Submitted to:

Pete Gaches
GoBe Consultants
34 Devon Square
Newton Abbot
TQ12 2HH

Tel: +44 (0)1626 323 890

E-mail: pete@gobeconsultants.com
Website: www.gobeconsultants.com

Submitted by:

Tim Mason
Subacoustech Environmental Ltd
Chase Mill
Winchester Road
Bishop’s Waltham
Hampshire
SO32 1AH

Tel: +44 (0)1489 892 881

E-mail: tim.mason@subacoustech.com
Website: www.subacoustech.com

Additional underwater noise modelling at Sofia offshore wind farm, Dogger Bank

R Barham, T Mason

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1 Introduction

Underwater noise propagation modelling was carried out by the National Physical Laboratory (NPL) (Theobald *et al*. 2013, hereafter the “NPL report”) to assess the effects of noise from the construction of the Sofia (then named Teesside B) offshore wind farm, part of the Dogger Bank development area.

Since the NPL modelling was completed, new noise thresholds and criteria have been developed by the US National Marine Fisheries Service (NMFS, 2016) for impacts on marine mammals. To obtain impact ranges using these criteria at Sofia, additional modelling has been carried out by Subacoustech Environmental.

The modelling undertaken by Subacoustech Environmental has sought to replicate the results of the NPL modelling as closely as possible, for equivalent inputs and scenarios. Initially the modelling was run to verify that results closely matched the NPL predicted ranges under the original scenarios, and the results were then re-analysed to output new ranges using the up to date criteria.

In addition to these new criteria, additional modelling has been carried out by Subacoustech Environmental to estimate noise levels produced by larger hammers using greater blow energies than those previously modelled.

A map of the Sofia site, with the modelled location is given in Figure 1-1.

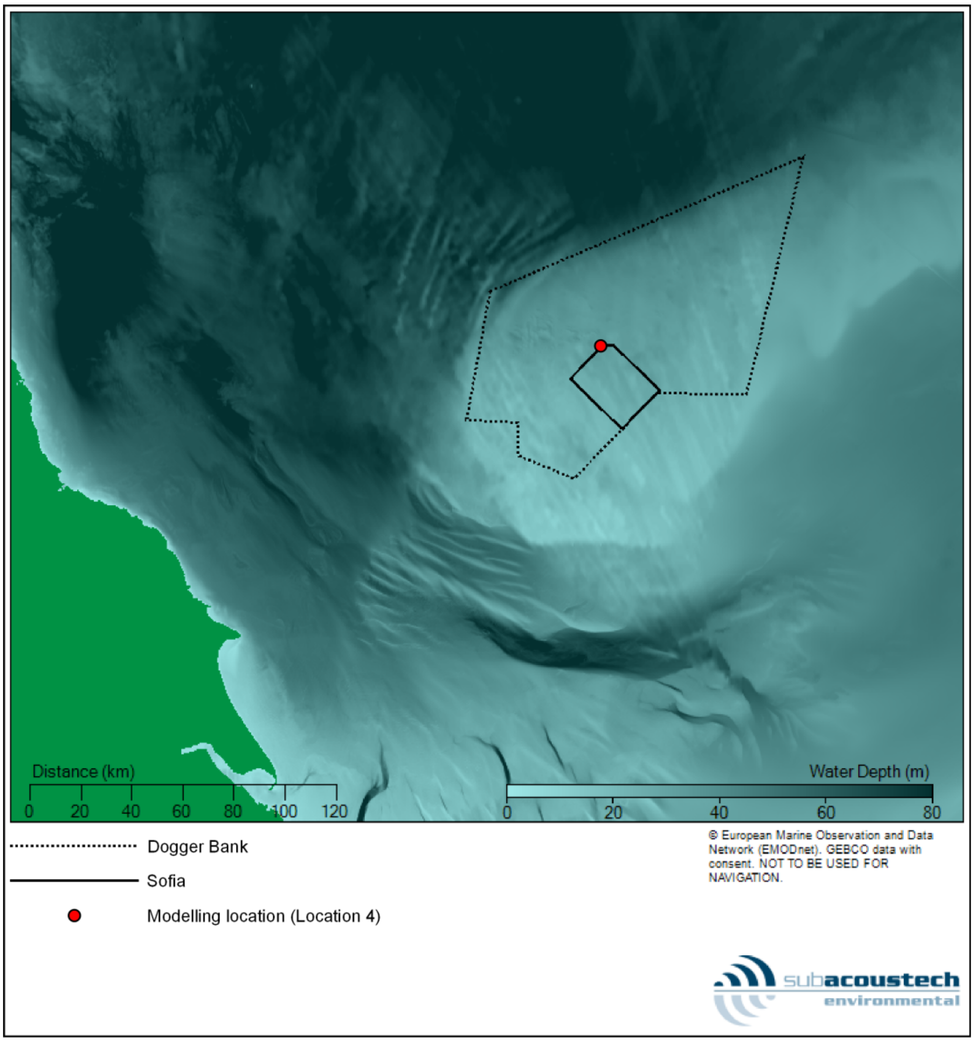

Figure 1-1 Overview map showing the windfarm boundaries and the approximate location used for the modelling

2 Modelling methodology

The primary goal in respect to the underwater modelling propagation methodology presented in this report was to replicate the results from the NPL modelling as closely as possible, to ensure that the new modelling was consistent with that undertaken previously. Results using the NMFS (2016) criteria could then be calculated with confidence.

2.1 NPL modelling

The modelling undertaken by NPL utilised an energy flux solution by Weston (1976), capable of propagation over large distances while accounting for range-dependent bathymetry and frequency-dependent absorption.

Twenty-seven locations were modelled by NPL, covering the extents of the Sofia site, and for each location pile driving noise was modelled for a hammer operating at up to 2300 kJ for pin pile installation and a hammer of up to 3000 kJ for monopiles.

Results were produced for a variety of available metrics and criteria, including:

- Southall *et al*. (2007) for species of cetaceans and pinnipeds; and
- Lucke *et al.* (2009) for harbour porpoises;

The model used by NPL is not openly available, and as such Subacoustech Environmental have used a different but comparable modelling method.

2.2 Subacoustech Environmental modelling

For the modelling in this study, Subacoustech Environmental have used the INSPIRE modelling software to predict noise levels and impact ranges from piling at Sofia.

The INSPIRE model (currently version 3.5) is a semi-empirical, depth-dependent, underwater noise propagation model based around a combination of numerical modelling and actual measured data from over 50 datasets of noise propagation, mostly surrounding the UK. It is designed to calculate the propagation of noise in shallow, mixed, coastal waters, typical of the conditions around the UK, and is well suited to the Dogger Bank and Sofia areas.

The model can provide estimates of unweighted SPL_{peak} (peak sound pressure level), SEL_{ss} (single strike sound exposure level), and SEL_{cum} (cumulative sound exposure level) noise levels as well as various other weighted noise metrics. Calculations made along 180 equally spaced radial transects, i.e. one every 2°. For each modelling run a criterion level is specified, allowing a noise contour to be drawn, 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.

The methods used within this report meet the requirements set by the NPL Good Practice Guide 133 for underwater noise measurement (Robinson *et al.* 2014).

The approach used considers a wide range of input parameters to ensure as detailed results as possible. The resulting transmission losses have then been compared to (and in some cases extrapolated from) the numbers given in the NPL report to ensure compatibility; this is discussed further in section 2.3.

2.2.1 Modelling location

Modelling has been undertaken at a single location in the Sofia site (location 4 – Table 4.2 in Theobald *et al*. 2013). This location has been chosen as the results in the NPL report use it as an example for each of the modelling scenarios. The location is at the northernmost edge of the Sofia site and is in some of the deepest water at the site. Deeper water tends to lead to the greatest underwater noise propagation and as such the ranges calculated should be considered worst case.

The approximate location is given in Figure 1-1 at the co-ordinates 55.12443°N, 002.145724°E in 32 m of water.

2.2.2 Modelling input parameters

The modelling undertaken considers many of the environmental parameters within the study area and the characteristics of the noise source. The following parameters have been assumed for the modelling.

Impact piling

The original modelling by NPL considered two primary scenarios: monopile foundations installed using a hammer with a maximum blow energy of 3000 kJ and pin pile foundations installed using a maximum blow energy of 2300 kJ. In addition to these, several lower blow energies were also modelled to show the 'soft start' and ramp up of the impact piling from the start to the maximum (300 kJ and 1900 kJ).

The above initial (comparative) scenarios, plus a higher potential maximum blow energy of 5500 kJ, have been modelled using the Subacoustech Environmental approach described above.

Source levels

Underwater noise modelling requires knowledge of the source level, which is the noise level at 1 m from the noise source. The source levels used by NPL for their modelling were not presented in their report. For this study, the source level has been derived by taking the modelled transmission loss of the noise over distance and fitting it to the impact ranges presented previously in the NPL report (Theobald *et al.* (2013)). The resulting source levels have been used for calculating the impact ranges for the NMFS (2016) criteria. The fitting of the data and comparisons with NPL modelling are presented in section 2.3.

The unweighted source levels used for the modelling are provided in Table 2-1 for the maximum blow energies, which are in line with those we have seen at other, similar scale projects.

	SPL_{peak} source level	**SEL_{ss} source level**
Pin Pile 2300 kJ (maximum)	244.1 dB re 1 μPa @ 1 m	217.8 dB re 1 $μPa^2s$ @ 1 m
Monopile 3000 kJ (maximum)	245.2 dB re 1 μPa @ 1 m	219.0 dB re 1 $μPa^2s$ @ 1 m
Monopile 4000 kJ (maximum)	246.5 dB re 1 μPa @ 1 m	220.2 dB re 1 $μPa^2s$ @ 1 m
Monopile 5500 kJ (maximum)	247.9 dB re 1 μPa @ 1 m	221.6 dB re 1 $μPa^2s$ @ 1 m

Table 2-1 Summary of the unweighted, single strike, source levels used for modelling in this study

It is important to note that the source level value is theoretical and does not necessarily, nor is intended to, represent the actual noise level at 1 m from the piling operation, which is highly complex close to a large source. Its purpose is for the accurate calculation of noise levels at greater distances from the source, to correspond with relevant thresholds, and crucially in this case, to agree with the original NPL modelling.

