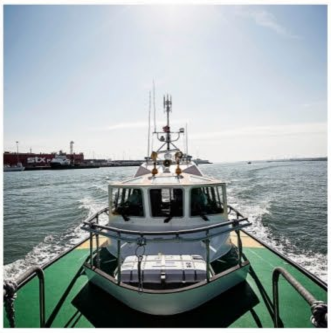
Port of Mostyn

Mostyn Energy Park Extension
Environmental Statement
Appendix 8.4: Underwater Noise Assessment

December 2022







Innovative Thinking - Sustainable Solutions

Mostyn Energy Park Extension

Environmental Statement

Appendix 8.4: Underwater Noise Assessment

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1 Introduction

This report presents an assessment of the potential effects of underwater noise and vibration from the proposed Mostyn Energy Park (MEP) Extension Project on marine fauna. The assessment has been undertaken to support the Environmental Statement (ES) that has been prepared for the proposed development. In particular, the assessment has informed the outcomes of the nature conservation and marine ecology assessment (Chapter 8 of the ES), which in turn will inform the Water Framework Direct (WFD) Compliance assessment and the Habitats Regulations Assessment (HRA) which are included in Appendix 7.1 and Appendix 8.5 of the Environmental Statement (ES) and will be submitted with the marine licence application. A detailed description of the proposed development and construction methodology on which this assessment is based on is included in Chapters 2 and 3 of the ES.

This report has been structured as follows:

Section 1:	Introduction provides a brief introduction to the project and need for this assessment;
Section 2:	Consultation provides a review of the consultation responses that have been received and relate to underwater noise;
Section 3:	Underwater Noise Propagation reviews the key factors influencing the propagation of underwater noise and presents the preferred underwater noise propagation model that has been applied in this underwater noise assessment;
Section 4:	Ambient Noise presents the baseline acoustic conditions of the study area;
Section 5:	Noise Characteristics of Proposed Development Activities presents the specific acoustic characteristics of the proposed construction and operational activities;
Section 6:	Hearing Sensitivity and Responses of Marine Fauna reviews the hearing sensitivity of marine fauna that occur in the study area and the latest available published criteria that have been applied to determine the scale of potential physiological and behavioural effects;
Section 7:	Noise Propagation Modelling Outputs presents the outputs of the underwater noise modelling;
Section 8:	Potential Effects reviews the potential effects on local marine fauna; and
Section 9:	Summ**ary and Conclusions** presents an overview of the outcome of the underwater noise assessment and proposed mitigation measures.

2 Consultation

Consultation with regard to the outcomes of the formal scoping process and whether there are any likely underwater noise and vibration effects of the MEP Extension Project has been undertaken as appropriate, with NRW.

The consultation that has been undertaken, along with the outcome of such consultation and how it has influenced the underwater noise assessment is provided in Table 1.

Table 1. Summary of consultation to date

Consultee	Reference, Date	Summary of Response	How Comments have Been Addressed in this Chapter
NRW Advisory	Scoping Opinion, 6 January 2022	A precautionary, conservative model should be used to ensure noise levels aren't underpredicted.	The model that has been applied is based on conservation assumptions to ensure that the approach that is followed is sufficiently precautionary. See Section 3 of this appendix.
NRW Advisory	Scoping Opinion, 6 January 2022	In the referenced NPL good practice guide, it is recommended that when making estimates of Energy Source Level for piling activity, it is advisable to base the estimate on measurements made on piles driven under similar conditions (e.g. hammer energy, water depth, sediment type, geographical location) – a semi-empirical approach. Information should be presented on how the source level was determined (including where the original measurements were from), in order to outline its suitability to inform an assessment of the potential environmental effects.	The source level estimates are based on piles driven in similar conditions. Further information on the source level that has been used is included in Section 5.1 of this appendix.
NRW Advisory	Scoping Opinion, 6 January 2022	Farcas *et al.* (2016)[3] demonstrate how the use of geometric spreading laws can lead to substantial errors if applied to the more complex environments typical of coastal and inland waters. Examples of approaches that can be taken to model pile driving in shallow	Further context and reasoning for the underwater noise modelling approach that has been used is provided in Section 3 of this appendix.

Consultee	Reference, Date	Summary of Response	How Comments have Been Addressed in this Chapter
		water are available in literature, such as Zampolli *et al.* (2013)[4], and Thompson *et al.* (2020)[5]. Context and reasoning for approaches taken should be presented. [3] Farcas, A., Thompson, P. M., & Merchant, N. D. (2016). Underwater noise modelling for environmental impact assessment. Environmental Impact Assessment Review, 57, 114-122. [4] Zampolli, M., Nijhof, M. J., de Jong, C. A., Ainslie, M. A., Jansen, E. H., & Quesson, B. A. (2013). Validation of finite element computations for the quantitative prediction of underwater noise from impact pile driving. The Journal of the Acoustical Society of America, 133(1), 72-81. [5] Thompson, P. M., Graham, I. M., Cheney, B., Barton, T. R., Farcas, A., & Merchant, N. D. (2020). Balancing risks of injury and disturbance to marine mammals when pile driving at offshore windfarms. Ecological Solutions and Evidence, 1(2), e12034.	
NRW Advisory	Scoping Opinion, 6 January 2022	If the NMFS calculator (NMFS 2021)[6] is used then the variables chosen and the justifications for these should be provided. [6] NMFS (2021) https://www.fisheries.noaa.gov/southeast/consultations/section-7-consultation-guidance	The parameters that have been used and the rationale for them is provided in Section 8 of this appendix.
NRW Advisory	Meeting, 21 April 2022	No further comments made in relation to underwater noise and the proposed approach to addressing the comments that were made in the Scoping Opinion.	No action.

3 Underwater Noise Propagation

In accordance with good practice guidance (NPL, 2014), a simple logarithmic spreading model has been used to predict the propagation of sound levels from the sources of construction and operational noise associated with the proposed development. This model is represented by a logarithmic equation and incorporates factors for noise attenuation and absorption losses. The advantage of this model is that it is simple to use and quick to provide first order calculations of the received (unweighted) levels with distance from the source due to geometric spreading.

$$L(R) = SL - N\,log_{10}(R) - \alpha R$$

Equation 1 Simple logarithmic spreading model

Where:

$L(R)$ is the received level at distance R from a source;
R is the distance in metres from the source to the receiver;
SL is the Source Level (i.e. the level of sound generated by the source);
N is a factor for attenuation due to geometric spreading; and
α is a factor for the absorption of sound in water and boundaries (i.e. the sediment or water surface) in dB m^{-1}.

The Environment Agency has compiled observed data representing factors for attenuation (N coefficient) and absorption (α coefficient) which were presented at the Institute of Fisheries Management (IFM) Conference on 23 May 2013. These observed data were collected from the following construction projects undertaken in similar shallow water estuarine and coastal locations to the Dee Estuary:

- Russian River New Bridge in Geyserville, California (Illinworth and Rodkin, 2007);
- San Rafael Sea Wall in San Francisco Bay, California (Illinworth and Rodkin, 2007);
- Scroby Sands Offshore Wind Farm located off the coast of Great Yarmouth (Nedwell *et al.*, 2007a);
- North Hoyle Offshore Wind Farm in Liverpool Bay (Nedwell *et al.*, 2007a);
- Kentish Flats Offshore Wind Farm located off the coast of Kent (Nedwell *et* al., 2007a);
- Burbo Bank Offshore Wind Farm in Liverpool Bay (Nedwell *et al.*, 2007a);
- Barrow Offshore Wind Farm located south west of Walney Island (Nedwell *et al.*, 2007a); and
- Belvedere Energy-from-Waste Plant on Thames Estuary (measurements collected by Subacoustech Ltd on behalf of the Environment Agency and Costain).

These provide a mean N coefficient of 17.91 (Standard Deviation (SD) 3.05) and α coefficient of 0.00523 dB m^{-1} (SD 0.00377 dB m^{-1}) based on 11 and 9 observations respectively. The Environment Agency has recommended the application of these model input values in underwater noise assessments undertaken in shallow water environments (e.g. URS Scott Wilson, 2011; ABPmer, 2015) and this semi-empirical approach has also been accepted by the MMO and their advisor Cefas for developments in England. These values are, therefore, considered to be appropriate to use for the underwater noise assessment in support of the MEP Extension Project.

Following advice from the MMO and Cefas on another recent project on the Humber Estuary (MMO, pers. comm., 5 May 2022), the received levels associated with the proposed development activities have been modelled in the SEL metric, where there is considered to be a better understanding of both source levels and propagation loss, and then translated to the peak SPL metric using equation (1) in Lippert *et al.* (2015):

$$SPL_{peak} = A\ SEL + B$$

Equation 2 Relationship between peak SPL and SEL

Where:

A	is an empirical constant estimated from measurements with an approximate value of 1.4; and
B	is an empirical constant estimated from measurements with an approximate value of –-40.

There are a number of limitations associated with the use of simple logarithmic spreading models (NPL, 2014). Such models do not account for changes in bathymetry, and therefore are not able to predict the changes in sound propagation caused by sand banks and changes in water depths. It is, therefore, important for underwater noise assessments in such environments to identify how different tidal states might result in any areas that are exposed/dry or very shallow and that limit the propagation of noise. The areas within the Dee Estuary that are under water (wet) at mean high water springs (MHWS) and mean low water springs (MLWS) and allow for the propagation of underwater noise are shown in Figure 1 and Figure 2 respectively. It is also important for any physical structures that have the potential to redirect or constraint noise transmission (e.g. breakwaters, harbour quay walls) to be considered.

