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Vattenfall Wind Power Ltd

Thanet Extension Offshore Wind Farm

Annex 6-3: Underwater Noise Assessment

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Thanet Extension: Underwater noise assessment

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1 Introduction

This report has been prepared by Subacoustech Environmental Ltd for GoBe Consultants Ltd (GoBe) and presents the underwater noise modelling results for impact piling operations at the proposed Thanet Extension Offshore Wind Farm (Thanet Extension) development.

1.1 Thanet Extension Offshore Wind Farm

Thanet Extension is a proposed offshore wind farm development located approximately 8 km east of the Isle of Thanet off the Kent coastline; the proposed site encircles the existing Thanet Offshore Wind Farm (TOWF). Once complete, the proposed project will cover an area of approximately 70 km^2 and will contain up to 34 wind turbine generators (WTGs) creating a total combined capacity of up to 340 MW. Water depths within the site range from 13 to 43 m.

Figure 1-1 shows the location of Thanet Extension.

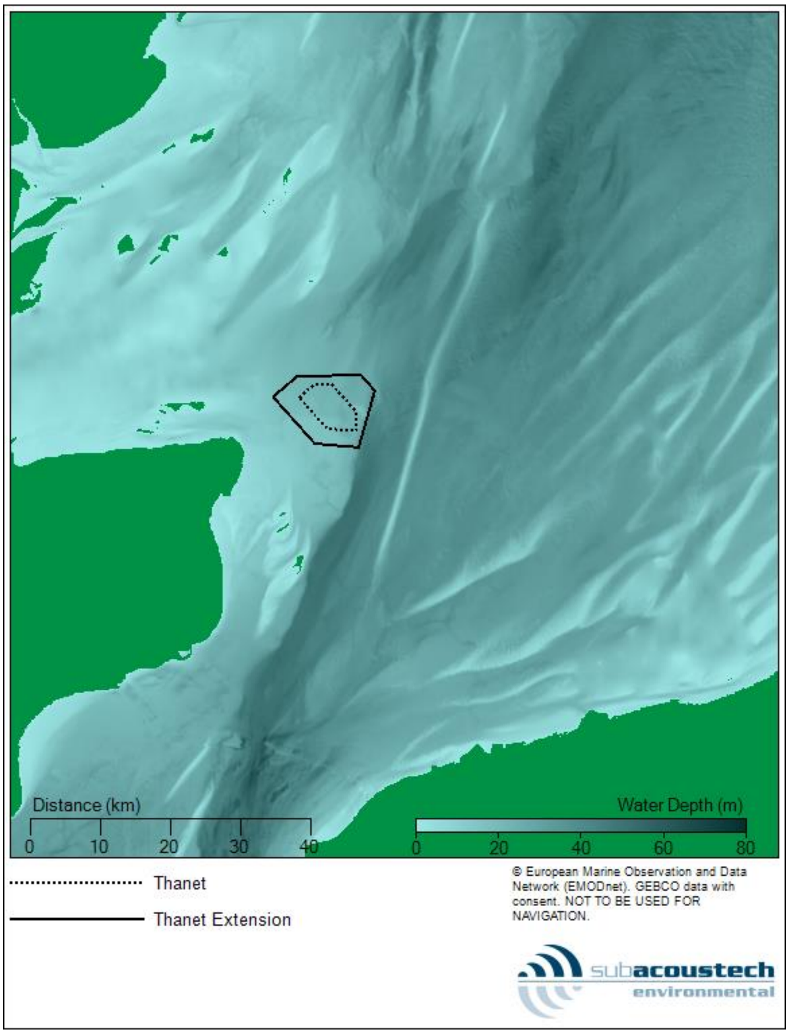

Figure 1-1 Map showing the boundaries of the Thanet Extension site and the existing TOWF

1.2 Noise assessment

This report details the expected noise levels from impact piling operations to construct Thanet Extension. The pile driving activities are the assessment focus as this has the potential to create high levels of noise over long periods of time.

The main modelling has been carried out using the semi-empirical INSPIRE model considering bathymetry, pile dimensions, hammer blow energy, animal flee speed and frequency content.

1.2.1 Impact piling

As part of a series of construction options, impact piling may be used to drive the WTG foundations into the seabed. The impact piling technique involves a large weight or "ram" being dropped or driven onto the top of a foundation pile, forcing it into the seabed. Usually, double-acting hammers are used in which a downward force on the ram is applied, 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 source of high level underwater impulsive noise (Würsig *et al*., 2000; Caltrans, 2001; Nedwell *et al*., 2003b and 2007; Parvin *et al*., 2006; and Thomsen *et al*., 2006).

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 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. Structural pressure waves in the submerged section of the pile transmit sound efficiently into the surrounding water. These waterborne pressure 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 wave. Since the speed of sound is generally greater in consolidated sediments than in water, these waves usually arrive at a distant receptor first as a precursor to the waterborne wave. Generally, the level of the seismic wave is typically 10 - 20 decibel (dB) below the waterborne arrival, and hence it is the latter that dominates the noise.

1.3 Scope of work

This report presents a detailed assessment of the potential underwater noise and its effects at Thanet Extension and covers the following:

- A review of background information on the units for measuring and assessing underwater noise and a review of the underwater noise metrics and criteria used to assess possible environmental effects in marine receptors (Section 2 of this Annex);
- A review of available data for baseline underwater noise levels (Section 3 of this Annex);
- Discussion of the approach, input parameters and assumptions for the noise modelling undertaken (Section 4.1 of this Annex);
- Presentation of detailed subsea noise modelling using unweighted metrics (Section 4.4 of this Annex) and interpretation of the subsea noise modelling results with regards to injury and behavioural effects in marine mammals and fish using various noise metrics and criteria (Section 4.5 of this Annex); and
- Summary and conclusions (Section 5 of this Annex).

The full noise modelling results are provided in Appendix A and TTS impact ranges are provided in Appendix B of this Annex.

2 Measurement of noise

2.1 Underwater noise

Sound travels much faster in water (approximately 1,500 ms^{-1}) than in air (340 ms^{-1}). 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 2007). It should be noted that stated underwater noise levels should not be confused with the noise levels in air, which use a different scale.

2.1.1 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” (SPL). The fundamental definition of the dB scale is given by:

$$Level = 10 \times \log_{10}\left(\frac{Q}{Q_{ref}}\right)$$

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, 6 dB 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 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, when the acoustic power level of a source rose by 10 dB the SPL would rise by 20 dB. So that variations in the units agree, the sound pressure must be specified in units of root mean square (RMS) pressure squared. This is equivalent to expressing the sound as:

$$SPL = 20 \times \log_{10}\left(\frac{P_{RMS}}{P_{ref}}\right)$$

For underwater sound, typically a unit of one micropascal (1 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.

Where not defined, all noise levels in this report are referenced to 1 µPa.

2.1.2 Sound Pressure Level

The SPL 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 RMS level of the time varying sound. The SPL can therefore be considered to be a measure of the average level of sound over the specific time period.

Where an SPL is used to characterise transient pressure waves such as that from seismic airguns, underwater blasting or impact piling, it is critical that the time period over which the RMS level is calculated is quoted. For instance, in the case of 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. Often, transient sounds such as these are quantified using “peak” SPLs.

2.1.3 Peak Sound Pressure Level (SPL_{peak})

Peak SPLs are often used to characterise sound transients from impulsive sources, such as percussive impact piling and seismic airgun sources. A peak SPL is calculated using the maximum variation of the pressure from positive to zero within the wave. This represents the maximum change in positive pressure (differential pressure from positive to zero) as the transient pressure wave propagates.

A further variation of this is the peak-to-peak SPL where the maximum variation of the pressure from positive to negative within the wave is considered. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak level will be twice the peak level, or 6 dB higher.

2.1.4 Sound Exposure Level (SEL)

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 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 (1953, 1954a, 1954b and 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 criteria for assessing the injury range from fish for various noise sources (Popper *et al.*, 2014).

The 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:

$$SE = \int_0^T p^2(t)dt$$

where p is the acoustic pressure in Pascals, T is the duration of the sound in seconds, and t is the 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 (${P^2}_{ref}$) and a reference time (T_{ref}). The SEL is then defined by:

$$SEL = 10 \times \log_{10}\left(\frac{\int_0^T p^2(t)dt}{{P^2}_{ref}T_{ref}}\right)$$

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

$$SEL = SPL + 10 \times \log_{10} T$$

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

This means that, for sounds of less than one second, the SEL will be lower than the SPL. For periods greater than one second, the SEL will be numerically greater than the SPL (i.e. for a continuous 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).

Weighted metrics for marine mammals have been proposed by the NMFS (2016) and Southall *et al.* (2007). These assign a frequency response to groups of marine mammals, and are discussed in detail in the following section.

2.2 Analysis of environmental effects

2.2.1 Background

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 impact in a species is dependent upon the incident sound level, sound frequency, duration of exposure and/or repetition rate of an impulsive sound (see for example Hastings and Popper, 2005). As a result, scientific interest in the hearing abilities of aquatic animal species has increased. Studies are primarily based on evidence from high level sources of underwater noise such as blasting or impact piling, as these sources are likely to have the greatest environmental impact and therefore the clearest observable effects, although there has been more interest in chronic noise exposure over the last five years.

The impacts of underwater sound on marine species can be broadly summarised as follows:

- Physical traumatic injury and fatality;
- Auditory injury (either permanent or temporary); and
- Disturbance.

The following sections discussed the agreed criteria for assessing these impacts in species of marine mammal and fish.

2.2.2 Criteria to be used

The main metrics and criteria that have been used in this study to assess environmental effect come from several key papers covering underwater noise and its effects:

- The marine mammal noise exposure criteria from Southall *et al.* (2007);
- Data from Lucke *et al.* (2009) regarding harbour porpoise response to underwater noise;
- The National Marine Fisheries Service guidance (NMFS, 2016) for marine mammals; and
- Sound exposure guidelines for fishes and sea turtles by Popper *et al.* (2014).

At the time of writing, these present the most up-to-date and authoritative criteria for assessing environmental effects for use in impact assessments.

2.2.2.1 Marine mammals

This assessment considers three sets of criteria to assess the effects of impact piling noise on marine mammals: Southall *et al.* (2007), Lucke *et al.* (2009) and NMFS (2016).

Southall *et al.* (2007) has been the source of the most widely used criteria to assess the effects of noise on marine mammals since it was published. The criteria from Southall *et al.* (2007) are based on M-Weighted SELs, which are generalised frequency weighting functions to filter underwater noise data to better represent the levels of underwater noise various marine species are likely to be able to hear. The authors group marine mammals into five groups, four of which are relevant to underwater noise (the fifth is for pinnipeds in air). For each group, an approximate frequency range of hearing is proposed based on known audiogram data, where available, or inferred from other information such as auditory morphology. The M-Weighting filters are summarised in Table 2-1.

Functional hearing group	Established auditory bandwidth	Genera represented	Example species
Low frequency (LF) cetaceans	7 Hz to 22 kHz	*Balaena, Caperea, Eschrichtius, Megaptera, Balaenoptera* (13 species/subspecies)	Grey whale, right whale, humpback whale, minke whale
Mid frequency (MF) cetaceans	150 Hz to 160 kHz	*Steno, Sousa, Sotalia, Tursiops, Stenella, Delphinus, Lagenodelphis, Lagenorhynchus, Lissodelphis, Grampus, Peponocephala, Feresa, Pseudorca, Orcinus, Globicephala, Orcaella, Physeter, Delphinapterus, Monodon, Ziphius, Berardius, Tasmacetus, Hyperoodon, Mesoplodon* (57 species/subspecies)	Bottlenose dolphin, striped dolphin, killer whale, sperm whale
High frequency (HF) cetaceans	200 Hz to 180 kHz	*Phocoena, Neophocaena, Phocoenoides, Platanista, Inia, Kogia, Lipotes, Pontoporia, Cephalorhynchus* (20 species/subspecies)	Harbour porpoise, river dolphins, Hector's dolphin
Pinnipeds (in water) (PW)	75 Hz to 75 kHz	*Arctocephalus, Callorhinus, Zalophus, Eumetopias, Neophoca, Phocarctos, Otaria, Erignathus, Phoca, Pusa, Halichoerus, Histriophoca, Pagophilus, Cystophora, Monachus, Mirounga, Leptonychotes, Ommatophoca, Lobodon, Hydrurga, Odobenus* (41 species/subspecies)	Fur seal, harbour (common) seal, grey seal

Table 2-1 Functional marine mammal groups, their assumed auditory bandwidth of hearing and genera presented in each group (from Southall et al., 2007)

The M-Weighted SEL criteria used in this study are summarised in Table 2-2, covering auditory injury, and TTS (temporary threshold shift, a short-term reduction in hearing acuity) for pinnipeds (in water). Where multiple pulse criteria (SEL_{cum}) are unavailable single strike criteria (SEL_{ss}) have been used in their place. Due to their sensitivity in the area, only TTS for the Pinnipeds (in water) hearing group has been considered. The HF cetacean group, the most significant of which in Thanet Extension being harbour porpoise, has not been included as the effect on harbour porpoise has been assessed using the Lucke *et al.* (2009) criteria.

Southall *et al.* (2007)	Auditory Injury (Unweighted SPL_{peak} dB re 1 µPa)	Auditory Injury (M-Weighted SEL_{cum} dB re 1 µPa^{2}s)	TTS (M-Weighted SEL_{ss} dB re 1 µPa^{2}s)
LF Cetaceans	230	198	-
MF Cetaceans	230	198	-
Pinnipeds (PW)	218	186	171

Table 2-2 Criteria for assessment of auditory injury and TTS in marine mammals (Southall et al., 2007)

Criteria from Lucke *et al.* (2009) have been used to further assess the effects of noise on harbour porpoise. The criteria from Lucke *et al.* (2009) are derived from testing harbour porpoise hearing thresholds before and after being exposed to seismic airgun stimuli (a pulsed noise like impact piling). All the criteria used unweighted single strike SELs. These are summarised in Table 2-3.

Lucke *et al.* (2009)	Auditory Injury (Unweighted SPL_{peak} dB re 1 µPa)	Auditory Injury (M-Weighted SEL_{ss} dB re 1 µPa^{2}s)	Behavioural (M-Weighted SEL_{ss} dB re 1 µPa^{2}s)
Harbour Porpoise	200	179	145

Table 2-3 Criteria for assessment of auditory injury, TTS and behavioural response in harbour porpoise (Lucke et al., 2009)

NMFS (2016) was co-authored by many of the same authors from the Southall *et al.* (2007) paper, and effectively updates its criteria for assessing the risk of auditory injury.

Similarly to Southall *et al.* (2007), the NMFS (2016) guidance groups marine mammals into functional hearing groups and applies filters to the unweighted noise to approximate the hearing sensitivity of the receptor. The weightings are different to the "M-weightings" used in Southall *et al*. The hearing groups given in the NMFS (2016) are summarised in Table 2-4 and Figure 2-1. A further group for Otariid Pinnipeds is also given in the guidance for sea lions and fur seals but this has not been used in this study as those species of pinnipeds are not commonly found in the North Sea.

