FIVE ESTUARIES OFFSHORE WIND FARM

VOLUME 6, PART 5, ANNEX 6.2: UNDERWATER NOISE REPORT – REVISION B (CLEAN)

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DEFINITION OF ACRONYMS

Term	Definition
ADD	Acoustic Deterrent Device
bl/min	Blows per minute
dB	Decibel
EIA	Environmental Impact Assessment
EMODnet	European Marine Observation and Data Network
GEBCO	General Bathymetric Chart of the Oceans
GIS	Geographic Information System
HF	High-frequency cetacean (Southall *et al*., 2019 weighting)
Hz	Hertz
INSPIRE	Impulsive Noise Sound Propagation and Impact Range Estimator
kHz	Kilohertz
kJ	Kilojoules
km	Kilometres
km^2	Square kilometres
LF	Low-frequency cetacean (Southall *et al*., 2019 weighting)
LvR	Level vs. Range
m	Metre
mm/s	Millimetres per second
m/s	Metres per second
MTD	Marine Technical Directorate Ltd.
MW	Megawatt
N edge	North edge (Modelling location)
NE corner	North East corner (Modelling location)
NMFS	National Marine Fisheries Service
NPL	National Physical Laboratory
Pa	Pascal
Pa^2s	Pascal squared seconds
PCW	Phocid carnivore in water (Southall *et al*., 2019 weighting)
PPV	Peak Particle Velocity
PTS	Permanent Threshold Shift

Term	Definition
RMS	Root Mean Square
SE	Sound Exposure
SEL	Sound Exposure Level
SEL_{cum}	Cumulative Sound Exposure Level
SEL_{ss}	Single-strike Sound Exposure Level
SPL	Sound Pressure Level
SPL_{peak}	Peak Sound Pressure Level
$SPL_{peak\text{-}to\text{-}peak}$	Peak-to-Peak Sound Pressure Level
SW corner	South West corner (Modelling location)
TNT	Trinitrotoluene (Explosive)
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance
VE	Five Estuaries Offshore Wind Farm
VHF	Very high-frequency cetacean (Southall *et al*., 2019 weighting)
WTG	Wind Turbine Generator
µPa	Micropascal

1 UNDERWATER NOISE

1.1 INTRODUCTION

1.1.1 The Five Estuaries Offshore Wind Farm (VE) is a proposed offshore wind farm situated in the southern North Sea; an extension to the existing Galloper Offshore Wind Farm. As part of the Environmental Impact Assessment (EIA) process, Subacoustech Environmental Ltd. has undertaken detailed modelling and analysis in relation to the effect of underwater noise on the marine mammals and fish at the site.

1.1.2 The VE site covers an area of approximately 128 km^2 and is situated, at its closest point, 37 km from the Suffolk shore. The location of VE is shown in Figure 1.1.

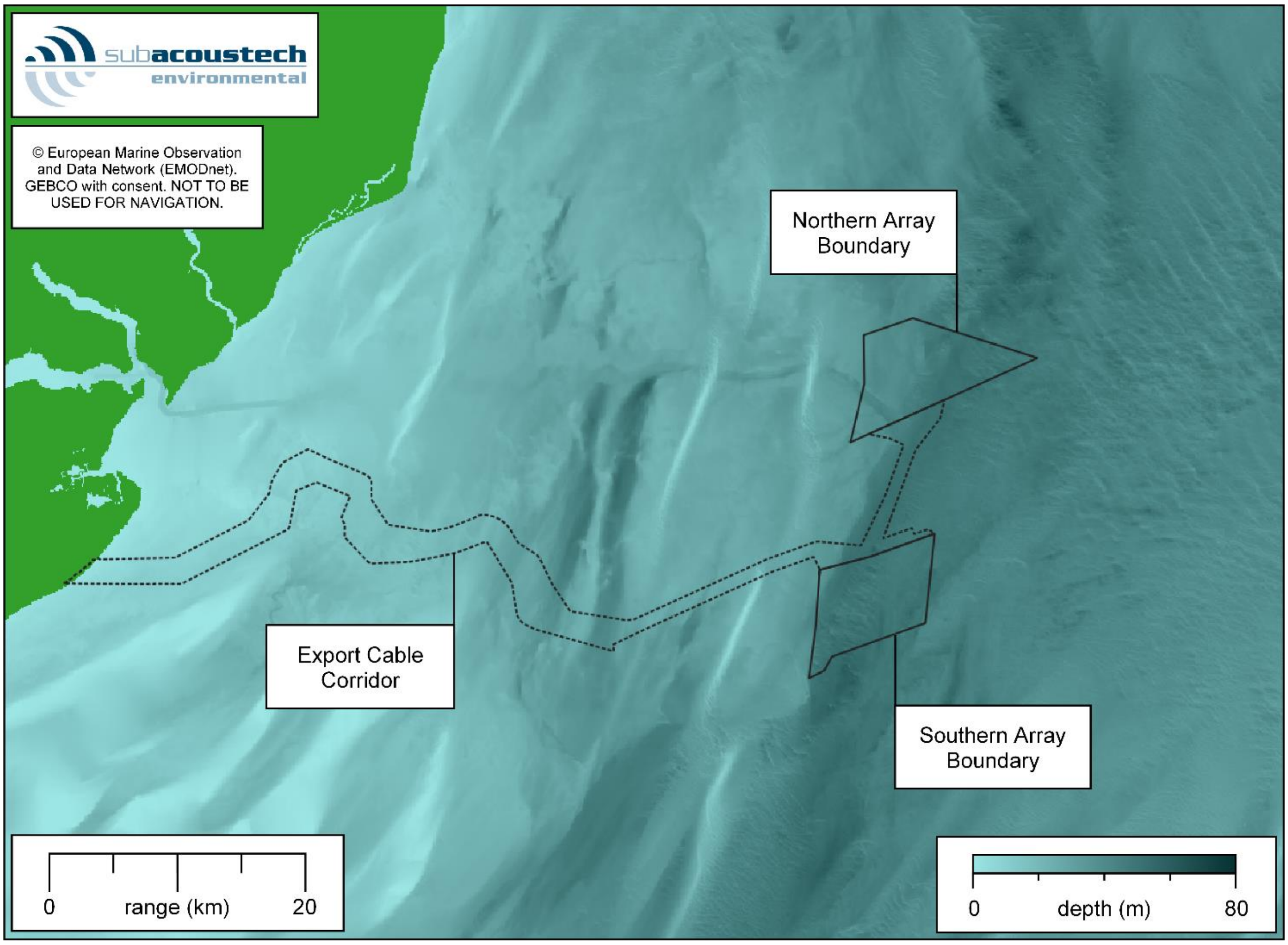

Figure 1.1: Overview map showing the VE boundary and the surrounding bathymetry.

1.1.3 This report presents a detailed assessment of the potential underwater noise during the construction and operation of VE, and includes the following:

> Background information covering the units for measuring and assessing underwater noise and a review of the underwater noise metrics and criteria used to assess the possible environmental effects in marine receptors (Section 1.2);

> Discussion of the approach, input parameters and assumptions for the detailed noise modelling undertaken (Section 1.3);

> Presentation and interpretation of the detailed subsea modelling for impact piling with regards to its effects on marine mammals and fish (Section 1.4);

- Noise modelling of other noise sources expected during the construction and operation of VE including cable laying, rock placement, dredging, trenching, vessel activity, operational Wind Turbine Generator (WTG) noise, and unexploded ordnance (UXO) clearance (Section 1.5); and
- Summary and conclusions (Section 1.6).

1.2 BACKGROUND TO UNDERWATER NOISE METRICS

UNDERWATER NOISE

1.2.1 Sound travels much faster in water (approximately 1,500 m/s) than in air (340 m/s). Since water is a relatively incompressible, dense medium, the pressure associated with underwater sound tends to be much higher than in air. As an example, background noise levels in the sea of 130 dB re 1 µPa for UK coastal waters are not uncommon (Nedwell *et al*., 2003; Nedwell *et al*., 2007).

1.2.2 It should be noted that stated underwater noise levels should not be confused with noise levels in air, which use a different scale.

UNITS OF MEASUREMENT

1.2.3 Sound measurements are usually expressed using the decibel (dB) scale, which is a logarithmic measure of sound. A logarithmic scale is used because a doubling of sound level will cause a roughly equal increase of "loudness", rather than equal additional increments.

1.2.4 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."

1.2.5 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.

1.2.6 The dB scale represents a ratio. 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 example, a reference quantity of 20 µPa is used for sound in air since that is the lower threshold of human hearing.

1.2.7 When used with sound pressure, the pressure value is squared. So that variations in the units agree, the sound pressure must be specified as units of Root Mean Square (RMS) pressure squared. This is equivalent to expressing the sound as:

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

1.2.8 For underwater sound, a unit of 1 µPa is typically used as the reference unit (P_{ref}); a Pascal is equal to the pressure exerted by one Newton over one square metre, one micropascal equals one millionth of this.

SOUND PRESSURE LEVEL

1.2.9 The Sound Pressure Level (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 period to determine the RMS level of the time-varying sound. The SPL can therefore be considered a measure of the average level of sound over the measurement period.

1.2.10 Where SPL is used to characterise transient pressure waves, such as that from impact piling, seismic airgun, or underwater blasting, it is critical that the period over which the RMS level is calculated is quoted. For instance, in the case of a pile strike lasting a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean averaged over one second. Often, transient sounds such as these are quantified using “peak” SPLs or Sound Exposure Levels (SELs).

1.2.11 Unless otherwise defined, all SPL noise levels in this report are referenced to 1 µPa.

PEAK SOUND PRESSURE LEVEL

1.2.12 Peak SPLs are often used to characterise transient sound from impulsive sources, such as percussive impact piling. SPL_{peak} 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.

1.2.13 A further variation of this is the peak-to-peak SPL ($SPL_{peak\text{-}to\text{-}peak}$) where the maximum variation of the pressure from positive to negative is considered. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak pressure will be twice the peak level, or 6 dB.

SOUND EXPOSURE LEVELS (SEL)

1.2.14 When considering the noise from transient sources, the issue of the duration 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, 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 injury ranges for fish and marine mammals from various noise sources (Popper *et al*., 2014; Southall *et al*., 2007; Southall *et al*., 2019).

1.2.15 The SEL sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound and the duration it 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 total duration sound in seconds, and t is the time in seconds. The SE is a measurement of acoustic energy and has units of Pascal squared seconds (Pa^2s).

1.2.16 To express the SE on a logarithmic scale by means of a dB, it must be compared with a reference acoustic energy level (${p^2}_{ref}$) and a reference time (T_{ref}). The SEL is then defined by:

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

1.2.17 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 broadband noise and the SEL sums the cumulative noise energy.

1.2.18 This means that, for continuous sound 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 continuous sound of 10 seconds of 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).

1.2.19 Where a single impulsive noise such as the soundwave from a pile strike is considered in isolation, this can be represented by a "single strike" SEL or SEL_{ss}. A cumulative SEL, or SEL_{cum}, accounts for the exposure from multiple impulses or pile strikes over time, where the number of impulses replaces the T in the equation above, leading to:

$$SEL_{cum} = SEL + 10 \times \log_{10} X$$

1.2.20 Where SEL is the sound exposure level of one impulse and X is the total number of impulses or strikes.

1.2.21 Unless otherwise defined, all SEL noise levels in this report are referenced to 1 µPa^{2}s.

ANALYSIS OF ENVIRONMENTAL EFFECTS

1.2.22 Over the last 20 years it has become increasingly evident that noise from human activities in and around underwater environments can have an impact on the marine species in that area. The extent to which intense underwater sound might cause adverse impacts in species is dependent upon the incident sound level, source 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 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 immediate environmental impact and therefore the clearest observable effects, although interest in chronic noise exposure is increasing.

1.2.23 The impacts of underwater sound on marine species can be broadly summarised into the following groups:

> Physical traumatic injury and fatality;

> Auditory injury (either permanent or temporary); and

- Disturbance.

1.2.24 The following sections discuss the underwater noise criteria used in this study with respect to the species of marine mammals and fish that may be present around VE.

1.2.25 The main metrics and criteria that have been used in this study to aid assessment of environmental effects come from two key papers covering underwater noise and its effects:

- Southall *et al*. (2019) marine mammal exposure criteria; and
- Popper *et al*. (2014) sound exposure guidelines for fishes and sea turtles.

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

MARINE MAMMALS

1.2.27 The Southall *et al*. (2019) paper is effectively an update of the previous Southall *et al*. (2007) paper and provides identical thresholds to those from the National Marine Fisheries Service (NMFS) (2018) guidance for marine mammals (although it names marine mammal categories slightly differently, see paragraph 1.2.35).

1.2.28 The Southall *et al*. (2019) guidance groups marine mammals into groups of similar species and applies filters to the unweighted noise to approximate the hearing sensitivities of the receptor in question. The hearing groups given by Southall *et al*. (2019) are summarised in Table 1.1 and Figure 1.2. Further groups for sirenians and other marine carnivores in water are given, but these have not been included in this study as those species are not commonly found in the North Sea.

Table 1.1: Marine mammal hearing groups (from Southall *et al*., 2019).

Hearing group	Generalised hearing range	Example species
Low-frequency cetaceans (LF)	7 Hz to 35 kHz	Baleen whales
High-frequency cetaceans (HF)	150 Hz to 160 kHz	Dolphins, toothed whales, beaked whales, bottlenose whales (including bottlenose dolphin)
Very high-frequency cetaceans (VHF)	275 Hz to 160 kHz	True porpoises (including harbour porpoise)
Phocid carnivores in water (PCW)	50 Hz to 86 kHz	True seals (including harbour seal)

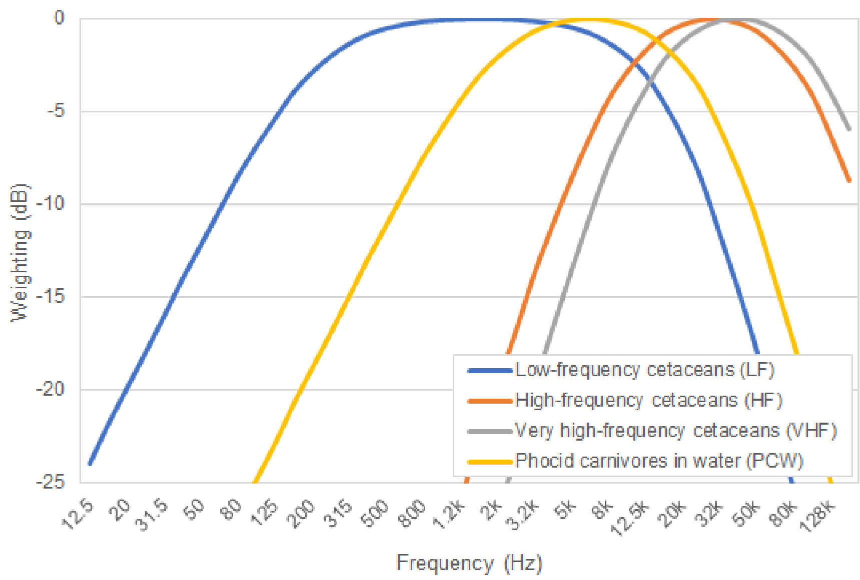

Figure 1.2: Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall *et al*., 2019).

1.2.29 Southall *et al*. (2019) also gives individual criteria based on whether the noise source is considered impulsive or non-impulsive. Southall *et al*. (2019) categorises impulsive noises as having high peak sound pressure, short duration, fast rise-time and broad frequency content at source, and non-impulsive sources as steady state noise. Explosives, impact piling and seismic airguns are considered impulsive noise sources, whereas sonars, vibro-piling, drilling and other low-level, continuous noises are considered non-impulsive. A non-impulsive noise does not necessarily have to have a long duration.

1.2.30 Southall *et al*. (2019) presents single strike, unweighted peak criteria (SPL_{peak}) and cumulative weighted sound exposure criteria (SEL_{cum}, i.e., can include the accumulated exposure of multiple pulses), for both permanent threshold shift (PTS), where unrecoverable (but incremental) hearing damage may occur, and temporary threshold shift (TTS), where a temporary reduction in hearing sensitivity may occur in individual receptors. These dual criteria (SPL_{peak} and SEL_{cum}) are only used for impulsive noise: the criteria set giving the greatest calculated range is typically used as the relevant impact range.

1.2.31 As sound pulses propagate through the environment and dissipate, they also lose their most injurious characteristics (e.g., rapid pulse rise-time and high peak sound pressure) and becomes more like a non-impulsive noise at greater distances; Southall *et al*. (2019) briefly discusses this. Active research is currently underway into the identification of a distance at which the pulse can be considered non-impulsive, and Hastie *et al*. (2019) have analysed a series of impulsive data to investigate it. Although the situation is complex, the paper recorded that most signals crossed their threshold for rapid rise-time and high peak sound pressure characteristics associated with impulsive noise at around 3.5 km from the source. Southall (2021) discusses this further and suggests that the impulsive characteristics can correspond with significant energy content of the pulse above 10 kHz. This will naturally change depending on the noise source and environment over which it travels.

1.2.32 Research by Martin *et al*. (2020) casts doubt on these findings, showing that noise in this category should be considered impulsive as long as it is above effective quiet, or a noise sufficiently quiet enough that it does not contribute significantly to any auditory impairment or injury. To provide as much detail as possible, both impulsive and non-impulsive criteria from Southall *et al*. (2019) have been included in this study.

1.2.33 Although the use of impact ranges derived using the impulsive criteria are recommended for all but the clearly non-impulsive sources, it should be recognised that where calculated ranges are beyond 3.5 km, they would be expected to become increasingly less impulsive and harmful, and the impact range is therefore likely to be somewhere between the modelled impulsive and non-impulsive impact range. Where the impulsive range is significantly greater than 3.5 km, the non-impulsive range should be considered.

Table 1.2: Single strike SPL_{peak} criteria for PTS and TTS in marine mammals (Southall *et al*. (2019).

Southall *et al*. (2019) Unweighted SPL_{peak} (dB re 1 μPa)	Impulsive	
	PTS	TTS
Low-frequency cetaceans (LF)	219	213
High-frequency cetaceans (HF)	230	224
Very high-frequency cetaceans (VHF)	202	196
Phocid carnivores in water (PCW)	218	212

Table 1.3: Impulsive and non-impulsive SEL_{cum} criteria for PTS and TTS in marine mammals (Southall *et al*., 2019).

Southall *et al*. (2019) Unweighted SEL_{cum} (dB re 1 μPa^2s)	Impulsive		Non-impulsive	
	PTS	TTS	PTS	TTS
Low-frequency cetaceans (LF)	183	168	199	179
High-frequency cetaceans (HF)	185	170	198	178
Very high-frequency cetaceans (VHF)	155	140	173	153
Phocid carnivores in water (PCW)	185	170	201	181

1.2.34 Where SEL_{cum} exposure thresholds are required, a fleeing animal model has been used for marine mammals. This assumes that a receptor, when exposed to high noise levels, will swim away from the noise source. A constant fleeing speed of 3.25 m/s has been assumed for the low-frequency cetaceans (LF) group, based on data for minke whale (Blix and Folkow, 1995). For other receptors, a constant rate of 1.5 m/s has been assumed for flee speed, which is a cruising speed for a harbour porpoise (Otani *et al*., 2000). These are considered worst-case assumptions as marine mammals are expected to be able to swim much faster under stress conditions (Kastelein *et al*., 2018), especially at the start of any noise process when the receptor will be closest to the noise source.

1.2.35 It is worth noting that, when comparing Southall *et al*. (2019) to NMFS (2018), the two guidance papers apply different names to otherwise identical marine mammal groups and weightings, which are otherwise numerically identical. For example, what Southall *et al*. (2019) calls HF cetaceans, NMFS (2018) calls MF cetaceans, and what Southall *et al*. (2019) calls VHF cetaceans, NMFS (2018) refers to as HF cetaceans. As such, care should be taken when comparing results using the Southall *et al*. (2019) and NMFS (2018) criteria, especially as the HF groupings and criteria cover different species depending on which study is being used.

FISH

1.2.36 The large number of, and 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 studies applied broad criteria based on limited studies of fish that are not present in UK waters (e.g., McCauley *et al*., 2000) or measurement data not intended to be used as criteria (Hawkins *et al*., 2014), the publication of Popper *et al*. (2014) provides an authoritative summary of the latest research and guidelines for fish exposure to sound and uses categories for fish that are representative of the species present in UK waters.

1.2.37 The Popper *et al*. (2014) study groups species of fish by whether they possess a swim bladder, and whether it is involved in its hearing; groups for sea turtles and fish eggs and larvae are also included. The guidance also gives specific criteria (as both unweighted SPL_{peak} and unweighted SEL_{cum} values) for a variety of noise sources. (It is recognised that these are related to sound pressure, whereas more recent documents (e.g., Popper and Hawkins, 2019) clearly state that many fish species are most sensitive to particle motion. This is discussed in the following dedicated section on particle motion).

1.2.38 For this study, criteria for impact piling, continuous noise sources, and explosions have been considered; these are summarised in Table 1.4 to Table 1.6.

Table 1.4: Criteria for mortality and potential mortal injury, recoverable injury, and TTS in species of fish from impact piling noise (Popper *et al*., 2014).

Type of animal	Mortal and potential mortal injury	Impairment	
		Recoverable injury	TTS
Fish: no swim bladder	> 219 dB SEL_{cum} > 213 dB peak	> 216 dB SEL_{cum} > 213 dB peak	>> 186 dB SEL_{cum}
Fish: swim bladder is not involved in hearing	210 dB SEL_{cum} > 207 dB peak	203 dB SEL_{cum} > 207 dB peak	> 186 dB SEL_{cum}
Fish: swim bladder involved in hearing	207 dB SEL_{cum} > 207 dB peak	203 dB SEL_{cum} > 207 dB peak	186 dB SEL_{cum}
Sea turtles	> 210 dB SEL_{cum} > 207 dB peak	See Table 1.7	
Eggs and larvae	> 210 dB SEL_{cum} > 207 dB peak		

Table 1.5: Criteria for recoverable injury and TTS in species of fish from continuous noise sources (Popper *et al*., 2014).

Type of animal	Impairment	
	Recoverable injury	TTS
Fish: swim bladder involved in hearing	170 dB RMS for 48 hrs	158 dB RMS for 12 hrs

Table 1.6: Criteria for potential mortal injury in species of fish from explosions (Popper *et al*., 2014).

Type of animal	Mortality and potential mortal injury
Fish: no swim bladder	229 – 234 dB peak

Type of animal	Mortality and potential mortal injury
Fish: swim bladder is not involved in hearing	229 – 234 dB peak
Fish: swim bladder involved in hearing	229 – 234 dB peak
Sea turtles	229 – 234 dB peak
Eggs and larvae	> 13 mm/s peak velocity

1.2.39 Where insufficient data are available, Popper *et al*. (2014) also gives quantitative criteria that summarise the effect of the noise as having either a high, moderate, or low effect on an individual in either the near-field (tens of metres), intermediate-field (hundreds of metres), or far-field (thousands of metres). These qualitative effects are reproduced in Table 1.7 to Table 1.9.

Table 1.7: Summary of the qualitative effects on species of fish from impact piling noise (Popper *et al*., 2014) (N = Near-field; I = Intermediate-field; F = Far-field).

