Annex 10.3

MEP Impacts of Underwater Piling Noise on Migratory Fish

(Subacoustech Environmental)

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Executive Summary

Subacoustech Environmental has undertaken a study on behalf of Able UK Ltd to assess the impact of underwater noise produced during pile driving operations within the Humber. This is due to the proposed construction of the Able Marine Energy Park (MEP) within the Humber.

The levels of underwater noise from the installation of 1.8 m and 2.1 m diameter piles have been estimated using a proprietary underwater sound propagation model, INSPIRE v3.0.7, that enables the level of noise from the piling and its behaviour with range to be estimated for varying tidal conditions, water depths and piling locations. The model is based on, and validated against, an existing database of measurements of piling noise. The INSPIRE model has been used to calculate the expected noise level on 180 transects radiating outwards from the piling location at the proposed Able MEP site and the results interpreted to yield impact range contours.

Estimates of underwater noise in terms of unweighted sound levels have been made using this model to indicate the range at which lethality and physical injury, and of the dB_{ht} level (perceived level by marine species) of the noise to predict the range at which injury or behavioural avoidance might occur, with particular attention given to salmon.

The effects of different sized diameter piles, with a given blow energy, has been presented as well as the effects of piling at high and low tide and the initial impact ranges that occur due to a soft start.

1 Introduction

1.1 Project description

The Able Marine Energy Park (MEP) is to be located within the Humber and lies between the Humber Sea Terminal and ABP Immingham Port.

As part of the construction for the MEP, piles for the foundations will be driven into the substrate by impact piling. Impact piling is a large source of noise, which is readily transmitted into the surrounding water. This noise has potentially adverse effects on marine life and as a consequence the effect needs to be taken into consideration.

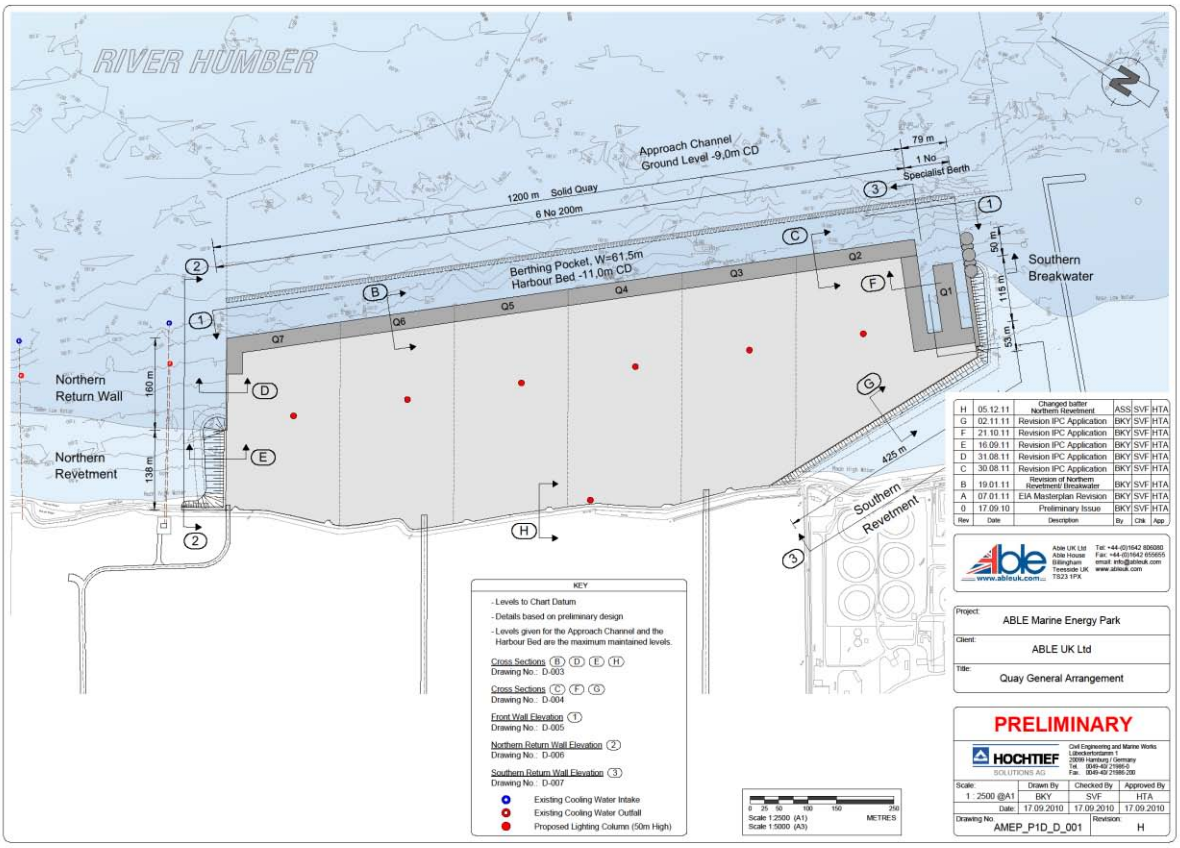

Figure 1-1 Able MEP Quay General Arrangement

1.2 Project objectives

This report has been compiled by Subacoustech Environmental Limited to estimate the likely level of underwater noise during the construction of the Able MEP in relation to the effect of noise on salmon using dB_{ht}(*Salmo salar*). Subacoustech Environmental has completed the following project objectives:

- A review of background information on the units for measuring and assessing underwater noise and vibration;
- Subsea noise modelling to estimate the potential for physical injury and fatality to marine species based on predicted unweighted levels of underwater noise;
- Modelling of sound propagation in the dB_{ht}(*Species*) metrics for 1.8 m and 2.1 m diameter piles;
- Impact zone analysis for salmon;

- Summary and Conclusions.

This report quantifies the potential effects and impacts of the underwater noise that is likely to be generated by impact piling operations during the construction of the MEP in the Humber.

1.3 Impact piling

It has been proposed that impact piling is used to drive the piles into the seabed. This technique involves a large weight or "ram" being dropped or driven onto the top of the pile, driving it into the sea bed. Usually, double-acting hammers are used in which compressed air not only lifts the ram, but also imparts a downward force on the ram, exerting a larger force than would be the case if it were only dropped under the action of gravity. Percussive impact piling has been established as a high level source of underwater impulsive noise (Wursig, 2000; Caltrans, 2001; Nedwell *et al,* 2003b; Parvin *et al,* 2006; Thomsen *et al,* 2006; Nedwell *et al* 2007a).

Noise is created in air by the hammer, partly 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, due to its high sound speed (1,500 m/s, as opposed to 340 m/s for air), 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 mean 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 wave. 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 10 – 20 dB below the waterborne arrival, and hence it is the latter that dominates the noise. In the context of this study, it should be noted that where mitigation measures such as pile cladding are used to attenuate the waterborne noise, the seismic wave may remain and limit the effectiveness of the technique.

2 Measurement of underwater noise

2.1 Introduction

Sound travels much faster in water (approximately 1,500 m/s) than in air (340 m/s). Since water is a relatively incompressible, dense medium, the pressures associated with underwater sound tend to be much higher than in air. As an example, background levels of sea noise of approximately 130 dB re 1 µPa for UK coastal waters are not uncommon (Nedwell *et al,* 2003a and 2007a). This level equates to about 100 dB re 20 µPa in the units that would be used to describe a sound level in air. Such levels in air would be considered to be hazardous. However, marine mammals and fish have evolved to live in this environment and are thus relatively insensitive to sound pressure compared with terrestrial mammals. The most sensitive thresholds are often not below 100 dB re 1 µPa and typically not below 70 dB re 1 µPa (44 dB re 20 µPa using the reference unit that would be used in air).

