JNCC Report 798

Evidence review of harbour porpoise disturbance ranges in the context of the assessment and management of impulsive noise in Special Areas of Conservation: unexploded ordnance clearance, explosives for decommissioning, seismic (airgun) survey, sub-bottom profilers, ultra-short baseline acoustic positioning, acoustic deterrent devices, multi-beam echosounders, and military sonar

Majewska, K., Brown, A.M., Charish, R., Quinn, M. and Matei, M.

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For further information please contact:
JNCC, Quay House, 2 East Station Road, Fletton Quays, Peterborough PE2 8YY.
https://jncc.gov.uk/

Communications@jncc.gov.uk

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Author affiliations:
[1] SMRU Consulting, Scottish Oceans Institute, East Sands, University of St Andrews

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Preface

This is a JNCC-commissioned report completed by SMRU Consulting. The primary intended audience is the JNCC and other statutory nature conservation bodies, to provide a resource to inform development of their guidance.

This report represents one of two complementary reports in contribution to an evidence review of harbour porpoise disturbance ranges in the context of the assessment and management of impulsive noise in Special Areas of Conservation. One report covers impact piling (Brown *et al.* 2025). The current report covers all other relevant categories of noise source, including:

- unexploded ordnance (UXO) clearance,
- explosives for decommissioning,
- seismic (airgun) survey,
- sub-bottom profilers (SBPs),
- ultrasonic baseline (USBL) acoustic positioning,
- acoustic deterrent devices (ADDs),
- multi-beam echosounders (MBES),
- military sonar.

Each report has been written to be stand-alone, so some introductory material is duplicated between the two reports.

Summary

In 2020, the Joint Nature Conservation Committee (JNCC), Natural England and the Department of Agriculture, Environment and Rural Affairs published guidance on the management of impulsive noise within harbour porpoise Special Areas of Conservation (SACs) (JNCC 2020). A key feature of this guidance was the recommendation of default effective deterrence ranges (EDRs) for specific categories of impulsive noise-generating activities, to assess the spatio-temporal extent of disturbance within SACs in English, Northern Irish and Welsh offshore waters. EDRs provide a radius around activities within which it is assumed that animals are disturbed. Where available, EDRs are based on empirical evidence of harbour porpoise responses to relevant activities. This radius is not equivalent to 100% deterrence/disturbance, but the range within the which the bulk of the effect had been detected (JNCC 2020). The extent of evidence supporting EDRs varies between activities, is very limited for some, and continues to increase over time. As such, periodic review of default recommended EDRs is required to ensure that guidance remains current and is based on the best available evidence.

To inform the development of updated guidance on noise management in harbour porpoise SACs, a review was undertaken of evidence relating to harbour porpoise disturbance to impulsive noise sources. Specifically, the review aimed to:

(i) review the evidence underpinning the current EDRs and subsequently published studies,

(ii) where possible, revisit existing data with the aim of defining default EDRs in a more standardised way,

(iii) recommend default EDRs, and

(iv) recommend priorities for filling evidence gaps. The current report covers the following categories of noise source: unexploded ordnance (UXO) clearance, explosives use for decommissioning, seismic (airgun) survey, sub-bottom profilers (SBPs), ultra-short baseline (USBL) acoustic positioning systems, acoustic deterrent devices (ADDs), multi-beam echosounders (MBES) and military sonar. A complementary report covers impact piling (Brown *et al.* 2025).

The availability and type of relevant evidence varied by noise source. Evidence was placed into three different categories:

(i) empirical studies of responses of animals to noise sources (‘empirical response studies’),

(ii) studies reporting on measured noise levels during use of relevant sources (‘noise measurement studies’), and

(iii) studies undertaking modelling to estimate noise levels from relevant sources (‘noise modelling studies’). Unlike empirical response studies, noise measurement and modelling studies do not provide direct observations of animal responses; instead, the potential for disturbance inferences must be made based on assumptions of the noise levels at which animals respond, using fixed response thresholds. While interpreting noise measurement and modelling studies to estimate disturbance ranges carries additional uncertainty over empirical response studies, the paucity of the latter for many noise sources necessitates such an approach.

Building on earlier reviews, relevant studies for each noise source were summarised, scrutinised and tabulated to include a summary of the reported response ranges / distances to thresholds, along with key attributes of the specific study and its associated activity. Each

piece of evidence was also assigned a score based on specific evaluation criteria, including the type of study (empirical response, noise measurement or modelling), a study's ability to estimate an EDR, and several additional criteria relating to the relevance of the study to current UK practices and limitations of the study design or analysis. Where possible, data and plots presented in existing studies were examined to estimate EDRs according to a common definition, that being a distance representing the average habitat loss per individual.

Overall, empirical data on harbour porpoise behavioural responses to different noise sources remain limited. Empirical response studies which were considered suitable for informing the spatial extent of disturbance were largely restricted to seismic (airgun) surveys and ADDs. For noise sources, such as UXO clearance and SBPs, some empirical evidence was available, but with notable limitations. In the case of UXO clearance, evidence was limited to a few high-order clearances, and porpoise responses could not be clearly separated from concurrent ADD use. However, a considerable volume of noise measurement data now exist for high- and low-order UXO clearance, with consistency among reported noise levels for low-order clearance. Far less evidence is available for the use of explosives in decommissioning. For SBPs, the single empirical response study was opportunistic and insufficient to define a reliable spatial extent of behavioural effects. There is a substantial body of evidence for cetacean responses to military sonar; however, most studies have focused on deep-diving species and data specific to harbour porpoise are restricted to experimental exposures in captive settings. For most noise sources, noise measurement studies formed an important component of the evidence base to inform EDRs.

Recommendations for default EDRs are provided for all noise sources reviewed, accompanied by relevant caveats and limitations. These include several noise sources for which EDRs have not previously been proposed and recommended refinements to many of the current EDRs. Where evidence allows, EDRs are recommended for sub-categories of EDR (e.g. high- vs low-order UXO clearance, short vs long ADD durations). Overall, recommendations follow a general trend of being the same or smaller than current default EDRs. Considerable uncertainties remain around all EDRs, but evidence scores were higher for UXO, seismic (airgun) surveys and ADDs than other noise sources which were more reliant on limited measurement, modelling and/or studies from proxy species. Evidence which relies on assumptions about the noise levels at which disturbance will occur carries additional uncertainties over empirical response studies, as the behavioural response thresholds used are not universally accepted or based on evidence specific to the species and/or activity to which they are being applied.

Priorities for filling evidence gaps are proposed for each noise activity presented within this report. Above all, to improve the evidence base underlying EDRs, there is a need for empirical studies of harbour porpoise responses to all noise sources. These should be appropriately designed to allow estimation of a gradient of responses with distance to source, including the maximum extent of effects. In addition, there is a need for expanded data collection on underwater noise levels across many of the reviewed noise sources, to improve understanding of noise characteristics, propagation and its potential impacts on marine receptors.

Contents

1. Introduction

1.1. Overview: Harbour porpoise SAC management and EDRs

Special Areas of Conservation (SACs) have been designated for harbour porpoise (*Phocoena phocoena*) in UK waters with the main aims of protecting recognised important habitats for the species and avoiding significant disturbance to allow those habitats to contribute in the best possible way to supporting the species (JNCC 2020a). Conservation objectives for harbour porpoise SACs in waters of England, Wales and Northern Ireland are provided in Table 1, one of which is ensuring that there is no significant disturbance of the species.

Table 1. Conservation objectives for harbour porpoise SACs in waters of England, Wales and Northern Ireland.

To ensure that the integrity of the site is maintained and that it makes an appropriate contribution to maintaining Favourable Conservation Status (FCS) for harbour porpoise in UK waters. In the context of natural change, this will be achieved by ensuring that:	
Objective	**Requirement**
Objective 1	Harbour porpoise is a viable component of the site.
Objective 2	There is no significant disturbance of the species.
Objective 3	The condition of the supporting habitats and processes, and the availability of prey is maintained.

Harbour porpoise are considered sensitive to underwater noise associated with industrial activities (e.g. impulsive noise associated with pile driving for construction of offshore wind farms (OWFs)) and field studies have shown that animals respond to such activities. Given the scale of noise-generating activity planned within and adjacent to some SACs, an approach to managing the extent of noise disturbance within these sites was developed.

Guidance on the management of impulsive noise within harbour porpoise SACs in waters of England, Wales and Northern Ireland (JNCC 2020) defines significant disturbance through quantitative time-area thresholds for the spatio-temporal extent of disturbance within the SAC. The method of estimating the spatial extent of disturbance advised for SACs in English, Northern Irish and Welsh offshore waters is by using effective deterrence ranges (EDRs) for specific impulsive noise-generating activities (Table 2). EDRs assume a fixed disturbance range for harbour porpoise for different activities, which equates to the average habitat lost by individual animals. Other methods of estimating the spatial extent of disturbance include the use of noise propagation modelling and response thresholds, with such an approach recommended by Natural Resources Wales (NRW) for SACs in Welsh waters (NRW 2023).

The EDR approach is strongly influenced by the size of activity-specific EDRs - for which there are considerable uncertainties. The Joint Nature Conservation Committee (JNCC) guidance provided recommended EDRs for several categories of impulsive noise-generating activities, including: impact pile-driving (monopiles and pin-pile, with and without noise abatement, and conductor piling), unexploded ordnance (UXO) detonation, seismic (airgun) survey and high-resolution geophysical survey (JNCC 2020). More recently, default EDRs have been recommended for all activities listed in the UK Marine Noise Registry (MNR) (JNCC 2023a), including further sub-categories of those presented in JNCC (2020).

Where such data exist, activity-specific EDRs are based on empirical evidence from field studies of porpoise responses to those noise sources. However, a Department for Environment Food and Rural Affairs (Defra)-commissioned review of the evidence underlying the EDRs, published in 2023, identified that empirical data of harbour porpoise responses was only available for impact-piling of wind farm foundations, and to a lesser extent for seismic surveys and Acoustic Deterrent Devices (ADDs) (Brown *et al.* 2023 - see Section 1.2 for a summary of key findings). Therefore, precautionary EDRs have been set based on proxies or consideration of relative noise levels.

1.1.1. Current EDRs for relevant noise sources

The current recommended activity-specific EDRs for noise sources other than impact piling are presented in Table 2. There are no EDRs currently recommended for the use of ADDs or military sonar, but they have been included in this review as additional sources tracked within the MNR. Also included are ultrasonic baseline (USBL) acoustic positioning systems, which also generate short pulses of sound and are widely used in association with high-resolution geophysical and geotechnical surveys.

Table 2. Current recommended activity-specific EDRs, excluding impact piling, for the management of impulsive noise within harbour porpoise SACs in waters of England, Wales and Northern Ireland (JNCC 2020).

Activity	EDR (km)	References from which EDRs were based
UXO clearance (high order)	26	Based on monopile EDR (JNCC 2020)
UXO clearance with noise abatement (high order)	15	N/A, presented in JNCC (2023a)
UXO clearance (low order)	5	Project-specific casework
Explosives (open water) > 2 kg, > 2 kg with noise abatement, < 2 kg	26, 15, 5	N/A, presented in JNCC (2023a)
Explosives (within 100 m of the mudline) > 2 kg, > 2 kg with noise abatement, < 2 kg	15, 5, 5	N/A, presented in JNCC (2023a)
Seismic (airgun) surveys (excluding mini airgun)	12	Thompson *et al.* (2013); Sarnocińska *et al.* (2020)
Other geophysical surveys / sub-bottom profiler (SBPs) surveys (including mini airgun)	5	Crocker and Fratantonio (2016); Crocker *et al.* (2019)
Multibeam echosounders	5	Based on SBP surveys

Where based on empirical studies of harbour porpoise responses to activities, the recommended EDRs were based on ranges "*where the bulk of the effect (reduction in porpoise vocal activity or sightings) had been detected*", noting that:

- The EDRs do not represent 100% disturbance in an associated area, nor do they represent the maximum range at which disturbance effects can be detected.
- Only the most detectable effects on the animals are observed by those studies informing the EDRs.

- The observed disturbance effects reported in the different studies were not derived in a comparable way.

The latter point is particularly important in terms of how suitable the reported disturbance effects are for deriving an EDR according to the definition of the "average level of habitat loss". Among the studies cited for non-piling noise sources, none presented effect ranges which aligned with a clear definition of EDR that related to average temporary habitat loss per individual (see Section 2.2 for further details).

1.1.2. Review of EDRs

The JNCC (2020) guidance notes that the default recommended EDRs for all noise sources will be under regular review considering emerging evidence such as that gathered through monitoring associated with licensed activities. The need for consideration of emerging evidence and additional review of existing evidence is a key driver of the EDR evidence review presented in this current report.

1.2. The Defra-commissioned review of evidence underlying EDRs

In 2023, a Defra-commissioned review of evidence supporting the management of disturbance in harbour porpoise SACs was published, which included a review of the evidence underlying the current EDRs used in porpoise SAC management (Brown *et al.* 2023). At the time of publication, key findings relating to noise sources other than impact piling included:

- There is a very limited evidence base of empirical studies of harbour porpoise responses to non-piling noise sources, with few studies of far-field effects available for seismic (airgun) survey or ADDs. At the time that review was completed, there were no empirical studies available for UXO clearance or other impulsive noise sources such as SBPs.
- Noise measurement studies are improving our understanding of the likely noise levels and propagation into the marine environment from UXO clearance. However, the uncertainty regarding the noise levels at which harbour porpoise exhibit responses to single loud impulses limits their interpretation from a behavioural response and EDR perspective.
- Among empirical studies of harbour porpoise responses to noise sources, there was considerable variation in the approach to data analysis and reporting of results, which complicates comparison of results and adds considerable uncertainty to the estimation of effects ranges.
- No studies for non-piling noise sources provided a clear definition of (/approach to estimating) EDR that related to average temporary habitat loss per individual. As such, it can be difficult to interpret effect ranges with greater resolution than the maximum distance of detectable effect, or a wide range of distances over which effects appear to plateau.

1.3. Objectives

The overall aim of this study is to put forward recommendations for updated EDRs used in the management of harbour porpoise SACs for the following noise sources/source categories:

- UXO clearance (Section 3),
- Explosives for decommissioning (Section 4),
- Seismic (airgun) survey (Section 5),
- SBPs and USBL acoustic positioning (Section 6),
- ADDs (Section 7),
- MBES (< 12 kHz, Section 8),
- Military sonar (Section 9).

This will be achieved through four specific objectives:

1. Review literature (grey and peer-reviewed) for empirical evidence of harbour porpoise disturbance in relation to impulsive noise for relevant noise sources.
2. Review noise measurement and noise modelling studies to assess the potential for disturbance inferences using fixed response thresholds.
3. Recommend default EDRs for each relevant noise source, listing respective underpinning evidence and limitations.
4. Recommend priorities for filling evidence gaps on harbour porpoise disturbance from relevant noise sources.

2. Approach

2.1. Literature review

In the current study, we build upon the literature review undertaken by Brown *et al.* (2023) to identify and review evidence relevant to harbour porpoise responses to the noise sources of interest. Our approach to identifying evidence included the following:

- Drawing upon SMRU Consulting's internal database of literature and general awareness of relevant studies.
- Drawing upon key literature review studies; for example: McGarry *et al.* (2022) (ADDs), Jiménez-Arranz *et al.* (2020) (various oil and gas-related sources), Genesis (2011) (various oil and gas-related sources), Hartley Anderson Ltd (2020) (seismic, SBPs, MBES).
- Engaging with relevant external research groups to identify any new evidence.
- Google scholar search, utilising 'cited by' function on key references; for example: von Benda-Beckmann *et al.* (2015) (UXOs), Brandt *et al.* (2013c) (ADDs), Thompson *et al.* (2013) (seismic survey), Crocker *et al.* (2019) (SBP, MBES).

Due to the limited number of empirical studies of harbour porpoise responses non-piling noise sources, our review considers the following three categories of evidence:

i. Empirical studies of responses of animals to noise sources ('empirical response studies').

ii. Studies reporting on measured noise levels during use of relevant sources ('noise measurement studies').

iii. Studies undertaking modelling to estimating noise levels from relevant sources ('noise modelling studies').

Empirical response studies (i) directly report on changes in animal vocalisations or distribution associated with noise sources. By contrast, with noise measurement (ii) and modelling studies (iii), to assess the potential for disturbance inferences must be made based on assumptions of the noise levels at which animals respond, generally using **fixed response thresholds** (see Appendix 1 for the list of considered thresholds). While interpreting noise measurement and modelling studies to estimate disturbance ranges carries additional uncertainty over empirical response studies, the paucity of the latter for many noise sources necessitates such an approach.

For each piece of relevant evidence reviewed, we aimed to document, at a minimum, the following information:

- Noise source (i.e. type and specific characteristics (e.g. explosive weight, airgun array size, SBP type and operating frequency)).
- Type of noise abatement (if used).
- Type of acoustic deterrence (if used), including duration.
- Geographical area.
- Water depth.