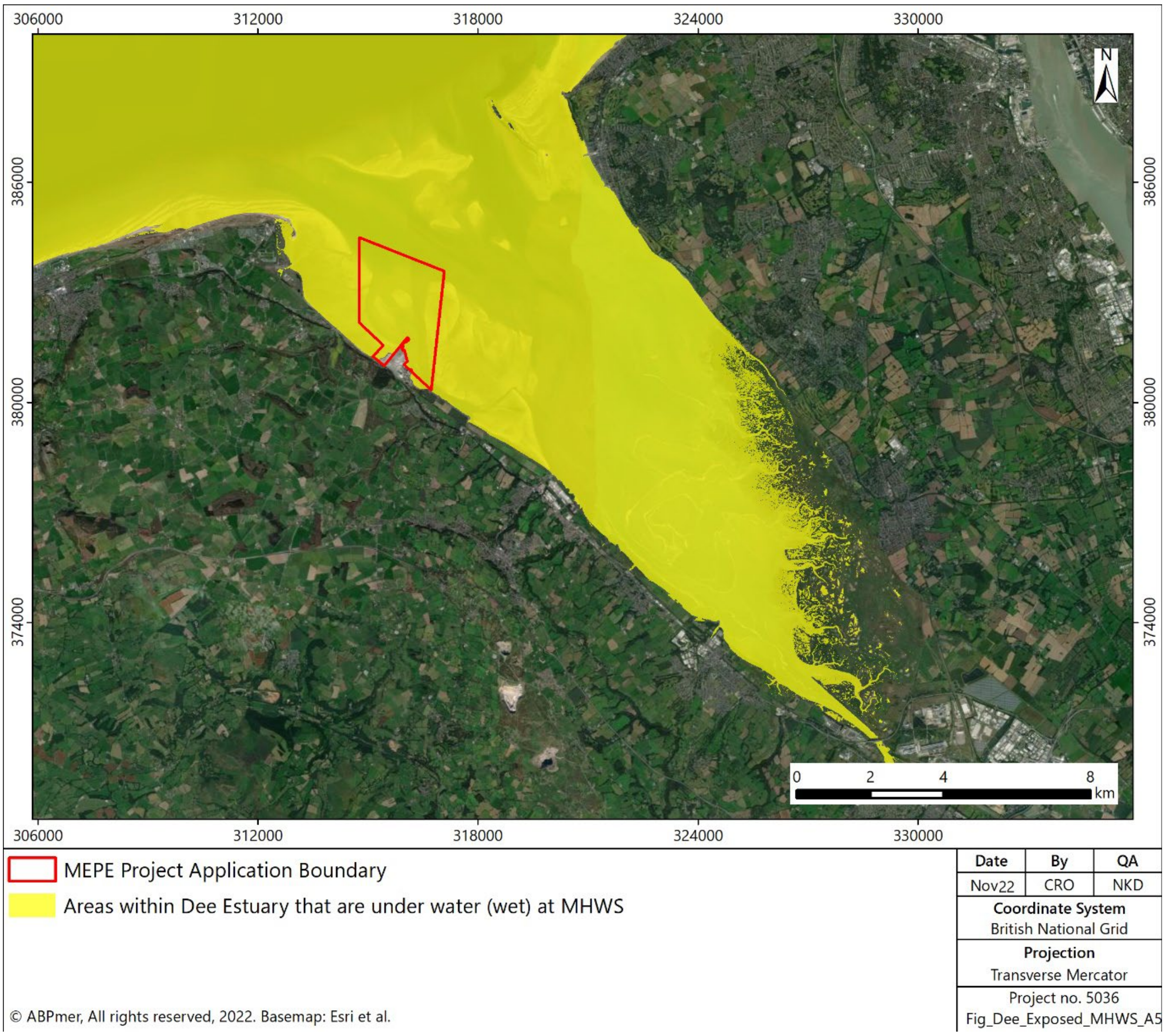

Figure 1. Areas within Dee Estuary that are under water (wet) at MHWS

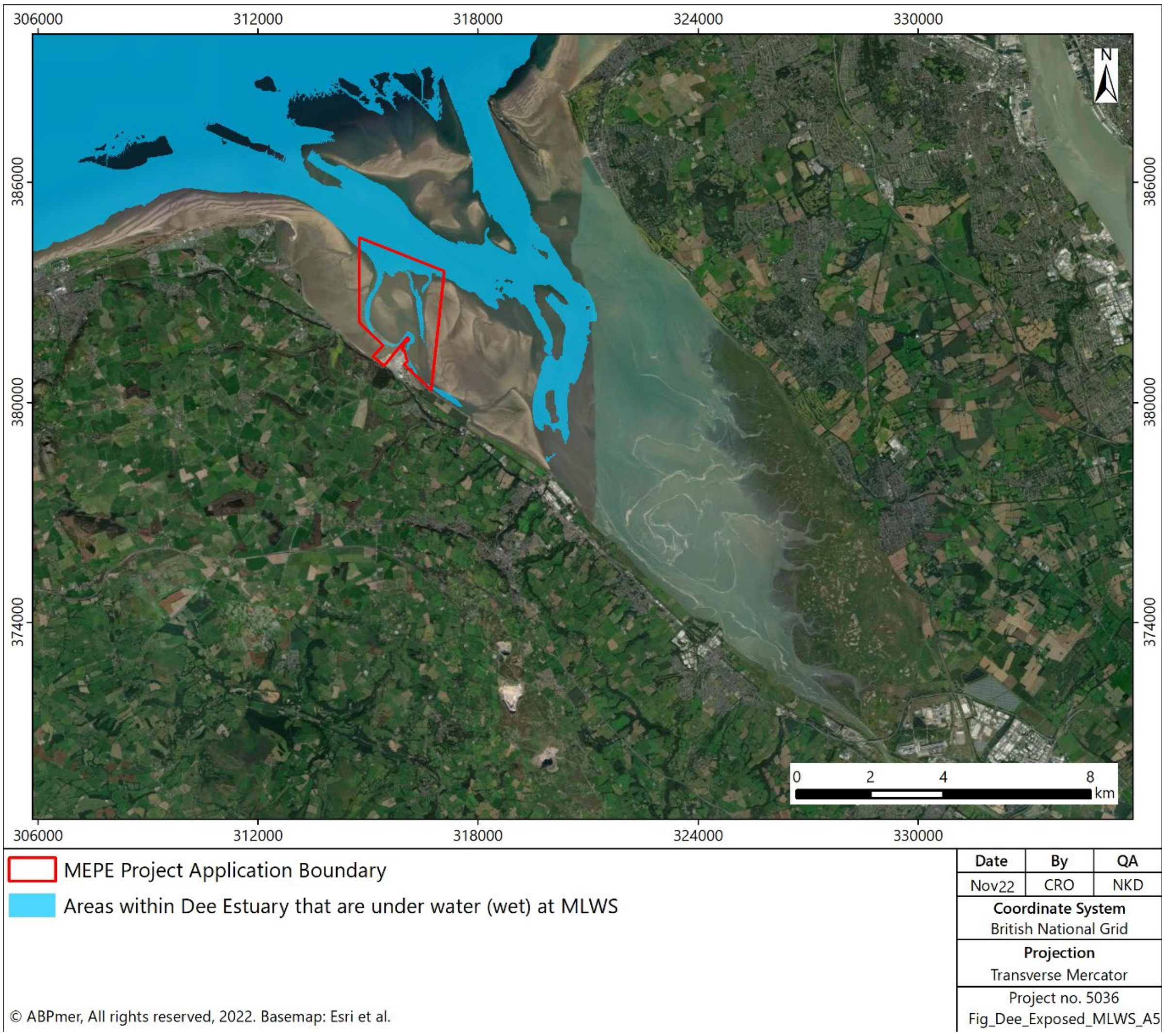

Figure 2. **Areas within Dee Estuary that are under water (wet) at MLWS**

An element of expert judgement and qualitative review of the implications of the site specific environment on noise propagation is therefore also required for underwater noise assessments that employ simple logarithmic spreading models.

Another limitation of simple logarithmic spreading models is that they do not explicitly include frequency dependence, and so cannot predict the increased transmission loss at high frequencies due to increased sound absorption. Farcas *et al*. (2016) also demonstrated how use of these simple models in complex environments typical of coastal and inland waters can underestimate noise levels close to the source and substantially overestimate noise levels further from the source. In other words, they can underestimate the risk of injury or disturbance to marine fauna close to the source whilst giving the impression that a larger area would be affected than would actually be the case.

Although more complex models are available, these tend to be computationally demanding, take longer to run and require the assessment of multiple scenarios (e.g. different tidal states/water depths), which generate more complex outputs that are challenging to interpret. They also often require a large number of model input parameters (e.g. hammer energy, pile penetration depth) that can only be appropriately defined and developed once the final design and methodology for the proposed development has been confirmed.

Despite the simple logarithmic spreading model (equation 1 above) representing a basic model of propagation loss, its use is an established approach in EIAs that has been widely accepted by UK regulators for recent port and waterfront developments in shallow water marine environments (ABPmer, 2020; 2021a; 2021b; ABPmer, 2022a; ABPmer, 2022b; RPS, 2018).

In terms of fish, the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) in the United States recommends the use of the practical spreading model to developers and has incorporated this model in its pile driving calculation spreadsheet to assess the potential impacts of pile driving on fish (NMFS, 2022). This calculator has, therefore, been used to calculate the range at which the peak SPL and cumulative SEL thresholds for pile driving (Popper *et al*., 2014) are reached. Further details of the assumptions and input values that have been applied are provided in Section 8.

In terms of marine mammals, NOAA (2022) has developed a user spreadsheet tool for assessing the potential effects of different types of noise activities on marine mammals which is based on the simple logarithmic spreading model. This spreadsheet tool has been used to predict the range at which the relevant weighted cumulative SEL and instantaneous peak SPL acoustic thresholds (NOAA, 2018) for the onset of temporary threshold shift (TTS) and permanent threshold shift (PTS) are reached during the proposed piling, dredging and vessel activity. Further details, including the input values that have been used are presented in Section 8.

The proposed development takes place in very shallow water and, therefore, the propagation of noise will be limited. Shallow water acts as a high pass filter that only allows signals to pass with a frequency higher than a certain cut-off frequency and attenuates signals with frequencies lower than this cut-off frequency. The cut-off frequency gets higher as the water gets shallower (Harland *et al*., 2005). In this way, the propagation of low frequency underwater noise such as piling will be reduced in very shallow water locations compared to in the deep oceanic waters. At high frequencies (>10 kHz), increasing absorption also prevents high frequency sound propagating over great distances in shallow water.

Overall, therefore, a simple logarithmic spreading model based on conservative assumptions is considered proportionate and sufficiently precautionary to use for this underwater noise assessment.

4 Ambient Noise

Ambient sound is an important consideration in underwater noise assessments as it allows the noise levels caused by a project to be assessed in the context of existing background levels of sound. This section reviews the characteristics of key sources of ambient sound in the study area and considers how these might propagate and vary in space and time.

Ambient sound is commonly defined as background acoustic sound without distinguishable sources (e.g. Wenz, 1962; Urick, 1983). This definition, however, has the problem of how to identify distinguishable sources, and how to eliminate them from the measurements.

Measurements to characterise the ambient sound in a specific location (i.e. incorporating both natural and anthropogenic sources) are becoming more common as interest grows in the trends in anthropogenic noise in the ocean, for example in response to the Marine Strategy Framework Directive (MSFD) and UK Marine Strategy (Defra, 2019).

Measurements that characterise the ambient sound at specific locations and include noise from identifiable sources together with non-identifiable sources, are also sometimes referred to as the local 'soundscape' (NPL, 2014).

4.1 Sources of ambient sound

Ambient sound covers the whole acoustic spectrum from below 1 Hz to well over 100 kHz (Harland *et al*., 2005). At the lower frequencies shipping noise dominates, while at the higher frequencies noise from waves and precipitation dominates.

Natural sources of ambient sound comprise both physical processes and biological activity. Physical processes that are relevant to the study area include wind- and wave-driven turbulence, precipitation and sediment transport processes (Malme *et al*., 1989; Harland *et al*., 2005). Biological activity includes echo locating marine mammals and fish communication (Battele, 2004; Harland *et al*., 2005). These sources of ambient sound vary on a diurnal cycle, a tidal cycle and/or an annual cycle.

A range of anthropogenic noise sources contribute to ambient sound. These can be of short duration and impulsive (e.g. seismic surveys, piling, explosions) or long lasting and continuous (e.g. dredging, shipping, trawling, sonar, drilling, small craft and energy installations) (Dekeling *et al*., 2014). Impulsive sounds may, however, be repeated at intervals (duty cycle) and such repetition may become 'smeared' with distance and reverberation and become indistinguishable from continuous noise. The key anthropogenic sources contributing to ambient sound in the study area are reviewed below.

4.1.1 Vessel traffic

Shipping noise is the dominant contributor to ambient sound in shallow water areas close to shipping lanes and in deeper waters. At longer ranges the sounds of individual ships merge into a background continuum (Harland *et al*., 2005). Shipping noise will vary on a diurnal cycle (e.g. ferry and coastal traffic) and an annual cycle (seasonal activity). The source levels (SLs) associated with large ships such as supertankers and container ships are in the range 180 to 190 dB re 1µPa m (MMO, 2015). For smaller shipping vessels and boats the range is 150 to 180 dB re 1µPa m (UKMMAS, 2010; CEDA, 2011). Although the exact characteristics depend on vessel type, size and operational mode, the strongest energy occurs below 1,000 Hz.

Small motorised craft (e.g. outboard powered inflatables, speed boats and work boats) produce relatively low levels of noise (75 to 159 dB re 1µPa m), and the output characteristics are highly dependent on speed and other operational characteristics (Richardson *et al.*, 1995). Many of these sources have greater sound energy in higher frequency bands (i.e. above 1,000 Hz) than large ships. Sail powered craft are generally very quiet with the only sound coming from flow noise, wave slap and rigging noise.

Vessel traffic in the study area originates from commercial vessels travelling to and from the Port of Mostyn and recreational vessels using the Dee Estuary. Further details of the movement of different types of vessels is provided in the commercial and recreational navigation chapter (Chapter 10 of the ES).

4.1.2 Dredging

Dredging activities emit moderate levels of broadband noise (around 150 to 188 dB re 1µPa m), mainly at lower frequencies (less than 500 Hz) (Thomsen *et al.*, 2009; Jones and Marten, 2016). Maintenance dredging is carried out in the main navigation channel, harbour area and berths at the Port of Mostyn. The amount of dredging and volume of material removed varies depending on the surveyed levels of the channel and the requirements of the Port. Further details of existing maintenance dredging activities in the study area are included in the physical processes chapter (Chapter 6 of the ES).