Hearing group	Example species	Generalised hearing range
LF Cetaceans	Baleen Whales	7 Hz - 35 kHz
MF Cetaceans	Dolphins, Toothed Whales, Beaked Whales, Bottlenose Whales (including Bottlenose Dolphin)	150 Hz - 160 kHz
HF Cetaceans	True Porpoises (including Harbour Porpoise	275 Hz - 160 kHz
Pinnipeds (PW)	True Seals (including Harbour Seal)	50 Hz - 86 kHz

Table 2-4 Marine mammal hearing groups (from NMFS, 2016)

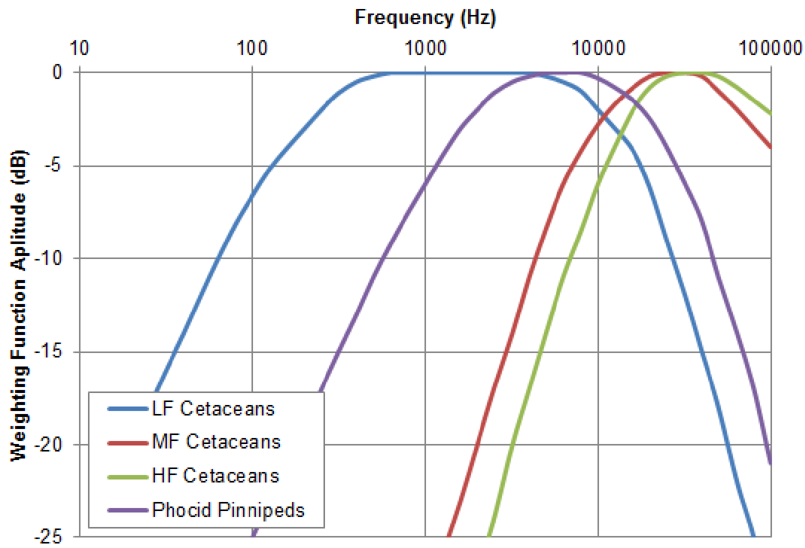

Figure 2-1 Auditory weighting functions for LF cetaceans, MF cetaceans, HF cetaceans, and PW (from NMFS, 2016)

NMFS (2016) presents single strike, unweighted peak criteria (SPL_{peak}) and cumulative (i.e. more than a single sound impulse), weighted sound exposure criteria (SEL_{cum}) for both permanent threshold shift (PTS) where unrecoverable hearing damage may occur and TTS where a temporary reduction in hearing sensitivity may occur in individual receptors.

Table 2-5 presents the NMFS (2016) criteria for onset of risk of PTS and TTS for each of the key marine mammal hearing groups.

NMFS (2016)	Auditory Injury (Unweighted SPL_{peak} dB re 1 µPa)	Auditory Injury (Weighted SEL_{cum} dB re 1 µPa²s)	Auditory Injury (Weighted SEL_{ss} dB re 1 µPa²s)
LF Cetaceans	219	183	183
MF Cetaceans	230	185	185
HF Cetaceans	202	155	155
Pinnipeds (PW)	218	185	185

Table 2-5 Criteria for assessment of auditory injury in marine mammals (NMFS, 2016)

Where SEL_{cum} are required, a fleeing animal model has been used. This assumes that the animal exposed to high noise levels will swim away from the noise source. For this a constant fleeing speed of 3.25 ms^{-1} has been assumed for the low frequency (LF) cetaceans group (Blix and Folkow, 1995), based on data for minke whale, and for other receptors a constant rate of 1.5 ms^{-1} has been assumed, which is a cruising speed for a harbour porpoise (Otani *et al.*, 2000). These are considered 'worst case' as marine mammals are expected to be able to swim much faster under stress conditions. The model assumes that a fleeing receptor stops if it reaches the coast before the noise exposure ends.

2.2.2.2 Fish

The large variation in fish species leads to a greater challenge in production of a generic noise criterion, or range of criteria, for the assessment of noise impacts. Whereas previous assessments applied broad criteria based on limited studies of fish not present in UK waters (e.g. McCauley *et al.*, 2000), the publication of Popper *et al.* (2014) provides an authoritative summary of the latest research and guidelines for the assessment of fish exposure to sound.

The Popper *et al.* (2014) study groups species of fish into whether they possess a swim bladder, and whether it is involved in its hearing. The guidance also gives specific criteria (as both SPL_{peak} and SEL_{cum} values) for a variety of noise sources. This assessment has used the criteria given for pile driving noise on fish. The modelled criteria are summarised in Table 2-6. Similarly to marine mammals for SEL_{cum} results, a fleeing animal model has been used assuming a receptor flees from the source at a constant rate of 1.5 ms^{-1} based on data from Hirata (1999).

Type of animal	Mortality and potential mortal injury	Impairment	
		Recoverable injury	TTS
Fish: no swim bladder	>219 dB SEL_{cum} or >213 dB SPL_{peak}	>216 dB SEL_{cum} or >213 dB SPL_{peak}	>>186 dB SEL_{cum}
Fish: swim bladder is not involved in hearing	210 dB SEL_{cum} or >207 dB SPL_{peak}	203 dB SEL_{cum} or >207 dB SPL_{peak}	>186 dB SEL_{cum}
Fish: swim bladder involved in hearing	207 dB SEL_{cum} or >207 dB SPL_{peak}	203 dB SEL_{cum} or >207 dB SPL_{peak}	186 dB SEL_{cum}

Table 2-6 Criteria for assessment of mortality and potential mortal injury, recoverable injury and TTS in species of fish (Popper et al., 2014)

3 Baseline ambient noise

The baseline noise level in the absence of any specific anthropogenic noise source is generally dependent on a mix of the movement of the water and sediment (especially in shallow water), weather conditions and distant shipping. There is a component of biological noise from marine mammal and fish vocalisation, with an element from invertebrates too.

Outside of the natural ambient noise, man-made noise dominates the background. The North Sea is heavily shipped by fishing, cargo and passenger vessels which contribute to the ambient noise in the water. The larger vessels are not only louder but the noise tends to have a lower frequency, which travels more readily especially in the deeper open water. Other vessels such as dredgers and small fishing boats, although present, have a lower overall contribution. There are no dredging areas or Active Dredge Zones and Dredging Application Option and Prospecting Areas within the TOWFor Thanet Extension boundary.

Other sources of anthropogenic noise include oil and gas platforms and other drilling activity, unexploded ordnance (UXO) and military exercises. Clearance of UXO contributes high but infrequent and localised noise. Little information is available on the scope and timing of military exercises but they are not expected to last for an extended period of time, and so would have little contribution to the long-term ambient noise in the area.

The Marine Strategy Framework Directive requires European Union members to ascertain baseline noise levels by 2020 and so processes are being put into place for this around Europe; although the monitoring this would lead to is likely to be somewhat limited, it is likely to add considerably to the availability of baseline noise levels in the future. However, good long-term underwater noise data for the region around Thanet Extension is not currently available.

Typical underwater noise levels show a frequency dependency in relation to different noise sources; the classic curves are given in Wenz (1962) and are reproduced in Figure 3-1 below. Sea-state refers to the roughness of the sea surface.

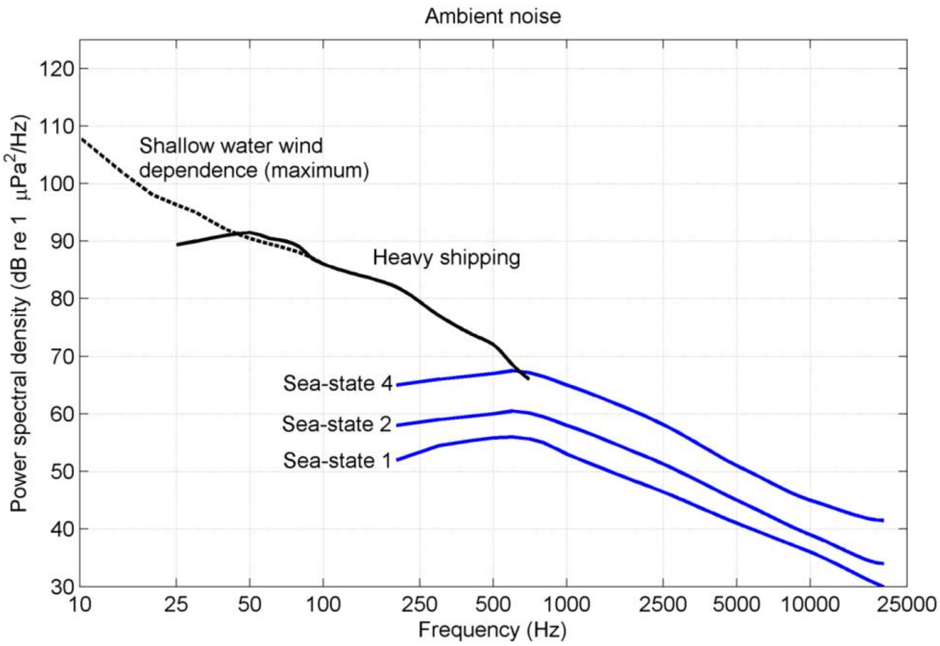

Figure 3-1 Ambient underwater noise as shown in Wenz (1962) showing frequency dependency from different noise sources

Figure 3-1 shows that any unweighted overall (i.e. single-figure non-frequency-dependent) noise level is typically dependent on the very low frequency element of the noise. The introduction of a nearby anthropogenic noise source (such as piling or sources involving engines) will tend to increase the noise levels in the 100 - 1000 Hz region, although often extends into higher and lower frequencies.

In 2009, during the construction of the TOWF, snapshot baseline underwater noise levels were sampled as part of the WTG installation noise survey (Nedwell *et al.,* 2009). Measurements were taken outside of the installation activity and in the absence of any nearby vessel noise over four separate days throughout installation. This survey sampled noise levels between 92 - 130 dB re 1 µPa (RMS) with average levels around 105 dB re 1 µPa (RMS) over the surveyed days, which were not considered to unusual for the area. The higher figure was due to higher sea state on that day. Unweighted overall noise levels of this type should be used with caution, without access to more detail regarding the duration, frequency content and conditions under which the sound was recorded.

In principle, when noise introduced by anthropogenic sources propagates far enough it will reduce to the level of ambient noise, at which point it can be considered negligible. In practice, as the underwater noise thresholds defined in Section 2.2.2 are all considerably above the level of background noise, any noise baseline would not feature in an assessment to these criteria.

4 Noise assessment

4.1 Modelling methodology

To estimate the noise levels likely to arise during construction of Thanet Extension, predictive underwater noise modelling has been undertaken. The methods described in this section and utilised within this report meet the requirements set by the National Physical Laboratory Good Practice Guide 133 for Underwater Noise (Robinson *et al.*, 2014).

4.2 Modelling Locations

Modelling has been undertaken at two representative locations covering the Thanet Extension site; the chosen locations are shown in Figure 4-1 and summarised in Table 4-1. The locations have been chosen to give a wide spatial coverage of the Thanet Extension site also covering deeper and shallower areas of the site.

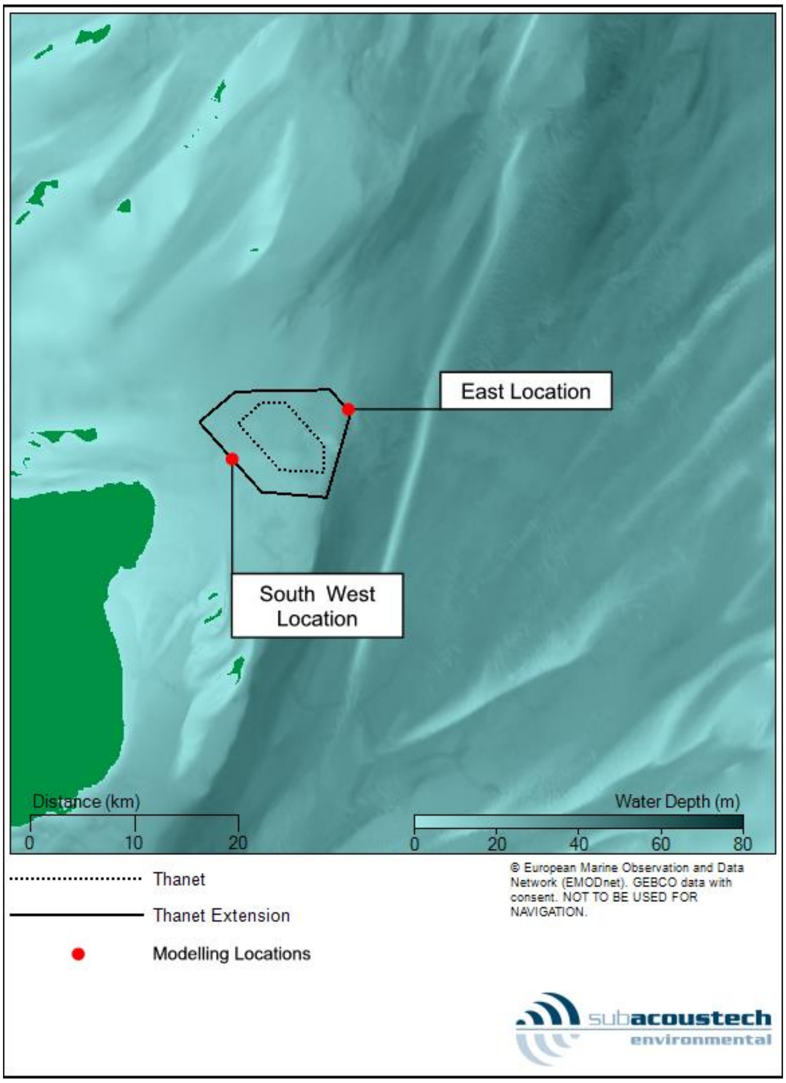

Figure 4-1 Map showing the modelled locations for the Thanet Extension site

	East	South West
Latitude	51.4534°N	51.4118°N
Longitude	001.7241°E	001.5617°E
Water depth (mean tide)	33 m	15 m

Table 4-1 Summary of the modelling locations and the water depths at each location

The modelling has been carried out using the INSPIRE noise model. The INSPIRE model (version 3.5) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling and actual measured data. INSPIRE is tuned using both measured SPL_{peak} and SEL noise data from both close range (within 50 m of the pile) to distances in excess of 40 km to provide confidence in the ranges predicted for both metrics. It is designed to calculate the propagation of noise in shallow, mixed, costal water, typical of the coastal conditions around the UK, and very well suited to the Thanet Extension area.

