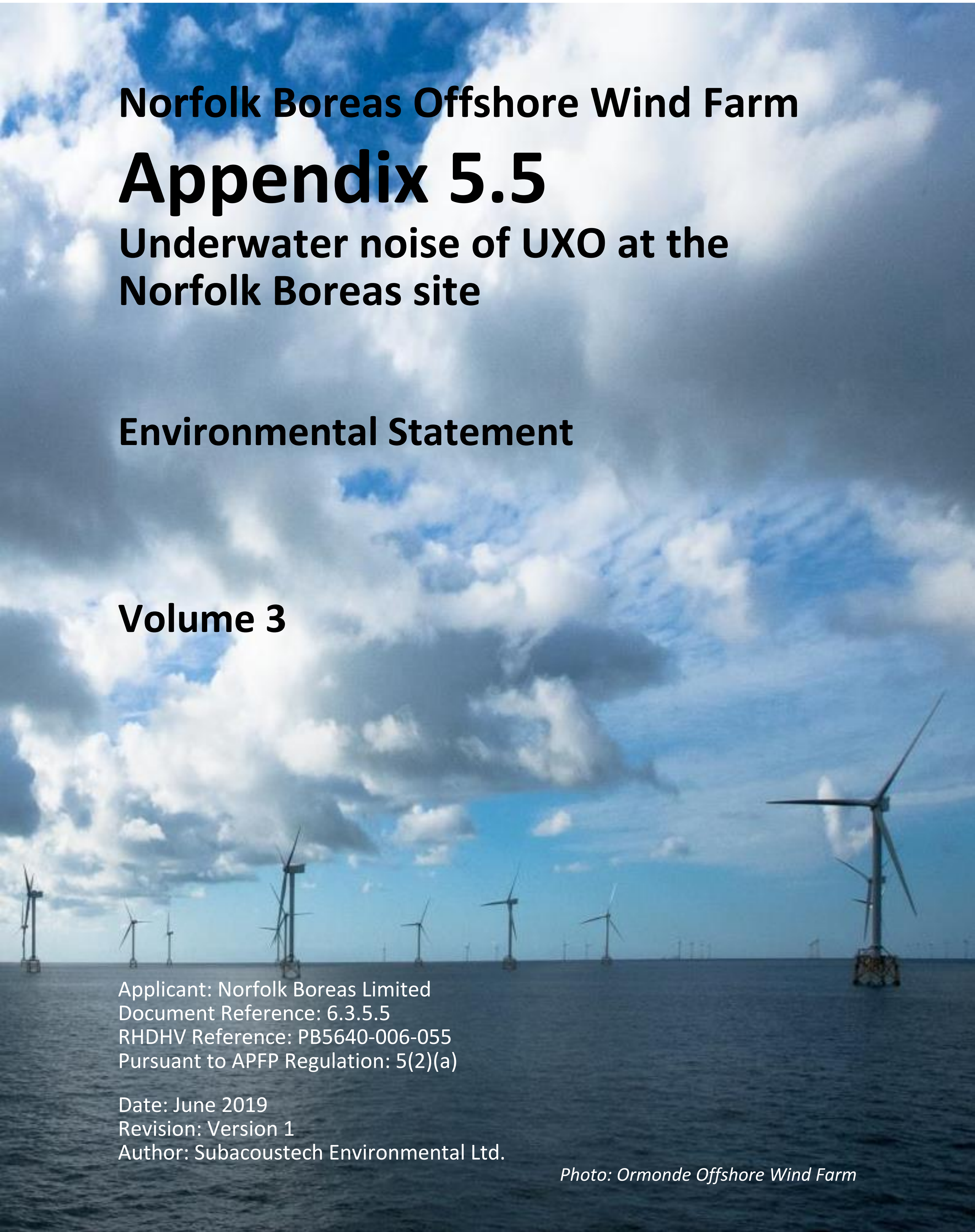

Norfolk Boreas Offshore Wind Farm

Appendix 5.5

Underwater noise of UXO at the Norfolk Boreas site

Environmental Statement

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Project title	Estimated ranges of impact for various UXO detonations, Norfolk Boreas OWF
Project number	P227
Author(s)	Tim Mason
Company	Subacoustech Environmental Ltd.
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Introduction

The risk associated with clearance of unexploded ordnance (UXO) associated with the Norfolk Boreas Offshore Windfarm (OWF) has been investigated by Subacoustech Environmental Ltd, in respect of the underwater noise produced. The range of impact in relation to marine mammals and fish injury from UXO detonation has been estimated.