4.2 Frequency dependence of sound propagation

Shallow and very shallow water[1], such as that at the study area, acts as a high pass filter that only allows signals to pass with a frequency higher than a certain cut-off frequency and attenuates signals with frequencies lower than this cut-off frequency. The cut-off frequency gets higher as the water gets shallower (Harland *et al.*, 2005). In this way, distant shipping makes a reduced contribution to ambient sound in very shallow coastal waters and low frequency sound originates from local sources rather than the great distances found in the deep oceanic waters. At high frequencies (>10 kHz), increasing absorption also prevents high frequency sound propagating over great distances in shallow water so the ambient sound at the study area is dominated by local sound sources.

4.3 Spatiotemporal variation

Ambient sound levels can show significant variation over space and time (NPL, 2014). The observed temporal and spatial variation in ambient sound level can be tens of decibels (in other words, the amplitude can vary by orders of magnitude). This variation can be in the short-term of minutes and hours, or a medium-term such as a diurnal variation (day to night), variation with tidal flows, or a longer-term seasonal variation. The sound level can also depend on location, an example of one cause of this being proximity to a shipping lane, another being proximity to a biological source such as snapping shrimp.

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[1] The definition of shallow water is somewhat arbitrary. For this underwater noise assessment, shallow water is defined as the depths found on the UK continental shelf i.e. 20 to 200 metres. Very shallow water has depths less than 20 metres.

5 Noise Characteristics of Proposed Development Activities

During the construction and operation of the proposed development there are a number of activities that are expected to generate underwater noise levels which may affect marine fauna. This section reviews the underwater noise characteristics of these activities and the associated noise levels that have been applied in the assessment. The worst case potential scenario is considered in order to define the project envelope.

5.1 Piling

The proposed development will involve the installation of approximately 200 tubular piles, which are estimated to be a maximum of 2 m diameter in size. The piles will be driven using both impact (percussive) and vibratory piling methods to reach the required design depths. The vibro hammer will be initially installed on the piling rig and the pile will be vibrated to refusal. This hammer will then be put down and the percussive hammer will be placed on top of the pile and driven to its final level.

Piling works are anticipated to be carried out by up to two piling rigs working over a 24/7 schedule, seven days per week. Every pile will involve a different duration of installation based on the specific ground conditions that the pile is being driven through. The assessment is, therefore, based on the likely timeframes that are estimated to be required. Each tubular pile is anticipated to require approximately 20 minutes of vibro piling and approximately 120 minutes of impact piling. The likely maximum impact piling scenario is for one tubular pile to be installed by each rig per day (i.e. a total of two piles will be installed per day). This will involve a total of approximately 40 minutes of vibro piling and 240 minutes of impact piling per day. The piling rig(s) will be either set up on jack up barges or alternatively a temporary raised stone bund will be constructed behind the line of the new quay wall to provide a stable platform or pad for the crane and associated piling rig(s).

5.1.1 Impact piling

The highest peak underwater noise levels generated during the proposed marine works will arise from impact piling. Impact piling involves a large weight or “ram” being dropped or driven onto the top of the pile, driving it into the seabed. Noise is created in air by the hammer, as a direct result of the impact of the hammer with the pile. Some of this airborne noise is transmitted into the water. Of more significance to the underwater noise, however, is the direct radiation of noise from the surface of the pile into the water as a consequence of the compressional, flexural or other complex structural waves that travel down the pile following the impact of the hammer on its head. As water is of similar density to steel and, in addition, due to its high sound speed, waves in the submerged section of the pile couple sound efficiently into the surrounding water. These waterborne waves will radiate outwards, usually providing the greatest contribution to the underwater noise.

At the end of the pile, force is exerted on the substrate not only by the force transmitted from the hammer by the pile, but also by the structural waves travelling down the pile which induce lateral waves in the seabed. These may travel as both compressional waves, in a similar manner to the sound in the water, or as a seismic wave, where the displacement travels as Rayleigh waves (Brekhovskikh, 1960). The waves can travel outwards through the seabed or by reflection from deeper sediments. As they propagate, sound will tend to “leak” upwards into the water, contributing to the waterborne soundwaves.

Since the speed of sound is generally greater in consolidated sediments than in water, these waves usually arrive first as a precursor to the waterborne wave. Generally, the level of the seismic wave is typically 10 to 20 dB below the waterborne arrival, and hence it is the latter that dominates the noise.

Impulsive sources such as pile driving should have SLs expressed for a single pulse as either SEL with units of dB re 1 µPa^2 s, or as a peak-peak or zero-peak SPL, with units of dB re 1 µPa (Farcas *et al.*, 2016). Impact piling is impulsive in character with multiple pulses occurring at blow rates in the order of 30 to 60 impacts per minute. Typical SLs range from peak SPL of 190 to 245 dB re 1 µPa (DPTI, 2012). Most of the sound energy usually occurs at lower frequencies between 100 Hz and 1 kHz. Factors that influence the SL include the size, shape, length and material of the pile, the weight and drop height of the hammer, and the seabed material and depth.

The SL of the impact driving of tubular piles for the proposed development has been estimated from the loudest near-source (100 m from the source) sound pressure measurements (in peak SPL, RMS and SEL) for the percussive piling installation of the nearest-sized steel pipe piles (2.4 m diameter) in a similar shallow water environment (10 m water depth) (Illinworth & Rodkin, 2007; Seiche Ltd., 2020). Back-calculating the sound pressure measurements to 1 m using the simple logarithmic spreading model (equation 1) provides a worst case estimated SL of 243 dB re 1 µPa m (peak SPL), 231 dB re 1 µPa m (RMS) and 219 dB re 1 µPa^2 s (SEL),

Piling has the potential to be undertaken simultaneously using two piling rigs. Adding two identical sources (i.e. doubling the signal) will increase the received level by 3 dB. In other words, the unweighted peak SL of concurrent impact piling by two piling rigs is assumed to be 246 dB re 1 µPa m (peak SPL metric), 234 dB re 1 µPa m (RMS metric) and 222 dB re 1 µPa^2 s (SEL metric).

5.1.2 Vibro piling

Vibratory hammers use oscillatory hammers that vibrate the pile, causing the sediment surrounding the pile to liquefy and allow pile penetration (ICF Jones & Stokes and Illingworth & Rodkin, 2009). Peak SPLs for vibratory hammers can exceed 180 dB; however, the sound from these hammers rises relatively slowly. The vibratory hammer produces sound energy that is spread out over time and is generally 10 to 20 dB lower than impact pile driving. Although peak sound levels can be substantially less than those produced by impact hammers, the total energy imparted can be comparable to impact driving because the vibratory hammer operates continuously and requires more time to install the pile.

The SL of the vibratory driving of tubular piles for the proposed development has been estimated from the loudest near-source (10 m from the source) sound pressure measurements (in peak SPL, RMS and SEL) for the vibratory piling installation of the nearest-sized steel pipe piles (1.83 m diameter) in a shallow water environment (approximately 5 m water depth) (Illinworth & Rodkin, 2007; ICF Jones & Stokes and Illingworth and Rodkin, 2009; Rodkin and Pommerenck, 2014). Back-calculating the sound pressure measurements to 1 m using the simple logarithmic spreading model (equation 1) provides an estimated SL of 213 dB re 1 µPa m (peak SPL metric), 198 dB re 1 µPa m (RMS metric) and 198 dB re 1 µPa^2 s (SEL metric).

Piling has the potential to be undertaken simultaneously using piling rigs. Adding two identical sources (i.e. doubling the signal) will increase the received level by 3 dB. In other words, the unweighted peak SL of concurrent vibro piling by two piling rigs is assumed to be 216 dB re 1 µPa m (peak SPL metric), 201 dB re 1 µPa m (RMS metric) and 201 dB re 1 µPa^2 s (SEL metric).

5.2 Dredging

The dredging requirements for the proposed development are likely to involve the use of a cutter suction dredger, trailing suction hopper dredger (TSHD), plough and water injection dredging (WID) techniques. Cutter suction dredging will involve the dredged material from the new berth pocket being pumped directly ashore as fill into the reclamation area. TSHD, plough and/or WID are the methods that are predominantly used for existing maintenance dredge activities within the Port of Mostyn and its approaches and will continue to be used in the future. Dredge operations will be continuous (24/7).

Dredging involves a variety of sound generating activities which can be broadly divided into sediment excavation, transport and placement of the dredged material at the disposal site (CEDA, 2011; WODA, 2013; Jones and Marten, 2016). For most dredging activities, the main source of sound relates to the vessel engine noise. In terms of the MEPE Project, the cutter suction dredger will be almost stationary when it is dredging. The TSHD will be travelling at very slow speeds of around 3 knots and, therefore, the levels of engine propeller noise will be very low. Dredging activities produce broadband and continuous sound[2], mainly at lower frequencies of less than 500 Hz and moderate RMS SLs from around 150 to 188 dB re 1 µPa m (Thomsen *et al*., 2009; CEDA, 2011; Robinson *et al*., 2011; WODA, 2013; MMO, 2015; Jones and Marten, 2016).

Cutter suction dredgers generate RMS SLs in the range of 172 to 185 dB re 1 µPa m (Reine *et al*., 2012; MMO, 2015). SLs of TSHDs are variable but generally range from 160 to above 180 dB re 1 µPa m for large TSHDs (Robinson *et al*., 2011). The most intense sound emissions from the TSHDs are in the low frequencies, up to and including 1,000 Hz in most cases (Robinson *et al*., 2011; De Jong *et al*., 2010).

Differences in sound levels are mainly a result of the difference in size between the dredging vessels observed rather than the materials dredged. High frequency components of the broadband sound are generated by sand and gravel movement through the suction pipes, the movement of the draghead on the seabed, splashing from the spillways, cavitation and use of positioning thrusters. Also, gravelly sand extraction resulted in higher levels of this sound than sandy gravel when comparing the same dredging vessel (Robinson *et al*., 2011).

There are no known underwater noise measurements of plough or WID activities. However, these dredging techniques are likely to generate lower levels of noise than cutter suction dredgers of TSHDs given that they involve smaller vessels and less physically intrusive operations.

Overall, the dredgers involved in the proposed development during construction and operation are anticipated to generate a worst case unweighted RMS SL of up to 188 dB re 1 µPa m.

5.3 Vessel movements

Vessels involved during the construction of the proposed development will primarily be the jack up barges, dredgers and existing safety boats/crew transfer vessels (CTVs) operating at the Port. During operation, the new berths are designed to accommodate offshore jack up installation vessels, as well as Service Operation Vessels (SOVs). A TSHD, plough and WID will be involved in any future maintenance dredging requirements for the berths, harbour and navigation channel.

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[2] Continuous sound is defined here as a sound wave with a continuous waveform, as opposed to transient/pulsed sounds such as pile driving that start and end in a relatively short amount of time.

Jack up barges are anticipated to generate SLs in the region of 85 to 127 dB re 1µPa m (MMO, 2015). Dredgers are assumed to generate SLs of up to 188 dB re 1 µPa m (Section 5.2). The CTVs are smaller in size and involve smaller engines which will produce lower levels of noise in the region of 150 to 160 dB re 1µPa m (MMO, 2015). The SOVs are anticipated to generate SLs of up to 180 dB re 1µPa m (UKMMAS, 2010; CEDA, 2011).

Overall, the vessels movements involved in the construction and operation of the proposed development are anticipated to generate worst case unweighted RMS SLs of up to 188 dB re 1 µPa m. Continuous (24/7) noise generation from vessel activities has been assumed and as such, provides a precautionary assessment.

6 Hearing Sensitivity and Responses of Marine Fauna

The impact of underwater noise upon wildlife is primarily dependent on the sensitivity of the species likely to be affected. The following sections describe the hearing sensitivity of marine fauna that occur in the study area and the latest available published criteria that have been applied in the underwater noise assessment to determine the scale of potential physiological and behavioural effects.

6.1 Benthic invertebrates

Benthic invertebrates lack a gas-filled bladder and are, therefore, unable to detect the pressure changes associated with sound waves (Carrol *et al.*, 2017). All cephalopods as well as some bivalves, echinoderms, and crustaceans, however, have a sac-like structure called a statocyst which includes a mineralised mass (statolith) and associated sensory hairs. Statocysts develop during the larval stage and may allow an organism to detect the particle motion associated with soundwaves in water to orient itself (Carrol *et al.*, 2017). In addition to statocysts, cephalopods have epidermal hair cells which help them to detect particle motion in their immediate vicinity, comparable to lateral lines in fish. Similarly, decapods have sensory setae on their body, including on their antennae which may be used to detect low-frequency vibrations. Whole body vibrations due to particle motion have been detected in cuttlefish and scallops, although species names and details of associated behavioural responses are not specified (Carrol *et al.*, 2017).