The model provides estimates of unweighted SPL_{peak}, SEL_{ss} and SEL_{cum} noise levels as well as various other noise metrics. Calculations are made along 180 equally spaced radial transects (one every 2°). For each modelling run a criterion level can be specified allowing a contour within which a given effect may occur. These results are then plotted over digital bathymetry data so that impact ranges can be clearly visualised and assessed as necessary.

4.3 Input parameters

4.3.1 Impact piling

Two piling source scenarios have been modelled for monopile and pin pile WTG foundation types across the Thanet Extension site. These are:

- Monopiles installed using a maximum blow energy of 5000 kJ; and
- Pin piles installed using a maximum blow energy of 2700 kJ.

For cumulative SELs, the soft start and ramp up of blow energies along with the total duration and strike rate of the piling have also been considered; these parameters are summarised in Table 4-2. The soft start and ramp up takes place over 60 minutes, gradually increasing in blow energy until reaching the maximum energy. The piling operation has been assumed to last eight hours for monopiles and 2.5 hours for each pin pile.

	Soft Start (10%)	Ramp Up	Full Energy
Monopile blow energy	500 kJ	Gradual increase	5000 kJ
Pin pile blow energy	270 kJ	Gradual increase	2700 kJ
Total strikes	8000 strikes (monopile) / 2680 strikes (pin pile)		
Duration	20 minutes	40 minutes	7 hours (monopile) 1.5 hours (pin pile)

Table 4-2 Summary of the ramp up scenarios used for calculating cumulative SELs

4.3.2 Source levels

Modelling requires knowledge of the source level, which is the theoretical noise level at 1 m from the noise source. Subacoustech has undertaken numerous measurements of impact piling offshore and have developed a sound level model based primarily on the blow energy used during a piling operation and the subsequent subsea noise levels produced.

The unweighted source levels estimated for this project are provided below in Table 4-3.

Source Level	**Monopile (5000 kJ)**	**Pin pile (2700 kJ)**
SPL_{peak}	247.5 dB re 1 µPa @ 1 m	244.7 dB re 1 µPa @ 1 m
SEL	231.2 dB re 1 µPa^{2}s @ 1 m	228.5 dB re 1 µPa^{2}s @ 1 m

Table 4-3 Summary of the unweighted source levels (SPL_{peak} and SEL) used for modelling in this study

The size of the pile being installed is used for estimating the frequency content of the noise. For this modelling, frequency data has been sourced from Subacoustech's noise measurement database and an average taken to obtain representative third octave (i.e. frequency, see Figure 4-2) levels for installing monopiles and pin piles. Representative third octave levels used for modelling are illustrated in Figure 4-2 as an example; the shape of each spectrum is the same for all the other locations and blow energies, with the overall source levels adjusted. This frequency information has been used for calculating source levels for weighted metrics later in the report.

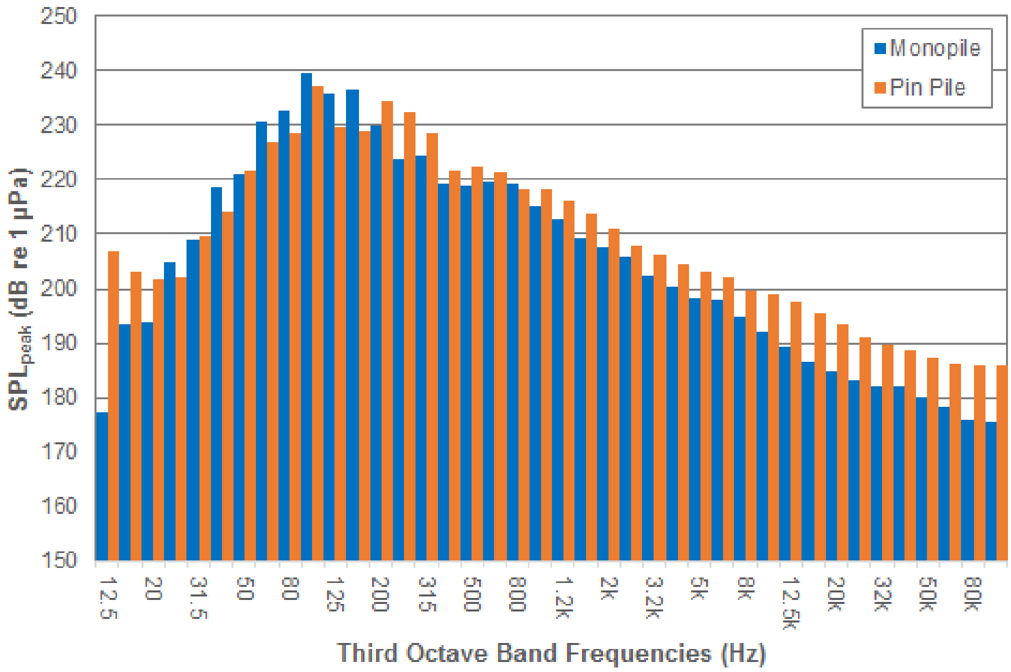

Figure 4-2 Third-octave input source level frequency spectra, maximum blow energy

Piles more than 7 m in diameter, the largest where measured data is available, have been used for the monopile modelling and piles of approximately 4 m in diameter have been used for pin pile modelling. It is worth noting that the monopiles contain more low frequency content and the pin piles contain more high frequency content, due to the dimensions and acoustics of the pile. This trend would be expected to continue to larger piles. As noted earlier in this section, this trend would have a negligible effect on the overall source level and could move the dominant frequency further below the frequencies of greatest hearing sensitivity of marine mammals, and thus would appear slightly quieter. Marine mammal hearing sensitivity is covered in Section 2.2

4.3.3 <u>Environmental conditions</u>

Accurate modelling of underwater noise propagation requires the best available knowledge of the sea and seabed conditions. The speed of sound in water at Thanet Extension has been calculated using temperature and salinity data for the area based on previous measurements undertaken by

Subacoustech; the speed of sound used in the model is 1488 ms^{-1}. A mean tide height has been used throughout this modelling based on bathymetry data from EMODnet.

Substrate and seabed type are not input parameters built into the INSPIRE model, however the data that has been used to build the model includes several full datasets of noise measurements collected in the vicinity of the Thanet Extension, including TOWF, London Array, Gunfleet Sands, Greater Gabbard and Kentish Flats. This greatly increases the confidence in modelling outputs for the Thanet Extension location.

4.4 Unweighted subsea noise modelling

This section presents the unweighted noise level results from the modelling undertaken for impact piling operations at Thanet Extension.

4.4.1 Unweighted levels

The following figures present unweighted SPL_{peak} noise levels from impact piling operations with 5 dB increment contours. Figure 4-3 and Figure 4-4 show the unweighted SPL_{peak} noise levels for monopiles (installed using a maximum blow energy of 5000 kJ) at the two modelling locations. These can be compared against Figure 4-5 and Figure 4-6 which show the same modelling locations but installing pin piles (installed using a maximum blow energy of 2700 kJ). The differences can be clearly seen when comparing the two sets of results, with monopiles producing larger impact ranges.

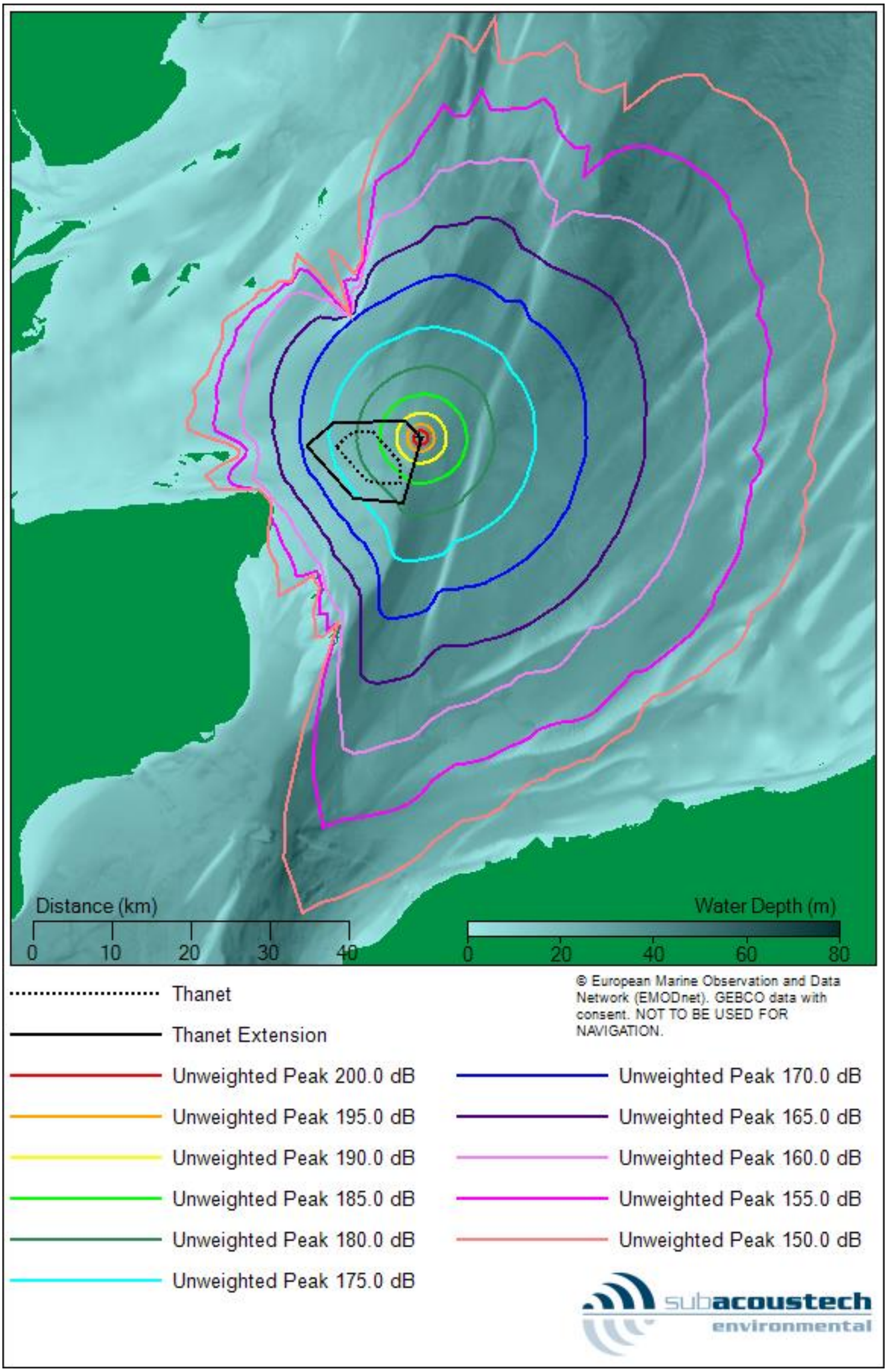

Figure 4-3 Contour plot showing the modelled unweighted SPL_{peak} values for installing a monopile using a maximum blow energy of 5000 kJ at the East modelling location

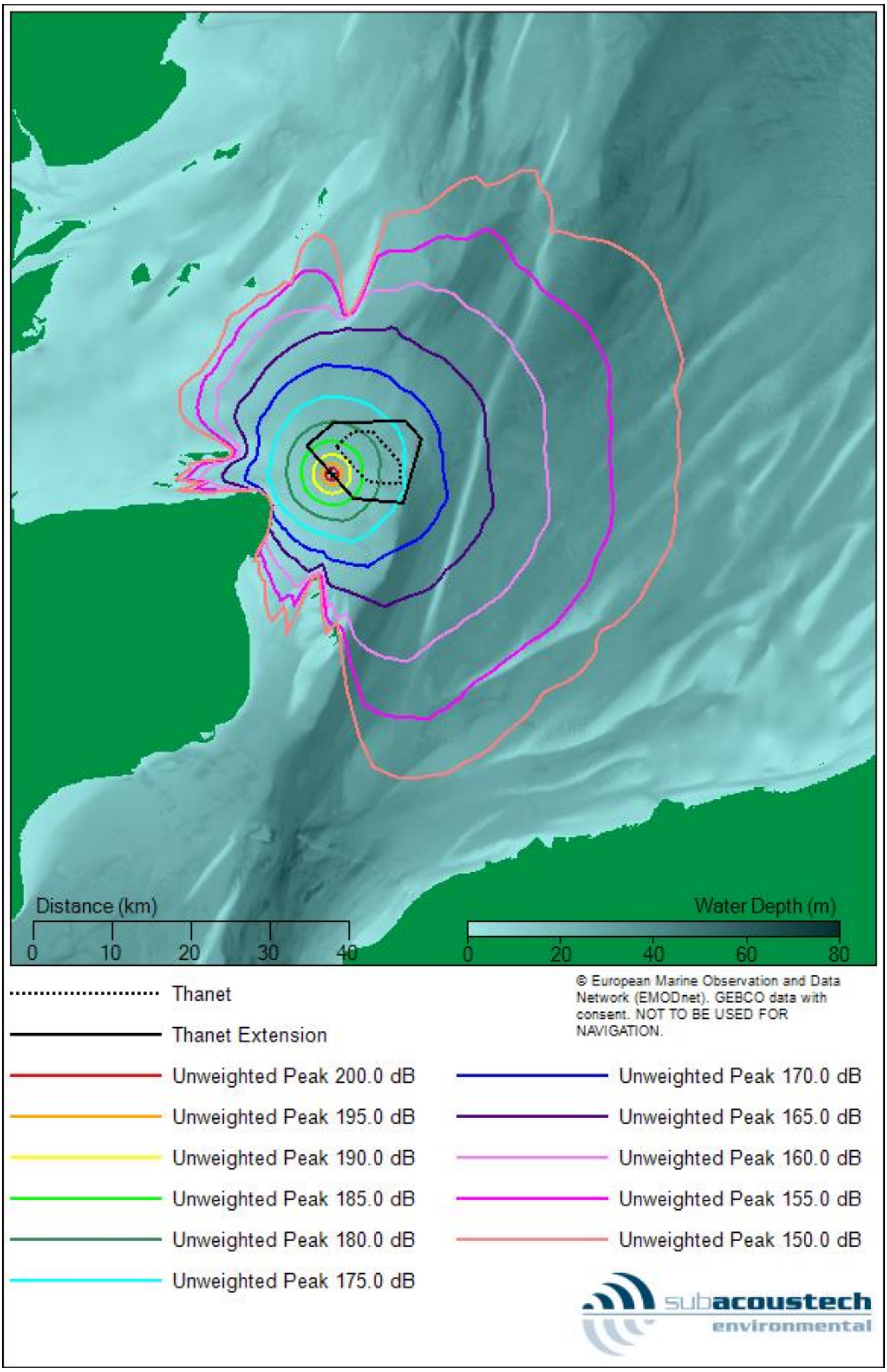

Figure 4-4 Contour plot showing the modelled unweighted SPL_{peak} values for installing a monopile using a maximum blow energy of 5000 kJ at the South West modelling location