2.2 Units of measurement

Sound measurements underwater are usually expressed using the decibel (dB) scale, which is a logarithmic measure of sound. A logarithmic scale is used because rather than equal increments of sound having an equal increase in effect, typically a constant ratio is required for this to be the case, that is, each *doubling* of sound level will cause a roughly equal increase in "loudness".

Any quantity expressed in this scale is termed a "level". If the unit is sound pressure, expressed on the dB scale, it will be termed a "Sound Pressure Level". The fundamental definition of the dB scale is given by:

$$\text{Level} = 10 \times \log_{10}(Q/Q_{ref}) \qquad \text{eqn. 2-1}$$

where Q is the quantity being expressed on the scale, and Q_{ref} is the reference quantity.

The dB scale represents a ratio and, for instance, 6dB really means "twice as much as …". It is, therefore, used with a reference unit, which expresses the base from which the ratio is expressed. The reference quantity is conventionally smaller than the smallest value to be expressed on the scale, so that any level quoted is positive. For instance, a reference quantity of 20 µPa is usually used for sound in air, since this is the threshold of human hearing.

A refinement is that the scale, when used with sound pressure, is applied to the pressure squared rather than the pressure. If this were not the case, if the acoustic power level of a source rose by 10 dB the Sound Pressure Level would rise by 20 dB. So that variations in the units agree, the sound pressure must be specified in units of RMS pressure *squared*. This is equivalent to expressing the sound as:

$$\text{Sound Pressure Level} = 20 \times \log_{10}(P_{RMS}/P_{ref}) \qquad \text{eqn. 2-2}$$

For underwater sound, typically a unit of one microPascal (µPa) is used as the reference unit; a Pascal is equal to the pressure exerted by one Newton over one square metre. One microPascal equals one millionth of this.

2.3 Quantities of measurement

Sound may be expressed in many different ways depending upon the particular type of noise, and the parameters of the noise that allow it to be evaluated in terms of a biological effect. These are described in more detail below.

2.3.1 Peak level

The peak level is the maximum level of the acoustic pressure, usually a positive pressure. This form of measurement is often used to characterise underwater blasts where there is a clear positive peak following the detonation of explosives. Examples of this type of measurement used to define underwater blast waves can be found in Bebb and Wright (1953, 1955), Richmond *et al* (1973), Yelverton *et al* (1973) and Yelverton (1981). The data from these studies have been widely interpreted in a number of reviews on the impact of high level underwater noise causing fatality and injury in human divers, marine mammals and fish (see for example Rawlins, 1974; Hill, 1978; Goertner, 1982; Richardson *et al,* 1995; Cudahy and Parvin, 2001; Hastings and Popper, 2005). The peak sound level of a freely suspended charge of Tri-Nitro-Toluene (TNT) in water can be estimated from Arons (1954), as summarised by Urick (1983). For offshore operations such as well head severance, typical charge weights of 40 kg may be used, giving a source peak pressure of 195 MPa or 285 dB re 1 µPa @ 1m (Parvin *et al,* 2007).

2.3.2 Peak to peak level

The peak to peak level is usually calculated using the maximum variation of the pressure from positive to negative within the wave. This represents the maximum change in pressure (differential pressure from positive to negative) as the transient pressure wave propagates. Where the wave is symmetrically distributed in positive and negative pressure, the peak to peak level will be twice the peak level, and hence 6 dB higher.

Peak to peak levels of noise are often used to characterise sound transients from impulsive sources such as percussive impact piling and seismic airgun sources. Measurements during offshore impact piling operations to secure tubular steel piles into the seabed have indicated peak to peak source level noise from 244 to 252dB re 1µPa @ 1m for piles from 4.0 to 4.7 m diameter (Parvin *et al,* 2006; Nedwell *et al,* 2007a).

2.3.3 Sound pressure level (SPL)

The Sound Pressure Level is normally used to characterise noise and vibration of a continuous nature such as drilling, boring, continuous wave sonar, or background sea and river noise levels. To calculate the SPL, the variation in sound pressure is measured over a specific time period to determine the Root Mean Square (RMS) level of the time varying sound. The SPL can therefore be considered to be a measure of the average unweighted level of the sound over the measurement period.

As an example, small sea going vessels typically produce broadband noise at source SPLs from 170 – 180 dB re 1 µPa @ 1 m (Richardson *et al,* 1995), whereas a supertanker generates source SPLs of typically 198 dB re 1 µPa @ 1 m (Hildebrand, 2004).

Where an SPL is used to characterise transient pressure waves such as that from seismic airguns, underwater blasting or piling, it is critical that the time period over which the RMS level is calculated is quoted. For instance, in the case of a pile strike lasting say a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean taken over one second.

2.3.4 Sound Exposure Level

When assessing the noise from transient sources such as blast waves, impact piling or seismic airgun noise, the issue of the time period of the pressure wave (highlighted above) is often addressed by measuring the total acoustic energy (energy flux density) of the wave. This form of analysis was used by Bebb and Wright (1951 to 1955), and later by Rawlins (1987) to explain the apparent discrepancies in the biological effect of short and long range blast waves on human divers. More recently, this form of analysis has been used to develop an interim exposure criterion for assessing the injury range for fish from impact piling operations (Hastings and Popper, 2005; Popper *et al*, 2006).

The Sound Exposure Level (SEL) sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound source and the duration the sound is present in the acoustic environment. Sound Exposure (SE) is defined by the equation:

$$SE = \int_0^T p^2(t)dt \qquad \text{eqn. 2-3}$$

where p is the acoustic pressure in Pascals, T is the duration of the sound in seconds and t is time in seconds.

The Sound Exposure is a measure of the acoustic energy and, therefore, has units of Pascal squared seconds (Pa^2s).

To express the Sound Exposure on a logarithmic scale by means of a dB, it is compared with a reference acoustic energy level of 1 µPa^2 (P^2_{ref}) and a reference time (T_{ref}).

The Sound Exposure Level (SEL) is then defined by:

$$SEL = 10\log_{10}\left(\frac{\int_0^T p^2(t)dt}{P_{ref}^2 T_{ref}}\right) \qquad \text{eqn. 2-4}$$

By selecting a common reference pressure P_{ref} of 1µPa for assessments of underwater noise, the SEL and SPL can be compared using the expression:

$$SEL = SPL + 10\log_{10}T \qquad \text{eqn. 2-5}$$

where the SPL is a measure of the average level of the broadband noise, and the SEL sums the cumulative broadband noise energy.

Therefore, for continuous sounds of duration less than one second, the SEL will be lower than the SPL. For periods of greater than one second the SEL will be numerically greater than the SPL (i.e. for a sound of ten seconds duration the SEL will be 10 dB higher than the SPL, for a sound of 100 seconds duration the SEL will be 20 dB higher than the SPL and so on).

