

Figure 7.40 shows the predicted single strike SEL sound field for the demolition activity noise source. Sound levels decrease with distance from the source, with the single strike SEL sound dropping below 130 dB re 1µPa²s less than 1 km away.



Figure 7.40: Predicted single strike SEL sound field for backhoe dredging at Location 4

Mammals

Table 7.12 shows the predicted distances to the impact thresholds for the mammal groups. SEL_{cum} PTS thresholds were not exceeded. TTS thresholds were exceeded for very high frequency cetaceans only, within 650 m of the noise source and applying to animals between the noise source and the shoreline.

For this activity, it was predicted that:

- For very high frequency cetaceans (VHF) (Figure 7.41):
 - The TTS threshold for SEL_{cum} was predicted to be exceeded only within 650 m of the dredging. The threshold was exceeded only for animals between the noise source and the shoreline;
 - The PTS threshold for SEL_{cum} was predicted not to be exceeded.
- For low frequency cetaceans (LF), high frequency cetaceans (HF) and pinniped, no thresholds were predicted to be exceeded.

Table 7.12: Distances to impact threshold for different mammal hearing groups (backhoe dredging at FLOW deck, Location 4)

	TTS			PTS		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
LF cetaceans (SEL _{cum})	0 m	0 m	0 m	0 m	0 m	0 m
HF cetaceans (SEL _{cum})	0 m	0 m	0 m	0 m	0 m	0 m
VHF cetaceans (SEL _{cum})	650 m *	520 m	260 m	0 m	0 m	0 m
Pinnipeds (SEL _{cum})	0 m	0 m	0 m	0 m	0 m	0 m

*Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted



Figure 7.41: Predicted SEL_{cum} impact footprint for the very high frequency cetacean hearing group for dredging with a backhoe at the FLOW deck (Location 4)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery

Behavioural disturbances

Areas of potential behavioural disturbance to marine mammals are shown in Figure 7.42, based on the criteria discussed in Section 2.2.2. A low level of behavioural disturbance was predicted within approximately 2 km of the noise source. The potential for behavioural disturbances does not account for hearing and sensitivity differences between the mammal groups because insufficient information is available regarding sound levels causing behavioural disturbance.

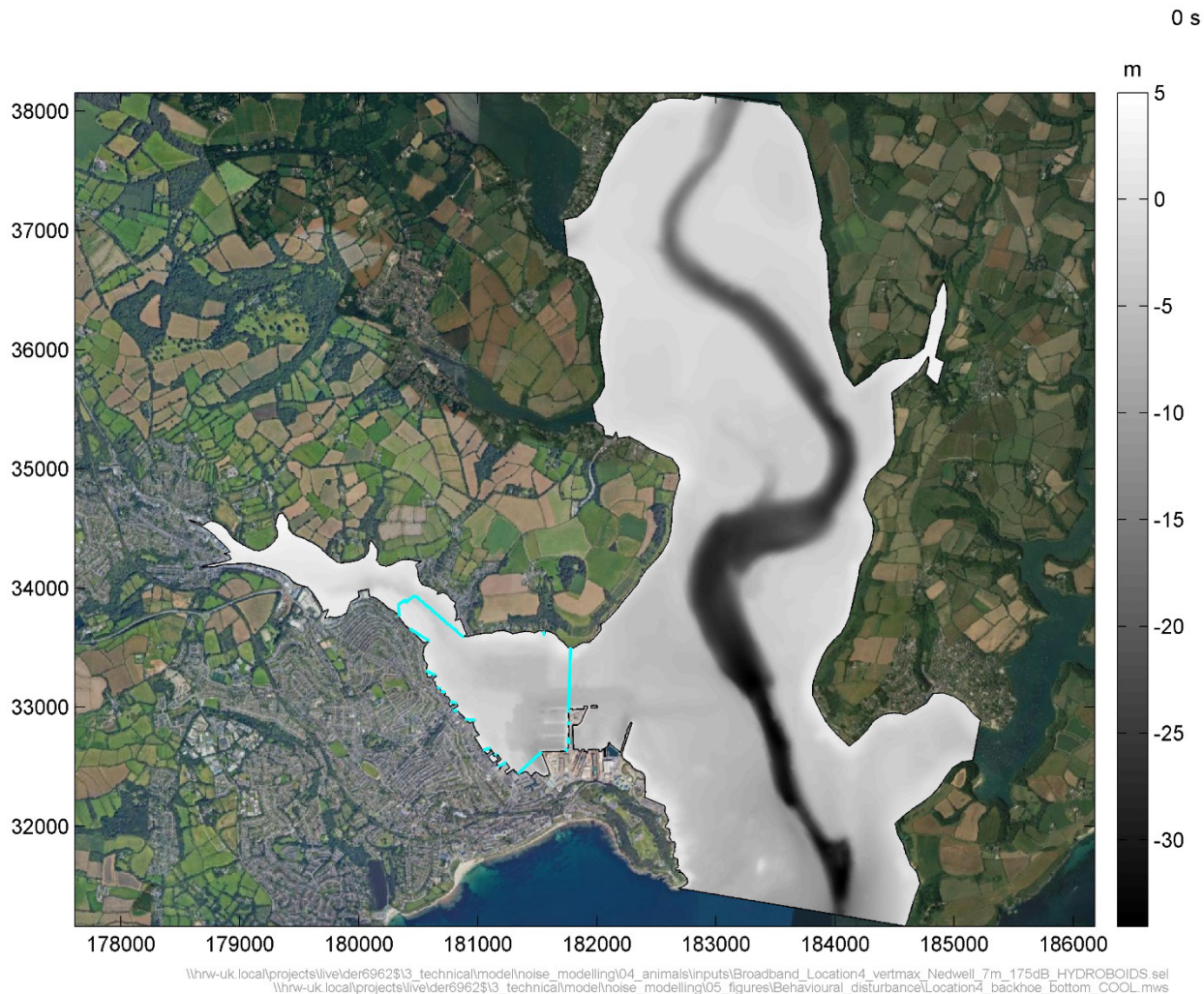


Figure 7.42: Impact contours for potential behavioural disturbance to marine mammals for dredging activities using a backhoe dredger (Location 4)

Notes: Low level disturbance threshold (140 dB re 1 µPa) – turquoise; higher level of disturbance (160 dB re 1 µPa) – magenta

Source: Uses Google Earth imagery

Fish

Fish impact thresholds for continuous noises, such as the backhoe dredging are based on the RMS sound pressure level:

- TTS if the RMS SPL exceeds 158 dB re 1 µPa for 12 hours;
- Injury if the RMS SPL exceeds 170 dB re 1 µPa for 48 hours.

Neither threshold is exceeded in this case.

7.4.2 Percussive piling with soft start only

Percussive piling will be required to install piles supporting the proposed suspended deck. Percussive piling is assumed to be used for a maximum of four hours in 24 hours.

Broadband sound field

Figure 7.26 shows the predicted single strike SEL sound field for the percussive piling noise source at the Western Wharf location. Sound levels decrease with distance from the source,

with the single strike SEL sound dropping below 170 dB re 1 μ Pa²s approximately 600 m away and below 160 dB re 1 μ Pa²s approximately 1700 m away.



Figure 7.43: Predicted single strike SEL sound field for percussive piling at Location 4

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery

Mammals

Table 7.13 shows the predicted distances to the impact thresholds for the mammal groups. For this activity, PTS and TTS thresholds for low frequency cetaceans and very high frequency cetaceans were predicted to be exceeded over the width of the estuary (north to south).

For this activity, it was predicted that:

- For low frequency cetaceans (LF) (Figure 7.44):
 - The TTS threshold for SEL_{cum} was predicted to be exceeded within 2200 m of the piling;
 - The PTS threshold for SEL_{cum} was predicted to be exceeded within 1400 m;
 - Areas exceeding both thresholds extend across the estuary to the north and south of the piling location.
- For high frequency cetaceans (HF) (Figure 7.45):
 - The maximum distance to the TTS threshold was 1000 m;

- The PTS threshold for SEL_{cum} was predicted to be exceeded within 650 m of the sound source and represented animals trapped between the noise source and the shoreline.
- For very high frequency cetaceans (VHF) (Figure 7.46):
 - The maximum distance to the SEL_{cum} TTS threshold was 3000 m;
 - The PTS threshold for SEL_{cum} was predicted to be exceeded within 1600 m;
 - Areas exceeding both thresholds extend across the estuary to the north and south of the piling location.
- For pinnipeds (Figure 7.47):
 - The maximum distance to the TTS threshold was 1500 m;
 - The maximum distance to the PTS threshold was 960 m.
- Distances to impact threshold were much smaller with SPL_{peak} compared to the SEL_{cum} :
 - Very high frequency cetaceans were predicted to experience peak SPL above their TTS threshold up to 800 m from the piling activity, and PTS up to 650 m;
 - Distances to peak SPL thresholds were less than 170 m for the other mammal groups.

Table 7.13: Distances to impact threshold for different mammal hearing groups (percussive piling with soft start for the FLOW deck, Location 4)

	TTS			PTS		
	R_{max}	R_{95}	R_{mean}	R_{max}	R_{95}	R_{mean}
LF cetaceans (SEL_{cum})	2200 m	2000 m	770 m	1400 m	1300 m	640 m
HF cetaceans (SEL_{cum})	1000 m	780 m	310 m	650 m *	520 m	210 m
VHF cetaceans (SEL_{cum})	3000 m	2600 m	910 m	1600 m	1300 m	630 m
Pinnipeds (SEL_{cum})	1500 m	1400 m	630 m	960 m	780 m	360 m
LF cetaceans (SPL_{peak})	130 m	120 m	90 m	60 m	60 m	50 m
HF cetaceans (SPL_{peak})	30 m	30 m	30 m	10 m	10 m	10 m
VHF cetaceans (SPL_{peak})	800 m	740 m	510 m	650 m	530 m	320 m
Pinnipeds (SPL_{peak})	170 m	140 m	110 m	70 m	60 m	50 m

*Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted



Figure 7.44: Predicted SEL_{cum} impact footprint for the low frequency cetacean hearing group percussive piling, with a soft start procedure, at the FLOW Deck (Location 4)

Notes: TTS - yellow; PTS - red

Source: Uses Google Earth imagery



Figure 7.45: Predicted SEL_{cum} impact footprint for the high frequency cetacean hearing group percussive piling, with a soft start procedure, at the FLOW Deck (Location 4)

Notes: TTS - yellow; PTS - red

Source: Uses Google Earth imagery



Figure 7.46: Predicted SEL_{cum} impact footprint for the very high frequency cetacean hearing group percussive piling, with a soft start procedure, at the FLOW Deck (Location 4)

Notes: TTS - yellow; PTS - red

Source: Uses Google Earth imagery



Figure 7.47: Predicted SEL_{cum} impact footprint pinnipeds for percussive piling, with a soft start procedure, at the FLOW Deck (Location 4)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery

Behavioural disturbances

Areas of potential behavioural disturbance to marine mammals are shown in Figure 7.48, based on the criteria discussed in Section 2.2.2. A low and higher level of behavioural disturbance was predicted within approximately 2.5 km of the noise source.

The potential for behavioural disturbances does not account for hearing and sensitivity differences between the mammal groups because insufficient information is available regarding sound levels causing behavioural disturbance.

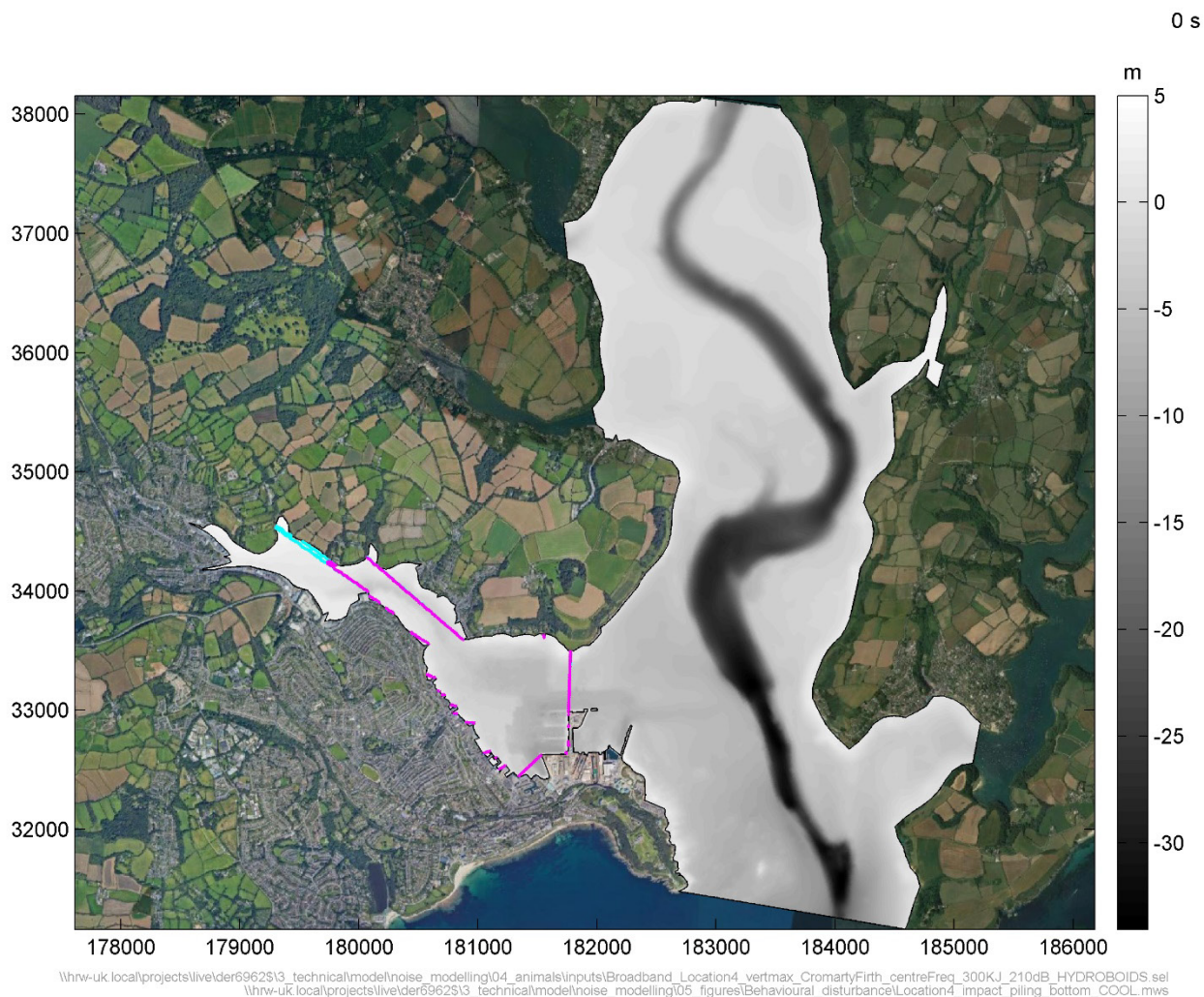


Figure 7.48: Impact contours for potential behavioural disturbance to marine mammals for piling activities using percussive piling

Notes: Low level disturbance threshold (140 dB re 1µPa) – turquoise; higher level of disturbance (160 dB re 1µPa) – magenta

Source: Uses Google Earth imagery

Fish

Impact distances are given for the most sensitive hearing groups, fish with swim bladders involved in hearing (category 3) and fish with swim bladders not involved in hearing (category 2). Fish may flee on exposure to noise, or may display other behaviours, such as swimming to the seabed. To cover the range of potential behaviours, fish are modelled as fleeing or stationary. The distances to impact thresholds for the piling activity (with soft-start) are shown in Table 7.14:

- For category 2 and 3 fleeing fish (Figure 7.49):
 - The TTS threshold was exceeded within 1300 m of the noise;
 - Recoverable injury and mortality thresholds were exceeded within 650 m of the piling, representing fish trapped between the noise and shoreline.
- For stationary fish (Figure 7.50), the maximum distance to the TTS threshold was 2700 m, to injury threshold was 1700 m and to mortality threshold was 910 m (category 3 fish) or 680 m (category 2 fish).
- SPL_{peak} thresholds for injury and mortality were exceeded within 650 m of the noise source.

Table 7.14: Distances from the pile to impact radii for fish with Location 4

	TTS			Recoverable Injury			Mortality		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
Fleeing (SEL _{cum}) (swim bladder involved in hearing)	1300 m	1200 m	630 m	650 m *	570 m	250 m	650 m	510 m	220 m
Fleeing (SEL _{cum}) (swim bladder not involved in hearing)	1300 m	1200 m	630 m	650 m *	570 m	250 m	650 m	540 m	310 m
Stationary (SEL _{cum}) (swim bladder involved in hearing)	2700 m	2400 m	860 m	1700 m	1300 m	710 m	910 m	780 m	560 m
Stationary (SEL _{cum}) (swim bladder not involved in hearing)	2700 m	2400 m	860 m	1700 m	1300 m	710 m	680 m	610 m	430 m
SPL _{peak} **				650 m	240 m	190 m	650 m	240 m	190 m

*Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted

**For SPL_{peak} only mortality and injury thresholds are available, and are equal

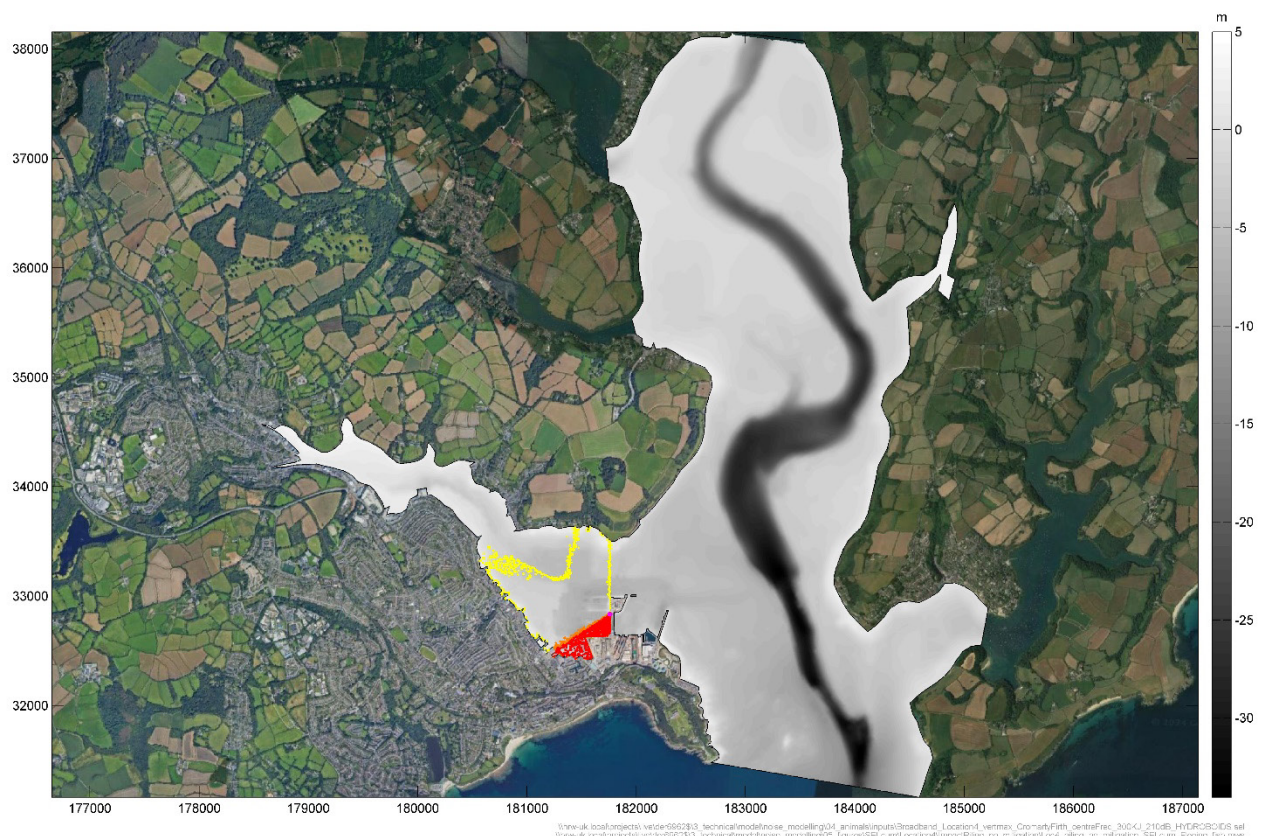


Figure 7.49: Predicted SEL_{cum} impact footprint for fleeing fish for percussive piling, with a soft start procedure, at the FLOW Deck (Location 4)

Notes: TTS – yellow; PTS – orange; mortal injury – red

Source: Uses Google Earth imagery

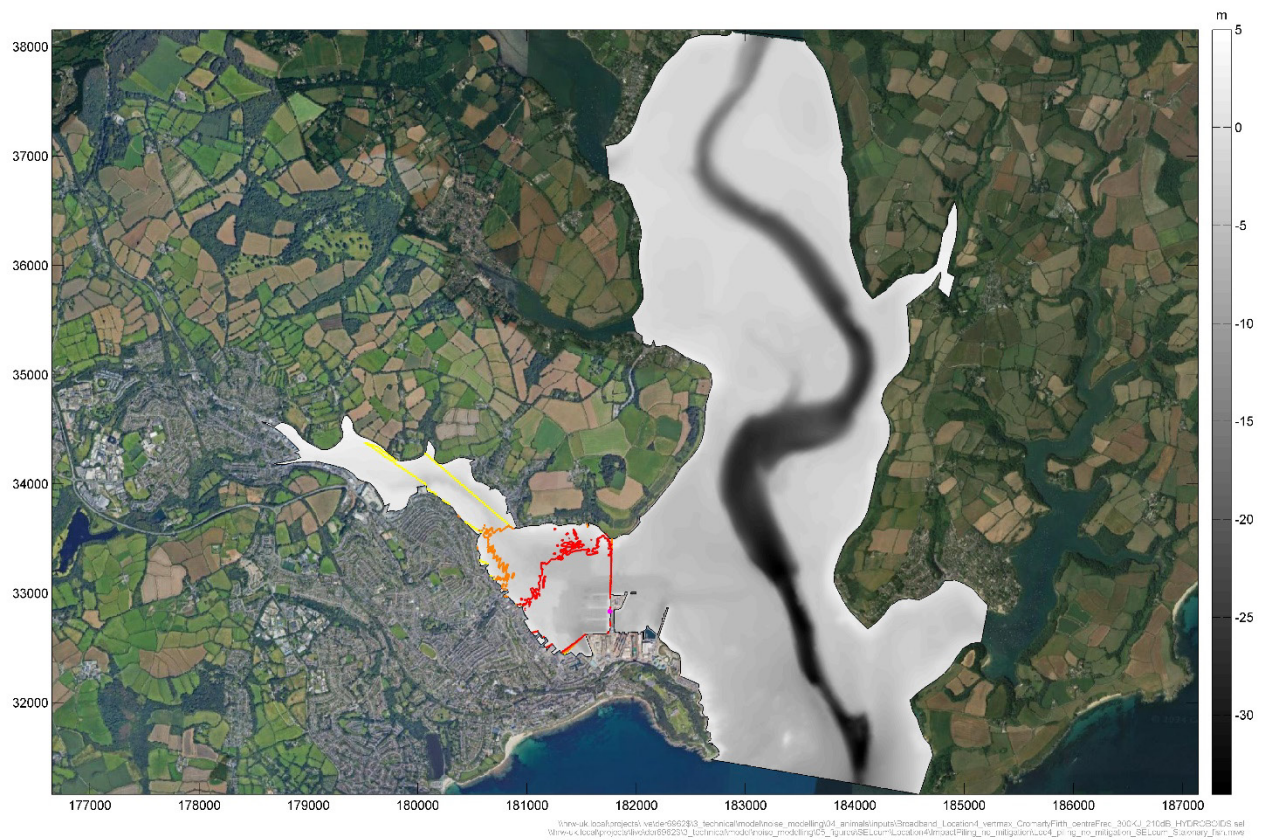


Figure 7.50: Predicted SEL_{cum} impact footprint for the for category 3 stationary fish for percussive piling, with a soft start procedure, at the FLOW Deck (Location 4)