A number of UXO devices with a range of charge weights (or quantity of contained explosive) may be present within the boundary of the Norfolk Boreas site. These may need to be removed before construction can begin. There are expected be a variety of explosive types, many of which are likely to have been subject to degradation or 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 sea bed. A selection of explosive sizes has been considered based on site surveys and in each case, it has been assumed that the maximum explosive charge in each device is present and detonates with the clearance.

Estimation of underwater noise levels

The noise produced by the detonation of explosives is affected by several different elements, only one of which, the charge weight, can easily be factored into a calculation. In this case the charge weight used for calculations 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 (i.e. the noise level at the position of the UXO). 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.

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 coverage by sediment and degradation would be expected.

The range of equivalent charge weights of the potential UXO devices that could be present within the Norfolk Boreas site boundaries have been estimated as from 25 to 770 kg (Table 1). Estimation of the source noise level for each charge weight was carried out in accordance with the methodology of Soloway and Dahl (2014)[1], which follows Arons (1954)[2] and MTD (1996)[3].

[1] Soloway A G, Dahl P H (2014). *Peak sound pressure and sound exposure level from underwater explosions in shallow water.* The Journal of the Acoustical Society of America, 136(3), EL219-EL223. http://dx.doi.org/ 10.1121/1.4892668
[2] Arons A B (1954). *Underwater explosion shock wave parameters at large distances from the charge.* J. Acoust. Soc. Am. 26, 343–346
[3] The Marine Technology Directorate Ltd (MTD) (1996). *Guidelines for the safe use of explosives under water*. MTD Publication 96/101. ISBN 1 870553 23 3

UXO Item	NEQ	TNT Eq.
German SC-50 bomb (amatol)	25 kg	25 kg
German SC-250 bomb (amatol)	145 kg	145 kg
250lb Allied bomb (Hexogen/TNT)	50 kg	60 kg
500lb Allied bomb (Hexogen/TNT)	126 kg	151 kg
1000lb Allied bomb (Hexogen/TNT)	260 kg	312 kg
500lb Allied mine (minol)	227 kg	340 kg
German LMB (GC) Ground Mine (Hexanite)	700 kg	770 kg

Table 1 – UXO devices potentially present at Norfolk Boreas site

Estimation of propagation of underwater noise

An overview knowledge of underwater acoustic theory is assumed in this study: a more detailed explanation of the concepts and terminology is contained within the underwater noise section in the Norfolk Boreas Environmental Statement.

For this assessment, the attenuation of the noise from UXO detonation has been accounted for in calculations using geometric spreading and a sound absorption coefficient based on methodologies cited in Soloway and Dahl (2014). These establish a trend based on measurements of underwater blast in open water given by, for SPL:

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

and for SEL:

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

These equations provide a relatively simple calculation which has been used to give an indication of the range of effect. The equation does not take into account variable bathymetry or seabed type, and thus calculation results will be the same regardless 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). The sound frequency of the noise and the species' hearing sensitivity (see the Impact Criteria section) has also been accounted for.

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)[4]. Soloway and Dahl (2014) only verify results from the equation above for relatively small charges and at ranges of less than 1 km. However, the results here do agree with the measurements presented by von Benda-Beckmann *et al*. (2014), which sampled 263 kg charges, at longer range. At these ranges greater confidence is expected with the calculations using the SEL metric.