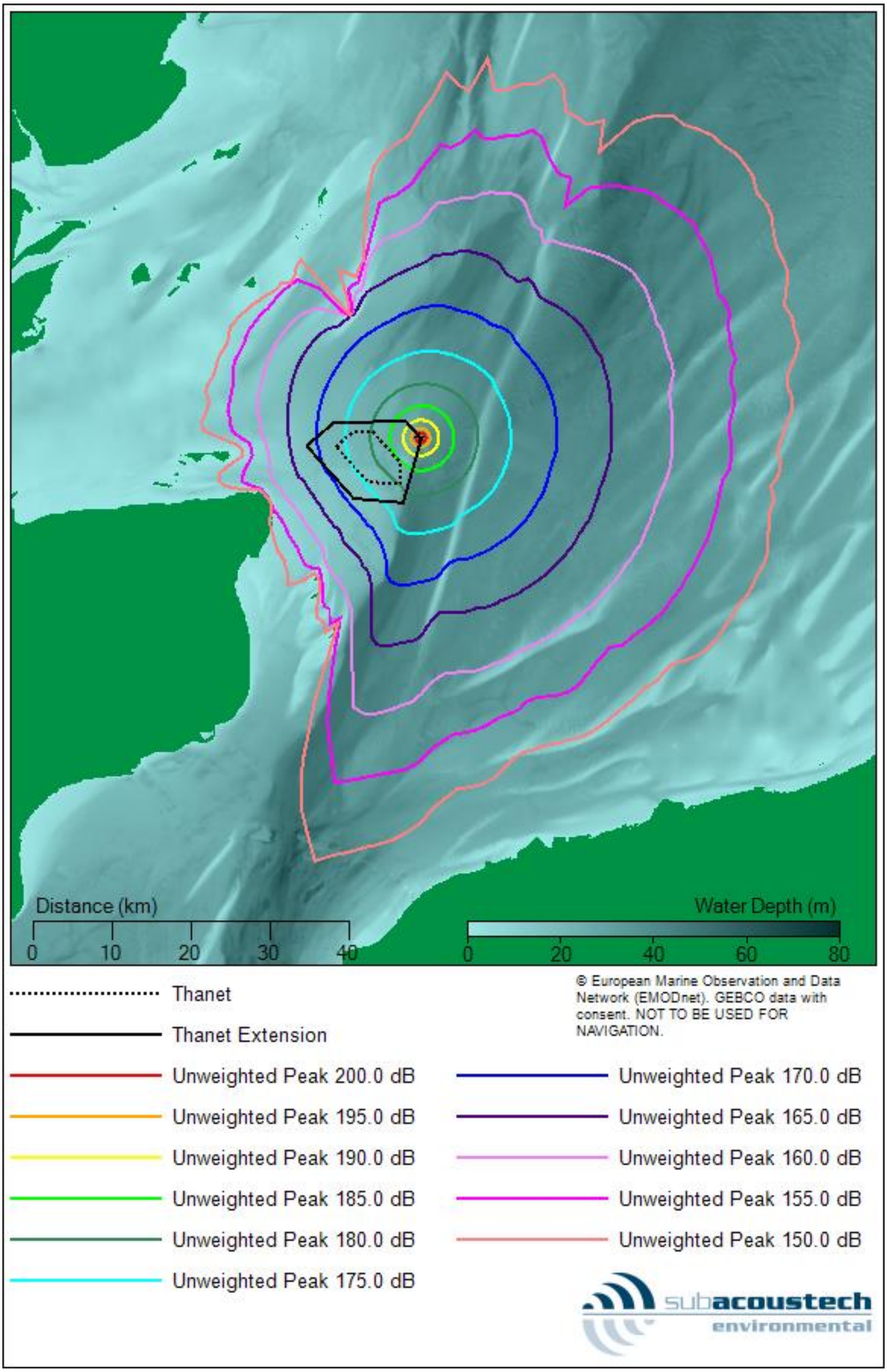

Figure 4-5 Contour plot showing the modelled unweighted SPL_{peak} values for installing a pin pile using a maximum blow energy of 2700 kJ at the East modelling location

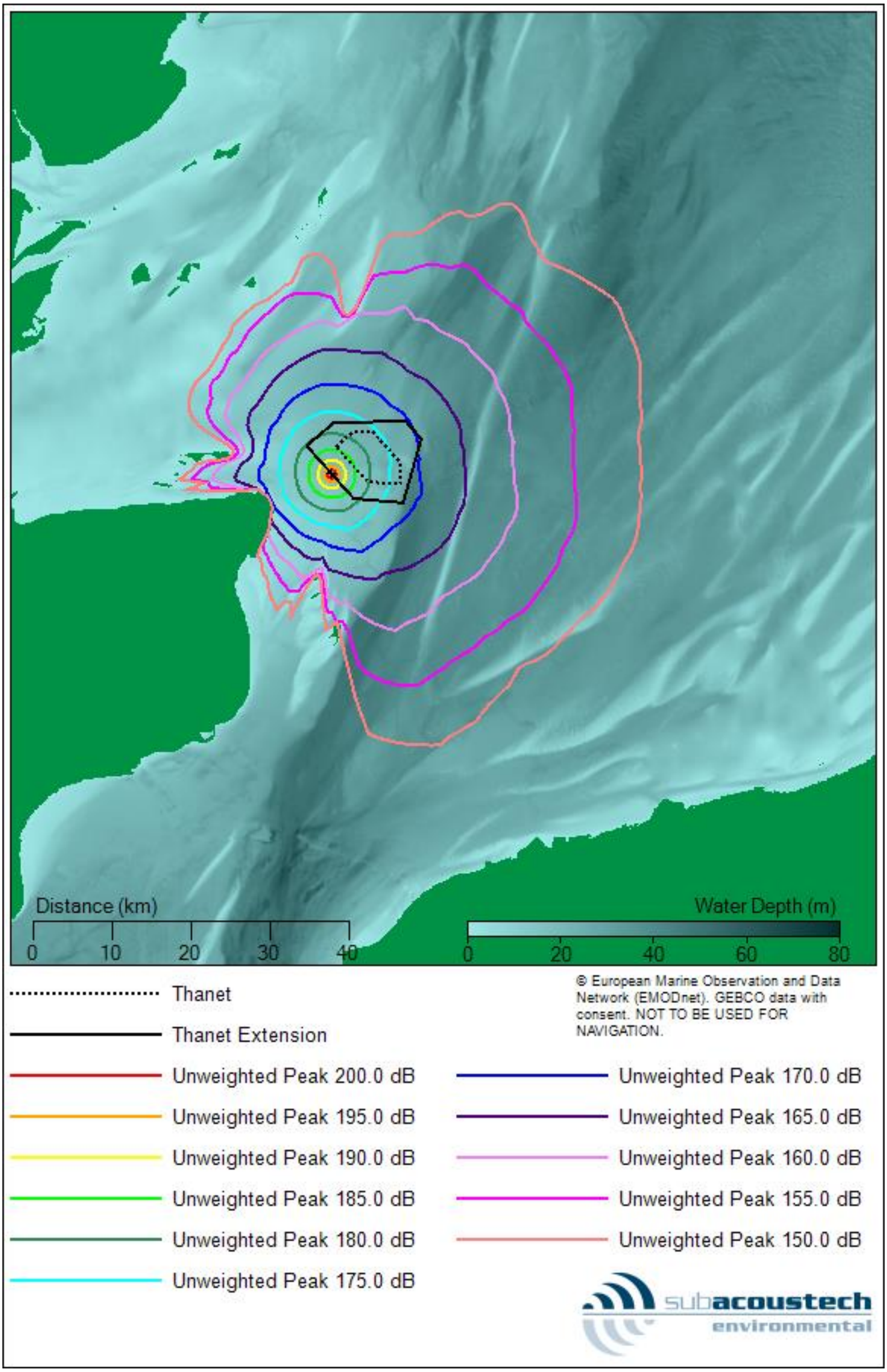

Figure 4-6 Contour plot showing the modelled unweighted SPL_{peak} values for installing a pin pile using a maximum blow energy of 2700 kJ at the South West modelling location

4.5 Interpretation of results

This Section presents the modelling results (Section 4.4) in terms of the noise metrics and criteria covered in Section 2.2. This discussion will guide the assessment of environmental impact to marine species from impact piling noise.

The full detailed modelling outputs are presented in Appendix A.

4.5.1 Impacts on marine mammals

The following sections present the modelling results in biologically significant terms for various species of marine mammal split up by the source of the guidance: Southall *et al.* (2007), Lucke *et al.* (2009) and NMFS (2016).

4.5.1.1 Southall et al. (2007) results

Table 4-4 and Table 4-5 present the predicted impact ranges for LF and MF cetacean, and pinniped hearing groups from Southall *et al.* (2007), as detailed in Section 2.2.2.1. The criteria are given as unweighted SPL_{peak} and M-Weighted SELs, as single (SEL_{ss}) and multiple pulse (SEL_{cum}). Multiple pulse includes the noise exposure to an animal receptor over the entire piling event. It should be noted that the SEL_{cum} ranges are calculated with a resolution of 10 m, hence some of the ranges being presented as < 10 m. HF cetaceans are given using the Lucke *et al.* (2009) criteria in Section 0.

In line with the unweighted results from Section 4.4, greatest ranges were predicted for monopile installed at the deeper East location.

Southall *et al.* (2007) – E location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
Unwtd SPL_{peak}	LF Cetaceans	230 dB	14 m	14 m	13 m	10 m	10 m	< 10 m
	MF Cetaceans	230 dB	14 m	14 m	13 m	10 m	10 m	< 10 m
	PW Pinnipeds	218 dB	70 m	70 m	69 m	48 m	48 m	47 m
M-Weighted SEL_{cum}	LF Cetaceans	198 dB	50 m	50 m	40 m	30 m	30 m	20 m
	MF Cetaceans	198 dB	30 m	30 m	20 m	20 m	20 m	10 m
	PW Pinnipeds	186 dB	5.4 km	3.9 km	2.7 km	3.7 km	2.9 km	2.1 km
M-Weighted SEL_{ss}	LF Cetaceans	198 dB	120 m	120 m	120 m	80 m	80 m	79 m
	MF Cetaceans	198 dB	46 m	46 m	45 m	38 m	38 m	37 m
	PW Pinnipeds	186 dB	390 m	390 m	390 m	320 m	320 m	320 m
	PW Pinnipeds	171 dB	2.9 km	2.8 km	2.7 km	2.4 km	2.4 km	2.3 km

Table 4-4 Summary of the impact ranges at the East location for injury criteria from Southall et al. (2007)

Southall *et al.* (2007) – SW location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
Unwtd SPL_{peak}	LF Cetaceans	230 dB	13 m	13 m	12 m	< 10 m	< 10 m	< 10 m
	MF Cetaceans	230 dB	13 m	13 m	12 m	< 10 m	< 10 m	< 10 m
	PW Pinnipeds	218 dB	65 m	65 m	64 m	44 m	44 m	43 m
M-Weighted SEL_{cum}	LF Cetaceans	198 dB	40 m	40 m	40 m	30 m	30 m	20 m
	MF Cetaceans	198 dB	10 m	10 m	10 m	< 10 m	< 10 m	< 10 m
	PW Pinnipeds	186 dB	1.9 km	1.5 km	1.1 km	1.3 km	1.0 km	800 m
M-Weighted SEL_{ss}	LF Cetaceans	198 dB	110 m	110 m	110 m	73 m	73 m	72 m
	MF Cetaceans	198 dB	43 m	43 m	42 m	35 m	35 m	34 m
	PW Pinnipeds	186 dB	340 m	340 m	340 m	280 m	280 m	280 m
	PW Pinnipeds	171 dB	2.3 km	2.2 km	2.1 km	1.9 km	1.9 km	1.8 km

Table 4-5 Summary of the impact ranges at the South West location for injury criteria from Southall et al. (2007)

There are situations where the range of impact calculated to a single strike SEL threshold can be greater than the equivalent cumulative SEL, which takes into account the entire piling sequence. This tends to occur in relatively low range situations. Cumulative SELs are calculated based on the entire piling sequence, beginning with the soft start, at which point a receptor starts to flee from the source and the hammer energies and associated noise levels slowly increase. This means that under some circumstances the receptor can be effectively out of range before the highest levels are present. In contrast, the single strike SEL modelled ranges assume the maximum hammer energy in 'one shot'; the receptor does not have the benefit of a period of time when it can swim away from the source while it is relatively quiet.

This situation also manifests in the results calculated to NMFS (2016) thresholds, e.g. as presented in Table 4-8.

4.5.1.2 Lucke et al. (2009) results

Table 4-6 and Table 4-7 present the predicted impact ranges in terms of the criteria from Lucke *et al.* (2009), covering auditory injury and behavioural reaction for harbour porpoise, in lieu of the HF cetacean criteria from Southall *et al.* (2007). The criteria from Lucke *et al.* (2009) are either unweighted SPL_{peak} or unweighted SEL_{ss}.

Lucke *et al.* (2009) – E location		Monopile (5000 kJ)			Pin Pile (2700 kJ)		
		Max	Mean	Min	Max	Mean	Min
Auditory injury (SPL_{peak})	200 dB	870 m	870 m	860 m	590 m	590 m	590 m
Auditory Injury (SEL_{ss})	179 dB	1.7 km	1.6 km	1.6 km	1.1 km	1.1 km	1.1 km
Behavioural (SEL_{ss})	145 dB	39 km	28 km	18 km	33 km	25 km	18 km

Table 4-6 Summary of the impact ranges at the East location for criteria from Lucke et al. (2009)

Lucke *et al.* (2009) – SW location		Monopile (5000 kJ)			Pin Pile (2700 kJ)		
		Max	Mean	Min	Max	Mean	Min
Auditory injury (SPL_{peak})	200 dB	790 m	730 m	720 m	510 m	510 m	500 m
Auditory Injury (SEL_{ss})	179 dB	1.3 km	1.3 km	1.3 km	950 m	940 m	920 m
Behavioural (SEL_{ss})	145 dB	26 km	19 km	8.5 km	22 km	17 km	8.5 km

Table 4-7 Summary of the impact ranges at the South West location for criteria from Lucke et al. (2009)

4.5.1.3 NMFS (2016) results

Predicted auditory injury impact ranges are given in Table 4-8 and Table 4-9 using the NMFS weighted SEL_{cum} criteria from NMFS (2016). SEL_{ss} ranges have also been included for completeness. TTS ranges have been included in Appendix B.