<table>
<tr><th rowspan="2">Type of animal</th><th colspan="3">Impairment</th><th rowspan="2">Behaviour</th></tr>
<tr><th>Recoverable injury</th><th>TTS</th><th>Masking</th></tr>
<tr><td>Fish: no swim bladder</td><td colspan="2" rowspan="3">See Table 1.4</td><td>(N) Moderate
(I) Low
(F) Low</td><td>(N) High
(I) Moderate
(F) Low</td></tr>
<tr><td>Fish: swim bladder is not involved in hearing</td><td>(N) Moderate
(I) Low
(F) Low</td><td>(N) High
(I) Moderate
(F) Low</td></tr>
<tr><td>Fish: swim bladder involved in hearing</td><td>(N) High
(I) High
(F) Moderate</td><td>(N) High
(I) High
(F) Moderate</td></tr>
<tr><td>Sea turtles</td><td>(N) High
(I) Low
(F) Low</td><td>(N) High
(I) Low
(F) Low</td><td>(N) High
(I) Moderate
(F) Low</td><td>(N) High
(I) Moderate
(F) Low</td></tr>
<tr><td>Eggs and larvae</td><td>(N) Moderate
(I) Low
(F) Low</td><td>(N) Moderate
(I) Low
(F) Low</td><td>(N) Moderate
(I) Low
(F) Low</td><td>(N) Moderate
(I) Low
(F) Low</td></tr>
</table>

Table 1.8: Summary of the qualitative effects on fish from continuous noise from Popper *et al.* (2014) (N = Near-field; I = Intermediate-field; F = Far-field).

Type of animal	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder involved in hearing	(N) Low (I) Low (F) Low	See Table 1.5		(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Sea turtles	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) High (I) Moderate (F) Low
Eggs and larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

Table 1.9: Summary of the qualitative effects on species of fish from explosions (Popper *et al*., 2014) (N = Near-field; I = Intermediate-field; F = Far-field).

Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
Fish: no swim bladder	(N) High (I) High (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing	(N) High (I) High (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) High (F) Low

Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
Fish: swim bladder involved in hearing	(N) High (I) High (F) Low	(N) High (I) High (F) Low	N/A	(N) High (I) High (F) Low
Sea turtles	(N) High (I) High (F) Low	(N) High (I) High (F) Low	N/A	(N) High (I) High (F) Low
Eggs and larvae	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low

1.2.40 Both fleeing animal and stationary animal models have been used to cover the SEL_{cum} criteria for fish. It is recognised that there is limited evidence for fish fleeing from high level noise sources in the wild, and it would be reasonably expected that the reaction would differ between species. Most species are likely to move away from a sound that is loud enough to cause harm (Dahl *et al*., 2015; Popper *et al*., 2014), some may seek protection in the sediment and others may dive deeper in the water column. For those species that flee, the speed chosen for this study of 1.5 m/s is relatively slow in relation to data from Hirata (1999) and thus is considered somewhat conservative.

1.2.41 Although it is feasible that some species will not flee, those that are likely to remain are thought more likely to be benthic species without a swim bladder; these are the least sensitive species to underwater sound. For example, from Popper *et al*. (2014):

"There is evidence (e.g., Goertner et al., 1994; Stephenson et al., 2010; Halvorsen et al., 2012) that little or no damage occurs to fish without a swim bladder except at very short ranges from an in-water explosion event. Goertner (1978) showed that the range from an explosive event over which damage may occur to a non-swim bladder fish is in the order of 100 times less than for the swim bladder fish."

1.2.42 Stationary animal modelling has been included in this study, acknowledging the limited evidence for fish fleeing behaviour as a result of noise exposure, and other modelling for similar EIA projects. However, basing the modelling on a stationary (zero flee speed) receptor is likely to overestimate the potential risk to fish species, assuming that an individual would remain in the high noise level region of the water column for the whole duration of piling, especially when considering the precautionary nature of the parameters already built into the cumulative exposure calculations.Particle motion

1.2.43 The criteria in the above section define the noise impacts on fishes in terms of sound pressure or sound pressure associated functions (i.e., SEL). It has been identified by researchers (e.g., Popper and Hawkins, 2019; Nedelec *et al*., 2016; Radford *et al*., 2012) that many species of fish, as well as invertebrates, detect particle motion rather than acoustic pressure. Particle motion describes the back-and-forth movement of a tiny theoretical “element” of water, substrate or other media as a sound wave passes, rather than the pressure caused by the action of the force created by this movement. Particle motion is usually defined in reference to the velocity of a particle (often a Peak Particle Velocity, PPV), but sometimes the related acceleration or displacement of the particle is used.

1.2.44 Popper and Hawkins (2018) state that in derivation of the sound pressure-based criteria in Popper *et al*. (2014) it may be the unmeasured particle motion detected by the fish, to which the fish were responding: there is a relationship between particle motion and sound pressure in a medium. This relationship is very difficult to define where the sound field is complex, such as close to the noise source, or where there are multiple reflections of the sound wave in shallow water; even the terms “shallow” and “close” do not have simple definitions.

1.2.45 The primary reason for the continuing use of sound pressure as the criteria, despite particle motion appearing to be the physical measure to which so many fish react or sense, is a lack of data (Popper and Hawkins, 2018). This is both in respect of predictions of the particle motion level as a consequence of a noise source such as piling, and a lack of knowledge of the sensitivity of a fish, or a wider category of fish, to a particle motion value. There continue to be calls for additional research on the levels of, and effects with respect to particle motion. Until sufficient data are available to enable revised thresholds based on a particle motion metric, Popper and Hawkins, 2019 states that:

> *“since there is an immediate need for updated criteria and guidelines on potential effects of anthropogenic sound on fishes, we recommend, as do our colleagues in Sweden (Andersson et al., 2017), that the criteria proposed by Popper et al. (2014) should be used.”*

1.3 MODELLING METHODOLOGY

1.3.1 To estimate the underwater noise levels likely to arise during the construction and operation of VE, predictive noise modelling has been undertaken. The methods described in this section, and used within this report, meet the requirements set out by the National Physical Laboratory (NPL) Good Practice Guide 113 for underwater noise measurement (Robinson *et al*., 2014).

1.3.2 Of those considered, the noise source most important to consider is impact piling, due to the noise levels and duration it will be present (Bailey *et al*., 2014). As such, the noise related to impact piling activities is the primary focus of this study.

1.3.3 The modelling of impact piling has been undertaken using the INSPIRE underwater noise model. The INSPIRE model (currently version 5.1) is a semi-empirical underwater noise propagation model based around a combination of numerical model, based on a combined geometric and energy flow/ hysteresis method, and actual measured data. It is designed to calculate the propagation of noise in shallow, mixed water, typical of the conditions around the UK and is well suited to the region around VE. The model has been tuned for accuracy using over 80 datasets of underwater noise propagation from monitoring around offshore piling activities.

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

1.3.5 INSPIRE considers a wide array of input parameters, including variations in bathymetry and source frequency to ensure accurate results are produced specific to the location and nature of the piling operation. It should also be noted that the results should be considered conservative as maximum design parameters and worst-case assumptions have been selected for:

- Piling hammer blow energies;
- Soft start, ramp up profile, and strike rate;
- Total duration of piling; and
- Receptor swim speeds.

1.3.6 A simple modelling approach has been used for noise sources other than piling that may be present during construction and operation of VE, and these are discussed in section 1.5.

MODELLING CONFIDENCE

1.3.7 INSPIRE is semi-empirical and thus a validation process is inherently built into the development process. Whenever a new set of good, reliable, impact piling measurement data is gathered through offshore surveys it is compared against the outputted levels from INSPIRE and, if necessary, the model can be recalibrated. Currently over 80 separate impact piling datasets from around the UK have been used as part of the development for the latest version of INSPIRE, and in each case, an average fit is used.

1.3.8 In addition, INSPIRE is also validated by comparing the noise levels outputted from the model with measurements and modelling undertaken by third parties, as well as in Thompson *et al*. (2013).

1.3.9 The current version of INSPIRE (version 5.1) is the product of re-analysing all the impact piling noise measurements in Subacoustech Environmental’ s measurement database and cross-referencing it with blow energy data from piling logs. This gives a database of single strike noise levels referenced to a specific blow energy at a specific range. This analysis showed that, based on the most up-to-date measurement data for large piles at high blow energies, the previous iterations of INSPIRE tended to overestimate the predicted noise levels at these blow energies.

1.3.10 The previous version of INSPIRE endeavoured to give a worst-case estimate of underwater noise levels produced by various permutations of impact piling parameters. There is always some natural variability with underwater noise measurements, even when considering measurements of pile strikes under the same conditions (i.e., at the same blow energy, taken at the same range). For example, there can be variations in noise levels of up to five or 10 dB, as seen in Bailey *et al*. (2010) and the data shown in Figure 1.3. When modelling using the upper bounds of this range, in combination with other worst-case parameter selections, conservatism can be compounded and create excessively overcautious predictions, especially when calculating SEL_{cum}. With this in mind, the current version of INSPIRE attempts to calculate closer to the average fit of the measured noise levels at all ranges.

1.3.11 Figure 1.3 and Figure 1.4 present a small selection of measured impact piling noise data, in terms of unweighted SPL_{peak} and SEL_{ss}, plotted against the outputs from INSPIRE. The plots show data points from measured data (in blue) plotted alongside the modelled data (in orange) using INSPIRE version 5.1, matching the pile size, blow energy and range from the measured data. These show the fit to the data, with the INSPIRE data points sitting very close to the middle of the measured noise levels at each range. When combined with the worst-case assumptions in parameter selection, modelled results will remain precautionary, and a more realistic worst case based on the maximum design scenario.

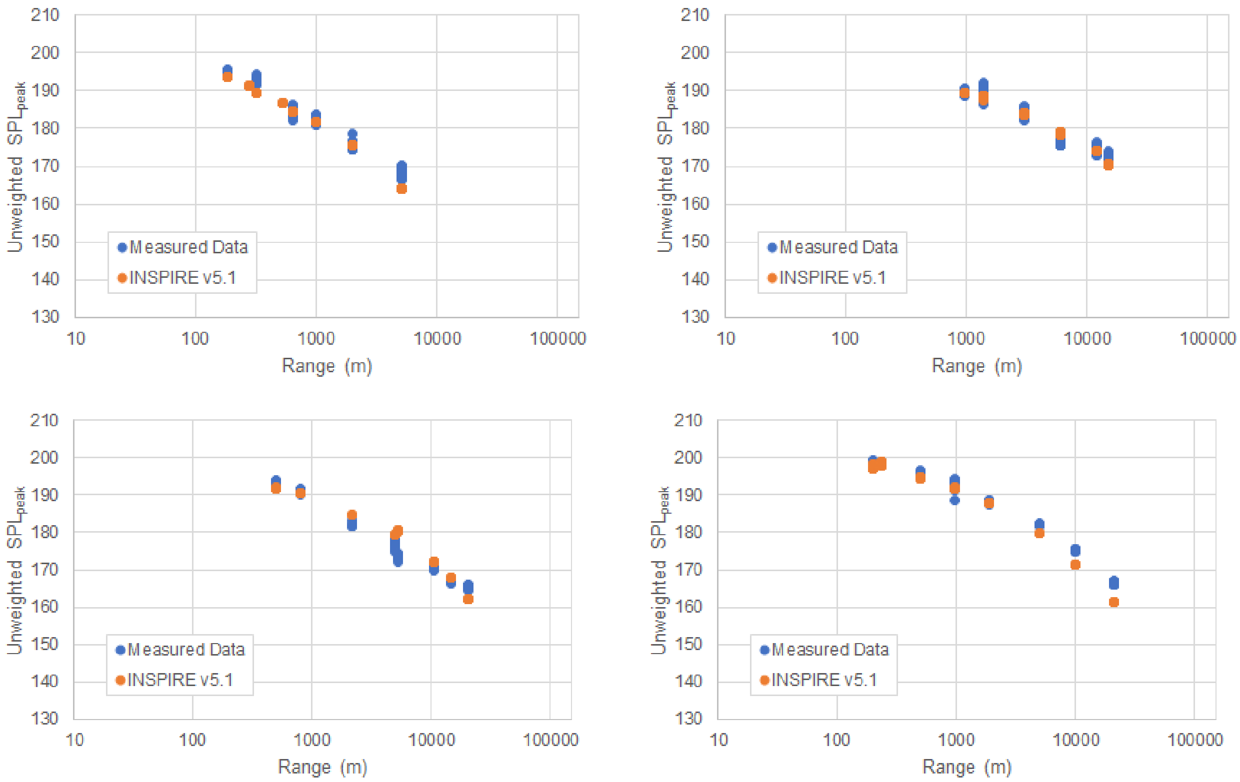

Figure 1.3: Comparison between example unweighted SPLpeak measured impact piling data (blue points) and modelled data using INSPIRE version 5.1 (orange points).

Top left: 1.8 m pile, 260 kJ maximum hammer energy, Irish Sea, 2010; Top right: 9.5 m pile, 1,600 kJ maximum hammer energy, North Sea, 2020; Bottom left: 6.1 m pile, 1,060 kJ maximum hammer energy, Southern North Sea, 2009; Bottom right: 6.0 m pile, 1,100 kJ maximum hammer energy, Southern North Sea, 2009.

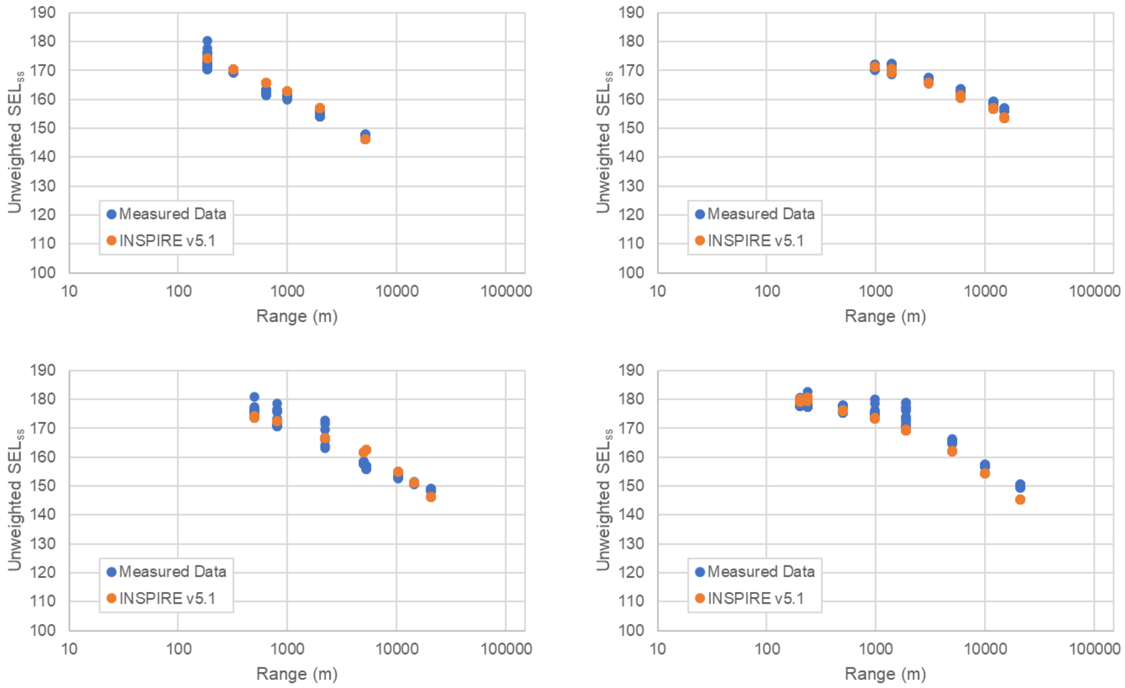

Figure 1.4 Comparison between example unweighted SEL_{ss} measured impact piling data (blue points) and modelled data using INSPIRE version 5.1 (orange points)

Top left: 1.8 m pile, 260 kJ maximum hammer energy, Irish Sea, 2010; Top right: 9.5 m pile, 1,600 kJ maximum hammer energy, North Sea, 2020; Bottom left: 6.1 m pile, 1,060 kJ maximum hammer energy, Southern North Sea, 2009; Bottom right: 6.0 m pile, 1,100 kJ maximum hammer energy, Southern North Sea, 2009.

1.3.12 The greatest deviations from the model tend to be at the greatest distances where the influence on the SEL_{cum} will be minimal.

NOISE MODELLING VERIFICATION

1.3.13 It is expected that, as per typical requirements in the UK, the underwater noise generated during the installation of a selection of the foundation piles will be sampled on site using hydrophones. By nature, these will be measurements of a specific piling event undertaken at a location and hammer energy profile which may or may not have been modelled previously.

1.3.14 The purpose of the monitoring is to determine the actual underwater noise levels on site for comparison with the modelled levels presented in this report and used as the basis for the impacts predicted in the EIA, which are themselves intended to be worst-case. The measurements taken during installation will be constrained by the piling plan and site limitations and a direct (like-for-like) comparison with a modelled scenario is unlikely to be possible. Such comparisons usually take the form of “level vs. range” (LvR) plots for a given transect and blow energy profile. The underlying calculations summarised in this report effectively comprise thousands of LvR plots and as such, these are not reproduced in full.

MODELLING PARAMETERS

MODELLING LOCATIONS

1.3.15 Modelling for WTG foundation impact piling has been undertaken at three representative locations covering the extents, and various water depths around VE.

- Southern Array – South-West (SW) corner – situated at the southernmost point of VE, chosen due to its proximity to sensitive seal areas;
- Northern Array – North-East (NE) corner – situated at the easternmost point of VE to show propagation into the wider North Sea; and
- Northern Array – North (N) edge – situated in the deepest water along the northern boundary.

1.3.16 These locations are summarised in Table 1.10 and illustrated in Figure 1.5.

Table 1.10: Summary of the underwater noise modelling locations used for this study.

Modelling locations	Southern Array – SW corner	Northern Array – NE corner	Northern Array – N edge
Latitude	51.7488°N	51.9736°N	51.9875°N
Longitude	002.0466°E	002.2997°E	002.2263°E
Water depth	44.7 m	48.2 m	53.9 m

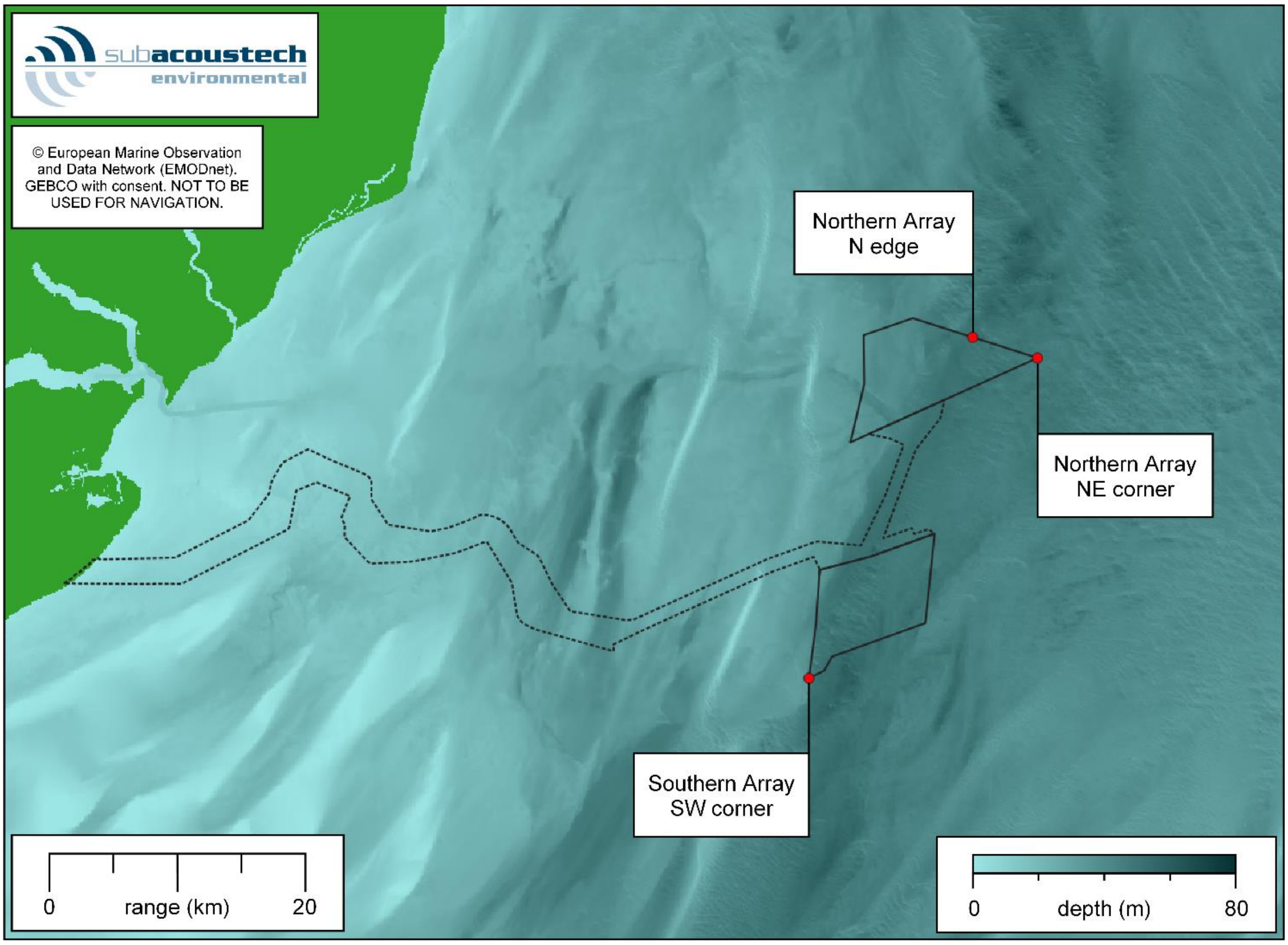

Figure 1.5: Approximate positions of the modelling locations at VE

WTG FOUNDATION AND IMPACT PILING PARAMETERS

1.3.17 Two foundation scenarios have been considered for this study. These are:

- A worst-case monopile scenario, installing a 15 m diameter pile with a maximum blow energy of 7,000 kJ; and
- A worst-case pin pile (jacket) scenario, installing 3.5 m diameter piles with a maximum energy of 3,000 kJ.

1.3.18 For SEL_{cum} criteria, the soft start and ramp up of the hammer blow energies, along with the total duration of piling and blow rate need to be considered. The scenarios used for modelling are summarised in Table 1.11 and Table 1.12.

1.3.19 In a 24-hour period there is the potential that up to four pin piles can be driven at a single WTG foundation location per piling vessel.

1.3.20 Further scenarios exploring piling at multiple locations have been considered, at the Southern Array – SW corner location and the Northern Array – N edge location to give a wide geographical spread as well as a worst case for water depths. Two different protocols have been investigated. Firstly, a sequential condition was run where pile installations are staggered as an experiment to avoid concurrent piling at multiple locations. Secondly, the concurrent condition had the piles at the north and south of the site installed simultaneously.

1.3.21 These scenarios are:

- Monopiles installed sequentially – alternate staggered installation at the Northern Array – N edge and Southern Array – SW corner, with two monopiles installed at each location (four total piles);
- Monopiles installed concurrently – simultaneous installation at the north and south, with two piles installed sequentially at each location (four total piles);
- Pin piles installed sequentially – installation of four piles (sequentially) at the Northern Array – N edge, followed on completion by the installation of four piles (sequentially) at the Southern Array – SW corner (eight total piles); and
- Pin piles installed concurrently – simultaneous installation at the north and south, with four piles installed sequentially at each location (eight total piles).

1.3.22 In addition, there is the potential for construction to take place with noise attenuation measures in place during the piling operations. The exact mitigation to be used has not yet been determined, but a flat, broadband, 10 dB reduction in source level has been used to reflect a noise attenuation. A 10 dB reduction gives a conservative estimate for most of the types of mitigation that could be considered, as derived from data presented in Verfuss *et al*. (2019). In this paper, data for the Big Bubble Curtain (BBC), a commonly deployed noise mitigation method, show that it provides a minimum of 10 dB attenuation in the frequency bands where marine mammals are most sensitive (i.e., 250 Hz and above). In a comprehensive review of pile driving with and without noise mitigation, Bellman *et al*. (2020) found that where it was deployed in depths of 30 m to 40 m, an attenuation in excess of 10 dB across the frequency spectrum could be achieved by a single BBC. This scenario has been considered for the worst-case multiple location scenario.