Notes: TTS - yellow; PTS - orange; mortal injury - red

Source: Uses Google Earth imagery

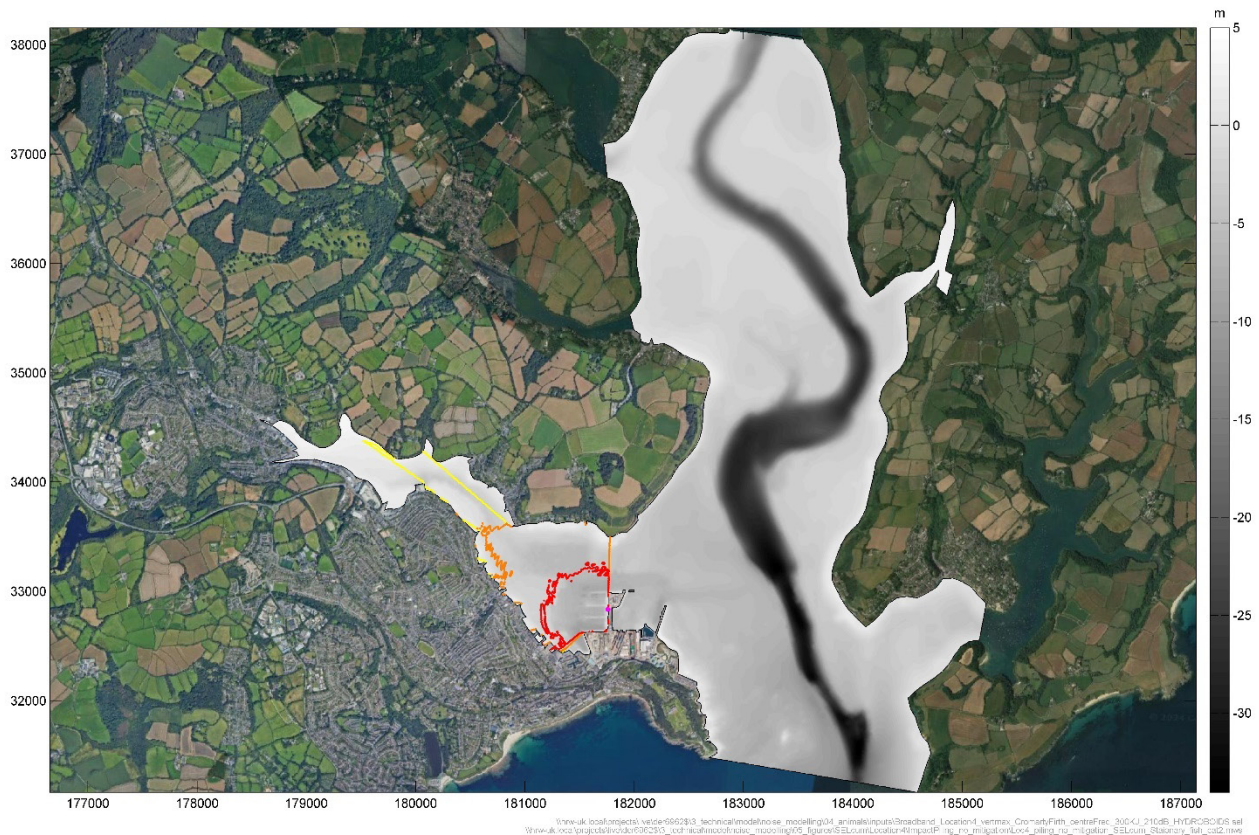


Figure 7.51: Predicted SEL_{cum} impact footprint for the for category 2 stationary fish for percussive piling, with a soft start procedure, at the FLOW Deck (Location 4)

Notes: TTS – yellow; PTS – orange; mortal injury – red

Source: Uses Google Earth imagery

7.4.3 Percussive piling with soft start and bubble curtain

Percussive piling will be required to install piles supporting the proposed suspended deck. Percussive piling is assumed to be used for a maximum of four hours in 24 hours. In this case, the source level is reduced to replicate the effect of a bubble curtain on the noise field, as described in Section 5.3.2.

Broadband sound field

Figure 7.52 shows the predicted single strike SEL sound field for the percussive piling noise source at the Western Wharf location. Sound levels decrease with distance from the source, with the single strike SEL sound dropping below 160 dB re 1 μ Pa²s approximately 400 m away and below 150 dB re 1 μ Pa²s approximately 1000 m away.



Figure 7.52: Predicted single strike SEL sound field for percussive piling with a bubble curtain at Location 4

Source: Uses Google Earth imagery

Mammals

Table 7.15 shows the predicted distances to the impact thresholds for the mammal groups. The areas impacted were reduced with for pile driving with a bubble curtain compared to pile driving without a bubble curtain. For this activity, it was predicted that:

- For low frequency cetaceans (LF):
 - The TTS threshold for SEL_{cum} was predicted to be exceeded within 1200 m of the piling (Figure 7.53);
 - The PTS threshold for SEL_{cum} was predicted to be exceeded within 650 m and within the model represented animals trapped between the noise source and the shoreline.
- For high frequency cetaceans (HF):
 - The maximum distance to the SEL_{cum} TTS threshold was 650 m and represented animals trapped between the noise source and the shoreline;
 - PTS was not exceeded.
- For very high frequency cetaceans (VHF) (Figure 7.54):
 - The maximum distance to the SEL_{cum} TTS threshold was 2200 m;

- The PTS threshold for SEL_{cum} was predicted to be exceeded within 960 m.
- For pinnipeds:
 - The maximum distance to the TTS threshold was 670 m;
 - PTS threshold was not exceeded.
- Distances to impact threshold were much smaller with SPL_{peak} compared to the SEL_{cum} :
 - Very high frequency cetaceans were predicted to experience peak SPL above their TTS threshold up to 120 m from the piling activity, and PTS up to 50 m;
 - Distances to peak SPL thresholds were less than 10 m for the other mammal groups.

Table 7.15: Distances to impact threshold for different mammal hearing groups (percussive piling with soft start and bubble curtain at the FLOW deck, Location 4)

	TTS			PTS		
	R_{max}	R_{95}	R_{mean}	R_{max}	R_{95}	R_{mean}
LF cetaceans (SEL_{cum})	1200 m	1000 m	570 m	670 m *	580 m	270 m
HF cetaceans (SEL_{cum})	650 m	510 m	220 m	0 m	0 m	0 m
VHF cetaceans (SEL_{cum})	2200 m	1800 m	870 m	960 m	820 m	350 m
Pinnipeds (SEL_{cum})	670 m *	610 m	260 m	0 m	0 m	0 m
LF cetaceans (SPL_{peak})	10 m	10 m	10 m	6 m	6 m	6 m
HF cetaceans (SPL_{peak})	3 m	3 m	3 m	2 m	2 m	2 m
VHF cetaceans (SPL_{peak})	120 m	110 m	80 m	50 m	50 m	40 m
Pinnipeds (SPL_{peak})	10 m	10 m	10 m	7 m	7 m	6 m

*Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted

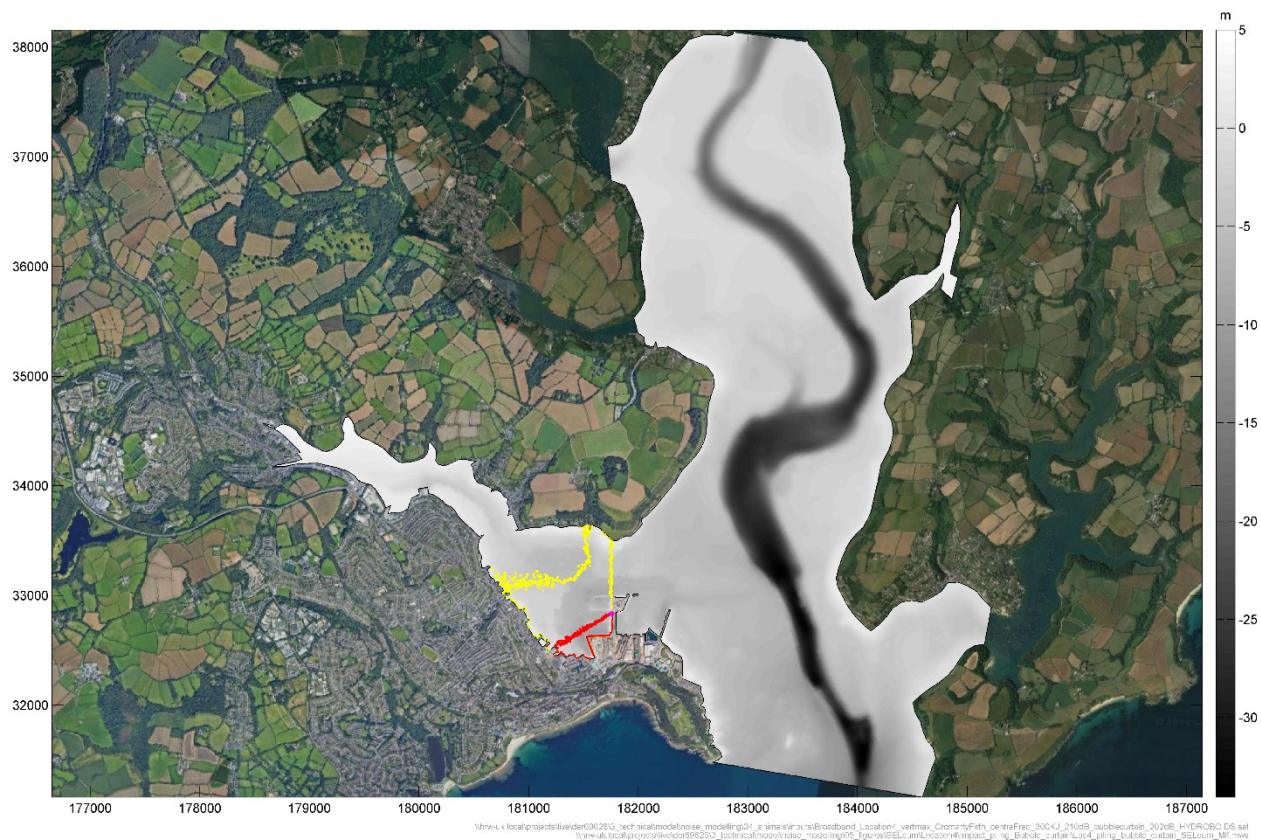


Figure 7.53: Predicted SEL_{cum} impact footprint for the low frequency cetacean hearing group percussive piling, with a soft start procedure and bubble curtain, at the FLOW deck (Location 4)

Notes: TTS - yellow; PTS - red

Source: Uses Google Earth imagery

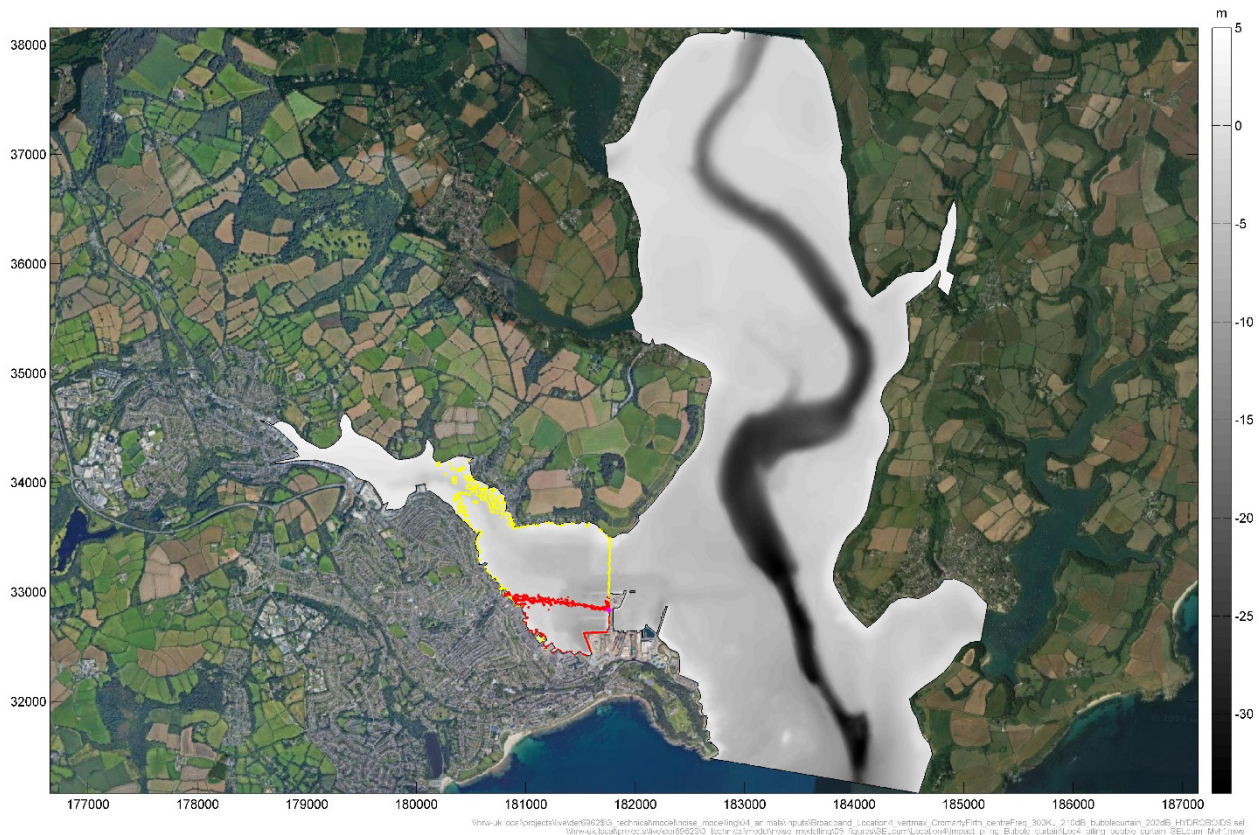


Figure 7.54: Predicted SEL_{cum} impact footprint for the very high frequency cetacean hearing group percussive piling, with a soft start procedure and bubble curtain, at the FLOW deck (Location 4)

Notes: TTS – yellow; PTS – red

Source: Uses Google Earth imagery

Behavioural disturbances

Areas of potential behavioural disturbance to marine mammals are shown in Figure 7.55, based on the criteria discussed in Section 2.2.2. A higher level of behavioural disturbance was predicted within approximately 1 km of the noise source. The potential for low level disturbance was predicted within 2-3 km.

The potential for behavioural disturbances does not account for hearing and sensitivity differences between the mammal groups because insufficient information is available regarding sound levels causing behavioural disturbance.

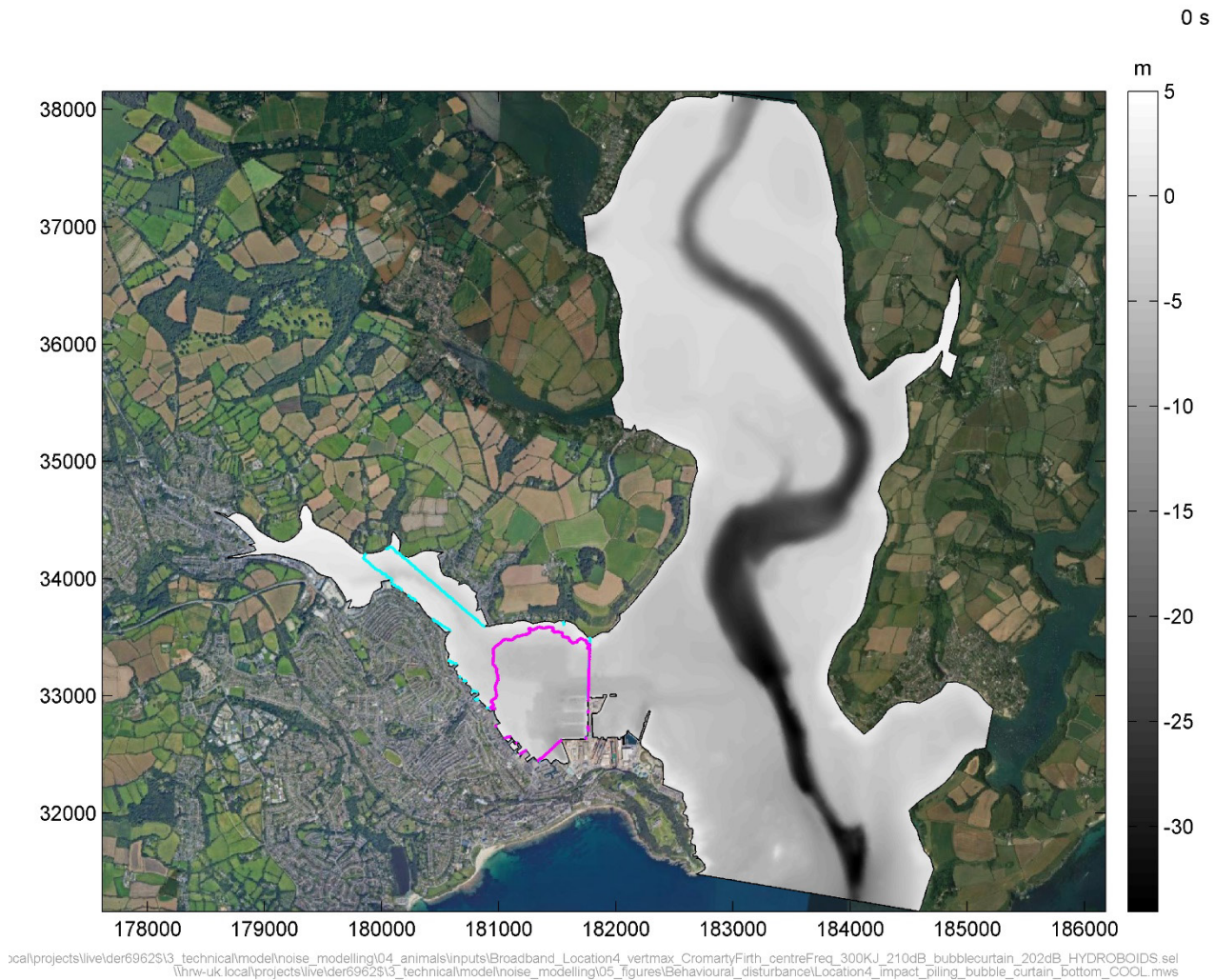


Figure 7.55: Impact contours for potential behavioural disturbance to marine mammals for piling activities using percussive piling with a bubble curtain (Location 4)

Notes: Low level disturbance threshold (140 dB re 1µPa) – turquoise; higher level of disturbance (160 dB re 1µPa) – magenta

Source: Uses Google Earth imagery

Fish

Impact distances are given for the most sensitive hearing group, fish with swim bladders involved in hearing. Fish may flee on exposure to noise, or may display other behaviours, such as swimming to the seabed. To cover the range of potential behaviours, fish are modelled as fleeing or stationary. The distances to impact thresholds for the piling activity (with soft-start and bubble curtain) are shown in Table 7.16:

- For category 2 and 3 fleeing fish (Figure 7.56):
 - The TTS threshold was exceeded within 650 m of the noise;
 - Recoverable injury and mortality thresholds were exceeded not exceeded.
- For stationary fish (Figure 7.57), the maximum distance to the TTS threshold was 1300 m, to injury threshold was 260 m and to mortality threshold was 130 m (category 3 fish) and 70 m (category 2 fish).
- SPL_{peak} thresholds for injury and mortality were exceeded within 30 m of the noise source.

Table 7.16: Distances from the pile to impact radii for fish with Location 4 with soft-start and bubble curtain

	TTS			Recoverable Injury			Mortality		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
Fleeing (SEL _{cum}) (swim bladder involved in hearing)	650 m *	580 m	250 m	0 m	0 m	0 m	0 m	0 m	0 m
Fleeing (SEL _{cum}) (swim bladder not involved in hearing)	650 m *	580 m	250 m	0 m	0 m	0 m	0 m	0 m	0 m
Stationary (SEL _{cum}) (swim bladder involved in hearing)	1300 m	1200 m	600 m	260 m	250 m	160 m	130 m	120 m	90 m
Stationary (SEL _{cum}) (swim bladder not involved in hearing)	1300 m	1200 m	600 m	260 m	250 m	160 m	70 m	70 m	50 m
SPL _{peak} **				30 m	30 m	20 m	30 m	30 m	20 m

*Threshold exceedance for occurs only for animals between the noise source and the shoreline, where fleeing is restricted

**For SPL_{peak} only mortality and injury thresholds are available, and are equal



Figure 7.56: Predicted SEL_{cum} impact footprint for fleeing fish for percussive piling, with a soft start procedure and bubble curtain, at the FLOW Deck (Location 4)

Notes: TTS - yellow; PTS - orange; mortal injury - red

Source: Uses Google Earth imagery

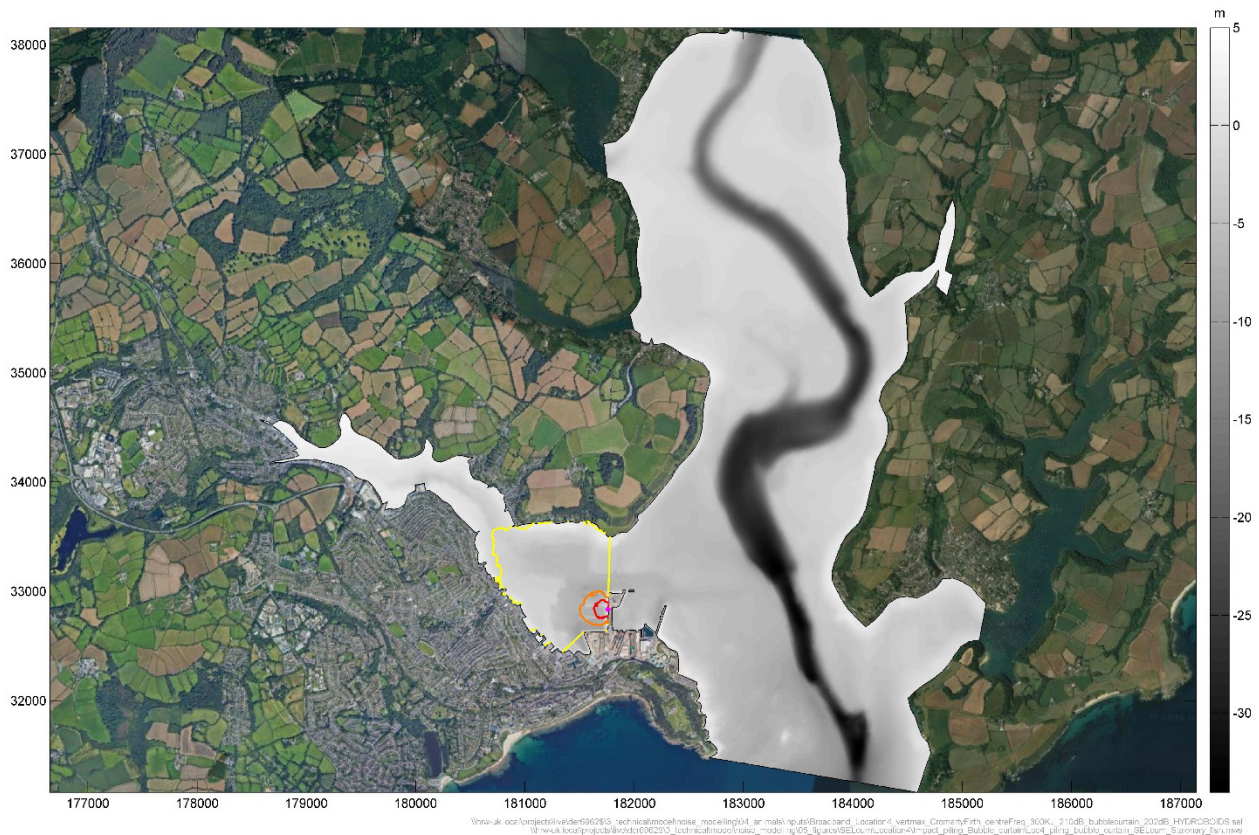


Figure 7.57: Predicted SEL_{cum} impact footprint for the for stationary fish for percussive piling, with a soft start procedure and bubble curtain, at the FLOW Deck (Location 4)

Notes: TTS – yellow; PTS – orange; mortal injury – red

Source: Uses Google Earth imagery

7.5 Construction schedule

The underwater noise modelling in this report assumes that the dock development happens in series, with different wharfs and structures constructed separately and hence the underwater noise predicted for each of the activities should not occur at the same time. It is possible however, that a parallel construction programme will be used, with different activities occurring in different locations at the same time. The potential parallel construction programme is described in detail in ES Volume 1 Chapter 5.