NMFS (2016) – E location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
Unwtd SPL_{peak}	LF Cetaceans	219 dB	61 m	61 m	60 m	41 m	41 m	40 m
	MF Cetaceans	230 dB	14 m	14 m	13 m	10 m	10 m	<10 m
	HF Cetaceans	202 dB	660 m	660 m	660 m	450 m	450 m	450 m
	PW Pinnipeds	218 dB	70 m	70 m	69 m	48 m	48 m	47 m
Weighted SEL_{cum}	LF Cetaceans	183 dB	1.7 km	1.3 km	900 m	990 m	760 m	570 m
	MF Cetaceans	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	HF Cetaceans	155 dB	60 m	60 m	50 m	1.2 km	960 m	710 m
	PW Pinnipeds	185 dB	40 m	30 m	30 m	30 m	30 m	20 m
Weighted SEL_{ss}	LF Cetaceans	183 dB	460 m	460 m	460 m	320 m	320 m	310 m
	MF Cetaceans	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	HF Cetaceans	155 dB	75 m	75 m	74 m	190 m	190 m	190 m
	PW Pinnipeds	185 dB	62 m	62 m	61 m	43 m	43 m	42 m

Table 4-8 Summary of the impact ranges at the East location for auditory injury (PTS) criteria from NMFS (2016)

NMFS (2016) – SW location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
Unwtd SPL_{peak}	LF Cetaceans	219 dB	57 m	57 m	56 m	39 m	39 m	38 m
	MF Cetaceans	230 dB	13 m	13 m	12 m	< 10 m	< 10 m	< 10 m
	HF Cetaceans	202 dB	570 m	560 m	560 m	390 m	390 m	390 m
	PW Pinnipeds	218 dB	65 m	65 m	64 m	44 m	44 m	43 m
Weighted SEL_{cum}	LF Cetaceans	183 dB	580 m	520 m	460 m	370 m	340 m	310 m
	MF Cetaceans	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	HF Cetaceans	155 dB	40 m	40 m	30 m	370 m	330 m	290 m
	PW Pinnipeds	185 dB	30 m	30 m	20 m	10 m	10 m	10 m
Weighted SEL_{ss}	LF Cetaceans	183 dB	400 m	400 m	400 m	280 m	280 m	280 m
	MF Cetaceans	185 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	HF Cetaceans	155 dB	69 m	69 m	68 m	170 m	170 m	170 m
	PW Pinnipeds	185 dB	58 m	58 m	57 m	40 m	40 m	39 m

Table 4-9 Summary of the impact ranges at the South West location for auditory injury (PTS) criteria from NMFS (2016)

The ranges of impact vary depending on the functional hearing (species) group and severity of impact. This variation is expressed clearly between the results using the NMFS (2016) criteria, shown above. Looking at results from the East monopile as an example, the mean SEL_{cum} ranges are collated in Table 4-10 below. The LF weighting leads to the greatest ranges as the MF and HF cetacean weightings filter out much of the piling energy, especially using the NMFS criteria (see below).

Auditory injury ranges (E location)		Weighted SEL_{cum} (Fleeing animal) (dB re 1 μPa²s)	
	Weighting	**Criterion**	**Mean range**
Monopile (5000kJ)	LF Cetaceans	183 dB	1.3 km
	MF Cetaceans	185 dB	< 10 m
	HF Cetaceans	155 dB	60 m
	Phocid Pinnipeds	185 dB	30 m

Table 4-10 Ranges for auditory injury for marine mammals at the East modelling location using the NMFS (2016) criteria

The SEL_{cum} and SEL_{ss} results for HF cetaceans using the NMFS (2016) criteria (Table 4-8 and Table 4-9) appear to give paradoxical results, as a larger hammer hitting a monopile results in lower impact ranges than a smaller hammer hitting a pin pile. This is explained by examining the difference in sensitivity between the marine mammal hearing groups and the sound frequencies produced by the different piles. This is also the case for MF cetaceans, however due to the low impact ranges this is not apparent in the tables.

The frequency spectra used as inputs to the model (Figure 4-2) show that the noise from pin piles contains more HF components than the noise from monopiles. The overall unweighted noise level is higher for the monopile due to the low frequency components of piling noise (i.e. most of the pile strike energy is in the lower frequencies). The HF and MF cetacean filters (Figure 2-1) both remove the LF components of the noise, as these receptors are much less sensitive to noise at these frequencies. This leaves the higher frequency noise, which, in the case of the pin piles, is higher than that for the monopiles.

To illustrate this, Figure 4-7 shows the sound frequency spectra for monopiles and pin piles, adjusted (weighted) to account for the sensitivities of HF and MF cetaceans. These can be compared to the original unweighted frequency spectra in Figure 4-2 (shown faintly in Figure 4-7). Overall, higher levels are present in the weighted pin pile spectrum.

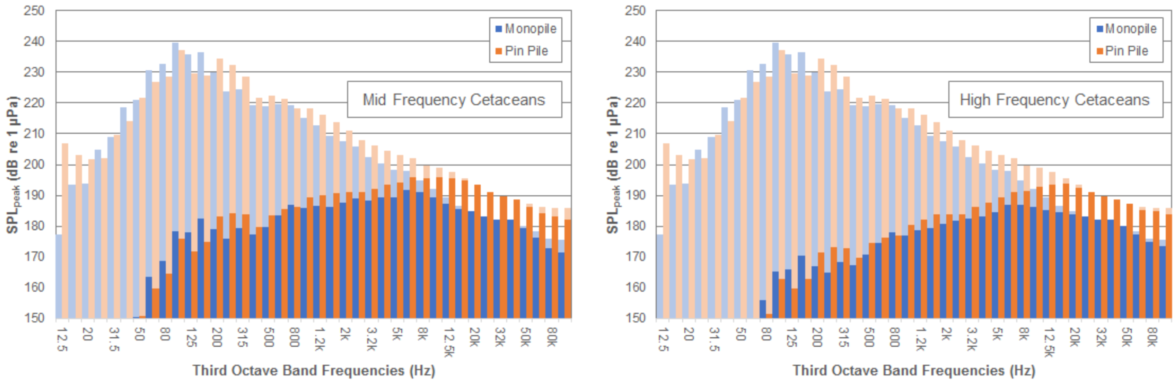

Figure 4-7 Filtered noise inputs for monopiles and pin piles using the MF and HF cetacean filters from NMFS (2016). The lighter coloured bars show the unweighted third octave levels

The effects of the weighting are presented above in terms of SPL_{peak} spectra, for illustration purposes. For modelling, the weighted thresholds as defined in Southall *et al* (2007) and NMFS (2016) are always in terms of the SEL metric.

4.5.2 Impacts on fish

Table 4-11 to Table 4-16 give the maximum, minimum, and mean impact ranges for species of fish based on the injury criteria found in the Popper *et al.* (2014) guidance. For the SEL_{cum} criteria a fleeing animal of 1.5 ms^{-1} has been used (Hirata, 1999). All the impact thresholds from the Popper *et al.* (2014) guidance are unweighted. It should be noted that some of the same noise levels are used as criteria for multiple effects, this is as per the Popper *et al.* (2014) guidelines (shown in Table 2-6), which is based on a comprehensive literature review. In fact, the data available to create the criteria is limited and most criteria are "greater than", with a precise threshold not identified. All ranges associated with criteria defined as ">",and even more so the criteria defined as ">>", are therefore somewhat conservative.

The results show that fish with swim bladders that are involved in hearing are the most sensitive to the impact piling noise with ranges of up to 40 m for recoverable injury and 9.9 km for TTS.

As previously, a receptor will reach higher injury thresholds (e.g. >213 dB) quickly, leading to smaller ranges than the much lower TTS thresholds.

Fish (no swim bladder) – E location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
SPL_{peak}	Mortality and potential mortal injury	>213 dB	140 m	140 m	140 m	96 m	96 m	95 m
	Recoverable injury	>213 dB	140 m	140 m	140 m	96 m	96 m	95 m
SEL_{cum}	Mortality and potential mortal injury	>219 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	Recoverable injury	>216 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	TTS	>>186 dB	9.9 km	7.1 km	4.7 km	5.9 km	4.5 km	3.2 km

Table 4-11 Summary of the impact ranges at the East location for fish with no swim bladder using the criteria from Popper et al. (2014)

Fish (no swim bladder) – SW location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
SPL$_{peak}$	Mortality and potential mortal injury	>213 dB	130 m	130 m	130 m	88 m	87 m	86 m
	Recoverable injury	>213 dB	130 m	130 m	130 m	88 m	87 m	86 m
SEL$_{cum}$	Mortality and potential mortal injury	>219 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	Recoverable injury	>216 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	TTS	>>186 dB	4.1 km	3.1 km	2.2 km	2.3 km	1.8 km	1.3 km

Table 4-12 Summary of the impact ranges at the South West location for fish with no swim bladder using the criteria from Popper et al. (2014)

Fish (swim bladder not involved in hearing) – E location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
SPL$_{peak}$	Mortality and potential mortal injury	>207 dB	330 m	330 m	330 m	220 m	220 m	220 m
	Recoverable injury	>207 dB	330 m	330 m	330 m	220 m	220 m	220 m
SEL$_{cum}$	Mortality and potential mortal injury	210 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	Recoverable injury	203 dB	40 m	40 m	30 m	10 m	10 m	10 m
	TTS	>186 dB	9.9 km	7.1 km	4.7 km	5.9 km	4.5 km	3.2 km

Table 4-13 Summary of the impact ranges at the East location for fish with swim bladder not involved in hearing using the criteria from Popper et al. (2014)

Fish (swim bladder not involved in hearing) – SW location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
SPL$_{peak}$	Mortality and potential mortal injury	>207 dB	290 m	290 m	290 m	200 m	200 m	200 m
	Recoverable injury	>207 dB	290 m	290 m	290 m	200 m	200 m	200 m
SEL$_{cum}$	Mortality and potential mortal injury	210 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	Recoverable injury	203 dB	30 m	30 m	20 m	< 10 m	< 10 m	< 10 m
	TTS	>186 dB	4.1 km	3.1 km	2.2 km	2.3 km	1.8 km	1.3 km

Table 4-14 Summary of the impact ranges at the South West location for fish with swim bladder not involved in hearing using the criteria from Popper et al. (2014)

Fish (swim bladder involved in hearing) – E location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	Mean	Min	Max	Mean	Min
SPL$_{peak}$	Mortality and potential mortal injury	>207 dB	330 m	330 m	330 m	220 m	220 m	220 m
	Recoverable injury	>207 dB	330 m	330 m	330 m	220 m	220 m	220 m
SEL$_{cum}$	Mortality and potential mortal injury	207 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	Recoverable injury	203 dB	40 m	40 m	30 m	10 m	10 m	10 m
	TTS	186 dB	9.9 km	7.1 km	4.7 km	5.9 km	4.5 km	3.2 km

Table 4-15 Summary of the impact ranges at the East location for fish with swim bladder involved in hearing using the criteria from Popper et al. (2014)

Fish (swim bladder involved in hearing) – SW location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
SPL_{peak}	Mortality and potential mortal injury	>207 dB	290 m	290 m	290 m	200 m	200 m	200 m
	Recoverable injury	>207 dB	290 m	290 m	290 m	200 m	200 m	200 m
SEL_{cum}	Mortality and potential mortal injury	207 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	Recoverable injury	203 dB	30 m	30 m	20 m	< 10 m	< 10 m	< 10 m
	TTS	186 dB	4.1 km	3.1 km	2.2 km	2.3 km	1.8 km	1.3 km

Table 4-16 Summary of the impact ranges at the South West location for fish with swim bladder involved in hearing using the criteria from Popper et al. (2014)

5 Summary and conclusions

Subacoustech Environmental have undertaken a study on behalf of GoBe to assess the effect of impact piling noise during construction of Thanet Extension.

The level of underwater noise from the installation of monopiles and pin piles during construction has been estimated by using the semi-empirical underwater noise model INSPIRE. The modelling considers a wide variety of input parameters including bathymetry, hammer blow energy, frequency content, strike rate and receptor fleeing speed.

Two representative locations were chosen at the Thanet Extension site to give spatial variation as well as changes in depth. At each location, monopiles installed with a maximum hammer blow energy of 5000 kJ and pin piles installed with a maximum hammer blow energy of 2700 kJ were modelled. The loudest levels of noise have been predicted overall at the deeper location when installing monopiles, compared with the shallower location and pin piles.

The modelling results were analysed in terms of relevant noise metrics and criteria to assess the impacts of the predicted impact piling noise on marine mammals (Southall *et al.*, 2007, Lucke *et al.*, 2009, and NMFS, 2016) and fish (Popper *et al.*, 2014), which will be used to aid biological assessments.

A summary of the maximum predicted impact ranges based on the various criteria and pile sizes are given in the table below.

	Species group	Criteria	Monopile (5000 kJ)	Pin Pile (2700 kJ)
Southall *et al.* (2007)	LF Cetacean Injury	198 dB M-Wtd SEL_{cum}	50 m	30 m
	MF Cetacean Injury	198 dB M-Wtd SEL_{cum}	30 m	20 m
	Pinnipeds (in water) Injury	186 dB M-Wtd SEL_{cum}	5.4 km	3.7 km
Lucke *et al.* (2009)	H. Porpoise Auditory Injury	179 dB SEL_{ss}	1.7 km	1.1 km
	H. Porpoise Behavioural	145 dB SEL_{ss}	39 km	33 km
NMFS (2016)	LF Cetacean Auditory Injury	219 dB SPL_{peak}	61 m	41 m
		183 dB Wtd SEL_{cum}	1.7 km	990 m
	MF Cetacean Auditory Injury	230 dB SPL_{peak}	14 m	10 m
		185 dB Wtd SEL_{cum}	< 10 m	< 10 m
	HF Cetacean Auditory Injury	202 dB SPL_{peak}	660 m	450 m
		155 dB Wtd SEL_{cum}	60 m	1.2 km
	Phocid Pinniped Auditory Injury	218 dB SPL_{peak}	70 m	48 m
		185 dB Wtd SEL_{cum}	40 m	30 m
Popper *et al.* (2014)	Fish (no swim bladder) Mortality	>213 dB SPL_{peak}	140 m	96 m
	Fish (no swim bladder) TTS	>>186 dB SEL_{cum}	9.9 km	5.9 km
	Fish (swim bladder not involved in hearing) Injury	>207 dB SPL_{peak}	330 m	220 m
	Fish (swim bladder not involved in hearing) TTS	>186 dB SEL_{cum}	9.9 km	5.9 km
	Fish (swim bladder involved in hearing) Injury	>207 dB SPL_{peak}	330 m	220 m
	Fish (swim bladder involved in hearing) TTS	186 dB SEL_{cum}	9.9 km	5.9 km

The outputs of this modelling have been used to inform further analysis of the impacts of underwater noise on marine mammals and fish in their respective reports.

6 References

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Appendix A Modelling figures

The following pages present the modelling outputs for Thanet Extension.

The following figures present the impact range contours for the marine mammal and fish results given in Sections 4.5.1 and 0. It should be noted that some contours (those measuring less than a few hundred metres) are not included as they are too small to be seen clearly with the scale of the figures.