A further limitation in the Soloway and Dahl (2014) equation that must be considered are that variation in noise levels at different depths of water are not taken into account. Where animals are swimming near the surface, the acoustics can cause the noise level, and hence the exposure, to be lower

[4] von Benda-Beckman A M, Aarts G, Sertlek H Ö, Lucke K, Verboom W C, Kastelein R A, Ketten D R, van Bemmelen R, Lam F-P A, Kirkwood R J, Ainslie M A (2015). *Assessing the impact of underwater clearance of unexploded ordnance on harbour porpoises (phocoena phocoena) in the southern North Sea.* Aquatic Mammals 2015, 41(4), 503-523, DOI 10.1578/AM.41.4.2015.503.

(MTD, 1996). The risk to animals near the surface may therefore be lower than indicated by the impact ranges and therefore the results can be considered conservative in respect of the impact at different depths.

A summary of the unweighted UXO source levels calculated using this method for this modelling are given in Table 2.

Charge weight	25 kg	60 kg	145 kg	151 kg	312 kg	340 kg	770 kg
SPL_{peak} dB re 1 µPa	284.9	287.7	290.6	290.7	293.1	293.4	296.1
SEL_{ss} dB re 1 µPa²s	227.9	230.3	232.8	232.9	234.9	235.1	237.4

Table 2 - Summary of the unweighted SPL_{peak} and SEL_{ss} source levels used for UXO modelling

These charge weights cannot take into account the range of variables noted above and thus will only provide an indication of the noise output from each detonation. They also assume a worst-case freely suspended charge.

Impact criteria

The prediction of impacts on marine fauna is split into how the noise affects marine mammals and fish.

Marine mammals

The selection of impact criteria uses thresholds and a weighting based on NMFS (2018)[5]. The thresholds indicate the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in various species of marine mammal. This is the point at which there is an increase in risk of permanent hearing damage in an underwater receptor.

The thresholds group a selection of species based on their hearing capabilities, or their particular sensitivity to low or high frequency sound. Blast noise is fairly broadband at source, comprising a wide range of low to high frequency sound, although the majority is at low frequency with a large reduction above 10 kHz.

The groupings and SEL thresholds for impulsive noise as given in the results are as follows:

- "LF": Low-frequency cetaceans, e.g. minke whale.
  183 dB re 1 µPa²s (PTS), 168 (TTS) re 1 µPa²s
- "MF": Mid-frequency cetaceans, e.g. dolphin species.
  185 dB re 1 µPa²s (PTS), 170 (TTS) re 1 µPa²s
- "HF": High-frequency cetaceans, e.g. harbour porpoise.
  155 dB re 1 µPa²s (PTS), 140 (TTS) re 1 µPa²s
- "PW": Phocid Pinnipeds (in water), e.g. harbour seal.
  185 dB re 1 µPa²s (PTS), 170 (TTS) re 1 µPa²s

The SEL criteria given in NMFS (2018) are weighted, which corrects the sound level at the receiver based on the sensitivity of the receiver, e.g. harbour porpoise are less sensitive to low frequency sound

[5] National Marine Fisheries Service (NMFS) (2018). *2018 Revisions to: Technical guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater thresholds for Onset of Permanent and Temporary Threshold Shifts*. U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum, NMFS-OPR-59.

than minke whale. NMFS (2018) also includes criteria based on SPL, which are unweighted and do not take species sensitivity into account.

Please note that both Sound Pressure Level (SPL) and Sound Exposure Level (SEL) values are included in the results, which are specific to different criteria used, and should not be confused or compared directly. All decibel SPL values are referenced to 1 µPa; all SEL values are referenced to 1 $\mu Pa^2 s$.

These thresholds are defined for an 'impulsive' noise type. They are most relevant close to the blast. At greater ranges, and especially in shallow water, the sound pulse will spread out in time, becoming less 'sharp' and thus less injurious. The draft of NMFS (2018) suggested 3,000 m as an estimate of a distance at which transition away from this impulse to a more non-pulse type of noise could occur, although the sound will not go through a 'step change' and this distance will change depending on the type of sound and situation. This consideration is still under review, although the relevant non-pulse criteria are available and results to these are included. These are significantly less stringent than the impulsive criteria. Explosive noise is highly impulsive and an upper conservative estimate of 5,000 m is suggested for the transition.