Under the parallel programme detailed in Figure 5.1 (ES Chapter 5), demolition of the Northern Arm of the Western Wharf occurs concurrently with dredging for the North Wharf/Queens Wharf. Piling and demolition activities do not overlap.

The underwater noise modelling presented here as separate activities can still be considered worst case because:

- Piling and demolition activity under the parallel programme will not occur at the same time.
- Dredging may overlap with piling or demolition activities, but the sound levels and impact footprint for dredging was predicted to be relatively small (behavioural impacts and possible limited TTS exceedance). Therefore, in areas affected by noise from both dredging and another percussive noise generating activity, the dredging noise will be almost indistinguishable in terms of sound exposure level.

- Sound from dredging may propagate into areas that are sheltered for the other piling or construction activities. This will create an effect area that is a composite of the two modelled activities, with a larger affected area than for just a single activity (e.g. Figure 7.58); however the area would be no greater than the total area for the two activities if they were carried out separately. The total duration of noise would also be shorter than if each activity were carried out at separate times.

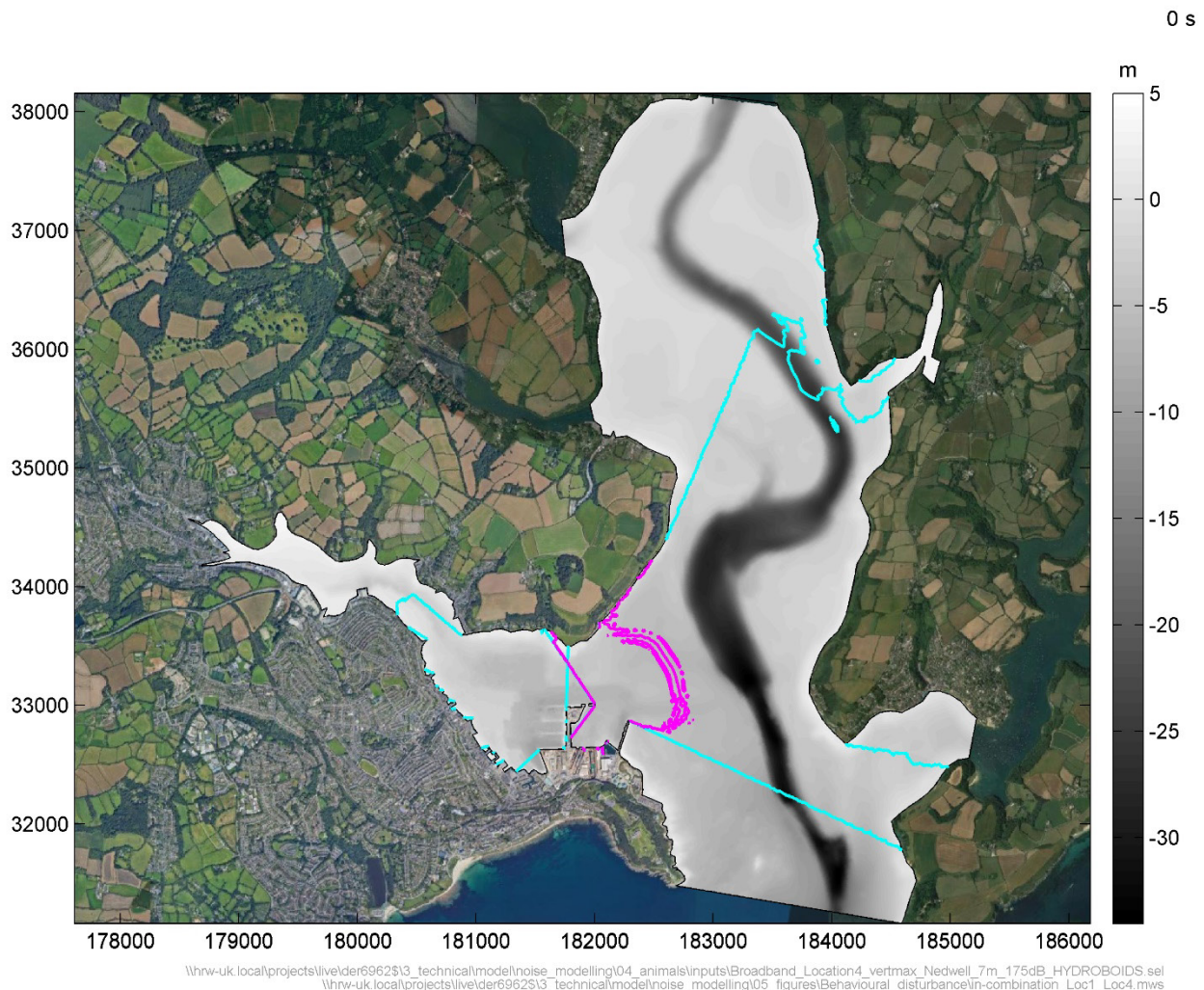


Figure 7.58: The in-combination behavioural disturbance contours for marine mammals considering demolition on the Northern Arm (Location 1) and backhoe dredging at the FLOW deck (Location 4)

Source: Uses Google Earth imagery

There will be other in-combination construction activities, however as these will be on land and emit no or low level noise into the underwater environment they are not considered here. Figure 7.59 shows the parallel program for the underwater noise related activities only.



8 Summary of Results

8.1 Mammals

8.1.1 Demolition

The demolition activity using a hydraulic hammer was predicted to cause TTS thresholds to be exceeded for most mammal groups, over distance of up to 3800 m, and PTS within up to 1700 m (very high frequency cetaceans). This is based on the assumption that the hydraulic hammer is used for one hour at a high strike rate (300 strikes/ minute) and could be less for different equipment is used.

8.1.2 Dredging

The dredging modelled was predicted to have only small impact areas (<500 m) for both low frequency cetaceans and very high frequency cetaceans. This assumed a backhoe, operating continuously for 24 hours.

8.1.3 Percussive piling

Percussive piling was predicted to cause TTS and PTS thresholds to be exceeded for each hearing group, sometimes over wide areas. Low frequency cetaceans and very high frequency cetaceans are particularly sensitive to pile driving noise. The distances to the SEL_{cum} thresholds are repeated here to allow comparisons to be made more easily with the predicted distances to thresholds for pile driving with a bubble curtain.

The distances to impact thresholds are predicted to be reduced when a bubble curtain is used the piling location. Note that, for the bubble curtain scenarios, the threshold exceedance for PTS generally occurred only for animals between the noise source and the shoreline, where fleeing is restricted.

Table 8.1: Distances to impact threshold for different mammal hearing groups (percussive piling with soft start procedure at the Western Wharf, Location 2, with and without a bubble curtain)

	TTS			PTS		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
LF cetaceans (SEL _{cum}) (without BC)	3500 m	2900 m	1200 m	1500 m	1200 m	700 m
HF cetaceans (SEL _{cum}) (without BC)	1300 m	1000 m	360 m	460 m	370 m	210 m
VHF cetaceans (SEL _{cum}) (without BC)	4100 m	3300 m	1400 m	2000 m	1700 m	850 m
Pinnipeds (SEL _{cum}) (without BC)	2300 m	2100 m	970 m	1100 m	840 m	270 m
LF cetaceans (SEL _{cum}) (with BC)	1300 m	1200 m	600 m	460 m	410 m	220 m
HF cetaceans (SEL _{cum}) (with BC)	460 m	350 m	200 m	0 m	0 m	0 m
VHF cetaceans (SEL _{cum}) (with BC)	2300 m	2000 m	1000 m	1500 m	1200 m	460 m
Pinnipeds (SEL _{cum}) (with BC)	460 m	410 m	210 m	0 m	0 m	0 m

Table 8.2: Distances to impact threshold for different mammal hearing groups (percussive piling with soft start at the Queen's Wharf, Location 3, with and without a bubble curtain)

	TTS			PTS		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
LF cetaceans (SEL _{cum}) (without BC)	3600 m	2900 m	1200 m	2000 m	1800 m	880 m
HF cetaceans (SEL _{cum}) (without BC)	860 m	640 m	310 m	0 m	0 m	0 m
VHF cetaceans (SEL _{cum}) (without BC)	3800 m	3300 m	1300 m	2600 m	2200 m	930 m
Pinnipeds (SEL _{cum}) (without BC)	3100 m	2500 m	1000 m	810 m	650 m	310 m
LF cetaceans (SEL _{cum}) (with BC)	990 m	860 m	570 m	670 m	600 m	280 m
HF cetaceans (SEL _{cum}) (with BC)	0 m	0 m	0 m	0 m	0 m	0 m
VHF cetaceans (SEL _{cum}) (with BC)	2800 m	2200 m	1100 m	810 m	680 m	330 m
Pinnipeds (SEL _{cum}) (with BC)	670 m	620 m	290 m	0 m	0 m	0 m

Table 8.3: Distances to impact threshold for different mammal hearing groups (percussive piling with soft start for the FLOW deck, Location 4, with and without a bubble curtain)

	TTS			PTS		
	R _{max}	R ₉₅	R _{mean}	R _{max}	R ₉₅	R _{mean}
LF cetaceans (SEL _{cum}) (without BC)	2200 m	2000 m	770 m	1400 m	1300 m	640 m
HF cetaceans (SEL _{cum}) (without BC)	1000 m	780 m	310 m	650 m	520 m	210 m
VHF cetaceans (SEL _{cum}) (without BC)	3000 m	2600 m	910 m	1600 m	1300 m	630 m
Pinnipeds (SEL _{cum}) (without BC)	1500 m	1400 m	630 m	960 m	780 m	360 m
LF cetaceans (SEL _{cum}) (with BC)	1200 m	1000 m	570 m	670 m	580 m	270 m
HF cetaceans (SEL _{cum}) (with BC)	650 m	510 m	220 m	0 m	0 m	0 m
VHF cetaceans (SEL _{cum}) (with BC)	2200 m	1800 m	870 m	960 m	820 m	350 m
Pinnipeds (SEL _{cum}) (with BC)	670 m	610 m	260 m	0 m	0 m	0 m

8.1.4 Behavioural disturbance and background noise

The baseline background sound levels within the Fal estuary, based on AIS data, were calculated to have an annual mean SPL above 120 dB re 1µPa within the main shipping channel. The larger vessels have source levels that may cause disturbance to marine mammals at distances of several kilometres (at 6 knots speed in deep water) but under 1 km on average. Disturbance to marine mammals under existing conditions is therefore likely to occur frequently and over a large part of the estuary, especially in the deeper parts of the estuary (> 10m depth), throughout the year. Following completion of the dock development, an increase in disturbance is predicted for transiting passenger and cargo vessels from approximately 60 hours per year (baseline conditions) to up to 75 hours per year (i.e. approximately up to 15 hours per year of additional disturbance). This should be considered in the context of disturbance by all large vessels (passenger, cargo, military and tanker) combined, which for the baseline are predicted create a

disturbance for approximately 120 – 140 hours per year (and higher still when smaller vessels are also considered).

It is noted that the predicted source levels for the Excellence-class cruise ships, due to their large size, are likely to be higher than the other vessels, with distances of disturbance of up to approximately 6 km from the vessel (at 6 knots in deep water). The behavioural disturbance effects are therefore likely to be more pronounced for the larger vessels, but below injury (TTS or PTS) level due to fact that vessel generate low frequency sound that is mainly below the marine mammal hearing sensitivity range.

Disturbance during the demolition and construction activities vary according to the activity being carried out. For backhoe dredging (which is considered a continuous type noise), the source levels are similar to large vessel source levels, so the disturbance will be similar to the mediums sized vessel noise disturbance (of the order 1 km of the noise source). Worst-case disturbance during unmitigated pile driving and hammering (impulsive noise sources) is likely to be over a considerably wider area limited only by the shoreline and shadowed by headlands, shallow areas and quay structures. The use of bubble curtains was predicted to reduce the areas of higher level disturbance (<160 dB); however areas of low level disturbance (<140 dB) would remain. Piling further south on the Western Wharf would have a smaller impact footprint due to shadowing by the Eastern Breakwater.

8.2 Fish

8.2.1 Demolition

Stationary fish were potentially impacted over an area of approximately 1.7 km², with the TTS threshold exceeded east of the noise location reaching the main channel through Carrick Roads. It was predicted that fleeing fish would only be impacted by the hydraulic hammer noise if they were between the noise source and the coastline/eastern breakwater when the noise began.

8.2.2 Dredging

Fish were not predicted to be impacted by the dredging noise at either the TTS or injury threshold level.

8.2.3 Pile driving

Stationary fish (i.e. worst case modelling assumption) were predicted to accumulate high SEL_{cum} doses, with injury and mortality thresholds exceeded over distance of up to 1700 m from the noise source. The SEL_{cum} TTS threshold was exceeded up to 4100 m from the noise source. For pile driving with a bubble curtain, impacted areas were predicted to be substantially smaller. Maximum distances to injury thresholds for stationary fish were reduced to 160 m (mortal injury), 290 m (PTS/injury) and up to 1700 m (TTS).

For pile driving with a soft start, the distance to SEL_{cum} TTS threshold for fleeing fish was up to 1500 m depending on location of the noise. Injury thresholds were exceeded close to the piles in areas where fish could not escape easily because they were between the noise source and the coastline (would have had to swim through an area with higher sound levels to escape). With a bubble curtain, it was predicted that the injury and mortality SEL_{cum} thresholds would not be exceeded for fleeing fish and the TTS threshold would only be exceeded for fish between the noise source and the shoreline, where fleeing routes were obstructed.

8.3 Potential for blocking of animal escape routes

The modelled patterns of SEL_{cum} for fleeing animals are influenced by the constrained geometry of the model domain. The animals in the model swim directly away from the noise source and also avoid land or very shallow water. These simplified behaviours mean that some animals in the

model take longer to leave the region compared to if they had been able to continue swimming directly away from the noise, and hence receive increased SEL_{cum} dosages. This is particularly the case for animals located between the noise source and the shoreline where there might be a bay or a structure such as the Eastern Breakwater. It is likely that real animals will display a more sophisticated response to noise than the modelled animals. However, to do so, the animals may need to pass through areas where the sound levels are higher than their start location and therefore their received sound levels will be higher than they would be if they could swim directly away. For this reason, and to be conservative, the threshold exceedances for animals in trapped areas have not been removed as part of the processing.

To reduce the chances of animals becoming trapped in such a way during the construction works, the use of monitoring using marine mammal observers (MMO) or passive acoustic monitoring (PAM) could be considered as a form of mitigation.

9 Conclusions

Underwater noise has the potential to impact on marine animals. Of the noise types assessed here, demolition using a hydraulic hammer and percussive piling had the potential to cause injury, permanent threshold shift or temporary threshold shifts for marine animals.

The modelling indicates that using a bubble curtain as mitigation measure during pile driving substantially reduces the area over which impact criteria are predicted to be exceeded.

The model predictions indicate that, at the start of a noise generating activity, animals may be in areas that do not have a direct escape route away from the sound source. In this case they may need to swim through an area of louder noise in order to escape. This has the result of making mitigation measures such as the bubble curtain less effective as they could be because the animals become trapped in the higher sound level regions. To reduce the chances of animals becoming trapped in such a way during the construction works, the use of monitoring using marine mammal observers (MMO) or passive acoustic monitoring (PAM) could be considered as a form of mitigation.

It is noted that the locations for the noise sources modelled here were chosen to be worst case. For much of the construction and demolition works, the impact areas will be smaller due to the greater shadowing of the noise caused by the existing dock structures (refer to Figure 5.2).

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Appendices

A Contour maps for all animals

A.1 Demolition with hydraulic hammer

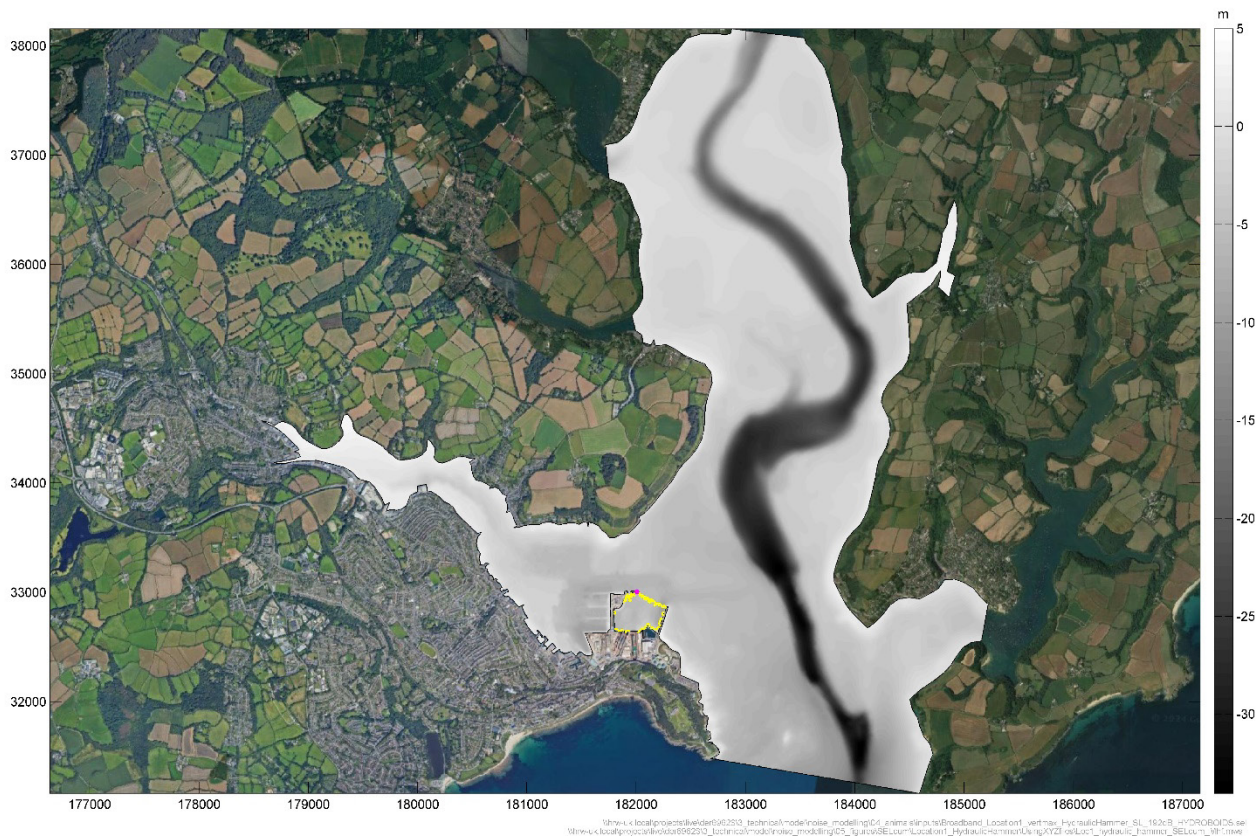


Figure A.1: Predicted SEL_{cum} impact footprint for the for high frequency cetaceans for hydraulic hammer, at the Northern Arm (Location 1)

Source: Uses Google Earth imagery

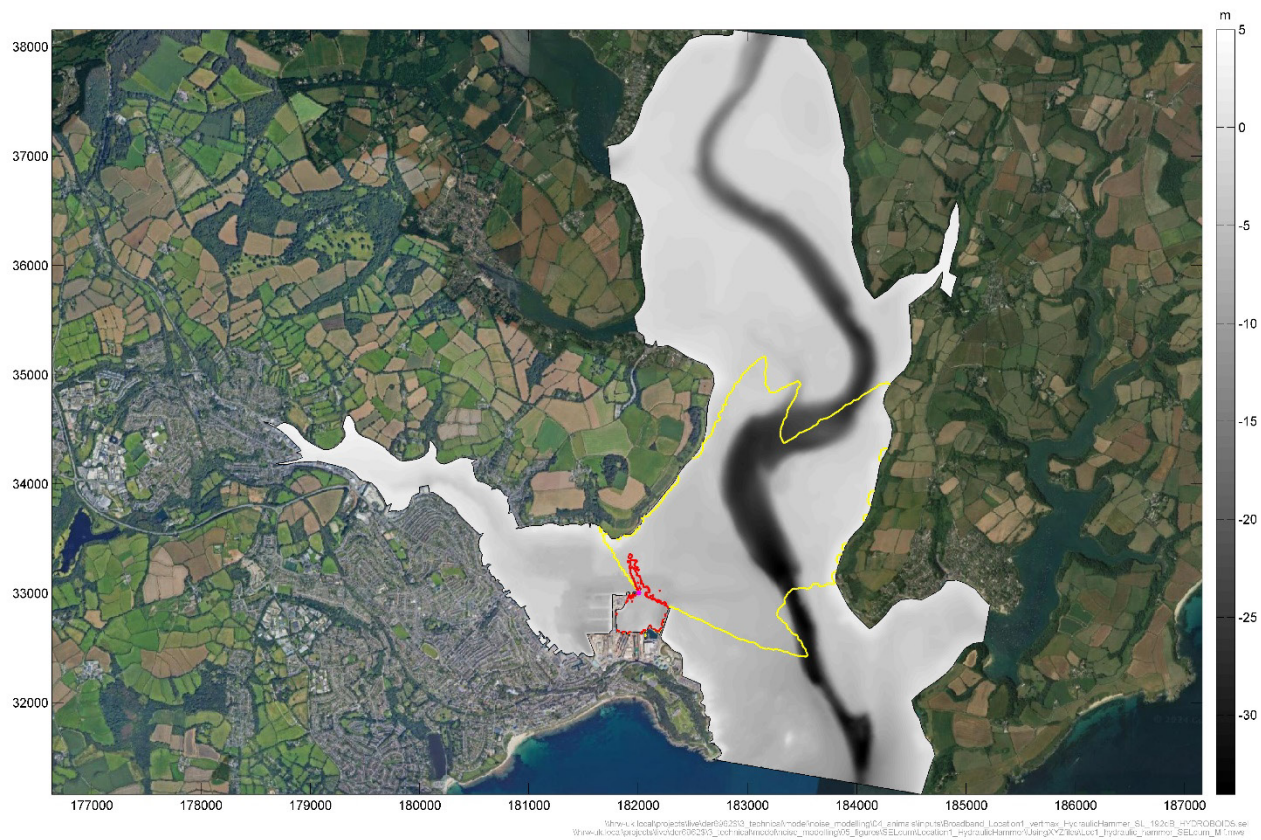
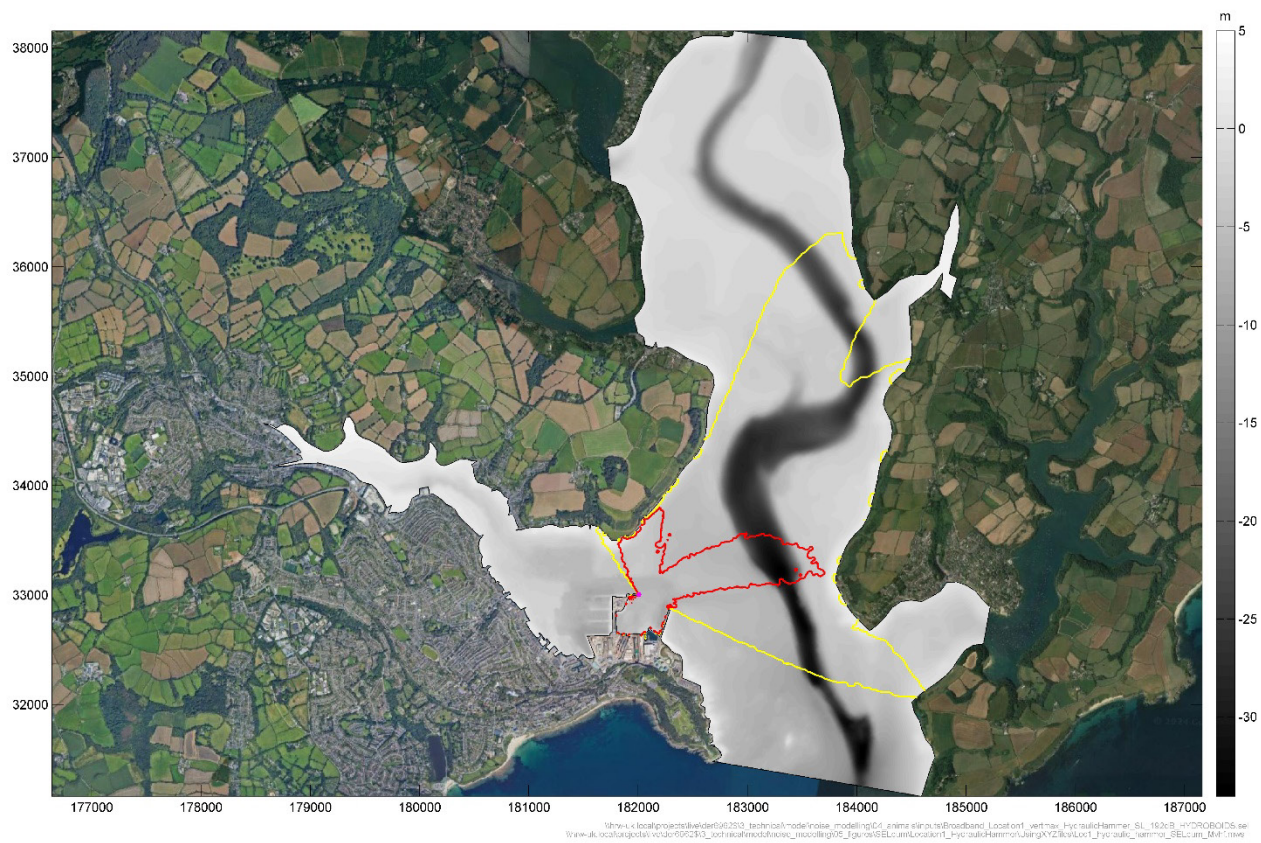