Table 1.11: Summary of the soft start and ramp up scenario used for the worst-case monopile modelling.

Monopile worst-case	1,050 kJ	1,050 kJ	1,400 kJ	2,800 kJ	4,200 kJ	5,600 kJ	7,000 kJ
Number of strikes	100	100	200	200	200	200	15,563
Duration	10 mins	5 mins	5 mins	5 mins	5 mins	5 mins	415 mins
Blow rate	10 bl/min	Burst*	40 bl/min				37.5 bl/min
* The "burst" stage represents 30 s piling at 40 bl/min followed by a 30 s pause in piling, repeated for 5 minutes. 1 pile: 16,563 strikes, 7 hours 30 minutes duration							

Table 1.12: Summary of the soft start and ramp up scenario used for the worst-case pin pile modelling.

Pin pile worst-case	450 kJ	450 kJ	600 kJ	1,200 kJ	1,800 kJ	2,400 kJ	3,000 kJ
Number of strikes	100	100	200	200	200	200	7,688
Duration	10 mins	5 mins	5 mins	5 mins	5 mins	5 mins	205 mins
Blow rate	10 bl/min	Burst*	40 bl/min				~37.5 bl/min
* The "burst" stage represents 30 s piling at 40 bl/min followed by a 30 s pause in piling, repeated for 5 minutes. 1 pile: 8,688 strikes, 4 hours 00 minutes duration 4 piles: 34,752 strikes, 16 hours 00 minutes duration							

SOURCE LEVELS

1.3.23 Noise modelling requires knowledge of the source level, which is the theoretical noise level at one metre from the noise source. The INSPIRE model assumes that the noise source – that is, the hammer striking the pile – acts as an effective single point, as it will appear at distance. The source level is estimated based on the pile diameter and the blow energy imparted on the pile by the hammer. This is adjusted depending on the water depth at the modelling location, to allow for the length of the pile (and effective surface area) in contact with the water, which can affect the amount of noise that is transmitted from the pile into its surroundings.

1.3.24 It is worth noting that the "source level" technically does not exist in the context of many shallow water (< 100 m) noise sources (Heaney *et al*., 2020). In practice, for underwater noise modelling such as this, it is effectively an "apparent source level" that is used, essentially a value that can be used to produce correct noise levels at range (for a specific model), as required in impact assessments.

1.3.25 The unweighted, single strike SPL_{peak} and SEL_{ss} source levels estimated for this study are provided in Table 1.13. These figures are presented in accordance with typical requirements by regulatory authorities, although as indicated above, they are not necessarily compatible or comparable with any other model or predicted source level. In each case, the differences in source level for each location are minimal.

Table 1.13: Summary of the unweighted source levels used for modelling.

Source levels	Location	Monopile worst-case (15 m diameter, 7,000 kJ)	Pin pile worst case (3.5 m diameter, 4,000 kJ)
SPL_{peak}	South – SW corner	243.2 dB re 1 µPa @ 1 m	241.6 dB re 1 µPa @ 1 m

Source levels	**Location**	**Monopile worst-case (15 m diameter, 7,000 kJ)**	**Pin pile worst case (3.5 m diameter, 4,000 kJ)**
	North – NE corner	243.2 dB re 1 µPa @ 1 m	241.6 dB re 1 µPa @ 1 m
	North – N edge	243.2 dB re 1 µPa @ 1 m	241.6 dB re 1 µPa @ 1 m
SEL_{ss}	South – SW corner	224.4 dB re 1 µPa^{2}s @ 1 m	222.4 dB re 1 µPa^{2}s @ 1 m
	North – NE corner	224.4 dB re 1 µPa^{2}s @ 1 m	222.4 dB re 1 µPa^{2}s @ 1 m
	North – N edge	224.4 dB re 1 µPa^{2}s @ 1 m	222.5 dB re 1 µPa^{2}s @ 1 m

ENVIRONMENTAL CONDITIONS

1.3.26 With the inclusion of measured noise propagation data for similar piling operations in UK waters, the INSPIRE model intrinsically accounts for various environmental conditions. This includes the differences that can occur with the temperature and salinity of the water, as well as the sediment type surrounding the site. Data from the British Geological Survey show that the seabed in and around VE is made up of various combinations of gravel and sand.

1.3.27 Digital bathymetry from the European Marine Observation and Data Network (EMODnet) has been used for this modelling. Mean tidal depth has been used throughout.

CUMULATIVE SELS AND FLEEING RECEPTORS

1.3.28 Expanding on the information in the Analysis of environmental effects section, and the fleeing animal model used for modelling, it is important to understand the meaning of the results that are presented in the following sections.

1.3.29 When an SEL_{cum} impact range is presented for a fleeing animal, this range can essentially be considered a starting position (at commencement of piling) for the fleeing animal receptor. For example, if a receptor began to flee in a straight line away from the noise source starting at the position (distance from the pile) denoted by a modelled PTS contour, the receptor would receive exactly that noise exposure as per the PTS criterion under consideration.

1.3.30 To help explain this, it is helpful to examine how the multiple pulse SEL_{cum} ranges are calculated. As explained in paragraph 1.2.15, the SEL_{cum} is a measure of the total received noise over the whole operation: in the cases of the Southall *et al*. (2019) and Popper *et al*. (2014) criteria, this covers noise in a 24-hour period unless otherwise specified.

1.3.31 When considering a stationary receptor for fish (i.e., one that stays at the same position throughout piling), calculating the SEL_{cum} is straightforward: all the noise levels produced and received at a single point along a transect are aggregated to calculate the SEL_{cum}. If this calculated level is greater than the threshold being modelled, the model steps away from the noise source and the noise levels at that new location are aggregated to calculate a new SEL_{cum}. This continues outward until the threshold has been met.

1.3.32 For a fleeing animal, the receptor's distance from the noise source while moving away also needs to be considered. To model this, a starting point close to the source is chosen and the received noise level for each noise event (e.g., pile strike) while the receptor is fleeing is noted. For example, if a noise pulse occurs every six seconds and an animal is fleeing at a rate of 1.5 m/s, it is 9 m further from the source after each noise pulse, resulting in a slightly reduced noise level each time. These values are then aggregated into a SEL_{cum} over the entire operation. The faster an animal is fleeing, the greater the distance travelled between each noise event. The impact range outputted by the model for this situation is the distance the receptor must be at the start of the operation to exactly meet the exposure thresholds.

1.3.33 As an example the graphs in Figure 1.6 and Figure 1.7 show the difference in the received SELs by a stationary receptor and a fleeing receptor travelling at a constant speed of 1.5 m/s, using the worst-case monopile scenario at the Northern Array – N edge modelling location.

1.3.34 The received SEL_{ss} from the stationary receptor, as illustrated in Figure 1.6, shows the noise level gradually increasing as the blow energy increases throughout the soft start and ramp up. These step changes are also visible for the fleeing receptor, but as the receptor is further from the source by the time the levels increase, the total received exposure reduces, resulting in progressively lower received noise levels. As an example, for the first 10 minutes of the piling scenario, where the blow energy is 1,050 kJ, at a rate of 1.5 m/s, the fleeing receptor will have moved 900 m away. After the full piling duration of 7.5 hours, the receptor will be over 40 km from the pile.

1.3.35 Figure 1.7 shows the effect these different received levels have when calculating the SEL_{cum}. It clearly shows the difference in cumulative effect for the receptor remaining stationary as opposed to fleeing. To use an extreme example, starting at a range of 1 m, the first strike results in a received level of 219.4 dB re 1 $\mu Pa^2 s$. If the receptor were to remain stationary throughout the piling operation it would receive a cumulative level of 263.5 dB re 1 $\mu Pa^2 s$, whereas when fleeing at 1.5 m/s over the same scenario the cumulative received level for the receptor would be 220.1 dB re 1 $\mu Pa^2 s$.

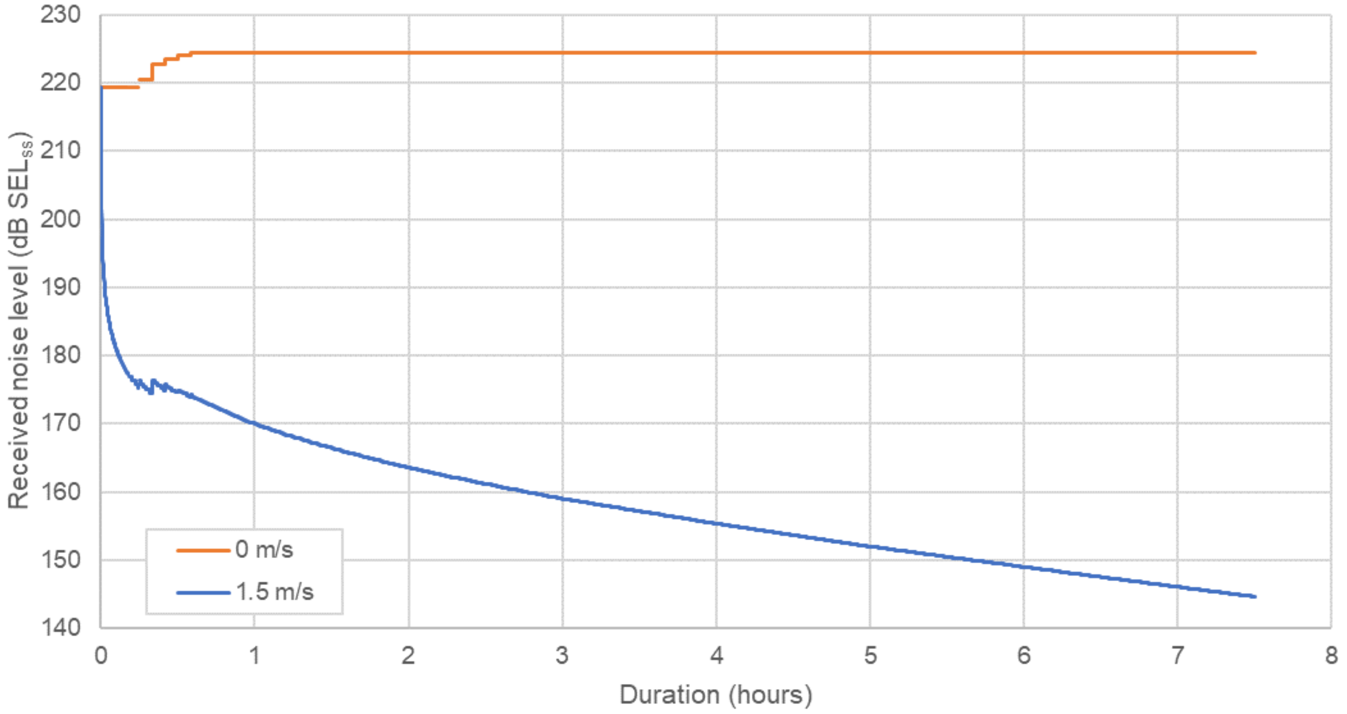

Figure 1.6: Received single-strike noise levels (SEL_{ss}) for receptors during the worst-case monopile foundation parameters at the Northern Array – N edge modelling location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source.

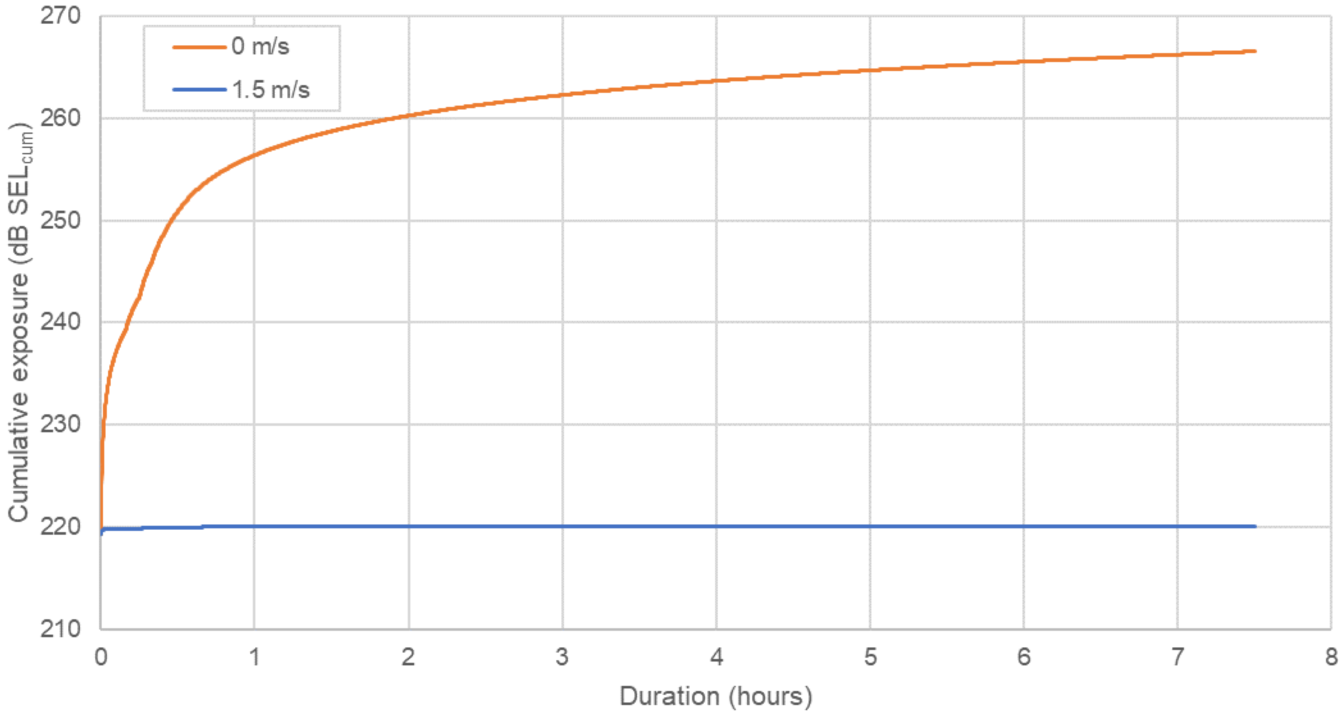

Figure 1.7: Cumulative received noise levels (SEL_{cum}) for receptors during the worst-case monopile foundation parameters at the Northern Array – N edge modelling location, assuming both a stationary and fleeing receptor starting at a location 1 m from the noise source.

1.3.36 To summarise, if the receptor were to start fleeing in a straight line from the noise source starting at a range closer than the modelled criteria value it would receive a noise exposure in excess of the criteria, and if the receptor were to start fleeing from a range further than the modelled value it would receive a noise exposure below the criteria. This is illustrated in Figure 1.8.

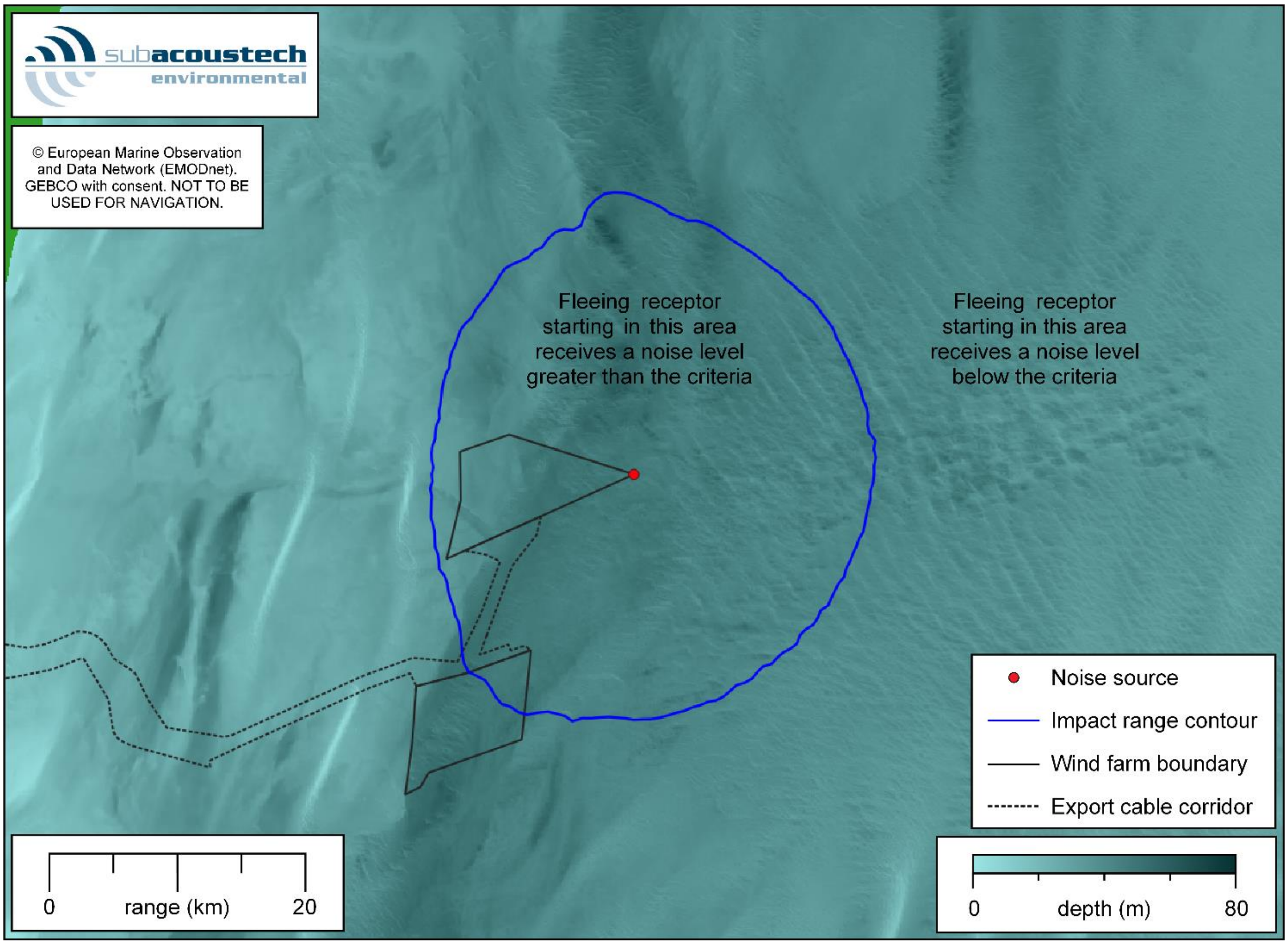

Figure 1.8: Plot showing a fleeing animal SEL$_{cum}$ criteria contour and the areas where the cumulative noise exposure will exceed the impact criteria.

1.3.37 Some modelling approaches include the effects of Acoustic Deterrent Devices (ADDs) that cause receptors to flee from the immediate area around the pile before activity commences. Subacoustech Environmental' s modelling approach does not include this, however the effects of using an ADD can still be inferred from the results. For example, if a receptor were to flee for 20 minutes from an ADD at a rate of 1.5 m/s, it would travel 1.8 km before piling begins. If a cumulative SEL impact range from INSPIRE was calculated to be below 1.8 km, it can be safely assumed that the ADD will be effective in eliminating the risk of injury to the receptor. The noise from an ADD is of a much lower level than impact piling, and as such the overall effect on the SEL$_{cum}$ exposure on a receptor would be minimal.

THE EFFECTS OF INPUT PARAMETERS ON CUMULATIVE SELS AND FLEEING RECEPTORS

1.3.38 As discussed earlier, parameters such as bathymetry, pile size, hammer blow energies, piling ramp up, blow rate and duration all have an effect on predicted noise levels. When considering SEL$_{cum}$ and a fleeing animal model, some of these parameters can have a greater influence than others.

1.3.39 Parameters like hammer blow energy can have a clear effect on impact ranges, with higher energies resulting in higher source noise levels and therefore larger impact ranges. When considering cumulative noise levels, these higher levels are compounded sometimes thousands of times due to the number of pile strikes. With this in mind, the ramp up from low blow energies to higher ones requires careful consideration for fleeing animals, as the received levels while the receptor is relatively close to the noise source will have a greater effect on the overall cumulative exposure level.

1.3.40 Linked to the effect of the ramp up is the blow rate, as the more pile strikes that occur while the receptor is close to the noise source, the greater the exposure and the greater effect it will have on the SEL_{cum} impact ranges. The faster the strike rate, the shorter the distance the receptor can flee between each pile strike, which ultimately leads to greater exposure.

1.4 MODELLING RESULTS

1.4.1 This section presents the modelled impact ranges for impact piling noise following the parameters detailed in section 1.3, covering the Southall *et al*. (2019) marine mammal criteria and the Popper *et al*. (2014) fish criteria. To aid navigation Table 1.14 contains a list of the impact range tables in this section.

1.4.2 For the results presented throughout this report, any predicted ranges smaller than 50 m and areas less than 0.01 km^2 for single strike criteria and ranges smaller than 100 m and areas less than 0.1 km^2 for cumulative criteria, have not been presented. At ranges this close to the noise source, the modelling processes are unable to model at a sufficient level of accuracy due to complex acoustic effects present near the pile. These ranges are given as “less than” this limit (e.g., “< 100 m”).

Table 1.14: Summary of the impact piling modelling results tables presented in this section.