Frequency content

The size of the pile being installed has been applied to the modelling to estimate the frequency content of the noise. Frequency data was not given in the NPL report. As such frequency data has been derived from sources using Subacoustech Environmental's noise measurement database. Representative, third-octave levels for the size of the monopiles and pin piles have been used for this modelling. The unweighted peak third-octave frequency spectrum levels used for modelling are illustrated in Figure 2-1. The shape of each spectrum is the same for all blow energies at source, with the overall source levels adjusted to account for the changing blow energy.

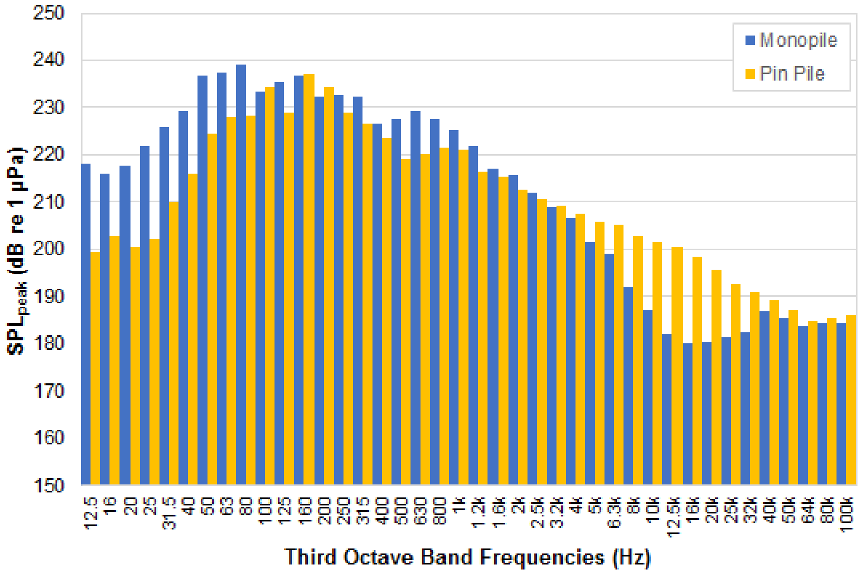

Figure 2-1 Unweighted peak third-octave source level frequency spectra used for modelling

The noise from monopiles contains more low frequency content and the pin piles contain more high frequency content, due to the dimensions and acoustics of the pile.

Environmental conditions

By inclusion of measured data from similar offshore impact piling events, the INSPIRE model intrinsically accounts for various environmental conditions. Data from the British Geological Survey (BGS) presented as part of the Marine Environmental Mapping Programme (MAREMAP) show that the areas around Sofia and the Dogger Bank region generally are made up of sand or gravelly sand.

Bathymetry from the European Marine Observation and Data Network (EMODnet) was used for this modelling. Mean tidal depth was used throughout for the bathymetry to match conditions used in the NPL report.

2.3 Results of original and revised modelling comparison

In order to obtain modelling results close to those produced in the NPL report, modelling was carried out using the INSPIRE model using the parameters detailed in the previous section to get a general transmission loss over multiple transects. These transmission losses were then compared against the results given in the NPL report. It was agreed that there was good correlation between the two resultant data sets. Figure 2-2 and Figure 2-3 compare the unweighted noise level plots from the NPL report and the Subacoustech modelling at the same scale. It should be noted that although the noise levels do not line up perfectly, the figures do show many of the same features, such as a largely uniform distribution, with larger ranges into the deeper water to the north and northwest and some effects of shallower areas and sandbanks to the south.

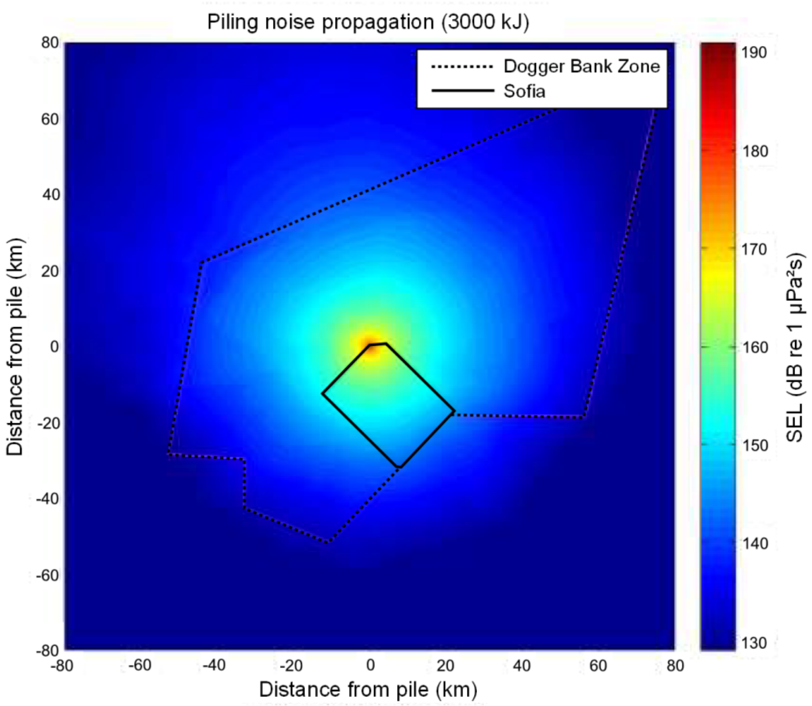

Figure 2-2 SEL$_{ss}$ impact piling noise propagation map for Location 4 for a 3000 kJ hammer from the NPL report (Theobald et al, 2013)

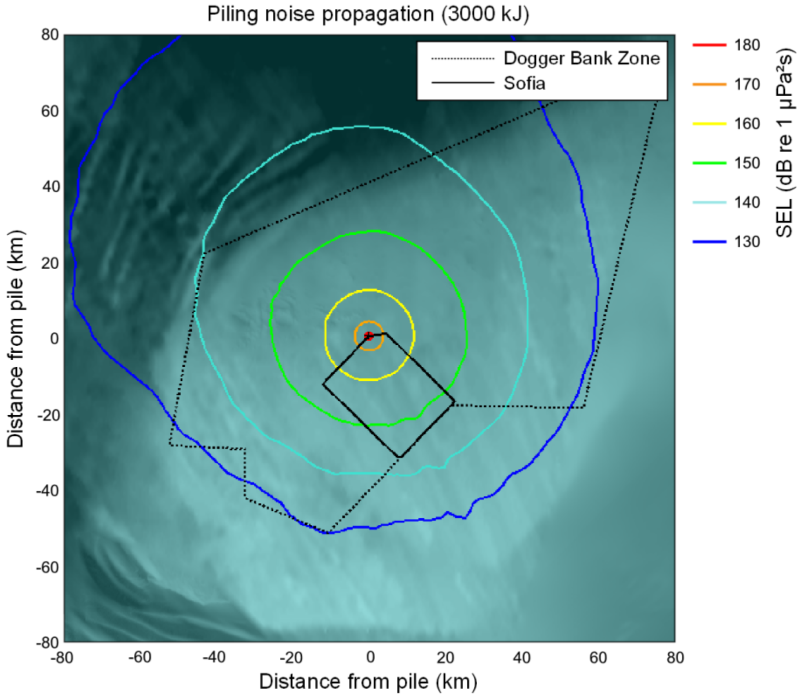

Figure 2-3 SEL$_{ss}$ impact piling noise propagation map for Location 4 for a 3000 kJ hammer showing the transmission losses predicted for the INSPIRE modelling

Next, the source level was ascertained by fitting the modelled transmission loss to the impact ranges given in the NPL report. Figure 2-4 and Figure 2-5 show how the worst-case transect lines up with the higher unweighted SPL$_{peak}$ and SEL$_{ss}$ impact ranges given in the NPL modelling report, resulting in the source levels to be used for modelling in this study, summarised in Table 2-1. A conservative fit to the data has been used so that levels predicted along the worst-case transect intersect with the highest levels reported by NPL, especially at the greatest distances; this data is summarised in Table 2-2 and Table 2-3.

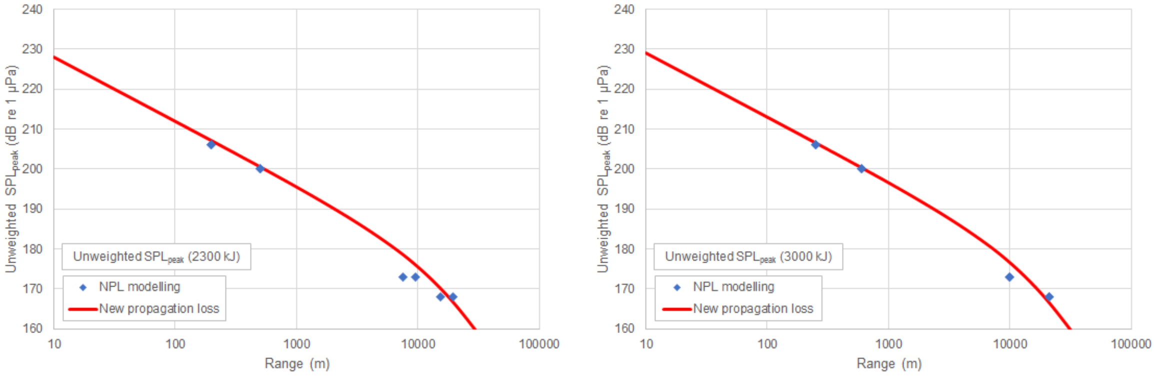

Figure 2-4 Level versus range plots showing a comparison between the reported NPL impact ranges and the new modelling fitted to the data