Figure A.2: Predicted SEL_{cum} impact footprint for the for low frequency cetaceans for hydraulic hammer, at the Northern Arm (Location 1)

Source: Uses Google Earth imagery



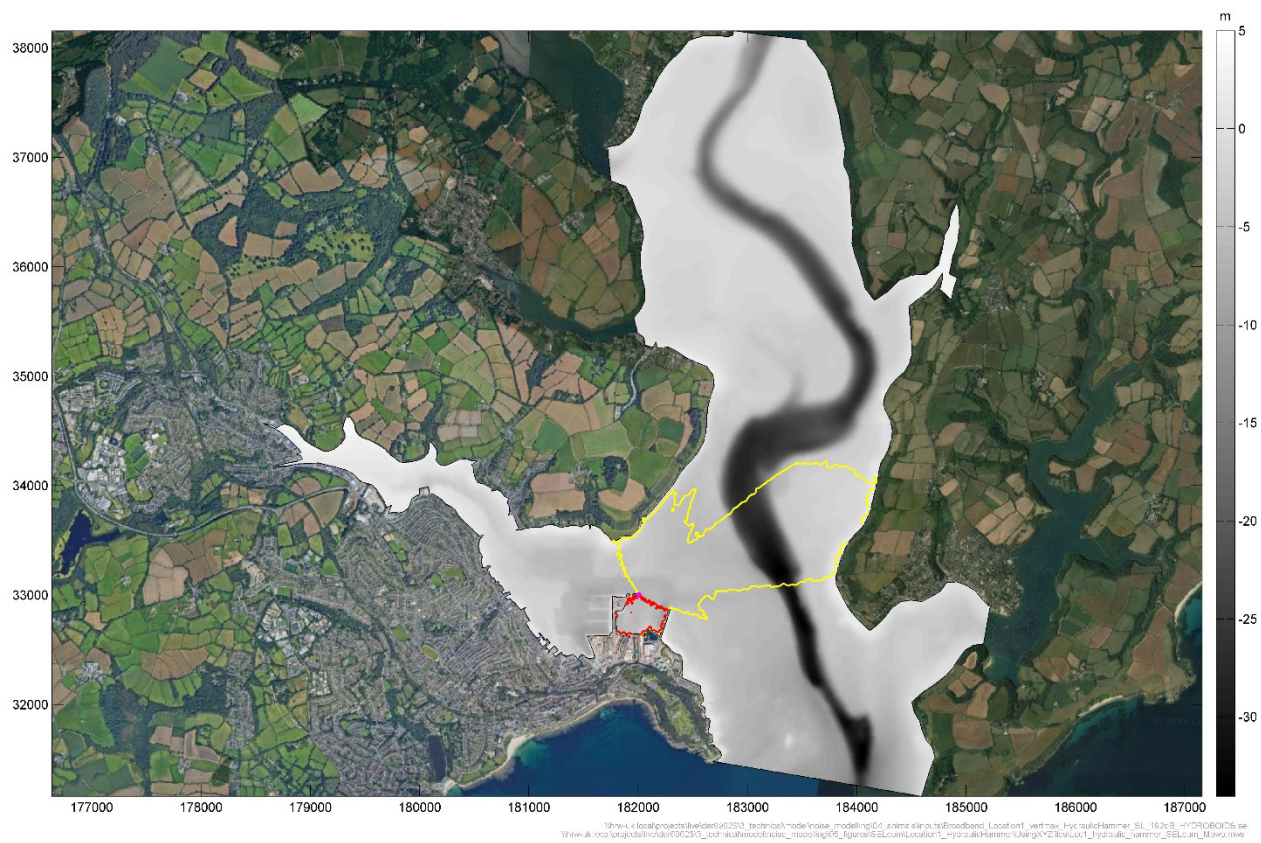


Figure A.4: Predicted SEL_{cum} impact footprint for the for pinnipeds for hydraulic hammer, at the Northern Arm (Location 1)

Source: Uses Google Earth imagery

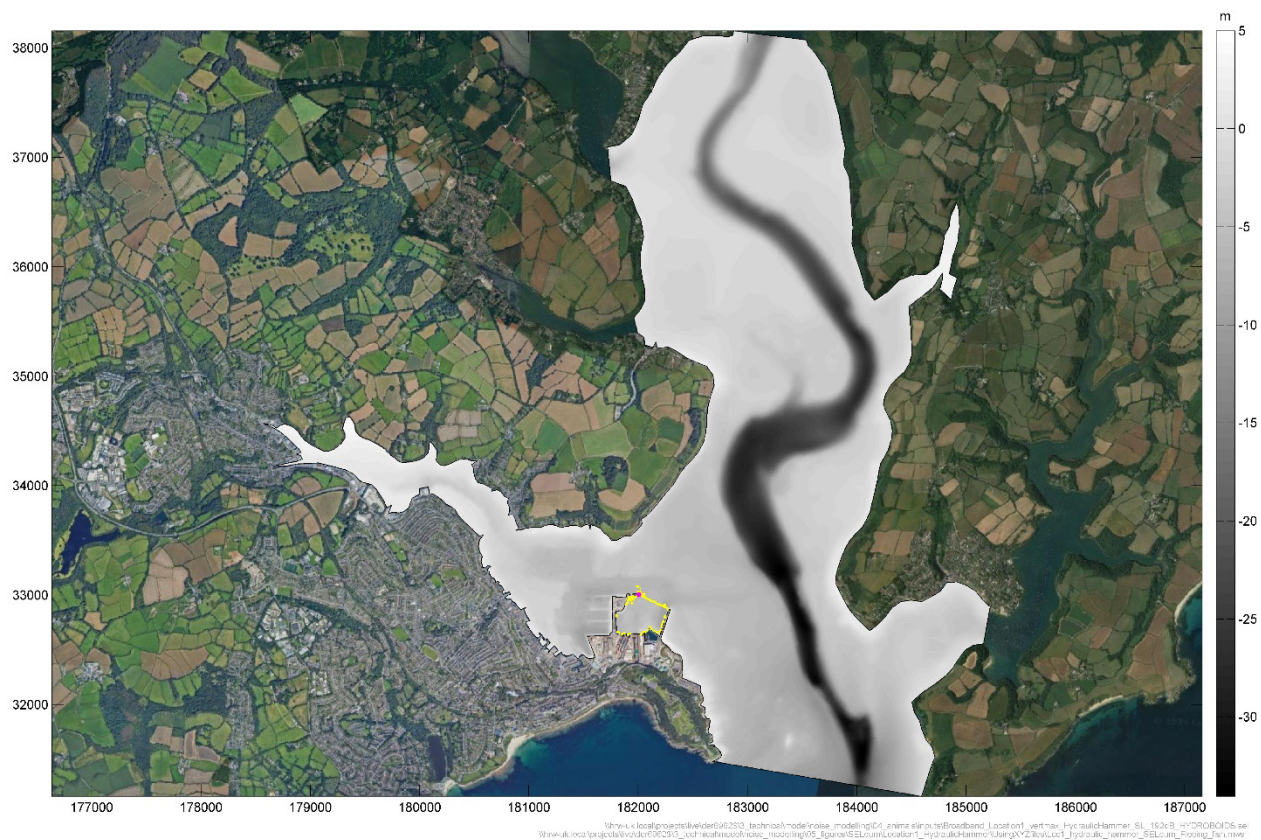


Figure A.5: Predicted SEL_{cum} impact footprint for the for fleeing fish for hydraulic hammer, at the Northern Arm (Location 1)

Source: Uses Google Earth imagery

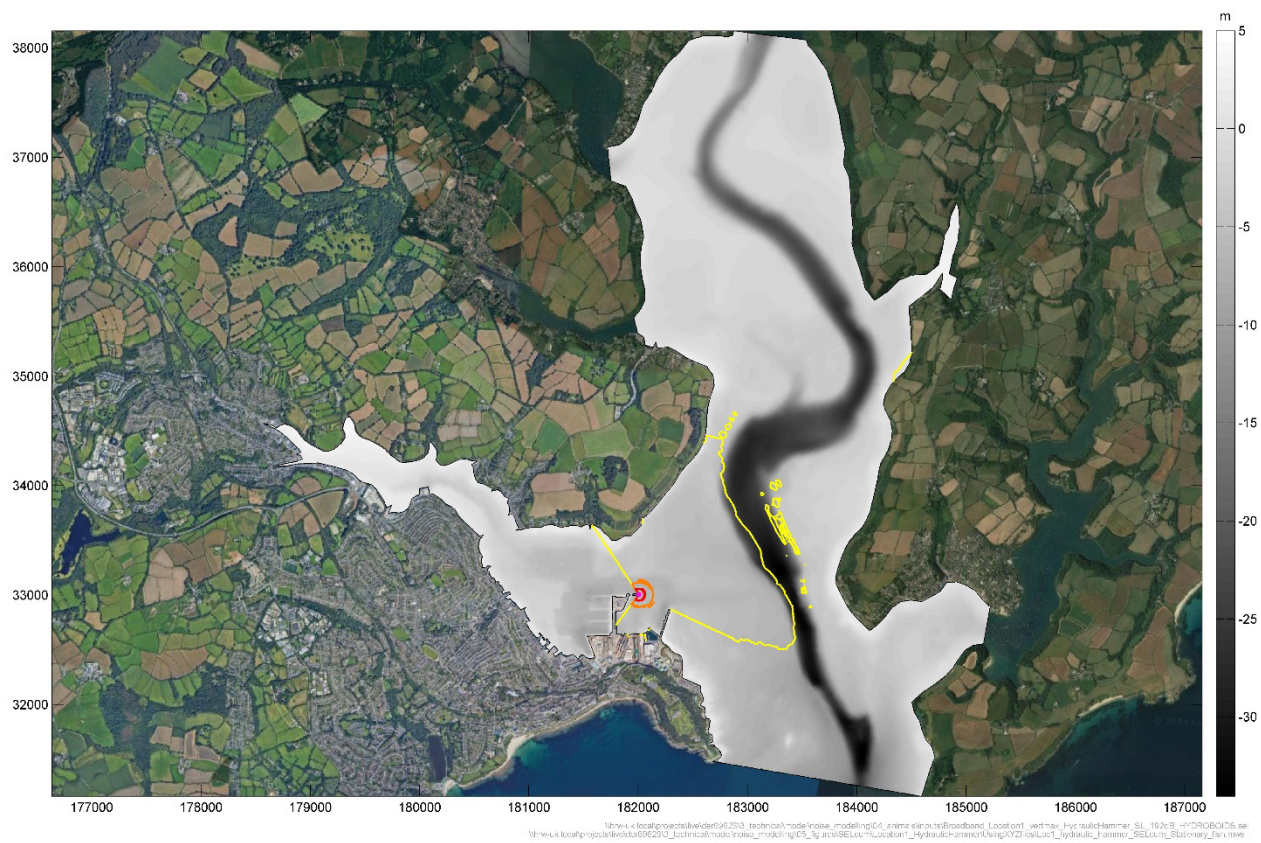


Figure A.6: Predicted SEL_{cum} impact footprint for the for stationary fish for hydraulic hammer, at the Northern Arm (Location 1)

Source: Uses Google Earth imagery

A.2 Dredging at Western Wharf



Figure A.7: Predicted SEL_{cum} impact footprint for the for high frequency cetaceans for dredging at Western Wharf (Location 2)

Source: Uses Google Earth imagery



Figure A.8: Predicted SEL_{cum} impact footprint for the for low frequency cetaceans for dredging at Western Wharf (Location 2)

Source: Uses Google Earth imagery



Figure A.9: Predicted SEL_{cum} impact footprint for the for very-high frequency cetaceans for dredging at Western Wharf (Location 2)

Source: Uses Google Earth imagery



Figure A.10: Predicted SEL_{cum} impact footprint for the for pinnipeds for dredging at Western Wharf (Location 2)

Source: Uses Google Earth imagery

A.3 Pile driving at Western Wharf



Figure A.11: Predicted SEL_{cum} impact footprint for the for high frequency cetaceans for pile driving at Western Wharf (Location 2)

Source: Uses Google Earth imagery

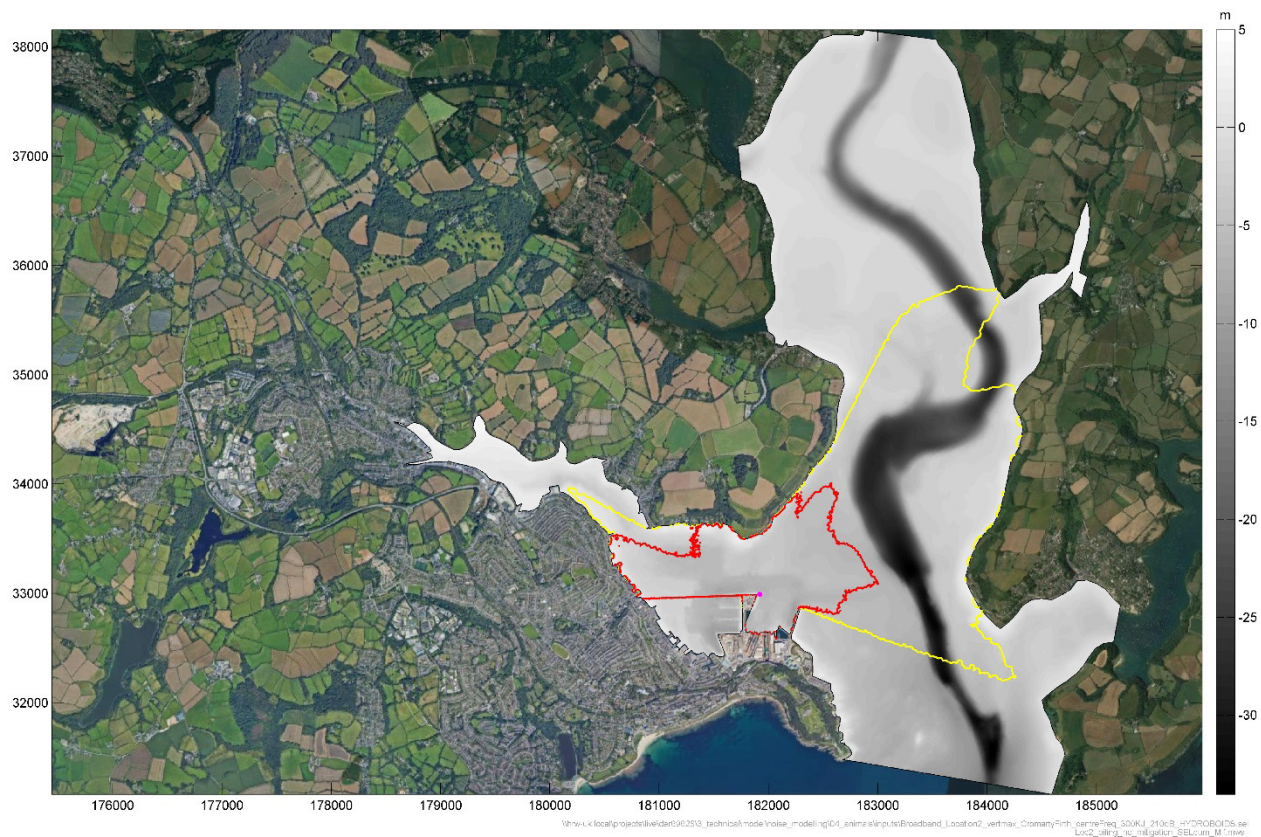


Figure A.12: Predicted SEL_{cum} impact footprint for the for low frequency cetaceans for pile driving at Western Wharf (Location 2)

Source: Uses Google Earth imagery

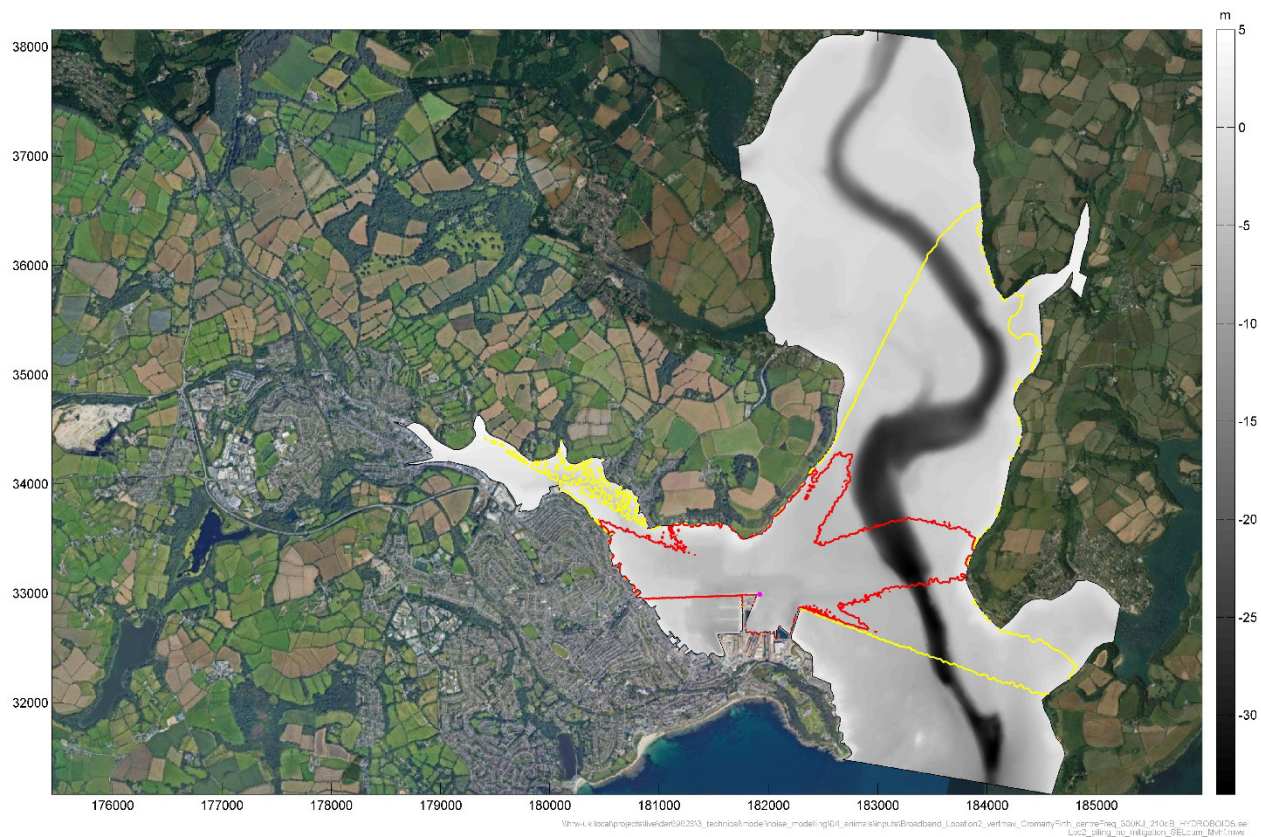


Figure A.13: Predicted SEL_{cum} impact footprint for the for very-high frequency cetaceans for pile driving at Western Wharf (Location 2)

Source: Uses Google Earth imagery

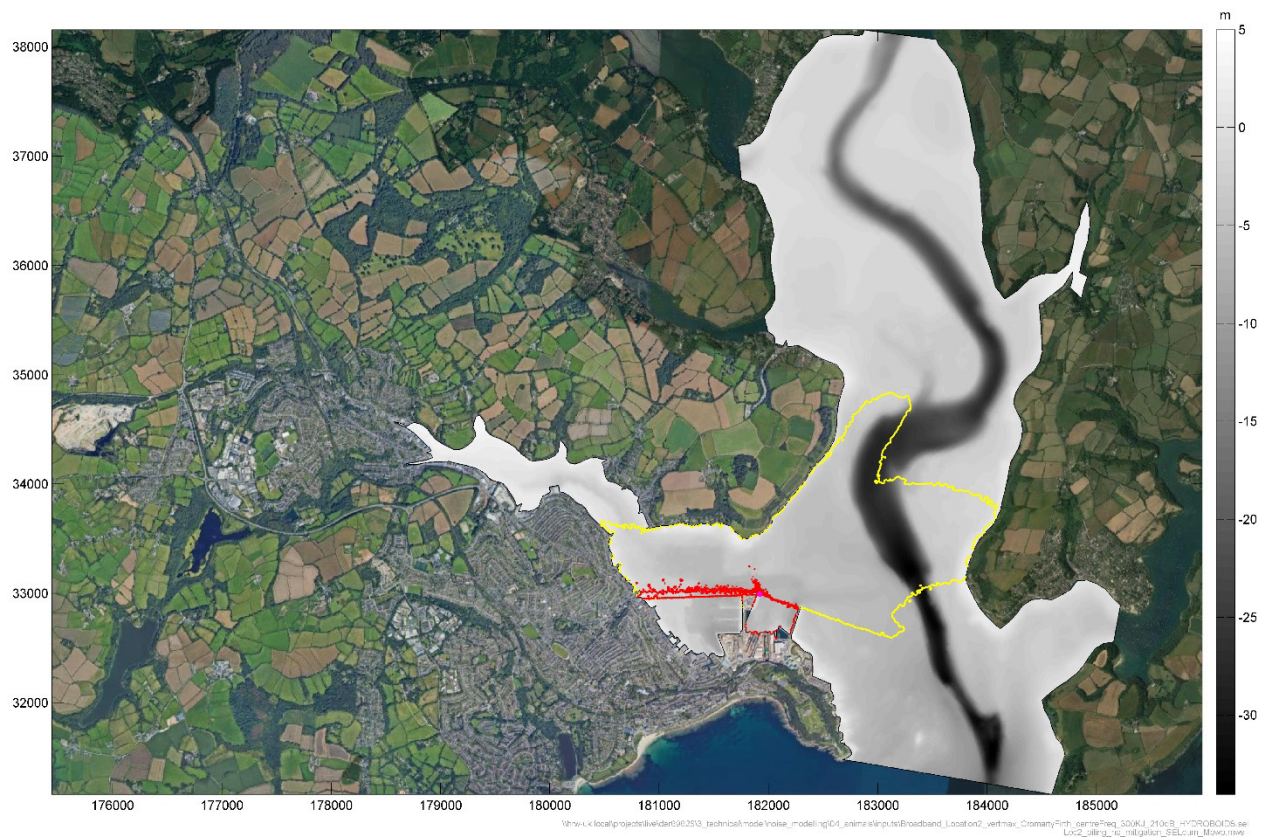


Figure A.14: Predicted SEL_{cum} impact footprint for the for pinnipeds for pile driving at Western Wharf (Location 2)