Table (page)	Parameters		Criteria	
Table 1.16 (p44)	Southern Array – SW corner	Monopile – Worst case	Southall *et al*. (2019) -- marine mammals	Unweighted SPL_{peak}
Table 1.17 (p44)				Weighted SEL_{cum} (Impulsive)
Table 1.18 (p45)				Weighted SEL_{cum} (Non-impulsive)
Table 1.19 (p45)			Popper *et al*. (2014) -- fish	Unweighted SPL_{peak}
Table 1.20 (p45)				Unweighted SEL_{cum} (Pile driving)
Table 1.21 (p46)	Northern Array – NE corner		Southall *et al*. (2019) -- marine mammals	Unweighted SPL_{peak}
Table 1.22 (p46)				Weighted SEL_{cum} (Impulsive)

Table (page)	Parameters		Criteria	
Table 1.23 (p47)				Weighted SEL_{cum} (Non-impulsive)
Table 1.24 (p47)			Popper *et al*. (2014) -- fish	Unweighted SPL_{peak}
Table 1.25 (p48)				Unweighted SEL_{cum} (Pile driving)
Table 1.26 (p48)	Northern Array – N edge		Southall *et al*. (2019) -- marine mammals	Unweighted SPL_{peak}
Table 1.27 (p49)				Weighted SEL_{cum} (Impulsive)
Table 1.28 (p49)				Weighted SEL_{cum} (Non-impulsive)
Table 1.29 (p50)			Popper *et al*. (2014) -- fish	Unweighted SPL_{peak}
Table 1.30 (p50)				Unweighted SEL_{cum} (Pile driving)
Table 1.31 (p51)	Southern Array – SW corner	Pin piles – Worst case	Southall et al. (2019) -- marine mammals	Unweighted SPLpeak
Table 1.32 (p51)				Weighted SEL_{cum} (Impulsive) – 4 piles
Table 1.33 (p52)				Weighted SEL_{cum} (Non-impulsive) – 4 piles
Table 1.34 (p52)			Popper *et al*. (2014) -- fish	Unweighted SPL_{peak}
Table 1.35 (p53)				Unweighted SEL_{cum} (Pile driving) – 4 piles
Table 1.36 (p53)	Northern Array – NE corner		Southall *et al*. (2019) -- marine mammals	Unweighted SPL_{peak}
Table 1.37 (p54)				Weighted SEL_{cum} (Impulsive) – 4 piles

Table (page)	Parameters	Criteria		
Table 1.38 (p54)				Weighted SEL_{cum} (Non-impulsive) – 4 piles
Table 1.39 (p55)			Popper *et al*. (2014) -- fish	Unweighted SPL_{peak}
Table 1.40 (p55)				Unweighted SEL_{cum} (Pile driving) – 4 piles
Table 1.41 (p56)	Northern Array – N edge		Southall *et al*. (2019) -- marine mammals	Unweighted SPL_{peak}
Table 1.42 (p56)				Weighted SEL_{cum} (Impulsive) – 4 piles
Table 1.43 (p56)				Weighted SEL_{cum} (Non-impulsive) – 4 piles
Table 1.44 (p57)			Popper *et al*. (2014) -- fish	Unweighted SPL_{peak}
Table 1.45 (p57)				Unweighted SEL_{cum} (Pile driving) – 4 piles
Table 1.46 (p60)	Northern Array – N edge & Southern Array – SW corner	Monopiles – Sequential	Southall *et al*. (2019) -- marine mammals	Weighted SEL_{cum} (Impulsive)
Table 1.47 (p60)				Weighted SEL_{cum} (Non-impulsive)
Table 1.48 (p61)			Popper *et al*. (2014) -- fish	Unweighted SEL_{cum} (Pile driving) fleeing
Table 1.49 (p62)				Unweighted SEL_{cum} (Pile driving) stationary
Table 1.50 (p63)		Pin piles – Sequential	Southall *et al*. (2019) --	Weighted SEL_{cum} (Impulsive)

Table (page)	Parameters		Criteria	
Table 1.51 (p63)			marine mammals	Weighted SEL_{cum} (Non-impulsive)
Table 1.52 (p64)			Popper *et al*. (2014) -- fish	Unweighted SEL_{cum} (Pile driving) fleeing
Table1.53 (p65)				Unweighted SEL_{cum} (Pile driving) stationary
Table 1.54 (p68)		Monopiles – Concurrent	Southall *et al*. (2019) -- marine mammals	Weighted SEL_{cum} (Impulsive)
Table 1.55 (p70)				Weighted SEL_{cum} (Non-impulsive)
Table 1.56 (p72)			Popper *et al*. (2014) -- fish	Unweighted SEL_{cum} (Pile driving)
Table 1.57(p74)		Pin piles – Concurrent	Southall *et al*. (2019) -- marine mammals	Weighted SEL_{cum} (Impulsive)
Table 1.58 (p76)				Weighted SEL_{cum} (Non-impulsive)
Table 1.59 (p78)			Popper *et al*. (2014) -- fish	Unweighted SEL_{cum} (Pile driving)
Table 1.60 (p80)		Monopiles – Concurrent (including noise abatement)	Southall *et al*. (2019) -- marine mammals	Weighted SEL_{cum} (Impulsive)
Table 1.61 (p82)				Weighted SEL_{cum} (Non-impulsive)
Table 1.62 (p84)			Popper *et al*. (2014) -- fish	Unweighted SEL_{cum} (Pile driving)

PREDICTED NOISE LEVEL AT 750 M FROM THE NOISE SOURCE

1.4.3 In addition to the source levels given in Table 1.13, it is useful to look at the potential noise levels at a range of 750 m from the noise source, which is a common consideration for underwater noise studies at offshore wind farms and has the added advantage of being comparable with other modelling or measurements. A summary of the modelled unweighted levels at a range of 750 m are given in Table 1.15 considering the transect with the greatest noise transmission at each location while piling at the maximum hammer blow energy.

Table 1.15: Summary of the maximum predicted unweighted SPL_{peak} and SEL_{ss} noise levels at a range of 750 m from the noise source when considering the maximum blow energy.

Predicted level at 750 m range	Location	Monopile worst-case (15 m diameter, 7,000 kJ)	Pin pile worst case (3.5 m diameter, 4,000 kJ)
Unweighted SPL_{peak}	South – SW corner	202.8 dB re 1 µPa	201.2 dB re 1 µPa
	North – NE corner	202.8 dB re 1 µPa	201.2 dB re 1 µPa
	North – N edge	202.8 dB re 1 µPa	201.3 dB re 1 µPa
Unweighted SEL_{ss}	South – SW corner	184.7 dB re 1 µPa^{2}s	182.6 dB re 1 µPa^{2}s
	North – NE corner	184.6 dB re 1 µPa^{2}s	182.6 dB re 1 µPa^{2}s
	North – N edge	184.7 dB re 1 µPa^{2}s	182.7 dB re 1 µPa^{2}s

PREDICTED NOISE LEVELS AGAINST RANGE

1.4.4 Figure 1.9 presents the predicted unweighted SPL_{peak} and SEL_{ss} noise levels from the North – NE corner location, during the maximum blow energy of the worst-case monopile scenario (15 m diameter pile, and 7,000 kJ blow energy), against range, over the longest calculated transect 002° to the North, which leads into deep water. This is provided on regulatory request. This plot has been presented in order to show the noise transmission, which can be used as a basis to compare and validate the levels against any future noise monitoring. It should not be assumed necessarily comparable to any other transect or blow energy.

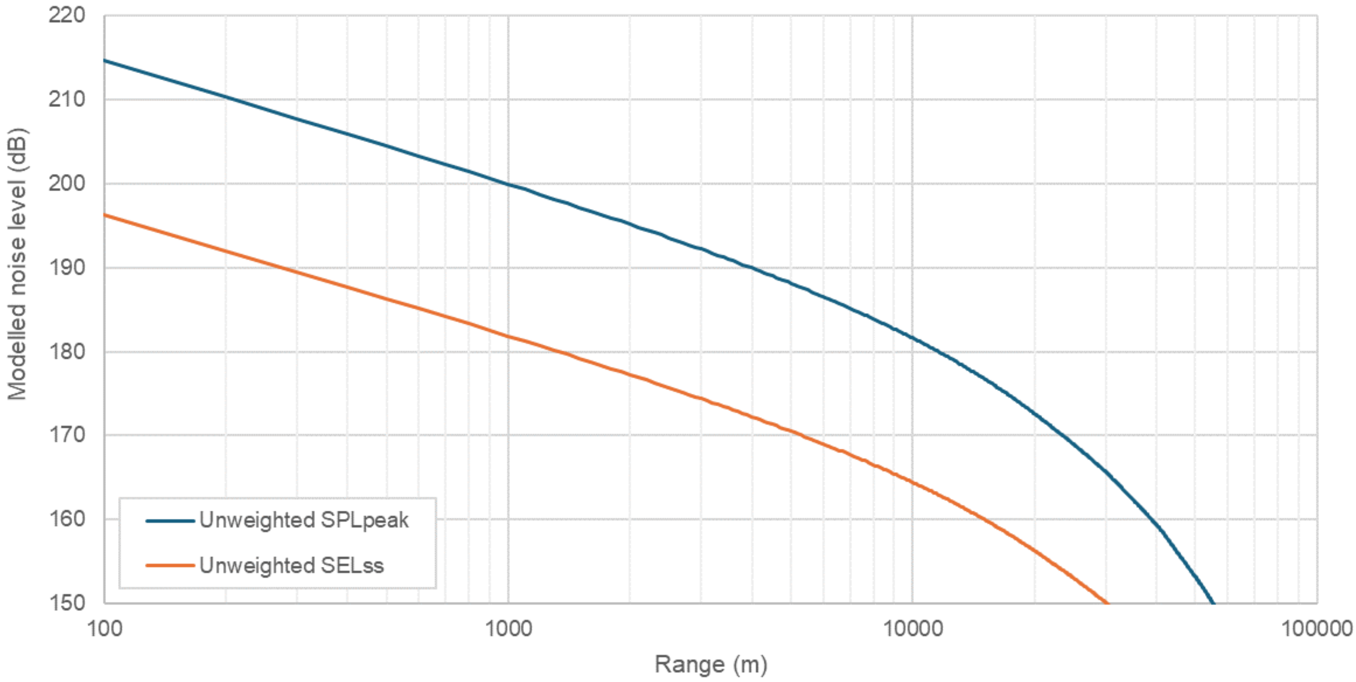

Figure 1.9: Modelled unweighted SPL_{peak} and SEL_{ss} noise levels with range for the maximum monopile blow energy along the 002° transect.

MONOPILE FOUNDATIONS

1.4.5 Table 1.16 to Table 1.30 present the modelling results for the worst-case monopile foundation modelling scenarios in terms of the Southall *et al*. (2019) marine mammal criteria and the Popper *et al*. (2014) fish criteria.

1.4.6 The largest marine mammal impact ranges for monopiles are predicted at the Northern Array NE corner location; however, all three modelling locations show similar impact ranges. Maximum PTS ranges are predicted for LF cetaceans, with ranges of up to 15 km at the Northern Array NE corner. The largest VHF cetacean PTS impact ranges are predicted at the Northern Array N edge location with maximum PTS ranges of up to 8.6 km.

1.4.7 For fish, the largest recoverable injury ranges (203 dB SEL_{cum} threshold) for monopiles are predicted to be 12 km assuming a stationary receptor; if a fleeing receptor is assumed, the impact ranges are reduced to 1.6 km at the Northern Array N edge location. Maximum TTS ranges (186 dB SEL_{cum} threshold) are predicted up to 37 km for a stationary animal, reducing to 23 km for a fleeing receptor.

SOUTHERN ARRAY – SW CORNER

Table 1.16: Summary of the unweighted SPL_{peak} impact ranges using the Southall *et al*. (2019) impulsive criteria for the worst case monopile modelling scenario at the SW corner of the Southern Array.

Southall *et al*. (2019) Unweighted SPL_{peak}		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	0.01 km^2	50 m	50 m	50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.6 km^2	730 m	700 m	720 m
	PCW (218 dB)	0.01 km^2	60 m	60 m	60 m
TTS	LF (213 dB)	0.05 km^2	130 m	130 m	130 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	9.2 km^2	1.8 km	1.6 km	1.7 km
	PCW (212 dB)	0.07 km^2	150 m	150 m	150 m

Table 1.17: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) impulsive criteria for the worst case monopile modelling scenario at the SW corner of the Southern Array assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	410 km^2	15 km	6.4 km	11 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	150 km^2	8.4 km	4.6 km	6.8 km
	PCW (185 dB)	0.1 km^2	300 m	< 100 m	200 m
TTS	LF (168 dB)	2,600 km^2	40 km	19 km	28 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	1,800 km^2	31 km	17 km	23 km
	PCW (170 dB)	460 km^2	15 km	7.8 km	12 km

Table 1.18: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) non-impulsive criteria for the worst case monopile modelling scenario at the SW corner of the Southern Array assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	800 km^2	21 km	9.6 km	16 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	240 km^2	11 km	5.7 km	8.6 km
	PCW (181 dB)	12 km^2	2.4 km	1.2 km	1.9 km

Table 1.19: Summary of the unweighted SPL_{peak} impact ranges using the Popper *et al*. (2014) impact piling criteria for the worst case monopile modelling scenario at the SW corner of the Southern Array.

Popper *et al*. (2014) Unweighted SPL_{peak}	Area	Maximum range	Minimum range	Mean range
213 dB	0.05 km^2	130 m	130 m	130 m
207 dB	0.35 km^2	340 m	340 m	340 m

Table 1.20: Summary of the unweighted SEL_{cum} impact ranges using the Popper *et al*. (2014) impact piling criteria for the worst case monopile modelling scenario at the SW corner of the Southern Array assuming both fleeing and stationary animals.

Popper *et al*. (2014) Unweighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	4.4 km^2	1.6 km	580 m	1.1 km

Popper *et al*. (2014) Unweighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
	186 dB	960 km^2	22 km	11 km	17 km
Stationary	219 dB	7.4 km^2	1.6 km	1.5 km	1.5 km
	216 dB	17 km^2	2.5 km	2.2 km	2.3 km
	210 dB	79 km^2	5.4 km	4.5 km	5.0 km
	207 dB	150 km^2	7.7 km	6.0 km	7.0 km
	203 dB	320 km^2	12 km	7.8 km	10 km
	186 dB	2,700 km^2	36 km	21 km	29 km

NORTHERN ARRAY – NE CORNER

Table 1.21: Summary of the unweighted SPL_{peak} impact ranges using the Southall *et al*. (2019) impulsive criteria for the worst case monopile modelling scenario at the NE corner of the Northern Array.

Southall *et al*. (2019) Unweighted SPL_{peak}		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	0.01 km^2	50 m	50 m	50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.7 km^2	730 m	730 m	730 m
	PCW (218 dB)	0.01 km^2	60 m	60 m	60 m
TTS	LF (213 dB)	0.05 km^2	130 m	130 m	130 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	9.7 km^2	1.8 km	1.8 km	1.8 km
	PCW (212 dB)	0.07 km^2	150 m	150 m	150 m

Table 1.22: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) impulsive criteria for the worst case monopile modelling scenario at the NE corner of the Northern Array assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	530 km^2	15 km	11 km	13 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	180 km^2	8.5 km	7.2 km	7.7 km

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
	PCW (185 dB)	0.2 km^2	280 m	230 m	250 m
TTS	LF (168 dB)	3,200 km^2	40 km	24 km	32 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	2,100 km^2	31 km	21 km	26 km
	PCW (170 dB)	570 km^2	16 km	12 km	14 km

Table 1.23: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) non-impulsive criteria for the worst case monopile modelling scenario at the NE corner of the Northern Array assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	1,000 km^2	22 km	15 km	18 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	300 km^2	11 km	9.0 km	9.8 km
	PCW (181 dB)	15 km^2	2.3 km	2.1 km	2.2 km

Table 1.24: Summary of the unweighted SPL_{peak} impact ranges using the Popper *et al*. (2014) impact piling criteria for the worst case monopile modelling scenario at the NE corner of the Northern Array.

Popper *et al*. (2014) Unweighted SPL_{peak}	Area	Maximum range	Minimum range	Mean range
213 dB	0.05 km^2	130 m	130 m	130 m
207 dB	0.35 km^2	340 m	340 m	340 m

Table 1.25: Summary of the unweighted SEL_{cum} impact ranges using the Popper *et al*. (2014) impact piling criteria for the worst case monopile modelling scenario at the NE corner of the Northern Array assuming both fleeing and stationary animals.

Popper *et al*. (2014) Unweighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	6.0 km^2	1.5 km	1.3 km	1.4 km
	186 dB	1,200 km^2	23 km	16 km	19 km
Stationary	219 dB	7.7 km^2	1.6 km	1.6 km	1.6 km
	216 dB	18 km^2	2.4 km	2.4 km	2.4 km
	210 dB	87 km^2	5.4 km	5.2 km	5.3 km
	207 dB	170 km^2	7.6 km	7.3 km	7.4 km
	203 dB	380 km^2	12 km	11 km	11 km
	186 dB	3,200 km^2	37 km	27 km	32 km

NORTHERN ARRAY – N EDGE

Table 1.26: Summary of the unweighted SPL_{peak} impact ranges using the Southall *et al*. (2019) impulsive criteria for the worst case monopile modelling scenario at the N edge of the Northern Array.

Southall *et al*. (2019) Unweighted SPL_{peak}		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	0.01 km^2	50 m	50 m	50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.7 km^2	740 m	740 m	740 m
	PCW (218 dB)	0.01 km^2	60 m	60 m	60 m
TTS	LF (213 dB)	0.07 km^2	160 m	150 m	150 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	10 km^2	1.8 km	1.8 km	1.8 km
	PCW (212 dB)	0.07 km^2	160 m	150 m	150 m

Table 1.27: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) impulsive criteria for the worst case monopile modelling scenario at the N edge of the Northern Array assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	510 km^2	15 km	9.6 km	13 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	180 km^2	8.6 km	6.5 km	7.6 km
	PCW (185 dB)	0.2 km^2	330 m	200 m	270 m
TTS	LF (168 dB)	3,100 km^2	40 km	22 km	31 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	2,100 km^2	31 km	19 km	25 km
	PCW (170 dB)	560 km^2	15 km	11 km	13 km

Table 1.28: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) non-impulsive criteria for the worst case monopile modelling scenario at the N edge of the Northern Array assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	970 km^2	21 km	13 km	17 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	290 km^2	11 km	8.1 km	9.6 km
	PCW (181 dB)	15 km^2	2.5 km	2.0 km	2.2 km

Table 1.29: Summary of the unweighted SPL_{peak} impact ranges using the Popper *et al*. (2014) impact piling criteria for the worst case monopile modelling scenario at the N edge of the Northern Array.

Popper *et al*. (2014) Unweighted SPL_{peak}	Area	Maximum range	Minimum range	Mean range
213 dB	0.05 km^2	130 m	130 m	130 m
207 dB	0.36 km^2	340 m	340 m	340 m

Table 1.30: Summary of the unweighted SEL_{cum} impact ranges using the Popper *et al*. (2014) impact piling criteria for the worst case monopile modelling scenario at the N edge of the Northern Array assuming both fleeing and stationary animals.

Popper *et al*. (2014) Unweighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	6.3 km^2	1.6 km	1.2 km	1.4 km
	186 dB	1,100 km^2	23 km	14 km	19 km
Stationary	219 dB	7.9 km^2	1.6 km	1.6 km	1.6 km
	216 dB	19 km^2	2.5 km	2.4 km	2.4 km
	210 dB	89 km^2	5.5 km	5.2 km	5.3 km
	207 dB	170 km^2	7.8 km	7.1 km	7.5 km
	203 dB	380 km^2	12 km	10 km	11 km
	186 dB	3,100 km^2	37 km	25 km	31 km

PIN PILE FOUNDATIONS

1.4.8 Table 1.31 to Table 1.45 present the modelling results for the worst-case pin pile foundation modelling scenarios in terms of the Southall *et al*. (2019) marine mammal criteria and the Popper *et al*. (2014) fish criteria. For the SEL_{cum} criteria, these results show the impact from both a single pin pile installation and four sequentially installed pin piles.

1.4.9 Similar to the monopile results, the largest marine mammal impact ranges for pin pile foundations are predicted at the Northern Array N edge location, but similar ranges are found at all three modelling locations. Maximum PTS ranges are predicted for LF cetaceans with ranges of up to 12 km and VHF cetaceans with PTS ranges of up to 6.6 km. All these marine mammal impact ranges are smaller than those predicted for monopiles.

1.4.10 For fish, the largest recoverable injury ranges (203 dB SEL_{cum} threshold) for pin piles are predicted to be 13 km assuming a stationary receptor; if a fleeing receptor is assumed, the impact ranges are reduced to 250 m. Maximum TTS ranges (186 dB SEL_{cum} threshold) are predicted up to 39 km for a stationary animal, reducing to 19 km for a fleeing receptor. Due to the consideration of four sequential pin piles the stationary results predicted are larger than those for monopiles; for fleeing animals the monopile impact ranges are larger than for pin piles.

SOUTHERN ARRAY – SW CORNER

Table 1.31: Summary of the unweighted SPL_{peak} impact ranges using the Southall *et al*. (2019) impulsive criteria for the worst case pin pile modelling scenario at the SW corner of the Southern Array.

Southall *et al*. (2019) Unweighted SPL_{peak}		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.0 km²	580 m	560 m	570 m
	PCW (218 dB)	0.01 km²	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.03 km²	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	5.9 km²	1.4 km	1.3 km	1.4 km
	PCW (212 dB)	0.04 km²	120 m	120 m	120 m

Table 1.32: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) impulsive criteria for the worst case pin pile modelling scenario at the SW corner of the Southern Array assuming a fleeing animal and four sequentially installed piles.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	260 km²	12 km	4.6 km	8.7 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	87 km²	6.4 km	3.5 km	5.2 km

Southall *et al.* (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	2,200 km²	36 km	17 km	26 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	1,500 km²	28 km	15 km	21 km
	PCW (170 dB)	380 km²	14 km	6.9 km	11 km

Table 1.33: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) non-impulsive criteria for the worst case pin pile modelling scenario at the SW corner of the Southern Array assuming a fleeing animal and four sequentially installed piles.

Southall *et al.* (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	560 km²	18 km	7.6 km	13 km
	HF (178 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	150 km²	8.6 km	4.5 km	6.9 km
	PCW (181 dB)	4.8 km²	1.6 km	680 m	1.5 km

Table 1.34: Summary of the unweighted SPL_{peak} impact ranges using the Popper *et al*. (2014) impact piling criteria for the worst case pin pile modelling scenario at the SW corner of the Southern Array.

Popper *et al*. (2014) Unweighted SPL_{peak}	Area	Maximum range	Minimum range	Mean range
213 dB	0.03 km²	100 m	100 m	100 m
207 dB	0.21 km²	260 m	260 m	260 m

Table 1.35: Summary of the unweighted SEL_{cum} impact ranges using the Popper *et al*. (2014) impact piling criteria for the worst case pin pile modelling scenario at the SW corner of the Southern Array assuming both fleeing and stationary animals and four sequentially installed piles.

Popper *et al*. (2014) Unweighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.1 km^2	230 m	< 100 m	120 m
	186 dB	680 km^2	19 km	9.3 km	14 km
Stationary	219 dB	9.8 km^2	1.9 km	1.7 km	1.8 km
	216 dB	23 km^2	2.9 km	2.5 km	2.7 km
	210 dB	100 km^2	6.2 km	5.0 km	5.7 km
	207 dB	190 km^2	8.6 km	6.5 km	7.7 km
	203 dB	390 km^2	13 km	8.4 km	11 km
	186 dB	3,000 km^2	38 km	22 km	31 km

NORTHERN ARRAY – NE CORNER

Table 1.36: Summary of the unweighted SPL_{peak} impact ranges using the Southall *et al*. (2019) impulsive criteria for the worst case pin pile modelling scenario at the NE corner of the Northern Array.

Southall *et al*. (2019) Unweighted SPL_{peak}		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.0 km^2	580 m	570 m	580 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.03 km^2	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	6.2 km^2	1.4 km	1.4 km	1.4 km
	PCW (212 dB)	0.04 km^2	120 m	120 m	120 m

Table 1.37: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) impulsive criteria for the worst case pin pile modelling scenario at the NE corner of the Northern Array assuming a fleeing animal and four sequentially installed piles.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	340 km^2	12 km	9.0 km	10 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	110 km^2	6.5 km	5.6 km	5.9 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	2,600 km^2	37 km	22 km	29 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	1,700 km^2	28 km	19 km	23 km
	PCW (170 dB)	470 km^2	14 km	11 km	12 km

Table 1.38: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) non-impulsive criteria for the worst case pin pile modelling scenario at the NE corner of the Northern Array assuming a fleeing animal and four sequentially installed piles.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	720 km^2	18 km	13 km	15 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	190 km^2	8.7 km	7.4 km	7.8 km
	PCW (181 dB)	6.4 km^2	1.6 km	1.4 km	1.4 km

Table 1.39: Summary of the unweighted SPL_{peak} impact ranges using the Popper *et al*. (2014) impact piling criteria for the worst case pin pile modelling scenario at the NE corner of the Northern Array.

Popper *et al*. (2014) Unweighted SPL_{peak}	Area	Maximum range	Minimum range	Mean range
213 dB	0.03 km^2	100 m	100 m	100 m
207 dB	0.22 km^2	260 m	260 m	260 m

Table 1.40: Summary of the unweighted SEL_{cum} impact ranges using the Popper *et al*. (2014) impact piling criteria for the worst case pin pile modelling scenario at the NE corner of the Northern Array assuming both fleeing and stationary animals and four sequentially installed piles.