- Figure A 1 Contour plot showing the impact ranges for pinnipeds (in water) (Southall et al., 2007) at the east location for installing a monopile with a maximum blow energy of 5000 kJ
- Figure A 2 Contour plot showing the impact ranges for pinnipeds (in water) (Southall et al., 2007) at the east location for installing a pin pile with a maximum blow energy of 2700 kJ
- Figure A 3 Contour plot showing the impact ranges for pinnipeds (in water) (Southall et al., 2007) at the south west location for installing a monopile with a maximum blow energy of 5000 kJ
- Figure A 4 Contour plot showing the impact ranges for pinnipeds (in water) (Southall et al., 2007) at the south west location for installing a pin pile with a maximum blow energy of 2700 kJ
- Figure A 5 Contour plot showing the impact ranges for harbour porpoise (Lucke et al., 2009) at the east location for installing a monopile with a maximum blow energy of 5000 kJ
- Figure A 6 Contour plot showing the impact ranges for harbour porpoise (Lucke et al., 2009) at the east location for installing a pin pile with a maximum blow energy of 2700 kJ
- Figure A 7 Contour plot showing the impact ranges for harbour porpoise (Lucke et al., 2009) at the south west location for installing a monopile with a maximum blow energy of 5000 kJ
- Figure A 8 Contour plot showing the impact ranges for harbour porpoise (Lucke et al., 2009) at the south west location for installing a pin pile with a maximum blow energy of 2700 kJ
- Figure A 9 Contour plot showing the impact ranges for low frequency cetaceans (NMFS, 2016) for both modelling locations for both monopile and pin pile scenarios
- Figure A 10 Contour plot showing the TTS impact ranges for species of fish (Popper et al., 2014) for both modelling locations for both monopile and pin pile scenarios

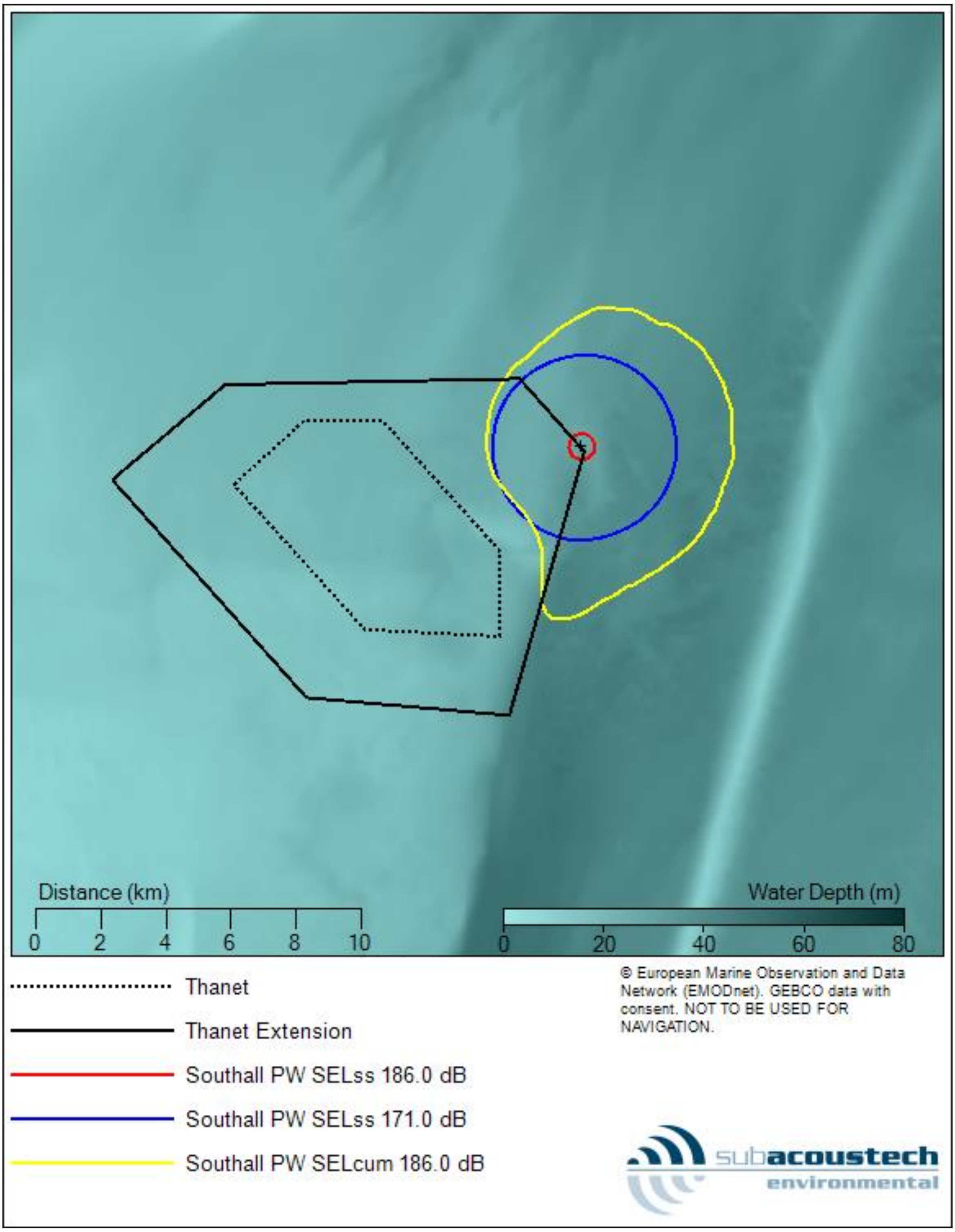

Figure A 1 Contour plot showing the impact ranges for pinnipeds (in water) (Southall et al., 2007) at the east location for installing a monopile with a maximum blow energy of 5000 kJ

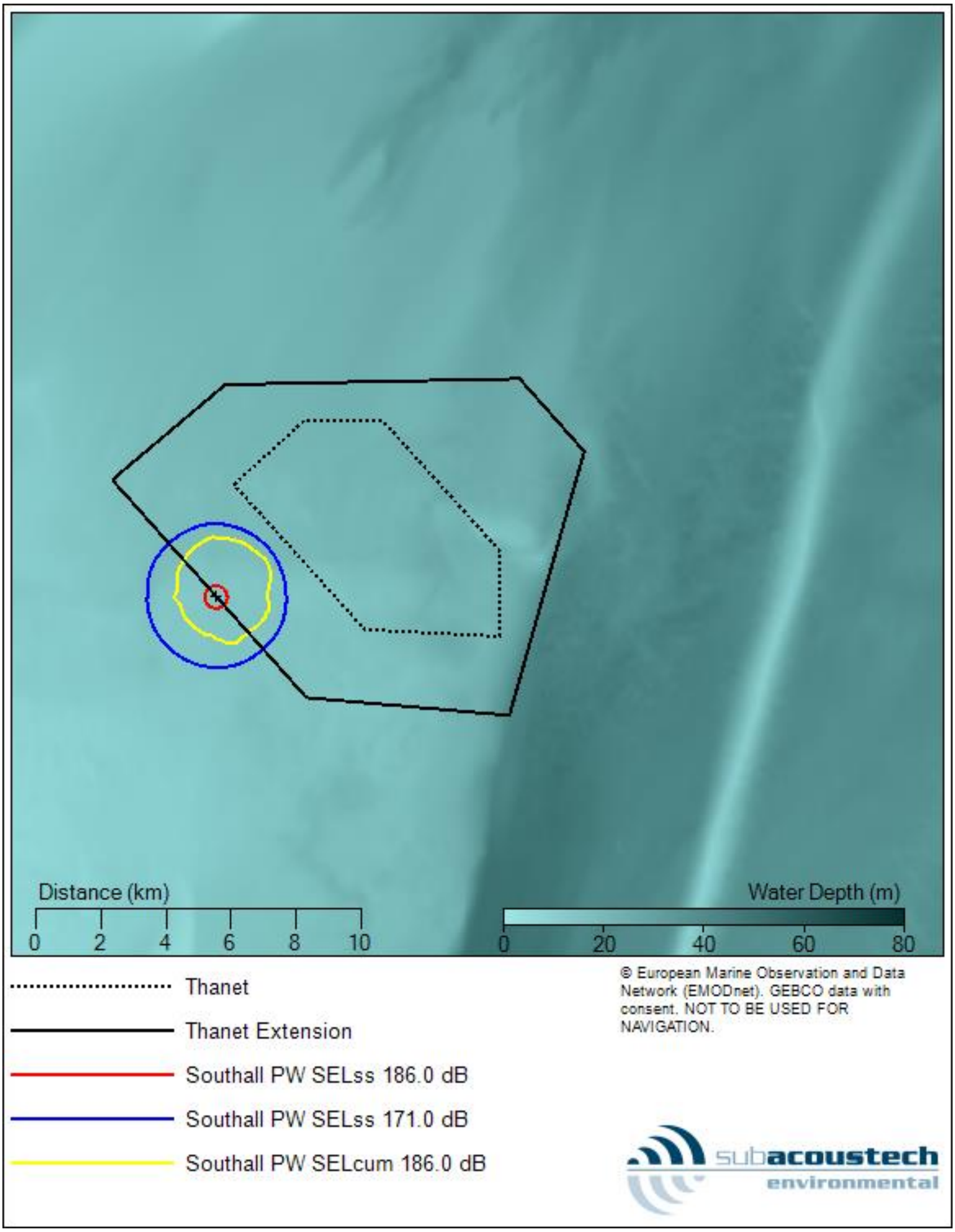

Figure A 2 Contour plot showing the impact ranges for pinnipeds (in water) (Southall et al., 2007) at the east location for installing a pin pile with a maximum blow energy of 2700 kJ

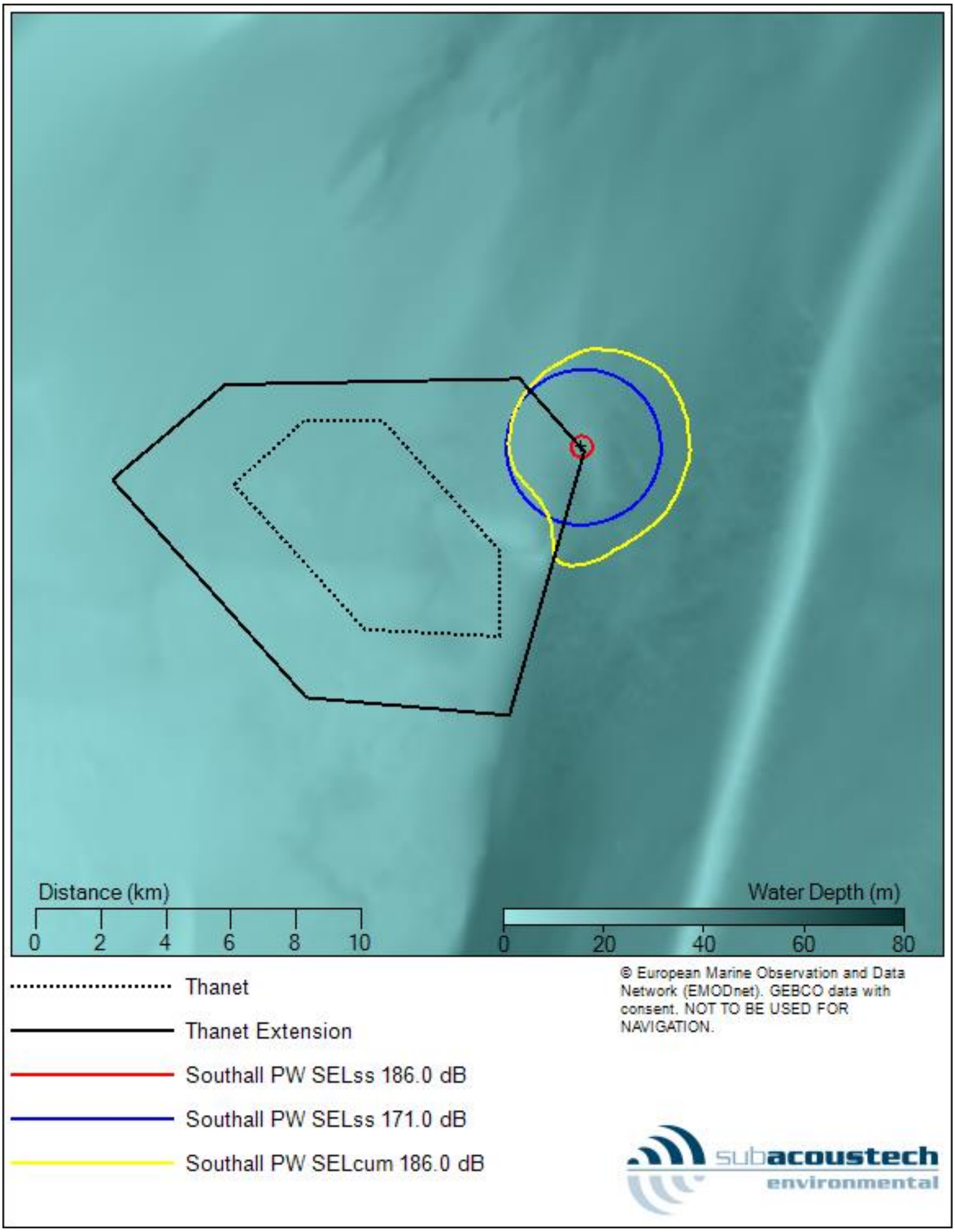

Figure A 3 Contour plot showing the impact ranges for pinnipeds (in water) (Southall et al., 2007) at the south west location for installing a monopile with a maximum blow energy of 5000 kJ