Scientific understanding of the potential effects of underwater noise on invertebrates is relatively underdeveloped (Hawkins *et al.*, 2015). There is limited research to suggest that exposure to near-field low-frequency sound may cause anatomical damage (Carrol *et al.*, 2017). Anecdotal evidence indicates there was pronounced statocyst and organ damage in seven stranded giant squid after nearby seismic surveys (Guerra *et al.*, 2004). Day *et al.* (2016) found airgun exposure caused damaged statocysts in rock lobsters up to a year later. No such effects, however, were detected in other studies (Christian *et al.*, 2003; Lee-Dadswell, 2009). The disparate results between studies seem to be due to differences in SELs and duration, in some cases due to tank interference, although taxa-specific differences in physical vulnerability to acoustic stress cannot be discounted (Carrol *et al.*, 2017).

There is increasing evidence to suggest that benthic invertebrates respond to particle motion[3] (Roberts *et al.*, 2016). For example, blue mussels *Mytilus edulis* vary valve gape, oxygen demand and clearance rates (Spiga *et al.*, 2016; Roberts *et al.*, 2016) and hermit crabs *Paganus bernhardus* shift their shell and at very high amplitudes, leave their shell, examine it and then return (Roberts *et al.*, 2016). The vibration levels at which these responses were observed generally correspond to levels measured near anthropogenic operations such as pile driving and up to 300 m from explosives testing (blasting) (Roberts *et al.*, 2016). A range of behavioural effects have also been recorded in decapod crustaceans, including a change in locomotion activity, reduction in antipredator behaviour and change in foraging habits (Tidau and Briffa, 2016). Population level and mortality effects, however, are considered unlikely. Effects on benthic invertebrates are, therefore, not considered further in this assessment.

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[3] Particle motion is a back and forth motion of the medium in a particular direction; it is a vector quantity that can only be fully described by specifying both the magnitude and direction of the motion, as well as its magnitude, temporal, and frequency characteristics.

6.2 Fish

In comparison to marine mammals, fish are more sensitive to noise at lower frequencies and generally have a reduced range of hearing than marine mammals (i.e. their hearing ability spans a restricted range of frequencies).

There is a wide diversity in hearing structures in fish which leads to different auditory capabilities across species (Webb *et al*., 2008). All fish can sense the particle motion component of an acoustic field via the inner ear as a result of whole-body accelerations (Radford *et al*., 2012), and noise detection ('hearing') becomes more specialised with the addition of further hearing structures. Particle motion is especially important for locating sound sources through directional hearing (Popper *et al*., 2014; Hawkins *et al*., 2015; Nedelec *et al*., 2016). Although many fish are also likely to detect sound pressure[4], particle motion is considered equally or potentially more important (Hawkins and Popper, 2017).

From the few studies of hearing capabilities in fishes that have been conducted, it is evident that there are potentially substantial differences in auditory capabilities from one fish species to another (Hawkins and Popper, 2017). Since it is not feasible to determine hearing sensitivity for all fish species, one approach to understand hearing has been to distinguish fish groups on the basis of differences in their anatomy and what is known about hearing in other species with comparable anatomy (Popper *et al*., 2014).

The nature conservation and marine ecology chapter (Chapter 8 of the ES) provides a detailed review of the fish receptors that occur in the study area. Categories proposed by Popper *et al.* (2014) for each of the key fish species are included in Table 2.

Table 2. Categorisation of key fish species in the study area according to Popper et al. (2014) criteria

Swim Bladder or Air Cavities Aid Hearing	Swim Bladder Does Not Aid Hearing	No Swim Bladder
Allis shad (*Alosa alosa*) Herring (*Clupea harengus*) Sprat (*Spratus spratus*) Twaite shad (*Alosa fallax*)	Atlantic cod (*Gadus morhua*) European eel (*Anguilla anguilla*) Atlantic salmon (*Salmo salar*) European seabass (*Dicentrarchus labrax*) European smelt (*Osmerus eperlanus*) Sea trout (*Salmo trutta*) Whiting (*Merlangius merlangus*)	Dab (*Limanda limanda*) Dover sole (*Solea solea*) European plaice (*Pleuronectes platessa*), Flounder (*Platichthys flesus*) Gobies (*Pomatoschistus* spp.) Lesser weever (*Echiichthys viper*) River lamprey (*Lampetra fluviatilis*) Sandeel (Ammodytes spp.) Sea lamprey (*Petronmyzon marinus*) Small-spotted catshark (*Scyliorhinus canicular*) Thornback ray (*Raja clavata*)

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[4] Pressure fluctuations in the medium above and below the local hydrostatic pressure; it acts in all directions and is a scalar quantity that can be described in terms of its magnitude and its temporal and frequency characteristics.

The first category comprises fish that have special structures mechanically linking the swim bladder to the ear. These fish are sensitive primarily to sound pressure, although they also detect particle motion (Hawkins and Popper, 2017). They have a wider frequency range, extending to several kHz and generally show higher sensitivity to sound pressure than fishes in the other categories.

The second category comprises fish with a swim bladder where the organ does not appear to play a role in hearing. Some of the fish in this category are considered to be more sensitive to particle motion than sound pressure (see below) and show sensitivity to only a narrow band of frequencies, namely the salmonids (Salmonidae) (Hawkins and Popper, 2016). This second category also comprises fishes with swim bladders that are close, but not intimately connected, to the ear, such as codfishes (Gadidae) and eels (Anguillidae). These fish are sensitive to both particle motion and sound pressure, and show a more extended frequency range, extending up to about 500 Hz (Popper and Coombs, 1982; Popper and Fay, 2011; Hawkins and Popper, 2017).

The third category comprises fish which lack swim bladders that are sensitive only to sound particle motion and show sensitivity to only a narrow band of frequencies (e.g. flatfishes, sharks, skates and rays). Particle motion rather than sound pressure is considered to be potentially more important to fish without swim bladders. Acoustic particle motion in the water and seabed, for example, has been shown to induce behavioural reactions in sole (Mueler-Blenkle *et al*., 2010). However, there is no published literature on the levels of particle motion generated during construction activities (e.g. pile-driving) and the distance at which they can be detected. This may be due to the fact that there are far fewer devices (and less skill in their use) for detection and analysis of particle motion compared to hydrophone devices for detection of sound pressure (Martin *et al*., 2016). Direct measurements and estimations of particle motion have also been hampered in the past by the lack of guidance on analytical methods. The recently published best practice guide for underwater particle motion measurement for biological applications (Nedelec *et al*., 2021) aims to provide guidance for scientific researchers making particle motion measurements. This is likely to result in an increase in the publication of standardised measurements and a possible greater understanding of the potential effects of particle motion on marine fauna.

Particle velocity can be calculated indirectly from sound pressure measurements using relatively simple models (MacGillivray *et al*., 2004). However, such estimates of sound particle velocity are only valid in environments that are distant from reflecting boundaries and other acoustic discontinuities. These conditions are rarely met in the shelf-sea and shallow-water habitats that most aquatic organisms inhabit and that are applicable to the study area (Nedelec *et al*., 2016; Nedelec *et al*., 2021).

Steps that are required to improve knowledge of the effects of particle motion on marine fauna have recently been set out (Popper and Hawkins, 2018). Although particle motion measurement standards have recently been published (Nedelec *et al*., 2021), there continues to be a lack of easy to use and reasonably priced instrumentation to measure particle motion, and lack of sound exposure criteria for particle motion to determine the potential effects on marine fauna. As such, the scope for considering particle motion in underwater noise assessments is currently limited (Faulkner *et al*., 2018). The underwater noise assessment has, therefore, been based on the latest available evidence and focused on the effects of sound pressure.

The extent to which intense underwater sound might cause an adverse environmental impact in a particular fish species is dependent upon the level of sound pressure or particle motion, its frequency, duration and/or repetition (Hastings and Popper, 2005). The range of potential effects from intense sound sources, such as pile driving, includes immediate death, permanent or temporary tissue damage and hearing loss, behavioural changes and masking effects. Tissue damage can result in eventual death or may make the fish less fit until healing occurs, resulting in lower survival rates. Hearing loss can also lower fitness until hearing recovers. Behavioural changes can potentially result in animals avoiding migratory routes or leaving feeding or reproduction grounds with potential population level consequences. Biologically important sounds can also be masked where the received levels are marginally above existing background levels (Hawkins and Myrberg Jr, 1983). The ability to detect and localise the source of a sound is of considerable biological importance to many fish species and is often used to assess the suitability of a potential mate or during territorial displays and during predator prey interactions.

The published noise exposure criteria for fish that have been used in this underwater noise assessment are presented in Table 3.

The Popper *et al.* (2014) quantitative instantaneous peak SPL and cumulative SEL criteria for different marine activities involved in the proposed development (i.e. piling, dredging and vessel movements) have been used to determine the mortality/potential mortal injury and recoverable injury for all the fish hearing categories representing the key fish species that occur in the study area (Table 2). These guidelines are based on an understanding that fish will respond to sounds and their hearing sensitivity.

While the Popper *et al.* (2014) noise exposure criteria provide thresholds for auditory impairment, there are many data gaps that preclude the setting of specific noise exposure criteria for behavioural responses in fish (Popper *et al.*, 2014; Hawkins and Popper, 2017; Faulkner *et al.*, 2018). The onset of behavioural responses is much more difficult to quantify as reactions are likely to be strongly influenced by behavioural or ecological context and the effect of a particular response is often unclear and may not necessarily scale with received sound level (Hawkins and Popper, 2014; Hawkins *et al.*, 2015; Faulkner *et al.*, 2018). In other words, behaviour may be more strongly related to the particular circumstances of the animal, the activities in which it is engaged, and the context in which it is exposed to sounds (Ellison *et al.*, 2012; Pena *et al.*, 2013). For example, a startle or reflex response to the onset of a noise source does not necessarily lead to displacement from the ensonified area.

This uncertainty is further compounded by the limitations of observing fish behavioural responses in a natural context. Few studies have conducted behavioural field experiments with wild fish and laboratory experiments may not give a realistic measure of how fish will respond in their natural environment (Hastings and Popper, 2005; Kastelein *et al.*, 2008; Popper and Hastings, 2009). As a consequence, only hearing data based on behavioural experiments is considered acceptable for assessing the ability of fish to detect sound (Sisneros *et al.*, 2016).

Recent studies have considered approaches to quantify the risk of behavioural responses, for example through dual criteria based on dose-response curves for proximity to the sound source and received sound level (Dunlop *et al.*, 2017). An empirical behavioural threshold could also be adopted using *in situ* observed responses of fish to similar sound sources (Faulkner *et al.*, 2018). A study observing the responses of caged fish to nearby air gun operations found that initial increases in swimming behaviour may occur at a level of 156 dB re 1 µPa RMS (McCauley *et al.*, 2000). At levels of around 161-168 dB re 1 µPa RMS active avoidance of the air gun source would be expected to occur (Pearson *et al.*, 1992; McCauley *et al.*, 2000). These responses may, however, differ from those of unconfined fish.

Work has been undertaken by Hawkins *et al.* (2014) on the behavioural responses of schools of wild sprat and mackerel to playbacks of pile driving. At a single-pulse peak-to-peak SPL of 163 dB re 1 µPa[5], schools of sprat and mackerel were observed to disperse or change depth on 50 % of presentations. In the absence of similar data for other species, this threshold has been applied for all fish species (Table 3).

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[5] This is equivalent to peak SPL of 157 dB re 1 µPa using the metric conversion provided by NOAA Fisheries in their spreadsheet tool and associated user manual; NOAA (2021).