Popper *et al*. (2014) Unweighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	0.1 km^2	200 m	130 m	160 m
	186 dB	850 km^2	19 km	14 km	16 km
Stationary	219 dB	11 km^2	1.9 km	1.8 km	1.8 km
	216 dB	24 km^2	2.8 km	2.8 km	2.8 km
	210 dB	110 km^2	6.1 km	5.9 km	6.0 km
	207 dB	220 km^2	8.5 km	8.1 km	8.3 km
	203 dB	460 km^2	13 km	12 km	12 km
	186 dB	3,500 km^2	39 km	28 km	33 km

NORTHERN ARRAY – N EDGE

Table 1.41: Summary of the unweighted SPL_{peak} impact ranges using the Southall *et al*. (2019) impulsive criteria for the worst case pin pile modelling scenario at the N edge of the Northern Array.

Southall *et al*. (2019) Unweighted SPL_{peak}		Area	Maximum range	Minimum range	Mean range
PTS	LF (219 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF (230 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (202 dB)	1.1 km^2	590 m	580 m	580 m
	PCW (218 dB)	0.01 km^2	< 50 m	< 50 m	< 50 m
TTS	LF (213 dB)	0.03 km^2	100 m	100 m	100 m
	HF (224 dB)	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF (196 dB)	6.5 km^2	1.4 km	1.4 km	1.4 km
	PCW (212 dB)	0.05 km^2	120 m	120 m	120 m

Table 1.42: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) impulsive criteria for the worst case pin pile modelling scenario at the N edge of the Northern Array assuming a fleeing animal and four sequentially installed piles.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	330 km^2	12 km	7.7 km	10 km
	HF (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	110 km^2	6.6 km	5.1 km	5.9 km
	PCW (185 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	2,600 km^2	37 km	20 km	29 km
	HF (170 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	1,700 km^2	28 km	17 km	23 km
	PCW (170 dB)	460 km^2	14 km	9.8 km	12 km

Table 1.43: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) non-impulsive criteria for the worst case pin pile modelling scenario at the N

edge of the Northern Array assuming a fleeing animal and four sequentially installed piles.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	700 km^2	18 km	11 km	15 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	190 km^2	8.8 km	6.6 km	7.8 km
	PCW (181 dB)	6.8 km^2	1.7 km	1.3 km	1.5 km

Table 1.44: Summary of the unweighted SPL_{peak} impact ranges using the Popper *et al*. (2014) impact piling criteria for the worst case pin pile modelling scenario at the N edge of the Northern Array.

Popper *et al*. (2014) Unweighted SPL_{peak}	Area	Maximum range	Minimum range	Mean range
213 dB	0.03 km^2	100 m	100 m	100 m
207 dB	0.22 km^2	270 m	270 m	270 m

Table 1.45: Summary of the unweighted SEL_{cum} impact ranges using the Popper *et al*. (2014) impact piling criteria for the worst case pin pile modelling scenario at the N edge of the Northern Array assuming both fleeing and stationary animals and four sequentially installed piles.

Popper *et al*. (2014) Unweighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	0.1 km^2	250 m	100 m	180 m

Popper *et al*. (2014) Unweighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
	186 dB	830 km^2	19 km	12 km	16 km
Stationary	219 dB	11 km^2	1.9 km	1.8 km	1.9 km
	216 dB	25 km^2	2.9 km	2.8 km	2.8 km
	210 dB	110 km^2	6.2 km	5.8 km	6.0 km
	207 dB	220 km^2	8.8 km	7.9 km	8.3 km
	203 dB	460 km^2	13 km	11 km	12 km
	186 dB	3,400 km^2	39 km	26 km	33 km

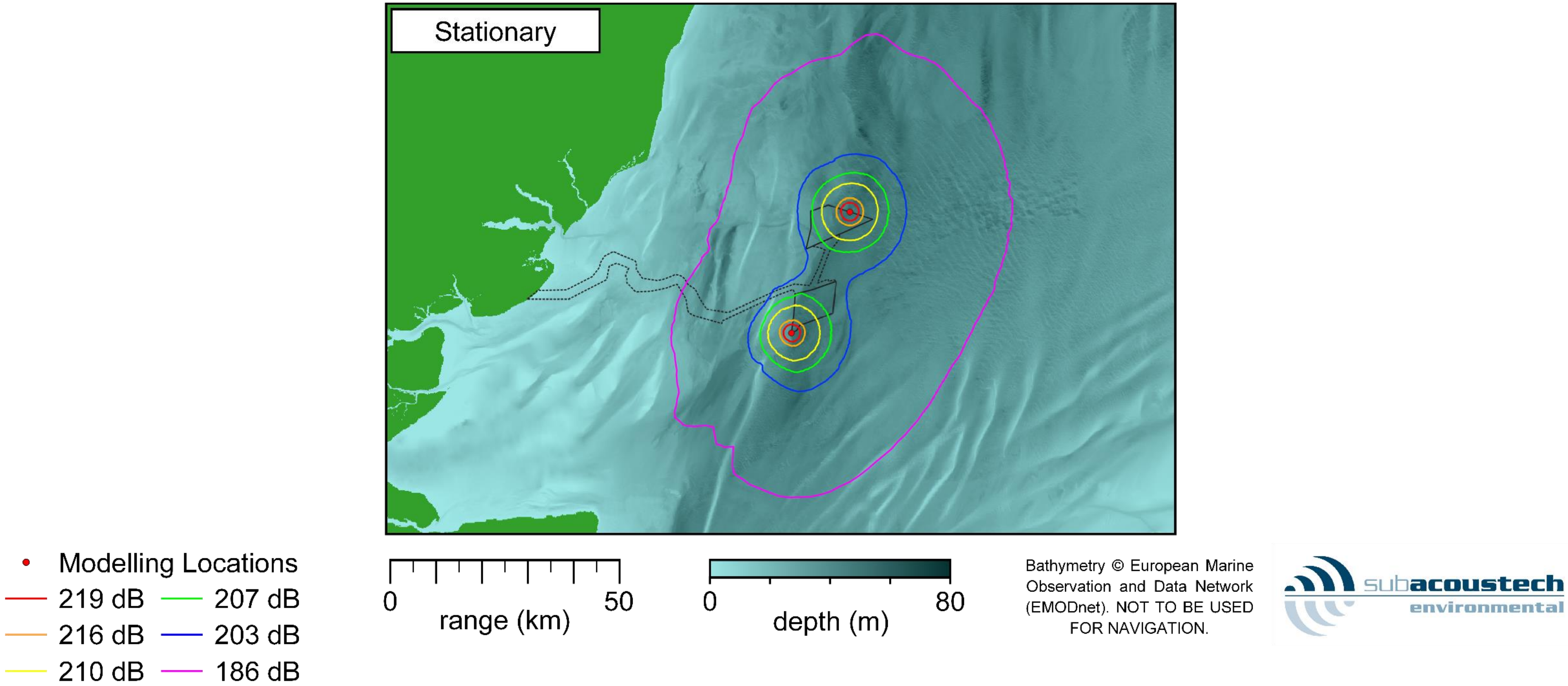

Figure 1.10 Contour plot showing the in-combination impacts of the sequential installation of pin pile foundations at two locations across VE for fish using the pile driving Popper et al. (2014)

SEQUENTIAL PILE INSTALLATION

1.4.11 This section presents the modelled results for sequentially installed piles at multiple locations, as described in paragraph 1.3.20. Two piles are installed at both the north and the south, one by one, avoiding any simultaneous piling. For fleeing animals these are presented as tables of impact ranges and areas as per the previous sections. The ranges calculated for a fleeing animal start at a position centered on the first pile in the north, and piles are installed in a staggered fashion. For stationary animals the north and south piling locations need to be considered, and as such only impact areas (rather than linear ranges) can be presented as there is no single starting point. In these cases, contour plots have also been included to aid presentation of the results.

1.4.12 Table1.53, Figure 1.9 and Figure 1.11. For the stationary animal impact areas, fields with a dash "-" show where there is no in-combination effect when piling occurs at the two locations, generally where the ranges at the separate sites are small enough such that the distant site does not produce an influencing additional exposure.

1.4.13 Also, it is noted that the SEL_{cum} criteria from Southall *et al*. (2019) and Popper *et al*. (2014) specify the effects of the noise over a 24-hour period, and that the sequential scenarios considered here both exceed this time. Additional investigational modelling was carried out and showed that clipping these scenarios at 24-hours resulted in no measurable difference in impact ranges, and thus this technical exceedance does not affect the assessment.

Table 1.46: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) impulsive criteria for the sequential monopile modelling scenario at the N edge of the Northern Array and the SW corner of the Southern array assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	520 km²	15 km	9.6 km	13 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	190 km²	8.8 km	6.5 km	7.7 km
	PCW (185 dB)	0.4 km²	400 m	300 m	340 m
TTS	LF (168 dB)	3,100 km²	40 km	22 km	31 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	2,100 km²	31 km	19 km	26 km
	PCW (170 dB)	570 km²	16 km	11 km	13 km

Table 1.47: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) non-impulsive criteria for the sequential monopile modelling scenario at the N

edge of the Northern Array and the SW corner of the Southern array assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	980 km^2	22 km	13 km	18 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	300 km^2	11 km	8.1 m	9.8 km
	PCW (181 dB)	17 km^2	2.6 km	2.0 km	2.3 km

Table 1.48: Summary of the unweighted SEL_{cum} impact ranges using the Popper *et al*. (2014) impact piling criteria for the sequential monopile modelling scenario at the N edge of the Northern Array and the SW corner of the Southern array assuming a fleeing animal.

Popper *et al*. (2014) Unweighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	7.1 km^2	1.8 km	1.3 km	1.5 km
	186 dB	1,200 km^2	23 km	15 km	19 km

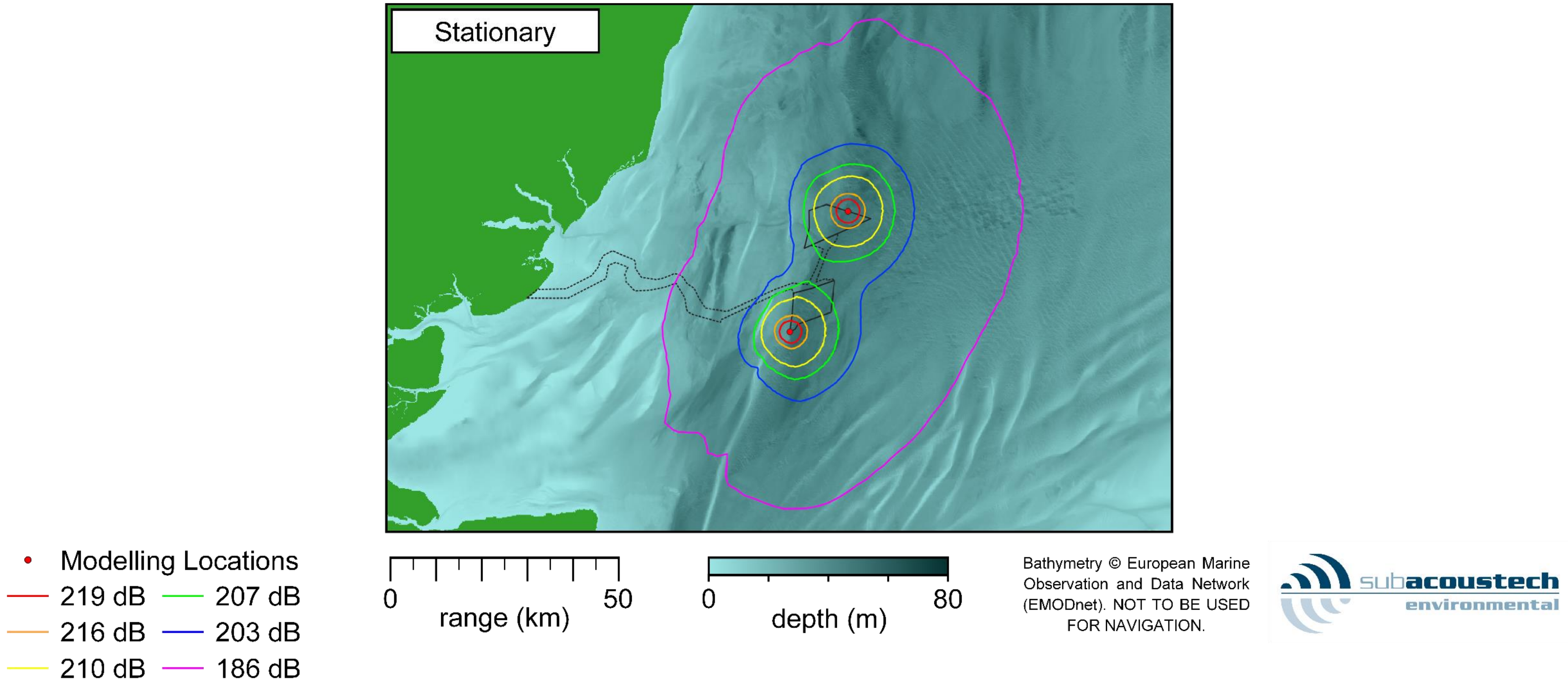

Figure 1.11: Contour plot showing the in-combination impacts of the sequential installation of monopile foundations at two locations across VE for fish using the pile driving Popper *et al*. (2014) criteria assuming a stationary animal.

Table 1.49: Summary of the unweighted SEL_{cum} impact areas using the Popper *et al*. (2014) impact piling criteria for the sequential monopile modelling scenario at the N edge of the Northern Array and the SW corner of the Southern array assuming a stationary animal.

Monopile foundations Popper *et al*. (2014) Unweighted SEL_{cum} (Pile driving)		Southern Array – SW corner	Northern Array – N edge	In-combination area
Stationary	219 dB	7.4 km²	7.9 km²	39 km²
	216 dB	17 km²	19 km²	85 km²
	210 dB	79 km²	89 km²	340 km²
	207 dB	150 km²	170 km²	630 km²
	203 dB	320 km²	380 km²	1,300 km²
	186 dB	2,700 km²	3,100 km²	5,900 km²

Table 1.50: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) impulsive criteria for the sequential pin pile modelling scenario at the N edge of the Northern Array and the SW corner of the Southern array assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (183 dB)	330 km²	12 km	7.7 km	10 km
	HF (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (155 dB)	110 km²	6.7 km	5.1 km	5.9 km
	PCW (185 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
TTS	LF (168 dB)	2,600 km²	37 km	20 km	29 km
	HF (170 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m
	VHF (140 dB)	1,700 km²	28 km	17 km	23 km
	PCW (170 dB)	470 km²	14 km	9.7 km	12 km

Table 1.51: Summary of the weighted SEL_{cum} impact ranges using the Southall *et al*. (2019) non-impulsive criteria for the sequential pin pile modelling scenario at the N edge of the Northern Array and the SW corner of the Southern array assuming a fleeing animal.

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
PTS	LF (199 dB)	< 0.1 km²	< 100 m	< 100 m	< 100 m

Southall *et al*. (2019) Weighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
	HF (198 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (173 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	PCW (201 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
TTS	LF (179 dB)	710 km^2	18 km	11 km	15 km
	HF (178 dB)	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	VHF (153 dB)	190 km^2	8.9 km	6.6 km	7.8 km
	PCW (181 dB)	7.4 km^2	1.8 km	1.3 km	1.5 km

Table 1.52: Summary of the unweighted SEL_{cum} impact ranges using the Popper *et al*. (2014) impact piling criteria for the sequential pin pile modelling scenario at the N edge of the Northern Array and the SW corner of the Southern array assuming a fleeing animal.

Popper *et al*. (2014) Unweighted SEL_{cum}		Area	Maximum range	Minimum range	Mean range
Fleeing	219 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.1 km^2	< 100 m	< 100 m	< 100 m
	203 dB	0.3 km^2	400 m	200 m	280 m
	186 dB	840 km^2	19 km	13 km	16 km

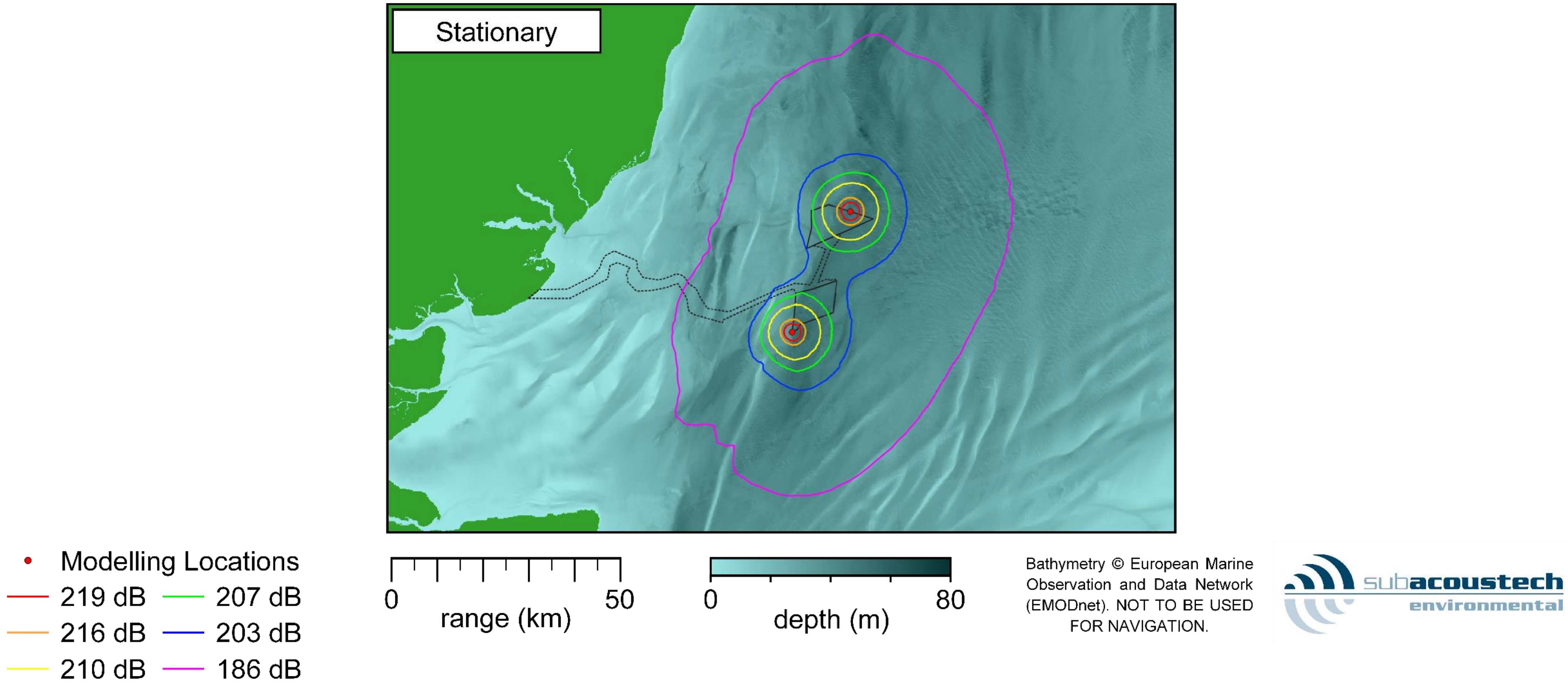

Figure 1.12: Contour plot showing the in-combination impacts of the sequential installation of pin pile foundations at two locations across VE for fish using the pile driving Popper *et al*. (2014) criteria assuming a stationary animal

Table1.53: Summary of the unweighted SEL_{cum} impact areas using the Popper *et al*. (2014) impact piling criteria for the sequential pin pile modelling scenario at the N edge of the Northern Array and the SW corner of the Southern array assuming a stationary animal.

Pin pile foundations Popper *et al*. (2014) Unweighted SEL_{cum} (Pile driving)		Southern Array – SW corner	Northern Array – N edge	In-combination area
Stationary	219 dB	9.8 km²	11 km²	23 km²
	216 dB	23 km²	25 km²	51 km²
	210 dB	100 km²	110 km²	220 km²
	207 dB	190 km²	220 km²	430 km²
	203 dB	390 km²	460 km²	950 km²
	186 dB	3,000 km²	3,400 km²	5,200 km²

CONCURRENT PILE INSTALLATION

1.4.14 This section presents the modelled results for concurrently installed piles at the north and south modelling locations, as detailed in paragraph 1.3.20. In the same way the stationary receptor results were presented in the previous section, concurrent modelling considers multiple starting locations and as such only impact areas can be calculated. These are presented in Table 1.54 t**o** Table 1.59 with accompanying contour plots in Figure 1.11 to Figure 1.16. Fields with a dash "-" indicate where there is no in-combination effect when simultaneous piling occurs at the two locations, generally where the individual ranges are small enough that the distant site does not produce an influencing additional exposure. Contours that are too small to be seen clearly at the scale of the figures have not been included. Only areas are provided as results, as due to multiple 'starting' points there is no individual single 'impact range' from multiple locations.

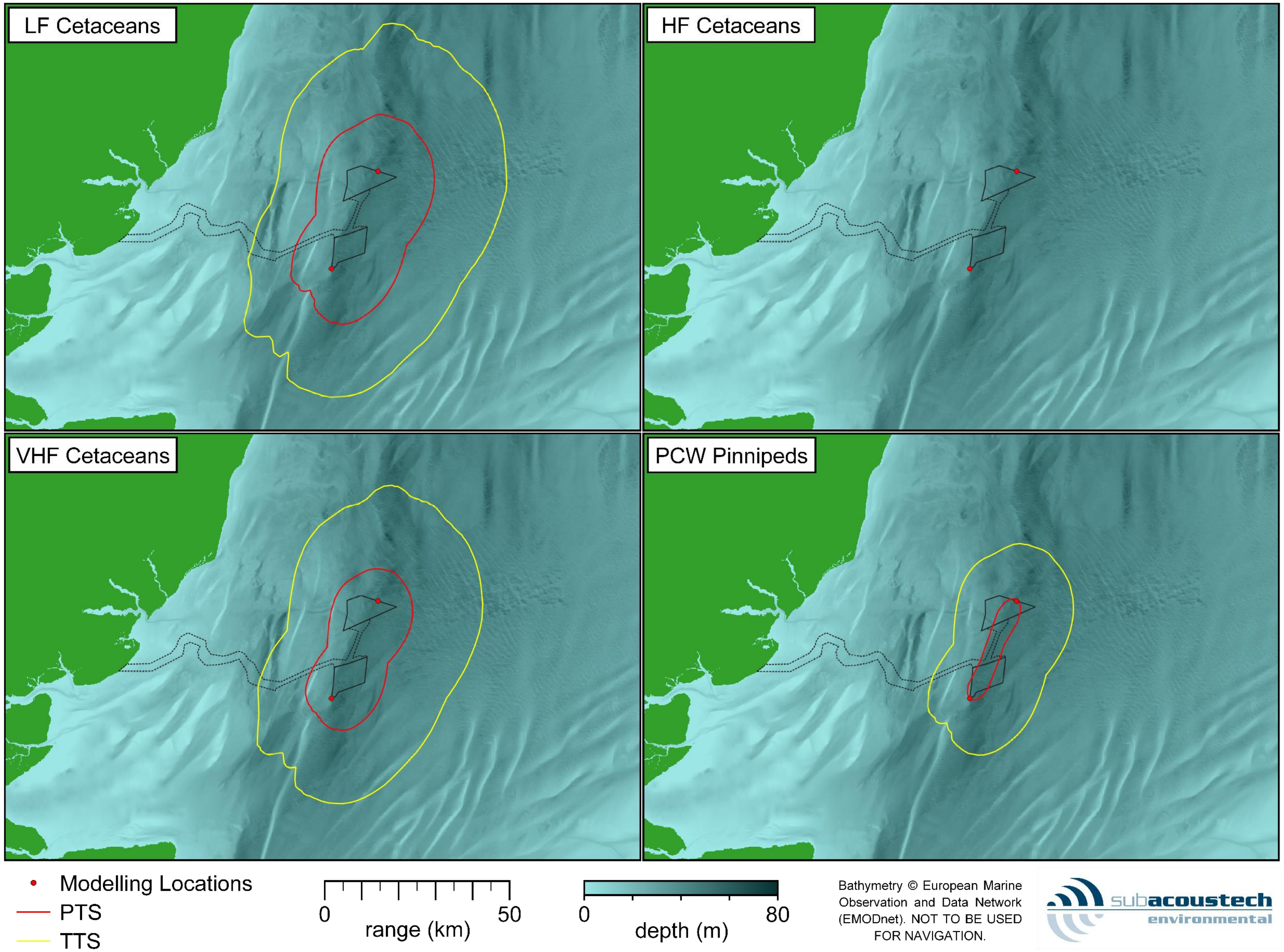

Figure 1.13: Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at two locations across VE for marine mammals using the impulsive Southall *et al*. (2019) criteria assuming a fleeing animal.