- Reported distance at which animals responded / distance at which animals were exposed to noise (empirical response studies); where distance is unavailable, received noise level at which animals responded is provided.
- Reported distance to proposed behavioural response threshold(s), including noise metrics used (noise measurement and modelling studies).

2.1.1. Evidence scoring

Evidence scoring methodology was also developed so that recommended default EDRs could be accompanied by a measure confidence associated with the robustness of the evidence, its relevance to harbour porpoise in UK waters and volume of underlying evidence. This process involves evaluating individual studies across various criteria; average scores are also calculated for specific categories of evidence. Empirical studies of animal responses, such as direct observations or acoustic detections, receive the highest confidence scores. Additional scoring adjustments consider a study's ability to estimate an EDR, species relevance, environmental characteristics, and alignment with UK-specific activity parameters. Minor penalties apply for limitations such as small datasets or lack of statistical analysis. The scoring framework follows a decision-tree approach, where all studies are initially assigned a baseline score, and penalties can be subsequently applied under each criterion. Details are provided in Appendix 2.

2.2. Defining the EDR

As described by Brown *et al.* (2023), while empirical studies of responses to noise sources generally report on the spatial extent of responses, it is uncommon for such studies to estimate the EDR. Therefore, it is challenging to determine if reported response ranges are under- or over-estimating response ranges in terms of the average habitat loss per individual.

Where possible, we consider the results of the reviewed literature in the context of the definition of an EDR as developed from a deterrence function (response *vs* distance), as per Tougaard *et al.* (2013) and analogous to the Effective Response Range described in Tyack and Thomas (2019). This provides a measure of the average temporary habitat loss per individual, and accounts for individual differences in responses of animals at a given range from the source, with some not responding at closer ranges (losing less habitat) and some responding at larger ranges (losing more habitat). The EDR is a threshold distance: beyond this distance the number of animals responding to the disturbance equals the number of animals not responding within that distance (Figure 1).

The aforementioned EDR metric is preferred to alternative metrics such as R_{50} (the distance at which there is a 50% probability of response), which fails to account for the exponential increase in size of disturbed area with range from source and therefore underestimates the number of animals responding and the average habitat loss (Tyack & Thomas 2019).

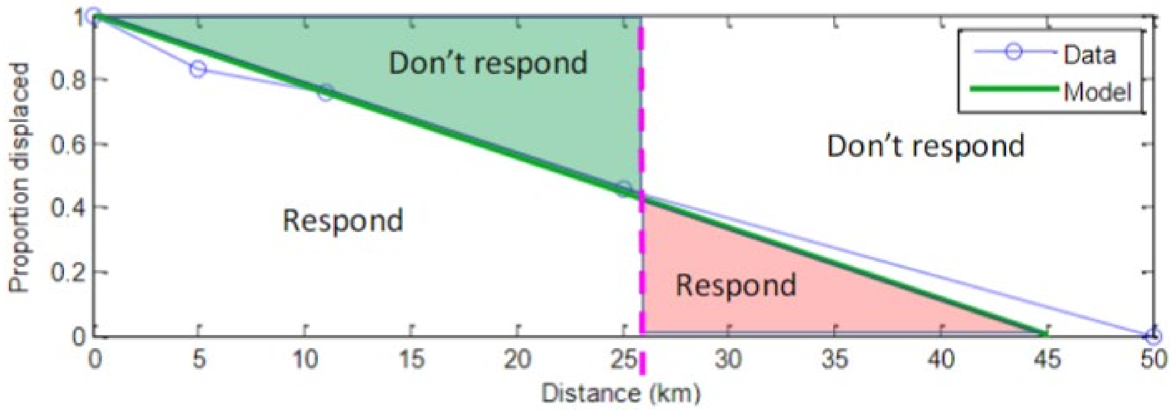

Figure 1. A modification of Figure 7 from Tougaard *et al.* (2013) to illustrate how the EDR (pink dashed line at 26 km) relates to a deterrence function. By assuming a uniform density of animals across the area of impact and that the deterrence function is symmetrical in all directions, the proportion displaced (or probability of response) is used to estimate the cumulative number of animals responding and not responding with increasing range from source. The EDR is a threshold distance: beyond this distance the number of animals *responding* to the disturbance (represented by the red triangle) equals the number of animals *not responding* within that distance (green triangle).

2.3. Estimation of EDRs from existing data

As emphasised in Brown *et al.* (2023), to derive methodologically-comparable estimates of EDR from empirical response studies and robustly explore the factors which may be driving different levels of porpoise response between studies, a meta-analysis is required which involves the acquisition and re-analysis of data according to a common approach (Brown *et al.* 2023). As such an exercise is beyond the scope of the current study, we instead attempt to introduce greater comparability between existing studies by examination of their results to estimate EDRs according to a consistent definition. It is noted that a Defra-funded scoping exercise for such a meta-analysis for piling was completed in 2023 (Verfuss *et al.* 2023), and that further scoping efforts are currently underway to facilitate such a project commencing in 2025 (Brown *et al.* 2025).

2.3.1. General approach

Where possible, we estimated EDRs from existing data through the examination/ interpretation of deterrence functions (magnitude/ probability of response vs distance to noise source) within published studies, similar to that performed by Tougaard *et al.* (2013) on data presented in Dähne *et al.* (2013). This involved extracting values from published studies, either directly from data tables or by using the '[graphreader]' online tool to extract values from plots. In some cases, trend lines were fitted to data points to provide a deterrence function. Further details are provided in the noise source-specific sections below. While the values extracted from plots are an approximation of the data underlying the plots, a validation exercise (Appendix 3) on plots where the underlying data are known showed them to be accurate for this application.

Studies for which this approach applied were those which met the following requirements:

i. the study included a data table or figure which presented the change in porpoise detections function of distance to noise source,

ii. the reported change in porpoise detections could be interpreted as proportional change relative to a reference period,

iii. values were provided along a gradient of distances from the noise source, covering a minimum of three discrete distances/distance bins,

iv. results were presented over a sufficient distance from the noise source to reasonably estimate the distance at which zero change in porpoise detections.

There were three studies identified as meeting these requirements, one for ADDs (Dähne *et al.* 2017; Thompson *et al.* 2020) and one for seismic surveys (Sarnocińska *et al.* 2020). For other noise sources, no studies meeting these criteria were found, and as a result, EDRs could not be calculated. Instead, available empirical data, noise measurements (see Section 2.4) and noise modelling studies were reviewed, and the reported or estimated spatial extents of effects were discussed.

2.4. Estimation of disturbance ranges from existing noise measurement data

As a component of this review, we sought to acquire noise measurement reports and data from field operations of relevant noise sources which were not currently accessible in the public domain. From these, we estimated distances to proposed behavioural response thresholds, either directly from data or fitted transmission loss functions, or from plots presented in reports using the graphreader online tool to extract values. Such an exercise was also conducted on studies identified in the literature review where the presentation of results allowed. For studies where such analyses were carried out, this is indicated under the subheading *"Interpreting results for inferred response ranges"* within the relevant study-specific section.

3. UXO clearance

Numerous items of UXO exist on the seabed around the UK and wider north-western Europe, primarily remaining from wartime military operations but also historical munitions dumping or more recent military training activities. These items, consisting of air-dropped bombs, mines, torpedoes and other munitions, present a potentially significant health and safety hazard to offshore activities, particularly wind farm construction including cable and foundation installation (von Benda-Beckmann *et al.* 2015). While UXO may be avoided or relocated to avoid interactions with activities, it is often necessary to carry out UXO clearance *in situ* using explosives. For activities with a large spatial footprint in areas of high UXO incidence, such as wind farms in the southern North Sea, several tens of UXO may require clearance for a single project. Individual UXO range in size and net explosive quantity (NEQ) from a few hundred grams for small munitions to several hundred kilograms for the largest air-dropped bombs and mines.

Underwater explosions, particularly the full detonation of UXO, are considered to be one of the loudest sources of all underwater anthropogenic noise (von Benda-Beckmann *et al.* 2015). They result in a broadband acoustic pulse with very high peak source level and rise time which is extremely brief relative to airgun array and other non-explosive seismic sources (Richardson, 1995). Shock waves are formed during UXO detonations, and can be perceived at distances close to the explosion; at greater ranges, the wave propagates as a normal sound wave (Parvin *et al.* 2007). Example source sound pressure levels (SPL_{pk} (zero-to-peak) dB re 1 μPa @ 1 m) for detonation of freely-suspended certain charge weights (TNT equivalent) include: 0.5 kg = 267 dB; 2 kg = 271 dB; 40 kg = 285 dB (Richardson 1995; Parvin *et al.* 2007). Across a variety of historic UXO charge sizes (0.1 kg - 295 kg TNT equivalent) detonated on the seabed in Scottish waters, broadband noise levels of SPL_{pk} > 190 dB re 1 μPa and Sound Exposure Level (SEL) > 170 dB re 1 $\mu Pa^2 s$ were routinely recorded at < c. 7 km of the source (Robinson *et al.* 2022). Most of the emitted acoustic energy is below a few hundred Hz, decreasing on average by about SEL 10 dB per decidecade above 100 Hz, and there is a particularly pronounced drop-off in energy levels above c. 5–10 kHz (von Benda-Beckmann *et al.* 2015; Salomons *et al.* 2021).

3.1. Description of activity

When using explosives to clear UXO from the seabed, this is currently undertaken using either high-order or low-order techniques. High-order detonations result in a very rapid exothermic chemical reaction resulting in a supersonic blast or shock wave. Low-order explosives use a mixture of chemical that burn rapidly at sub-sonic speeds and do not produce high shock waves.

High-order clearance involves the detonation of a donor charge placed adjacent to the UXO, triggering its detonation. High-order clearance generally uses a donor charge of up to several kg, with the resulting noise levels being proportional to the size of the donor charge plus the explosive mass of the UXO. For the purpose of estimating appropriate mitigation measures for high-order UXO clearance , it is assumed that noise levels will be proportional to full detonation of the NEQ of the UXO, although it is acknowledged that noise levels may not reflect those predicted in noise assessments as these typically don't account for absorption of energy by the seabed or degradation of the UXO (Robinson *et al.* 2022). High-order approaches were exclusively used for UXO clearance in commercial marine operations until recent years when low-order methods became commercially available, primarily low-order deflagration.

Low-order clearance generally involves the use of a shaped charge to generate a plasma jet, which penetrates the UXO casing and induces combustion of the explosive material without detonation, known as 'deflagration'. This method significantly reduces noise emissions (Lepper *et al.* 2024). Low-order clearance generally uses smaller donor charge compared to high order detonation (up to 0.45 kg in the current review), with the resulting noise levels being proportional to the size of the donor charge as the explosive material within the UXO does not undergo detonation. Low-order deflagration is currently the only low-order clearance method which has been successfully utilised in marine UXO clearance at a commercial scale and is the focus of this review.

The size of UXOs and other charges are typically described in terms of their NEQ, which refers to the weight of explosive material which they contain, regardless of its composition. Alternatively, UXO/charge size may be described as TNT equivalent, which is a standardised measure of explosive power relative to trinitrotoluene (TNT). The ratio of NEQ to TNT equivalent will vary according to the composition of the explosives in the UXO. In the review here, whichever term is used in the study reviewed is retained.

3.1.1. Vessels, deterrence and noise abatement procedures

For UXO clearance operations, a limited number of vessels is typically required, ranging from large ships to small fast-rescue craft. Dynamic positioning is often considered the most suitable method for maintaining vessel position during clearance activities and ensuring operational safety.

ADDs are commonly deployed for a specific duration to deter marine animals from the zone where they could experience injurious effects. The duration of ADD use is typically based on the estimated time it would take animals, given assumptions about swimming speed and fleeing behaviour, to exit the radius of predicted injury (blast trauma or onset of permanent threshold shift, PTS). ADD durations for low-order clearance are typically 10–20 minutes, depending on the size of the deflagration charge being used, while durations for high-order clearance depend on the combined size of the donor charge and the estimated UXO size. ADD durations are agreed with relevant Statutory Nature Conservation Bodies (SNCBs) at the consultation stage. Typical ADD durations can also vary between countries within the UK, where different regulators and their advisors have different expectations in terms of the metrics for auditory injury upon which mitigation and deterrence should be based (i.e. unweighted SPL_{pk} vs frequency-weighted SEL).

Stone (2023a) performed a review of marine mammal observations and compliance with mitigation guidelines associated with explosive use, including ADD use associated with UXO clearance. It was found that ADDs were used in 69% of UXO clearance projects, with licences specifying durations of between 15 to 80 minutes. However, it was noted that compliance was poor, with ADD durations typically longer than licences specified, particularly where specified durations were shorter. While reported durations were up to 121 minutes, 90% were less than 40 minutes.

For larger UXO and where ADDs are considered to be incapable of deterring animals to beyond the predicted injury radius, a series of small 'scarer' charges have been deployed in the past at short intervals in advance of the main clearance event. While scarer charges have been deployed in association with high-order UXO clearance in recent years (Robinson *et al.* 2022; van Geel *et al.* 2024), they alone generate considerable noise and are no longer considered an acceptable form mitigation for marine mammals by the SNCBs (JNCC 2025b). As such, use of scarer charges is not considered further in the report.

Noise abatement system (NAS), in the form of bubble curtains, has been applied to some high-order UXO clearance operations in the UK, and has featured as a mitigation measure for clearance events above a specified NEQ (e.g. 50 kg) in some marine mammal mitigation plans.

3.1.2. Low-order approaches as default

In 2021, the UK Government, relevant regulatory bodies and SNCBs issued a joint position statement stating that low noise (i.e. low-order) alternatives to high-order detonations should be prioritised when developing protocols to clear UXOs (Defra *et al.* 2021). The statement acknowledged that high-order detonation may be needed in some limited instances as a contingency, where low noise alternatives are not feasible, or where urgent clearance is required because of immediate safety concerns.

In January 2025, an updated joint position statement was issued (Defra *et al.* 2025) which strengthened this position, stating that:

- Low noise methods of clearance should be the default method used to clear any type of UXO in the marine environment.

- High-order methods should always be the last resort and used only in extraordinary circumstances where:
  - (i) low noise methods cannot be attempted or have failed following ≥ three attempts,
  - (ii) all best practice has been demonstrably applied, and
  - (iii) there is prior agreement with the licensing authority.

The supporting guidance (Defra 2025) notes that for any high-order UXO clearance licensed, applicants should expect noise abatement to be required.

As a result of the latest position statement and guidance, low-order method is anticipated to account for a large majority of future UXO clearances, with any high-order clearances likely to be accompanied by a noise abatement system such as a bubble curtain. Nonetheless, full consideration is given to evidence relating to high-order UXO clearance without noise abatement in the sections below. While this activity may no longer be commonplace in UK waters, understanding its potential for disturbance is important for assessment of SAC impulsive noise threshold compliance (including high-order clearances which are unplanned, occur in waters of adjacent states close to UK SACs, and for retrospective assessments).

3.2. Current recommended EDRs

The SAC noise guidance recommends a single EDR of 26 km for the high-order detonation of UXO (JNCC 2020). For high-order with noise abatement the recommended EDR is currently 15 km (JNCC 2023a). An EDR of 5 km is now advised for low-order deflagration of UXO based on the substantially lower noise levels resulting from this technique which have been shown to correspond to the size of the low-order donor charge only (Robinson *et al.* 2020; JNCC 2023a).

The justification for the 26 km EDR provided in JNCC (2020), which matches that of unabated impact pile-driving of monopile foundations, is that "*High order detonation of UXOs results in one of the loudest sources of underwater noise and although a one-off explosion would probably only elicit a startle response and would not cause widespread and prolonged displacement, these detonations are usually part of campaigns with potentially several detonations in the same general area over several days and involving multiple vessels as well as the deployment of ADDs.*"

3.3. Approach to evidence review

The overall approach to the evidence review is described in Section 2. Due to the near absence of empirical studies of harbour porpoise responses to UXO clearance, our review is dominated by examining:

(i) studies reporting on noise levels measured during UXO clearance, and

(ii) studies undertaking modelling to estimating noise levels from UXO clearance. For each of these two types of study, we summarise, where results allow, the reported ranges to the temporary threshold shift (TTS) onset criteria for impulsive sounds for very-high frequency (VHF) cetaceans (Southall *et al.* 2019), as follows:

- SPL_{pk} 196 dB re 1 µPa (unweighted).
- SEL 140 dB re 1 μPa^2s (frequency-weighted).

It is acknowledged that TTS-onset criteria are not empirically derived behavioural response thresholds. However, they are widely used and accepted in the UK by regulators and their advisors as a proxy for behavioural response thresholds to single impulses (i.e. explosions), with the assumption that they correspond to the noise level at which a fleeing response may be expected to occur in marine mammals. This is a result of discussion in Southall *et al.* (2007) which states that “*upon exposure to a single pulse, the onset of significant behavioral disturbance is proposed to occur at the lowest level of noise exposure that has a measurable transient effect on hearing (i.e. TTS onset).”* Further information is provided in Appendix 1.