Table 3. Fish response criteria applied in this assessment

Fish Hearing Category*	Piling		Dredging and Vessel Movements			Piling
	Mortality and Potential Mortal Injury*	Recoverable Injury*	Mortality and Potential Mortal Injury*	Recoverable Injury*	TTS*	Behaviour**
Swim bladder involved in hearing (primarily pressure detection)	207 dB SEL_{cum} >207 dB peak	203 dB SEL_{cum} >207 dB peak	(N) Low (I) Low (F) Low	170 dB RMS for 48 h	158 dB RMS for 12 h	> 157 dB peak
Swim bladder is not involved in hearing (particle motion detection)	210 dB SEL_{cum} >207 dB peak	203 dB SEL_{cum} >207 dB peak	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	> 157 dB peak
No swim bladder (particle motion detection)	>219 dB SEL_{cum} >213 dB peak	>216 dB SEL_{cum} >213 dB peak	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	> 157 dB peak
Eggs and larvae	210 dB SEL_{cum} >207 dB peak	(N) Moderate (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	> 157 dB peak

* Popper *et al.* (2014).

** Hawkins *et al.* (2014).

Peak and RMS SPL is in dB re 1 µPa and cumulative SEL (SEL_{cum}) is in dB re 1 µPa^{2}s.

All criteria are presented as sound pressure even for fish without swim bladders since no data for particle motion exist.

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

Auditory and non-auditory injuries in fish have not been observed or documented to occur in association with dredging (Thomsen *et al*., 2009). The literature suggests that dredging noise is unlikely to cause direct mortality or instantaneous injury. However, the (predominantly) low-frequency sounds produced by dredging overlap with the hearing range of many fish species, which may pose a risk in TTS, auditory masking, and behavioural effects (McQueen *et al*., 2019), as well increased stress-related cortisol levels in fish species (Wenger *et al*., 2017). A TTS involves a temporary reduction of hearing capability caused by exposure to underwater noise. An intense short exposure can produce the same scale of TTS as a long-term, repeated exposure to lower sound levels. The significance of the TTS varies among species depending on their dependence on sound as a sensory cue for ecologically relevant functions. Furthermore, it is important to note that the biological significance of such responses is largely unknown.

Potential behavioural effects in the past have also been inferred by comparing the received sound level with the auditory threshold of marine fauna. Richardson *et al*. (1995) and Thomsen *et al*. (2006), for example, have used received levels of noise in comparison with the corresponding hearing thresholds of marine fauna in order to estimate the range of audibility and zones of influence from underwater sound sources. This form of analysis was taken a stage further by Nedwell *et al*. (2007b), where the underwater noise was compared with receptor hearing threshold across the entire receptor auditory bandwidth in the same manner that the dB(A) is used to assess noise sources in air for humans. These included behavioural thresholds, where received sound levels around 90 dB above hearing threshold (dB_{ht}) were considered to cause a strong behavioural avoidance, levels around 75 dB_{ht} a moderate behavioural response and levels around 50 dB_{ht} a minor response.

The dB_{ht} criteria have been applied in a number of EIAs and the Environment Agency has previously recommended it to be used in impact assessments in coastal/estuarine environments (e.g. ABPmer, 2015; URS Scott Wilson, 2011). However, it is worth noting that the dB_{ht} criteria have not been validated by experimental study and have not been published in an independent peer-reviewed paper. The dB_{ht} approach does not take into account potential for sound sensitivity to changes with that of the life stage of the organism, time of year, animal motivation, or other factors that might affect hearing and behavioural responses to sound (Hawkins and Popper, 2017). Furthermore, the dB_{ht} criteria are based on measures of inner ear responses and should rather be based on behavioural threshold determinations (Popper *et al*., 2014; Hawkins and Popper, 2017). The use of dB_{ht} criteria is, therefore, not advisable and has not been applied to this assessment (Hawkins and Popper, 2017).

6.3 Marine mammals

Marine mammals are particularly sensitive to underwater noise at higher frequencies and generally have a wider range of hearing than other marine fauna, namely fish (i.e. their hearing ability spans a larger range of frequencies). The hearing sensitivity and frequency range of marine mammals varies between different species and is dependent on their physiology.

The impacts of underwater noise on marine mammals can broadly be split into lethal and physical injury, auditory injury and behavioural response. The possibility exists for lethality and physical damage to occur at very high exposure levels, such as those typically close to underwater explosive operations or offshore impact piling operations. A PTS is permanent hearing damage caused by very intensive noise or by prolonged exposure to noise. As explained above for fish, a TTS involves a temporary reduction of hearing capability caused by exposure to underwater noise. Both PTS and TTS are considered to be auditory/physiological injuries.

At lower SPLs, it is more likely that behavioural responses to underwater sound will be observed. These reactions may include the animals leaving the area for a period of time, or a brief startle reaction. Masking effects may also occur at lower levels of noise. Masking is the interference with the detection of biologically relevant communication signals such as echolocation clicks or social signals. Masking has been shown in acoustic signals used for communication among marine mammals (see Clark *et al.*, 2009). Masking may in some cases hinder echolocation of prey or detection of predators. If the signal-to-noise ratio prevents detection of subtle or even prominent pieces of information, inappropriate or ineffective responses may be shown by the receiving organism.

NOAA (2018) provides technical guidance for assessing the effects of underwater anthropogenic (human-made) sound on the hearing of marine mammal species. Specifically, the received levels, or acoustic thresholds, at which individual marine mammals are predicted to experience changes in their hearing sensitivity (either temporary or permanent) for acute, incidental exposure to underwater anthropogenic sound sources are provided. These thresholds update and replace the previously proposed criteria in Southall *et al.* (2007) for preventing auditory/physiological injuries in marine mammals. Further recommendations have recently been published regarding marine mammal noise exposure by Southall *et al.* (2019) which complement the NOAA (2018) thresholds and also look at a wider range of marine mammals species, as well as the hearing sensitivity of amphibious mammals (e.g. seals, sea otters) to airborne noise.

The NOAA (2018) and Southall *et al.* (2019) thresholds are categorised according to marine mammal hearing groups. The nature conservation and marine ecology chapter (Chapter 8 of the ES) provides a detailed review of the marine mammal receptors that occur in the study area. The key marine mammal species comprise grey seal, harbour porpoise, and bottlenose dolphin. According to NOAA (2018), grey seals are categorised as pinniped phocids in water (PW) (earless seals or "true seals"), harbour porpoises are categorised as high-frequency (HF) cetaceans and bottlenose dolphins as mid-frequency (MF) cetaceans.

NOAA (2018) and Southall *et al.* (2019) provide weighted cumulative SEL acoustic thresholds for non-impulsive sources (e.g. vibro piling) and unweighted peak SPL and weighted cumulative SEL acoustic thresholds for impulsive sources (e.g. impact piling) which are categorised according to marine mammal hearing groups. The relevant acoustic thresholds for the onset of TTS and PTS due to non-impulsive and impulsive sound sources for the relevant marine mammal groups are presented in Table 4.

Table 4. Marine mammal response criteria applied in this assessment

Marine Mammal Hearing Group	Impulsive (Impact Piling)		Non-Impulsive (Vibro Piling, Dredging and Vessel Movements)	
	TTS	PTS	TTS	PTS
Mid-frequency (MF) cetaceans (bottlenose dolphin)	170 dB SEL_{cum} 224 dB peak	185 dB SEL_{cum} 230 dB peak	178 dB SEL_{cum}	198 dB SEL_{cum}
High-frequency (HF) cetaceans (harbour porpoise)	140 dB SEL_{cum} 196 dB peak	155 dB SEL_{cum} 202 dB peak	153 dB SEL_{cum}	173 dB SEL_{cum}
Phocid pinnipeds in water (PW) (true seals)	170 dB SEL_{cum} 212 dB peak	185 dB SEL_{cum} 218 dB peak	181 dB SEL_{cum}	201 dB SEL_{cum}

Peak SPL has a reference value of 1 µPa and weighted cumulative SEL has a reference value of 1 $\mu Pa^2 s$.

Peak SPL acoustic thresholds for impulsive sound sources provide an estimate of the instantaneous worst-case potential effects on marine mammals. Cumulative SEL is calculated from the energy in a representative single pile strike and the number of strikes over a 24 hour period. This measure assumes that all strikes have the same received single strike SEL value, which is rarely the case since the animal (or source) is likely to be moving relative to each other. It also assumes that the animal is stationary within the zone of potential effect for a 24 hour period which is highly unlikely. Furthermore, it does not take potential physiological or physical recovery from any effects of a single signal exposure into account. As such, this averaging metric has the potential to result in false conclusions on the effects of sound exposure and needs to be treated with more caution as noted by Hawkins and Popper (2017).

There are no equivalent SPL behavioural response criteria that would represent the sources of underwater noise associated with the proposed development. Behavioural reactions to acoustic exposure are less predictable and difficult to quantify than effects of noise exposure on hearing or physiology as reactions are highly variable and context specific (Southall *et al.*, 2007).

Field studies have demonstrated behavioural responses of harbour porpoises to anthropogenic noise (Cefas, 2020). A number of studies have shown avoidance of pile driving activities during offshore wind farm construction (Brandt *et al.*, 2011; Carstensen *et al.*, 2006; Dähne *et al.*, 2013), with the range of measurable responses extending to at least 21 km in some cases (Tougaard *et al.*, 2009). Seismic surveys have also elicited avoidance behaviour in harbour porpoises, albeit short-term (Thompson *et al.*, 2013), and monitoring of echolocation activity suggests possible negative effects on foraging activity in the vicinity of seismic operations (Pirotta *et al.*, 2014). There is a scarcity of studies quantifying behavioural impacts from dredging (Thomsen *et al.*, 2011). An investigation by Diederichs *et al.* (2011) showed that harbour porpoises temporarily avoided an area of sand extraction off the Island of Sylt in Germany. Diederichs *et al.* (2011) found that, when the dredging vessel was closer than 600 m to the porpoise detector location, it took three times longer before a porpoise was again recorded than during times without sand extraction. However, after the ship left the area, the clicks resumed to the baseline rate.

Few studies have documented responses of seals to underwater noise in the field (Cefas, 2020). Tracking studies found reactions of the grey seals to pile driving during the construction of windfarms were diverse (Aarts *et al.*, 2017). These included altered surfacing or diving behaviour, and changes in swim direction including swimming away from the source, heading into shore or travelling perpendicular to the incoming sound, or coming to a halt. Also, in some cases no apparent changes in their diving behaviour or movement was observed. Of the different behavioural changes observed a decline in descent speed occurred most frequent, which suggests a transition from foraging (diving to the bottom), to more horizontal movement. These changes in behaviour were on average larger and occurred more frequent at smaller distances from the pile driving events, and such changes were statistically significantly different at least up to 36 km. In addition to changes in dive behaviour, also changes in movement were recorded. There was evidence that on average grey seals within 33 km were more likely to swim away from the pile driving. In some cases, seals exposed to pile-driving at close range, returned to the same area on subsequent trips. This suggests that some seals had an incentive to go to these areas, which was stronger than the potential deterring effect of the pile-driving.

A telemetry study found no overall significant displacement of common seal during construction of a wind farm in The Wash, south-east England (Russell *et al.*, 2016). However, during piling, seal usage (abundance) was significantly reduced up to 25 km from the piling activity; within 25 km of the centre of the wind farm, there was a 19 to 83 % (95 % confidence intervals) decrease in usage compared to during breaks in piling, equating to a mean estimated displacement of 440 individuals. This amounts to significant displacement starting from predicted received levels of between 166 and 178 dB re 1 µPa (peak-peak). Displacement was limited to piling activity; within 2 hours of cessation of pile driving, seals were distributed as per the non-piling scenario.

Koschinski *et al.* (2003) conducted a playback experiment on harbour seals in which the recorded sound of an operational wind turbine was projected via a loudspeaker, resulting in modest displacement of seals from the source (median distance was 284 vs 239 m during control trials). Two further studies of ringed seals (*Phoca hispida*), which are closely related to both harbour and grey seals, have observed behaviour in response to anthropogenic noise: Harris *et al.*, (2001) reported animals swimming away and avoidance within ~150 m of a seismic survey, while Moulton *et al.*, (2003) found no discernible difference in seal densities in response to construction and drilling for an oil pipeline.