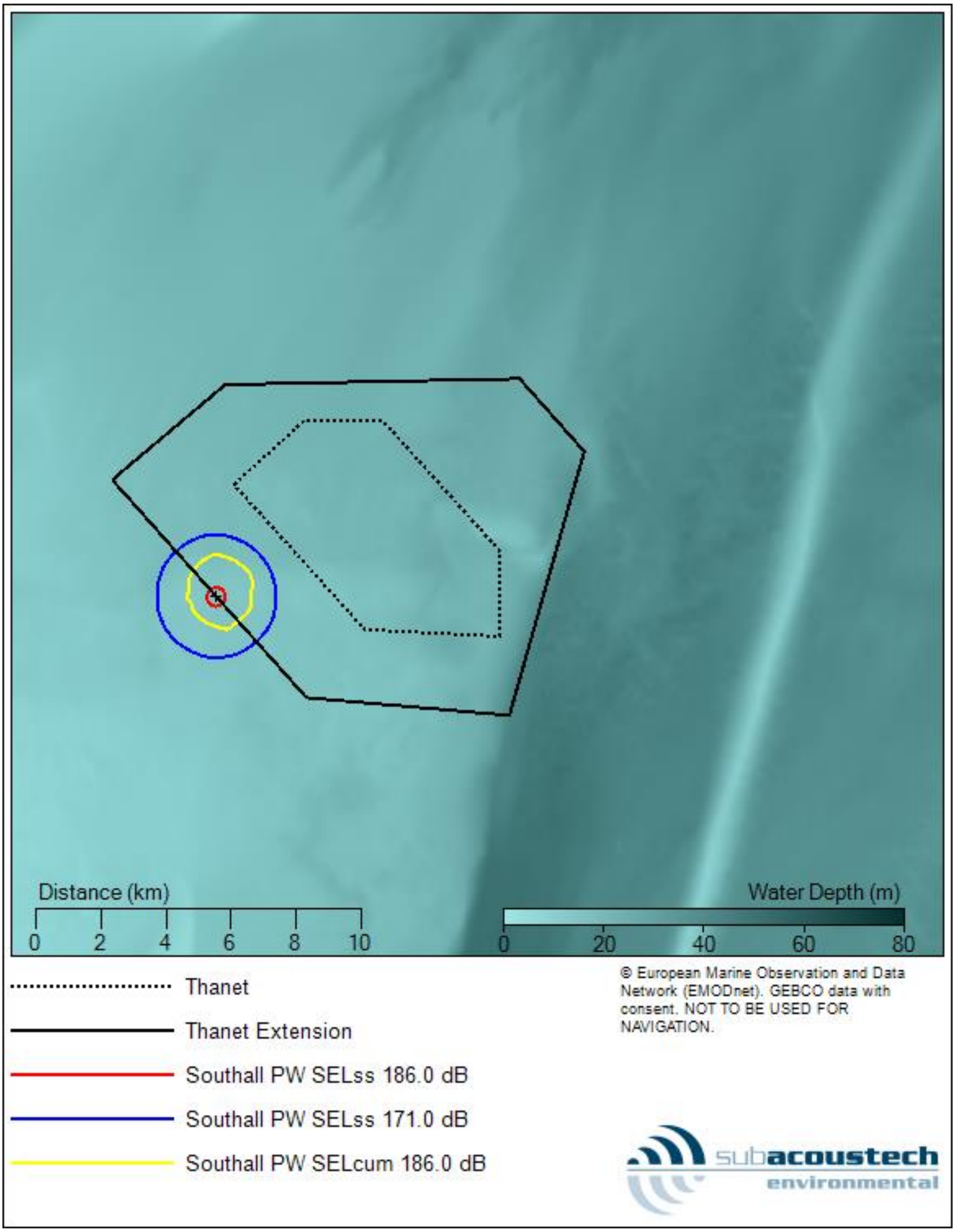

Figure A 4 Contour plot showing the impact ranges for pinnipeds (in water) (Southall et al., 2007) at the south west location for installing a pin pile with a maximum blow energy of 2700 kJ

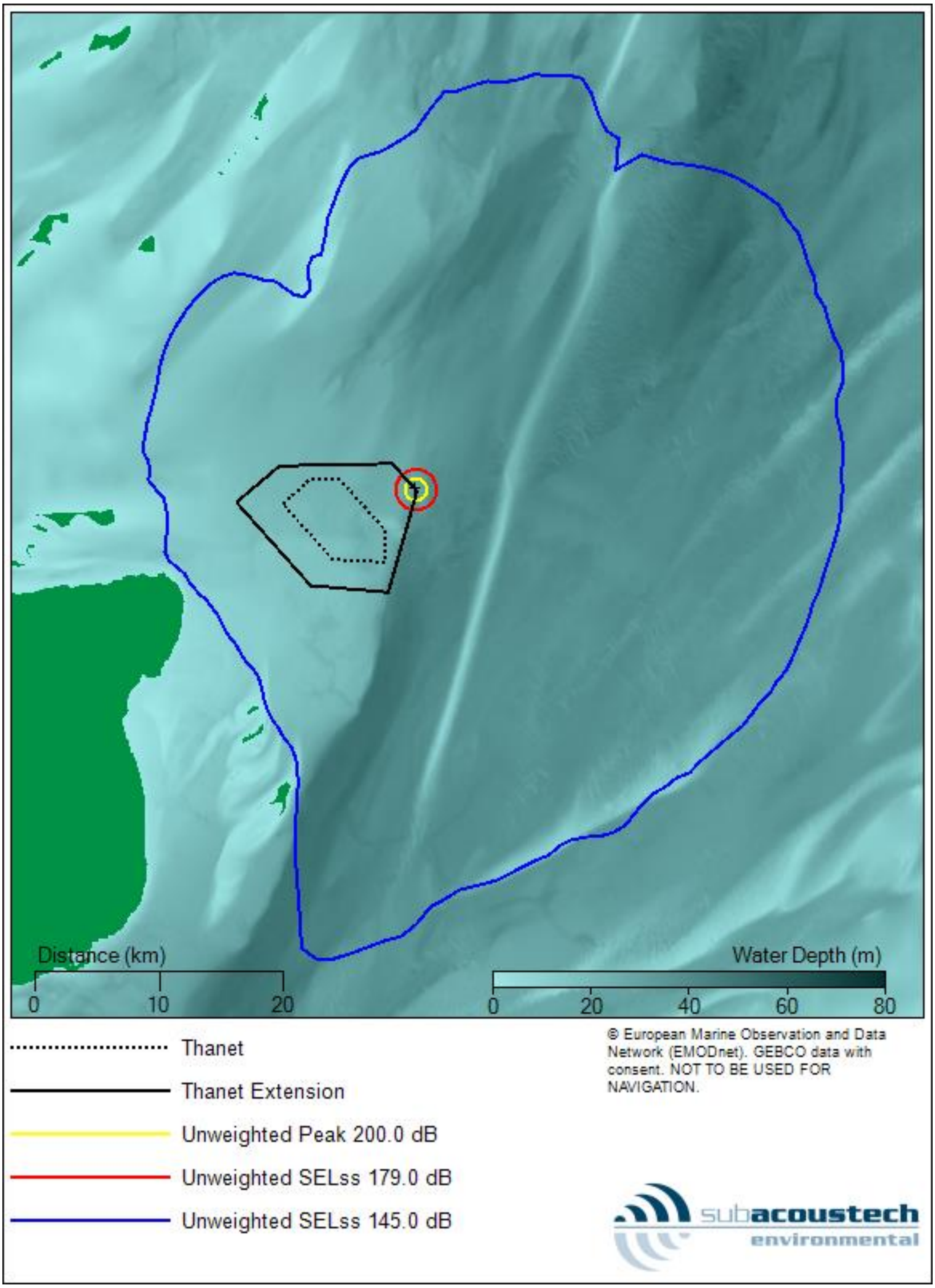

Figure A 5 Contour plot showing the impact ranges for harbour porpoise (Lucke et al., 2009) at the east location for installing a monopile with a maximum blow energy of 5000 kJ

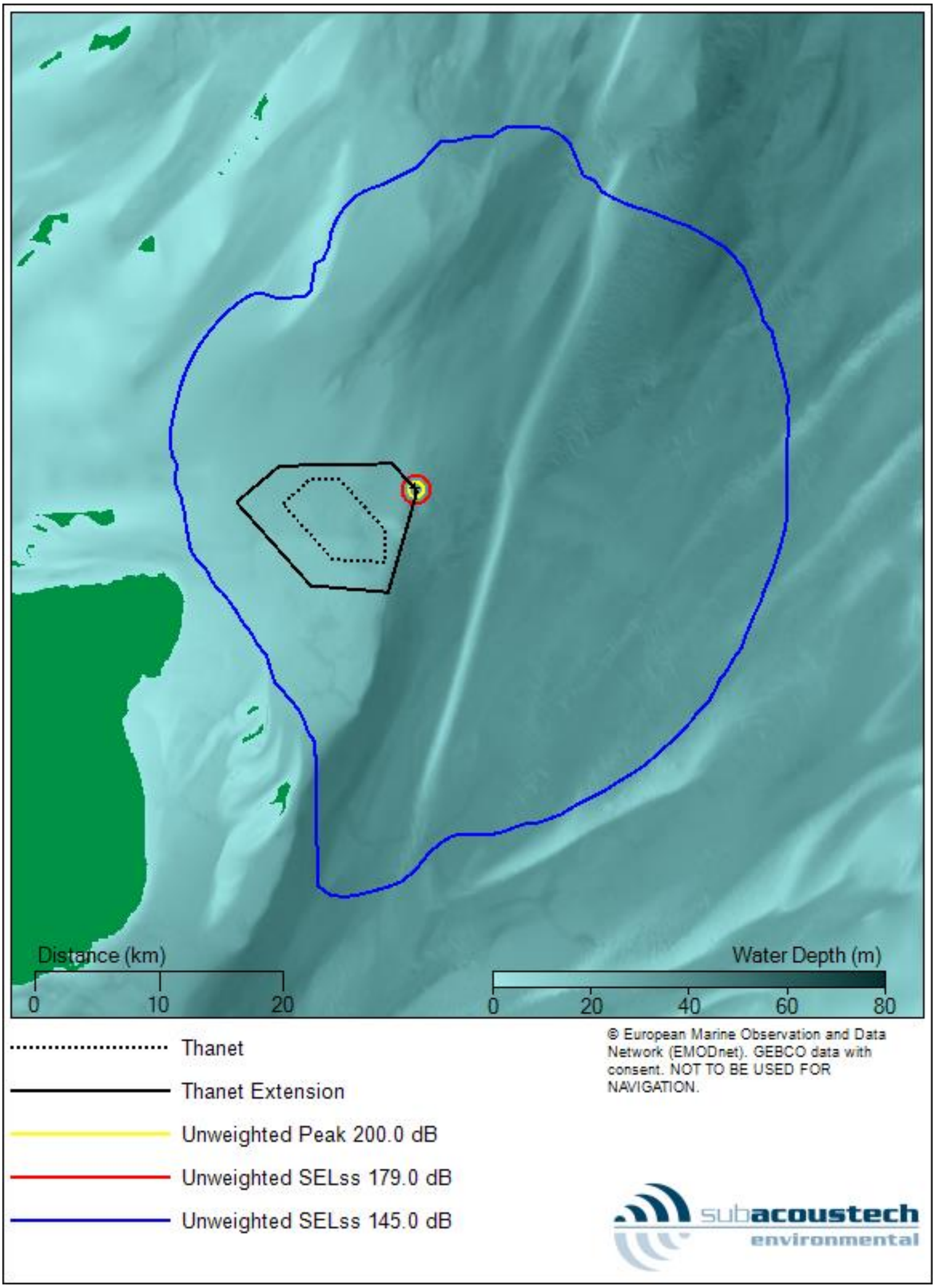

Figure A 6 Contour plot showing the impact ranges for harbour porpoise (Lucke et al., 2009) at the east location for installing a pin pile with a maximum blow energy of 2700 kJ

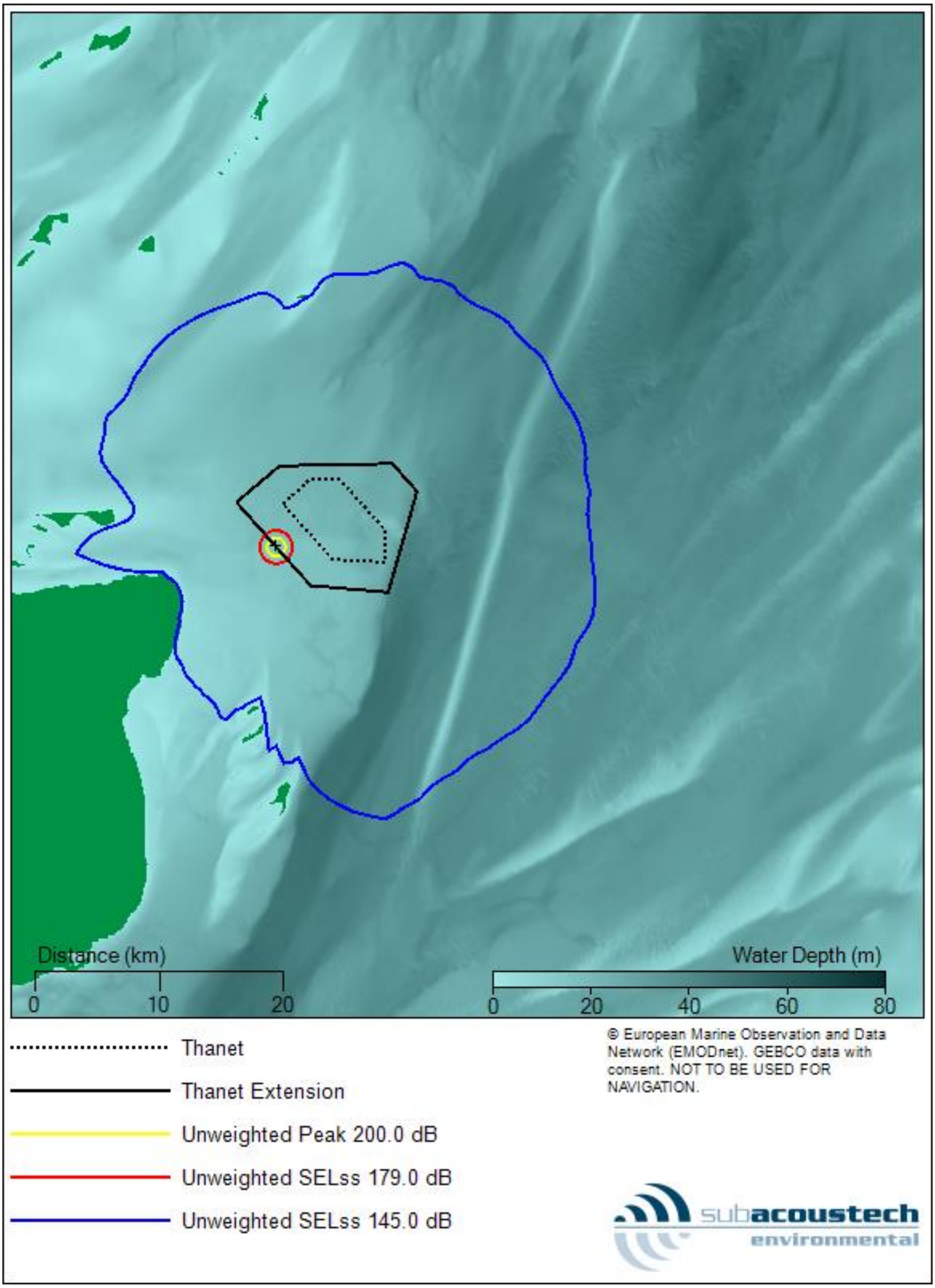

Figure A 7 Contour plot showing the impact ranges for harbour porpoise (Lucke et al., 2009) at the south west location for installing a monopile with a maximum blow energy of 5000 kJ