Distances to TTS-onset thresholds are widely reported in noise measurement and modelling studies for UXO. Where results allow, we also present the distance to a noise level of SPL_{pk} 168 dB re 1 µPa, at which aversive behavioural reactions were observed in a captive harbour porpoise when exposed to single airgun pulses (Lucke *et al.* 2009). This value of SPL_{pk} 168 dB re 1 µPa is adjusted from the $SPL_{pk\text{-}pk}$ (peak-to-peak) 174 dB re 1 µPa metric presented in Lucke *et al.* (2009), which is an appropriate adjustment for impulsive sounds (see Appendix 1 for more details). While the Lucke *et al.* (2009) threshold is relevant in that it relates to exposure to a single impulse, the context is very different to the more distant exposures which would occur in wild harbour porpoise from UXO clearance.

As described in Section 2.4, in cases where response ranges were not explicitly reported but sufficient study data were available, additional analyses were conducted to estimate the distances at which noise levels reached TTS-onset and/or behavioural response thresholds. These estimations were derived using the graphreader online tool to extract data points from relevant figures. For studies where such analyses were carried out, this is indicated under the subheader *"Interpreting Results for Inferred Response Ranges".*

3.3.1. Exclusions

Due to the recent proliferation of noise measurement studies of historic UXO clearance in the North Sea, our review does not include measurement studies of mid-water explosive detonations (e.g. Soloway & Dahl 2014). While such studies have the advantage of using an explosive of known NEQ, data from actual open-ocean UXO clearance operations are considered more relevant and are favoured here. Similarly, quarry trials (e.g. Robinson *et al.* 2020; Cheong *et al.* 2023a) have been invaluable in advancing our understanding of noise from underwater explosions and testing low-order approaches; however, they are also not included here in detail alongside evidence from open-ocean UXO clearance studies due to being restricted to close-proximity measurements of small charges and not reporting distances to TTS-onset thresholds. These trials are regarded as proof of concept rather than representative of what may occur within the marine environment.

3.4. Evidence

In Sections 3.4.1 to 3.4.3 below, we provide summary reviews of relevant empirical, measurement and modelling studies identified in our review. In Section 3.4.4 we provide a tabulation of all evidence reviewed in the current study, including specific features of the activities (e.g. region, water depth, UXO size, mitigation used) and the reported as well as estimated spatial extent of deterrence effects / distance to threshold levels. This section also includes a figure plotting the reported spatial extent of deterrence effects / distances to thresholds, separated by low-order and high-order clearance types. Results of the evidence scoring exercise for UXO clearance is provided in Section 3.4.6.

3.4.1. Empirical response studies

3.4.1.1. van Geel *et al.* (2024) - East Anglia ONE OWF

van Geel *et al.* (2024) presented the results of Passive Acoustic Monitoring (PAM) during construction of the East Anglia ONE OWF in the southern North Sea, including a limited number of UXO clearance events. The PAM array was the same as that used to assess porpoise responses to piling (van Geel *et al.* (2023), comprising up to 12 cetacean porpoise detectors (CPODs) deployed between 4–36 km from UXO clearance sites).

While a total of 81 high-order UXO detonations took place over a campaign spanning 2018 to 2019, the authors focussed on four UXOs for which there was sufficient pre- (> 60 h) and post- (≥ 30 h) detonation monitoring effort devoid of other UXO detonations or pile driving. UXOs included a 1,000 lb (453 kg), two 500 lb (227 kg) and a 110 lb (50 kg) airdrop bombs (total weight). All were high order detonated in situ without the use of noise abatement. Water depths across the area ranged between approximately 30–40 m.

Porpoise acoustic activity was characterised as % porpoise positive minutes per hour (%PPM/h). For each UXO detonation, the median, mean and maximum %PPM/h were plotted vs distance to the UXO for both a period immediately following the detonation and a reference period of equivalent length a minimum of 12-h prior to the detonation. Assessment periods of 6-, 12- and 24-h were considered to explore the potential duration of any disturbance identified. Results were interpreted visually; no statistical tests were performed.

For the largest UXO detonated (a 1,000 lb airdrop bomb with up to 250 kg NEQ), acoustic detections were substantially reduced post-detonation at monitoring locations ≤ 12 km from the UXO for all assessment periods. At monitoring stations of ≥ 25 km distance to the UXO, median and maximum acoustic detections were slightly higher post-detonation than pre-detonation. This pattern of higher maximum detections at greater ranges was most pronounced for 12- and 24-h assessment periods, suggesting the presence of animals displaced from closer to the UXO detonation site. A similar pattern was observed when considering the presence of buzzes as a proxy for foraging activity.

A gap in monitoring locations between approx. 11 km and 25 km limits inference at these distances, which is compounded by very low acoustic detections both pre- and post-detonation at 25 km distance. However, the results suggest that the spatial extent of responses to this specific UXO detonation lies within this range. The authors concluded a reduced porpoise presence / acoustic activity up to 15–20 km from the UXO detonation location, irrespective of the assessment period length. It is noted that this value of 15–20 km does not meet the definition of an EDR as described in Section 2.2; rather, it represents the distance at which differences between pre- and post-detonation acoustic detections are no longer apparent.

Acoustic detections were much lower in advance of the other three UXO detonations and detection rates were generally similar between pre- and post-detonation periods, even at monitoring distances closest to the UXOs. However, at distances > 15 km from one of the other UXOs (a 500 lb bomb, roughly equivalent to a 101 kg NEQ) higher mean acoustic detections were recorded post-detonation than pre-detonation for the 12- and 24-h assessment periods, suggesting some displacement of animals from closer to the source. The authors discuss that while more pronounced responses might be expected to the largest UXO detonation due to louder noise levels, these may also be influenced by the higher pre-detonation acoustic detections, which was coincident with a 10-day break in piling - the longest of any of the four UXOs monitored.

It is important to note that the apparent responses to UXO detonation reported could not be disentangled from the pre-detonation use of ADDs (of up to 80 minutes duration) and fish scare charges (van Geel 2024). As reported elsewhere, prolonged exposure to an ADD can cause displacement of harbour porpoise to multiple kilometres, with an EDR of 11 km recommended for long ADD durations (37–235 minutes; see Section 7).

3.4.2. Noise measurement studies

3.4.2.1. Lepper *et al.* (2024) - Trials in the Great Belt (Danish waters)

Lepper *et al.* (2024) present the results of noise measurement during eight UXO clearance events in Danish waters (the Great Belt) by both high-order detonation and low-order deflagration methods. Water depths in the region were between 10–20 m dominated by muddy sand sediments. Noise levels were measured between approximately 2–25 km from the UXOs.

The four low-order UXO clearance events were mines of 340–430 kg NEQ, all neutralised with a single 250 g 'Pluton' shaped charge (manufactured by Alford Technologies). The four high-order UXO clearance events were mines of estimated 34–344 kg NEQ, all neutralised with a single 10 kg donor charge. One of the high-order clearances had previously been subject to a low-order method. No low-order attempts resulted in an unintended high-order detonation.

Sound propagation modelling was conducted on the two donor charge sizes and the maximum UXO size of 430 kg. These were then adjusted to fit the measurement data to provide upper and lower bounds of noise levels at range for the two clearance methods. Measured noise levels from high-order clearance events showed considerable variability, falling between model predictions for a 10 kg donor charge and the maximum UXO size of 430 kg NEQ, albeit well below the latter for the SEL metric, indicating that the detonated NEQ was less than the original UXO charge size (noise levels suggested between 16–28 kg NEQ for the four high-order events). The authors observed that, consistent with the hypotheses proposed in previous studies (von Benda-Beckmann *et al.* 2015; Robinson *et al.* 2022) a substantial amount of energy is likely absorbed by the seabed and the resultant seabed disruption. Noise levels from low-order clearance events were also somewhat variable, but the acoustic output appeared to be essentially consistent with the low-order deflagration charges on their own with little or no contribution from the historic charge detonating. Overall, low-order events were typically 15–20 dB lower than high-order events for both SEL and SPL_{pk} metrics.

The authors reported estimated distances to TTS-onset criteria for only two of the measured clearance events. The estimated relevant TTS-onset criteria impact ranges for one low-order event were 1.77 (± 0.74) km and 3.9 (± 0.8) km for unweighted SPL_{pk} and VHF-weighted SEL metrics, respectively (250 g deflagration charge used for 430 kg charge size, TNT equivalent). The equivalent ranges for one high-order event were 6.3 (± 1.0) km and

13.1 (± 2.2) km for unweighted SPL_{pk} and VHF-weighted SEL metrics, respectively (10 kg donor charge used for estimated 170 kg charge size, TNT equivalent).

Interpreting results for inferred response ranges

The authors presented SPL_{pk} data for eight clearance events as a function of range in Figure 12 of the Lepper *et al.* (2024) report. The dataset included three low-order events involving the deflagration of charge masses ranging from 340–349 kg, initiated using a 250 g deflagration charge. High-order detonations were also represented, with charge masses between 34 and 200 kg initiated using a 10 kg donor charge. This dataset was analysed using the graphreader online tool to extract values and fit curves through the lower and upper bounds of model fits encompassing all measured data points. Analysis of the resulting range of unweighted SPL_{pk} values suggests that estimated distances to TTS-onset criteria for harbour porpoise, as defined by Southall *et al.* (2019), range from approximately 0.6–2.1 km for low-order events and 3.3–7.2 km for high-order events. Were one to take the more conservative criteria for harbour porpoise behavioural responses to single impulses proposed by of SPL_{pk} 168 dB re 1µPa (Lucke *et al.* 2009), then impact ranges would be between approximately 7.9–15.8 km for low-order events and 22.1 - > 25 km for high-order events. These estimates should be interpreted with caution, as the threshold values are based on responses to airgun pulses in close proximity (captive setting), which have different signal characteristics and context compared to those produced by UXO detonations.

Lepper *et al.* (2024) presented plots of measured broadband SEL vs range, but not an equivalent for VHF-weighted SEL. Therefore, a complete range of distances to TTS-onset for the VHF-weighed criteria for all monitored clearance events could not be inferred.

3.4.2.2. Abad Oliva *et al.* (2024) - Low-order clearance at Moray West OWF

Abad Oliva *et al.* (2024) present the results of noise measurement during the clearance of 82 UXOs off the east coast of Scotland in the Moray Firth associated with construction of the Moray West OWF. The development site is in water depths ranging from 35–55 m.

Out of 82 UXOs, 30 UXOs with NEQ weight between 6–94 kg NEQ were selected for acoustic monitoring. Additionally, noise monitoring were made during the clearance operations of the 700 kg NEQ German Luftmine B mine. The size of donor charges ranged from 100–250 g. Most UXOs required only a single clearance attempt, although the 700 kg mine required a total of four. Across the 31 UXOs, the total number of clearance events was 44. Underwater acoustic measurements were conducted by deploying a series of Autonomous Recording Units (ARUs) on seabed moorings at approximate distances of 1 km, 5 km, and 10 km from selected individual UXO targets and UXO clusters.

Noise measurements revealed that noise levels were proportional to the size of the ≤ 250 g donor charge only, with no evidence of explosive detonation of the UXO material. For the SPL_{pk} metric, almost all measurements fell within the model for a 250 g charge, indicating that the distances to the TTS-onset threshold for SPL_{pk} (196 dB re 1µPa using Southall *et al.* (2019) criteria) were generally ≤ 2 km among the measured clearance events.

Interpreting results for inferred response ranges

While plots were not provided for VHF weighted SEL, data tables were provided for the minimum, mean and maximum of these values at each measurement distance for each category of UXO. The mean and/or maximum measurements showed exceedance of the SEL 140 dB re 1 µPa^2s (VHF-weighted) TTS-onset threshold at the 5 km distance for several categories of UXO. There were also some reported noise levels higher than the SEL

140 dB re 1 μPa^{2}s TTS-onset threshold at the 10 km measurement distance; however, caution is urged in interpreting these results as they coincide with reported increases in noise levels between the 5–10 km distances for the both the VHF- and HF-weighted SEL metrics. The observed slight increase in weighted SEL between 5–10 km in some cases has been attributed as likely due to high-frequency internal electrical noise from the hydrophone pre-amp or recorder (Lee *et al.* 2023) and therefore is over-estimating the noise level from the UXO clearance at 10 km. The extent to which measurements at 5 km range may be over-estimates is unknown. Based on the consistency in reported noise levels at 1 km across all UXO sizes, the trajectory of transmission loss between the 1 and 5 km measurement distances, and the reported issues with some more distant measurements, it is likely that distances to the TTS-onset threshold were ≤ 7.5 km and largely ≤ 5.0 km.

The plots presented in Abad Oliva *et al.* (2024) did not readily allow for estimation of distances to the proposed SPL_{pk} 168 dB re 1μPa thresholds for behavioural responses, but it is noted that almost all noise measurements at 10 km distance exceeded SPL_{pk} 168 dB re 1μPa (noting that the issues affecting VHF-weighted measurements at 10 km were not apparent for the broadband SPL_{pk} metric).

3.4.2.3. Midforth (2024) - Low-order clearance at East Anglia Three OWF

Midforth (2024) presents the results of noise measurement during 19 UXO clearance events in UK waters of the southern North Sea associated with construction of the East Anglia Three OWF. Water depths in the region were between 29.5–45.5 m. The area of operations overlapped entirely with the Southern North Sea SAC (including summer and winter components).

All clearance events used low-order deflagration to neutralise a total of 12 UXOs, including nine air-dropped bombs, one buoyant mine and one anti-submarine device. The UXOs were neutralised using charge weights primarily of 0.15 kg, with a limited number at 0.2 kg or 0.25 kg. The NEQ of the UXOs was estimated to range from 16.4–226 kg. Four fixed acoustic monitoring stations were deployed for each UXO clearance event to record underwater noise at varying distances from the target: 1–3 km, 3–5 km, 6–8 km, and beyond 10 km. Each station was equipped with a hydrophone positioned at a fixed height of approximately 2.5 meters above the seabed.

The results showed that the noise emitted from the clearance event could be entirely attributed to the deflagration charge, with no correlation between measured noise levels and the NEQ of the target UXO. The maximum measurement distance at which the TTS-onset threshold for VHF cetaceans was reached or exceeded was 2.8 km for the VHF-weighted SEL metric. For the SPL_{pk} metric, TTS-onset thresholds were not reached at any measurement distance, although were within 1 dB of the threshold for two clearance events at a 1.1 km distance.

Interpreting results for inferred response ranges

Midforth (2024) provided a model fit for SPL_{pk} and unweighted SEL for each clearance event, including the associated equation with parameters for source level, transmission loss and absorption. Using these equations, the distances to thresholds could be estimated for TTS onset (SPL_{pk} 196 dB re 1μPa unweighted using Southall *et al.* (2019) criteria) and the proposed behavioural response threshold of SPL_{pk} 168 dB re 1μPa unweighted (Lucke *et al.* 2009). The estimated distances to the TTS-onset threshold ranged between 0.4–1.1 km, while the estimated distances to the proposed behavioural response threshold ranged between 6.1–10.6 km. While plots and equations were not provided for VHF weighted SEL, data tables were provided for these values at each measurement distance. Plotting these values for all clearance events where the VHF-weighted SEL TTS-onset threshold (140 dB re 1µPa²s) was reached for at least one measurement distance (n = 10) indicated that the maximum distance to the TTS-onset threshold was approximately 3.1 km.

3.4.2.4. Donaghy and Lee (2024a, b) – NeuConnect Interconnector

Noise monitoring was undertaken during of UXO clearance associated with the construction of the NeuConnect Interconnector in the southern North Sea. This included two low-order clearance events on a single UXO in shallow waters (5–10 m) of the Outer Thames Estuary (Donaghy & Lee 2024a) and one low-order and one high-order clearance events on a single UXO in offshore waters of 40–50 m depth (Donaghy & Lee 2024b).

The nearshore, shallower water clearance events involved the use of 0.45 kg deflagration charges on a UXO (aerial bomb) of estimated 25 kg NEQ (Donaghy & Lee 2024a). Damage was incurred to one of three deployed hydrophones, resulting in noise measurements collected from distances of 1 and 5 km from the UXO only. During both clearance events, measured SPL_{pk} noise levels were less than the TTS-onset threshold for harbour porpoise (196 dB re 1µPa) at 1 km. During the second clearance event, measured noise levels at 1 km were 147 dB re dB re 1 µPa²s, which exceeded the VHF-weighted TTS-onset threshold of 140 dB re dB re 1 µPa²s.