Although the stricter impulsive ranges should be considered in the first instance, this study would draw attention to the above acoustical consideration for circumstances where impact ranges are modelled to be of the order of thousands of metres.

Fish

The vast variation between fish species, and studies have only been done on the impacts of noise to a small number of them, which makes an assessment challenging. Criteria for marine mammals have been simplified by categorising them according to the hearing sensitivity of a species group; for fish Popper *et al*. (2014)[6] have proposed criteria for species divided into three groups:

- Fish with no swim bladder (e.g. dab and other flatfish)
- Fish where a swim bladder is not involved in hearing (e.g. Atlantic salmon)
- Fish where a swim bladder is involved in hearing (e.g. Atlantic cod and herring)

However, in consideration of explosives and potential mortality, all species groups are considered equivalent and there is no frequency weighting to account for variations in hearing sensitivity. Two thresholds are provided, 229 and 234 dB SPL_{peak}, which represent the range of potential impact.

It is also considered that there is insufficient data for a quantitative calculation of impact ranges for recoverable injury or hearing impairment in respect of blast. The risk of the effect is therefore considered as either 'low', 'moderate' or 'high' at range in the Popper *et al*. (2014) study.

[6] Popper A N, Hawkins A D, Fay R R, Mann D A, Bartol S, Carlson T J, Coombs S, Ellison W T, Gentry R L, Halvorsen M B, Løkkeborg S, Rogers P H, Southall B L, Zeddies D G, Tavolga W B (2014). *Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI*, pp. 33–51. Springer, New York

Impact ranges

Table 3 to Table 6 present the impact ranges for UXO detonation, considering various charge weights and impact criteria. Ranges smaller than 100 m have not been presented.

Although the impact ranges presented in the following tables are large, the duration the noise is present must be taken into account. For detonation of UXO each explosion is only a single noise event, compared to the multiple pulse nature of impact piling.

NMFS (2018) Unweighted SPL_{peak}		25 kg	60 kg	145 kg	151 kg	312 kg	340 kg	770 kg
PTS (Impulsive)	219 dB (LF)	810 m	1.0 km	1.4 km	1.4 km	1.9 km	1.9 km	2.5 km
	230 dB (MF)	260 m	350 m	480 m	480 m	610 m	630m	830 m
	202 dB (HF)	4.6 km	6.1 km	8.3 km	8.4 km	10.7 km	11.0 km	14.4 km
	218 dB (PW)	900 m	1.2 km	1.6 km	1.6 km	2.1 km	2.1 km	2.8 km
TTS (Impulsive)	213 dB (LF)	1.5 km	2.0 km	2.7 km	2.7 km	3.5 km	3.6 km	4.7 km
	224 dB (MF)	490 m	650 m	880 m	890 m	1.1 km	1.1 km	1.5 km
	196 dB (HF)	8.5 km	11.3 km	15.2 km	15.4 km	19.6 km	20.2 km	26.5 km
	212 dB (PW)	1.6 km	2.2 km	3.0 km	3.0 km	3.8 km	3.9 km	5.2 km

Table 3 - Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, unweighted SPL_{peak}, noise criteria from NMFS (2018) for marine mammals at Norfolk Boreas

NMFS (2018) Weighted SEL_{ss}		25 kg	60 kg	145 kg	151 kg	312 kg	340 kg	770 kg
PTS (Impulsive)	183 dB (LF)	2.1 km	3.3 km	5.1 km	5.2 km	7.4 km	7.7 km	11.4 km
	185 dB (MF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	155 dB (HF)	560 m	760 m	1.0 km	1.0 km	1.2 km	1.2 km	1.5 km
	185 dB (PW)	380 m	590 m	910m	930 m	1.3 km	1.3 km	2.0 km
TTS (Impulsive)	168 dB (LF)	28.8 km	42.6 km	62.1 km	63.1 km	84.8 km	87.7 km	119 km
	170 dB (MF)	150 m	220 m	320 m	330 m	440 m	450 m	610 m
	140 dB (HF)	2.4 km	2.8 km	3.3 km	3.3 km	3.7 km	3.7 km	4.2 km
	170 dB (PW)	5.2 km	7.7 km	11.5 km	11.7 km	15.9 km	16.5 km	23.0 km