SPL$_{peak}$	**Criteria**	**NPL modelling**	**INSPIRE worst case**
2300 kJ	206 dB re 1 µPa	200 m	230 m
	200 dB re 1 µPa	500 m	540 m
	173 dB re 1 µPa	7.5 to 9.5 km	12.4 km
	168 dB re 1 µPa	15.5 to 19.5 km	17.9 km
3000kJ	206 dB re 1 µPa	250 m	270 m
	200 dB re 1 µPa	600 m	630 m
	173 dB re 1 µPa	10.0 km	13.5 km
	168 dB re 1 µPa	21.0 km	19.4 km

Table 2-2 Summary of the modelled SPL$_{peak}$ values compared in Figure 2-4

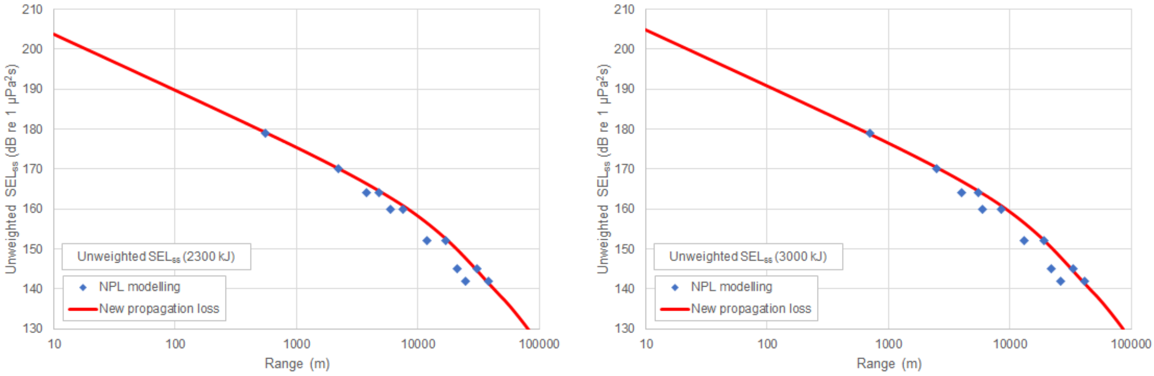

Figure 2-5 Level versus range plots showing a comparison between the reported NPL impact ranges and the new modelling parameters fitted to the data (unweighted SEL$_{ss}$)

SEL$_{ss}$	Criteria	NPL modelling	INSPIRE worst case
2300 kJ	179 dB re 1 μPa^{2}s	550 m	570 m
	164 dB re 1 μPa^{2}s	3.8 to 4.8 km	5.1 km
	145 dB re 1 μPa^{2}s	21.0 to 30.5 km	29.9 km
	170 dB re 1 μPa^{2}s	2.2 km	2.3 km
	160 dB re 1 μPa^{2}s	6.0 to 7.5 km	8.3 km
	152 dB re 1 μPa^{2}s	12.0 to 17.0 km	17.8 km
	142 dB re 1 μPa^{2}s	24.5 to 38.0 km	36.7 km
3000kJ	179 dB re 1 μPa^{2}s	700 m	680 m
	164 dB re 1 μPa^{2}s	4.0 to 5.5 km	5.9 km
	145 dB re 1 μPa^{2}s	22.0 to 33.5 km	32.4 km
	170 dB re 1 μPa^{2}s	2.5 km	2.7 km
	160 dB re 1 μPa^{2}s	6.0 to 8.5 km	9.4 km
	152 dB re 1 μPa^{2}s	13.0 to 19.0 km	19.5 km
	142 dB re 1 μPa^{2}s	26.0 to 41.0 km	39.8 km

Table 2-3 Summary of the SEL$_{ss}$ values compared in Figure 2-5

2.3.1 Modelling confidence

Expanding on the data from the previous section, Table 2-4 and Table 2-5 give summaries of direct comparisons between the modelled impact ranges for all blow energies presented by NPL, and the modelling undertaken by Subacoustech Environmental for this report. All the values are either unweighted SPL$_{peak}$ values or unweighted single strike SEL$_{ss}$ values. As stated earlier, where a range of distances are given in the NPL report, the greatest distances have been used to ensure a conservative fit to the data. Generally, the Subacoustech model shows good correlation at close range and fits the larger, more conservative, ranges at greater distances. It should also be noted that the ranges given in the NPL report, and presented below in Table 2-4 and Table 2-5, consider all modelling locations at Sofia, whereas the Subacoustech Environmental modelling has only considered the worst-case location 4.

Overall, there is a good level of correlation between the two datasets and the results from the INSPIRE model provide a good substitute for the NPL modelling in calculating the NMFS (2016) and Popper *et al*. (2014) criteria. The full modelling results undertaken by Subacoustech Environmental ("Sub-E") for the criteria given in the NPL report are presented in section 4.1.

Unwtd SPL$_{peak}$	300 kJ hammer energy		1900 kJ hammer energy		2300 kJ hammer energy		3000 kJ hammer energy	
	NPL	Sub-E	NPL	Sub-E	NPL	Sub-E	NPL	Sub-E
206 dB	< 100 m	70 m	< 200 m	220 m	< 200 m	250 m	< 250 m	290 m
200 dB	< 200 m	170 m	< 400 m	500 m	< 500 m	560 m	< 600 m	650 m
173 dB	~ 3.2 to 4.0 km	5.3 to 5.4 km	~ 8.5 to 11.0 km	11.1 to 11.6 km	~ 7.5 to 9.5 km	11.7 to 12.4 km	~ 8.0 to 10.0 km	12.7 to 13.6 km
168 dB	~ 8.5 km	8.6 to 8.9 km	~ 18.5 to **26.5 km**[*]	15.5 to 17.1 km	~ 15.5 to 19.5 km	16.3 to 18.1 km	~ 17.5 to 21.0 km	17.4 to 19.6 km

Table 2-4 Comparison between ranges to unweighted SPL$_{peak}$ values given in the NPL report for location 4 and the comparative modelling undertaken by Subacoustech Environmental (Sub-E) (Note: one of the NPL ranges, denoted bold with an asterisk, appears to be an outlier and may be a typo in the original report)

Unwtd SEL_{ss}	**300 kJ hammer energy**		**1900 kJ hammer energy**		**2300 kJ hammer energy**		**3000 kJ hammer energy**	
	NPL	Sub-E	NPL	Sub-E	NPL	Sub-E	NPL	Sub-E
179 dB	< 200 m	150 m	< 500 m	520 m	< 550 m	590 m	< 700 m	700 m
170 dB	< 600 m	600 m	< 2.0 km	2.0 km	< 2.2 km	2.3 km	< 2.5 km	2.7 km
164 dB	< 1.5 km	1.5 km	~ 3.6 to 4.2 km	4.6 km	~ 3.8 to 4.8 km	5.1 to 5.2 km	~ 4.0 to 5.5 km	5.8 to 6.0 km
160 dB	< 2.5 km	2.7 km	~ 3.6 to 4.2 km	7.3 to 7.6 km	~ 6.0 to 7.5 km	8.0 to 8.3 km	~ 6.0 to 8.5 km	9.0 to 9.4 km
152 dB	~ 5.0 to 7.0 km	7.3 to 7.6 km	~ 11.0 to 15.5 km	15.3 to 16.8 km	~ 12.0 to 17.0 km	16.3 to 18.0 km	~ 13.0 to 19.0 km	17.6 to 19.8 km
145 dB	~ 10.0 to 14.0 km	14.1 to 15.4 km	~ 19.5 to 29.5 km	23.8 to 28.6 km	~ 21.0 to 30.5 km	24.9 to 30.2 km	~ 22.0 to 33.5 km	26.3 to 32.7 km
142 dB	~ 13.0 to 19.0 km	17.6 to 19.8 km	~ 23.0 to 36.0 km	27.6 to 34.9 km	~ 24.5 to 38.0 km	28.5 to 36.9 km	~ 26.0 to 41.0 km	29.9 to 40.0 km

Table 2-5 Comparison between ranges to unweighted SEL_{ss} values given in the NPL report for location 4 and the comparable modelling undertaken by Subacoustech Environmental (Sub-E)

3 Assessment criteria

3.1 Background

Over the past 20 years it has become increasingly evident that noise from human activities in and around underwater environments have the potential to cause adverse impacts on marine species in the area. The extent to which intense underwater sound might cause an adverse environmental impact to a species is dependent upon the incident sound level, sound frequency, duration of exposure and/or repetition rate of an impulsive sound (Hastings and Popper, 2005), as well as the sensitivity of the species. 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 the clearest observable effects, although there has been more interest in chronic noise exposure over the last ten years.

For this study, various criteria have been used, covering the values used in the NPL report, and the more up to date studies from NMFS (2016) for marine mammals.

3.2 Criteria from the NPL report

As mentioned in section 2.1, the following criteria were used in the NPL report and have been used to give a direct comparison between the NPL modelling and the INSPIRE modelling carried out for this study.

- Southall *et al.* (2007) for species of cetaceans and pinnipeds;
- Lucke *et al.* (2009) for harbour porpoises;

These criteria are summarised in Table 3-1 to Table 3-4 as they appear in the NPL report. It should be noted that the Southall and Lucke criteria presented in the NPL reports, and here as a comparison, are only for single strike SEL.