Table 1.54: Summary of the weighted SEL_{cum} impact areas using the Southall *et al*. (2019) impulsive criteria for the concurrent monopile modelling scenario at the N edge of the Northern Array and the SW corner of the Southern array assuming a fleeing animal.

Monopile foundations Southall *et al*. (2019) Weighted SEL_{cum} (Impulsive)		Southern Array – SW corner	Northern Array – N edge	In-combination area
PTS (Impulsive)	LF (183 dB)	410 km^2	510 km^2	1,400 km^2
	HF (185 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (155 dB)	150 km^2	180 km^2	3,600 km^2
	PCW (185 dB)	0.1 km^2	0.2 km^2	140 km^2
TTS (Impulsive)	LF (168 dB)	2,600 km^2	3,100 km^2	4,900 km^2
	HF (170 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (140 dB)	1,800 km^2	2,100 km^2	3,600 km^2
	PCW (170 dB)	460 km^2	560 km^2	1,500 km^2

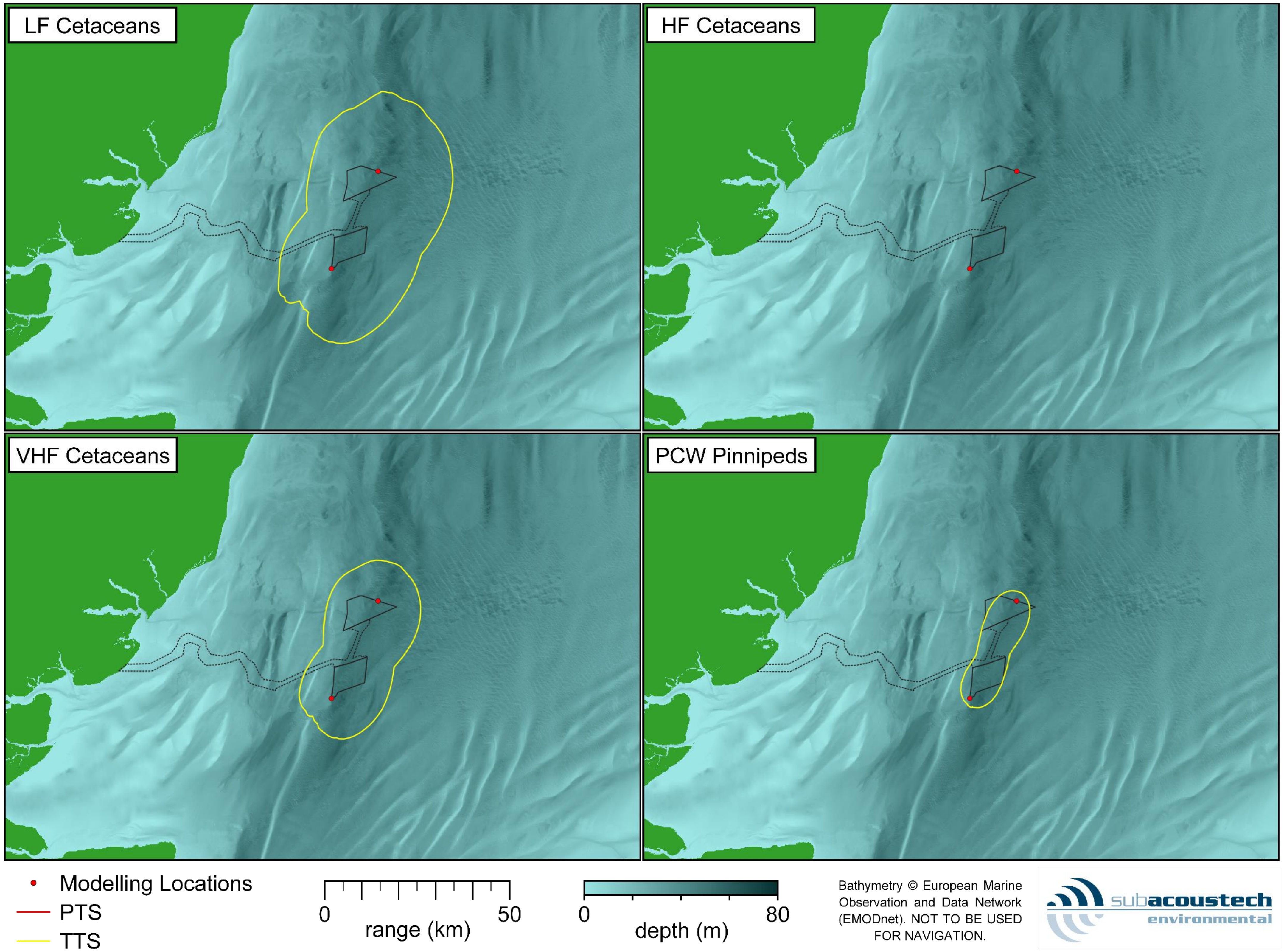

Figure 1.14: Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at two locations across VE for marine mammals using the non-impulsive Southall *et al*. (2019) criteria assuming a fleeing animal.

Table 1.55: Summary of the weighted SEL_{cum} impact areas using the Southall *et al*. (2019) non-impulsive criteria for the concurrent monopile modelling scenario at the N edge of the Northern Array and the SW corner of the Southern array assuming a fleeing animal.

Monopile foundations Southall *et al*. (2019) Weighted SEL_{cum} (non-impulsive)		Southern Array – SW corner	Northern Array – N edge	In-combination area
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 0.1 km²	-
	HF (198 dB)	< 0.1 km²	< 0.1 km²	-
	VHF (173 dB)	< 0.1 km²	< 0.1 km²	-
	PCW (201 dB)	< 0.1 km²	< 0.1 km²	-
TTS (Non-impulsive)	LF (179 dB)	800 km²	970 km²	2,100 km²
	HF (178 dB)	< 0.1 km²	< 0.1 km²	-
	VHF (153 dB)	240 km²	290 km²	1,000 km²
	PCW (181 dB)	12 km²	15 km²	310 km²

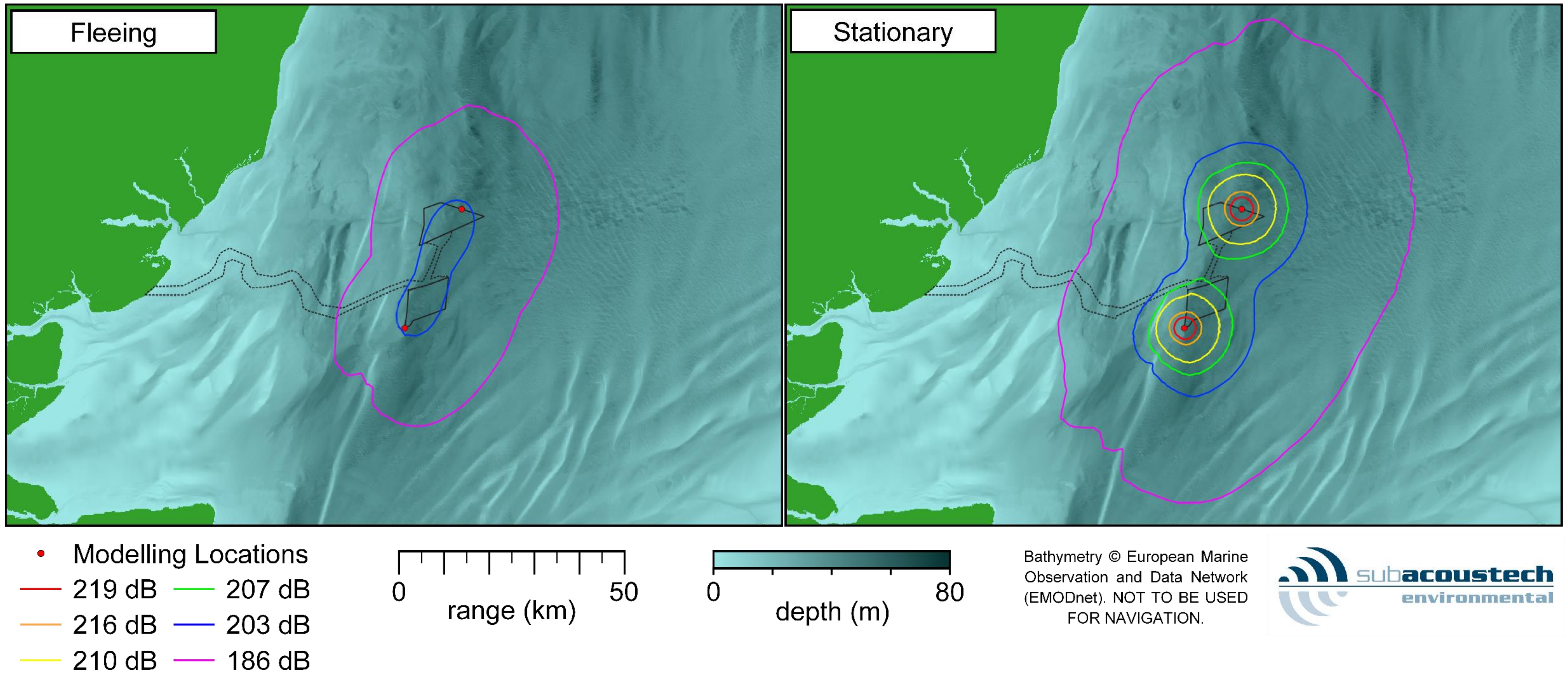

Figure 1.15: Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at two locations across VE for fish using the impact piling Popper *et al*. (2019) criteria assuming both fleeing and stationary animals.

Table 1.56: Summary of the unweighted SEL_{cum} impact areas using the Popper *et al*. (2014) impact piling criteria for the concurrent monopile modelling scenario at the N edge of the Northern Array and the SW corner of the Southern array assuming both fleeing and stationary animals.

Monopile foundations Popper *et al*. (2014) Unweighted SEL_{cum} (Pile driving)		Southern Array – SW corner	Northern Array – N edge	In-combination area
Fleeing	219 dB	< 0.1 km^2	< 0.1 km^2	-
	216 dB	< 0.1 km^2	< 0.1 km^2	-
	210 dB	< 0.1 km^2	< 0.1 km^2	-
	207 dB	< 0.1 km^2	< 0.1 km^2	-
	203 dB	4.4 km^2	6.3 km^2	260 km^2
	186 dB	960 km^2	1,100 km^2	2,400 km^2
Stationary	219 dB	7.4 km^2	7.9 km^2	39 km^2
	216 dB	17 km^2	19 km^2	85 km^2
	210 dB	79 km^2	89 km^2	340 km^2
	207 dB	150 km^2	170 km^2	630 km^2
	203 dB	320 km^2	380 km^2	1,300 km^2
	186 dB	2,700 km^2	3,100 km^2	5,900 km^2

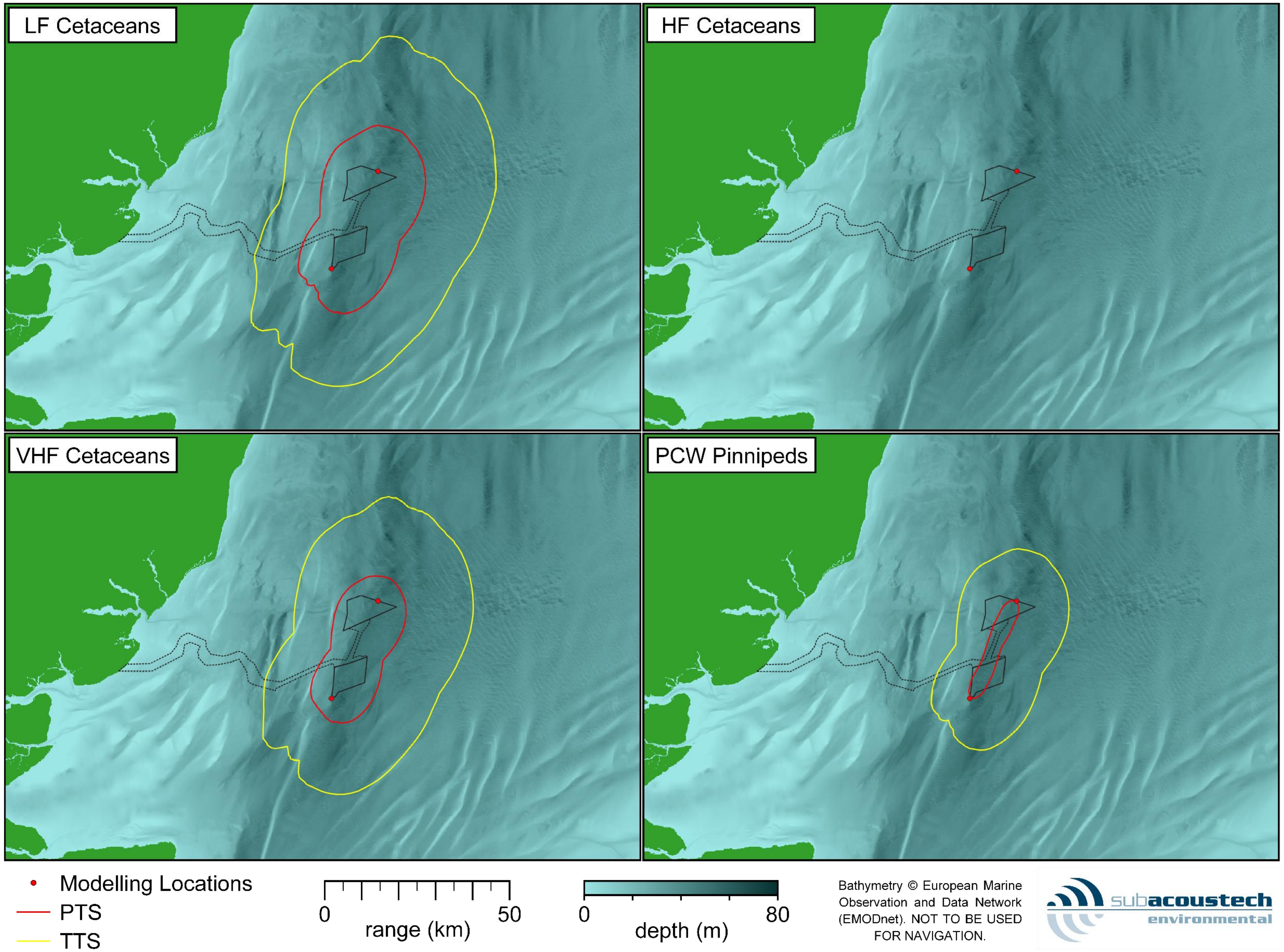

Figure 1.16: Contour plots showing the in-combination impacts of concurrent installation of pin pile foundations at two locations across VE for marine mammals using the impulsive Southall *et al*. (2019) criteria assuming a fleeing animal.

Table 1.57: Summary of the weighted SEL_{cum} impact areas using the Southall *et al*. (2019) impulsive criteria for the concurrent pin pile modelling scenario at the N edge of the Northern Array and the SW corner of the Southern array assuming a fleeing animal.

Pin pile foundations Southall *et al*. (2019) Weighted SEL_{cum} (Impulsive)		Southern Array – SW corner	Northern Array – N edge	In-combination area
PTS (Impulsive)	LF (183 dB)	260 km^2	330 km^2	1,100 km^2
	HF (185 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (155 dB)	87 km^2	110 km^2	640 km^2
	PCW (185 dB)	< 0.1 km^2	< 0.1 km^2	120 km^2
TTS (Impulsive)	LF (168 dB)	2,200 km^2	2,600 km^2	4,300 km^2
	HF (170 dB)	< 0.1 km^2	< 0.1 km^2	-
	VHF (140 dB)	1,500 km^2	1,700 km^2	3,100 km^2
	PCW (170 dB)	380 km^2	460 km^2	1,300 km^2

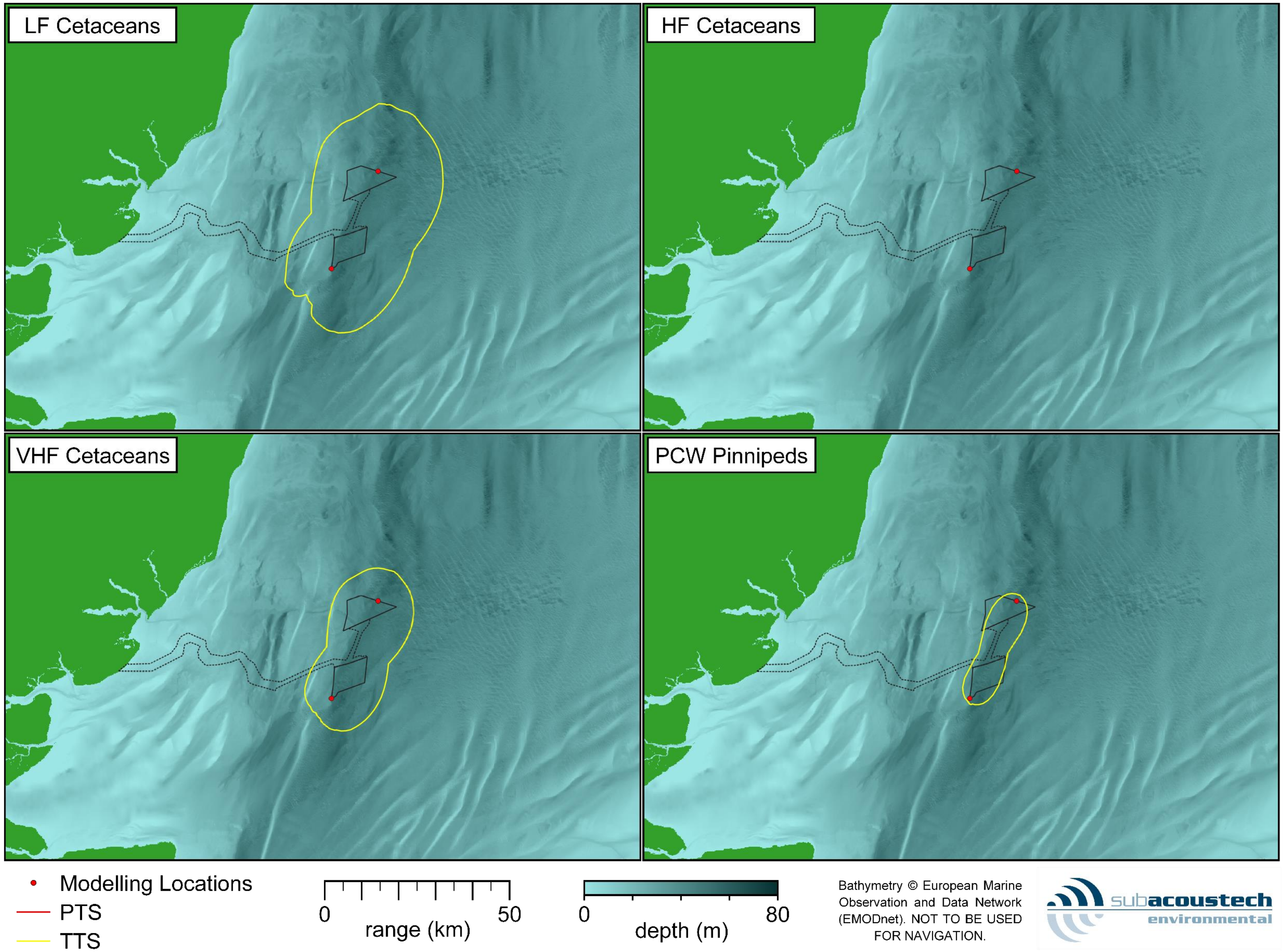

Figure 1.17: Contour plots showing the in-combination impacts of concurrent installation of pin pile foundations at two locations across VE for marine mammals using the non-impulsive Southall *et al*. (2019) criteria assuming a fleeing animal.

Table 1.58: Summary of the weighted SEL_{cum} impact areas using the Southall *et al*. (2019) non-impulsive criteria for the concurrent pin pile modelling scenario at the N edge of the Northern Array and the SW corner of the Southern array assuming a fleeing animal.

Monopile foundations Southall *et al*. (2019) Weighted SEL_{cum} (non-impulsive)		Southern Array – SW corner	Northern Array – N edge	In-combination area
PTS (Non-impulsive)	LF (199 dB)	< 0.1 km²	< 0.1 km²	-
	HF (198 dB)	< 0.1 km²	< 0.1 km²	-
	VHF (173 dB)	< 0.1 km²	< 0.1 km²	-
	PCW (201 dB)	< 0.1 km²	< 0.1 km²	-
TTS (Non-impulsive)	LF (179 dB)	560 km²	700 km²	1,800 km²
	HF (178 dB)	< 0.1 km²	< 0.1 km²	-
	VHF (153 dB)	150 km²	190 km²	830 km²
	PCW (181 dB)	4.8 km²	6.8 km²	270 km²

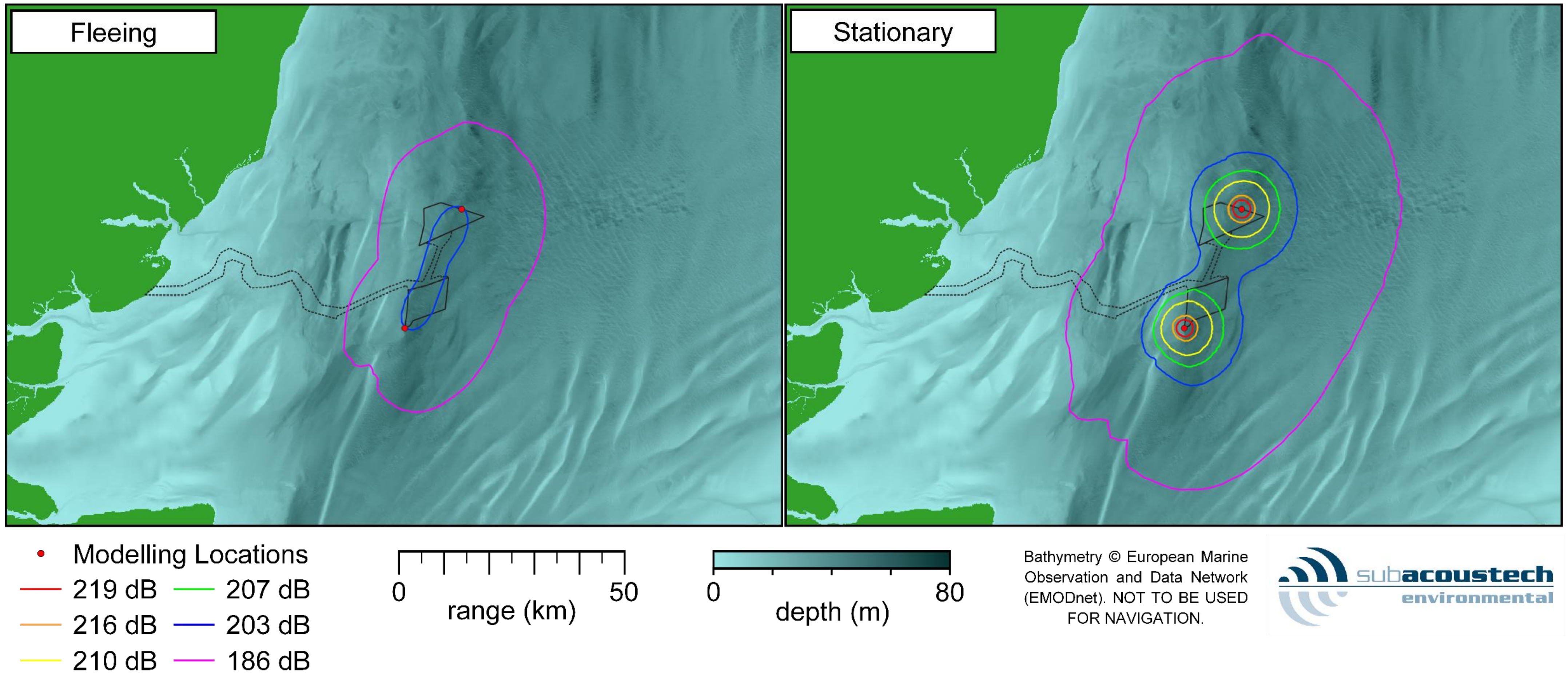

Figure 1.18: Contour plots showing the in-combination impacts of concurrent installation of pin pile foundations at two locations across VE for fish using the impact piling Popper *et al*. (2019) criteria assuming both fleeing and stationary animals.