The offshore, deeper water clearance events involved the use of 0.125 kg deflagration charges on a UXO (aerial bomb) of estimated 162 kg NEQ (Donaghy & Lee 2024b). One of three deployed hydrophones was lost, resulting in noise measurements collected from distances of 1 and 10 km from the UXO only. The first clearance event was a low-order which did not fully neutralise the UXO; measured SPL_{pk} and VHF-weighted SEL noise levels exceeded the TTS-onset threshold for harbour porpoise at 1 km, but not at 10 km. The second attempted low-order clearance event resulted in a high-order detonation (confirmed by noise levels and seabed crater); measured SPL_{pk} and VHF-weighted SEL noise levels exceeded the TTS-onset threshold for harbour porpoise at 1 km, but not at 10 km.

Interpreting results for inferred response ranges

To estimate more accurate distances to TTS-onset thresholds from four clearance events, the relevant plots and data tables presented in Donaghy and Lee (2024a) were examined using the graphreader online tool.

Nearshore, shallower waters

For SPL_{pk}, the model line for a 0.45 kg charge was duplicated over the measured data points to provide upper and lower bounds for each clearance event; values were then extracted from these upper and lower bound lines using graphreader to estimate distances to TTS-onset thresholds between 0.1–0.4 km. For VHF-weighted SEL, values of SEL at 1 and 5 km distance were plotted with distance on a log scale and simply joined by a straight line; values were then extracted from these straight lines using graphreader to estimate approximate distances to TTS-onset thresholds between 1.2–1.6 km.

Offshore, deeper waters

For SPL_{pk}, the model line for a 0.125 kg charge was duplicated over the measured data points to provide upper and lower bounds for each clearance event; values were then extracted from these upper and lower bound lines using graphreader to estimate TTS-onset distances between 0.8–1.4 km and 7–11 km for the low-order and high-order clearance events, respectively. For VHF-weighted SEL, values of SEL at 1 and 10 km distance were plotted with distance on a log scale and simply joined by a straight line; values were then extracted from these straight lines using graphreader to estimate approximate TTS-onset distances of 2.4 km and 7.5 km for the low-order and high-order clearance events, respectively.

3.4.2.5. Lee *et al.* (2022) - Sofia OWF

Lee *et al.* (2022) present the results of noise measurement during the clearance of two UXOs in the southern North Sea associated with construction of the Sofia OWF. The development site is in water depths ranging from 24–32 m. Both UXOs were disposed of by high-order methods, albeit with two unsuccessful low-order attempts made on one of the UXO prior to high-order clearance. The two UXO comprised a sea mine of estimated 328 kg NEQ and an air-dropped bomb of estimated 220 kg NEQ. Low-order clearance attempts used a 0.03 kg 'JFR Barracuda' shaped charge. High-order clearance attempts used a 2.5 kg high explosive charge. A bubble curtain was deployed at a radius of approximately 45 m around each of the high-order clearances.

Underwater acoustic measurements were conducted by deploying a series of ARUs on seabed moorings at approximate distances of approximately 1 km, 5 km, 10 km and 15–28 km to the UXO clearance sites. Noise levels during the two low-order clearance events indicated a minor exceedance of the SPL_{pk} threshold for TTS onset (196 dB re 1μPa) at 1 km. Measured noise levels during the high-order clearances (with bubble curtain) were close to the SPL_{pk} threshold for TTS onset at 1 km for the 328 kg NEQ UXO, and at 10 km range, but not 15 km, for the 220 kg UXO. Reported noise levels for the VHF-weighted SEL metric appeared to suffer from the same internal electrical noise issue as described above for Moray West and are not considered reliable so are not included here.

Interpreting results for inferred response ranges

Closer examination of the associated plots for low-order clearance events presented in Lee *et al.* (2022) using graphreader provided estimated SPL_{pk} TTS-onset (196 dB re 1μPa) distances of up to 1.4 km. The high-order clearance of the 328 kg NEQ UXO with a bubble curtain resulted in the smallest distances to TTS onset, of approximately 1 km; noise levels were approximately SPL_{pk} 16 dB lower than predicted for an unabated detonation of the 2.5 kg donor charge, suggesting that the bubble curtain provided effective noise abatement and that the main UXO did not undergo full detonation. However, noise levels were much higher during the high-order clearance of the 220 kg NEQ UXO with a bubble curtain, with SPL_{pk} levels reaching the TTS-onset threshold at 10 km. For this clearance, closer examination of the associated plots presented in Lee *et al.* (2022) using graphreader provided estimated SPL_{pk} TTS-onset distances of up to 14.1 km. The authors discussed that, in this instance, the bubble curtain was likely ineffective, as measured noise levels were approximately as predicted for a 220 kg charge. It was suggested that the bubble curtain was disrupted by the initial blast wave from the explosion, rendering it ineffective (Lee *et al.* 2022).

3.4.2.6. Robinson *et al.* (2022) - High-order clearance off eastern Scotland

Robinson *et al.* (2022) analysed acoustic measurement data collated during high-order controlled explosions in UK waters during the pre-construction phases of two OWFs off the east coast of Scotland between 2019 and 2020: Moray East (in the Moray Firth) and Neart na Gaiothe (NnG, off the Firth of Forth). The average water depth for Moray East was around 45 meters, while for NnG it was 50 meters. The study used data from 54 UXOs: 17 at Moray East detonated with UXO weight ranging from less than 0.5 kg to 295 kg TNT equivalent and 37 at NnG, detonated with charge sizes from 0.1 kg to 102 kg TNT equivalent. Donor charges used ranged from 1 kg to 25 kg at Moray East, and from 2.5 kg to 5 kg at NnG. At the Moray East site, a thin layer of gravelly sand with an average thickness of about 2 m exists above layers of tills of up to 70 m, with a sandstone basement layer. At the NnG site, there is a sand layer of mean thickness of 12.9 m above a limestone basement.

For Moray East, measurements were taken between 5–58 km, while for NnG, the range was 1.5–35 km. Two acoustic metrics were calculated: SPL_{pk} and SEL, with the SEL calculated both as a broadband value and in one third octave bands. ADDs and scare charges of up to 250 g each were deployed to deter marine mammals from potential zone of impacts. No noise abatement techniques like bubble curtains were employed during the detonations.

The acoustic measurements of UXO detonations and scare charges showed significant variability, even for charges of similar size at comparable distances. While some variation was expected at Moray East due to the wider range of UXO sizes, a similar degree of variability was observed at NnG, despite many UXOs being nominally identical. The study suggested that uncertainty in UXO charge size, and their condition influenced results, as some may have been partially buried and degraded, affecting their detonation efficiency and acoustic output. In several cases, measured levels suggested that only the donor charge detonated, rather than the UXO itself.

Interpreting results for inferred response ranges

The study focused on estimates of PTS ranges and did not report distances to TTS-onset thresholds or potential behavioural disturbance ranges. However, plots were provided of measured sound levels at range for both SPL_{pk} and broadband SEL, overlain with model predictions for detonations of several different charge sizes.

For Moray East, for SPL_{pk}, the model for a 6 kg charge was the smallest plotted; here, we took this to be a conservative lower bound of reported noise levels as many measured noise levels fell on or below this model line, including multiple measurements from UXOs + donor charges with a combined estimated charge size of up to approximately 50 kg. While measurements from the largest charge sizes (approx. 200–300 kg) were limited, these generally fell between the models plotted for 25 kg and 201.5 kg charge sizes (the two largest plotted). Therefore, as an upper bound, we took a line intermediate to the 25 and 201.5 kg models, which encompassed all the measured noise levels. With distance plotted on a log scale, SPL_{pk} vs distance was linear in shape, allowing extrapolation to shorter distances than the minimum 11 km plotted and yielding an estimated distance to the TTS-onset threshold (SPL_{pk} 196 dB re 1µPa) of 6–12 km.

A similar approach was taken for the SPL_{pk} plot for NnG, with the upper bound taken to be the plotted 107 kg charge weight model, and a conservative lower bound of the plotted 2.5 kg charge weight model. This provided an estimated distance to the TTS-onset threshold (SPL_{pk} 196 dB re 1µPa) of 4–10 km.

3.4.2.7. Bellmann *et al.* (2021) – High-order clearance at NnG OWF

The study summarises noise measurement results of the high-order UXO clearance campaign that took place in 2020, in the NnG OWF area, located in the outer Firth of Forth, Scottish North Sea. These data were analysed within Robinson *et al.* (2022) (see Section 3.4.2.6) and so detailed results are not repeated again here. However, additional observations and reported TTS-onset ranges for a selection for representative individual UXO clearances are presented below.

The study found that detonation noise remained prominent at high frequencies (several kHz) and can propagate over considerable distances. Contrary to measurements from mid-water detonations of known charge sizes (Soloway & Dahl 2014), there was no significant correlation between UXO NEQ and measured noise levels. The authors suggest that this discrepancy may be due to the variable detonation efficiency, as many of the UXOs had been underwater for decades, making it uncertain how much of their TNT equivalent weight detonated. Pre-detonations of 50 g, 100 g, and 150 g TNT equivalent scare charges were used to deter marine mammals before UXO clearance, and for these small charges the measurements confirmed an increase in sound levels with charge weight. The differences between measured and predicted noise levels using the Soloway and Dahl (2014) model were relatively small for these pre-detonations. Measured underwater noise levels showed good correlation with predicted values for 2.5 kg and 5 kg charges. Another key finding was that the recorded transmission loss was unusually high, likely because most UXOs were partially buried in the seabed which significantly influenced how noise propagated.

Bellmann *et al.* (2021) reported TTS-onset ranges for a selection for representative individual UXO clearances (between 2.6–107 kg NEQ including donor charge) for both unweighted and weighted metrics. TTS-onset ranges for SPL_{pk} (196 dB re 1µPa) were between 1.5–6.9 km and for VHF-weighted SEL (140 dB re 1 $\mu Pa^2 s$) were between 2.0–6.6 km.

3.4.2.8. Salomons *et al.* (2021) – High-order clearance in the North Sea

Salomons *et al.* (2021) analysed the impact of underwater explosions from the clearance of UXOs in the North Sea. The detonations took place in 2018, around a planned OWF. The water depth in the region was approximately 20 m. Two UXO items were detonated using high-order method: a British MK 4 ground mine with an explosive weight of 325 kg TNT equivalent, and a British HII MK II buoyant mine containing 140 kg TNT equivalent. A 10 kg TNT equivalent donor charge was used to initiate the explosions, and assessments confirmed full detonations. The study doesn't mention whether ADDs or scare charges were used prior to the detonations.

To measure the acoustic effects, four autonomous hydrophone recording stations were deployed at distances of 1.5 km, 3 km, 6 km, and 12 km (noting that data from the 3 km station were unusable). The study found a reasonable agreement between measured and model-predicted SEL distances up to 12 km, with deviations of around 5 dB. The measured SEL values decreased by approximately 30 dB per decade of distance, which was greater than the 20 dB per decade reduction expected in free-field conditions. This steeper decline was attributed to shallow-water waveguide effects and sediment attenuation. When comparing SPL_{pk} with empirical scaling relations, measured values were systematically lower than predictions from deep-water models (e.g. Arons 1954). A key observation was that measured SEL values for 140 kg TNT equivalent UXO were higher than for 325 kg TNT equivalent at distant locations (6–12 km), despite differences in explosive mass. Authors suggested that it may be due to the differences in propagation conditions, possibly due to variations in seabed sediment composition between the two detonation sites.

The study found that harbour porpoises could experience TTS onset at distances of 5–7 km and 10–15 km from the explosion sites, based on the unweighted SPL_{pk} (196 dB re 1µPa) and VHF-weighted SEL (140 dB re 1 $\mu Pa^2 s$) metric, respectively.

3.4.2.9. Mason *et al.* (2020) – Hornsea Project Two OWF

Mason *et al.* (2020) presented the results of noise measurement during four UXO clearance events within the Hornsea Project Two zone of the North Sea in September 2019. Water depths of UXOs ranged between 20–30 m. Two of the four UXO clearance events were mines of 240 kg NEQ and the other two were of 525 kg NEQ, with nominal gross weights of 1,000 lb (453 kg) and 2,000 lb (907 kg), respectively.

Before each UXO clearance, an ADD was activated for 60 minutes, followed by a 30-minute period over which deterrent charges of different masses (50 g, 100 g and 150 g) were detonated in order of increasing size. Noise levels were measured at multiple stations between 400 m and 12.8 km from each UXO, though not all these stations recorded useful measurements which were analysed in the results due to high levels of background noise. A big bubble curtain (BBC) was activated around each UXO after the detonation of the deterrence charges and before the final clearance.

Reported source levels from noise measurements were highest for the two clearance events of the 240 kg NEQ UXOs, with SPL_{pk} estimates of 296.9 and 300.9 dB dB re 1 µPa @ 1 m, and SEL estimates of 233.5 dB and 237.5 dB re 1 $\mu Pa^2 s$ @ 1 m. In comparison, source levels for clearance of the two 525 kg NEQ UXOs were reported with SPL_{pk} estimates of 245.2 and 246.6 dB re 1 µPa, and SEL estimates of 210.7 and 211.7 dB re 1 $\mu Pa^2 s$, respectively.

Reasons as to why the noise levels recorded were lower for the larger UXOs are unknown, but this may be attributed to the larger UXO being heavily degraded, potentially resulting in a reduced effective NEQ. Alternatively, the bubble curtain may have been more effective in mitigating noise from the larger UXO. A combination of both factors is also possible. The authors note that it is not possible to draw definitive conclusions regarding the effectiveness of the bubble curtain, as no detonations were conducted without its use for comparison.

Interpreting results for inferred response ranges

Mason *et al.* (2020) provided parameters for source level and spreading coefficient for each clearance event (for SPL_{pk} and unweighted SEL; section 4.3 of the report). Using these parameters, the distances to thresholds could be estimated for unweighted TTS onset (SPL_{pk} 196 dB re 1µPa based on Southall *et al.* (2019) criteria) and the proposed behavioural response threshold of SPL_{pk} 168 dB re 1µPa unweighted (Lucke *et al.* 2009). The estimated distances to the TTS-onset threshold were up to 0.3 km and 5.6 km for 525 kg and 240 kg NEQ UXOs, respectively. The estimated distances to the proposed behavioural response threshold were up to 11.3 km and 55.8 km, for the 525 kg and 240 kg NEQ UXOs, respectively.

It is noted that the estimated TTS-onset ranges for the louder 220 kg NEQ UXOs, at up to 5.6 km, are considerably smaller than the model-predicted range for an equivalent UXO size (see Section 3.4.3 below). While this might suggest an effect of the bubble curtain, such a TTS-onset range is not dissimilar to those reported among studies reviewed here for high-order clearances without a bubble curtain for similar- or larger-sized UXOs, further supporting the authors' comments than definitive conclusions could not be drawn.

3.4.2.10. von Benda-Beckmann *et al.* (2015) – High order clearance

The study examined the controlled detonations of UXOs in the Dutch Continental Shelf (DCS) of the southern North Sea. Noise measurements were conducted during the high-order detonation of seven aerial bombs in September 2010, comprised of six 1,000 lb bombs (453 kg total weight, 263 kg NEQ) and one 500 lb bomb (227 kg total weight, 121 kg NEQ). All bombs were originally discovered on land and detonated on the seafloor in an area with a water depth of 26–28 m over a sandy seabed. The monitoring setup included hydrophones and pressure gauges positioned at depths ranging from 4–25 m and at distances between 100–2,000 m from the detonation site. Measurements from the detonation of the five 263 kg UXOs at varying depths indicated that SEL levels reached 191 dB re 1 $\mu Pa^2 s$ at 2 km.

Interpreting results for inferred response ranges

Estimated distances to TTS-onset thresholds, or other proposed behavioural response thresholds, were not provided; instead, the study focussed on extrapolating the noise measurements to records of UXO occurrence on the DCS to estimate the number of animals likely to experience hearing damage. However, the measurement data were plotted in the later study by Salomons *et al.* (2021) in a way in which facilitated estimates of SPL_{pk} noise levels at ranges > 2 km and, therefore, TTS-onset distances. From our interpretation of this plot (Fig.11 in Salomons *et al.* 2021), aided by the use of graphreader, estimated TTS-onset ranges were between 10–21 km based on a model fit to the lower and upper bounds of the measurement points.

3.4.3. Noise modelling studies

There is an abundance of modelling studies supporting OWF and other marine infrastructure projects license and consent applications which provide predictions of noise levels at range from clearance of UXOs of various sizes. However, these all use identical or very similar modelling approaches, typically based on measurements from mid-water detonations of charges of known TNT equivalent in shallow water (Soloway & Dahl 2014). To avoid excessive duplication of results, we selected three relatively recent underwater noise technical reports compiled to support the EIA for OWFs in the southern North Sea: Dogger Bank South, North Falls, and Outer Dowsing (Subacoustech 2024a, b, c). These modelling studies followed a similar approach based on methodologies from Soloway and Dahl (2014), Arons (1954) and Marine Technical Directorate (1996). This approach is consistent with methodologies applied in other OWF assessments. Furthermore, these three studies were selected due to the use of similar UXO weight models, which facilitates direct comparison. Water depth among these three projects is representative of the southern North Sea, averaging between 20–50 m.