Effect	Criteria
Instantaneous injury / PTS	Single pulse SEL 179 dB re 1 µPa^{2}s
TTS / fleeing response	Single pulse SEL 164 dB re 1 µPa^{2}s
Possible avoidance from area	Single pulse SEL 145 dB re 1 µPa^{2}s

Table 3-1 Criteria for assessing harbour porpoise impacts as presented in the NPL report. These have been derived from Lucke et al. (2009)

Effect	Criteria
Instantaneous injury / PTS	M_{mf} weighted SEL 198 dB re 1 µPa^{2}s
TTS / fleeing response	M_{mf} weighted SEL 183 dB re 1 µPa^{2}s
Likely avoidance from area	Single pulse SEL 170 dB re 1 µPa^{2}s
Possible avoidance from area	Single pulse SEL 160 dB re 1 µPa^{2}s

Table 3-2 Criteria for assessing mid-frequency (MF) cetaceans impacts as presented in the NPL report. These have been derived from Southall et al. (2007)

Effect	Criteria
Instantaneous injury / PTS	M_{lf} weighted SEL 198 dB re 1 µPa^{2}s
TTS / fleeing response	M_{lf} weighted SEL 183 dB re 1 µPa^{2}s
Likely avoidance from area	Single pulse SEL 152 dB re 1 µPa^{2}s
Possible avoidance from area	Single pulse SEL 142 dB re 1 µPa^{2}s

Table 3-3 Criteria for assessing low-frequency (LF) cetaceans impacts as presented in the NPL report. These have been derived from Southall et al. (2007)

Effect	Criteria
Instantaneous injury / PTS	M_{pw} weighted SEL 186 dB re 1 μPa^{2}s
TTS / fleeing response	M_{pw} weighted SEL 171 dB re 1 μPa^{2}s

Table 3-4 Criteria for assessing pinnipeds (in water) impacts as presented in the NPL report. These are from Southall et al. (2007)

3.3 Impacts on marine mammals (NMFS, 2016)

Since it was published, Southall *et al.* (2007) has been the source of the most widely used criteria to assess the effects of noise on marine mammals, and was the main criteria, along with Lucke *et al.* (2009) used in the NPL report for marine mammals. 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 hearing groups and applies filters to the unweighted noise to approximate the hearing sensitivity of the receptor. It should be noted that the filters used in Southall *et al.* (2007) differ from those used in NMFS (2016).

The hearing groups given in the NMFS (2016) guidance are summarised in Table 3-5 and Figure 3-1. A further hearing groups for Otariid Pinnipeds is also given for sea lions and fur seals, however this has not been used in this study as those species are not commonly found in the areas surrounding Sofia.

Hearing group	Example species	Generalised hearing range
Low Frequency (LF) cetaceans	Baleen whales	7 Hz to 35 kHz
Mid Frequency (MF) cetaceans	Dolphins, Toothed Whales, Beaked Whales, Bottlenose Whales (including Bottlenose Dolphin)	150 Hz to 160 kHz
High Frequency (HF) cetaceans	True Porpoises (including Harbour Porpoise)	275 Hz to 160 kHz
Phocid Pinnipeds (PW) (underwater)	True Seals (including Harbour Seal)	50 Hz to 86 kHz

Table 3-5 Marine mammal hearing groups (from NMFS, 2016)

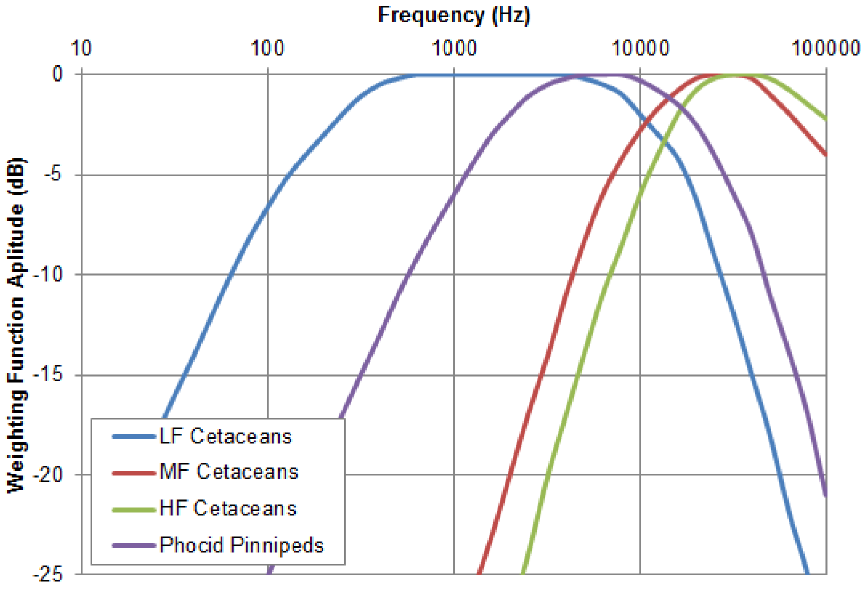

Figure 3-1 Auditory weighting functions for low frequency (LF) cetaceans, mid frequency (MF) cetaceans, high frequency (HF) cetaceans, and phocid pinnipeds (PW) (underwater) (from NMFS, 2016)

NFMS (2016) presents single strike, unweighted peak criteria (SPL_{peak}) and cumulative (i.e. more than a single impulsive sound) weighted sound exposure criteria (SEL_{cum}) for both permanent threshold shift (PTS) where unrecoverable hearing damage may occur and temporary threshold shift (TTS) where a temporary reduction in hearing sensitivity may occur in individual receptors. However, as no like-for-like comparisons are available for the weighted SEL_{cum} criteria in the original ES, these have not been considered further in this study.

Table 3-6 presents the NMFS (2016) criteria used in this study for each of the key marine mammal hearing groups.

Impulsive noise	TTS criteria	PTS criteria
Functional Group	**SPL_{peak} (unweighted) dB re 1 µPa**	**SPL_{peak} (unweighted) dB re 1 µPa^{2}s**
LF Cetaceans	213	219
MF Cetaceans	224	230
HF Cetaceans	196	202
PW Pinnipeds	212	218

Table 3-6 Assessment criteria for marine mammals from NMFS (2016) for impulsive noise

4 Modelling results

The following sections present the modelling impact ranges for the criteria discussed in section 3 at the Sofia site and a comparison with the results presented in the NPL modelling report.

4.1 Previously considered criteria

Table 4-1 to Table 4-4 present the impact ranges from the INSPIRE modelling considering the single pulse noise criteria used in the NPL report, covering unweighted SPL$_{peak}$ and SEL$_{ss}$ metrics, and M-Weighted SEL$_{ss}$ values from Southall *et al*. (2007). Also included for comparison are the results for the 5500 kJ hammer energies (in bold). The predicted ranges smaller than 50 m, and area less than 0.1 km^2 have not been presented as the modelling processes are unable to specify that level of accuracy with confidence due to acoustic effects near the source and other noise processes at close ranges. A complete comparison between the NPL modelling and the equivalent INSPIRE modelling is given in Appendix A. The results that are large enough to be shown clearly are also presented in Appendix B as contour plots.

Harbour porpoise - impact criterion		300 kJ hammer energy	1900 kJ hammer energy	2300 kJ hammer energy	3000 kJ hammer energy	4000 kJ hammer energy	5500 kJ hammer energy
Instantaneous injury/PTS (pulse SEL 179 dB re 1 µPa^{2}s)	Max	150 m	520 m	590 m	700 m	850 m	**1.1 km**
	Min	140 m	510 m	580 m	690 m	840 m	**1.0 km**
	Mean	150 m	520 m	590 m	700 m	850 m	**1.0 km**
	Area	< 0.1 km^2	0.8 km^2	1.1 km^2	1.5 km^2	2.2 km^2	**3.4 km^2**
TTS/fleeing response (pulse SEL 164 dB re 1 µPa^{2}s)	Max	1.5 km	4.6 km	5.2 km	6.0 km	6.9 km	**8.1 km**
	Min	1.5 km	4.6 km	5.1 km	5.8 km	6.7 km	**7.9 km**
	Mean	1.5 km	4.6 km	5.1 km	5.9 km	6.8 km	**7.9 km**
	Area	7.0 km^2	66.2 km^2	81.5 km^2	108 km^2	145 km^2	**197 km^2**
Possible avoidance of area (pulse SEL 145 re 1 µPa^{2}s)	Max	15.4 km	28.6 km	30.3 km	32.7 km	35.5 km	**38.9 km**
	Min	14.1 km	23.8 km	24.9 km	26.3 km	27.8 km	**29.5 km**
	Mean	14.7 km	26.2 km	27.6 km	29.5 km	31.7 km	**34.2 km**
	Area	676 km^2	2160 km^2	2390 km^2	2740 km^2	3160 km^2	**3680 km^2**

Table 4-1 Predicted harbour porpoise impact ranges using criteria derived from Lucke et al. (2009)

Mid-frequency cetaceans - impact criterion		300 kJ hammer energy	1900 kJ hammer energy	2300 kJ hammer energy	3000 kJ hammer energy	4000 kJ hammer energy	5500 kJ hammer energy
Instantaneous injury/PTS (M$_{mf}$ SEL$_{ss}$ 198 dB re 1 µPa^{2}s)	Max	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	**< 50 m**
	Min	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	**< 50 m**
	Mean	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	**< 50 m**
	Area	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	**< 0.1 km^2**
TTS/fleeing response (M$_{mf}$ SEL$_{ss}$ 183 dB re 1 µPa^{2}s)	Max	< 50 m	100 m	110 m	140 m	160 m	**200 m**
	Min	< 50 m	90 m	100 m	130 m	150 m	**190 m**
	Mean	< 50 m	95 m	110 m	135 m	160 m	**200 m**
	Area	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	**0.1 km^2**
Likely avoidance of area (pulse SEL 170 re 1 µPa^{2}s)	Max	600 m	2.0 km	2.3 km	2.7 km	3.2 km	**3.9 km**
	Min	590 m	2.0 km	2.3 km	2.7 km	3.2 km	**3.8 km**
	Mean	600 m	2.0 km	2.3 km	2.7 km	3.2 km	**3.8 km**
	Area	1.1 km^2	12.7 km^2	16.2 km^2	22.5 km^2	31.8 km^2	**46.2 km^2**
Possible avoidance of area (pulse SEL 160 re 1 µPa^{2}s)	Max	2.7 km	7.6 km	8.3 km	9.4 km	10.7 km	**12.3 km**
	Min	2.7 km	7.3 km	8.0 km	9.0 km	10.2 km	**11.6 km**
	Mean	2.7 km	7.4 km	8.1 km	9.2 km	10.4 km	**11.9 km**
	Area	22.5 km^2	172 km^2	207 km^2	264 km^2	339 km^2	**444 km^2**

Table 4-2 Predicted mid-frequency cetacean impact ranges using criteria derived from Southall et al. (2007)