2.4 INSPIRE

The Impulse Noise Sound Propagation and Impact Range Estimator (INSPIRE) model has been developed specifically to model the propagation of impulsive broadband underwater noise in shallow waters. It uses a combined geometric and energy flow/hysteresis loss model to conservatively predict propagation in relatively shallow coastal water environments, and has been tested against actual results from a large number of other offshore wind farm piling operations.

The model is able to provide a wide range of physical outputs, including the peak pressure, impulse, SEL, dB_{ht} of the noise. Transmission Losses are calculated by the model on a fully range and depth dependent basis. The INSPIRE model imports electronic bathymetry data as a primary input to determine the transmission losses along transects extending from the pile location which has been input in addition to other simple physical data.

INSPIRE has a model of mitigation built in, which allows the effect of bubble curtains, cladding, and other mitigation methods to be estimated. It should be noted that when the frequency-dependent behaviour of these methods is considered, they are often found to be less effective than if simple measures of overall sound level such as peak pressure are used.

3 Impact of underwater sound on marine species

3.1 Introduction

Over the past 20 years it has become increasingly evident that noise from human activities in and around underwater environments may have an impact on the marine species in the area. The extent to which intense underwater sound might cause an adverse environmental impact in a particular species is dependent upon the incident sound level, frequency content, duration and/or repetition rate of the sound wave (see, for example Hastings and Popper, 2005). As a result, scientific interest in the hearing abilities of aquatic animal species has increased.

A review by Popper *et al* (2006) suggests the use of unweighted sound exposure metrics such as peak level of underwater noise, and the SEL of the noise, to develop an interim guidance for estimating the injury range for fish from pile driving operations. Similarly, a review of underwater noise from offshore wind farms on marine mammals (Madsen *et al,* 2006) discusses the use of frequency weighting of the underwater noise. The authors of the latter study comment that the impact of underwater sound on the auditory system is frequency dependent and ideally, noise levels should (as for humans) be weighted using the defined frequency responses of the auditory system of the animal in question.

The approach that has been adopted in this study is to use unweighted sound level metrics to define the potential for gross damage such as fatality, swim bladder rupture or tissue damage, since hearing is not involved in this process. In addition, frequency weighted measures of the sound based on the hearing threshold of the affected species have been applied to assess the perceived loudness of the noise for representative marine species, and hence the range at which an aversive response to the piling may be expected.

3.2 Lethality and injury impacts and their associated sound levels

3.2.1 Introduction

At the highest level, typically during underwater blast from explosives, sound has the ability to cause injury and, in extreme cases, the death of exposed animals.

Due to the current lack of information on potential lethal and physical injury effects from impact piling, this study has used the data from blast exposures to estimate impact zones. The wave forms from these two noise sources are rather different; the transient pressure wave from an impact piling operation has roughly equal positive and negative pressure amplitude components and a relatively long duration of up to a few hundred milliseconds. By contrast, blast waves have a very high positive pressure peak followed by a much lower amplitude, negative wave due to the momentum imparted to the water surrounding the explosive gas bubble. The pressure of a blast wave is normally quantified therefore in terms of the peak level, due to the dominance of the positive peak of the waveform. There is, therefore, a level of uncertainty as to whether a blast wave criterion can be directly applied to a transient waveform arising from an impact piling operation.

3.2.2 Observations of lethality and physical injury

Lethal and direct physical injury from an underwater transient pressure wave are related to the peak pressure level, rise time and duration that the peak pressure acts on the body (usually measured by the impulse of the blast wave). The criteria that have been developed for assessing gross injury of this type are based on data from blast injury at close range to explosives. Injury has been related both to the incident peak positive pressure of the wave and to the impulse. To obtain an effective measure of the impulse of the wave, an estimate of the effective duration must be made by integrating over the waveform. A number of different techniques for assessing the duration of an impulsive waveform are described by Hamernik and Hsueh (1991) based on the studies by Coles *et al* (1968), Pfander *et al* (1980), and Smoorenburg (1982). The measure of impulse will, therefore, depend upon which technique is applied.

There is currently very limited data relating to fish kill from piling (Hastings *et al*, 2005), although the study by Caltrans (2001) during impact piling operations on the San Francisco to Oakland Bay Bridge indicated fish kill to a range of approximately 50 m. By fitting the results of Abbot *et al* (2002) to a spreading model, it is possible to estimate the Source Level of the piling to be about 242 dB re 1 µPa @ 1 m. This equates to fish being killed when the peak pressure level exceeds about 208 dB re 1 µPa, which corresponds to an interim criterion that has been proposed by Popper, discussed in the following section.

Studies carried out on the effects of blast on various species of fish by Yelverton *et al* (1975) (also reproduced in Richardson *et al,* 1995) demonstrated that mortality rates were related to body mass and magnitude of the impulsive wave. The results show that a 50% mortality rate would occur in fish weighing 1 kg when exposed to an impulse of about 340 Pa.s. According to this model, to cause the same mortality rate in fish weighing 10 kg they would have to be exposed to an impulse of approximately 800 Pa.s. The work indicates that there are levels below which a sound would cease to be lethal to a fish of a certain weight. While this sound level may not cause the swim bladder to rupture or kidney and liver damage that may be seen after lethal doses of sound, there may still be considerable tissue damage to susceptible organs such as the lungs, gastro-intestinal tract or eyes and hence possible long term survival implications.

3.2.3 Criteria for assessing lethality and physical injury

The following criteria have been applied in this study for levels of noise likely to cause physical effects (Parvin *et al* (2007), based on data in the studies of Yelverton (1975), Turnpenny *et al* (1994), Hastings and Popper (2005)):

- Lethal effect may occur where peak to peak levels exceed 240 dB re 1 µPa, or an impulse of 100 Pa.s; and
- Physical injury may occur where peak to peak levels exceed 220 dB re 1 µPa, or an impulse of 35 Pa.s.

It might be noted however that for smaller fish sizes of mass 0.01 g, Hastings and Popper (2005), and Popper *et al* (2006) recommend an interim “no injury” criteria for fish exposed to impact piling noise of 208 dB re 1 µPa peak level (equivalent to 214 dB re 1 µPa peak to peak level) or a Sound Exposure Level of 187 dB re 1 $\mu Pa^2 s$. In view of the very small fish size that this limit addresses, and the fact that it is extrapolated from limited data, it has not been used herein.

3.3 Behavioural impacts and their associated sound levels

3.3.1 Introduction

At levels lower than those that cause physical injury, noise may nevertheless have important behavioural effects on a species, of which the most significant is avoidance of the insonified area (the region within which noise from the source of interest is above ambient underwater noise levels). The significance of the effect requires an understanding of its consequences; for instance, avoidance may be significant if it causes a migratory species to be held up. However, in other cases, the movement of species from one area to another may be of no consequence.

Avoidance appears to be associated with a sensation of “unbearable loudness”. Hence, in order to judge the potential of a noise to cause avoidance, it is necessary to be able to ascertain the perception of the sound by the species, that is, how loud it appears to individuals of that species. Individuals of species having poor hearing may perceive the level as low, and hence not react to the noise, whereas a species that is sensitive may find the level unbearably loud and react by swimming away. Therefore, of key importance in the process is an understanding of the hearing ability of the species that may be affected.