Within each report, potential impact ranges (including TTS onset) were estimated for a variety of potential charge sizes, covering indicative low-order charge sizes alone up to UXO of 800 kg NEQ plus donor. For a given charge size, predicted impact ranges were identical across the three reports as the modelling approach is independent of water depth and other site-specific characteristics. In Table 3, we provide predicted TTS-onset ranges for a range of charge / UXO sizes compiled across these three reports, including both unweighted SPL_{pk} (196 dB re 1µPa) and VHF-weighted SEL (140 dB re 1µPa^{2}s) metrics. Higher UXO charge weights correspond to greater TTS-onset ranges as it is assumed that the maximum explosive charge in each device is present and fully detonates. For detonations of 0.25–0.5 kg charge sizes, assumed to represent the maximum output associated with low-order clearance, TTS-onset ranges were 1.8–2.3 km (SPL_{pk}) and 0.8–0.9 km (VHF-weighted SEL). For high-order clearance of a 240 kg NEQ UXO (plus 0.5 kg donor charge), TTS-onset ranges were 18 km (SPL_{pk}) and 3.5 km (VHF-weighted SEL). For the maximum UXO size of 800 kg NEQ modelled, the predicted TTS-onset ranges were 26 km (SPL_{pk}) and 4.2 km (VHF-weighted SEL).

It is noted that the predictions are larger for the unweighted SPL_{pk} metric than the VHF-weighted SEL metric for a given charge size. This is contrary to the results of most noise measurements studies, which generally indicate larger distances to TTS-onset thresholds for VHF-weighted SEL than unweighted SPL_{pk}. This suggests that current modelling practices (at least those based on Soloway & Dahl 2014) are underestimating VHF-weighted impact ranges.

Table 3. TTS-onset ranges (km) predicted for different UXO/charge sizes, as reported in Subacoustech (2024a, b, c).

TTS-onset metric	donor / UXO charge size (kg NEQ)									
	Low order		High order							
	0.25	0.5	25.5	55.5	120.5	240.5	525.5	700.5	750.5	800.5
SPL_{pk} (unweighted)	1.8	2.3	8.5	11	14	18	23	25	26	26
SEL (VHF-weighted)	0.75	0.9	2.4	2.8	3.2	3.5	4.0	4.1	4.2	4.2

3.4.4. Tabulation of reported and estimated spatial extent of deterrence effects

Figure 2 presents the reported spatial extent of deterrence effects and estimated distances to thresholds for empirical and noise measurement studies, respectively, separated by low-order and high-order clearance types. Further details are provided in Table 4.

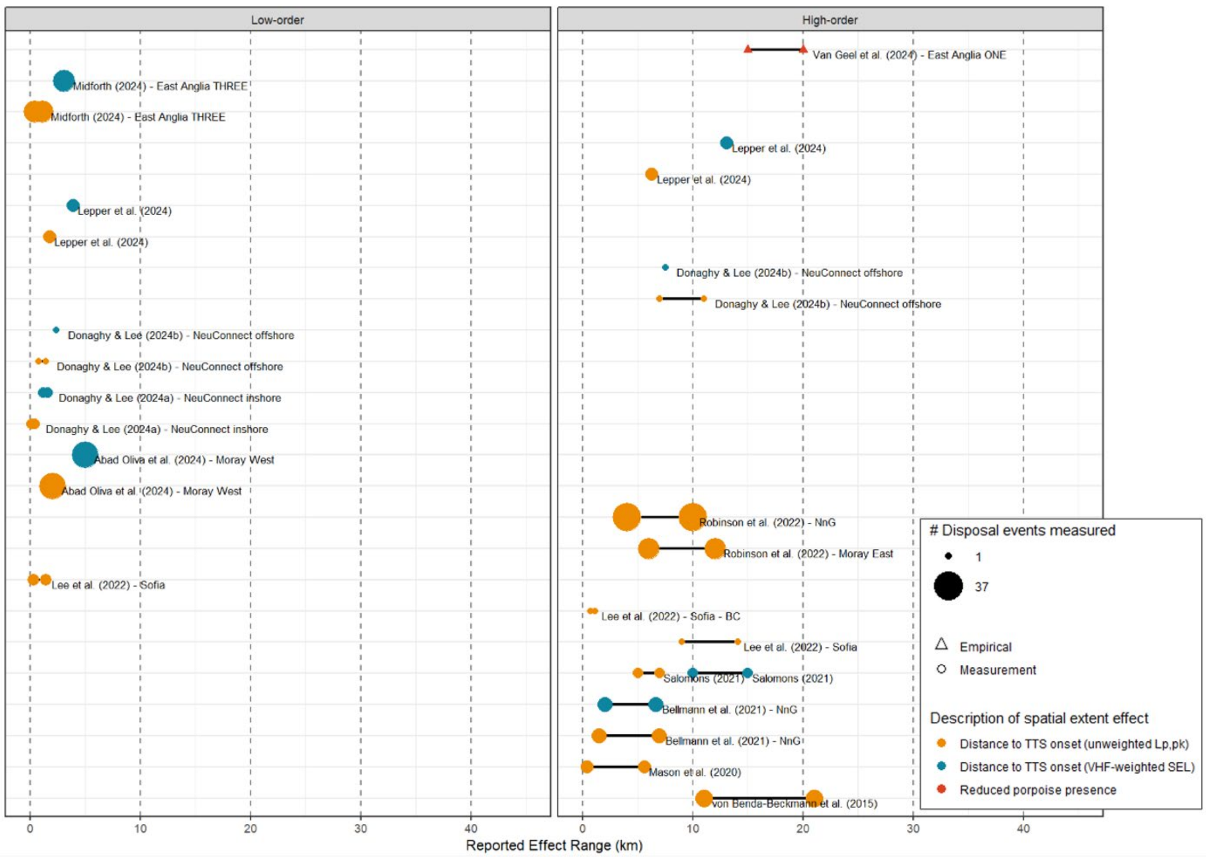

Figure 2. Summary of reported spatial extent of effects / reported distance to TTS-onset noise levels from studies of UXO clearance. Studies are split between high-order and low-order methods, with symbology differentiating between study type and the measure of effect. Studies reported either a single value (dots) or a range of values (dots connected with line). It should be noted that Lee *et al.* (2022) and Mason *et al.* (2020) reported distances to TTS-onset threshold based on high order detonation with use of bubble curtain.

Table 4. Summary of evidence relating to harbour porpoise response ranges from UXO clearance. The spatial extent of effects include ranges reported/estimated within cited studies as well as inferred via additional analyses as described in Section 3.4.2.

Study		**Region (country); water depth**	**UXO clearance method**	**Deterrence**	**NAS**	**UXO charge weight (kg NEQ)**	**Donor charge weight (kg NEQ)**	**# clearance events**	**Reported and estimated spatial extent of effect and description**
Empirical response studies	Van Geel *et al.* (2024) - East Anglia ONE OWF	Southern North Sea (UK) 30–40 m	High order	ADD (80 minutes) Scare charges	None	101–250	Not reported	4	**15–20 km** = Distance to which porpoise presence / acoustic activity was reduced following the clearance event with the most pronounced response (1 of 4).
Noise measurement studies	Lepper *et al.* (2024)	The Great Belt (DK) 10–20 m	Low order	Not reported	None	340–430	0.25	4	**0.6–2.1 km** = Distance to TTS-onset threshold (unweighted SPL_{pk}) **3.9 km (± 0.8)** =Distance to TTS-onset threshold (VHF-weighted SEL) **7.9–15.8 km** = Distance to SPL_{pk} 168 dB re 1μPa threshold (Lucke *et al.* 2009)

Study		Region (country); water depth	UXO clearance method	Deterrence	NAS	UXO charge weight (kg NEQ)	Donor charge weight (kg NEQ)	# clearance events	Reported and estimated spatial extent of effect and description
Noise measurement studies	Lepper *et al.* (2024)		High order			34–344	10	4	**3.3–7.2 km** = Distance to TTS-onset threshold (unweighted SPL_{pk}) **13.1 (± 2.2) km** = Distance to TTS-onset threshold (VHF-weighted SEL) **22.1 - > 25 km** = Distance to SPL_{pk} 168 dB re 1µPa threshold (Lucke *et al.* 2009)
	Abad Oliva *et al.* (2024) - Moray West OWF	Moray Firth (UK) 35–55 m	Low order	ADD (11 minutes; one UXO (700 kg) at 23 minutes)	None	6–700	0.10–0.25	44	**≤ 2 km** = Distance to TTS-onset threshold (unweighted SPL_{pk}) **≤ 5 km =** Distance to TTS-onset threshold (VHF-weighted SEL; ranges exceeding 5 km for this metric were considered erroneous due to issues with measurement equipment (see Section 3.4.2.2) **> 10 km** = Distance to SPL_{pk} 168 dB re 1µPa threshold (Lucke *et al.* 2009)

Study		Region (country); water depth	UXO clearance method	Deterrence	NAS	UXO charge weight (kg NEQ)	Donor charge weight (kg NEQ)	# clearance events	Reported and estimated spatial extent of effect and description
Noise measurement studies	Midforth (2024) - East Anglia THREE OWF	Southern North Sea (UK) 30–46 m	Low order	Not reported	None	16.4–226	0.15–0.25	19	**0.4–1.1 km =** Distance to TTS-onset threshold (unweighted SPL_{pk}) **≤ 3.1 km** = Distance to TTS-onset threshold (VHF-weighted SEL) **6.1–10.6 km** = Distance to SPL_{pk} 168 dB re 1μPa threshold (Lucke *et al.* 2009)
	Donaghy and Lee (2024a) - NeuConnect interconnector	Outer Thames Estuary (UK) 5–10 m	Low order	ADD (10–14 minutes)	None	25	0.45	2	**0.1–0.4 km** = Distance to TTS-onset threshold (unweighted SPL_{pk}) **1.2–1.6 km** = Distance to TTS-onset threshold (VHF-weighted SEL)
	Donaghy and Lee (2024b) - NeuConnect interconnector	Southern North Sea (UK) 40–50 m	Low order	ADD (4–45 minutes)	None	162	0.125	1	**≤ 1.4 km** = Distance to TTS-onset threshold (unweighted SPL_{pk}) **2.4 km** = Distance to TTS-onset threshold (VHF-weighted SEL)

Study		Region (country); water depth	UXO clearance method	Deterrence	NAS	UXO charge weight (kg NEQ)	Donor charge weight (kg NEQ)	# clearance events	Reported and estimated spatial extent of effect and description
Noise measurement studies	Donaghy and Lee (2024b) - NeuConnect interconnector		High order (not intended)		None	162	0.125	1	**7–11 km** = Distance to TTS-onset threshold (unweighted SPL_{pk}) **7.5 km** = Distance to TTS-onset threshold (VHF-weighted SEL)
	Lee *et al.* (2022) - Sofia OWF	North Sea (UK) 21–37 m	High order	ADD (30–109 minutes)	BC	328	2.5	1	**1.0 km =** Distance to TTS-onset threshold (unweighted SPL_{pk}).
			High order		BC [not effective]	220	2.5	1	**10.0–14.1 km =** Distance to TTS-onset threshold (unweighted SPL_{pk}).
			Low order (not successful)		None	220	0.03	2	**≤ 1.4 km =** Distance to TTS-onset threshold (unweighted SPL_{pk}).
	Robinson *et al.* (2022) - Moray East and Neart na Gaiothe OWFs	Moray Firth (UK) 40 m	High order	ADD (up to 30 minutes) Scare charges for larger UXO	None	0.5–295	1–25	17	**6–12 km** = Distance to TTS-onset threshold (unweighted SPL_{pk})
		Firth of Forth (UK) 50 m				0.1–102	2.5–5	37	**4–10 km** = Distance to TTS-onset threshold (unweighted SPL_{pk})

Study		Region (country); water depth	UXO clearance method	Deterrence	NAS	UXO charge weight (kg NEQ)	Donor charge weight (kg NEQ)	# clearance events	Reported and estimated spatial extent of effect and description
Noise measurement studies	Bellmann *et al.* (2021) - Neart na Gaiothe OWF	Firth of Forth (UK) 50 m	High order	ADD (up to 30 minutes) Scare charges for larger UXO	None	0.1–102	2.5–5	6	**1.5–6.9 km** = Distance to TTS-onset threshold (unweighted SPL_{pk}) **2.0–6.6 km** = Distance to TTS-onset threshold (VHF-weighted SEL)
	Salomons (2021)	Southern North Sea (NL) 20 m	High order	Not reported	None	140–325	10	2	**5–7 km** = Distance to TTS-onset threshold (unweighted SPL_{pk}) **10–15 km** = Distance to TTS-onset threshold (VHF-weighted SEL)
	Mason *et al.* (2020)	North Sea (UK)	High order	ADD (60 minutes) Scare charges	BBC	240–525	Not reported	4	**0.4–5.6 km** = Distance to TTS-onset threshold (unweighted SPL_{pk}) **11.3–55.8 km** = Distance to SPL_{pk} 168 dB re 1μPa threshold (Lucke *et al.* 2009)

Study		Region (country); water depth	UXO clearance method	Deterrence	NAS	UXO charge weight (kg NEQ)	Donor charge weight (kg NEQ)	# clearance events	Reported and estimated spatial extent of effect and description
Noise measurement studies	von Benda-Beckmann *et al.* (2015)	North Sea (NL) 26–28 m	High order	Not reported	None	121–263	Not reported	7	**10–21 km** = Distance to TTS-onset threshold (unweighted SPL_{pk}), interpreted from Fig.11 in Salomons *et al.* (2021). Distance to TTS-onset was not directly reported in von Benda-Beckmann *et al.* (2015).
Noise modelling studies	Subacoustech (2024a, b, c)	Southern North Sea (UK) 20–50 m	Low order	NA	None	NA	0.25–0.5	NA	**1.8–2.3 km** = Distance to TTS-onset threshold (unweighted SPL_{pk}) **0.8–0.9 km** = Distance to TTS-onset threshold (VHF-weighted SEL)
			High order	NA	None	25	0.5	NA	**8.5 km** = Distance to TTS-onset threshold (unweighted SPL_{pk}) **2.4 km** = Distance to TTS-onset threshold (VHF-weighted SEL)

Study		Region (country); water depth	UXO clearance method	Deterrence	NAS	UXO charge weight (kg NEQ)	Donor charge weight (kg NEQ)	# clearance events	Reported and estimated spatial extent of effect and description
Noise modelling studies	Subacoustech (2024a, b, c)			NA	None	120	0.5	NA	**14 km** = Distance to TTS-onset threshold (unweighted SPL_{pk}) **3.2 km** = Distance to TTS-onset threshold (VHF-weighted SEL)
				NA	None	750–800	0.5	NA	**26.0 km** = Distance to-TTS onset threshold (unweighted SPL_{pk}) **4.2 km** = Distance to TTS-onset threshold (VHF-weighted SEL)

3.4.5. Estimation of EDRs from existing data

No studies were assessed as suitable for estimation of EDR for UXO clearance.

3.4.6. Evidence scores

Detailed methods and results of the evidence scoring exercise are presented in Appendix 2, Table 26; a summary is provided here. One empirical response, 11 noise measurement and three noise modelling studies were reviewed and assigned scores based on specific evaluation criteria (Figure 7, Appendix 2). A single scoring was performed for the three noise modelling studies as they each used an identical methodology and provided the same results for equivalent charge sizes. This group of three modelling studies were representative of other relevant modelling studies, which typically using the same or a very similar modelling approach and therefore yielding comparable predictions of noise levels.

All studies were assigned an initial score of 10, with penalties subsequently applied as appropriate for criteria including: the study type, the study's suitability for estimating an EDR (empirical response studies only); the relevance of the species studied (no penalties applied in this instance), the relevance of the study area to the UK (i.e. water depth); the relevance of the activity to current and near-future UK OWF construction (e.g. donor charge sizes, ADD use, use of scarer charges); and, other study limitations (e.g. limited baseline data, limited sample sizes, potential for biases).

For **high-order UXO clearance without noise abatement**, the single relevant empirical response study received a score of 6 (out of a maximum of 10). There were 7 relevant noise measurement studies which received scores ranging from 4 to 6, with an average score of 5.0. The score assigned to modelling studies was 4.0. The overall average across the three study type scores is 5.0.

For **low-order UXO clearance**, there were 6 relevant noise measurement studies which received scores ranging from 4 to 6, with an average score of 5.0. The score assigned to modelling studies was 4.0. The overall average across the two study type scores is 4.5.

For **high-order UXO clearance with noise abatement**, there were two noise measurement studies which received a score of 5.0.