Low-frequency cetaceans - impact criterion		**300 kJ hammer energy**	**1900 kJ hammer energy**	**2300 kJ hammer energy**	**3000 kJ hammer energy**	**4000 kJ hammer energy**	**5500 kJ hammer energy**
Instantaneous injury/PTS (M$_{lf}$ SEL$_{ss}$ 198 dB re 1 μPa^{2}s)	Max	< 50 m	< 50 m	< 50 m	< 50 m	50 m	**60 m**
	Min	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	**50 m**
	Mean	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	**60 m**
	Area	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	**< 0.1 km^2**
TTS/fleeing response (M$_{lf}$ SEL$_{ss}$ 183 dB re 1 μPa^{2}s)	Max	90 m	280 m	320 m	380 m	460 m	**570 m**
	Min	80 m	270 m	310 m	370 m	450 m	**560 m**
	Mean	85 m	280 m	320 m	380 m	460 m	**570 m**
	Area	< 0.1 km^2	0.2 km^2	0.3 km^2	0.4 km^2	0.7 km^2	**1.0 km^2**
Likely avoidance of area (pulse SEL 152 re 1 μPa^{2}s)	Max	7.6 km	16.8 km	18.0 km	19.8 km	21.8 km	**24.1 km**
	Min	7.3 km	15.3 km	16.3 km	17.6 km	19.1 km	**20.8 km**
	Mean	7.4 km	16.0 km	17.1 km	18.7 km	20.4 km	**22.5 km**
	Area	172 km^2	800 km^2	913 km^2	1090 km^2	1310 km^2	**1580 km^2**
Possible avoidance of area (pulse SEL 142 re 1 μPa^{2}s)	Max	19.8 km	34.9 km	36.9 km	40.0 km	43.6 km	**48.2 km**
	Min	17.6 km	27.5 km	28.5 km	29.9 km	31.5 km	**33.4 km**
	Mean	18.7 km	31.3 km	32.8 km	34.9 km	37.3 km	**40.0 km**
	Area	1090 km^2	3080 km^2	3380 km^2	3830 km^2	4370 km^2	**5060 km^2**

Table 4-3 Predicted low-frequency cetacean impact ranges using criteria derived from Southall et al. (2007)

Pinnipeds (in water) - impact criterion		**300 kJ hammer energy**	**1900 kJ hammer energy**	**2300 kJ hammer energy**	**3000 kJ hammer energy**	**4000 kJ hammer energy**	**5500 kJ hammer energy**
Instantaneous injury/PTS (M$_{pw}$ SEL$_{ss}$ 186 dB re 1 μPa^{2}s)	Max	< 50 m	110 m	120 m	140 m	170 m	**210 m**
	Min	< 50 m	100 m	110 m	130 m	160 m	**200 m**
	Mean	< 50 m	110 m	120 m	140 m	170 m	**210 m**
	Area	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	**0.1 km^2**
TTS/fleeing response (M$_{pw}$ SEL$_{ss}$ 171 dB re 1 μPa^{2}s)	Max	300 m	1.0 km	1.2 km	1.4 km	1.7 km	**2.1 km**
	Min	290 m	1.0 km	1.2 km	1.4 km	1.7 km	**2.0 km**
	Mean	300 m	1.0 km	1.2 km	1.4 km	1.7 km	**2.1 km**
	Area	0.3 km^2	3.3 km^2	4.2 km^2	6.1 km^2	8.8 km^2	**13.2 km^2**

Table 4-4 Predicted pinniped (in water) impact ranges using criteria from Southall et al. (2007)

4.2 NMFS (2016) impact ranges

Table 4-5 to Table 4-8 present the impact ranges for the NMFS (2016) criteria for marine mammals. As before, ranges smaller than 50 m have not been presented.

The results show that, using the NMFS (2016) SPL$_{peak}$ criteria, ranges are largely within a few hundred metres, with only the TTS ranges for high-frequency cetaceans extending over 1 km.

A full comparison between the results for PTS, TTS and behavioural criteria used in the NPL report and the new criteria used for this study are given in Appendix A. The ranges for all species groups are greater with the increase in maximum monopile blow energy.

Comparing the criteria used previously to the SPL$_{peak}$ NMFS (2016) criteria, reductions in impact ranges are shown for every hearing group.

Low-frequency cetaceans - impact criterion		**2300 kJ hammer energy**	**3000 kJ hammer energy**	**4000 kJ hammer energy**	**5500 kJ hammer energy**
PTS unweighted SPL_{peak} (219 re 1 μPa)	Maximum	50 m	60 m	70 m	**80 m**
	Minimum	< 50 m	50 m	60 m	**70 m**
	Mean	< 50 m	55 m	65 m	**75 m**
	Area	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	**< 0.1 km^2**
TTS unweighted SPL_{peak} (213 re 1 μPa)	Maximum	100 m	120 m	140 m	**160 m**
	Minimum	90 m	110 m	130 m	**150 m**
	Mean	95 m	120 m	140 m	**160 m**
	Area	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	**< 0.1 km^2**

Table 4-5 Predicted low-frequency cetacean unweighted SPL_{peak} impact ranges using criteria from NMFS (2016)

Mid-frequency cetaceans - impact criterion		**2300 kJ hammer energy**	**3000 kJ hammer energy**	**4000 kJ hammer energy**	**5500 kJ hammer energy**
PTS unweighted SPL_{peak} (230 re 1 μPa)	Maximum	< 50 m	< 50 m	< 50 m	**< 50 m**
	Minimum	< 50 m	< 50 m	< 50 m	**< 50 m**
	Mean	< 50 m	< 50 m	< 50 m	**< 50 m**
	Area	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	**< 0.1 km^2**
TTS unweighted $SPL_{peak=}$ (224 re 1 μPa)	Maximum	< 50 m	< 50 m	< 50 m	**50 m**
	Minimum	< 50 m	< 50 m	< 50 m	**< 50 m**
	Mean	< 50 m	< 50 m	< 50 m	**< 50 m**
	Area	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	**< 0.1 km^2**

Table 4-6 Predicted mid-frequency cetacean unweighted SPL_{peak} impact ranges using criteria from NMFS (2016)

High-frequency cetaceans - impact criterion		**2300 kJ hammer energy**	**3000 kJ hammer energy**	**4000 kJ hammer energy**	**5500 kJ hammer energy**
PTS unweighted SPL_{peak} (202 re 1 μPa)	Maximum	430 m	500 m	590 m	**710 m**
	Minimum	420 m	490 m	580 m	**700 m**
	Mean	430 m	500 m	590 m	**710 m**
	Area	0.6 km^2	0.8 km^2	1.1 km^2	**1.6 km^2**
TTS unweighted SPL_{peak} (196 re 1 μPa)	Maximum	960 m	1.1 km	1.3 km	**1.6 km**
	Minimum	950 m	1.1 km	1.3 km	**1.6 km**
	Mean	950 m	1.1 km	1.3 km	**1.6 km**
	Area	2.8 km^2	3.8 km^2	5.3 km^2	**7.7 km^2**

Table 4-7 Predicted high-frequency cetacean unweighted SPL_{peak} impact ranges using criteria from NMFS (2016)

Phocid pinnipeds - impact criterion		**2300 kJ hammer energy**	**3000 kJ hammer energy**	**4000 kJ hammer energy**	**5500 kJ hammer energy**
PTS unweighted SPL_{peak} (218 re 1 μPa)	Maximum	60 m	70 m	80 m	**90 m**
	Minimum	50 m	60 m	70 m	**80 m**
	Mean	55 m	65 m	75 m	**85 m**
	Area	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	**< 0.1 km^2**
TTS unweighted SPL_{peak} (212 re 1 μPa)	Maximum	110 m	130 m	160 m	**190 m**
	Minimum	100 m	120 m	150 m	**180 m**
	Mean	110 m	130 m	160 m	**190 m**
	Area	< 0.1 km^2	< 0.1 km^2	< 0.1 km^2	**0.1 km^2**

Table 4-8 Predicted phocid pinniped unweighted SPL_{peak} impact ranges using criteria from NMFS (2016)

5 Summary and conclusions

Underwater noise modelling was carried out by NPL in 2013 to assess the effects of impact piling noise from the construction of the Sofia offshore windfarm, in the Dogger Bank development area. In the time since the original modelling was completed, new noise thresholds and criteria have been developed by NMFS (2016) for marine mammals. To obtain impact ranges for these new criteria, additional modelling has been carried out by Subacoustech Environmental. This additional modelling has sought to be compatible with the results of the NPL modelling.

In addition to modelling to the new criteria, two piling hammer blow energies greater than that considered originally have been assessed.

The modelling undertaken by NPL utilised an energy flux solution, and the model used is not openly available. Subacoustech have used a different but comparable method using the semi-empirical INSPIRE model.

Modelling was carried out to obtain source levels and propagation losses comparable with those used in the NPL modelling. A conservative fit to the data was used so that levels predicted along the worst-case transect match with the highest levels reported by NPL, especially at the greatest distances. Overall, there was a good level of correlation between the two modelling result datasets.

The modelling results using the new metrics showed that, using the NMFS (2016) $\mathrm{SPL}_{\mathrm{peak}}$ criteria, ranges are largely within a few hundred metres, with only the TTS ranges for high-frequency cetaceans extending over 1 km.

All modelled scenarios using the increased maximum blow energy for monopiles result in larger impact ranges than with the largest monopile blow energy used in the original report.

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Appendix A Modelling comparisons

This appendix collects the impact ranges for PTS, TTS, and behavioural response given using the criteria as presented in the NPL report (Theobald *et al*. 2013) and compares them to the like-for-like criteria for the new modelling.

This gives a reference to compare like-for-like criteria so that the differences between the metrics, criteria and impact ranges can be easily made.