3.3.2 Overview of hearing in fish

Behavioural impacts in fish following their exposure to underwater sound relate to the way in which they hear and how they may subsequently respond to the sound. Variation in the anatomy and physiology of the ears and associated structures in fish is extensive, indicating that different species detect sound in different ways (Popper and Fay, 1993). Furthermore, published data also indicates that there is a considerable variation in the hearing abilities of fish sensitive to sound, both in terms of the minimum levels of sound perceptible and the frequency range over which they can hear (e.g. Hawkins, 1981; Lovell *et al*, 2005; Popper *et al,* 2004; Hastings and Popper, 2005; Thomsen *et al,* 2006; Madsen *et al,* 2006). Any assessment of potential impacts on a particular species must therefore take this into account. The dB_{ht}, which is a probabilistic model, takes this into account by estimating the proportion of a population that will react, rather than trying to estimate whether an individual will.

This variation appears to be linked to particular physiological adaptations in the distance of the swim bladder to the inner ear. The herring for example has an extension of the swim bladder that terminates within the inner ear (Blaxter *et al*, 1981; Popper *et al,* 2004). By comparison, the swim bladder in salmon is not in close proximity to the ear anatomy and, as such, this species has poorer hearing. Species such as dab, sole and lemon sole, do not have a swim bladder and thus tend to have a lower hearing ability than many other species of fish.

In general, fish that are considered hearing specialists such as the herring are able to perceive sounds in the frequency range 30 Hz – 4 kHz, though at these higher frequencies sensitivity is very low. Threshold levels for these species are at approximately 75 dB re 1 μPa at frequencies between 30 Hz – 1 kHz.

In comparison, the less sensitive group, termed hearing generalists including the dab and the bass, are only able to perceive sounds between about 30 – 400 Hz with peak sensitivity at 118 dB re 1 μPa over this range, though the salmon, representing one of the more sensitive hearing generalists has a threshold level of 95 dB re 1 μPa at 160 Hz. In comparison, the dab, a hearing generalist, has threshold frequencies of approximately 90 dB re 1 μPa at frequencies between 30 – 200 Hz.

3.3.3 Audiograms of underwater species

The metric that has been used in this study to estimate the effect of noise, the dB_{ht}, is based on the audiogram of a species. When measuring the audiogram of an animal, it is necessary to determine the response to the sound by a technique that does not require cognitive compliance. Two principal techniques have been used to determine the audiogram of fish and marine mammal species, these involve either a behavioural response technique or auditory evoked potential measurements (monitoring of the electrical activity of the animals hearing mechanism) see for example Lovell *et al* (2005).

3.3.4 Criteria for assessing behavioural response

Measurements of noise are frequently made using an overall linear level of that sound, such as peak pressure. This, however, does not provide an indication of the impact that the sound will have upon a particular fish or marine mammal species. This is of fundamental importance when considering the behavioural response of species to activities generating underwater noise, as avoidance is associated with the perceived level of loudness and vibration of the sound by the species. Therefore, the same underwater noise may have a different impact on different species with different hearing sensitivities.

Where the intention is to estimate these more subtle behavioural or audiological effects of noise, caused by "loudness", hearing ability has to be taken into account and simple metrics based on unweighted measures are inadequate. For instance, it has been determined that in humans a metric incorporating a frequency weighting that parallels the sensitivity of the human ear is required to accurately assess the behavioural effects of noise, hence the use of frequency weighted measures by regulatory bodies worldwide, such as the Health and Safety Executive in the UK, as a method off assessing the impacts of noise in the workplace. The most widely used metric in this case is the dB(A), which incorporates a frequency weighting (the A-weighting), based on the 40-phon human hearing curve.

The dB_{ht}(*Species*) metric (Nedwell *et al,* 2007b) has been developed as a means for quantifying the potential for a behavioural impact on a species in the underwater environment. As any given sound will be perceived differently by different species (since they have differing hearing abilities) the species name must be appended when specifying a level. For instance, the same construction event might have a level of 70 dB_{ht}(*Salmo salar*) for a salmon, and 110 dB_{ht}(*Tursiops truncatus)* for a bottlenose dolphin.

The perceived noise levels of sources measured in dB_{ht}(*species*) are usually much lower than the unweighted (linear) levels, both because the sound will contain frequency components that the species cannot detect, and also because most species that live in the underwater environment have high thresholds of perception (*i.e.* are relatively insensitive) to sound.

If the level of sound is sufficiently high on the dB_{ht}(*species*) scale, it is likely that an avoidance reaction will occur. The response from a species will be probabilistic in nature (e.g. at 75 dB_{ht} (*Species*) one individual from a species may react, whereas another individual may not; the metric indicates the *probability* of an individual reacting), and may also vary depending upon the type of signal. A level of 0 dB_{ht}(*species*) represents a sound that is at the hearing threshold for that species and is, therefore, at a level at which sound will start to be 'heard'. At this and lower perceived sound levels, no response occurs as the receptor cannot hear the sound.

Currently, on the basis of a large body of measurements of fish avoidance of noise (Maes *et al,* 2004), and from re-analysis of marine mammal behavioural response to underwater sound, the following assessment criteria was published by the UK Department of Business, Enterprise and Regulatory Reform (BERR) (Nedwell *et al,* 2007b) to assess the potential impact of the underwater noise on marine species:

Level in dB_{ht}(species)	**Effect**
90 and above	Strong avoidance reaction by virtually all individuals.
Above 110	Tolerance limit of sound; unbearably loud.
Above 130	Possibility of traumatic hearing damage from single event.

Table 3-1 Assessment criteria used in this study to assess the potential impact of underwater noise on marine species

In addition, a lower level of 75 dB_{ht} has sometimes been used for analysis as a level of "significant avoidance". At this level, about 50% of individuals will react to the noise, although the effect will probably be limited by habituation.

4 Modelling of sound levels as a function of range

4.1 Introduction to subsea noise propagation modelling using INSPIRE

As part of this study, the propagation of underwater noise from the pile driving operations has been modelled, in order to provide estimates of underwater sound levels as a function of range from the proposed Able Marine Energy Park in the Humber.

Transmission of sound in the underwater environment is highly variable from region to region, and can also vary considerably with the local bathymetry and physical conditions. Some frequency components of piling noise can be more rapidly attenuated than others in very shallow water regions typical of the silt and sandbank regions located around coastal and estuary areas.

In general, in shallow coastal environments, the lower the frequency of sound, the more efficiently the sound propagates. High frequency components, by contrast, are more heavily attenuated in shallow water, especially when the water depth decreases with range. In these conditions there is also a greater interaction of the sound with the seabed, and the sound is therefore more rapidly absorbed than would be the case in the deep ocean. In shallow water geometric spreading can also be important. Sound may spread not only through the water but also through the underlying sediments, resulting in attenuation of its level as a result of energy being lost into the underlying rock.

In the conditions typical of those in which piles are installed (estuaries and shoals), for various constructions (e.g. windfarms, quays and piers), the underwater sound may vary considerably temporally and spatially due to these factors. The approach used in this study and previous ones is, therefore, to base the modelling and assessment on a suitable acoustic model, which has been validated against a database of measured data in similar operations.

The Impulse Noise Sound Propagation and Impact Range Estimator (INSPIRE) model has been specifically developed by Subacoustech to model the propagation of impulsive noise in shallow water. It uses a combined geometric and energy flow/hysteresis loss model to model propagation in shallow water. The INSPIRE model v3.0.7 has also been tested “blind” against measured impact piling noise data from several offshore construction operations, as well as a range of shallow water estuarine piling operations, and has been found to provide accurate results.