Although there are no known published field studies of the behavioural responses of the Atlantic bottlenose dolphin (*Tursiops truncates*) to underwear noise, a non-invasive combination of visual and acoustic monitoring was conducted by Marley *et al*. (2017) on the Indo-Pacific bottlenose dolphin (*Tursiops aduncus*) community using the Fremantle Inner Harbour, Western Australia, which is exposed to high levels of vessel traffic. Dolphins were found to significantly increase their average movement speeds in high vessel densities, but only for some activity states. Behavioural budgets also changed in the presence of vessels, with animals spending greater time travelling and less time resting or socialising. Finally, multiple whistle characteristics varied with rising levels of broadband noise, and other contextual variables. Despite being acoustically specialised for higher frequencies, dolphins had the strongest acoustic variation during low-frequency noise. This study highlights the complexity of disturbance responses in this species.

A number of field observations of harbour porpoise and pinnipeds to multiple pulse sounds have been made and are reviewed by Southall *et al.* (2007). The results of these studies are considered too variable and context-specific to allow single disturbance criteria for broad categories of taxa and of sounds to be developed. Another way to evaluate the responses of marine mammals and the likelihood of behavioural responses is by comparing the received sound level against species specific hearing threshold levels. Further information on the dB_{ht} metric and its limitations is provided in Section 0 and is, therefore, not repeated here.

Masking effects may also occur at lower levels of noise. Masking is the interference with the detection of biologically relevant communication signals such as echolocation clicks or social signals. Masking has been shown in acoustic signals used for communication among marine mammals. Masking may in some cases hinder echolocation of prey or detection of predators. If the signal-to-noise ratio prevents detection of subtle or even prominent pieces of information, inappropriate or ineffective responses may be shown by the receiving organism.

7 Noise Propagation Modelling Outputs

The simple logarithmic spreading model (equation 1) described in Section 3 was applied to the worst case (highest) unweighted SLs associated with the proposed development activities (i.e. impact piling with two rigs, vibro piling with two rigs, dredging and vessel movements) to determine the unweighted received levels with range. These received levels represent unweighted metrics as recommended in NPL (2014). Table 5 shows the results of this analysis at various distances from the sources of noise associated with the proposed development.

Table 5. Maximum predicted unweighted received levels during proposed development activities

Range (m)	Impact Piling (SEL in dB 1 μPa^2·s)	Vibro Piling (SEL in dB 1 μPa^2·s)	Dredging and Vessel Movements (RMS in dB re 1 μPa)
1	222	201	188
10	204	183	170
100	186	165	152
200	180	159	146
600*	169	148	135
1,000	163	142	129
3500	140	119	106
7,000**	117	96	83
10,000	98	77	64

* Approximate maximum distance from the most seaward point of the proposed development and opposite exposed Salisbury Bank at low water.

** Approximate maximum distance from the most seaward point of the proposed development and opposite West Kirby shore at high water.

The SEL received levels of underwater noise generated during impact piling for the proposed development are predicted to reduce to around 163 dB 1 μPa^2·s within 1 km of the source of piling which is equivalent to peak SPL of 188 dB re 1 μPa using equation 2 (Section 3) and comparable to the worst case SL generated by dredging (Section 0). The peak levels of underwater noise that can physically reach the opposite Salisbury Bank at low water are predicted to be approximately 169 dB 1 μPa^2·s (equivalent to 199 dB re 1 μPa) and comparable to the SL generated by a supertanker or container ship (MMO, 2015). The peak levels of underwater noise that can physically reach the opposite West Kirby shore at high water are predicted to be approximately 117 dB 1 μPa^2·s (equivalent to 157 dB re 1 μPa) and comparable to the SL generated by a crew boat or fishing trawler (MMO, 2015).

The instantaneous peak levels of underwater noise generated during vibro piling are predicted to reduce to around 142 dB 1 μPa^2·s within 1 km of the source of piling which is equivalent to peak SPL of 159 dB re 1 μPa and comparable to the SL generated by a passenger vessel or a recreational boat (MMO, 2015).

The levels of underwater noise generated by dredging and vessel movements are predicted to reduce to around 129 dB re 1 μPa within 1 km of the source of piling which is below the SL generated by most anthropogenic activities (MMO, 2015) and is unlikely to be discernible against existing background noise. It should be noted that the proposed development is located at the Port of Mostyn which already experiences intermittent elevated levels of underwater noise of a similar scale to that which is predicted due to the range of vessels that already operate in this area and ongoing maintenance dredging.

8 Potential Effects

8.1 Fish

8.1.1 Impact piling

The calculator developed by NMFS (2022) as a tool for assessing the potential effects to fish exposed to elevated levels of underwater sound produced during pile driving has been used to calculate the range at which the instantaneous peak and cumulative SEL thresholds for pile driving (Popper *et al.*, 2014) are reached. The model input values and associated assumptions for impact piling are included in Table 6.

Table 6. NMFS piling calculator input values for impact piling

Model Inputs	Value	Assumptions
Number of strikes per pile	675	Maximum published value provided for existing field data of percussive piling of steel piles and, therefore, considered a reasonable worst case (WSDOT, 2017 cited in NMFS, 2021).
Number of piles per day	2	The maximum impact piling scenario is for the marine works to comprise the installation of up to 2 tubular piles each day (see Section 5.1).
Peak SPL SL (dB re 1 μPa m)	246	Loudest near-source (100 m from the source) sound pressure measurements for the percussive piling installation of the nearest-sized steel pipe piles (2.4 m diameter) in a similar shallow water environment (10 m water depth) (Illinworth & Rodkin, 2007; Seiche Ltd., 2020) back-calculated to 1 m and the assumption that two piling rigs with impact hammers will be used concurrently (see Section 5.1).
SEL SL (dB re 1 μPa^2 s)	222	As above.
Distance from source (m)	1	The sound levels that were measured for percussive piling installation of the nearest-sized steel pipe piles (2.4 m diameter) in a similar shallow water environment (10 m water depth) (Illinworth & Rodkin, 2007; Seiche Ltd., 2020) have been back-calculated to 1 m from the source (see Section 5.1).
Noise reduction due to abatement (dB)	NA	Not applicable.
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 3).

The distances at which potential mortality/injury and behavioural effects in fish are theoretically predicted to occur during impact piling activities associated with the construction of the proposed development are included in Table 7. Based on the existing bathymetry and physical constraints of the study area, in particular the areas of the estuary that are under water and exposed (dry) during MHWS and MLWS, the maximum predicted zones of potential mortality/injury and behavioural effects in fish as a result of the impact piling for the new quay wall have been refined and are illustrated on Figure 3 and Figure 4.

Table 7. Approximate distances (metres) fish response criteria are reached during concurrent impact piling

Fish Hearing Category	Mortality/ Potential Mortal Injury		Recoverable Injury		Behaviour
	Peak	SEL_{cum}	Peak	SEL_{cum}	Peak
Swim bladder involved in hearing (primarily pressure detection)	151	385	151	644	3,433
Swim bladder is not involved in hearing (particle motion detection)	151	262	151	644	3,433
No swim bladder (particle motion detection)	70	82	70	121	3,433
Eggs and larvae	151	262	(N) Moderate (I) Low (F) Low		3,433

Figure 3. Maximum predicted zone of injury and behavioural effects on fish during impact piling at MHWS

Figure 4. **Maximum predicted zone of injury and behavioural effects on fish during impact piling at MLWS**

The Dee Estuary is around 7 km wide at the location of the proposed development at high water. Given the mobility of fish, any individuals that might be present within the relatively localised areas associated with potential mortality/injury during pile driving activities would be expected to move away and avoid harm. At low water, the large expanses of intertidal flats will limit the propagation of noise to the immediate deeper locations of the Port of Mostyn berths, harbour area and Salisbury channel. Fish are anticipated to be mainly using other channels and parts of the Dee Estuary which are less disturbed by existing vessels and maintenance dredging activities. Overall, the potential mortality/injury effects of the proposed percussive piling activities on fish are not considered to be significant.

Behavioural reactions are anticipated to occur across approximately 50 % width of the Dee Estuary at high water and limited to within the Port of Mostyn berths and small part of the harbour area at low water given that the existing sandbanks will be exposed and will act as a barrier to the transmission of underwater sound pressure. Although there is considered to be some potential for the percussive piling activity to result in a partial temporary barrier to fish movements, a significant part of the estuary will still be available for fish to move upstream and downstream unimpeded. The scale of the behavioural response within this predicted zone of influence is partly dependent on the hearing sensitivity of the species. Fish with a swim bladder involved in hearing (e.g. herring and shad) may exhibit a moderate behavioural reaction within distance in which a behavioural response is predicted (e.g. a sudden change in swimming direction, speed or depth). Fish with a swim bladder that is not involved in hearing (e.g. Atlantic salmon and European eel) are likely to display a milder behavioural reaction. Fish without a swim bladder (e.g. lamprey and plaice) are anticipated to only show very subtle changes in behaviour in this zone.

The scale of the behavioural effect is also dependent on the size of fish (which affects maximum swimming speed). Smaller fish, juveniles and fish larvae swim at slower speeds and are likely to move passively with the prevailing current. Larger fish are more likely to actively swim and, therefore, may be able to move out of the behavioural effects zone in less time, although it is recognised that the movement of fish is very complex and not possible to define with a high degree of certainty.

The effects of piling noise on fish also need to be considered in terms of the duration of exposure. Piling noise will take place over a period of approximately 12 months. However, piling will not take place continuously as there will be periods of downtime, pile positioning and set up. The assessment has been undertaken on the assumption that piling works will be undertaken 24/7 and seven days per week. The maximum impact piling scenario is for 2 tubular piles to be installed each day, involving approximately 240 minutes of impact piling per day. There will, therefore, be significant periods over a 24-hour period when fish will not be disturbed by any impact piling noise. The actual proportion of impact piling is estimated to be around 17 %. In other words, any fish that remain within the predicted behavioural effects zone at the time of percussive piling will be exposed to this disturbance only 17 % of the time over the piling programme.

It is also important to consider the noise from piling against existing background or ambient noise conditions (Section 4). The area in which the construction will take place already experiences regular vessel operations and ongoing maintenance dredging, and, therefore, fish are likely to be habituated to a certain level of intermittent anthropogenic background noise.

8.1.2 Vibro piling

The calculator developed by NMFS (2022) has been used to calculate the range at which the instantaneous peak and cumulative SEL thresholds for pile driving (Popper *et al*., 2014) are reached. The model input values and associated assumptions for vibro piling are included in Table 8.

Table 8. NMFS piling calculator input values for vibro piling

Model Inputs	Value	Assumptions
Number of strikes per pile	675	Maximum published value provided for existing field data of percussive piling of steel piles and, therefore, considered a reasonable worst case (WSDOT, 2017 cited in NMFS, 2021).
Number of piles per day	2	The maximum impact piling scenario is for the marine works to comprise the installation of up to 2 tubular piles each day (see Section 5.1).
Peak SPL SL (dB re 1 µPa m)	216	Loudest near-source (10 m from the source) sound pressure measurements for the vibratory piling installation of 1.83 m steel pipe piles in a shallow water environment (approximately 5 m water depth) (Illinworth & Rodkin, 2007; ICF Jones & Stokes and Illingworth and Rodkin, 2009; Rodkin and Pommerenck, 2014) back-calculated to 1 m and the assumption that two piling rigs with vibro hammers will be used concurrently (see Section 5.1).

Model Inputs	Value	Assumptions
SEL SL (dB re 1 μPa^2 s)	201	Loudest near-source (10 m from the source) sound pressure measurements for the vibratory piling installation of 1.83 m steel pipe piles in a shallow water environment (approximately 5 m water depth) (Illinworth & Rodkin, 2007; ICF Jones & Stokes and Illingworth and Rodkin, 2009; Rodkin and Pommerenck, 2014) back-calculated to 1 m and the assumption that two piling rigs with vibro hammers will be used concurrently (see Section 5.1).
RMS SL (dB re 1 μPa m)	201	Loudest near-source (10 m from the source) sound pressure measurements for the vibratory piling installation of 1.83 m steel pipe piles in a shallow water environment (approximately 5 m water depth) (Illinworth & Rodkin, 2007; ICF Jones & Stokes and Illingworth and Rodkin, 2009; Rodkin and Pommerenck, 2014) back-calculated to 1 m and the assumption that two piling rigs with vibro hammers will be used concurrently (see Section 5.1).
Distance from source (m)	1	The sound levels that were measured for the vibratory piling installation of 1.83 m steel pipe piles in a shallow water environment (Illinworth & Rodkin, 2007; ICF Jones & Stokes and Illingworth and Rodkin, 2009; Rodkin and Pommerenck, 2014) have been back-calculated to 1 m from the source (see Section 5.1).
Noise reduction due to abatement (dB)	NA	Not applicable.
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 3).