High-Frequency Cetaceans (Harbour Porpoise)	**300 kJ hammer energy**	**1900 kJ hammer energy**	**2300 kJ hammer energy**	**3000 kJ hammer energy**	**4000 kJ hammer energy**	**5500 kJ hammer energy**
NPL PTS unweighted (pulse SEL 179 dB re 1 $\mu Pa^2 s$)	< 200 m	< 500 m	< 550 m	< 700 m	-	-
Updated PTS unweighted (pulse SEL 179 dB re 1 $\mu Pa^2 s$)	140 to 150 m	510 to 520 m	580 to 590 m	690 to 700 m	840 to 850 m	**1.0 to 1.1 km**
NPL TTS unweighted (pulse SEL 164 dB re 1 $\mu Pa^2 s$)	< 1.5 km	3.6 to 4.2 km	3.8 to 4.8 km	4.0 to 5.5 km	-	**-**
Updated TTS unweighted (pulse SEL 164 dB re 1 $\mu Pa^2 s$)	1.5 km	4.6 km	5.1 to 5.2 km	5.8 to 6.0 km	6.7 to 6.9 km	**7.9 to 8.1 km**
NPL behavioural response unweighted (pulse SEL 145 dB re 1 $\mu Pa^2 s$)	10.0 to 14.0 km	19.5 to 29.5 km	21.0 to 30.5 km	22.0 to 33.5 km	-	**-**
Updated behavioural response unweighted (pulse SEL 145 dB re 1 $\mu Pa^2 s$)	14.1 to 15.4 km	23.8 to 28.6 km	24.9 to 30.3 km	26.3 to 32.7 km	27.8 to 35.5 km	**29.5 to 38.9 km**

Table A 1 Comparison of criteria for high-frequency cetaceans including harbour porpoise

Mid-Frequency Cetaceans	**300 kJ hammer energy**	**1900 kJ hammer energy**	**2300 kJ hammer energy**	**3000 kJ hammer energy**	**4000 kJ hammer energy**	**5500 kJ hammer energy**
NPL PTS weighted (198 dB re 1 $\mu Pa^2 s$ SEL_{ss} M_{mf})	< 100 m	< 100 m	< 100 m	< 100 m	-	-
Updated PTS weighted (198 dB re 1 $\mu Pa^2 s$ SEL_{ss} M_{mf})	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	**< 50 m**
NPL TTS weighted (183 dB re 1 $\mu Pa^2 s$ SEL_{ss} M_{mf})	< 100 m	< 150 m	< 200 m	< 200 m	-	**-**
Updated TTS weighted (183 dB re 1 $\mu Pa^2 s$ SEL_{ss} M_{mf})	< 50 m	90 to 100 m	100 to 110 m	130 to 140 m	150 to 160 m	**190 to 200 m**
NPL behavioural response unweighted (pulse SEL 170-160 dB re 1 $\mu Pa^2 s$)	0.6 to 2.5 km	2.0 to 4.2 km	2.2 to 7.5 km	2.5 to 8.5 km	-	**-**
Updated behavioural response unweighted (pulse SEL 170-160 dB re 1 $\mu Pa^2 s$)	0.59 to 2.7 km	2.0 to 7.6 km	2.3 to 8.3 km	2.7 to 9.4 km	3.2 to 10.7 km	**3.8 to 12.3 km**

Table A 2 Comparison of impact criteria for mid-frequency cetaceans

Low-Frequency Cetaceans	**300 kJ hammer energy**	**1900 kJ hammer energy**	**2300 kJ hammer energy**	**3000 kJ hammer energy**	**4000 kJ hammer energy**	**5500 kJ hammer energy**
NPL PTS weighted (198 dB re 1 μPa^2s SEL_{ss} M_{lf})	< 100 m	< 100 m	< 100 m	< 100 m	-	-
Updated PTS weighted (198 dB re 1 μPa^2s SEL_{ss} M_{lf})	< 50 m	< 50 m	< 50 m	< 50 m	50 m	**50 to 60 m**
NPL TTS weighted (183 dB re 1 μPa^2s SEL_{ss} M_{lf})	< 100 m	< 250 m	< 300 m	< 400 m	-	**-**
Updated TTS weighted (183 dB re 1 μPa^2s SEL_{ss} M_{lf})	80 to 90 m	270 to 280 m	310 to 320 m	370 to 380 m	450 to 460 m	**560 to 570 m**
NPL behavioural response unweighted (pulse SEL 152-142 dB re 1 μPa^2s)	5.0 to 19.0 km	11.0 to 36.0 km	12.0 to 38.0 km	13.0 to 41.0 km	-	**-**
Updated behavioural response unweighted (pulse SEL 152-140 dB re 1 μPa^2s)	7.3 to 19.8 km	15.3 to 34.9 km	16.3 to 36.9 km	17.6 to 40.0 km	19.1 to 43.6 km	**20.8 to 48.2 km**

Table A 3 Comparison of impact criteria for low-frequency cetaceans

Pinnipeds (in water)	**300 kJ hammer energy**	**1900 kJ hammer energy**	**2300 kJ hammer energy**	**3000 kJ hammer energy**	**4000 kJ hammer energy**	**5500 kJ hammer energy**
NPL PTS weighted (186 dB re 1 μPa^2s SEL_{ss} M_{pw})	< 100 m	100 m	< 200 m	< 200 m	-	-
Updated PTS weighted (186 dB re 1 μPa^2s SEL_{ss} M_{pw})	< 50 m	100 to 110 m	110 to 120 m	130 to 140 m	160 to 170 m	**200 to 210 m**
NPL TTS weighted (171 dB re 1 μPa^2s SEL_{ss} M_{pw})	< 400 m	< 1.5 km	1.5 km	1.7 km	-	**-**
Updated TTS weighted (171 dB re 1 μPa^2s SEL_{ss} M_{pw})	290 to 300 m	1.0 km	1.2 km	1.4 km	1.7 km	**2.0 to 2.1 km**

Table A 4 Comparison of impact criteria for pinnipeds

Appendix B Modelling figures

This appendix presents the modelled impact ranges from section 4 as contour plots. Only the impact ranges large enough to be shown clearly for the map scale have been included here.

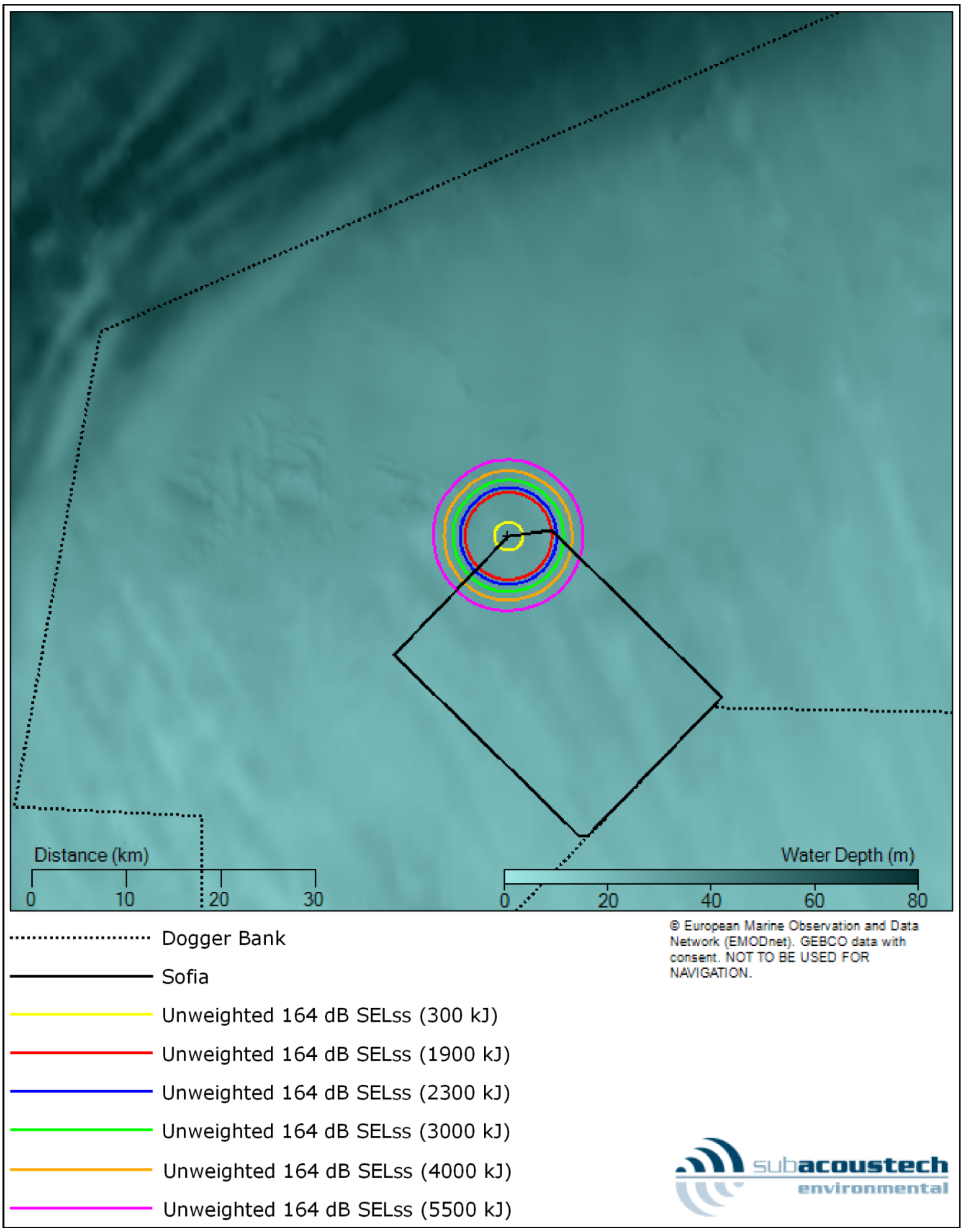

Figure B 1 Contour plot showing the unweighted 164 dB re 1 μPa²s SEL_{ss} *impact ranges for TTS/fleeing response in harbour porpoise for the six modelled hammer blow energies*