180 transects have been modelled for each pile location using INSPIRE. These transects are equally spaced at two degree intervals (taken from grid north) for 360 degrees around the pile position and are generally taken to the extent of any impact ranges or until land is reached. The bathymetry and depth profiles along each of these transects have been input into the INSPIRE model. In order to provide a balanced estimate of the likely impacts of underwater noise during piling at the Marine Energy Park site in the Humber, in terms of water depth, the varying tidal states that may be encountered have been taken into account. Modelling has been carried out for water depth at Mean High Water Springs (MHWS) and Mean Low Water Springs (MLWS) to ascertain the effect of these tidal states on sound propagation in the estuary. The tidal depth at MHWS has been taken to be 7.3 m above the Lowest Astronomical Tide (LAT, CD) and at MLWS taken to be 0.9 m above LAT (CD).

As there is the possibility of having up to two piling rigs operating at the same time, two piling locations approximately 100 metres apart have been modelled.

4.2 Impact contours of underwater piling noise: Unweighted and dB_{ht} modelling

The impact of the piling on salmon with respect to dB_{ht}(*Salmo salar*) has been undertaken. Pile diameters modelled include 1.8 m and 2.1 m are shown below. Figure 4-1 shows the range of effect based on the use of a 1.8 m pile diameter and 300 kJ blow energy, which are deemed to be the "most likely" engineering parameters to be used.

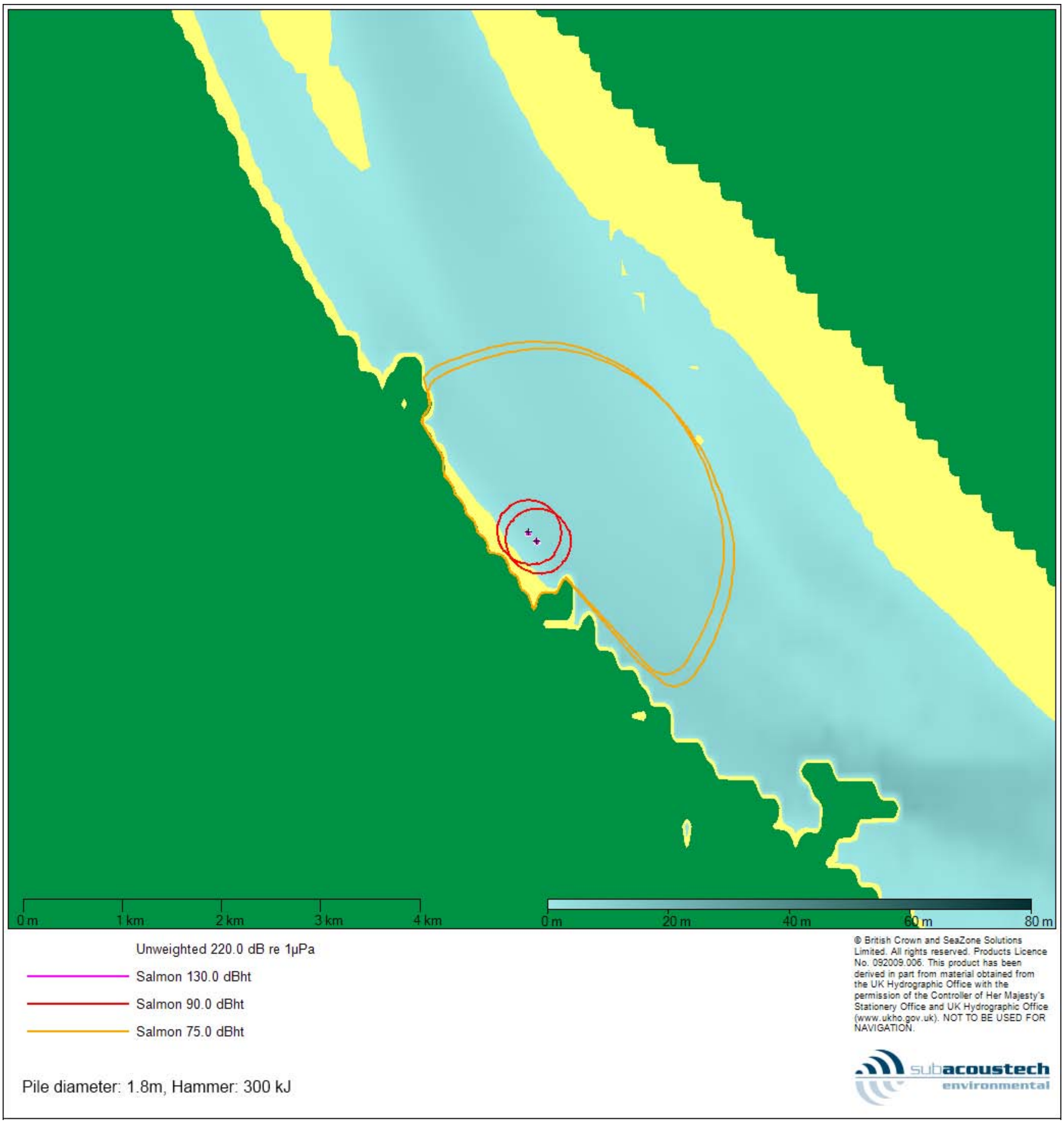

Figure 4-1 Contour plot showing modelled unweighted and dB_{ht}(Salmo salar) levels due to piling noise – "most likely" engineering parameters

The ranges for these contours are given in Table 4-1 below.

	240 dB re. 1 μPa	220 dB re. 1 μPa	130 dB_{ht}	90 dB_{ht}	75 dB_{ht}
Range	< 10 m	30 m	20 m	330 m	2.1 km

Table 4-1 Approximate maximum ranges for underwater noise transmitted from piles. (Pile diameter: 1.8 m, Hammer: 300 kJ)

Figure 4-2 gives the range of effects for a 2.1 m hammer and 400 kJ blow energy. These are deemed to be the “alternative” engineering parameters that may be used for the piling.