Table 1.59: Summary of the unweighted SEL_{cum} impact areas using the Popper *et al*. (2014) impact piling criteria for the concurrent pin pile modelling scenario at the N edge of the Northern Array and the SW corner of the Southern array assuming both fleeing and stationary animals.

Pin pile foundations Popper *et al*. (2014) Unweighted SEL_{cum} (Pile driving)		Southern Array – SW corner	Northern Array – N edge	In-combination area
Fleeing	219 dB	< 0.1 km²	< 0.1 km²	-
	216 dB	< 0.1 km²	< 0.1 km²	-
	210 dB	< 0.1 km²	< 0.1 km²	-
	207 dB	< 0.1 km²	< 0.1 km²	-
	203 dB	< 0.1 km²	0.1 km²	170 km²
	186 dB	680 km²	830 km²	1,900 km²
Stationary	219 dB	9.8 km²	11 km²	23 km²
	216 dB	23 km²	25 km²	51 km²
	210 dB	100 km²	110 km²	220 km²
	207 dB	190 km²	220 km²	430 km²
	203 dB	390 km²	460 km²	950 km²
	186 dB	3,000 km²	3,400 km²	5,200 km²

1.4.15 Comparing the results of the modelling for the sequential with the concurrent, the stationary animal model shows no difference, as is expected as a stationary animal would acquire the same exposure irrespective of the timing of the piles. With the fleeing animal model, the impact areas are marginally higher with the sequential (staggered) model, as this gives the animal an opportunity to be closer to a subsequent pile when activity starts.

NOISE ABATEMENT

1.4.16 As discussed in paragraph 1.3.22, modelling has been undertaken utilising generic noise abatement of -10 dB for the worst-case multiple location scenario, the concurrent monopile scenario from the previous section. Table 1.60 to Table 1.62 and Figure 1.17 to Figure 1.19 present these results and show the reductions in impact ranges when compared to the results in the previous section.

1.4.17 It is worth bearing in mind that broadband attenuations, as modelled here, are necessarily simplistic, as all noise mitigation systems affect the sound to different extents dependent on frequency. While an attempt has been made to be precautionary with the performance, predictions should be assumed indicative.

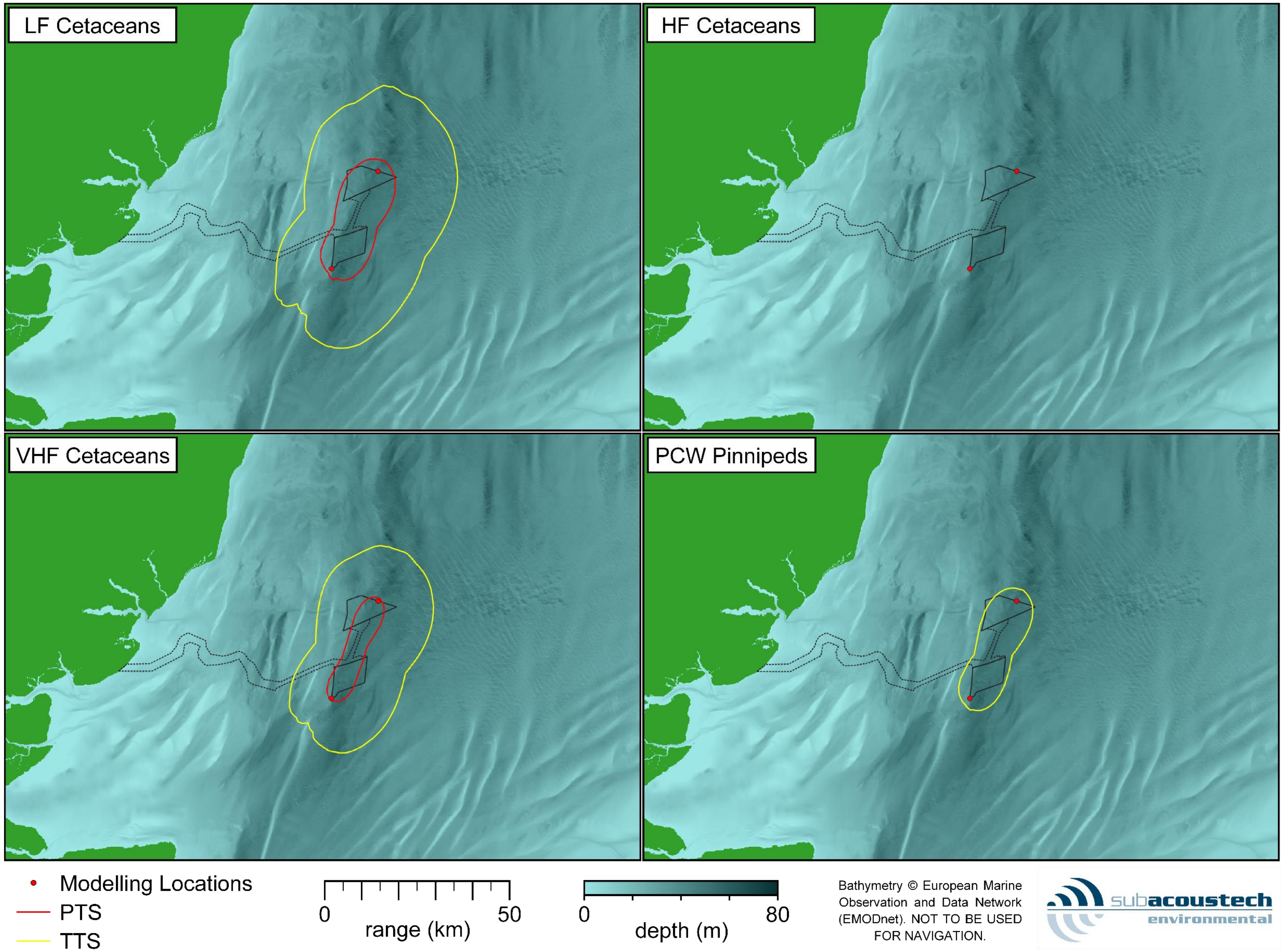

Figure 1.19: Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at two locations across VE including noise abatement for marine mammals using the impulsive Southall *et al*. (2019) criteria assuming a fleeing animal.

Table 1.60: Summary of the weighted SEL_{cum} impact areas using the Southall *et al*. (2019) impulsive criteria for the concurrent monopile modelling scenario including noise abatement at the N edge of the Northern Array and the SW corner of the Southern array assuming a fleeing animal.

Monopile foundations Southall *et al*. (2019) Weighted SEL_{cum} (Impulsive)		In-combination area (not mitigated)	In-combination area (mitigated)
PTS (Impulsive)	LF (183 dB)	1,400 km^2	410 km^2
	HF (185 dB)	-	-
	VHF (155 dB)	800 km^2	180 km^2
	PCW (185 dB)	140 km^2	-
TTS (Impulsive)	LF (168 dB)	4,900 km^2	2,300 km^2
	HF (170 dB)	-	-
	VHF (140 dB)	3,600 km^2	1,400 km^2
	PCW (170 dB)	1,500 km^2	370 km^2

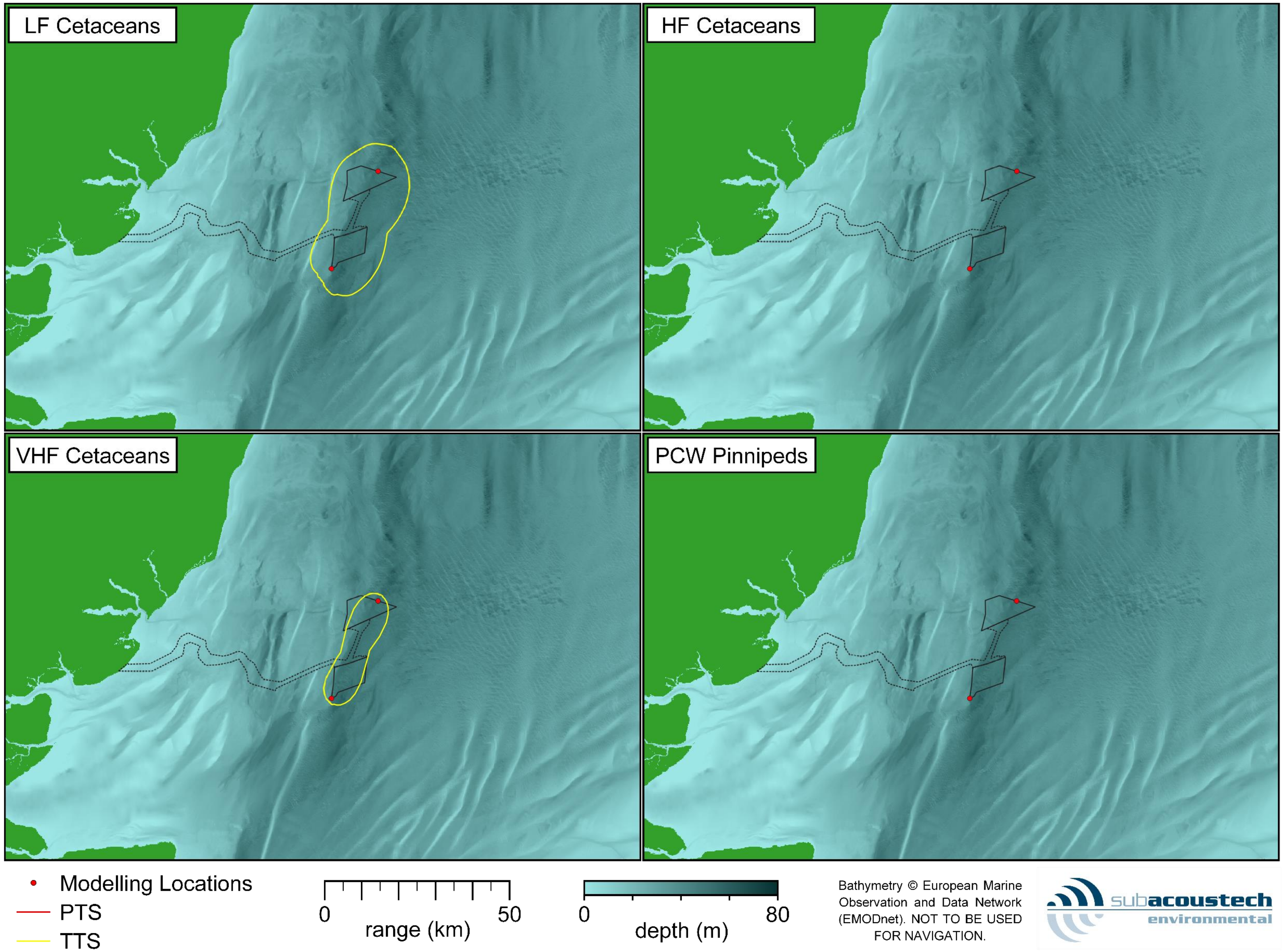

Figure 1.20: Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at two locations across VE including noise abatement for marine mammals using the non-impulsive Southall *et al*. (2019) criteria assuming a fleeing animal.

Table 1.61: Summary of the weighted SEL_{cum} impact areas using the Southall *et al*. (2019) non-impulsive criteria for the concurrent monopile modelling scenario including noise abatement at the N edge of the Northern Array and the SW corner of the Southern array assuming a fleeing animal.

Monopile foundations **Southall *et al*. (2019) Weighted SEL_{cum} (non-impulsive)**		**In-combination area (not mitigated)**	**In-combination area (mitigated)**
PTS (Non-impulsive)	LF (199 dB)	-	-
	HF (198 dB)	-	-
	VHF (173 dB)	-	-
	PCW (201 dB)	-	-
TTS (Non-impulsive)	LF (179 dB)	2,100 km^2	710 km^2
	HF (178 dB)	-	-
	VHF (153 dB)	1,000 km^2	260 km^2
	PCW (181 dB)	310 km^2	-

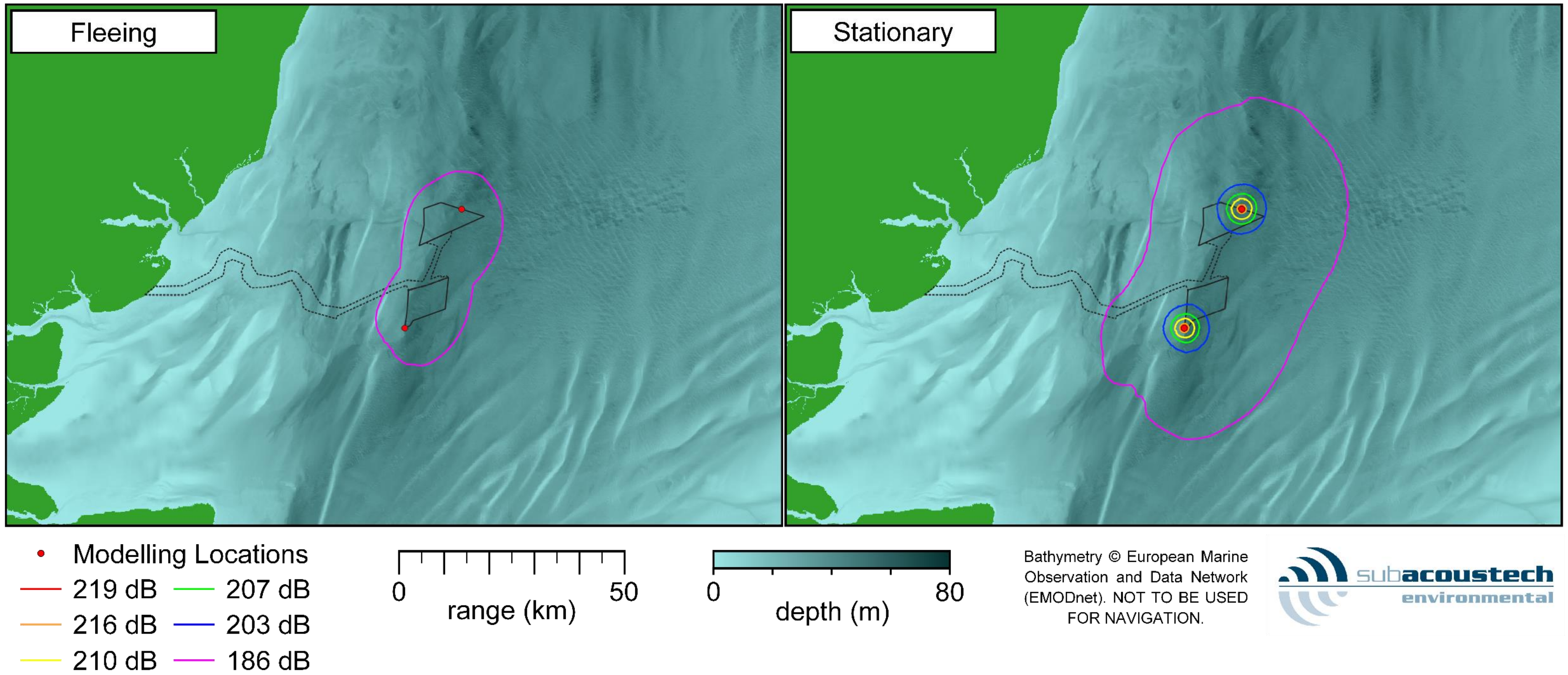

Figure 1.21: Contour plots showing the in-combination impacts of concurrent installation of monopile foundations at two locations across VE including noise abatement for fish using the impact piling Popper *et al*. (2019) criteria assuming both fleeing and stationary animals.

Table 1.62: Summary of the unweighted SEL_{cum} impact areas using the Popper *et al*. (2014) impact piling criteria for the concurrent monopile modelling scenario including noise abatement at the N edge of the Northern Array and the SW corner of the Southern array assuming both fleeing and stationary animals.

Monopile foundations **Popper *et al*. (2014) Unweighted SEL_{cum} (Pile driving)**		**In-combination area (not mitigated)**	**In-combination area (mitigated)**
Fleeing	219 dB	-	-
	216 dB	-	-
	210 dB	-	-
	207 dB	-	-
	203 dB	260 km^2	-
	186 dB	2,400 km^2	770 km^2
Stationary	219 dB	39 km^2	2.7 km^2
	216 dB	85 km^2	5.7 km^2
	210 dB	340 km^2	30 km^2
	207 dB	630 km^2	66 km^2
	203 dB	1,300 km^2	180 km^2
	186 dB	5,900 km^2	2,700 km^2

1.5 OTHER NOISE SOURCES

1.5.1 Although impact piling is expected to be the greatest overall noise source during offshore construction and development (Bailey *et al*., 2014), several other anthropogenic noise sources may be present. Each of these has been considered, and relevant biological noise criteria presented, in this section.

1.5.2 Table 1.63 provides a summary of the various noise producing source, aside from impact piling, that are expected to be present during the construction and operation of VE.

Table 1.63: Summary of the possible noise making activities at VE other than impact piling.

Activity	Description
Cable laying	Noise from the cable laying vessel and any other associated noise during the offshore cable installation.
Dredging	Dredging may be required on site for seabed preparation work for certain foundation options, as well as for the export cable, array cables and

Activity	Description
	interconnector cable installation. Suction dredging has been assumed as a worst-case.
Trenching	Plough trenching may be required during offshore cable installation.
Rock placement	Potentially required on site for installation of offshore cables (cable crossings and cable protection) and scour protection around foundation structures.
Vessel noise	Jack-up barges for piling substructures and WTG installation. Other large and medium sized vessel to carry out other construction tasks and anchor handling. Other small vessels for crew transport and maintenance on site.
Operational WTG	Noise transmitted through the water from operation WTG.
UXO clearance	There is a possibility that unexploded ordnance (UXO) may exist within the boundaries of VE, which would need to be cleared before construction can begin.

1.5.3 The NPL Good Practice Guide 133 for underwater noise measurements (Robinson *et al*., 2014) indicates that under certain circumstances, a simple modelling approach may be considered acceptable. Such an approach has been used for the noise sources in this section, which are either quiet compared to impact piling (e.g., cable laying and dredging), or where detailed modelling would imply unjustified accuracy (e.g., where data is limited such as with large operation WTG noise or UXO detonation). The high-level overview of modelling that has been presented here is considered sufficient and there would be little benefit in using a more detailed model at this stage. The limitations of this approach are noted, including the lack of frequency or bathymetric dependence.

1.5.4 Most of these activities are considered in the following section, with operational WTG noise and UXO clearance assessed separately.

NOISE MAKING ACTIVITIES

1.5.5 For the purposes of identifying the greatest noise levels, approximate subsea noise levels have been predicted using a simple modelling approach based on measurement data from Subacoustech Environmental’ s own underwater noise measurement database, scaled to relevant parameters for the site and to the specific noise sources to be used. The calculation of underwater noise transmission loss for the non-impulsive sources is based on an empirical analysis of noise measurements taken along transects around these sources by Subacoustech Environmental. The predictions use the following principle fitted to the measured data, where R is the range from the source, N is the transmission loss, and α is the absorption loss.

$$Recieved\ level = Source\ level\ (SL) - N \log_{10} R - \alpha R$$

1.5.6 Predicted source levels and propagation calculations for the construction activities are presented in Table 1.64 along with a summary of the number of datasets used in each case. All SEL_{cum} criteria use the same assumptions as presented earlier and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. It should be noted that this modelling approach does not take bathymetry or any other environmental conditions into account, and as such can be applied to any location at or surrounding VE.

Table 1.64: Summary of the estimated unweighted source levels and transmission losses for the different construction noise sources considered.

Source	Estimated unweighted source level	Approximate transmission loss values	Comments
Cable laying	171 dB re 1 µPa @ 1 m (RMS)	N: 13 α: (no absorption)	Based on 11 datasets from a pipe laying vessel measuring 300 m in length; this is a worst-case noise source for cable laying operations.
Suction dredging	186 dB re 1 µPa @ 1 m (RMS)	N: 19 α: 0.0009	Based on five datasets from suction and cutter suction dredgers.
Trenching	172 dB re 1 µPa @ 1 m (RMS)	N: 13 α: 0.0004	Based on three datasets of measurements from trenching vessels more than 100 m in length.
Rock placement	172 dB re 1 µPa @ 1 m (RMS)	N: 12 α: 0.0005	Based on four datasets from rock placement vessel 'Rollingstone'.
Vessel noise (large)	168 dB re 1 µPa @ 1 m (RMS)	N: 12 α: 0.0021	Based on five datasets of large vessels including container ships, floating production storage and offloading vessels and other vessels more than 100 m in length. Vessel speed assumed as 10 knots.
Vessel noise (medium)	161 dB re 1 µPa @ 1 m (RMS)	N: 12 α: 0.0021	Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 10 knots.

1.5.7 All values of N and α are empirically derived and will be linked to the size and shape of the machinery and the noise source on it, the transect on which the measurements are taken and the local environment at the time.

1.5.8 For SEL_{cum} calculations, the duration the noise is present also needs to be considered, with all sources assumed to operate constantly for 24 hours to give a worst-case assessment of the noise.

1.5.9 To account for the weightings required for modelling using the Southall *et al*. (2019) criteria, reductions in source level have been applied to the various noise sources. Figure 1.20 shows the representative noise measurements used, which have been adjusted for the source levels given in Table 1.64. Table 1.65 presents details of the reductions in source levels for each of the weightings used for modelling.

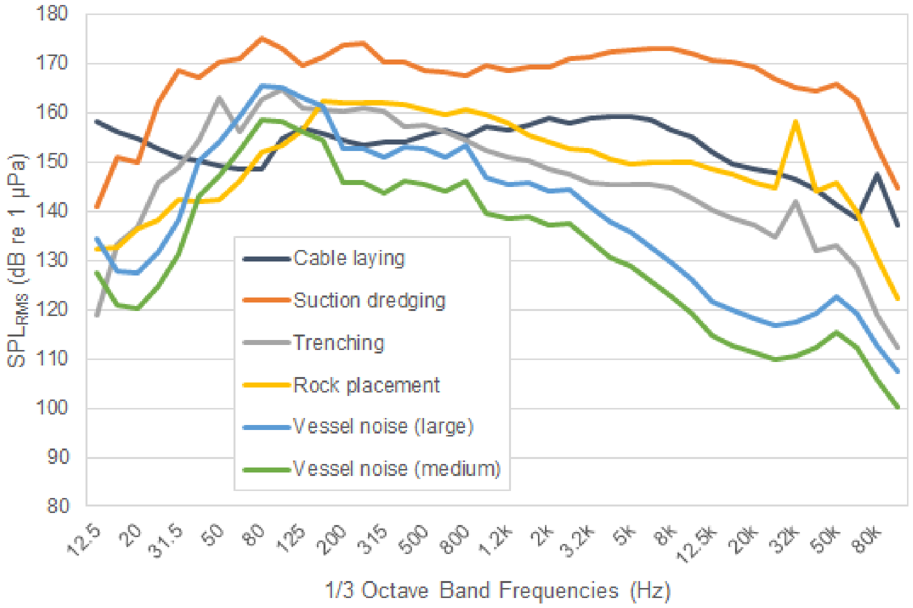

Figure 1.22: Summary of the 1/3rd octave frequency bands to which the Southall *et al*. (2019) weightings were applied in the simple modelling.