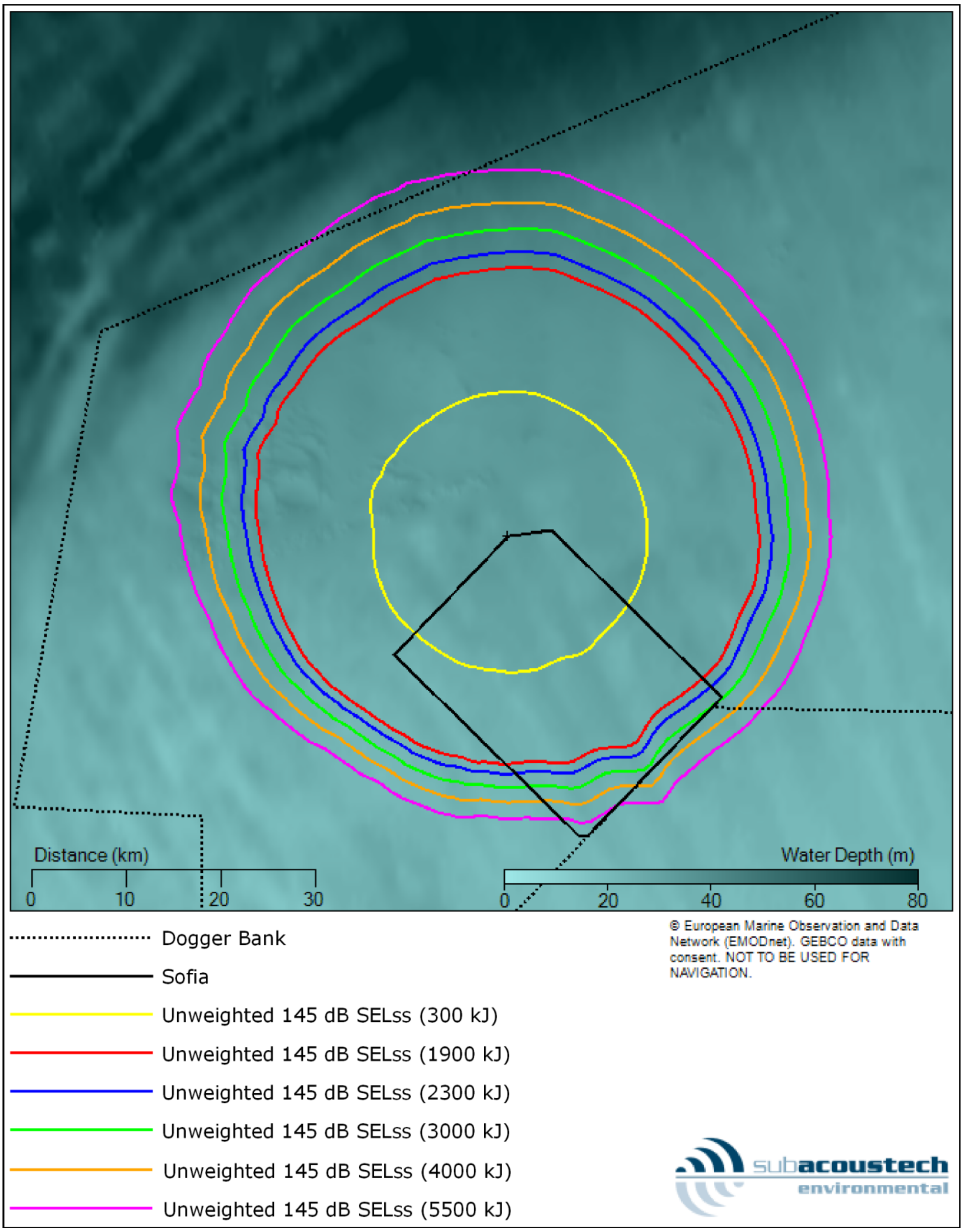

Figure B 2 Contour plot showing the unweighted 145 dB re 1 µPa²s SEL$_{ss}$ impact ranges for possible avoidance of area in harbour porpoise for the six modelled hammer blow energies

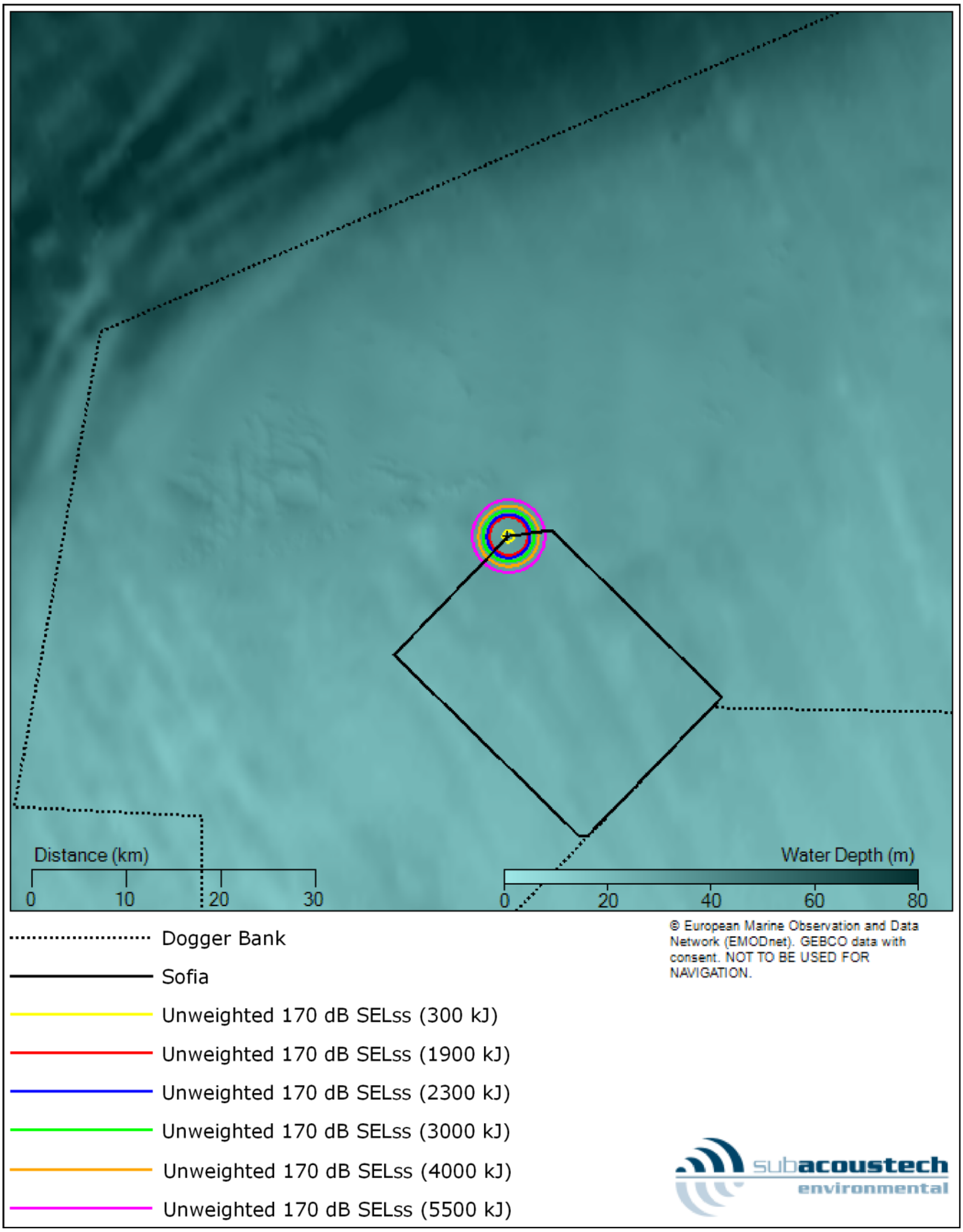

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Figure B 3 Contour plot showing the unweighted 170 dB re 1 µPa²s SEL$_{ss}$ impact ranges for likely avoidance of area in mid-frequency cetaceans for the six modelled hammer blow energies