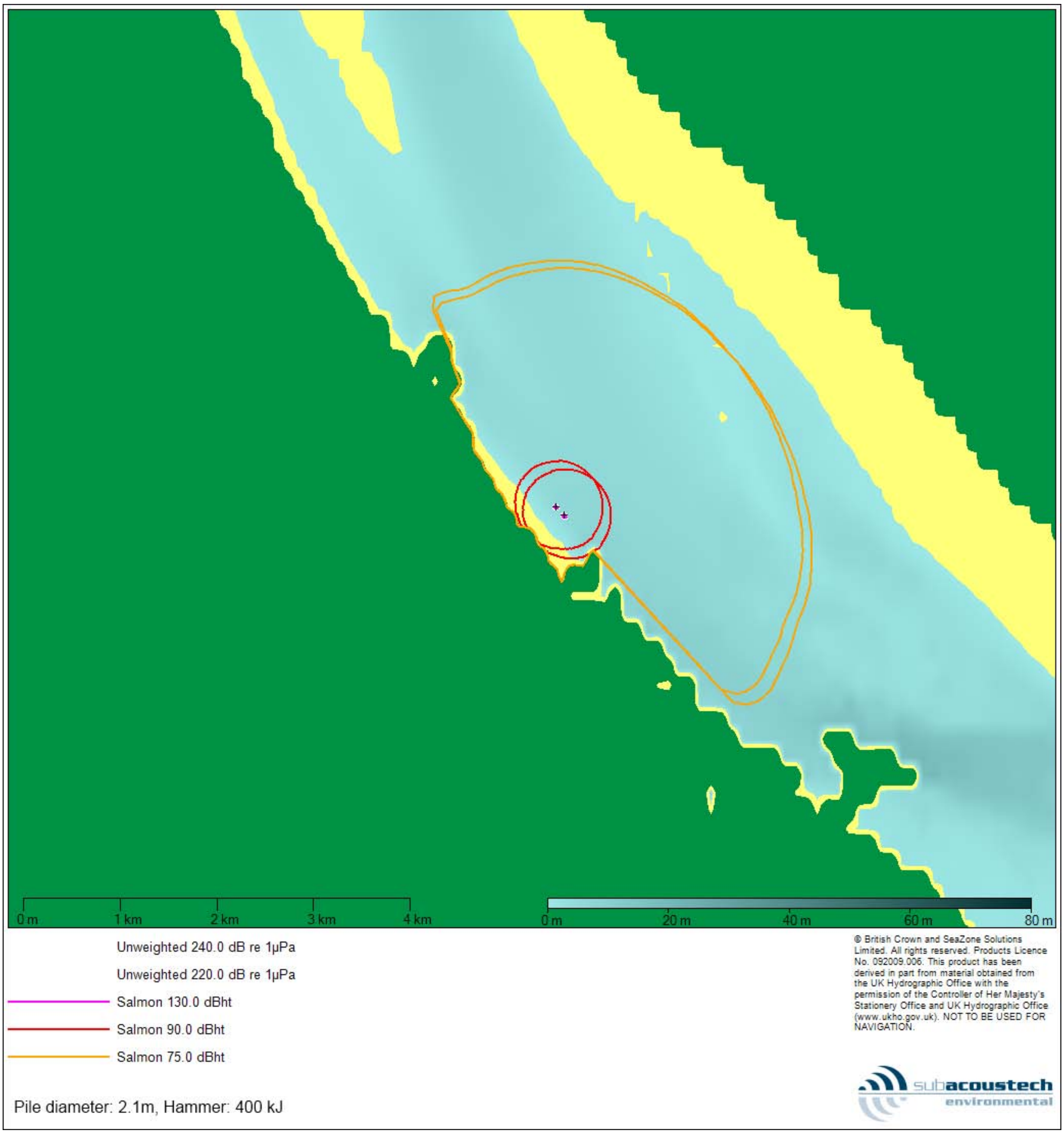

Figure 4-2 Contour plot showing modelled unweighted and dB$_{ht}$(Salmo salar) levels due to piling noise – “alternative” engineering parameters

The ranges for these contours are given in Table 4-2 below.

	240 dB re. 1 µPa	220 dB re. 1 µPa	130 dB$_{ht}$	90 dB$_{ht}$	75 dB$_{ht}$
Range	20 m	30 m	20 m	490 m	2.8 km

Table 4-2 Approximate maximum ranges for underwater noise transmitted from piles (Pile diameter: 2.1 m, Hammer: 400 kJ)

Figure 4-3 shows the effect of using a different size of pile diameter on the resultant noise level whilst using the same blow energy.

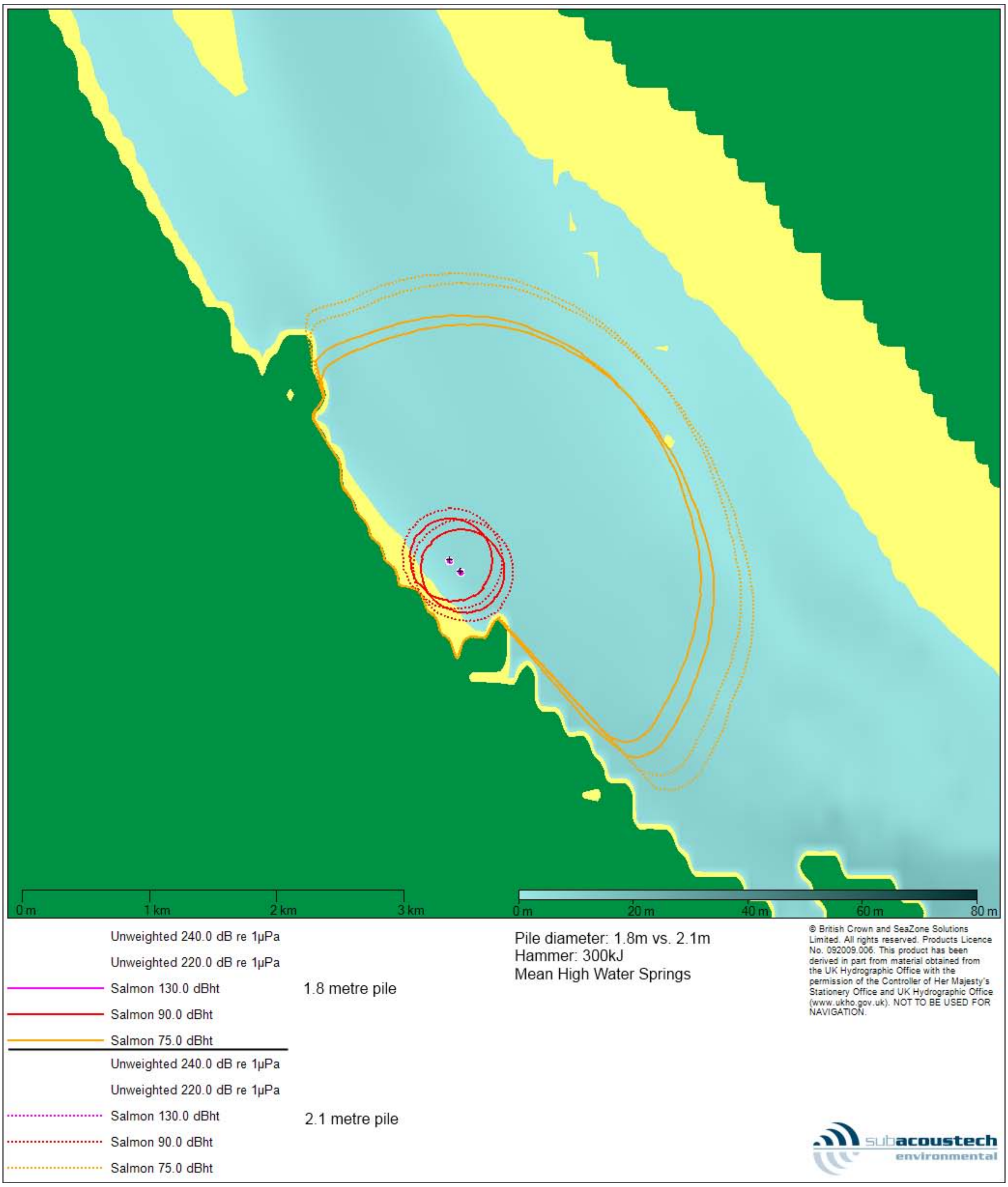

Figure 4-3 Contour plot showing modelled unweighted and dB_{ht}(Salmo salar) levels due to piling noise comparing the effect of pile diameter

The ranges for these contours are given in Table 4-3 below.