Source: Uses Google Earth imagery



Figure A.15: Predicted SELcum impact footprint for the for fleeing fish for pile driving, at the Western Wharf (Location 2)

Source: Uses Google Earth imagery

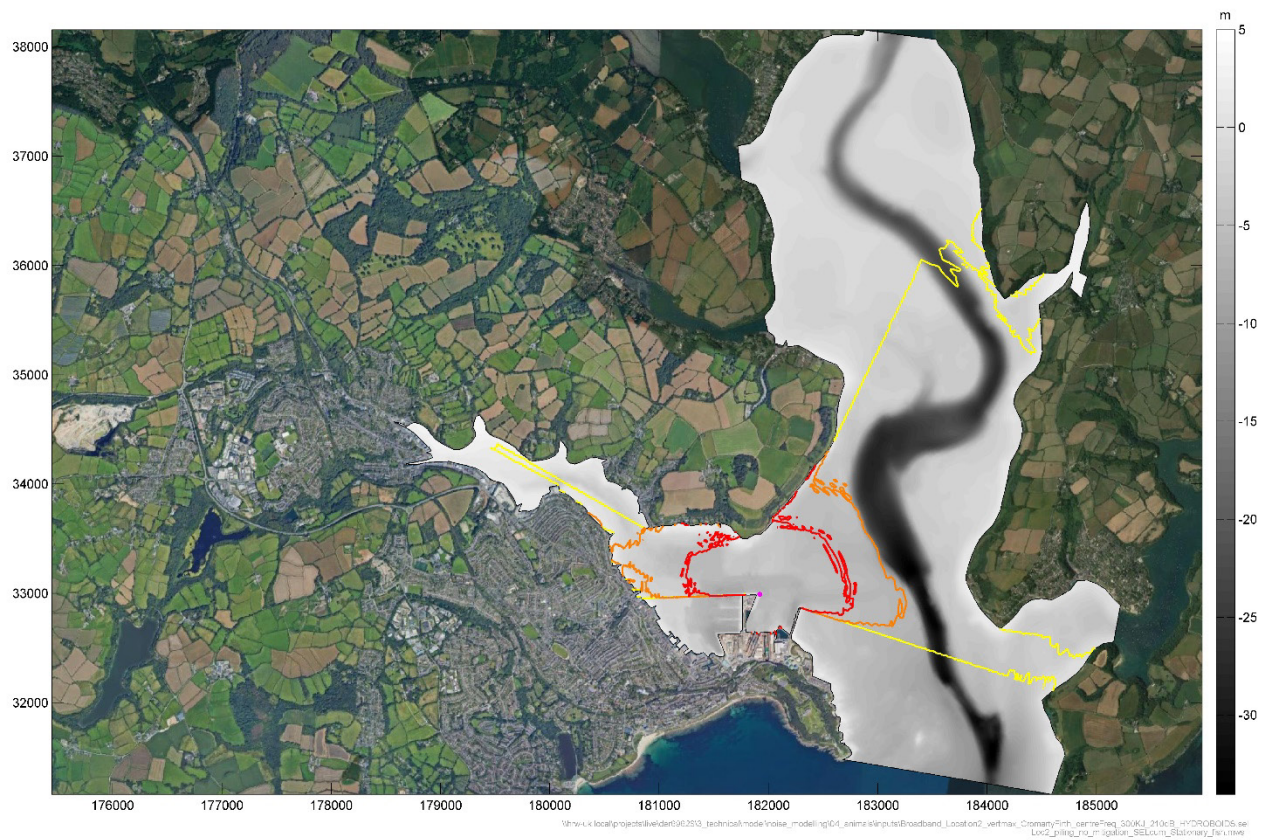


Figure A.16: Predicted SELcum impact footprint for the for stationary fish for pile driving, at the Western Wharf (Location 2)

Source: Uses Google Earth imagery

A.4 Pile driving with a bubble curtain at Western Wharf



Figure A.17: Predicted SEL_{cum} impact footprint for the for high frequency cetaceans for pile driving with a bubble curtain at Western Wharf (Location 2)

Source: Uses Google Earth imagery

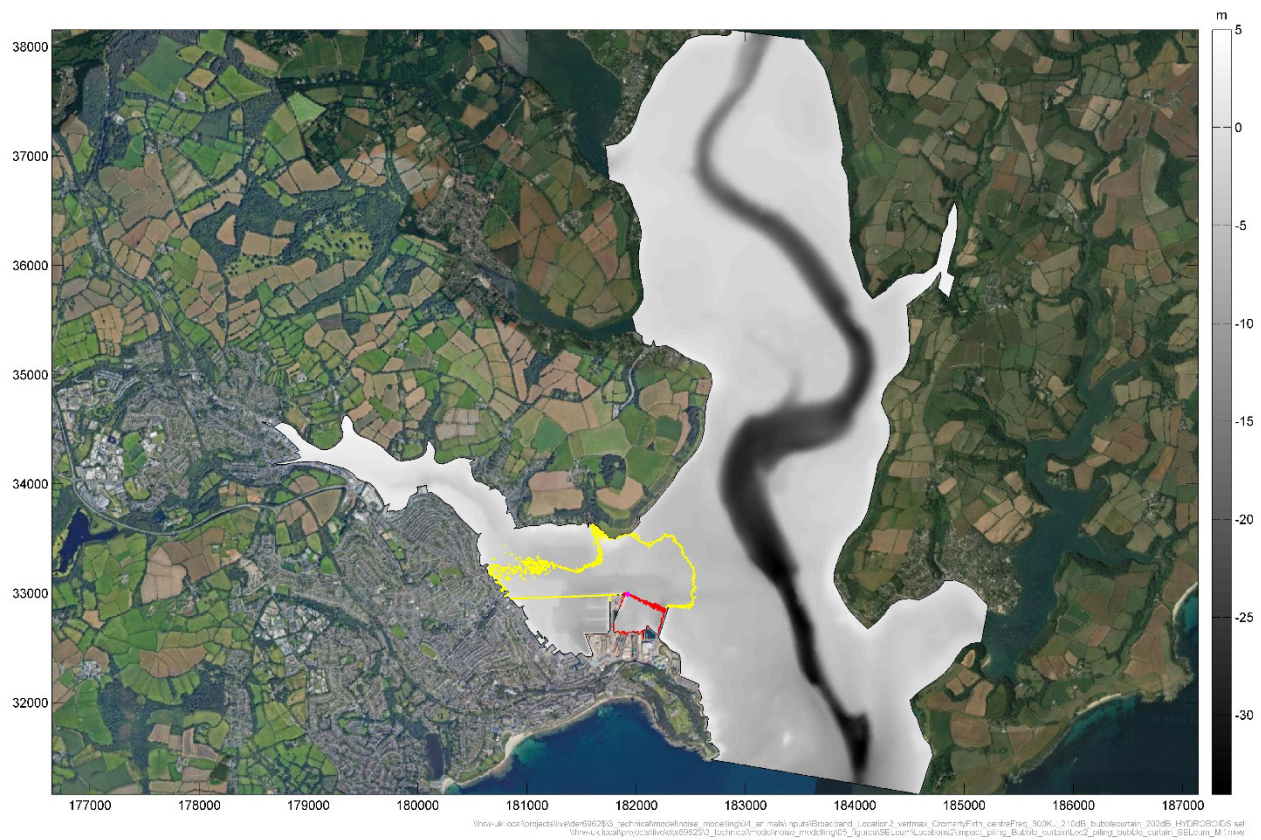


Figure A.18: Predicted SEL_{cum} impact footprint for the for low frequency cetaceans for pile driving with a bubble curtain at Western Wharf (Location 2)

Source: Uses Google Earth imagery

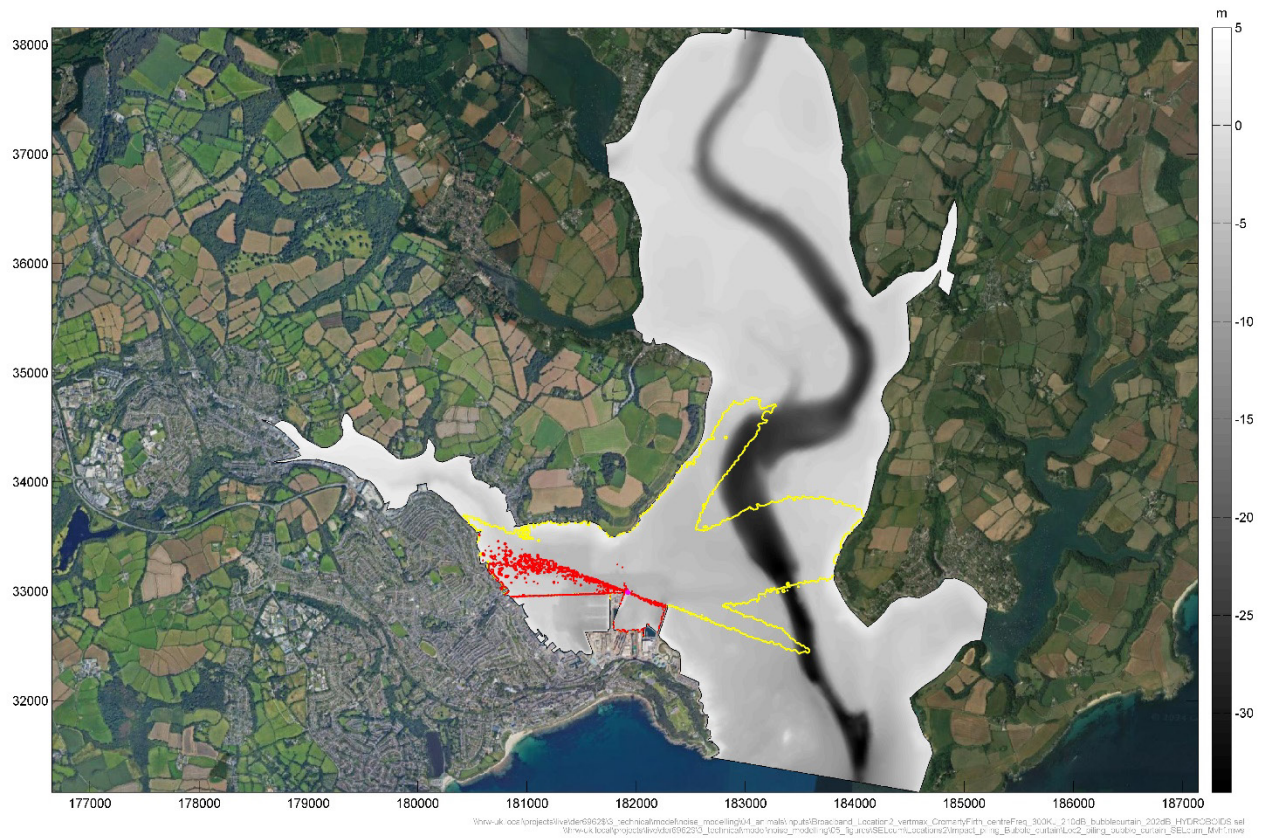


Figure A.19: Predicted SEL_{cum} impact footprint for the for very-high frequency cetaceans for pile driving with a bubble curtain at Western Wharf (Location 2)

Source: Uses Google Earth imagery

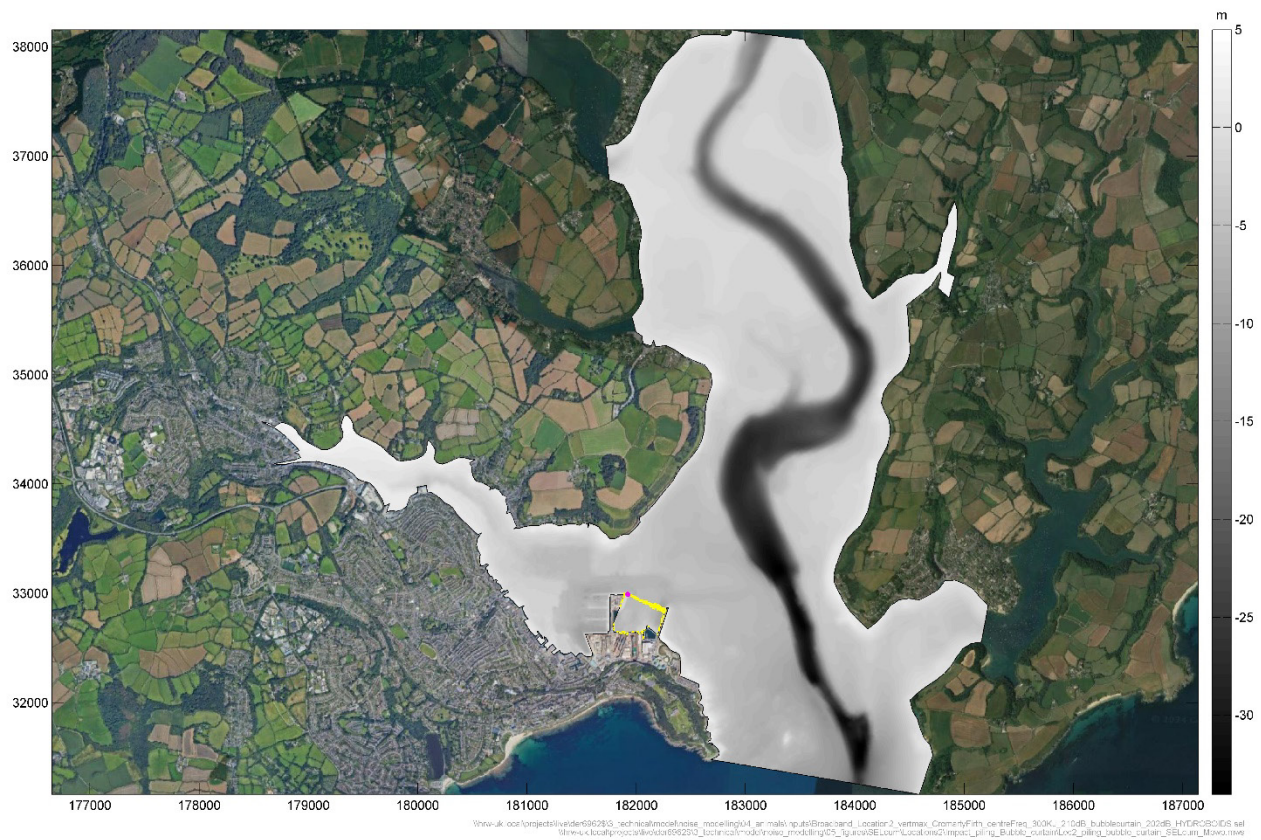


Figure A.20: Predicted SEL_{cum} impact footprint for the for pinnipeds for pile driving with a bubble curtain at Western Wharf (Location 2)

Source: Uses Google Earth imagery

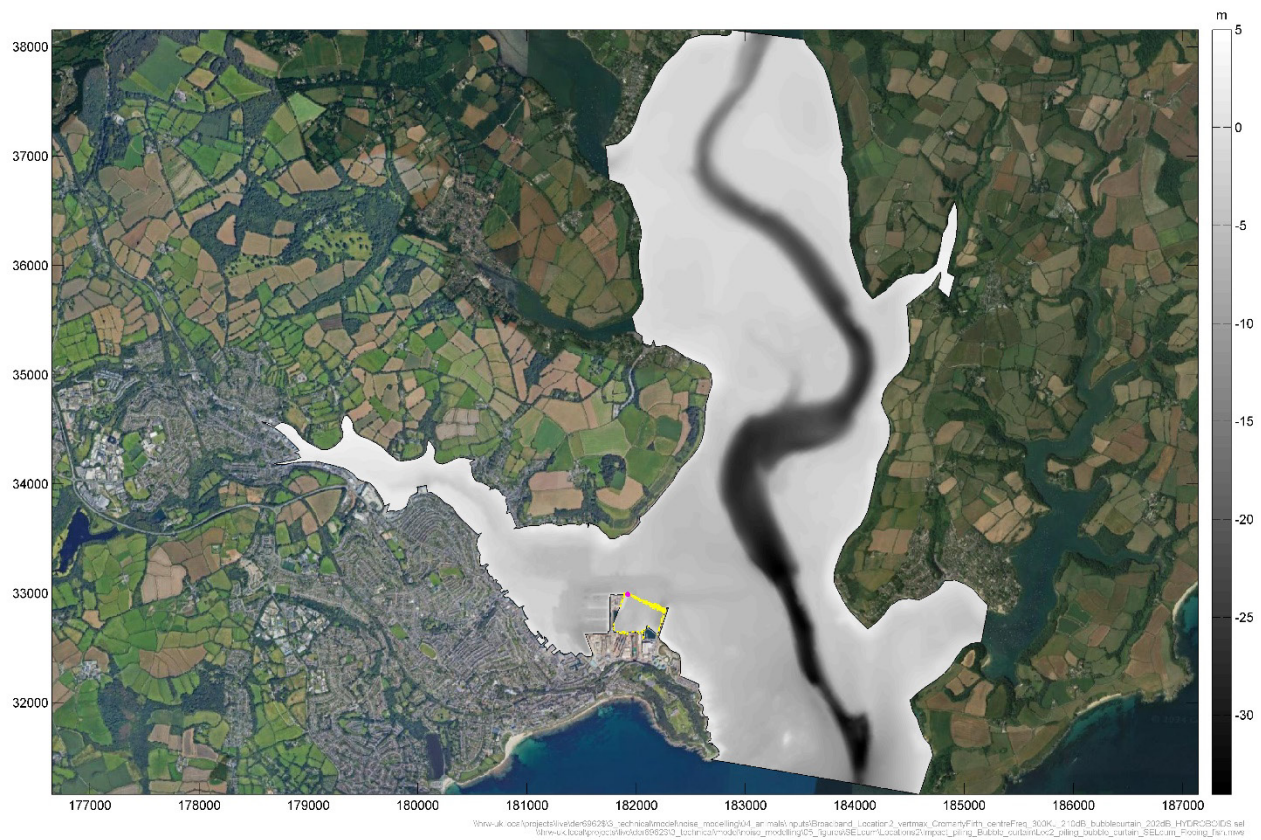


Figure A.21: Predicted SELcum impact footprint for the for fleeing fish for pile driving with a bubble curtain , at the Western Wharf (Location 2)

Source: Uses Google Earth imagery

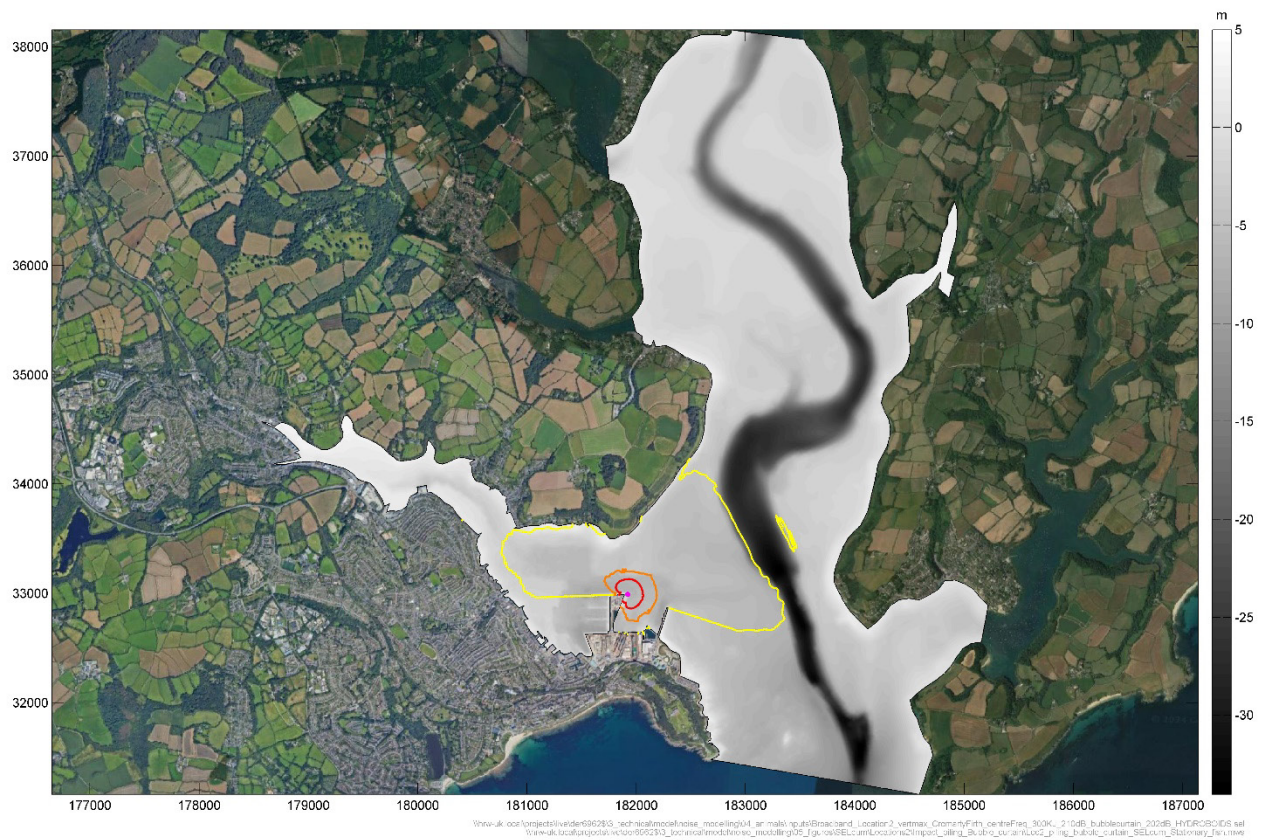


Figure A.22: Predicted SELcum impact footprint for the for stationary fish for pile driving with a bubble curtain, at the Western Wharf (Location 2)

Source: Uses Google Earth imagery

A.5 Pile driving at Queen's Wharf



Figure A.23: Predicted SEL_{cum} impact footprint for the for high frequency cetaceans for pile driving at Queen's Wharf (Location 3)

Source: Uses Google Earth imagery

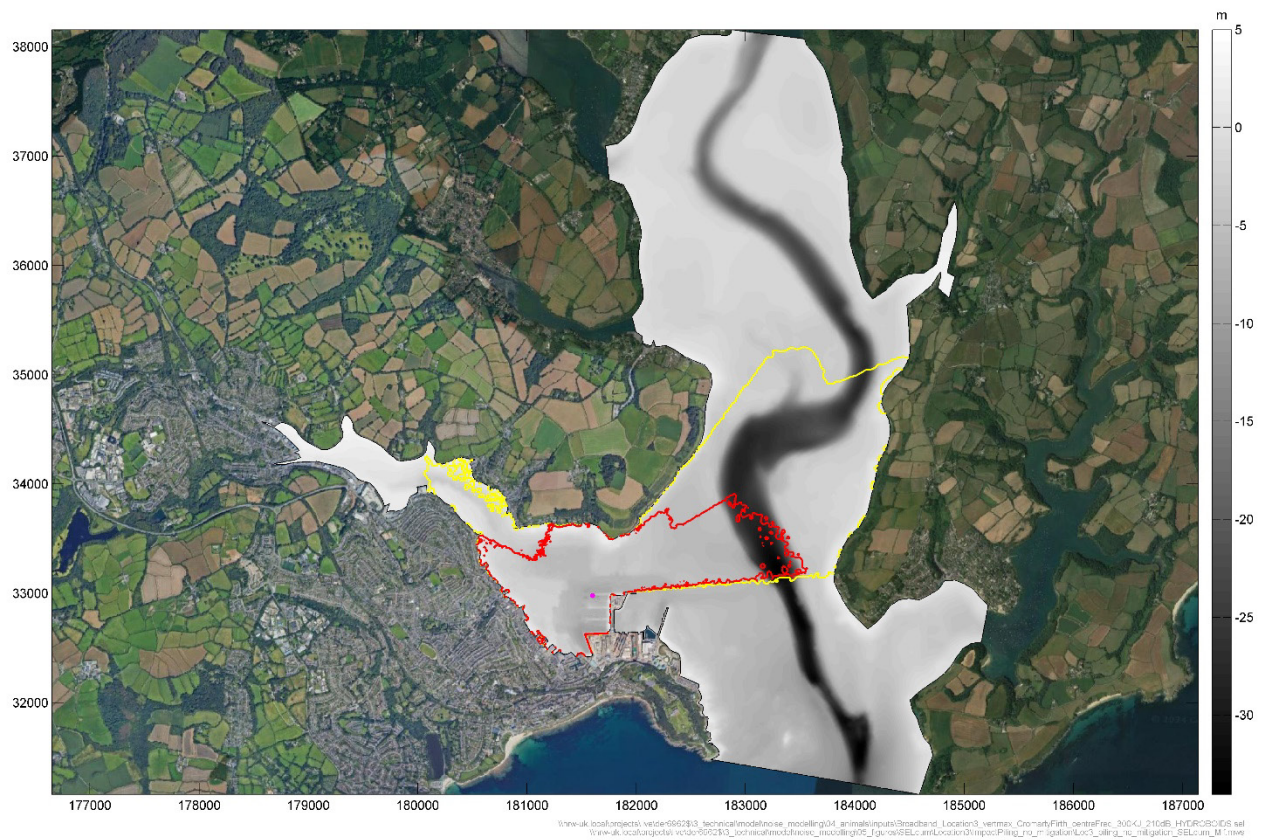


Figure A.24: Predicted SEL_{cum} impact footprint for the for low frequency cetaceans for pile driving at Queen's Wharf (Location 3)