3.5. Recommending default EDRs

3.5.1. Overview: Evidence base

Our review of evidence relating to harbour porpoise responses to UXO clearance included a single empirical study of porpoise responses to high-order UXO clearance, with a limited sample size. A total of 11 noise measurement studies, from which distance to proxy behavioural response thresholds (TTS-onset), were reviewed, seven of which included UXO clearance operations in UK waters. Of these 11, three included only low-order clearance events, five included only high-order clearance events, and three included both low- and high-order clearance events. The reported effects ranges across these studies are summarised in Table 5.

Numerous noise modelling studies exist, albeit based on very similar modelling assumptions; one group of three near-identical modelling studies were reviewed here. Modelling studies reported a variety of effect ranges (distance to TTS-onset) which were proportional to the assumed charge size: for low-order clearance these were ≤ 2.3 km; for high-order clearance, up to 26 km for a UXO of 800 kg NEQ. Modelling studies received a comparably low evidence score, show a wide range of reported effects ranges which are directly proportional to assumed charge sizes and their predicted effects ranges for SPL_{pk} are routinely much higher than reported from measurements of real-world UXO clearance. Given the substantial noise measurement evidence base for both high-order and low-order UXO clearance, modelling studies are not considered further.

In the sections below, we discuss a few key themes among the evidence reviewed and considerations when interpreting the evidence base to recommend default EDRs.

Table 5. Summary of reported and estimated effects ranges among the one empirical response and 11 noise measurement studies.

UXO clearance method	Number of studies; clearance events	Reported effects range (km)
Low-order UXO clearance	Measurement: 6; 166	Measurement: TTS-onset SPL_{pk} = 0.1–2.0 Measurement: TTS-onset SEL = 1.2–5.0
High-order UXO clearance	Empirical: 1; 4 Measurement: 7; 97	Empirical: 15–20 Measurement: TTS-onset SPL_{pk} = 1.5–21.0 Measurement: TTS-onset SEL = 2.0–15.0
High-order UXO clearance with NAS	Measurement: 2; 5[1]	Measurement: TTS-onset SPL_{pk} = 0.4–5.6

[1] *While Lee* et al. *(2022) reported results for two clearance events with a bubble curtain, the bubble curtain was not effective for one of these events and so is grouped with high-order clearance without noise abatement.*

3.5.1.1. Noise levels and effects ranges from high-order clearance

Despite high-order clearance involving the detonation of the full explosive material estimated within the UXO, studies did not report a strong correlation between estimated UXO NEQ and measured noise levels (e.g. Robinson *et al.* 2022). There is uncertainty over how much of the UXO does detonate, with many measurements appearing to be consistent with the levels for the donor charge alone. Further, it has been suggested that the seabed may reduce the radiated sound compared to that predicted for a mid-water explosion, with models based on the latter generally overestimating noise levels at large ranges (Robinson *et al.* 2022). For example, despite measurements studies including multiple high-order clearances of UXOs > 200 kg and up to 344 kg NEQ, a majority of studies reported rages to TTS-onset for SPL_{pk} of < 15 km. Such a range was associated with a UXO of approximately 120 kg NEQ within modelling studies.

3.5.1.2. Choice of metric

Noise measurement studies generally reported slightly larger ranges to TTS-onset for the VHF weighted SEL metric than the unweighted SPL_{pk}. This runs contrary to model-predictions, suggesting that current modelling practices (at least those based on Soloway & Dahl 2014) may be underestimating the amount of energy at higher-frequencies generated by UXO clearance events and/or over-estimating the attenuation of higher-frequency noise with range from source. Where such modelling approaches are used to inform mitigation measures, it is recommended that mitigation is based on ranges associated with the SPL_{pk} metric.

3.5.1.3. Influence of ADDs

Noise measurement and modelling results for low-order clearance indicate, almost without exception, that distances to TTS-onset thresholds are within 4 km of the noise source. At such ranges, it may be that the disturbance effect of ADD use (and to a lesser extent, vessel traffic) is of a similar or possibly greater magnitude than that which may arise from the use of explosives (Brandt *et al.* 2013b; Thompson *et al.* 2020; Benhemma-Le Gall *et al.* 2021). It is important to carefully balance the risk of injury with that of unnecessary disturbance and carefully select deterrence and mitigation procures with minimise disturbance. See Section 7 for EDR estimation for ADDs.

3.5.2. Recommended default EDRs

Recommended default EDRs are presented below. These follow consideration of all the evidence reviewed in the current study, including reported and estimated effects ranges, but also the limitations and relevance of specific evidence.

For low-order UXO clearance, an EDR in of 5 km is recommended.

- The current EDR for low-order clearance of 5 km is well-supported by evidence from noise measurement studies as encompassing the reported range to TTS-onset thresholds from a considerable number of clearance events (with weight of donor charge sizes ranging between 0.1–0.45 kg) in relevant environments. The noise measurement studies based on which this EDR was estimated received scores between 4–6 (out of 10), with an average score of 5. It is noted that this EDR lacks evidence from empirical response studies, and these are urgently required to understand how porpoise respond to the combined effect of a short ADD exposure, vessels and potentially more than one low-order clearance event within a day.

For high-order UXO clearance *without* noise abatement, an EDR in the region of 15–20 km is recommended.

- While it is noted that modelling can be used to predict TTS-onset ranges for specific UXO sizes, measurement data suggest wide variability in noise levels with a poor correlation to UXO size. Although empirical data on porpoise responses to UXO clearance are very limited, they are favoured to predictions of noise levels at range and assumptions of how they may elicit responses in harbour porpoises. As such, this EDR is largely based on the findings of van Geel *et al.* (2024) for high-order clearance of 101 and 250 kg NEQ UXOs. This study achieved a score of 6. Although the responses to UXO detonation could not be disentangled from the pre-detonation use of ADDs, the use of ADDs proportional to the UXO size is currently to be expected for any high-order UXO clearance without noise abatement.
- There are a few studies for which distance to TTS-onset threshold for high order detonation is smaller than 15–20 km, with reported distances ranging between 1.5–12 km and 2.0–15 km for unweighted SPL_{pk} and VHF-weighted SEL, respectively. However, 15–20 km encompasses the largest measured distances to TTS-onset across high-order clearances for UXO sizes between 121–263 kg based on inferred data from von Benda-Beckmann *et al.* (2015) and Salomons *et al.* (2021). Additionally, distances to aversive behavioural reaction threshold of SPL_{pk} 168 dB re 1μPa inferred from data in Lepper *et al.* (2024) for UXO charge weight of 34–344 kg NEQ suggest potential for behavioural disturbance within that range. These noise measurement studies received between 4 to 6 points, with an average score of 5 out of 10.

For high-order UXO clearance *with* noise abatement, an EDR of 10 km is recommended.

- From two measurement studies, the inferred distances to the unweighted TTS-onset threshold for clearance events with successful applications of bubble curtains range between 0.4–5.6 km. However, these are drawn from a very limited evidence base: only 5 clearance events (240–525 kg NEQ), with inconclusive evidence of the effectiveness of the bubble curtain.
- While not considered key resources in the current review, data from quarry trials of small charges (Cheong *et al.* 2023b) and open-ocean high-order clearance studies not suitable for estimation of TTS-onset ranges (Schmidtke 2010; Grimsbo & Kvadsheim 2018), indicate that effective abatement can be achieved with a bubble curtain, yielding reductions in SPL_{pk} of 12–17 dB. However, the evidence from the reviewed open ocean UXO clearance is inconclusive with regard to both the magnitude and consistency of effectiveness of bubble curtains in reducing noise levels from high-order UXO clearance. As such, until the evidence base improves, a precautionary approach is recommended, and the suggested EDR reflects this.

4. Explosives in decommissioning

4.1. Description of activity

Explosives are used regularly for activities related to oil and gas decommissioning such as the severance of wellheads, cutting of piles and steel elements of subsea structures, and breaking up of concrete elements (DeMarsh 2000; Gitschlag *et al.* 2001; Associates 2004; DESNZ 2023; Zawawi *et al.* 2023). Between 2010 and 2021, 55 oil and gas explosive decommissioning projects were licensed in the UK; of these, ten were downhole projects deep enough (generally > 700 m below the seabed) so that mitigation was not required and six projects only planned to use explosives as a possible backup for other decommissioning methods (Stone 2023a).

Generally, charges used in decommissioning activities are classified into two main categories:

- Bulk charges are often used to sever and recover subsea well heads and are generally made up of C-4 or Comp B (Associates 2004). The charges are lowered into pilings or well conductors (DESNZ 2023).
- Cutting charges stem into two categories - linear shaped charges (LSC) and foam clad breeching charges (sometimes referred to as cutting tape). LSCs often contain RDX or PBX and can be placed inside or outside of targets (Dzwilewski & Fenton 2003; Associates 2004; DESNZ 2023). Foam clad breeching charges function in the same way as LSCs but they are flexible and can be bent around target structures. However, they are currently not as efficient as LSCs and generally viewed as more appropriate for top side decommissioning as they are not used beyond 10 m below the seabed in subsea decommissioning (Associates 2004; DESNZ 2023).

The most common charge size for explosives used in decommissioning is < 50 kg NEQ (Ainslie *et al.* 2009; DESNZ 2023). Charges of up to 86 kg NEQ were reported among UK projects between 2010–2021, with 58% using an NEQ exceeding 30 kg (Stone 2023a). A variety of explosive material was used, with nitromethane and Semtex being the most common.

ADDs are widely used in association with explosives use in decommissioning where mitigation is required, as a means of deterring marine mammals from zones of potential injury. Based on available MMO/PAM data from projects involving explosives in UK waters, ADDs were used in 63% of decommissioning projects and almost always as a requirement of the project licence (Stone 2023a). In all but two cases, a Lofitech Seal Scarer was used (fundamental frequency of 14.6 kHz and a source level of SPL_{pk} 204 dB re 1 µPa) (McGarry *et al.* 2017; Stone 2023a). The length of ADD deployments varied but 90% of deployments lasted less than 40 minutes with the longest recorded duration lasting 2.01 hours (Stone 2023a).

4.2. Current recommended EDRs

The current recommended EDRs for the use of explosives in decommissioning differentiates between their use in open water and within 100 m of the mudline (i.e. below the seabed). They are as follows (JNCC 2023a):

- Explosives in open water:
  - > 2 kg = 26 km,
  - > 2 kg with noise abatement = 15 km,

  - < 2 kg = 5 km.
- Explosives within 100 m of the mudline:
  - > 2 kg = 15 km,
  - > 2 kg with noise abatement = 5 km,
  - < 2 kg = 5 km.

For open water, the EDRs align with those currently recommended for UXO clearance for high-order (26 km), high-order with abatement (15 km) and low-order (5 km).

No EDRs are recommended for the use of explosives > 100 m below the mudline. Noise measurements carried out during two well perforation campaigns in the southern North Sea (Confidential 2018c, a) at depths between 193 to 2,734 m below the mudline using 0.4 kg of high-explosives showed that sound levels within the water column remained consistent with ambient levels. Additionally, see Section 4.4.1 and Confidential (2020a) for a discussion of expected noise levels for multiple small charges detonated at depths of 70 to 160 m below the seabed.

4.3. Approach to evidence review

The overall approach to the evidence review is described in Section 2. Due to the absence of empirical studies of harbour porpoise responses to explosives use in decommissioning, the review presented in Section 4.4 is based on noise measurement studies. Similar to the approach selected for UXO clearance (Section 3.3), we summarise, where results allow, the reported ranges to the TTS-onset threshold for impulsive sounds for VHF cetaceans. A key question considered during this evidence review for explosive in decommissioning was: “How do noise levels from explosive use in decommissioning differ from those associated with UXO clearance?”.

As described in Section 2.4, in cases where response ranges were not explicitly reported but sufficient study data were available, additional analyses were conducted to estimate the distances at which TTS-onset thresholds might be reached. These estimations were derived using the graphreader online tool to extract data points from relevant figures. For studies where such analyses were carried out, this is indicated under the sub header *"Interpreting results for inferred response ranges".*

Additionally, the report includes a discussion comparing the sound levels measured during explosive detonations at various depths below the seabed with those recorded for charges detonated in open water (see Section 4.4.2).

4.4. Evidence

In Sections 4.4.1 and 4.4.2 we provide summary reviews of relevant measurement and modelling studies identified in our review for explosive use in decommissioning. Results of the evidence scoring exercise is provided in Section 4.4.4.

4.4.1. Noise measurement studies

4.4.1.1. Nedwell *et al.* (2001)

This study reports on noise levels associated with wellheads in the North Sea removed using explosives as part of an abandonment program from 2000–2001. The water depths in the study area ranged from 32–116 m. Overall, 16 blasts were fired using charge weights ranged from 36–81 kg and all but one of the blasts occurred 2–3 m below the seabed. The remaining blast was conducted above the seabed.

Blast pressure measurements were measured from the vessel at least 600 m away from the detonation. Closer blast pressure measurements were also taken on an opportunistic basis using a submersible blast recording workstation attached to the firing line. Ultimately, measurements were made 75–800 m away from the blast and it was concluded that, based on injury criteria from Yelverton *et al.* (1973), the recorded sound pressure levels could cause moderately severe injury to marine mammals.

In the Genesis (2011) review, authors reproduced SPL_{pk} recorded from the detonation of 45 kg explosive charges, measured at ranges from explosion, originally presented in Nedwell *et al.* (2001). The 45 kg charges were detonated at a depth of 2–3 m below the seabed. For the purpose of this review, the sound levels at distance were compared to the unweighted TTS-onset threshold (SPL_{pk} 196 dB re 1µPa) based on Southall *et al.* (2019) criteria. Sound levels from 45 kg charges were between SPL_{pk} 225–232 dB re 1 µPa at measurement ranges between 75–400 m from source, therefore all exceeding unweighted TTS-onset thresholds for harbour porpoise. Sound levels from charge sizes of 36–81 kg were between SPL_{pk} 211–226 dB re 1 µPa at measurement ranges between 575–800 m from source, which also all exceeded unweighted TTS-onset thresholds for harbour porpoise. The authors noted that the measured noise levels agreed reasonably well with theoretical predictions for detonation of unconfined underwater charges of comparable size, with no apparent indication that the peak pressure or impulse of the blast had been attenuated as a result of the charge being confined within the wellhead.

Interpreting results for inferred response ranges

The results discussed above do not include measurements across a sufficient range and number of distances from the source to enable accurate estimation of distances to TTS-onset levels. Given that the measured noise levels aligned with predictions for open-water detonations, approximate distances to the TTS-onset threshold (SPL_{pk}) were estimated using an average transmission loss model of $18\log(R) - 0.001(R)$, based on data from 19 low-order UXO detonations in the southern North Sea (Midforth 2024). This transmission loss equation was used to back-calculate the source level @ 1m from measured noise levels at known distances during 16 detonations involving charges between 36–81 kg (Nedwell *et al.* 2001). Applying the derived source level to the model, the estimated range to the TTS-onset extended up to approximately 10 km from the source.

4.4.1.2. Confidential (2020a)

The measurements of wellhead perforations at two locations in the North Sea (in approximately 93–95 m water depths) were analysed and reported on by Confidential (2020a). The perforations were conducted at a total of three wellheads (two at one location). At one of the locations, shallow wellhead perforations were conducted at 4.3 m and 5.2 m below the seabed, and deep wellhead perforations were conducted at 156.7 m and 73.8 m respectively. At the second location, perforations were conducted at 8.5 m and 138.1 m below the seabed.

All perforations comprised of 120 shots of explosive material, placed at 1.5 m intervals. Each shot contained 22.7 g of explosive materials. The total charge weight used at each wellhead perforation, irrespective of depth, was 2.724 kg (i.e. the cumulative mass of 120 shots of explosive material each weighing 22.7 g). Two hydrophones were placed above each wellhead to measure the underwater noise levels from the perforations. One hydrophone was located ~ 3 m above the seabed, directly above the wellhead itself, and the other was located ~ 3 m above the seabed but 5–10 m away from the wellheads.

The measured SPL_{pk} show that the shallow perforations (up to 8.5 m) resulted in higher noise levels than the corresponding deeper perforations (between 73.8–156.7 m). The shallower perforation noise level measurements made close to the wellheads (0–5 m) were above the TTS-onset thresholds for VHF cetaceans. Measured noise levels were all SPL_{pk} ≤ 211 dB re 1 µPa (with the highest measured at 0 m from the well; Table 6). Assuming a typical propagation loss model of 15log(*R*), where *R* is the distance from the noise source, a 15 dB transmission loss would be expected within 10 m from the source. For the deeper perforations, no measurements exceeded TTS-onset threshold for SPL_{pk}.