	240 dB re. 1 μPa	220 dB re. 1 μPa	130 dB_{ht}	90 dB_{ht}	75 dB_{ht}
Range (ø = 1.8 m)	< 10 m	~30 m	~20 m	330 m	2.1 km
Range (ø = 2.1 m)	< 10 m	~30 m	~20 m	420 m	2.5 km

Table 4-3 Approximate maximum ranges for underwater noise transmitted from two different pile diameters (Pile diameter: 1.8 m and 2.1 m, Hammer: 300 kJ)

Figure 4-4 shows a plot comparing the effect of noise due to piling in high water and low water.

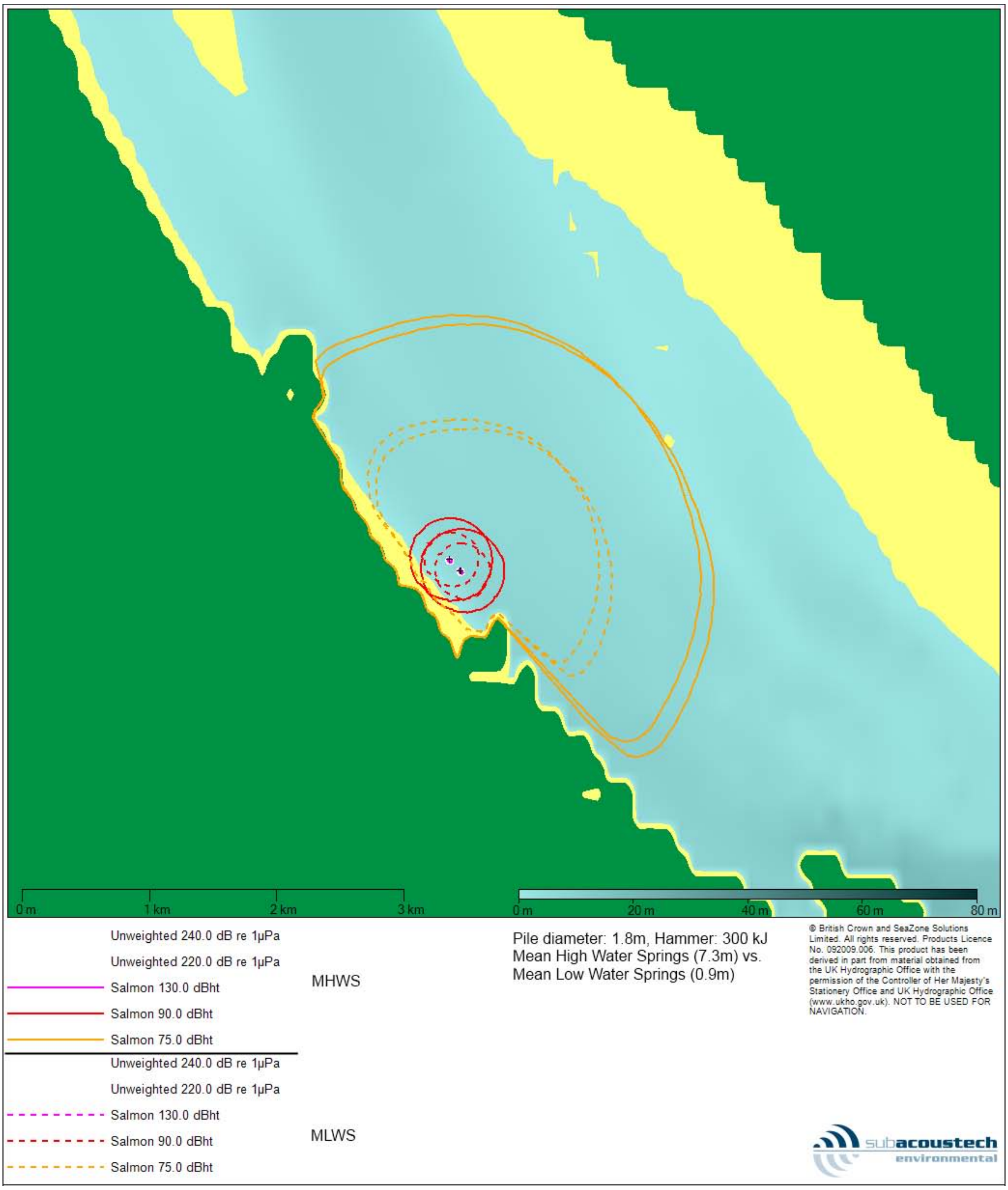

Figure 4-4 Contour plot showing modelled unweighted and dB$_{ht}$(Salmo salar) levels due to piling noise comparing the effect of high and low water

The ranges for these contours are given in Table 4-4 below.

	240 dB re. 1 µPa	220 dB re. 1 µPa	130 dB_{ht}	90 dB_{ht}	75 dB_{ht}
Range (Low Water)	< 10 m	30 m	20 m	230 m	1.2 km
Range (High Water)	< 10 m	30 m	20 m	330 m	2.1 km

Table 4-4 Approximate maximum ranges for underwater noise transmitted from piles piled in low water and high water (Pile diameter: 1.8 m, Hammer: 300 kJ)

Figure 4-5 shows a plot comparing the effect of implementing a soft start (reduced blow energy) with using the maximum blow energy of the hammer.