The distances at which potential mortality/injury and behavioural effects in fish are theoretically predicted to occur during vibro piling activities associated with the construction of the proposed development are included in Table 9. Based on the existing bathymetry and physical constraints of the study area, the predicted zones of potential mortality/injury and behavioural effects in fish as a result of the vibro piling for the new quay wall have been refined and are illustrated on Figure 5 and Figure 6.

Table 9. Approximate distances (metres) fish response criteria are reached during concurrent vibro piling

Fish Hearing Category	Mortality/ Potential Mortal Injury		Recoverable Injury		Behaviour
	Peak	SEL$_{cum}$	Peak	SEL$_{cum}$	Peak
Swim bladder involved in hearing (primarily pressure detection)	3	26	3	43	1,105
Swim bladder is not involved in hearing (particle motion detection)	3	18	3	43	1,105
No swim bladder (particle motion detection)	1	6	1	8	1,105
Eggs and larvae	3	18	(N) Moderate (I) Low (F) Low		1,105

Figure 5. **Maximum predicted zone of injury and behavioural effects on fish during vibro piling at MHWS**

The Dee Estuary is around 7 km wide at the location of the proposed development at high water. Given the mobility of fish, any individuals that might be present within the very localised areas associated with potential mortality/injury during vibro pile driving activities would be expected to move away and avoid harm. At low water, the large expanses of intertidal flats will limit the propagation of noise to the immediate deeper locations of the Port of Mostyn berths, harbour area and Salisbury channel. Fish are anticipated to be mainly using other channels and parts of the Dee Estuary which are less disturbed by existing vessels and maintenance dredging activities. Overall, the potential mortality/injury effects of the proposed vibro piling activities on fish are not considered to be significant.

Behavioural reactions are anticipated to occur across approximately 16 % of the width of the Dee Estuary at high water and limited to within the Port of Mostyn berths and harbour area at low water given that the existing sandbanks will be exposed and will act as a barrier to the transmission of underwater sound pressure. Vibro piling is, therefore, not considered to result in a potential significant barrier to fish movements in the Dee Estuary. As discussed in Section 8.1.1, the scale of the behavioural response within this predicted zone of influence is partly dependent on the hearing sensitivity of the species and on the size of fish (which affects maximum swimming speed).

Figure 6. **Maximum predicted zone of injury and behavioural effects on fish during vibro piling at MLWS**

The effects of piling noise on fish also need to be considered in terms of the duration of exposure. Piling noise will take place over a period of approximately 12 months. However, piling will not take place continuously as there will be periods of downtime, pile positioning and set up. The assessment has been undertaken on the assumption that piling works will be undertaken 24/7 and seven days per week. The maximum piling scenario is for 2 tubular piles to be installed each day, involving approximately 40 minutes of vibro piling per day. There will, therefore, be significant periods over a 24-hour period when fish will not be disturbed by any vibro piling noise. The actual proportion of vibro piling is estimated to be around 3 %. In other words, any fish that remain within the predicted behavioural effects zone at the time of vibro piling will be exposed to this disturbance only 3 % of the time over the piling programme.

It is also important to consider the noise from piling against existing background or ambient noise conditions (Section 4). The area in which the construction will take place already experiences regular vessel operations and ongoing maintenance dredging, and, therefore, fish are likely to be habituated to a certain level of intermittent anthropogenic background noise.

8.1.3 Dredging and vessel movements

The relative risk and distances at which potential mortality/injury and behavioural effects in fish are predicted to occur as a result of the dredging and vessel movements associated with the construction and operation of the proposed development are included on Table 10.

The worst case SL generated by dredging and vessels is below the Popper *et al.* (2014) quantitative instantaneous peak SPL and cumulative SEL thresholds for pile driving, which indicates that there is no risk of mortality, potential mortal injury or recoverable injury in all categories of fish even at the very source of the dredger or vessel noise. This appears to correlate with the Popper *et al.* (2014) recommended qualitative guidelines for continuous noise sources which consider that the risk of mortality and potential mortal injury in all fish is low in the near, intermediate and far-field (Table 10).

According to Popper *et al*. (2014), the risk of recoverable injury is also considered low for fish with no swim bladder and fish with a swim bladder that is not involved in hearing. There is a greater risk of recoverable injury in fish where the swim bladder is involved in hearing (e.g. herring and shad) whereby a cumulative noise exposure threshold is recommended (170 dB rms for 48 h). The distance at which recoverable injury is predicted in these fish as a result of dredging and vessel movements is 10 m (Table 10)

Popper *et al*. (2014) advise that there is a moderate risk of TTS occurring in the nearfield (i.e. tens of metres from the source) in fish with no swim bladder and fish with a swim bladder that is not involved in hearing and a low risk in the intermediate and far-field. There is a greater risk of TTS in fish where the swim bladder is involved in hearing (e.g. herring) whereby a cumulative noise exposure threshold is recommended (158 dB rms for 12 h). The distance at which TTS is predicted in these fish as a result of dredging and vessel movements is 46 m (Table 10).

Popper *et al.* (2014) guidelines suggest that there is considered to be a high risk of potential behavioural responses occurring in the nearfield (i.e. tens of metres from the source) for fish species with a swim bladder involved in hearing and a moderate risk in other fish species (Table 10).

At intermediate distances (i.e. hundreds of metres from the source) there is considered to be a moderate risk of potential behavioural responses in all fish and in the farfield (i.e. thousands of metres from the source) there is considered to be a low risk of a response in all fish.

Overall, there is considered to be a low risk of any injury in fish as a result of the underwater noise generated by dredging and vessel movements although recoverable injury could potentially occur in very close proximity to the dredger in fish where the swim bladder is involved in hearing (e.g. herring). The level of exposure will depend on the position of the fish with respect to the source, the propagation conditions which will be influenced by the tidal state, and the individual's behaviour over time.

However, it is unlikely that a fish would remain in the vicinity of a dredger or vessel for extended periods. Behavioural responses are anticipated to be spatially negligible in scale and fish will be able to move away and avoid the source of the noise as required.

Furthermore, the proposed capital dredging and vessel activities involved during construction will be temporary. Operational vessel movements and maintenance dredging will take place on a more regular but intermittent basis.

Table 10. **Relative risk and distances (metres) fish response criteria are reached during dredging and vessel movements**

Fish Hearing Category	Mortality/ Potential Mortal Injury/ Recoverable Injury	Recoverable Injury	TTS	Behaviour
Swim bladder involved in hearing (primarily pressure detection)	(N) Low (I) Low (F) Low	10	46	(N) High (I) Moderate (F) Low
Swim bladder is not involved in hearing (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Moderate (F) Low
No swim bladder (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Moderate (F) Low
Eggs and larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Moderate (F) Low
Distances are in metres (m). 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).				

8.2 Marine mammals

8.2.1 Impact piling

NOAA's user spreadsheet tool (NOAA, 2022) has been used to predict the range at which the weighted cumulative SEL and instantaneous peak SPL acoustic thresholds (NOAA, 2018) for the onset of PTS and TTS are reached during the proposed impact piling activity.

In accordance with the guidance provided in NOAA's user manual and the instructions included within the user spreadsheet, 'Tab E.1: Impact pile driving (stationary source: impulsive, intermittent)' and 'E1.1: Method to calculate peak and $\mathrm{SEL}_{\mathrm{cum}}$ (single strike equivalent' was selected as the most appropriate method to apply for the percussive piling activity. The model input values, and associated assumptions are included in Table 11.

Table 11. **NOAA user spreadsheet tool input values for 'Tab E.1: Impact pile driving (stationary source: impulsive, intermittent)'**

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2	Default value for impact pile driving hammers provided in the NOAA instructions (NOAA, 2022).
Lp,0-pk specified at "x" meters (dB re 1 μPa)	246	Loudest near-source (100 m from the source) sound pressure measurements for the percussive piling installation of the nearest-sized steel pipe piles (2.4 m diameter) in a similar shallow water environment (10 m water depth) (Illinworth & Rodkin, 2007; Seiche Ltd., 2020) back-calculated to 1 m and the assumption that two piling rigs with impact hammers will be used concurrently (see Section 5.1).

Model Inputs	Value	Assumptions
Single Strike SELss (LE,p, single strike) specified at "x" meters (dB re 1 μPa^2 s)	222	Loudest near-source (100 m from the source) sound pressure measurements for the percussive piling installation of the nearest-sized steel pipe piles (2.4 m diameter) in a similar shallow water environment (10 m water depth) (Illinworth & Rodkin, 2007; Seiche Ltd., 2020) back-calculated to 1 m and the assumption that two piling rigs with impact hammers will be used concurrently (see Section 5.1).
Distance of Lp,0-pk measurement (m)	1	The sound levels that were measured for percussive piling installation of the nearest-sized steel pipe piles (2.4 m diameter) in a similar shallow water environment (10 m water depth) (Illinworth & Rodkin, 2007; Seiche Ltd., 2020) have been back-calculated to 1 m from the source (see Section 5.1).
Number of strikes per pile	675	Maximum published value provided for existing field data of percussive piling of steel piles and, therefore, considered a reasonable worst case (WSDOT, 2017 cited in NMFS, 2021).
Number of piles per day	2	The maximum impact piling scenario is for the marine works to comprise the installation of up to 2 tubular piles each day (see Section 5.1).
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 3).
Distance of single strike SELss (LE,p, single strike) measurement (m)	1	The sound levels that were measured for percussive piling installation of the nearest-sized steel pipe piles (2.4 m diameter) in a similar shallow water environment (10 m water depth) (Illinworth & Rodkin, 2007; Seiche Ltd., 2020) have been back-calculated to 1 m from the source (see Section 5.1).

The distances at which PTS and TTS in marine mammals are theoretically predicted to occur during impact piling activities associated with the construction of the proposed development are included in Table 12.

Table 12. Approximate distances (metres) marine mammal response criteria are reached during impact piling

Marine Mammal Hearing Group	PTS		TTS	
	SEL$_{cum}$	Peak	SEL$_{cum}$	Peak
Mid-frequency (MF) cetaceans (bottlenose dolphin)	514	8	3,539	17
High-frequency (HF) cetaceans (harbour porpoise)	9,739	286	66,991	619
Phocid pinnipeds in water (PW) (true seals)	4,983	37	34,276	79

There is theoretically predicted to be a risk of instantaneous PTS and TTS in bottlenose dolphin within 8 m and 17 m respectively from the source of the percussive piling noise, and in harbour porpoise within 286 m and 619 m respectively. The risk of instantaneous PTS and TTS in seals is within 37 m and 79 m respectively. Based on the existing bathymetry and physical constraints of the study area, the worst case predicted zones of instantaneous PTS and TTS in harbour porpoise (the most noise sensitive of the marine mammals in the study area) as a result of the impact piling for the new quay wall have been refined and are illustrated on Figure 7 and Figure 8.

Figure 7. **Maximum predicted zone of instantaneous injury and behavioural effects on marine mammals (harbour porpoise) during impact piling at MHWS**

If the propagation of underwater noise from impact piling were unconstrained by any boundaries, the maximum theoretical distance at which the predicted cumulative SEL weighted levels of underwater noise during impact piling is within the limits of PTS and TTS in bottlenose dolphin is 514 m and 3.5 km respectively, and in harbour porpoise is 9.7 km and 67.0 km respectively. The maximum distance for PTS and TTS in seals is 5.0 km and 34.3 km respectively. As noted earlier, the propagation of noise, however, will be significantly limited by the existing bathymetry and physical constraints of the study area.