For the VHF-weighted SEL criteria, TTS-onset threshold of 140 dB re 1 µPa^2s was exceeded for all shallow perforations, with measured noise levels of up to 160.9 dB re 1 µPa^2s at 5 m from the source. For the VHF weighted SEL metric, TTS-onset thresholds were also exceeded for almost all deep perforations, albeit by < 10 dB (Table 6). As the measurements were taken in close proximity to the wellheads, elevated noise levels above ambient are expected to be confined to the immediate vicinity of the wells and are unlikely to propagate at distances larger than tens of meters. This is supported by measured data; for example, during a detonation at a depth of 73.8 m, the SEL recorded at the wellhead (0 m) was 148.8 dB re 1 µPa^2s, which decreased to 142.6 dB re 1 µPa^2s within the first 5 meters (Table 6).

These results do not include measurements across a sufficient range and number of distances from the source to enable estimation of distances to TTS-onset levels. However, measured noise levels from shallow perforations were all SPL_{pk} ≤ 211 dB re 1 µPa (Table 6), indicating that, with typical transmission loss, ranges to SPL_{pk} TTS-onset thresholds would not extend beyond a few tens of metres from the source.

Table 6. A summary of SPL_{pk} and SEL measured at different distances to explosive charges places at various depths below the seabed (Confidential 2020a).

Wellhead	Depth below seabed at which explosive charge was placed (m)	Water depth (m)	Recording depth (m)	Recording distance (m)	Charge style	Charge size (g)	SPL_{pk}		VHF-weighted SEL	
							SPL_{pk} (dB re 1 μPa)	TTS-onset threshold exceeded?	SEL (dB re 1 $μPa^2s$)	TTS-onset threshold exceeded?
Wellhead 1	4.3	~ 95	~ 3 m above seabed	~ 0 m	120 shots at 1.5 m intervals	22.7 per shot (totalling 2,724)	202.0	Yes	162.5	Yes
	4.3	~ 95	~ 3 m above seabed	~ 5 m	120 shots at 1.5 m intervals	22.7 per shot (totalling 2,724)	198.7	Yes	156.9	Yes
	156.7	~ 95	~ 3 m above seabed	~ 0 m	120 shots at 1.5 m intervals	22.7 per shot (totalling 2,724)	189.7	No	141.3	Yes
	156.7	~ 95	~ 3 m above seabed	~ 5 m	120 shots at 1.5 m intervals	22.7 per shot (totalling 2,724)	182.2	No	137.4	No

Wellhead	**Depth below seabed at which explosive charge was placed (m)**	**Water depth (m)**	**Recording depth (m)**	**Recording distance (m)**	**Charge style**	**Charge size (g)**	**SPL_{pk}**		**VHF-weighted SEL**	
							SPL_{pk} (dB re 1 µPa)	TTS-onset threshold exceeded?	SEL (dB re 1 μPa^2s)	TTS-onset threshold exceeded?
Wellhead 2	5.2	~ 95	~ 3 m above seabed	~ 0 m	120 shots at 1.5 m intervals	22.7 per shot (totalling 2,724)	207.5	Yes	163.1	Yes
	5.2	~ 95	~ 3 m above seabed	~ 5 m	120 shots at 1.5 m intervals	22.7 per shot (totalling 2,724)	208.7	Yes	157.0	Yes
	73.8	~ 95	~ 3 m above seabed	~ 0 m	120 shots at 1.5 m intervals	22.7 per shot (totalling 2,724)	193.6	No	148.8	Yes
	73.8	~ 95	~ 3 m above seabed	~ 5 m	120 shots at 1.5 m intervals	22.7 per shot (totalling 2,724)	188.8	No	142.6	Yes

Wellhead	Depth below seabed at which explosive charge was placed (m)	Water depth (m)	Recording depth (m)	Recording distance (m)	Charge style	Charge size (g)	SPL_{pk}		VHF-weighted SEL	
							SPL_{pk} (dB re 1 μPa)	TTS-onset threshold exceeded?	SEL (dB re 1 $\mu Pa^2 s$)	TTS-onset threshold exceeded?
Wellhead 3	8.5	~ 93–95	~ 3 m above seabed	~ 0 m	120 shots at 1.5 m intervals	22.7 per shot (totalling 2,724)	211.0	Yes	167.5	Yes
	8.5	~ 93–95	~ 3 m above seabed	~ 5 m	120 shots at 1.5 m intervals	22.7 per shot (totalling 2,724)	204.6	Yes	160.9	Yes
	138.1	~ 93–95	~ 3 m above seabed	~ 0 m	120 shots at 1.5 m intervals	22.7 per shot (totalling 2,724)	193.0	No	146.8	Yes
	138.1	~ 93–95	~ 3 m above seabed	~ 10 m	120 shots at 1.5 m intervals	22.7 per shot (totalling 2,724)	188.3	No	140.6	Yes

4.4.2. Noise modelling studies

We did not review noise modelling studies specific to the use of explosives in decommissioning for detonations below the mudline. However, based on the noise measurements of detonations close to the mudline presented in Nedwell *et al.* (2001) being comparable to those of unconfined detonations, modelling studies for UXO clearance are relevant. While these typically over-estimate noise SPL_{pk} levels from UXOs due to conservative assumptions about the total charge size, among other factors, they are based on results from mid-water detonations (e.g. Soloway & Dahl 2014) and are expected to be reasonably accurate for known charge sizes detonated within a few metres of the mudline. As such, the reader is referred to the UXO Section 3.4.3 of the current review.

4.4.3. Estimation of EDRs from existing data

No studies were assessed as suitable for estimation of EDR for explosives in decommissioning.

4.4.4. Evidence scores

Detailed methods and results of the evidence scoring exercise are presented in Appendix 2**,** Table 27**;** a summary is provided here. The two noise measurement studies scored a 5 and 4, with the score for relevant modelling studies being 4. Measurement studies were penalised for their limited spatial extent of measurement locations, in addition to water depths greater than those within UK harbour porpoise SACs for one.

4.5. Recommending default EDRs

4.5.1. Overview: evidence base

One of the two studies reviewed illustrated that noise levels from explosive use approximately 70–160 m below the mudline resulted in elevated noise levels in the water column, albeit not at levels anticipated to cause disturbance using unweighted SPL_{pk} TTS-onset thresholds as a proxy. Using the VHF-weighted SEL metric, the TTS-onset thresholds could be exceeded in the immediate vicinity of the well (within a few tens of meters) and therefore is unlikely to result in any measurable behavioural response. It is important to note that this study used only small quantities of explosives (less than 3 kg per event). While the use of larger explosive charges at similar depths is considered unlikely (JNCC, *pers. comm.*), the noise levels observed in this study may not be representative of those generated by larger bulk charges at comparable depths.

Noise levels from explosives use within a few metres of the mudline were higher. For small volumes of perforation charges (< 3 kg total per event) detonated at depths 5.2–8.5 m below seabed, ranges to TTS-onset thresholds were exceeded in close proximity to the source (Confidential 2020a). However, due to the limited spatial extent of measurements the range to the TTS-onset threshold could not be estimated. The source levels at monitoring stations located at 0 m distance from the well were less than would be expected from an open water detonation of a similar total quantity of explosives. By contrast, the use of bulk charges of 36–81 kg within 2–3 m of the mudline resulted in noise levels from which unweighted SPL_{pk} TTS-onset ranges were estimated to extend up to approximately 10 km (Nedwell *et al.* 2001). This distance is comparable to model-predictions of open water detonations of similar charge sizes (i.e. up to c. 50 kg - see Section 3.4.3), as the authors concluded.

It is noted that the evidence base is limited, far more so than for explosives use in UXO clearance, with fewer studies but similar scores. In the UK to date, noise abatement systems have not been employed for explosive use in decommissioning activities; consequently, no data were available to inform the assessment of noise levels associated with mitigated explosive use.

4.5.2. Recommended default EDRs

For open water detonations and detonations up to 10 m below the mudline, it is recommended that EDRs are assigned on a case-by-case basis in accordance with model-predicted TTS-onset ranges proportional to the charge size being used.

- This recommendation is considered to be more appropriate than the current arbitrary categories of < or > 2 kg charge sizes.
- This recommendation can also be applied to the use of explosives with noise abatement, with assumptions made about the anticipated noise level reductions with noise abatement applied.
- The recommendation is mainly based on a review of a single noise measurement study, which detonated UXO charge sizes of 36–81 kg at the depth between 2–3 m and received a score of 5 in the scoring exercise. It is noted that this recommendation may over-estimate TTS-onset ranges/EDRs for confined detonations of specialised cutting charges of small total NEQ.
- “Up to 10 m below the mudline” captures the evidence available (Nedwell *et al.* 2001; Confidential 2020a), but evidence is currently too limited to assess the applicability of this recommendation to depths > 10 m below the mudline but < 100 m.

5. Seismic (airgun) surveys

5.1. Description of activity

Seismic surveys using airgun arrays are used for a variety of commercial applications to image geological layers below the seabed, including deep geological exploration for hydrocarbons, characterising and monitoring geological features for carbon capture and storage, and shallow geological investigations to inform drilling and infrastructure construction (Hartley Anderson Ltd 2020). The characteristics of these surveys and the noise generated have been widely reviewed (e.g. Richardson 1995; OGP & IAGC 2011; DECC 2016; Hartley Anderson Ltd 2020).

The primary energy source for marine seismic surveys is an array of airguns towed behind a seismic survey vessel. One or more airguns in the array explosively release a high-pressure bubble of air to generate an acoustic pulse. Typically, airguns are arranged in an array of one or more clusters of multiple airguns in a configuration that generates a single signal focused on the seabed. The signal is a short impulse of low frequency with most energy < 200 Hz, but with energy extending to 10 kHz and above (e.g. Hermannsen *et al.* 2015). To capture the reflected seismic waves, hydrophones are deployed in long cables known as streamers, which are towed behind the vessel or, less frequently, positioned on the seabed.

The main types of seismic surveys undertaken in UK waters include: two-dimensional (2D), 3D, ocean-bottom seismic (OBS) and vertical-seismic profiling (VSP) (see Hartley Anderson Ltd 2020). A 2D survey can include airgun arrays of small to large total volumes and are commonly used for early exploration and shallow geological investigations. Repeated parallel line surveys are run at intervals of several kilometres (minimum 0.5 km) and a second set of lines at right angles to the first is used to form a grid pattern. For regional-scale surveys it is common for 2D lines to cover very large distances of > 50 km. 3D surveys typically use two airgun arrays and different streamer configurations to obtain higher density data at regional or reservoir scales; these surveys may take several months to complete and cover areas of 300–3,000 km^2. Repeated 3D surveys over time are referred to as 4D surveys. OBS surveys use airgun arrays similar to 2D or 3D as the source of sound but instead of hydrophones in streamers they use static geophone sensors placed directly on the seabed. VSP is a type of bore hole survey and is used to assist well evaluation by deploying a small airgun array from a vessel or rig and deploying geophones into a well.

Airgun arrays used on 2D, 3D, 4D and OBS surveys typically produce frequencies predominantly up to around 200 Hz, with a source level of around $SPL_{pk\text{-}pk}$ 262 dB re 1 µPa @ 1m (Stone 2024a). Arrays used on site surveys and some VSP operations typically produce frequencies predominantly up to around 250 Hz, with a source level of around $SPL_{pk\text{-}pk}$ 242 dB re 1 µPa @ 1m (Stone 2024a). As described by Hartley Anderson Ltd (2020), when airguns are configured in an array, amplitude is increased above what any single airgun can produce by ensuring the signal from each airgun arrives simultaneously at the required point below the array to combine additively in the downward vertical. Off vertical, signals do not arrive at the same time, reducing the signal amplitude. Therefore, while less directional than high-resolution geophysical sources such as SBPs, airgun arrays are a directional source of sound with measured levels in the horizontal 15–24 dB lower than in the vertical (Landro & Amundsen 2018).

Data collection along multiple parallel survey lines is a standard approach in seismic surveys, particularly in 3D seismic exploration. This method significantly improves data quality and resolution compared to single-line surveys. Breaks in data collection are often required during line changes when the survey vessel repositions for the next parallel track, primarily for mitigation purposes. The time needed for vessel realignment depends on factors such as streamer length and water conditions. Additionally, streamers may require adjustments to maintain optimal towing depth and spacing. Stone (2024a) reported that the primary reasons for planned short breaks in seismic surveys are line changes and sound checks, with the average duration of short breaks between 2010 and 2020 recorded at 4.6 minutes.

While geophysical survey sources other than airguns can be considered seismic sources, in this evidence review, seismic surveys specifically refer to surveys using airguns. The size of airguns/arrays and associated noise levels varies considerably between studies. Stone (2024b) splits seismic airgun surveys into the following two categories:

- Single airguns and arrays with a total volume of **≤ 1,200 in^3**. Such arrays are typical of those used for site characterisation surveys and VSP.
- Arrays with a total volume of **> 1,200 in^3**. Such arrays are typical of those used in regional-scale exploration (2D), detailed reservoir surveys (3D), 3D seismic surveys repeated at an interval of months or years (4D) and Ocean Bottom Seismic (OBS) surveys.

Additionally, we note the different treatment of single mini-airguns in mitigation guidelines (JNCC 2017) and current recommended default EDRs (JNCC 2023a). A mini airgun is defined in the JNCC (2017) guidance as ≤ 10 in^3; however, in line with JNCC (2025a) draft guidance as well as Stone (2024a) report, the volume for a mini airgun is now considered as ≤ 12 in^3. Such equipment is considered a high-resolution seismic source and is typically deployed alongside sources such as sub-bottom profilers and seabed mapping sources.

As some studies provide evidence spanning two or three of the aforementioned categories, we do not differentiate between these in the structure of the descriptive sections below. However, a distinction is made in summary table and when recommending default EDRs.

5.2. Current recommended EDRs

Based on Thompson *et al.* (2013), a consultation draft of the JNCC (2020) harbour porpoise SAC noise guidance recommended a 10 km EDR for seismic surveys, which was increased to 12 km for the final guidance in response to the publication of Sarnocińska *et al.* (2020). These studies reported harbour porpoise response to 2D and 3D seismic surveys of very different airgun volumes; however, the resulting EDR of 12 km has been applied to all seismic survey types (except mini airgun). More recent guidance advises an EDR of 5 km for mini-airguns (JNCC 2023b), aligning with the default recommended EDR for SBPs.

The seismic survey is a moving source and therefore the potential daily disturbance area for harbour porpoise varies based on the number of line turns, vessel speed, and other operational factors. In the preparation of EIAs and HRAs for planned activities the aim is for the daily disturbance footprint to be appropriately assessed using project-specific information on the average survey line length per day to which the EDR is applied (JNCC, pers. comm.). In practice, where such information is lacking, JNCC (2023b) currently recommends using a default daily disturbance area of 1,759 km^2 for proposed large-scale mobile activities, based on the HRA for the ION Southern North Sea Seismic Survey 2021. For completed activities in the MNR, the EDR is applied as a buffer to the specific oil and gas licencing blocks that were surveyed on any given day (minus overlap) to estimate the disturbed area, although an option to enter actual survey lines is provided. For VSP surveys, the daily disturbance footprint is calculated as a circular area with a 12 km radius (equivalent to 452 km^2), reflecting the stationary nature of this survey method. For mini-airgun surveys, a 5 km radius is applied to the survey lines, or in the absence of lines, the disturbed area will be the area of the oil and gas blocks (JNCC, pers. comm.).

5.3. Approach to evidence review

The evidence base for seismic surveys includes a combination of data sources and study types. Empirical response studies are reviewed to examine the nature of the noise source, environment, monitoring approach and how animals responded as a function of distance and/or received noise level. Where empirical response studies meet the necessary criteria (see Section 2.3), results are further examined to estimate an EDR. It is worth noting that the evidence used to support the existing EDRs is included in this review (Thompson *et al.* 2013; Sarnocińska *et al.* 2020), with additional analyses (see Section 5.4.5) on the Sarnocińska *et al.* (2020) study data carried out in order to extract the EDR in line with the definition outlined in Section 2.2.

Also included in the literature review are:

(i) studies reporting on noise levels measured during seismic surveys, and

(ii) studies undertaking modelling to estimate noise levels from seismic surveys. In relation to noise measurement studies, some datasets not in the public domain were acquired.

For both noise measurement and modelling studies, we summarise, where results allow, the reported ranges to the following proposed behavioural response thresholds:

- SEL 145 dB re 1 µPa^{2}s / $SPL_{pk\text{-}pk}$ 174 dB re 1 µPa (unweighted) aversive behavioural reactions (Lucke *et al.* 2009) - adjusted to 168 dB $SPL_{pk.}$
- SPL_{rms} 160 dB re 1 µPa National Marine Fisheries Service (NMFS) Level B harassment threshold (NOAA 2005).
- Alternative thresholds as reported in individual studies.