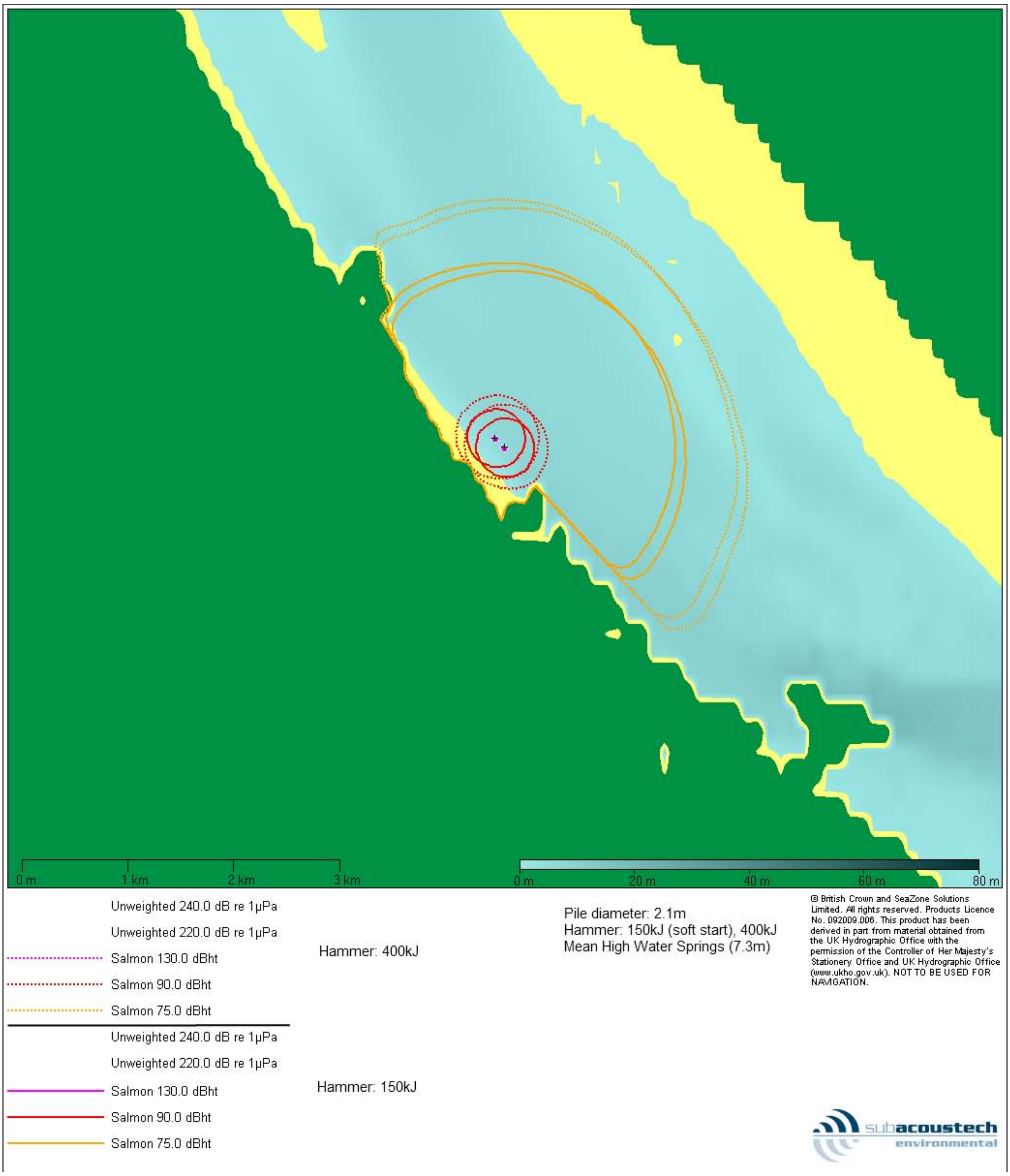

Figure 4-5 Contour plot showing modelled unweighted and dB$_{ht}$(Salmo salar) levels due to piling noise, comparing the effect of blow energy used

The ranges for these contours are given in Table 4-5 below.

	240 dB re. 1 µPa	220 dB re. 1 µPa	130 dB$_{ht}$	90 dB$_{ht}$	75 dB$_{ht}$
Range (150 kJ)	< 10 m	~20 m	~20 m	290 m	1.8 km
Range (400 kJ)	~20 m	~30 m	~20 m	490 m	2.8 km

Table 4-5 Approximate maximum ranges for underwater noise transmitted from piles with same diameter using different blow energies (Pile diameter: 2.1 m, Hammer: 150 kJ and 400 kJ)

4.3 Discussion

The results of modelling piling noise on the impact ranges of dB_{ht}(*Salmo salar*) differ with a number of variables. Firstly, the diameter of a pile and the blow energy used both have an effect on the range to which noise propagates. The most likely pile size to be used is 1.8 m, piled using a maximum blow energy of 300 kJ, which produces impact ranges estimated to be 30 m or less for unweighted sound levels of 240 (lethality) and 220 (physical injury) dB re. 1 µPa. The estimated maximum ranges of impact on salmon are 30m for 130 dB_{ht}, 330 m for 90 dB_{ht} and 2.1 km for 75 dB_{ht}. It should be noted that these ranges have been calculated at high tide when the sound transmissibility is at a maximum and therefore this would be when the impact ranges are at a maximum. It can be seen from Figure 4-1 that the north bank of the Humber will always be outside of the 75 dB_{ht} contour.

The effect of using a pile diameter of 2.1 m with 400 kJ blow energy increases the ranges of impact, as expected. This alternative option would have a greater impact. The dB_{ht}(*Salmo salar*) approximate maximum ranges for this option are 20 m for 130 dB_{ht}, 490 m for 90 dB_{ht} and 2.8 km for 75 dB_{ht}. This shows a 0.7 km increase in 75 dB_{ht} range.

The effects of using different pile diameters but with the same blow energy is shown in Figure 4-3. It is observed that a larger size diameter pile does have an increased effect on the range of noise propagation. For 75 dB_{ht}(*Salmo salar*) the range of impact using a 1.8 m diameter pile is 2.1 km compared with the impact of a 2.1 m diameter pile of 2.5 km.

It has already been noted that the maximum sound transmissibility occurs at high tide. Figure 4-4 shows a plot of the comparative impact contours for Mean High and Mean Low Water Springs. It can be seen that there is a significant difference in the contour areas. For 75 dB_{ht}(*Salmo salar*) the range of impact at high tide is approximately 2.1 km whereas at low tide it is 1.2 km, almost a kilometre difference.

One form of mitigation is to use a soft start, beginning piling with a reduced initial blow energy to minimise initial effects and give any potentially affected species in the area time to flee before the higher energies are used. Figure 4-5 shows a plot of impact contours for a soft start using a blow energy of 150 kJ, as well as impact contours using the maximum blow energy, 400 kJ, for a pile size of 2.1 m. The difference in the 75 dB_{ht}(*Salmo salar*) ranges is 1 km. This shows that using a soft start will have a lower impact on the salmon initially.

5 Summary and Conclusions

Subacoustech Environmental has undertaken a study on behalf of Able UK to assess the impact of underwater piling within the Humber located in the North East of England. This is connected with the proposed construction of the Able Marine Energy Park within the Humber.

The level of underwater noise from the installation of 1.8 m and 2.1 m diameter piles have been estimated by using a proprietary underwater sound propagation model that enables the behaviour of noise with range from the piling to be estimated for varying tidal conditions, water depths and piling locations based on an existing database of measurements of piling noise.

Estimates of underwater noise in terms of unweighted peak-to-peak sound levels 240 and 220 dB re. 1 µPa as well as 130, 90 and 75 dB_{ht}(*Salmo salar*) in order to obtain estimates of approximate maximum ranges.

1. The ranges to which the unweighted levels of 240 and 220 dB re. 1 µPa, for all parameters modelled were found to be equal to or less than 20 m and 30 m respectively.
2. For the most likely scenario to be used, 1.8 m diameter piles using a blow energy of 300 kJ, the behavioural response and auditory injury with respect to dB_{ht}(*Salmo salar*) have been calculated at high tide. Auditory injury (130 dB_{ht}) to salmon is calculated to occur out to approximately 20 m from the noise source, a strong avoidance reaction (90 dB_{ht}) is calculated to occur out to 330 m and a significant avoidance behaviour reaction (75 dB_{ht}) is calculated to occur out to 2.1 km.
3. For the alternative scenario to be considered, 2.1 m diameter pile using a blow energy of 400 kJ, the behavioural response and auditory injury with respect to dB_{ht}(*Salmo salar*) have been calculated at high tide. Auditory injury (130 dB_{ht}) to salmon is calculated to occur out to approximately 20 m from the noise source, a strong avoidance reaction (90 dB_{ht}) is calculated to occur out to 490 m and significant avoidance behaviour (75 dB_{ht}) is calculated to occur out to 2.8 km.
4. The effect of using a different pile size whilst using the same blow energy has been shown to have an impact on the range to which the noise is transmitted, with an increase of approximately 400 m in the 75 dB_{ht} range at the 2.1 m pile diameter.
5. The difference of high and low tide has shown to be significant, producing a difference in range of 900 m for 75 dB_{ht}.
6. With respect to a soft start, the initial impact ranges would be reduced, for example for the difference in 75 dB_{ht} ranges is 1 km between 150 kJ and 400 kJ.

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