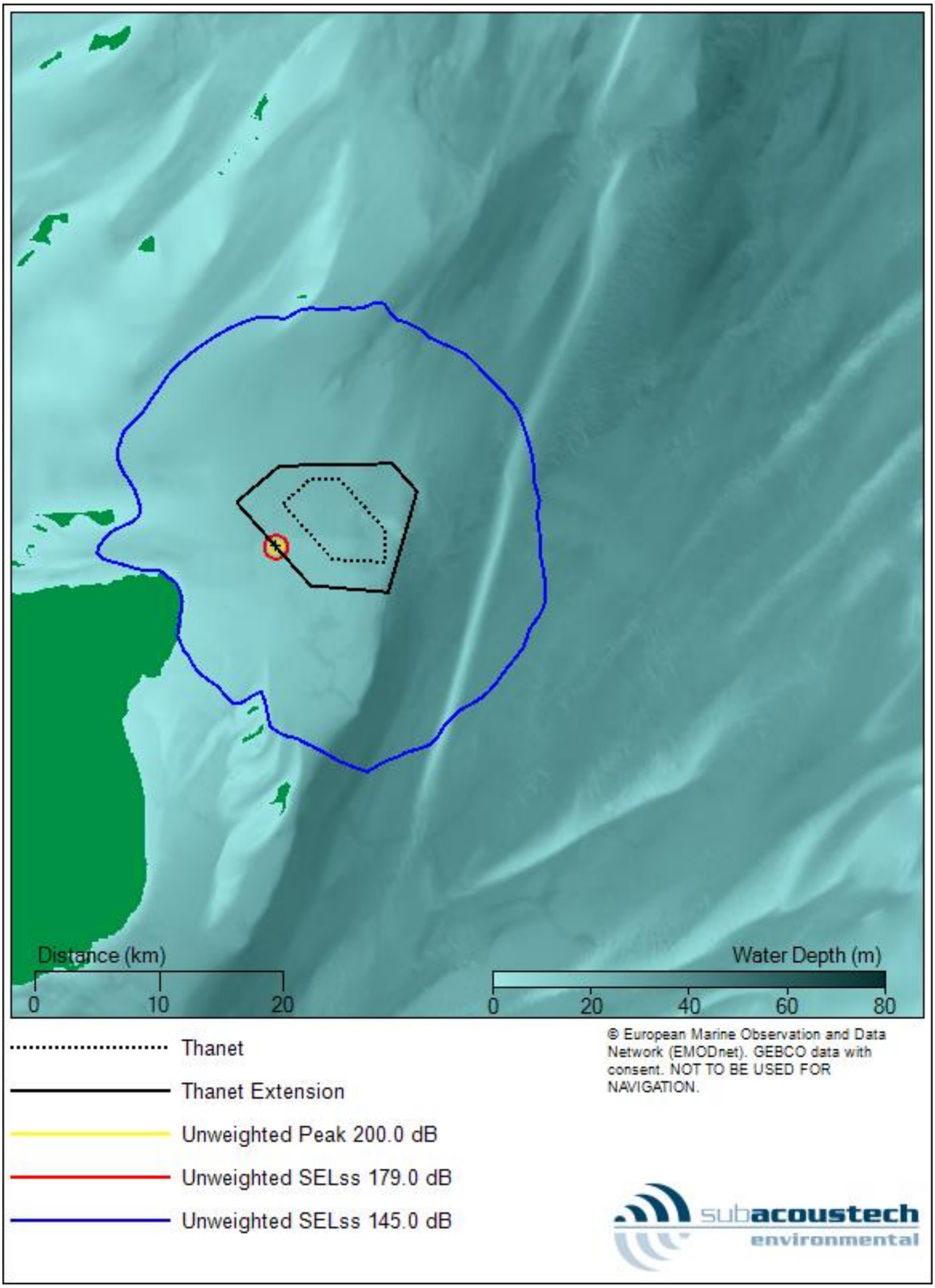

Figure A 8 Contour plot showing the impact ranges for harbour porpoise (Lucke et al., 2009) at the south west location for installing a pin pile with a maximum blow energy of 2700 kJ

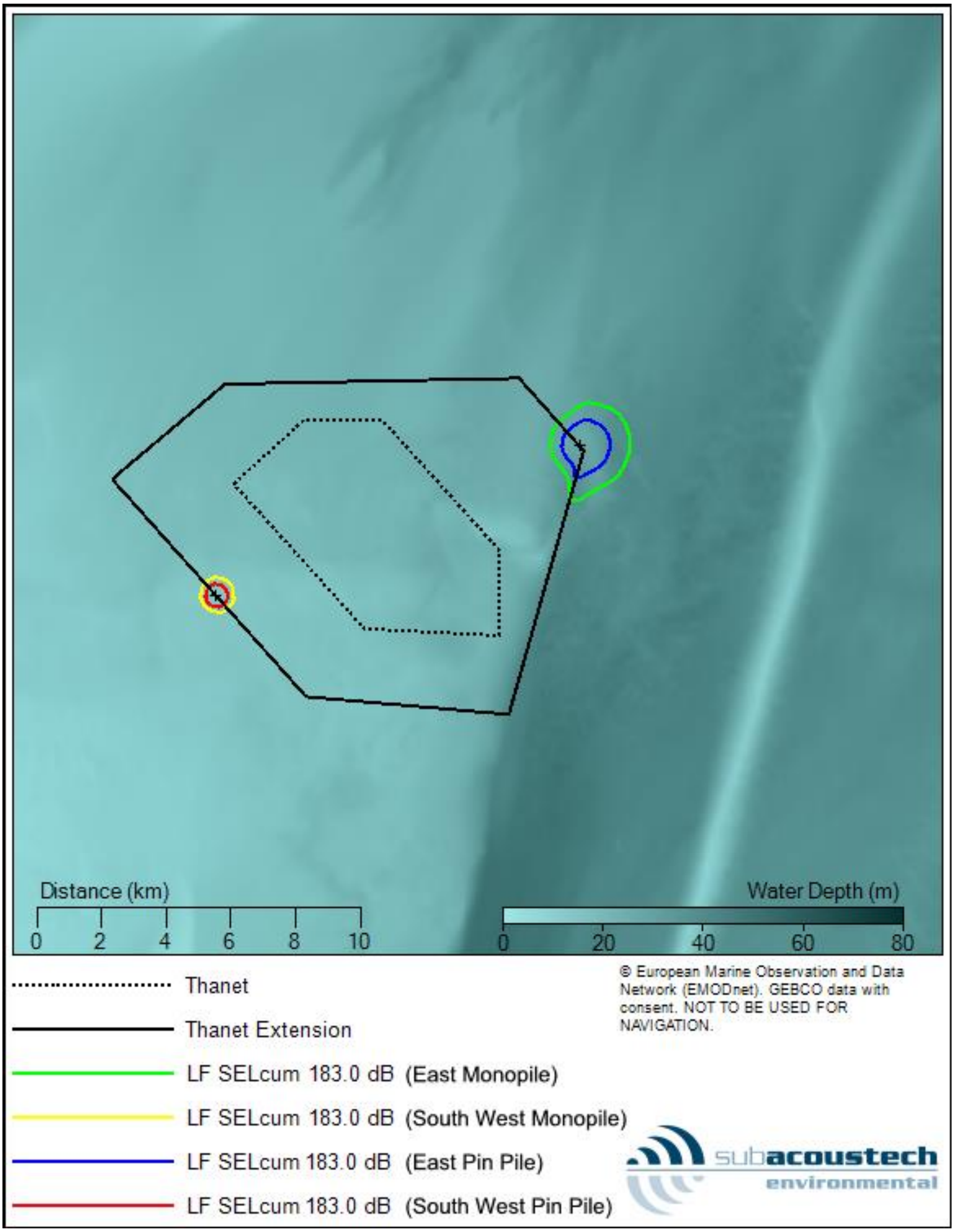

Figure A 9 Contour plot showing the impact ranges for low frequency cetaceans (NMFS, 2016) for both modelling locations for both monopile and pin pile scenarios

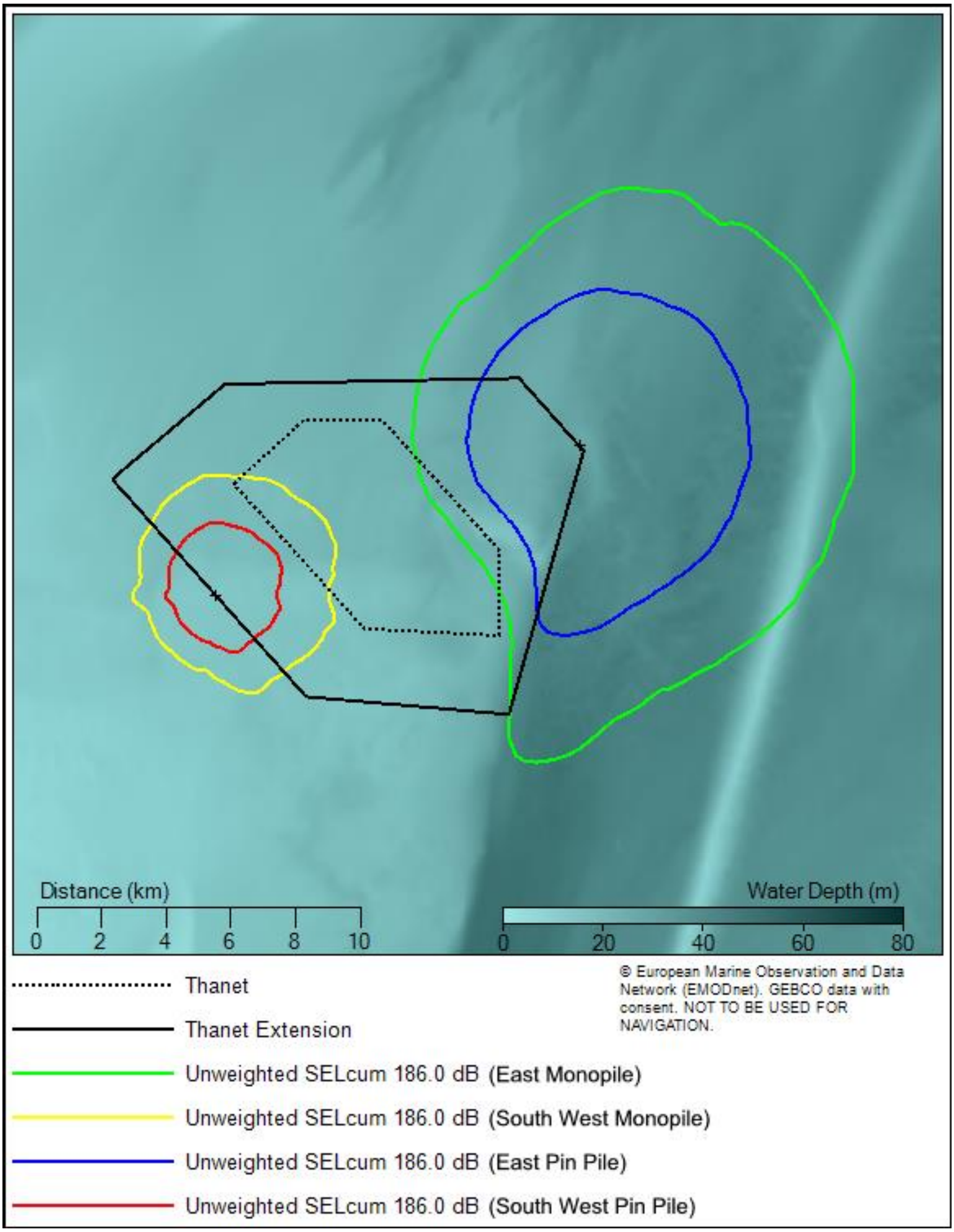

Figure A 10 Contour plot showing the TTS impact ranges for species of fish (Popper et al., 2014) for both modelling locations for both monopile and pin pile scenarios

Appendix B TTS Ranges

In addition to the NMFS (2016) PTS (Permanent Threshold Shift) ranges presented in section 4.5.1.3, further modelling has been carried out for the NMFS (2016) TTS (Temporary Threshold Shift) criteria. These ranges are summarised in Table B 1 and Table B 2.

NMFS (2016) – TTS – E location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
Unwtd SPL_{peak}	LF Cetaceans	213 dB	140 m	140 m	140 m	96 m	96 m	95 m
	MF Cetaceans	224 dB	31 m	31 m	30 m	21 m	21 m	20 m
	HF Cetaceans	196 dB	1.5 km	1.5 km	1.5 km	1.0 km	1.0 km	1.0 km
	PW Pinnipeds	212 dB	160 m	160 m	160 m	110 m	110 m	110 m
Weighted SEL_{cum}	LF Cetaceans	168 dB	22 km	15 km	8.5 km	20 km	13 km	7.5 km
	MF Cetaceans	170 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	HF Cetaceans	140 dB	9.5 km	6.8 km	4.5 km	19 km	14 km	8.6 km
	PW Pinnipeds	170 dB	7.7 km	5.6 km	3.7 km	4.6 km	3.6 km	2.5 km
Weighted SEL_{ss}	LF Cetaceans	168 dB	3.4 km	3.3 km	3.2 km	2.8 km	2.8 km	2.7 km
	MF Cetaceans	170 dB	23 m	23 m	22 m	37 m	37 m	36 m
	HF Cetaceans	140 dB	610 m	610 m	610 m	1.5 km	1.5 km	1.5 km
	PW Pinnipeds	170 dB	510 m	510 m	510 m	370 m	370 m	360 m

Table B 1 Summary of the impact ranges at the East location for TTS criteria from NMFS (2016)

NMFS (2016) – TTS – SW location			Monopile (5000 kJ)			Pin Pile (2700 kJ)		
			Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
Unwtd SPL_{peak}	LF Cetaceans	213 dB	130 m	130 m	130 m	88 m	87 m	86 m
	MF Cetaceans	224 dB	29 m	29 m	28 m	20 m	20 m	20 m
	HF Cetaceans	196 dB	1.2 km	1.2 km	1.2 km	850 m	850 m	840 m
	PW Pinnipeds	212 dB	150 m	150 m	150 m	100 m	100 m	99 m
Weighted SEL_{cum}	LF Cetaceans	168 dB	12 km	7.7 km	4.2 km	9.7 km	6.6 km	3.8 km
	MF Cetaceans	170 dB	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m	< 10 m
	HF Cetaceans	140 dB	3.9 km	2.9 km	2.1 km	9.8 km	7.1 km	4.1 km
	PW Pinnipeds	170 dB	3.0 km	2.3 km	1.7 km	1.7 km	1.4 km	1.0 km
Weighted SEL_{ss}	LF Cetaceans	168 dB	2.6 km	2.5 km	2.4 km	2.2 km	2.1 km	2.1 km
	MF Cetaceans	170 dB	21 m	21 m	20 m	35 m	35 m	34 m
	HF Cetaceans	140 dB	530 m	520 m	520 m	1.2 km	1.2 km	1.2 km
	PW Pinnipeds	170 dB	440 m	440 m	440 m	320 m	320 m	320 m

Table B 2 Summary of the impact ranges at the South West location for TTS criteria from NMFS (2016)

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