Figure 8. Maximum predicted zone of instantaneous injury and behavioural effects on marine mammals (harbour porpoise) during impact piling at MLWS

Assuming a lower worst case swimming speed of 1.5 m/s for all marine mammal species (including both adults and juveniles), the maximum time that would take bottlenose dolphin to leave the cumulative SEL weighted PTS and TTS injury zones during impact piling is estimated to be around 6 and 39 minutes respectively. In harbour porpoise it is estimated to be 1.8 hours and 12.4 hours respectively. The maximum time that would take seals to leave the PTS and TTS zones is estimated to be 55 minutes and 6.4 hours respectively. These durations equate to around 3 %, 50 % and 27 % of the time that would be required for a temporary injury to occur in bottlenose dolphin, harbour porpoise and seals respectively and, therefore, assuming marine mammals evade the injury effects zone, they are not considered to be at risk of any permanent or temporary injury during impact piling.

Any marine mammals present are likely to evade the area. Behavioural responses could include movement away from a sound source, aggressive behaviour related to noise exposure (e.g. tail/flipper slapping, fluke display, abrupt directed movement), visible startle response and brief cessation of reproductive behaviour (Southall *et al.*, 2007). Mild to moderate behavioural responses of any individuals within these zones could include movement away from a sound source and/or visible startle response (Southall *et al.*, 2007).

The effects of piling noise on marine mammals also need to be considered in terms of the duration of exposure. Piling noise will take place over a period of approximately 12 months. However, piling will not take place continuously as there will be periods of downtime, pile positioning and set up. The assessment has been undertaken on the assumption that piling works will be undertaken 24/7 and seven days per week. The maximum impact piling scenario is for 2 tubular piles to be installed each day, involving approximately 240 minutes of impact piling per day. There will, therefore, be significant periods over a 24-hour period when marine mammals will not be disturbed by any impact piling noise. The actual proportion of impact piling is estimated to be around 17 %. In other words, any marine mammals that remain within the predicted behavioural effects zone at the time of percussive piling will be exposed to this disturbance only 17 % of the time over the piling programme.

It is also important to consider the noise from piling against existing background or ambient noise conditions (Section 4). The area in which the construction will take place already experiences regular vessel operations and ongoing maintenance dredging, and, therefore, marine mammals are likely to be habituated to a certain level of anthropogenic background noise.

8.2.2 Vibro piling

NOAA's user spreadsheet tool (NOAA, 2022) has been used to predict the range at which the weighted cumulative SEL acoustic thresholds (NOAA, 2018) for the onset of PTS and TTS are reached during the proposed vibro piling activity.

In accordance with the guidance provided in NOAA's user manual and the instructions included within the user spreadsheet, 'Tab A.1: Vibratory pile driving (stationary source: non-impulsive, continuous)' was selected as the most appropriate method to apply for the vibro piling activity. The model input values and associated assumptions are included in Table 13.

Table 13. NOAA user spreadsheet tool input values for 'Tab A.1: Vibratory pile driving (stationary source: non-impulsive, continuous)'

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2.5	Default value for vibratory pile driving hammers provided in the NOAA instructions (NOAA, 2022).
Sound Pressure Level (L_{rms}), specified at "x" metres (dB re 1 µPa)	201	Loudest near-source (10 m from the source) sound pressure measurements for the vibratory piling installation of 1.83 m steel pipe piles in a shallow water environment (approximately 5 m water depth) (Illinworth & Rodkin, 2007; ICF Jones & Stokes and Illingworth and Rodkin, 2009; Rodkin and Pommerenck, 2014) back-calculated to 1 m and the assumption that two piling rigs with vibro hammers will be used concurrently (see Section 5.1).
Number of piles within 24 hr period	2	The maximum vibro piling scenario is for the marine works to comprise up to 4 tubular piles to be installed each day (see Section 5.1).
Duration to drive a single pile (minutes)	20	Each tubular pile will require 20 minutes of vibro piling (see Section 5.1).
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 3).

Model Inputs	Value	Assumptions
Distance of sound pressure level measurement (m)	1	The sound levels that were measured for the vibratory piling installation of 1.83 m steel pipe piles in a shallow water environment (Illinworth & Rodkin, 2007; ICF Jones & Stokes and Illingworth and Rodkin, 2009; Rodkin and Pommerenck, 2014) have been back-calculated to 1 m from the source (see Section 5.1).

The distances at which PTS and TTS in marine mammals are theoretically predicted to occur during vibro piling activities associated with the construction of the proposed development are included in Table 14.

Table 14. Approximate distances (metres) marine mammal response criteria are reached during vibro piling

Marine Mammal Hearing Group	PTS	TTS
Mid-frequency (MF) cetaceans (bottlenose dolphin)	13	171
High-frequency (HF) cetaceans (porpoises, river dolphins)	138	1,801
Phocid pinniped (PW) (true seals)	65	855

If the propagation of underwater noise from vibro piling were unconstrained by any boundaries, the maximum theoretical distance at which the predicted cumulative SEL weighted levels of underwater noise during vibro piling is within the limits of PTS and TTS in bottlenose dolphin is 13 m and 171 m respectively, and in harbour porpoise is 138 m and 1.8 km respectively. The maximum distance for PTS and TTS in seals is 65 m and 855 m respectively. The propagation of noise, however, will be significantly limited by the existing bathymetry and physical constraints of the study area.

Assuming a lower worst case swimming speed of 1.5 m/s for all marine mammal species (including both adults and juveniles), the maximum time that would take bottlenose dolphin to leave the cumulative SEL weighted PTS and TTS injury zones during vibro piling is estimated to be 9 seconds and 1.9 minutes respectively. In harbour porpoise it is estimated to be 1.5 minutes and 20 minutes respectively. The maximum time that would take seals to leave the PTS and TTS zones is estimated to be 44 seconds and 9.5 minutes respectively. These durations equate to around 0.1 %, 1.4 % and 0.7 % of the time that would be required for a temporary injury to occur in bottlenose dolphin, harbour porpoise and seals respectively and, therefore, assuming marine mammals evade the injury effects zone, they are not considered to be at risk of any permanent or temporary injury during vibro piling.

Any marine mammals are likely to evade the area. Behavioural responses could include movement away from a sound source, aggressive behaviour related to noise exposure (e.g. tail/flipper slapping, fluke display, abrupt directed movement), visible startle response and brief cessation of reproductive behaviour (Southall *et al*., 2007). Mild to moderate behavioural responses of any individuals within these zones could include movement away from a sound source and/or visible startle response (Southall *et al*., 2007).

The effects of piling noise on marine mammals also need to be considered in terms of the duration of exposure. Piling noise will take place over a period of approximately 12 months. However, piling will not take place continuously as there will be periods of downtime, pile positioning and set up. The assessment has been undertaken on the assumption that piling works will be undertaken 24/7 and seven days per week. The maximum piling scenario is for 2 tubular piles to be installed each day, involving approximately 40 minutes of vibro piling per day. There will, therefore, be significant periods over a 24-hour period when marine mammals will not be disturbed by any vibro piling noise. The actual proportion of impact piling is estimated to be around 3 %. In other words, any marine mammals that remain within the predicted behavioural effects zone at the time of vibro piling will be exposed to this disturbance only 3 % of the time over the piling programme.

It is also important to consider the noise from piling against existing background or ambient noise conditions. The area in which the construction will take place already experiences regular vessel operations, and, therefore, marine mammals are likely to be habituated to a certain level of anthropogenic background noise disturbance.

8.2.3 Dredging and vessel movements

NOAA's user spreadsheet tool (NOAA, 2022) has been used to predict the range at which the weighted cumulative SEL acoustic thresholds (NOAA, 2018) for PTS and TTS are reached during the proposed dredging and vessel movements associated with the construction and operation of the proposed development.

In accordance with the guidance provided in NOAA's user manual and the instructions included within the user spreadsheet, 'Tab C: Mobile source, non-impulsive, continuous ("safe distance" methodology)' was selected as the most appropriate method to apply for the dredging and vessel activity. The model input values, and associated assumptions are included in Table 15.

Table 15. NOAA user spreadsheet tool input values for 'Tab C: Mobile source, non-impulsive, continuous ("safe distance" methodology)'

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2.5	The maximum recommended default value provided in the user spreadsheet (NOAA, 2022) that leads to the greatest predicted ranges for PTS and TTS and is, therefore, considered a worst case.
Source Level (L_{rms})	188	The maximum estimated RMS SL for all forms of dredging and vessels that will be involved in construction and operation of the proposed development (see Section 0 and Section 5.3).
Source velocity (m/s)	1	Value is based on the minimum sailing speed of a dredging vessel as it removes material from the seabed. A lower source velocity value predicts greater ranges at which PTS and TTS are reached and, therefore, the lowest reasonable source velocity associated with the dredging and vessel activity has been applied as a worst case.

The distances at which PTS and TTS in marine mammals are predicted to occur during dredging and vessel movements associated with the construction and operation of the proposed development are included in Table 16.

Table 16. Approximate distances (metres) marine mammal response criteria are reached during dredging and vessel movements

Marine Mammal Hearing Group	PTS	TTS
Mid-frequency (MF) cetaceans (bottlenose dolphin)	<1	1
High-frequency (HF) cetacean (harbour porpoise)	<1	44
Phocid pinniped (PW) (grey seal and common seal)	<1	12

There is predicted to be no risk of PTS in any of the key marine mammal species found in the study area. The risk of TTS in bottlenose dolphin is limited to within 1 m from the dredging and vessel activity, and within 44 m in harbour porpoise and 12 m in seals (Table 16).

Overall, there is not considered to be any risk of injury or significant disturbance to marine mammals from the proposed dredging and vessel activities that are proposed at the Port of Mostyn even if the dredging and vessel movements were to take place continuously 24/7.

9 Summary and Conclusions

This report presents the underwater noise assessment that has been undertaken to determine the potential impacts of underwater noise on key marine receptors in the study area as a result of the construction and operation of the MEP Extension Project.

In accordance with available guidance (NPL, 2014; Farcas *et al.*, 2016; Faulkner *et al.*, 2018), and as discussed with NRW, a simple logarithmic spreading model has been selected to predict the propagation of sound pressure from the key sources of underwater noise, taking account of its limitations and constraints. The predicted levels of underwater noise have been compared against peer-reviewed noise exposure criteria to determine the potential risk of impact on marine fauna (Hawkins *et al.*, 2014; Popper *et al.*, 2014; NOAA, 2018; Southall *et al.*, 2019).

A number of mitigation measures are proposed to reduce or minimise potential adverse effects during construction:

- **Soft start**: The gradual increase of piling power, incrementally, until full operational power is achieved will be used as part of the piling methodology. This will give fish and marine mammals the opportunity to move away from the area before the onset of full impact strikes. The duration of the soft start is proposed to be 20 minutes in line with the JNCC piling protocol (JNCC, 2010);
- **Vibro piling**: Vibro piling is proposed to be used where possible (which produces lower peak source noise levels than percussive piling). However, in order to drive the piles to the required design level in certain circumstances percussive piling is likely to be required given the underlying geology and depth of piling that is required to ensure the necessary structural integrity and stability of the piles; and
- **Marine Mammal Observer**: In addition, in order to further reduce the significance of the impact to marine mammals the JNCC "Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals during piling" (JNCC, 2010) will be followed during percussive piling.

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11 Abbreviations/Acronyms

ABP	Associated British Ports
CEDA	Centre for Environmental Data Analysis
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CTVs	Crew Transfer Vessels
dB	Decibel
Defra	Department for Environment, Food and Rural Affairs
DPTI	Department for Infrastructure and Transport
ES	Environmental Statement
EU	European Union
HF	High Frequency
HRA	Habitats Regulations Assessment
IFM	Institute of Fisheries Management
JNCC	Joint Nature Conservation Committee
MEP	Mostyn Energy Park
MEPE	Mostyn Energy Park Extension
MF	Mid Frequency
MLWS	Mean Low Water Springs
MHWS	Mean High Water Springs
MSFD	Marine Strategy Framework Directive
µPa	microPascal
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPL	National Physical Laboratory
NRW	Natural Resources Wales
Pa	Pascal
RMS	Root Mean Square
SD	Standard Deviation
SEL	Sound Exposure Level
SL	Source Level
SOVs	Service Operation Vessels
SPL	Sound Pressure Level
TSHD	Trailing Suction Hopper Dredger
TTS	Temporary Threshold Shift
UKMMAS	UK Marine Monitoring Assessment Strategy
WFD	Water Framework Directive
WID	Water Injection Dredging
WODA	World Organisation of Dredging Associations

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

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