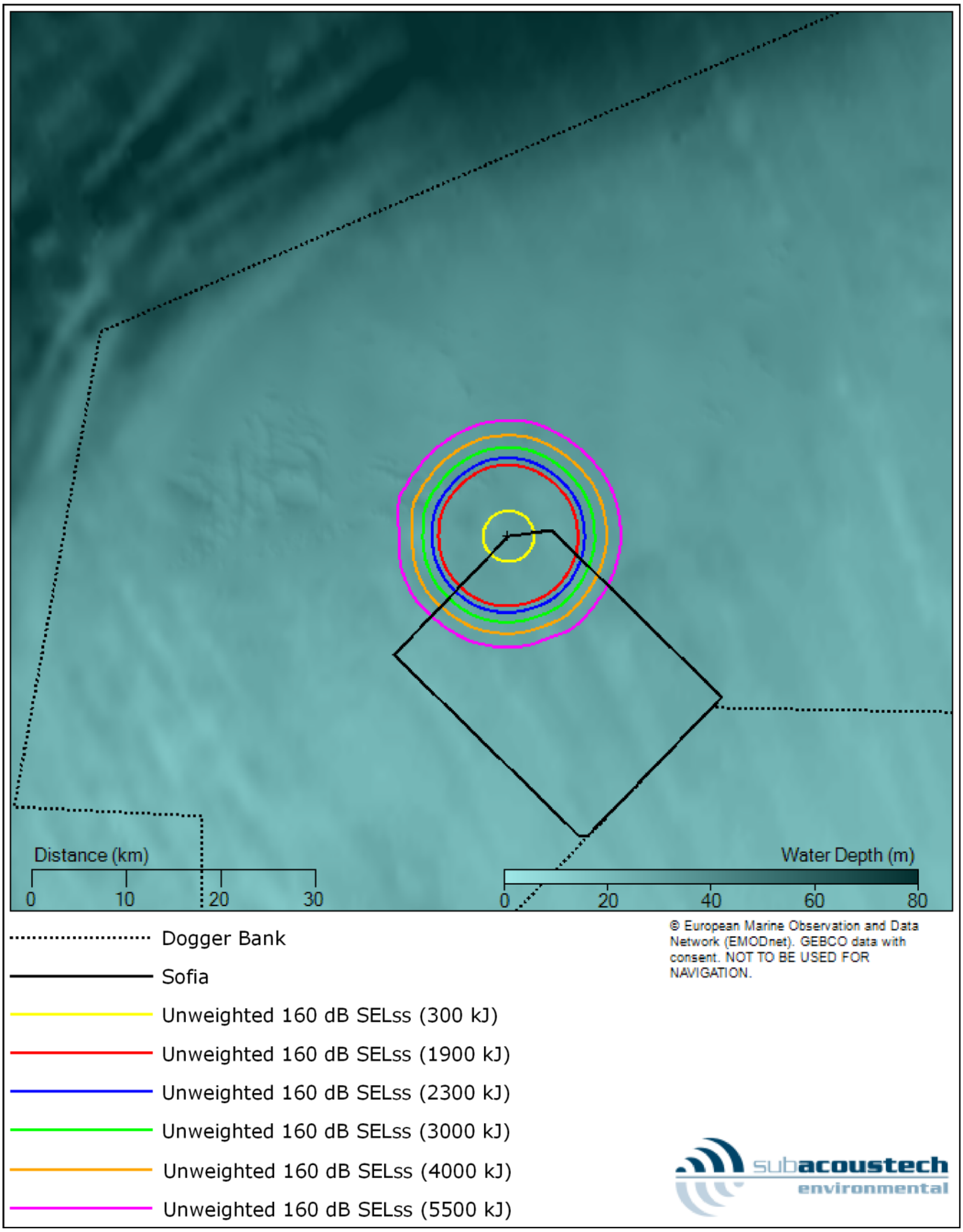

Figure B 4 Contour plot showing the unweighted 160 dB re 1 μPa²s SEL_{ss} impact ranges for possible avoidance of area in mid-frequency cetaceans for the six modelled hammer blow energies

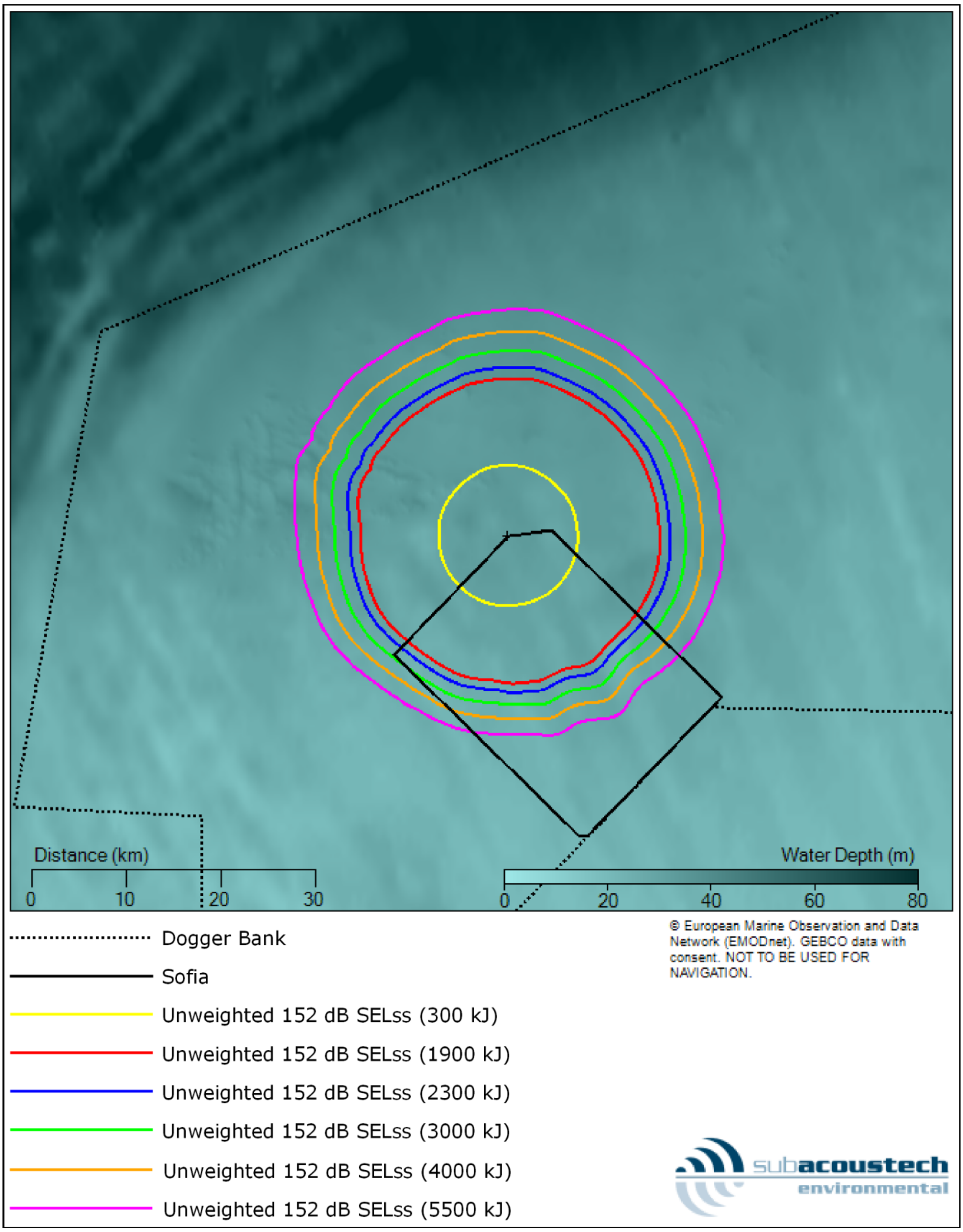

Figure B 5 Contour plot showing the unweighted 152 dB re 1 μPa^{2}s SEL$_{ss}$ impact ranges for likely avoidance of area in low-frequency cetaceans for the six modelled hammer blow energies

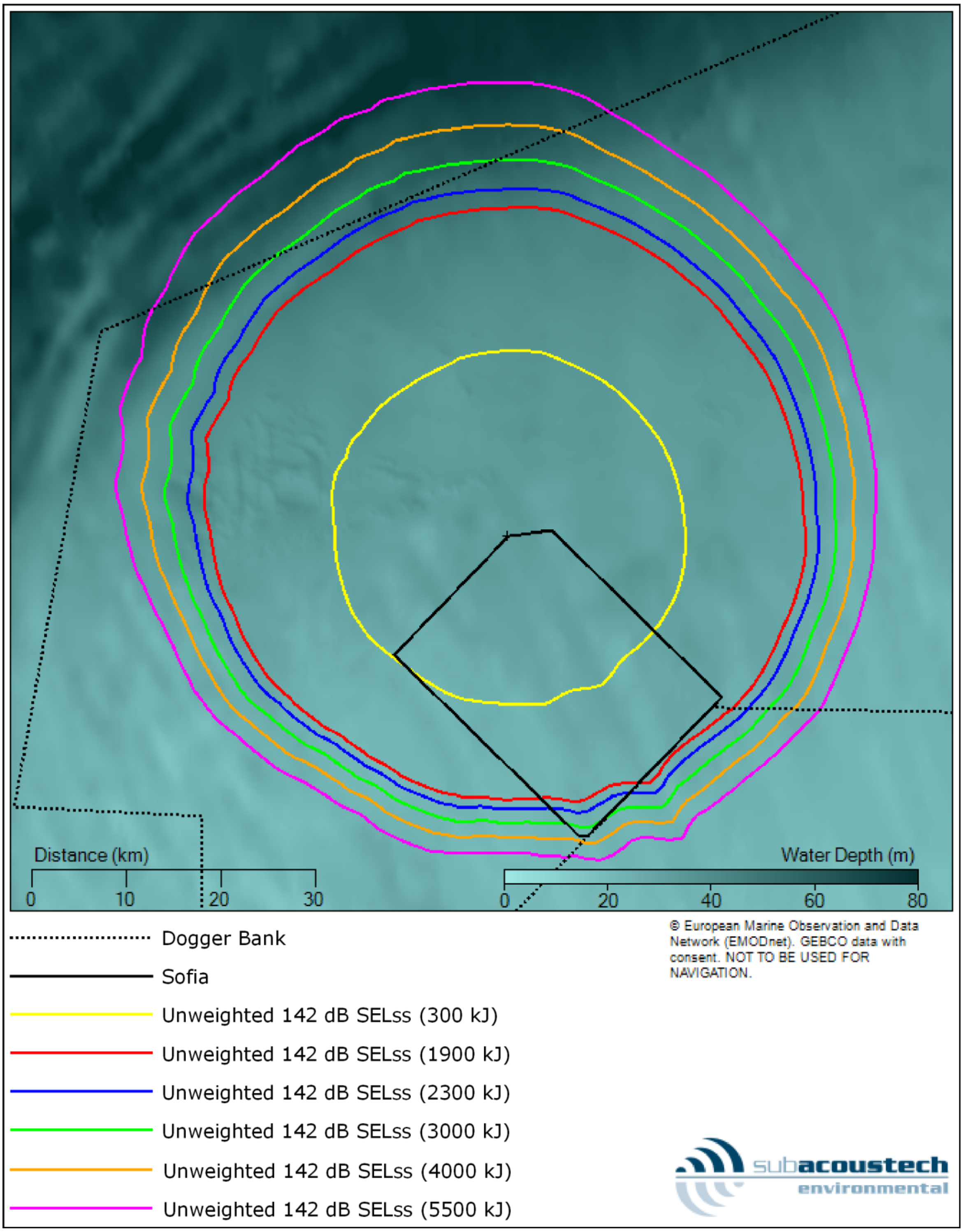

Figure B 6 Contour plot showing the unweighted 142 dB re 1 µPa^{2}s SEL$_{ss}$ impact ranges for possible avoidance of area in low-frequency cetaceans for the six modelled hammer blow energies

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