Table 4 - Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, weighted SEL_{ss}, noise criteria from NMFS (2018) for marine mammals at Norfolk Boreas

NMFS (2018) Weighted SEL_{ss}		25 kg	60 kg	145 kg	151 kg	312 kg	340 kg	770 kg
PTS (Non-impulsive)	199 dB (LF)	120 m	190 m	300 m	310 m	440 m	460 m	690 m
	198 dB (MF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	173 dB (HF)	< 100 m	< 100 m	< 100 m	< 100 m	100 m	110 m	160 m
	201 dB (PW)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	120 m
TTS (Non-impulsive)	179 dB (LF)	4.4 km	6.7 km	10.2 km	10.4 km	14.7 km	15.3 km	22.5 km
	178 dB (MF)	< 100 m	< 100 m	< 100 m	< 100 m	130 m	130 m	190 m
	153 dB (HF)	730 m	960 m	1.2 km	1.2 km	1.5 km	1.5 km	1.8 km
	181 dB (PW)	780 m	1.1 km	1.8 km	1.8 km	2.6 km	2.7 km	4.0 km

Table 5 - Summary of the PTS and TTS impact ranges for UXO detonation using the non-impulsive, weighted SEL_{ss}, noise criteria from NMFS (2018) for marine mammals at Norfolk Boreas

It can be seen that the ranges of impact for PTS to LF and HF cetaceans using impulse-type criteria are in excess of 5 km. However, using the non-pulse criteria, the impact ranges for all species for PTS criteria are less than 1 km. It is suggested that 5 km is likely to be the limit of risk of PTS onset. Similarly, the prediction of TTS ranges, especially for LF cetaceans, are expected to be over-estimated in practice.

Popper *et al.* (2014) Unweighted SPL_{peak}	25 kg	60 kg	145 kg	151 kg	312 kg	340 kg	770 kg
234 dB (Potential mortal injury)	170 m	230 m	310 m	320 m	410 m	420 m	550 m
229 dB (Potential mortal injury)	290 m	390 m	530 m	530 m	680 m	700 m	920 m

Table 6 - Summary of the impact ranges for UXO detonation using the unweighted SPL_{peak}, explosion noise criteria (upper and lower limit) from Popper et al. (2014) for marine mammals at Norfolk Boreas

Conclusions

The impact ranges for a selection of charge weights have been presented. The large number of unknown variables that will affect the output of UXO located for an extended period on the seabed lead to a great degree of uncertainty which makes accuracy challenging in a desktop assessment. The assessment is based on calculations using a simple methodology proposed by Soloway and Dahl (2014) following Arons (1954) and MTD (1996). It is expected that the presented ranges overestimate the actual ranges of impact that would occur in practice, both from physical sound propagation and biological perspective.

The calculation parameters are all chosen to be conservative, leading to an upper estimate for source noise levels, and the risk of impact will be reduced over increasing range as the initial shock wave dissipates.

The sound levels have been converted to impact ranges using sets of criteria from NMFS (2018), which, although describing nominally the same injury to the hearing of a species, use different criteria, leading to multiple estimates of the range of impact. No single set of criteria can be assumed to be definitive or 'correct'. It is worth noting also that the criteria refer only to the 'onset' of injury risk rather than a confident assessment of an occurrence of the effect. More research into the effects of noise on marine species will be required to increase confidence in the impacts in real open water circumstances.

Data presented in von Benda-Beckmann *et al.* (2015) show a level of 179 dB SEL re 1 $\mu Pa^2 s$ (equivalent to the non-impulsive PTS threshold for LF cetaceans) will be reached, in depths of 10-20 m of water, at a range of the order of 6 to 8 km for a charge weight of approximately 700 kg. This suggests that the simple calculation methodology overestimates the noise propagation at long range.

There is little data available for the impact of different sized charges on fish species. However, calculated ranges for the risk of mortal injury to individuals have been provided. The risk of potential mortal injury to fish is predicted to be within 1,000 m of the UXO location, for the largest charge weight.