Source: Uses Google Earth imagery

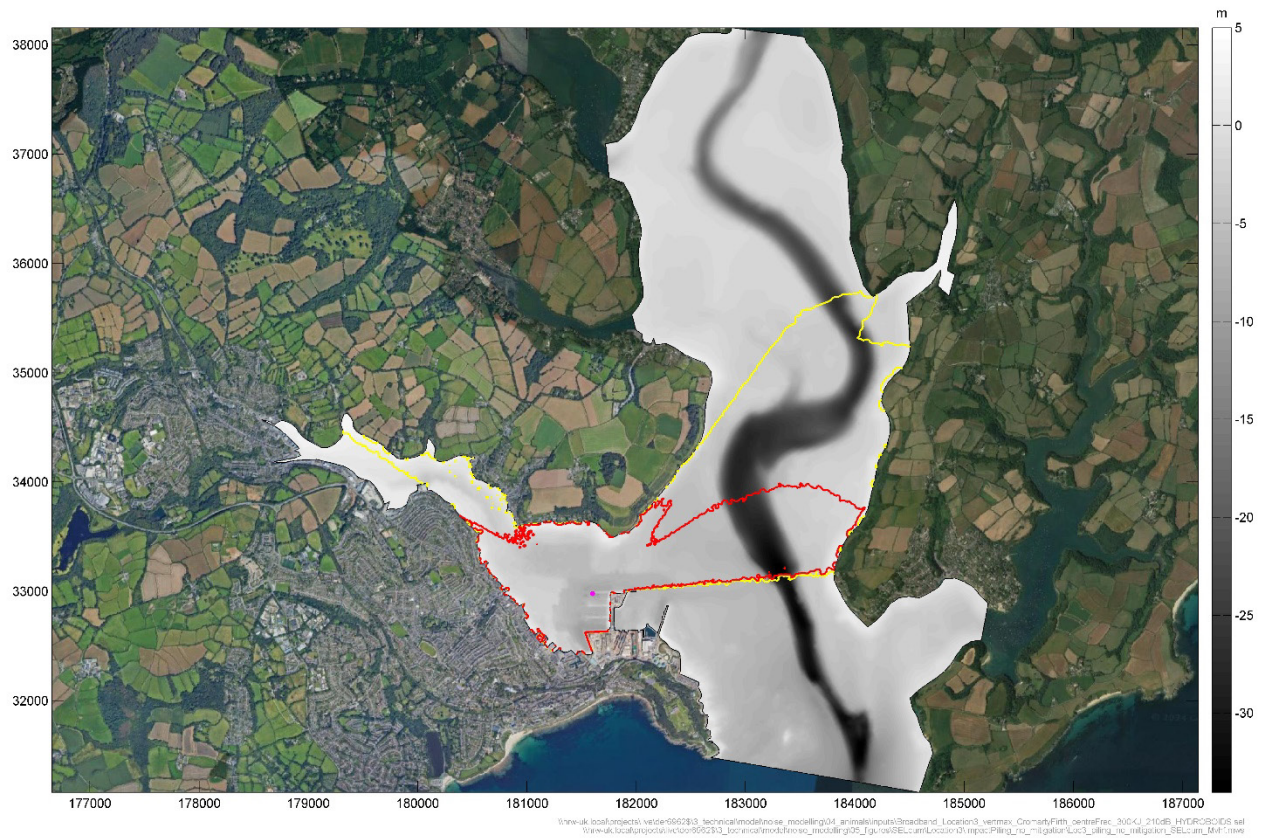


Figure A.25: Predicted SEL_{cum} impact footprint for the for very-high frequency cetaceans for pile driving at Queen's Wharf (Location 3)

Source: Uses Google Earth imagery

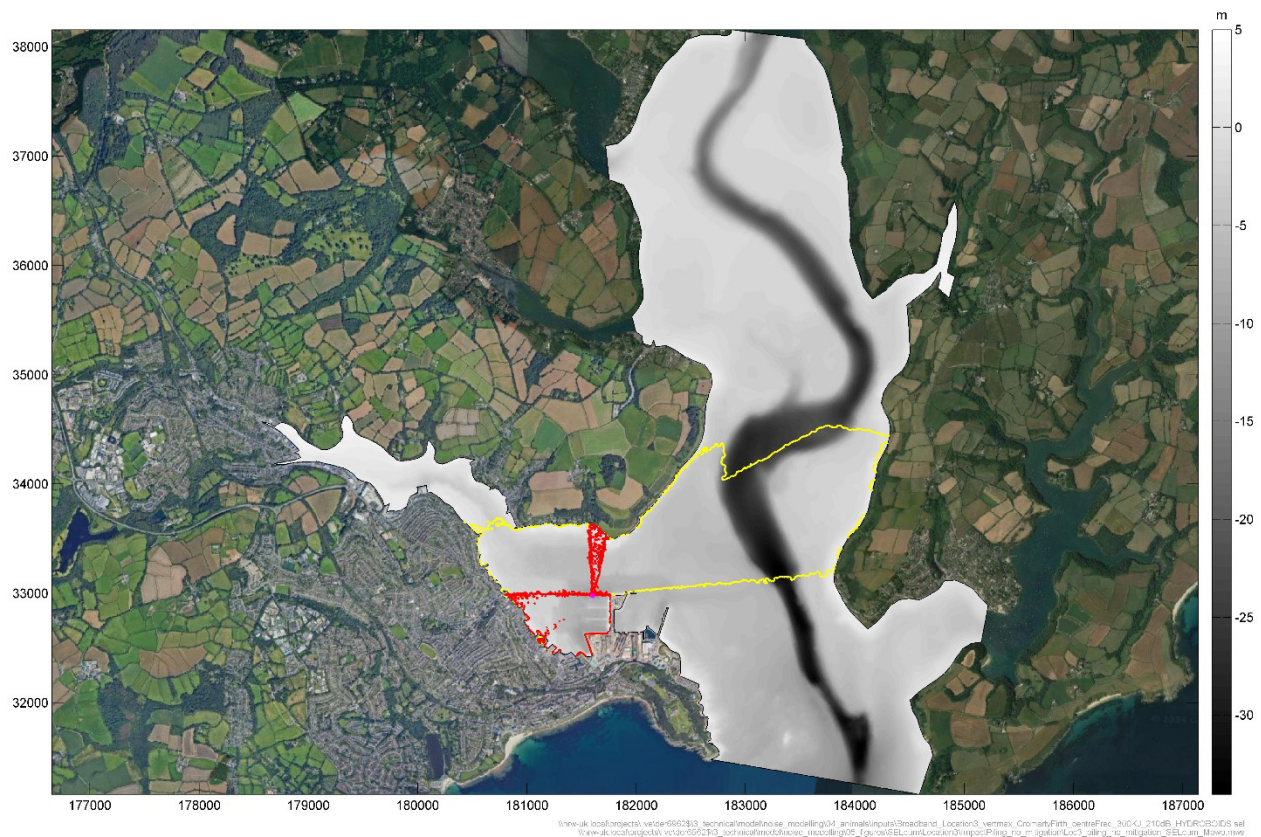


Figure A.26: Predicted SEL_{cum} impact footprint for the for pinnipeds for pile driving at Queen's Wharf (Location 3)

Source: Uses Google Earth imagery

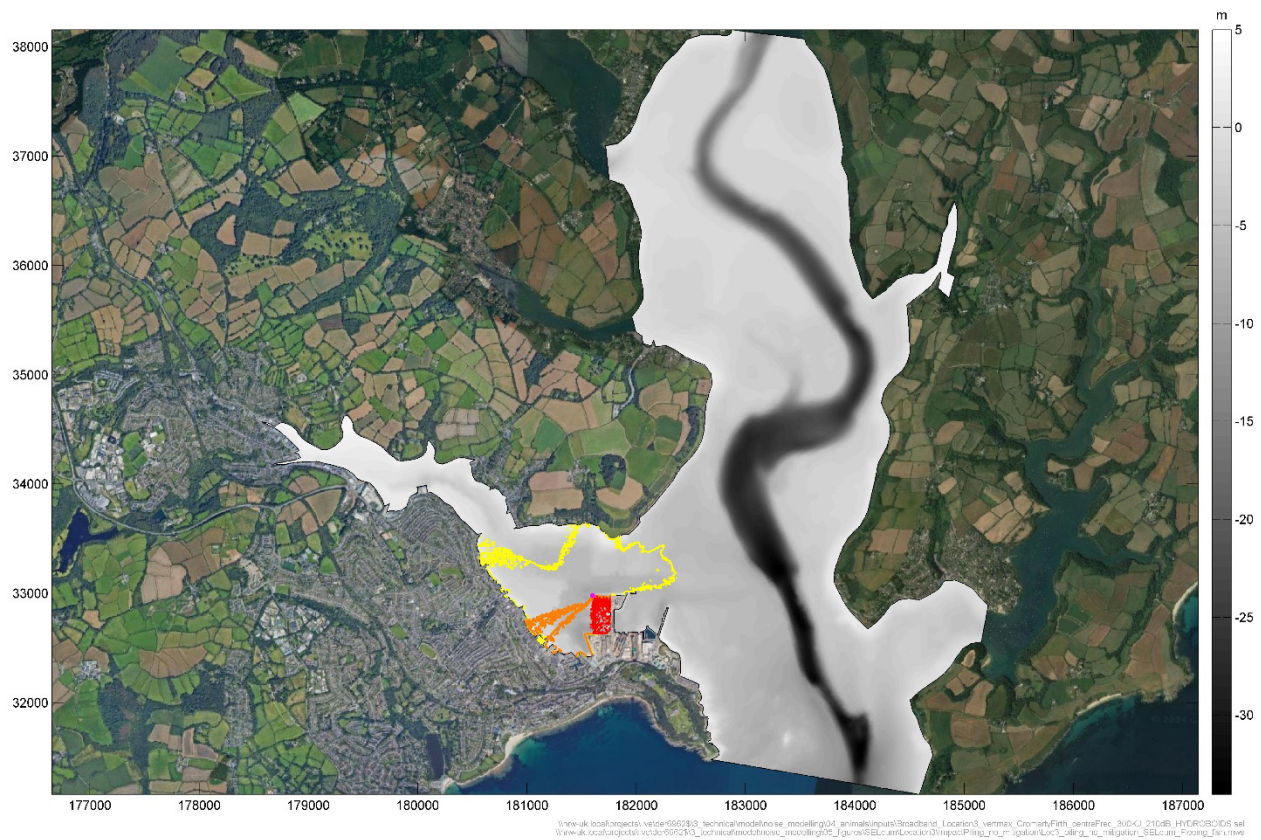


Figure A.27: Predicted SELcum impact footprint for the for fleeing fish for pile driving, at the Queen's Wharf (Location 3)

Source: Uses Google Earth imagery

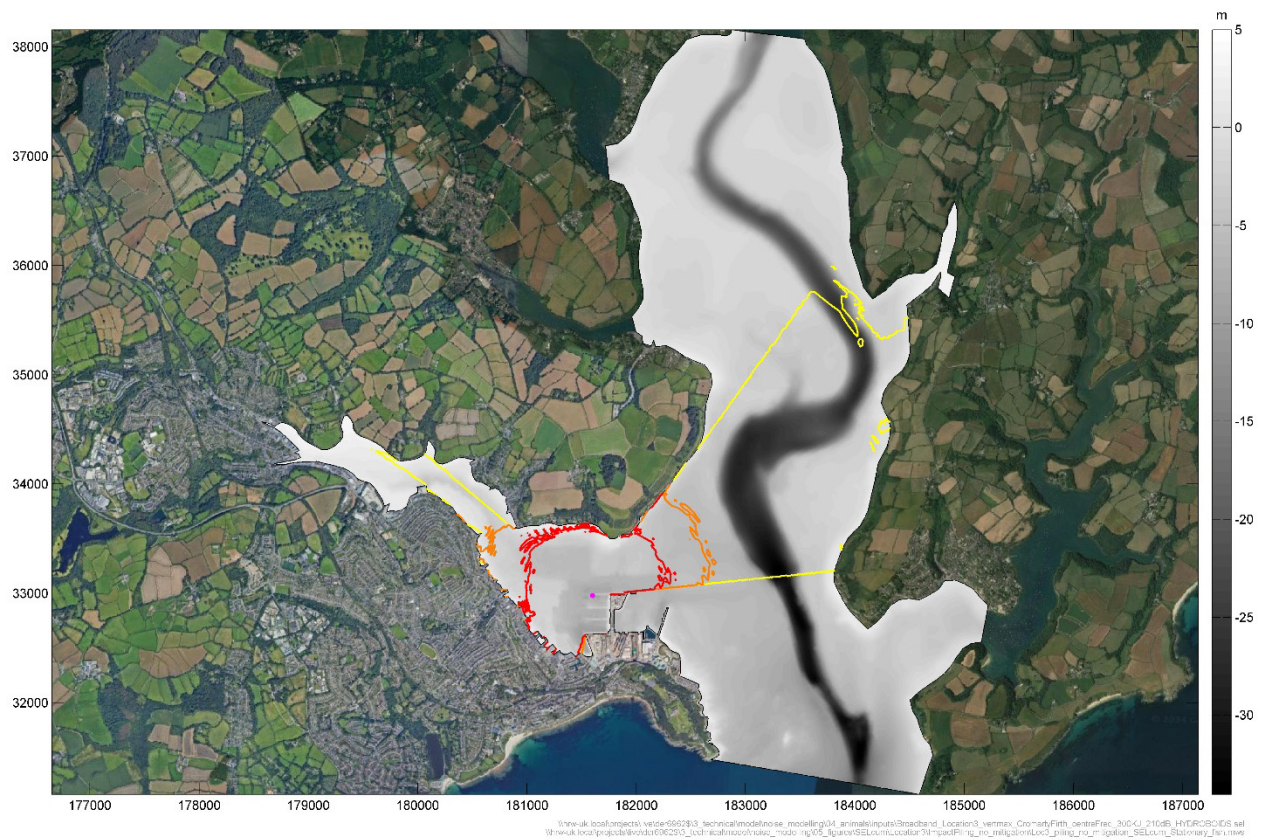


Figure A.28: Predicted SELcum impact footprint for the for stationary fish for pile driving, at the Queen's Wharf (Location 3)

Source: Uses Google Earth imagery

A.6 Pile driving at Queen's Wharf with a bubble curtain



Figure A.29: Predicted SEL_{cum} impact footprint for the for high frequency cetaceans for pile driving with a bubble curtain at Queen's Wharf (Location 3)

Source: Uses Google Earth imagery

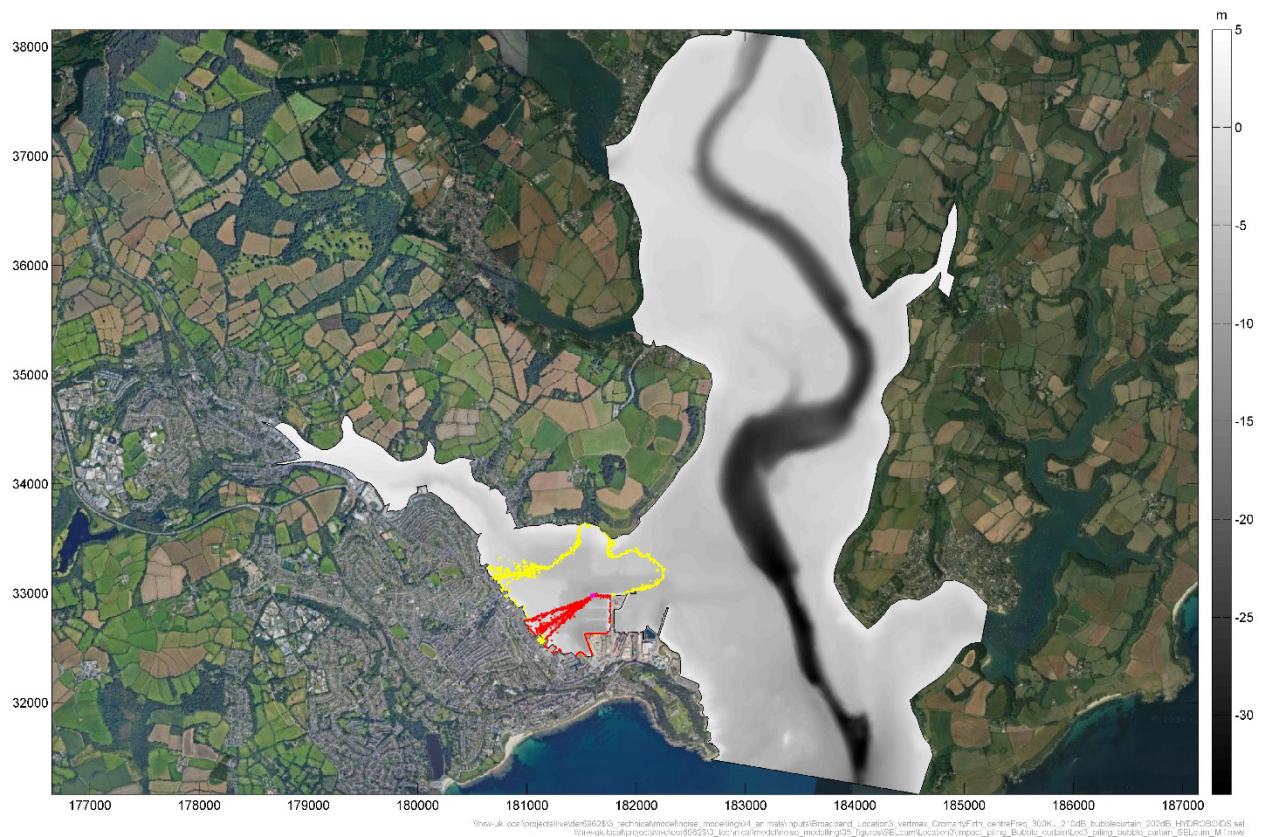


Figure A.30: Predicted SEL_{cum} impact footprint for the for low frequency cetaceans for pile driving with a bubble curtain at Queen's Wharf (Location 3)

Source: Uses Google Earth imagery

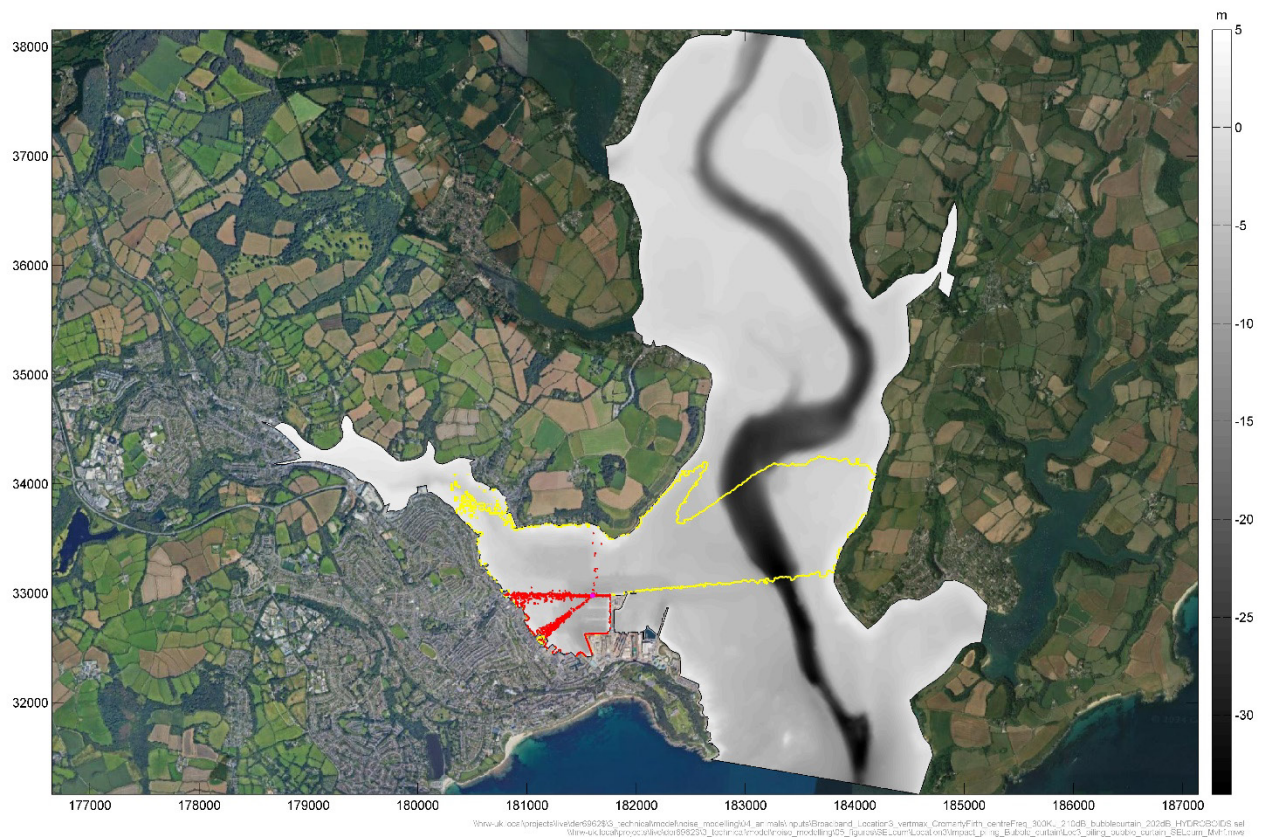


Figure A.31: Predicted SEL_{cum} impact footprint for the for very-high frequency cetaceans for pile driving with a bubble curtain at Queen's Wharf (Location 3)