Table 1.65: Reductions in source level for the different construction noise sources considered when the Southall *et al*. (2019) weightings are applied.

Source	**Reduction in source level from the unweighted level (Southall *et al*. (2019)**			
	LF	**HF**	**VHF**	**PCW**
Cable laying	3.6 dB	22.9 dB	23.9 dB	13.2 dB
Suction dredging	2.5 dB	7.9 dB	9.6 dB	4.2 dB
Trenching	4.1 dB	23.0 dB	25.0 dB	13.7 dB
Rock placement	1.6 dB	11.9 dB	12.5 dB	8.2 dB
Vessel noise	5.5 dB	34.4 dB	38.6 dB	17.4 dB

1.5.10 Table 1.66 and Table 1.67 summarise the predicted impact ranges for these noise sources. All the sources presented are considered non-impulsive or continuous.

1.5.11 Given the modelled impact ranges, any marine mammal would have to be closer than 100 m from the continuous noise source at the start of the activity in most cases to acquire the necessary exposure to induce PTS as per Southall *et al*. (2019). The exposure calculation assumes the same receptor swim speeds as the impact piling modelling in section 1.4. As explained earlier, this would only mean that the receptor reaches the potential 'onset' of PTS at this range. This is the minimum exposure that could potentially lead to the start of a PTS or TTS impact and may only be marginal.

1.5.12 For fish, there is a minimal risk of any injury or TTS with reference to the SPL_{RMS} guidance for continuous noise sources in Popper *et al*. (2014).

1.5.13 All sources presented here result in much quieter levels than those presented for impact piling in section 1.4.

Table 1.66: Summary of the impact ranges for the different construction noise sources using the non-impulsive criteria from Southall *et al*. (2019) for marine mammals.

Southall *et al*. (2019) Weighted SEL_{cum}		Cable laying	Suction dredging	Trenching	Rock placement	Vessels (large)	Vessels (medium)
PTS	199 dB (LF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	198 dB (HF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	173 dB (VHF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	201 dB (PCW)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
TTS	179 dB (LF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	178 dB (HF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	153 dB (VHF)	< 100 m	230 m	< 100 m	990 m	< 100 m	< 100 m
	181 dB (PCW)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

1.5.14 Ranges for a stationary animal are theoretical only and are expected to be over-conservative as the assumption is for the animal to remain stationary in respect to the noise source, when the source itself is moving in most cases.

Table 1.67: Summary of the impact ranges for fish from Popper *et al*. (2014) for shipping and continuous noise, covering the different construction noise sources.

Popper *et al*. (2014) Unweighted SPL_{RMS}	Cable laying	Suction dredging	Trenching	Rock placement	Vessels (large)	Vessels (medium)
Recoverable injury: 170 dB (48 hours)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
TTS: 158 dB (12 hours)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m

OPERATIONAL WTG NOISE

1.5.15 The main source of underwater noise from operational WTGs will be mechanically generated vibration from the rotating machinery in the WTGs which is transmitted into the sea through the structure of the WTG tower and foundations (Nedwell *et al*., 2003; Tougaard *et al*., 2020). Noise levels generated above the water surface are low enough that no significant airborne sound will pass from the air to the water.

1.5.16 Tougaard *et al*. (2020) published a study investigating noise data from 17 operational WTGs in Europe and the United States, from 0.2 MW to 6.15 MW nominal power output. The paper identified the nominal power output and wind speed as the two primary driving factors for underwater noise generation. Although the datasets were acquired under different conditions, the authors devised a formula based on the published data for the operational wind farms, allowing a broadband noise level to be estimated based on the application of wind speed, turbine size (by nominal power output) and distance from the turbine:

$$L_{eq} = C + \alpha \log_{10}\left(\frac{distance}{100m}\right) + \beta \log_{10}\left(\frac{wind\ speed}{10ms^{-1}}\right) + \gamma \log_{10}\left(\frac{turbine\ size}{1\ MW}\right)$$

where C is a fixed constant and the coefficients α, β, and γ are derived from the empirical data from the 17 datasets.

1.5.17 The turbine sizes under consideration for VE are much larger than those used to develop the estimation above, so caution must be used when considering the results presented in this section. Nominal large power outputs have been used for the above calculation, as this has not been confirmed at this stage, and these will be referred to as ‘larger’ and ‘smaller’ turbines. As can been seen in the following sections, there is no significant impact expected irrespective of size.

1.5.18 Figure 1.21 presents a Level vs. range plot for the turbine sizes using the Tougaard *et al*. (2020) calculation, assuming an average 6 m/s wind speed. Although wind speeds and thus operational levels may be greater than this, this will not represent the typical condition. It is also worth noting that the background noise levels will also naturally increase, somewhat offsetting any additional impact this may have.

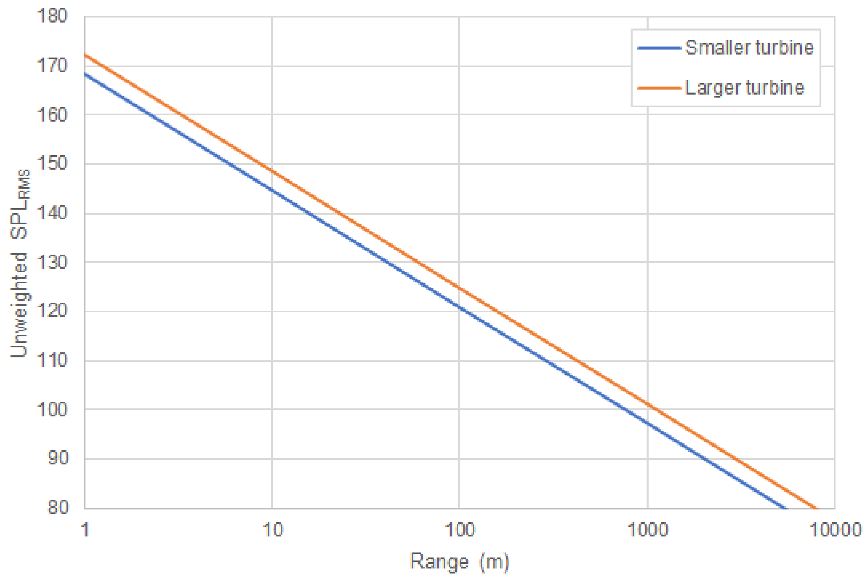

Figure 1.23: Predicted unweighted SPL_{RMS} from operational WTGs with nominally 'larger' and 'smaller' power outputs using the calculation from Tougaard *et al*. (2020).

1.5.19 Using this data, a summary of the predicted impact ranges has been produced, shown in Table 1.68 and Table 1.69. All SEL_{cum} criteria use the same assumptions as the previously presented modelling, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. The operational WTG source is considered a non-impulsive or continuous source. For SEL_{cum} calculations it has been assumed that the operational WTG noise is present 24 hours a day.

Table 1.68: Summary of the operational WTG noise impact ranges using the non-impulsive noise criteria from Southall *et al*. (2019) for marine mammals.

Southall *et al*. (2019) Weighted SEL_{cum}		Operational WTG (smaller)	Operational WTG (larger)
PTS (non-impulsive)	199 dB (LF)	< 100 m	< 100 m
	198 dB (HF)	< 100 m	< 100 m
	173 dB (VHF)	< 100 m	< 100 m
	201 dB (PCW)	< 100 m	< 100 m
TTS (non-impulsive	179 dB (LF)	< 100 m	< 100 m
	178 dB (HF)	< 100 m	< 100 m
	153 dB (VHF)	< 100 m	< 100 m
	181 dB (PCW)	< 100 m	< 100 m

Table 1.69: Summary of the operational WTG noise impact ranges using the continuous noise criteria from Popper *et al*. (2014) for fish (swim bladder involved in hearing).

Popper *et al*. (2014) Unweighted SPL_{RMS}	Operational WTG (smaller)	Operational WTG (larger)
Recoverable injury: 170 dB (48 hours)	< 50 m	< 50 m
TTS: 158 dB (12 hours)	< 50 m	< 50 m

1.5.20 These results show that, for operational WTGs, injury risk is minimal. Increasing the wind speed would not lead to significant increases in the impact ranges. Taking the results from this and the previous section, and comparing them to the impact piling results in section 1.4, it is clear that the noise from impact piling results in much greater noise levels and impact ranges, and hence should be considered the activity which has the potential to have the greatest effect during the construction and lifecycle of VE.

1.5.21 Stöber & Thomsen (2021) produced a similar study of an operational wind turbine dataset to Tougaard *et al*. (2020) and raises the potential for behavioural disturbance caused by larger wind turbines. While prospective turbine sizes are increasing, Stöber & Thomsen conclude that these might only have limited impacts related to behavioural response on marine mammals and fish, although there is considerable uncertainty in criteria available to assess these. However, based on the highly precautionary NOAA Level B behavioural threshold (120 dB SPL_{RMS}, see NOAA, 2005) that the study utilises, it is estimated that the WTGs may only reach that threshold at around 200 m away. As the distance between turbines is 950 m at the closest point, this would indicate that any array effect from the turbines is not expected.

UXO CLEARANCE

1.5.22 It is possible that UXO devices with a range of charge weights (or quantity of contained explosives) are present within the boundaries of VE. These would need to be cleared before any construction can begin. When modelling potential noise from UXO clearance, a variety of explosive types need to be considered, with the potential that many have been subject to degradation and burying over time. Two otherwise identical explosive devices are likely to produce different blasts in the case where one has spent an extended period on the seabed. A selection of explosive sizes has been considered based on what might be present, it has been assumed that the maximum explosive charge in each device is present and entirely detonates with the clearance.

ESTIMATION OF UNDERWATER NOISE LEVELS

1.5.23 The noise produced by the high order detonation of explosives is affected by several different elements, only one of which can easily be factored into a calculation: the charge weight. In this case, the charge weight is based on the equivalent weight of TNT. Many other elements relating to its situation (e.g., its design, composition, age, position, orientation, whether it is covered by sediment) and exactly how they will affect the sound produced by detonation are usually unknown and cannot be directly considered in this type of assessment. This leads to a high degree of uncertainty in the estimation of the source noise level. A worst-case estimation has therefore been used for calculations, assuming the UXO to be detonated is not buried, degraded or subject to any other significant attenuation from its "as new" condition.

1.5.24 The consequence of this is that the noise levels produced, particularly by the larger explosives under consideration, are likely to be over-estimated as some degree of degradation would be expected.

1.5.25 The maximum equivalent charge weight for the potential UXO devices that could be present within the VE site boundary has been estimated as 698 kg, this has been modelled alongside a range of smaller devices; these are 25, 55, 120, 120, and 525 kg. In each case, an additional donor weight of 0.5 kg has been included to initiate detonation. In addition, low-order deflagration has been assessed, which assumes that the donor or shaped-charge (charge weight 0.5 kg) detonates fully but without the follow-up detonation of the UXO. No mitigation has been considered for UXO modelling.

1.5.26 Estimation of the source level for each charge weight has been carried out in accordance with the methodology of Soloway and Dahl (2014), which follows Arons (1954) and the Marine Technical Directorate Ltd (MTD) (1996).

ESTIMATION OF UNDERWATER NOISE PROPAGATION

1.5.27 For this assessment, the attenuation of the noise from UXO has been accounted for in calculations using geometric spreading and a sound absorption coefficient, primarily using the methodologies cited in Soloway and Dahl (2014), which establishes a trend based on measured data in open water. These are, for SPL_{peak}:

$$SPL_{peak} = 52.4 \times 10^6 \left(\frac{R}{W^{1/3}}\right)^{-1.13}$$

and for SEL_{ss}:

$$SEL = 6.14 \times \log_{10}\left(W^{1/3}\left(\frac{R}{W^{1/3}}\right)^{-2.12}\right) + 219$$

where W is the equivalent charge weight for TNT in kilograms, and R is the range from the source.

1.5.28 These equations give a relatively simple calculation which can be used to give an indication of the range of effect. The equation does not consider variable bathymetry or seabed type, and thus calculation results will be the same regardless of where it is used. An attenuation correction has been added to the Soloway and Dahl (2014) equations for the absorption over long ranges (i.e., of the order of thousands of metres), based on measurements of high intensity noise propagation taken in the North Sea and Irish Sea in similar depths to VE. This uses standard frequency-based absorption coefficients for the seawater conditions expected in the region.

1.5.29 Despite this attenuation correction, the resulting noise levels still need to be considered carefully. For example, SPL_{peak} noise levels over larger distances are difficult to predict accurately (von Benda-Beckmann *et al*., 2015). Soloway and Dahl (2014) only present results from the equations above for small charges at ranges of less than 1 km, although the results are similar to the measurements presented by von Benda-Beckmann *et al*. (2015). At longer ranges, greater confidence is expected with the SEL calculations.

1.5.30 A further limitation in the Soloway and Dahl (2014) equations that must be considered are that variations in noise levels at different depths are not considered. Where animals are swimming near the surface, the acoustics can cause the noise level, and hence the exposure, to be lower (MTD, 1996). The risk to animal near the surface may therefore be lower than indicated by the impact ranges and therefore the results presented can be considered conservative in respect of the impact at different depths.

1.5.31 Additionally, an impulsive wave tends to be smoothed (i.e., the pulse becomes longer) over distance (Cudahy and Parvin, 2001), meaning the injurious potential of a wave at greater range can be even lower than just a reduction in the absolute noise level. An assessment in respect of SEL is considered preferential at long range as it considers the overall energy, and the degree of smoothing of the peak with increasing distance is less critical.

1.5.32 The selection of assessment criteria must also be considered in light of this. As discussed in section 1.2, the smoothing of the pulse at range means that a pulse may be considered non-impulsive with distance, suggesting that, at greater ranges, it may be more appropriate to use the non-impulsive criteria. This consideration may begin at 3.5 km (Hastie *et al*., 2019).

1.5.33 A summary of the unweighted UXO source levels calculated using the earlier equations (paragraph 1.5.27) are given in Table 1.70.

Table 1.70: Summary of the unweighted SPL_{peak} and SEL_{ss} source levels used for UXO clearance modelling.

Charge weight	0.5 kg	25 kg + donor	55 kg + donor	120 kg + donor	240 kg + donor	525 kg + donor	698 kg + donor
SPL_{peak} source level (dB re 1 µPa @ 1 m)	272.1	284.9	287.5	290.0	292.3	294.8	295.7

Charge weight	0.5 kg	25 kg + donor	55 kg + donor	120 kg + donor	240 kg + donor	525 kg + donor	698 kg + donor
SEL_{ss} source level (dB re 1 µPa^{2}s @ 1 m)	217.1	228.0	230.1	232.3	234.2	236.4	237.1

IMPACT RANGES

1.5.34 Table 1.71 to Table 1.74 present the impact ranges for UXO detonation, considering various charge weights and impact criteria. It should be noted that Popper *et al*. (2014) gives specific impact criteria for explosions (Table 1.6). A UXO detonation source is defined as a single pulse, as such the SEL_{cum} criteria from Southall *et al*. (2019) have been given as SEL_{ss}. Thus, fleeing animal assumptions do not apply. As with the previous sections, ranges smaller than 50 m have not been presented.

1.5.35 Although the impact ranges in Table 1.71 to Table 1.74 are large, the duration the noise is present must also be considered. For the detonation or a UXO, each explosion is a single noise event, compared to the multiple pulse mature and longer durations of impact piling.

Table 1.71: Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, unweighted SPL_{peak} noise criteria from Southall *et al*. (2019) for marine mammals.

Southall *et al*. (2019) Unweighted SPL_{peak}		0.5 kg	25 kg + donor	55 kg + donor	120 kg + donor	240 kg + donor	525 kg + donor	698 kg + donor
PTS	219 dB (LF)	220 m	820 m	1.0 km	1.3 km	1.7 km	2.2 km	2.4 km
	230 dB (HF)	70 m	260 m	340 m	450 m	560 m	730 m	810 m
	202 dB (VHF)	1.2 km	4.6 km	6.0 km	7.8 km	9.8 km	12 km	13 km
	218 dB (PCW)	240 m	910 m	1.1 km	1.5 km	1.9 km	2.5 km	2.7 km
TTS	213 dB (LF)	410 m	1.5 km	1.9 km	2.5 km	3.2 km	4.1 km	4.5 km
	224 dB (HF)	130 m	490 m	640 m	830 m	1.0 km	1.3 km	1.4 km
	196 dB (VHF)	2.3 km	8.5 km	11 km	14 km	18 km	23 km	25 km
	212 dB (PCW)	450 m	1.6 km	2.1 km	2.8 km	3.5 km	4.6 km	5.0 km

Table 1.72: Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, weighted SELss noise criteria from Southall *et al*. (2019) for marine mammals.

Southall *et al*. (2019) Weighted SELss		0.5 kg	25 kg + donor	55 kg + donor	120 kg + donor	240 kg + donor	525 kg + donor	698 kg + donor
PTS	183 dB (LF)	320 m	2.2 km	3.2 km	4.7 km	6.5 km	9.5 km	10 km
	185 dB (HF)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	50 m	60 m
	155 dB (VHF)	110 m	570 m	740 m	950 m	1.1 km	1.4 km	1.5 km
	185 dB (PCW)	60 m	390 m	570 m	830 m	1.1 km	1.6 km	1.9 km
TTS	168 dB (LF)	4.5 km	29 km	41 km	57 km	76 km	100 km	110 km
	170 dB (HF)	< 50 m	150 m	210 m	300 m	390 m	530 m	590 m
	140 dB (VHF)	930 m	2.4 km	2.8km	3.2 km	3.5 km	4.0 km	4.1 km
	170 dB (PCW)	800 m	5.2 km	7.5 km	10 km	14 km	19 km	22 km

Table 1.73: Summary of the PTS and TTS impact ranges for UXO detonation using the non-impulsive, weighted SELss noise criteria from Southall *et al*. (2019) for marine mammals.

Southall *et al*. (2019) Weighted SELss		0.5 kg	25 kg + donor	55 kg + donor	120 kg + donor	240 kg + donor	525 kg + donor	698 kg + donor
PTS	199 dB (LF)	< 50 m	130 m	190 m	280 m	390 m	570 m	660 m
	198 dB (HF)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 50 m	< 50 m	< 50 m	70 m	100 m	130 m	150 m
	201 dB (PCW)	< 50 m	< 50 m	< 50 m	< 50 m	70 m	100 m	110 m
TTS	179 dB (LF)	650 m	4.4 km	6.4 km	9.4 km	13 km	18 km	21 km
	178 dB (HF)	< 50 m	< 50 m	60 m	80 m	110 m	160 m	180 m
	153 dB (VHF)	150 m	730 m	940 m	1.1 km	1.4 km	1.7 km	1.8 km
	181 dB (PCW)	110 m	790 m	1.1 km	1.6 km	2.3 km	3.3 km	3.8 km

Table 1.74: Summary of the impact ranges for UXO detonation using the unweighted SPL_{peak} explosion noise criteria from Popper *et al*. (2014) for species of fish.

Southall *et al*. (2019) Unweighted SPL_{peak}		0.5 kg	25 kg + donor	55 kg + donor	120 kg + donor	240 kg + donor	525 kg + donor	698 kg + donor
Mortality & potential mortal injury	234 dB	< 50 m	170 m	230 m	300 m	370 m	490 m	530 m
	229 dB	80 m	290 m	380 m	490 m	620 m	810 m	890 m

SUMMARY

1.5.36 The maximum PTS range calculated for UXO is 13 km for the VHF cetacean category, based on the unweighted SPL_{peak} criteria, for SEL_{ss} criteria, the largest PTS range is calculated for LF cetaceans, with a predicted impact of 10 km using the impulsive noise criteria. As explained earlier, this assumes no degradation of the UXO and no smoothing of the pulse over that distance, which is highly precautionary. Although the assumption of non-pulse could under-estimate the potential impact (Martin *et al*., 2020) (the equivalent PTS range based on LF cetacean non-pulse criteria is 660 m), it is likely that the long-range smoothing of the pulse peak would reduce its potential harm and the maximum 'impulsive' range for all species is very precautionary.

1.6 SUMMARY AND CONCLUSIONS

1.6.1 Subacoustech Environmental has undertaken a study to assess potential underwater noise and its effects during the construction and operation of VE, an extension to the existing Galloper Offshore Wind Farm, located in the southern North Sea.

1.6.2 The level of underwater noise from the installation of WTG foundations during the construction has been estimated using the semi-empirical underwater noise model INSPIRE. The modelling considers a wide variety of input parameters including bathymetry, hammer blow energy, blow rate, and receptor flee speed.

1.6.3 Three representative modelling locations were chosen to give special variation as well as account for changes in water depth around the site. At each location, two modelling scenarios were considered:

> A worst-case monopile scenario, installing 15 m diameter pile with a maximum blow energy of 7,000 kJ; and

> A worst-case pin pile scenario, installing a 3.5 m diameter pile with a maximum blow energy of 3,000 kJ.

1.6.4 It is expected that up to four pin piles could be sequentially installed in a 24-hour period per vessel, and that two piling rigs could be operational at the same time.

1.6.5 The loudest levels of noise and greatest impact ranges have been largely predicted for the monopile scenarios, with similar ranges predicted across the three modelling locations.

1.6.6 The modelling results were analysed in terms of relevant noise metrics and criteria to assess the effects of the impact piling on marine mammals (Southall *et al*., 2019) and fish (Popper *et al*., 2014), which have been used to aid biological assessments.

1.6.7 For marine mammals, maximum PTS range were predicted for LF cetaceans, with ranges of up to 15 km predicted for the monopile scenario. For fish, the largest recoverable injury ranges (203 dB SEL_{cum}) were predicted out to 1.6 km for a fleeing receptor for the monopile scenario. When a stationary receptor was considered the maximum recoverable injury range was predicted to be 12 km for the four sequential pin pile installation scenario.

1.6.8 Noise sources other than piling were considered using a high-level, simple modelling approach, including cable laying, trenching, rock placement, dredging, vessel noise and operational WTG noise. The predicted noise levels for the other construction noise sources and during WTG operation are well below those predicted for impact piling noise. The risk of any potential injurious effects to fish or marine mammals from these sources are expected to be minimal as the noise emissions from these are close to, or below, the appropriate injury criteria even when very close to the source of the noise.

1.6.9 UXO clearance has also been considered at the VE site, and for the expected UXO clearance noise, there is a risk of PTS up to 13 km for the largest, 698 kg UXO device considered, using the unweighted SPL_{peak} criteria for VHF cetaceans. However, this is likely to be precautionary as the impact range is based on a worst-case criterion and a calculation methodology that does not account for any smoothing of the pulse over long ranges, which would reduce the pulse peal and other characteristics of the sound that cause injury.

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

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FIVE ESTUARIES OFFSHORE WIND FARM

PHONE	0333 880 5306
EMAIL	fiveestuaries@rwe.com
WEBSITE	www.fiveestuaries.co.uk
ADDRESS	Five Estuaries Offshore Wind Farm Ltd Windmill Hill Business Park Whitehill Way, Swindon, SN5 6PB
COMPANY NO	Registered in England and Wales company number 12292474