Source: Uses Google Earth imagery

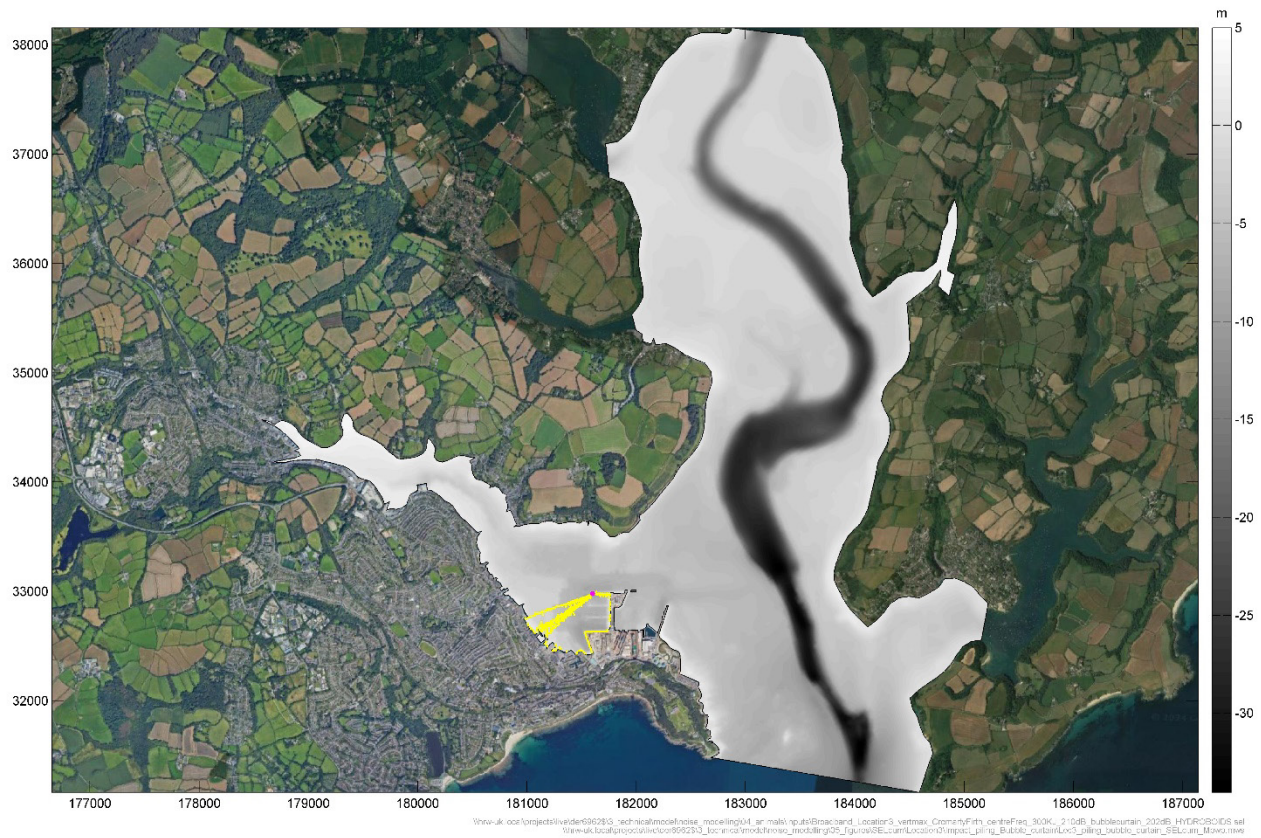


Figure A.32: Predicted SEL_{cum} impact footprint for the for pinnipeds for pile driving with a bubble curtain at Queen's Wharf (Location 3)

Source: Uses Google Earth imagery

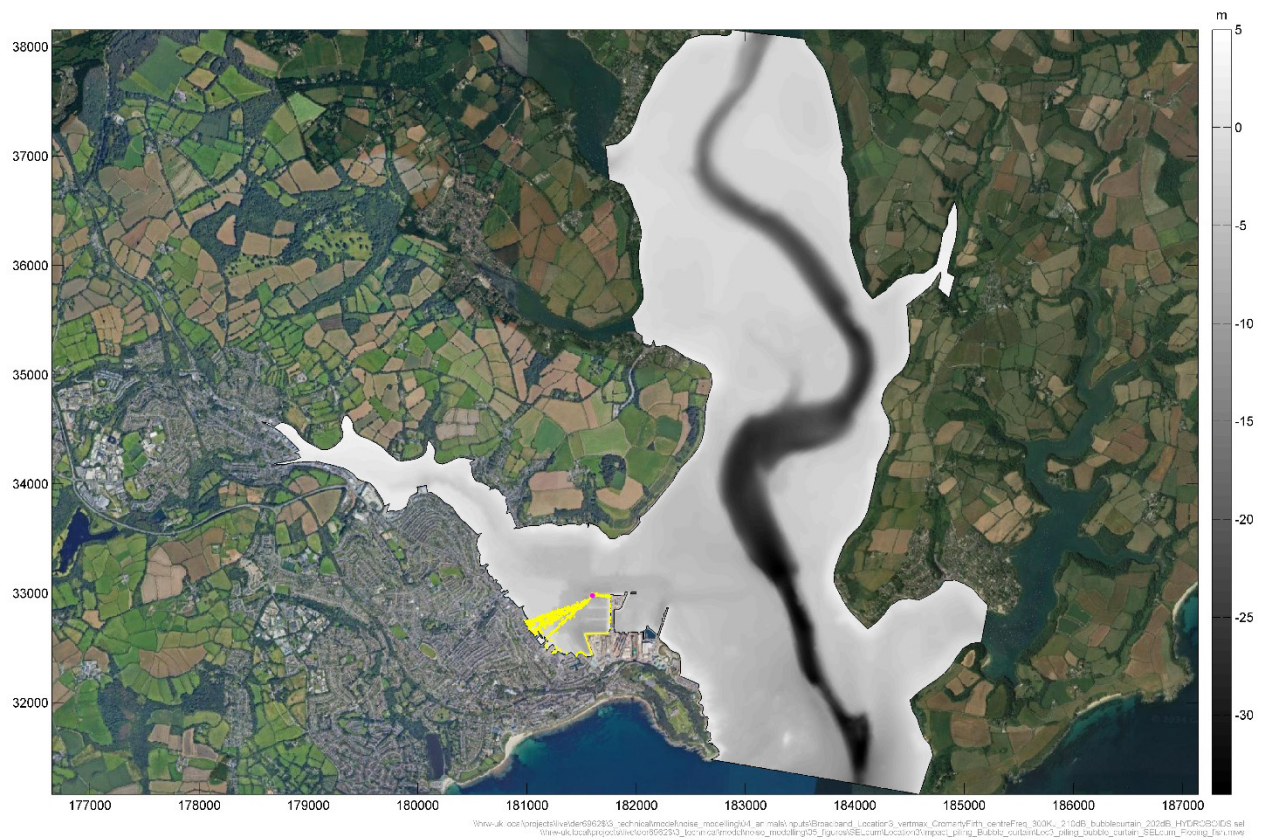


Figure A.33: Predicted SELcum impact footprint for the for fleeing fish for pile driving with a bubble curtain, at the Queen's Wharf (Location 3)

Source: Uses Google Earth imagery

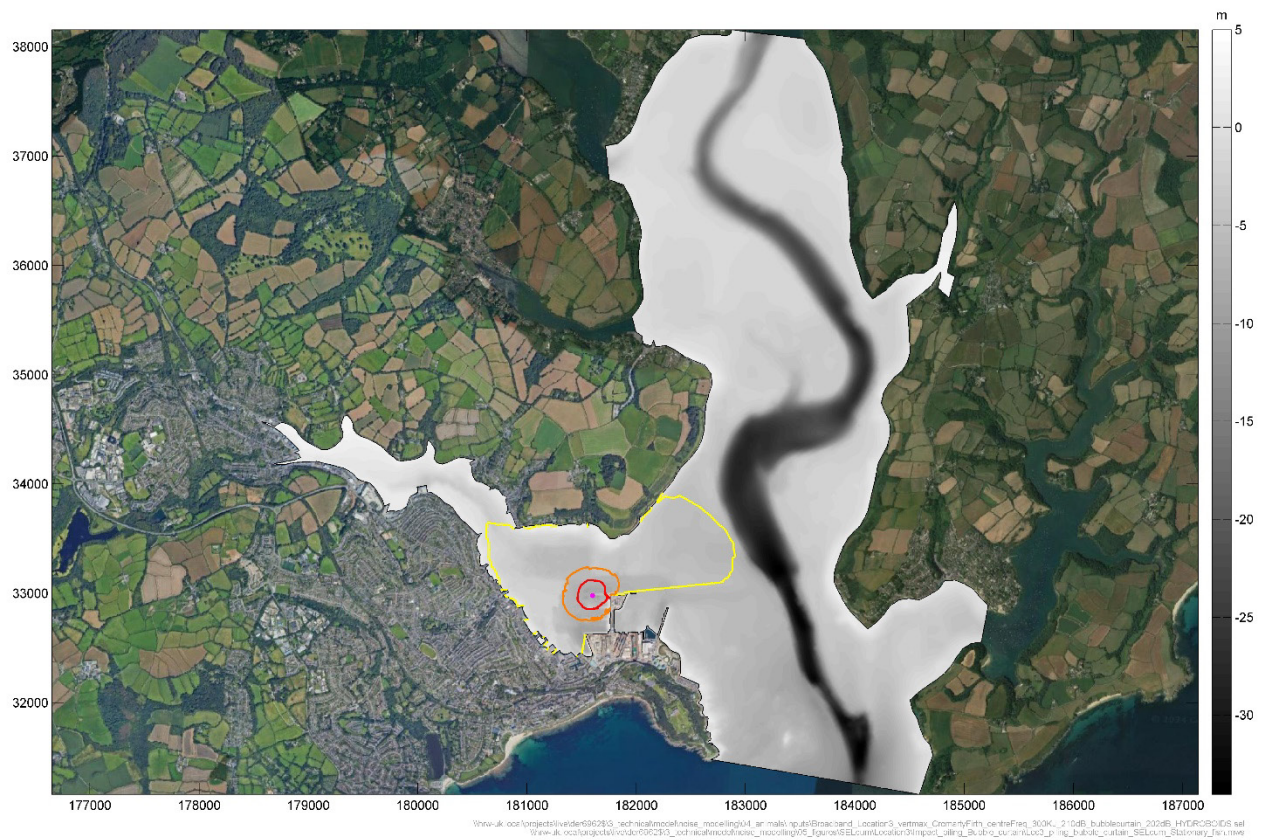


Figure A.34: Predicted SELcum impact footprint for the for stationary fish for pile driving with a bubble curtain, at the Queen's Wharf (Location 3)

Source: Uses Google Earth imagery

The figure is an aerial photograph of a coastal region, likely the Port of Rotterdam, with a coordinate grid and a color scale bar. The X-axis (horizontal) ranges from 177000 to 187000, and the Y-axis (vertical) ranges from 32000 to 38000. A color scale bar on the right indicates values from -30 to 5. A yellow line highlights a specific path or boundary, and a red area highlights a specific location. The map shows a mix of urban, agricultural, and coastal features.

Source: Uses Google Earth imagery

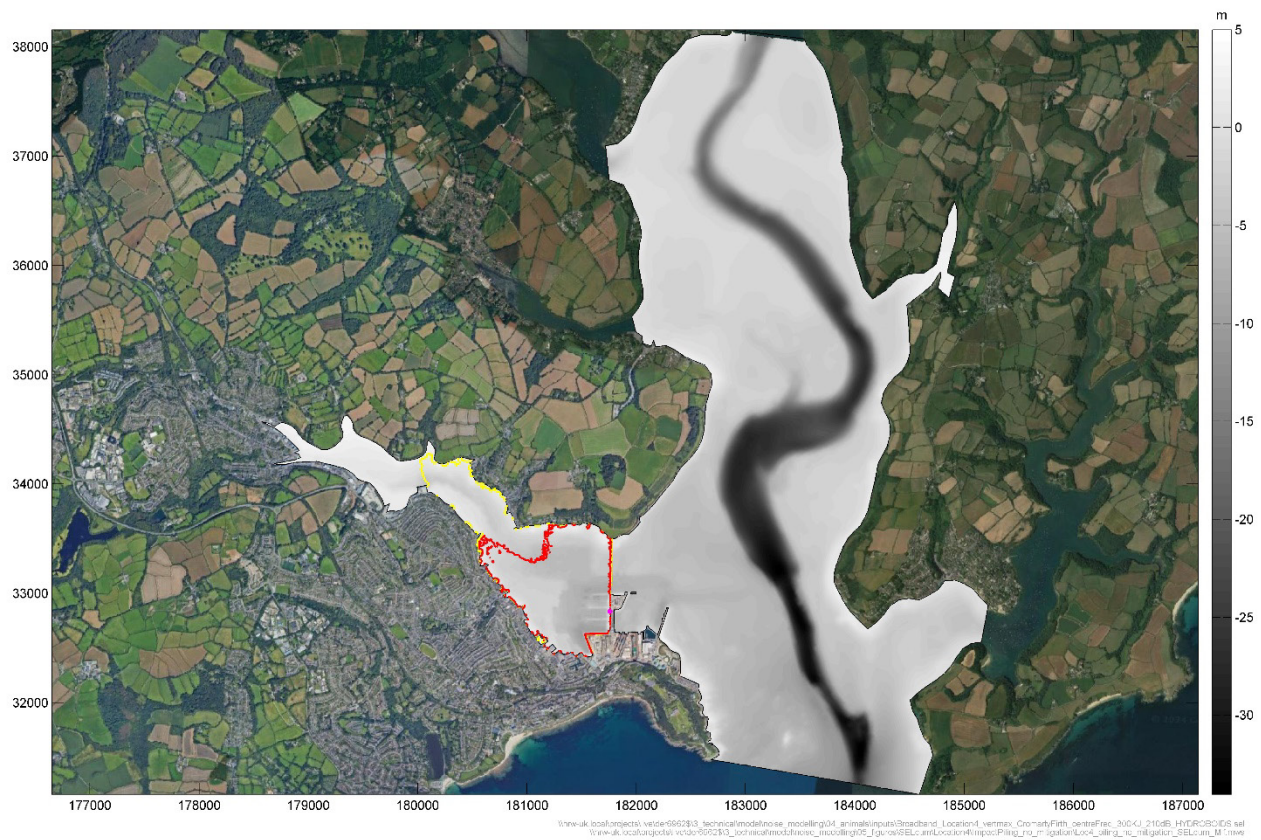


Figure A.36: Predicted SEL_{cum} impact footprint for the for low frequency cetaceans for pile driving at FLOW deck (Location 4)

Source: Uses Google Earth imagery

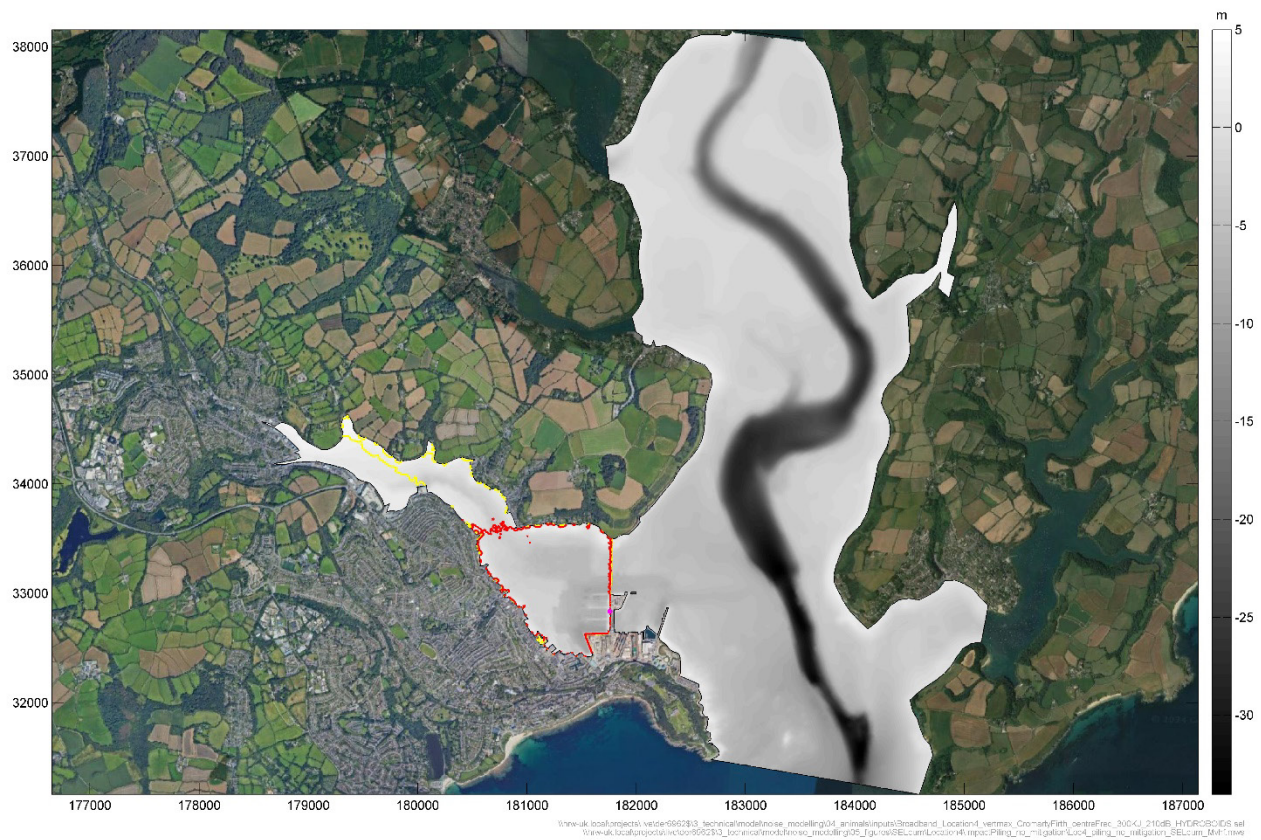
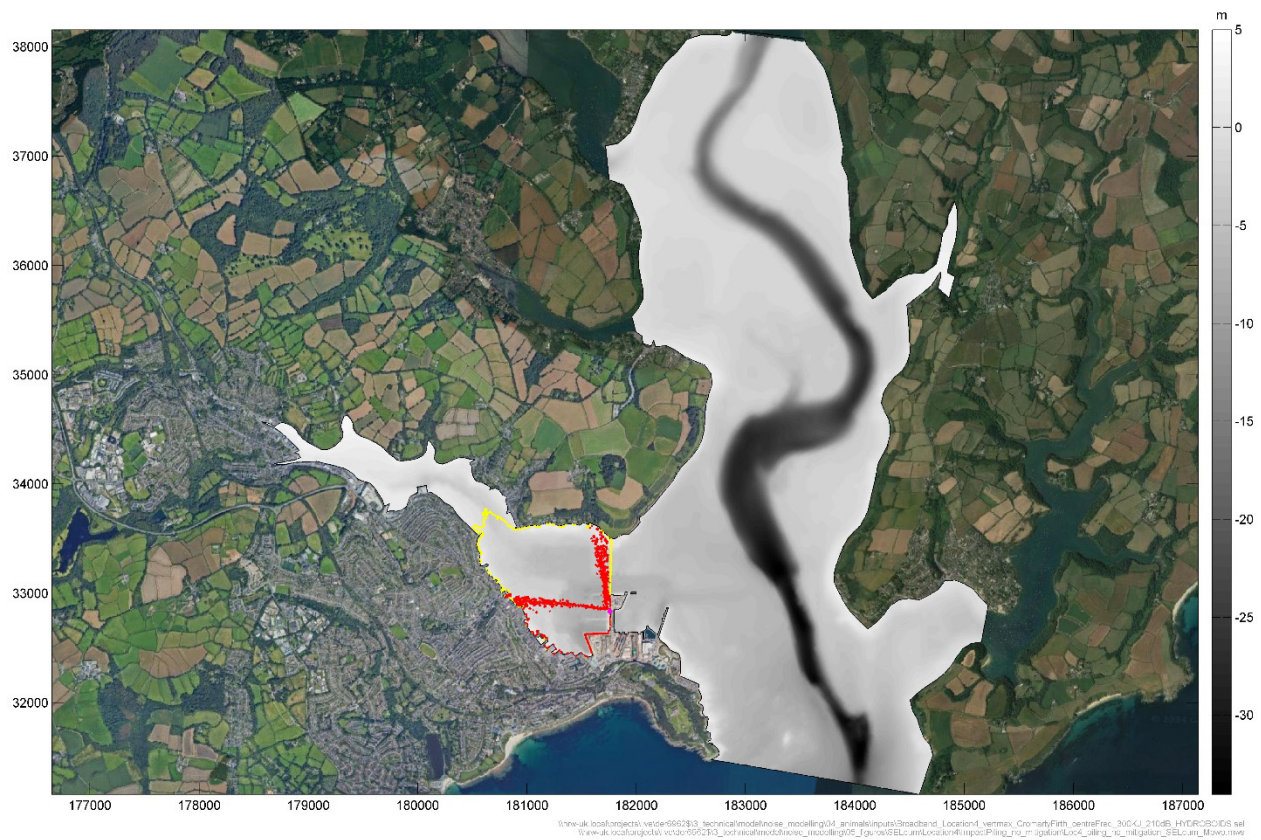
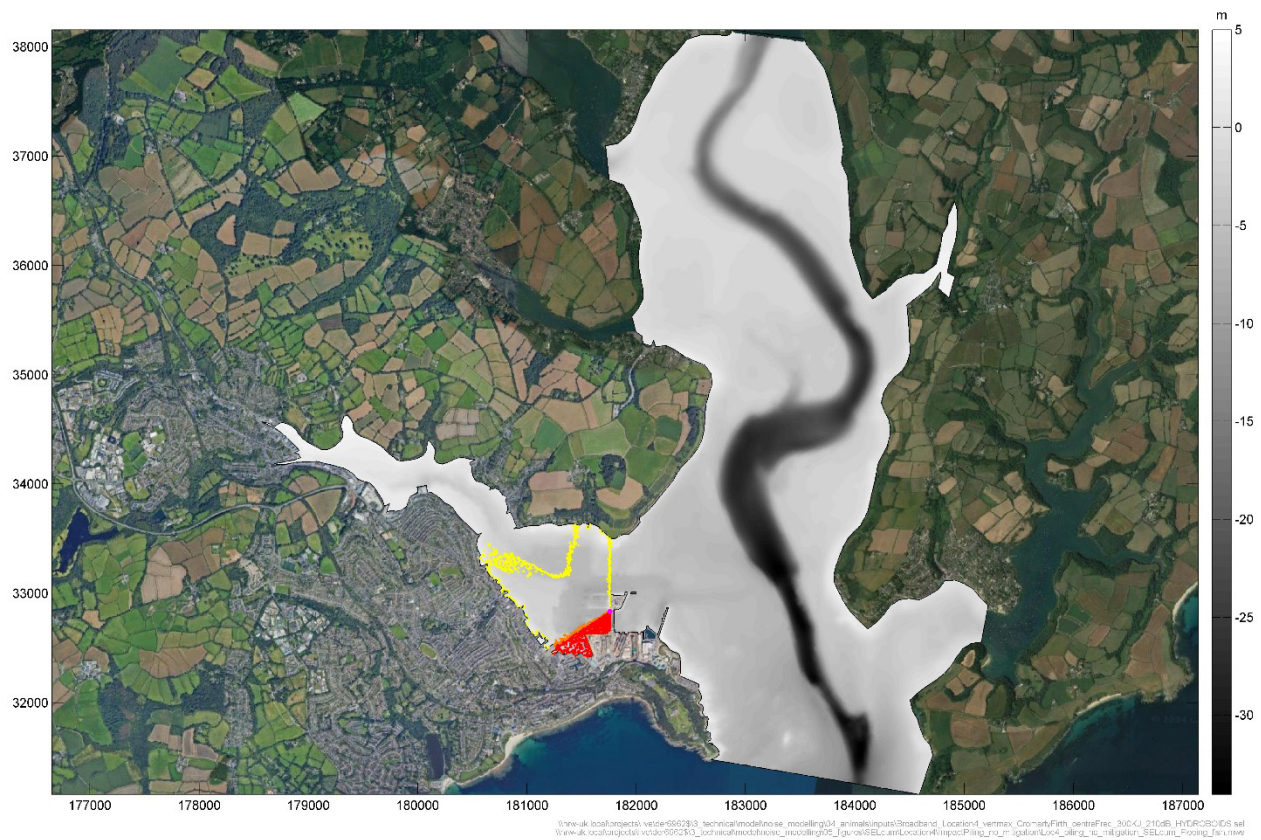
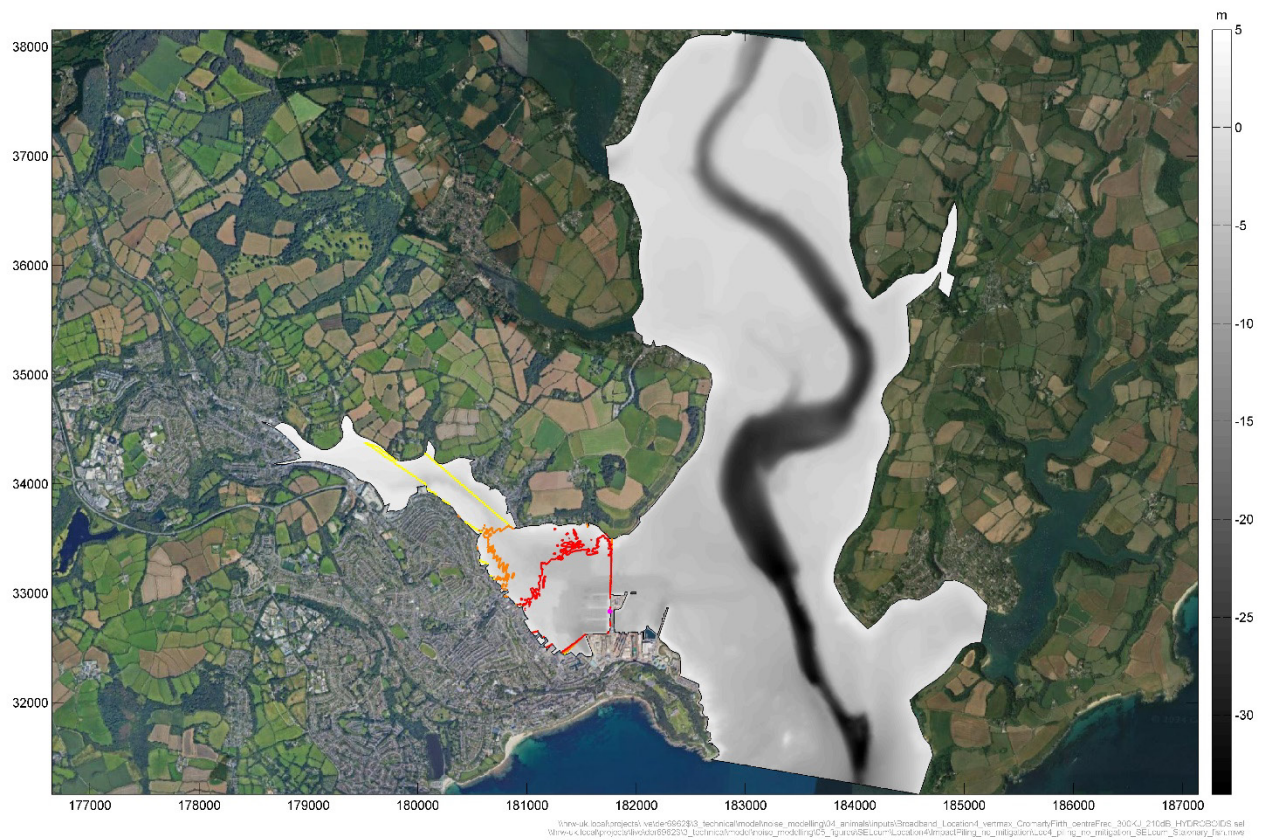


Figure A.37: Predicted SEL_{cum} impact footprint for the for very-high frequency cetaceans for pile driving at FLOW deck (Location 4)

Source: Uses Google Earth imagery







A.8 Pile driving with bubble curtain at FLOW deck

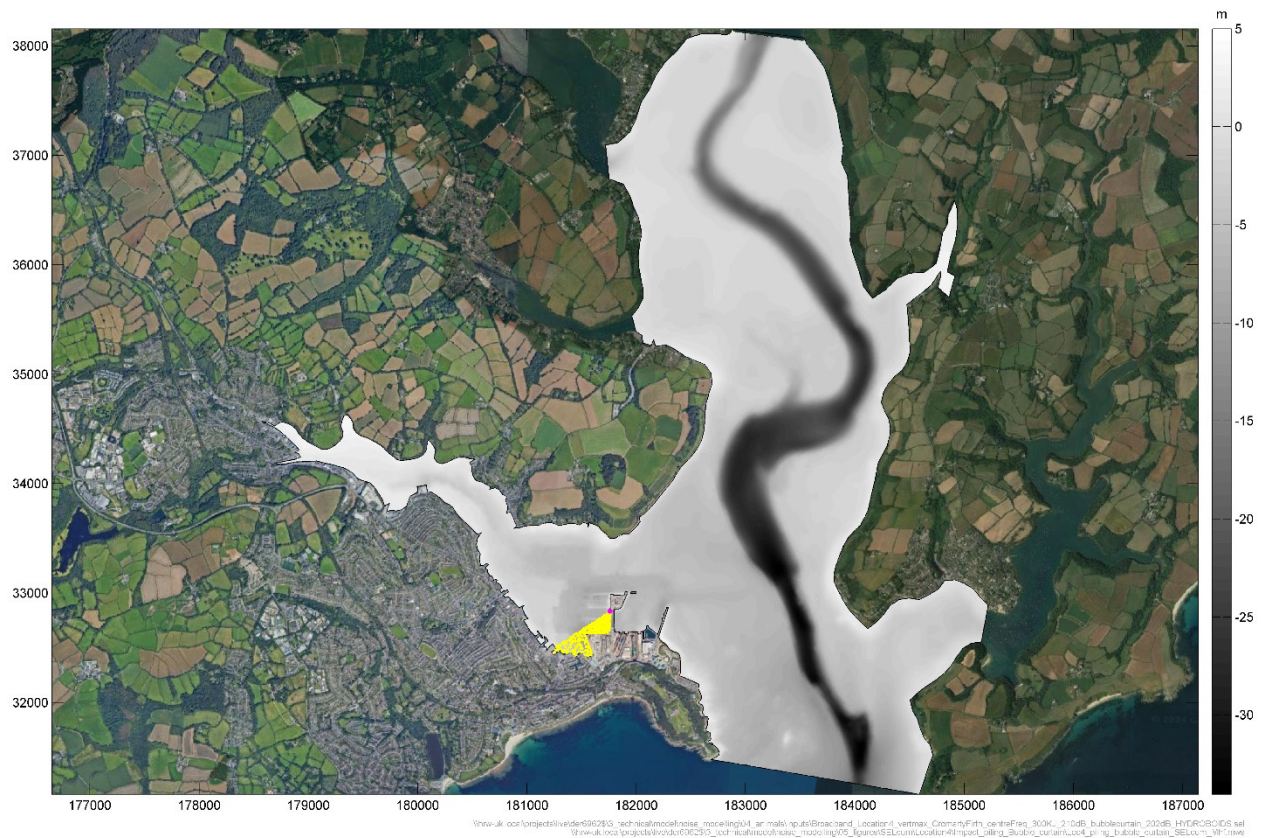


Figure A.41: Predicted SEL_{cum} impact footprint for the for high frequency cetaceans for pile driving with bubble curtain at FLOW deck (Location 4)

Source: Uses Google Earth imagery

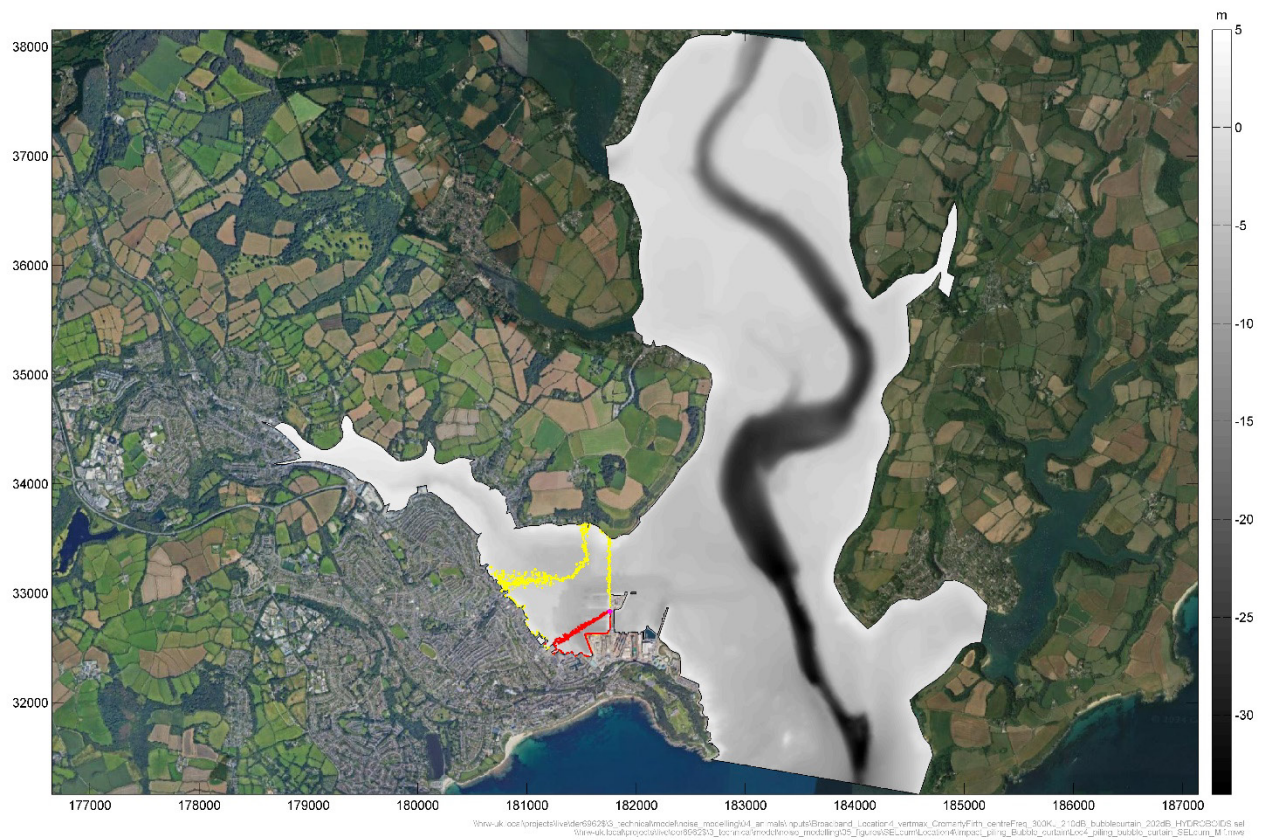


Figure A.42: Predicted SEL_{cum} impact footprint for the for low frequency cetaceans for pile driving with bubble curtain at FLOW deck (Location 4)

Source: Uses Google Earth imagery

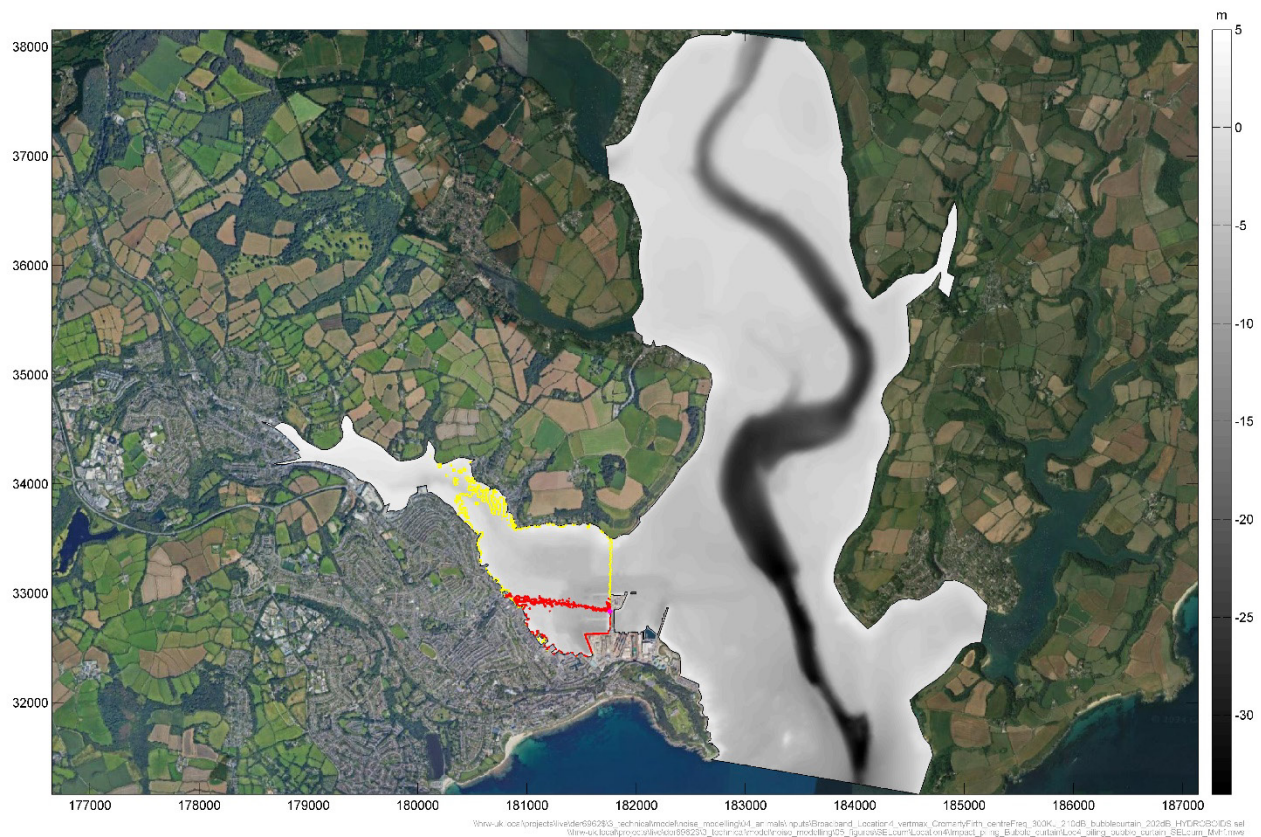


Figure A.43: Predicted SEL_{cum} impact footprint for the for very-high frequency cetaceans for pile driving with bubble curtain at FLOW deck (Location 4)

Source: Uses Google Earth imagery

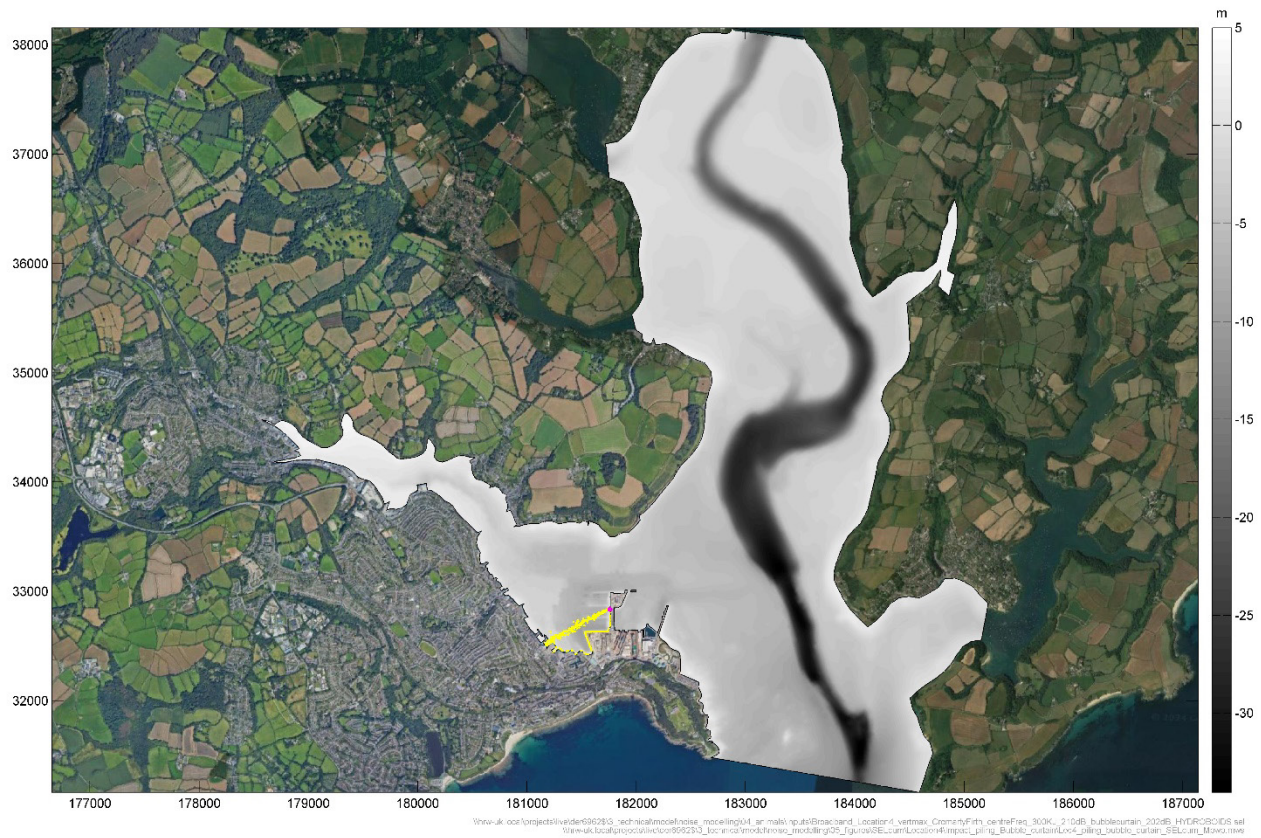


Figure A.44: Predicted SEL_{cum} impact footprint for the for pinnipeds for pile driving with bubble curtain at FLOW deck (Location 4)

Source: Uses Google Earth imagery

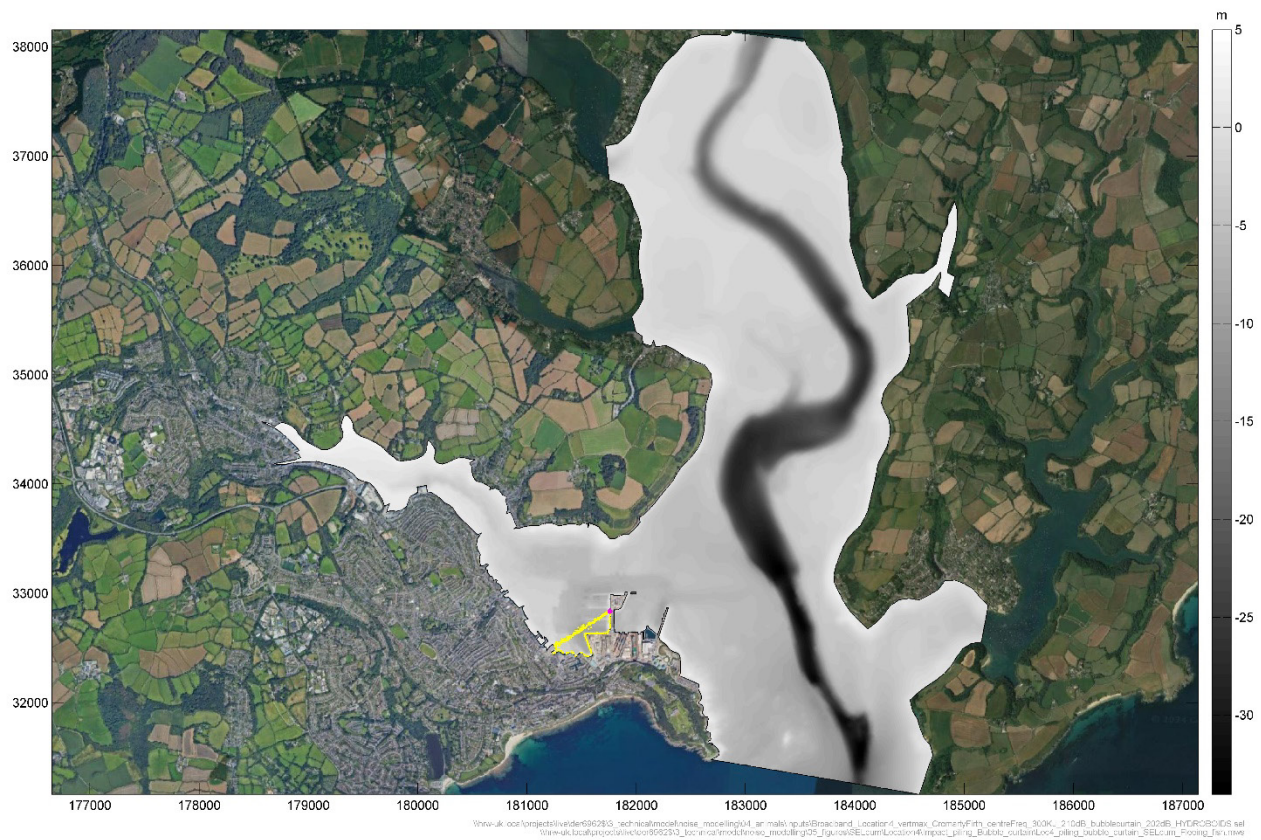


Figure A.45: Predicted SELcum impact footprint for the for fleeing fish for pile driving with bubble curtain at the FLOW deck (Location 4)

Source: Uses Google Earth imagery

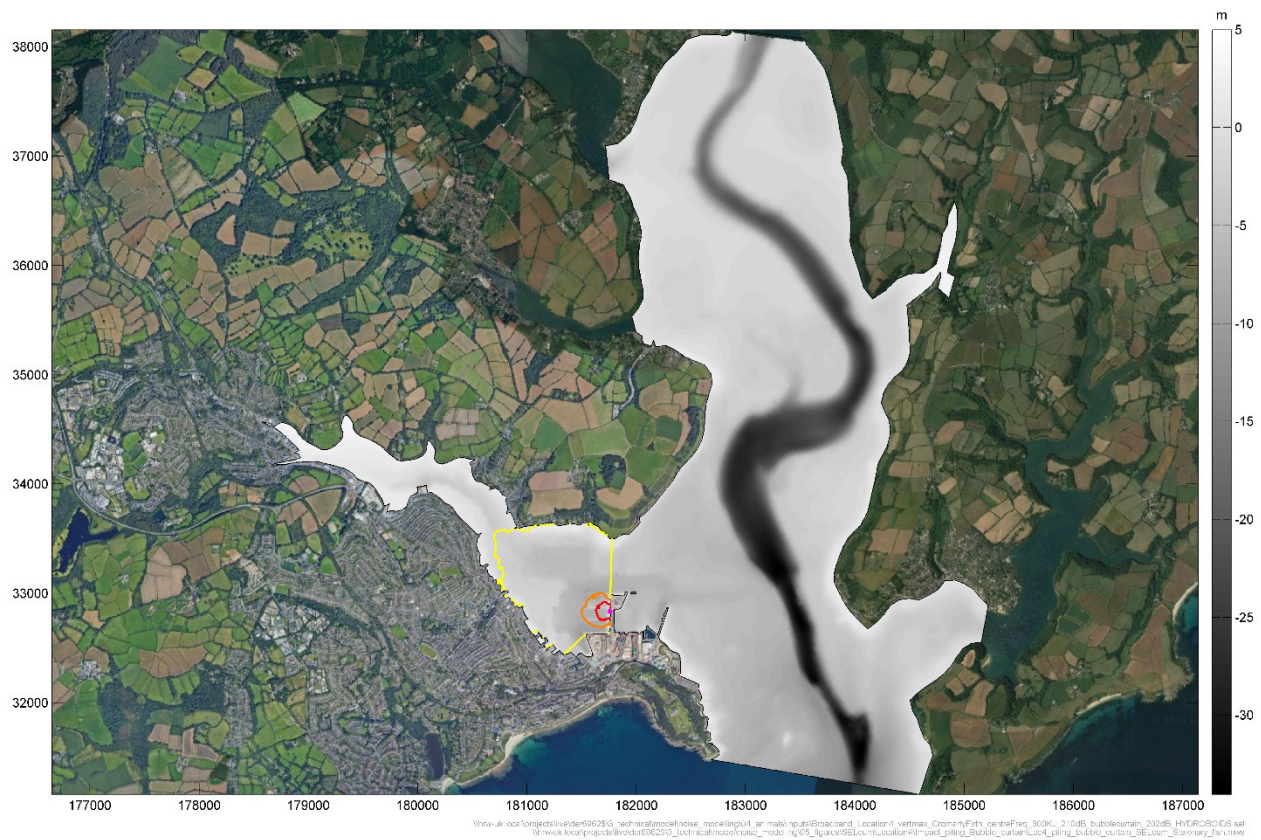


Figure A.46: Predicted SELcum impact footprint for the for stationary fish for pile driving with bubble curtain at the FLOW deck (Location 4)

Source: Uses Google Earth imagery

We design smarter, more resilient solutions across both the natural and built environment to help everyone live and work more sustainably with water.

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