One study Hermannsen *et al.* (2015) cited Tougaard *et al.* (2015) and reaction thresholds between SPL_{rms} 141 and 149 dB re 1 µPa. Most of the noise modelling studies, for example reports found on Offshore Petroleum Regulator for Environment and Decommissioning (OPRED) website, estimate behavioural reaction ranges based on SPL_{rms} 145 dB re 1 µPa or SEL_{ss} 145 dB re 1 µPa^{2}s, but do not provide sources for these thresholds.

It is acknowledged that there are no universally accepted behavioural response thresholds, but the above have been used in various assessments of potential behavioural responses of marine mammals to seismic and other anthropogenic noise sources in the UK. Further information on the evidence base behind these proposed thresholds is provided in Appendix 1.

As described in Section 2.4, where behavioural response ranges are not explicitly reported in studies we estimate these (where possible) from data or plots presented in reports, either using the graphreader online tool to extract values from relevant plots or directly from transmission loss models fitted to measured data within studies. For studies where such analyses were carried out, this is indicated under the subheader *"Interpreting results for inferred response ranges".*

5.4. Evidence

In Sections 5.4.1 to 5.4.3, we provide summary reviews of relevant empirical, measurement and modelling studies identified in our review for seismic survey. In Section 5.4.4 we provide a tabulation of all evidence reviewed in the current study for these noise sources, including specific features of the activities (e.g. region, water depth, airgun volume, source level) and the reported spatial extent of deterrence effects / distance to threshold levels. Results of the evidence scoring exercise for seismic survey is provided in Section 5.4.6.

5.4.1. Empirical response studies

5.4.1.1. Stone (2024b) - Responses of porpoise to small and large seismic surveys

Stone (2024b) investigated the impacts of geophysical and seismic surveys on marine mammals, including those on harbour porpoises. The study analysed marine mammal mitigation data from 1,940 geophysical surveys, collected between 1995–2020 in UK and adjacent waters. Marine mammal sightings and acoustic detections included details on species, observed behaviours, the closest surface distance of approach to the airguns and the airgun activity at the time of the encounter. The closest distance of approach to the source during an encounter was compared between periods when the source was active and periods when it was not active. The source was regarded as active whether it was at full power, undertaking a soft start or at reduced power for some reason other than a soft start.

The airgun array volumes varied significantly across surveys, ranging from a minimum of 4 in^3 (in some site surveys) to a maximum of 10,170 in^3 (in a 2D survey). Large airgun volumes were uncommon, with only nine surveys utilising volumes exceeding 6,000 in^3. Site surveys and VSPs generally employed smaller arrays with lower total volumes, typically up to 180 in^3 for site surveys and between 500–1,000 in^3 for VSPs. In contrast, 2D, 3D, 4D, and OBS surveys utilised larger arrays with greater numbers of airguns, often exceeding 3,000 in^3. As per the division suggested in Section 5.1, in Stone (2024b) "small arrays" are defined as those with a volume of 1,200 in^3 or less, while "large arrays" refer to those with a volume exceeding 1,200 in^3.

Based on available data, arrays used in 2D, 3D, 4D, and OBS surveys typically generated frequencies predominantly up to approximately 200 Hz, with source levels around $SPL_{pk\text{-}pk}$ 262 dB re 1 µPa @ 1 m. In contrast, arrays used in site surveys and some VSP operations primarily produced frequencies up to approximately 250 Hz, with source levels around $SPL_{pk\text{-}pk}$ 242 dB re 1 µPa @ 1 m.

Detection rates of harbour porpoises were significantly higher when airguns were inactive during surveys, regardless of array size (for large and small arrays). For both array sizes, the median detection rate of harbour porpoises was zero during airgun activity. In the absence of airgun activity, the median detection rates were 0.18 and 0.16 detections per hour for the small and large airgun arrays, respectively. For large airgun arrays, harbour porpoise detection rates were significantly higher in the week before operations began (median of 0.24 detections per hour) compared to the week after, when median was assessed as zero. In contrast, no significant differences in detection rates were observed for small airgun arrays.

Due to the potential biases in the data, Stone (2024b) made a few assumptions in ‘the closest distance of approach to the source (active versus not active)’ data analysis. There was a potential for errors in range estimation from PAM arising from factors such as the positioning of the hydrophone array and therefore only visual sightings were considered. Stone (2024b) also noted that weather conditions and the experience of the observer could result in bias towards closer distances and as such, the analysis used only sightings by observers with “good detection skills” (those with at least 20 sightings). Harbour porpoises were observed to approach closer to large airgun arrays when they were inactive compared to when they were active. The median closest distance to large airgun arrays was estimated at 725 m when inactive, compared to 1,100 m when active. For small airgun arrays (< 1,200 in^3), there were insufficient sample sizes to assess responses for harbour porpoise.

It is noted that values reported in this study do not meet the definition of an EDR as described in Section 2.2 and are not suitable for estimating a maximum spatial extent of effects or an EDR. Due to limitations of visual methods, the average approach distance during active airgun firing is likely to be an underestimate of the true spatial extent of avoidance effects. Therefore, a general finding of the study is that harbour porpoise appear to show an average minimum avoidance range of 1.1 km from active large airgun arrays.

5.4.1.2. Sarnocińska *et al.* (2020) - Responses of porpoise to a 3D survey

Sarnocińska *et al.* (2020) presented the findings of a study of the effects of a large 3D seismic survey (3,570 in^3) in the Danish sector of the North Sea on harbour porpoise echolocation activity. The survey lasted 103 days, with airguns operational on all but 17 days. Acoustic loggers were deployed at nine recording stations inside and adjacent to the seismic survey area, before, during and after the survey over a total duration of nine months. As the 3D seismic survey was conducted along transect lines, determining precise distances to the recording stations is challenging. However, six of these stations were positioned 100– 200 m from oil and gas platforms, one station was located 200 m from an inactive subsurface wellhead on the seafloor, and two reference stations were placed at least 15 km away from any seismic activity on the bare seabed.

Harbour porpoises were detected at all stations throughout the study period. Three acoustic measures of porpoise occurrence were analysed: number of clicks per minute (CPM; a measure of how intensely echolocation was used), porpoise positive minutes (PPM, proxy for porpoise presence) and ratio of minutes with high repetition rate click trains called buzzes (i.e. < 15 ms between clicks) to minutes with any click train calculated per hour (BPM/PPM; measure of foraging buzzes and social calls). All three measures of porpoise occurrence were lowest closest to the source vessel and showed a positive trend with distance up to 8 - 12 km away from the source vessel, followed by a reduction and levelling-off to assumed baseline activity levels from approximately 16–24 km (the maximum monitored distance). The presence of a 'bulge' of apparently elevated porpoise occurrence in the 8–12 km range to source makes it challenging to assess the distance to which porpoise are deterred from the source, but effects do not appear to extend beyond 12 km. The study noted a general increase in porpoise activity across the entire monitoring area over time, attributed to a seasonal influx of porpoises into the region.

It is noted that values reported in this study do not meet the definition of an EDR as described in Section 2.2; rather, these represent the extent to which porpoise acoustic activity appeared to be altered during seismic surveys and is therefore akin to the maximum distance of detectable effect. In Section 5.4.5, we revisit these results with a view to estimating a corresponding EDR.

5.4.1.3. van Beest *et al.* (2018) - Responses of tagged porpoise to a mini-airgun

van Beest *et al.* (2018) investigated the responses of harbour porpoises in inner Danish waters to experimental exposures to a mini airgun in water depths of < 60 m. Five harbour porpoises were equipped with high-resolution Global Positioning System (GPS) tags and dive loggers to record their movements. These individuals were exposed to noise generated by a 10-$inch^3$ underwater airgun, which produced pulses at intervals of 2–3 seconds for a duration of 1 minute. The noise exposure occurred at distances of 420 to 690 m from the airgun. Based on previous studies, the noise was estimated to have a source level of SPL_{pk-pk} 216 dB re 1 µPa @ 1m, with the porpoises experiencing received levels of SEL (unweighted) ranging between 135–147 dB re 1 μPa^2s.

During the noise exposure, two of the five porpoises exhibited measurable responses. Due to the variable time lags between successive GPS locations at the time of exposure, the exposure ranges presented in the study accommodated a 50% error in distance. The authors expected the true location of the individuals during the exposures to be within a range and therefore these are provided in brackets below. Similarly, estimated received noise levels are provided in ranges.

Animals were exposed to the airgun at distances between 420 (210–630 m) to 690 m (345–1,035 m). One individual (ID3), exposed at distance of 420 m (210–630 m) from the source, moved rapidly away from the airgun. Given the closest proximity across all individuals exposed, the authors estimated that this individual also received the highest noise exposure level ($SPL_{pk\text{-}pk}$ 171 (168–177) dB re 1µPa). The second porpoise which exhibited behavioural response (ID5, including shorter and shallower dives) was exposed to the airgun at unknown distance and therefore authors could not estimate received noise levels (horizontal movement data was missing). The authors estimated that other porpoises, which did not show any behavioural response were exposed to noise levels between $SPL_{pk\text{-}pk}$ 168 (165–173) and 169 (166–174) dB re 1µPa. These noise-induced behaviours typically lasted for up to 8 hours, followed by a recovery period of around 24 hours. The remaining porpoises did not show any significant behavioural changes in response to the noise.

It is noted that values reported in this study do not meet the definition of an EDR as described in Section 2.2 and are not suitable for estimating a maximum spatial extent of effects or an EDR. The exposure occurred at a known maximum distance of 690 m (345–1,035 m) from the airgun, and the response of at least one individual suggested that disturbance effects extended beyond this range. Therefore, a general finding of the study is that at < 1 km range, a proportion of harbour porpoise subject to a short exposure to a mini airgun may show behavioural disturbance, including aversive movement.

5.4.1.4. Thompson *et al.* (2013) - Responses of porpoise to a small 2D survey

Thompson *et al.* (2013) reported findings from a 10-day 2D seismic survey conducted over a 200 km² area in the Moray Firth, north-east Scotland. The seismic survey employed a small array of total 470 in^3 volume with shots fired at intervals of 5–6 seconds. The $SPL_{pk\text{-}pk\ was}$ estimated as 242–253 dB re 1 µPa @ 1 m.

Noise levels and harbour porpoise activity in the area were monitored via an array of 49 PAM moorings (including C-PODs and 15 moorings with broadband recorders) deployed at distances from 1.6–61.8 km from the seismic vessel. Digital aerial surveys were also flown across the area before and during the survey to assess changes in the relative density of harbour porpoise.

From acoustic data, the study measured ‘waiting times,’ defined as the intervals between acoustic detections of porpoises, and explored these as a function of distance to the seismic vessel. The response variable was the ratio of the first waiting time following the start of airgun activity (the soft start) to a baseline waiting time at each site representing 100 randomly selected values from the week prior to the survey. This metric served as a proxy for porpoise displacement due to disturbance caused by the seismic survey, acknowledging that it could represent changes in presence of animals and/or acoustic activity.

The results indicated increased waiting times during seismic survey operations, with the magnitude of the effect diminishing with distance from the source. However, considerable variation across the data complicated efforts to determine the distance at which waiting times did not deviate from baseline levels. Even at close ranges to the seismic vessel, porpoise were detected again within a few hours of the start of airgun activation, while the survey continued. While the study did not provide sufficient data to estimate a deterrence function based on PAM data, a linear model fitted to digital aerial survey data showed a reduction in porpoise density during the survey within 10 km of the survey vessel and an increase at greater distances, though variability in these results was high. Calibrated noise measurements indicated that received noise levels the region 5–10 km from source varied between SPL_{pk-pk} 165–172 dB re 1 µPa, SEL_{SS} 145–151 dB re 1 µPa^{2}s and SPL_{rms} 148–155 dB re 1 µPa. The authors noted that these received noise levels within this range were comparable to those shown to elicit avoidance behaviour in captive porpoises exposed to airgun noise (Lucke *et al.* 2009). From these observations, Thompson *et al.* (2013) concluded that porpoises exhibited avoidance movements within 5–10 km of the airgun source.

Interpreting results for inferred response ranges

The coefficients of the transmission loss formula (source level, propagation loss coefficient, absorption coefficient) were provided for the SPL_{pk-pk} and SPL_{rms} in captions to Table 3 in the Thompson *et al.* (2013) publication. The equation was used to estimate the distance from the airgun at which the SPL_{pk-pk} 174 dB re 1 µPa (Lucke *et al.* 2009) and SPL_{rms} 160 dB re 1µPa (NOAA 2005) behavioural response thresholds were exceeded. These distances were assessed as 4.2 km and 3.2 km, respectively.

It is noted that values reported in this study do not meet the definition of an EDR as described in Section 2.2**.** Rather, these represent the distance at which porpoise density was predicted to be lower during seismic surveys than a pre-survey baseline period, which was supported by a pattern of reductions in the frequency of acoustic detections following the onset of airgun activity. Therefore, the reported 10 km is an approximate maximum distance of detectable effect. Additional analysis allowed to estimate the distances to two behavioural disturbance thresholds, with a maximum of 4.2 km based on SPL_{pk-pk} 174 dB re 1 µPa (Lucke *et al.* 2009). These results, as currently presented, were not considered suitable for estimation of an EDR (see Section 2.3).

5.4.1.5. Pirotta *et al.* (2014) - Responses of porpoise to a small 2D survey

Following the Thompson *et al.* (2013) study, Pirotta *et al.* (2014) used data from the same 2D survey of total 470 in^3 volume to assess the effect of seismic surveys on the occurrence of buzz inter-click intervals when porpoises were present (i.e. in hours in which at least one inter-click interval was detected). Calibrated noise measurements were made at 15 sites between 1.6 and 61.8 km from the seismic vessel. Buzz activity is considered a proxy measure of foraging activity among harbour porpoise. The analysis was divided into two main areas: the impact areas, which were exposed to seismic noise, and control areas, which were not exposed to the noise.

The study found a similar pattern of results to Thompson *et al.* (2013), in that short-term responses did not result in broad-scale displacement. However, a noticeable reduction in buzz activity was observed during the seismic survey, with a 15% decrease in buzz occurrence within the impact area. As the distance from the seismic source increased, the probability of detecting buzz activity also increased with buzz occurrence ranging from 0.15 at 0 km to 0.35 at 40 km from the vessel; however, it is noted that more distant sites showed higher buzz occurrence regardless of seismic survey activity. Additionally, the study found a correlation between noise levels and the likelihood of buzz activity. As noise levels increased, the probability of buzzing decreased. For example, buzzing activity dropped from 0.31 at noise levels of 130 dB re 1 µPa²s to just 0.07 at 165 dB re 1 µPa²s.

While a plot was provided of the probability of porpoise buzz occurrence as a function of distance to the noise source, this was not compared to a baseline level of occurrence at each monitoring site. As such, while results showed that porpoise buzz activity was lower at closer distances to the seismic survey vessel, no specific spatial extent of effects was reported. Further, a deterrence function cannot be developed and an EDR cannot be estimated from the results.

5.4.2. Noise measurement studies

5.4.2.1. Jiménez-Arranz *et al.* (2020) - Review of noise measurements of various airguns/a airgun arrays

In a review of noise generated by activities associated with the oil and gas industry, Jiménez-Arranz *et al.* (2020) provide a compilation of noise measurement data from multiple studies spanning mini-airguns through to large volume arrays. For the majority of studies included, a regression equation is provided for the best fit to the measurement data, which allows estimation of the distance to a specific sound level (see Table 2.1 in Jiménez-Arranz *et al.* 2020). As the vast majority of reported noise levels among the studies were in SPL_{rms}, we estimated the distance to the Level B harassment SPL_{rms} 160 dB re 1 µPa threshold (NOAA 2005).

Interpreting results for inferred response ranges

We filtered measurement studies to only include those where:

- A regression equation was provided.
- Information on the distance range over which noise measurements were collected was provided.
- The review authors had not flagged concerns over the validity of the results presented in the individual study.
- The water depth was < 75 m (i.e. representative of UK harbour porpoise SACs).

Where an individual study reported results for multiple shallow water depths (< 50 m), the deeper of the two was selected as more representative of the depths at which seismic surveys are likely to occur in harbour porpoise SACs.

Once distances to the SPL_{rms} 160 dB re 1 µPa threshold had been estimated, we removed any studies where the estimated range to the threshold was > 10% larger than the maximum measurement range, as such results were considered unreliable extrapolations. This resulted in a total of 38 estimated disturbance ranges, derived from 14 different individual studies (many studies reported results for multiple airgun configurations, or study environments). Disturbance ranges are summarised according to three different categories of airgun volume in Table 7 and Figure 3.

Table 7. Distances to SPL_{rms} 160 dB re 1 μPa threshold levels among selected studies reviewed in Jiménez-Arranz *et al.* (2020) estimated from their reported best fit regression equations, grouped by airgun size category.

Airgun size category	**N studies; reported distances**	**Water depth range (m)**	**Estimated distance to SPL_{rms} 160 dB re 1 μPa threshold (km)**		
			Range	**Median**	**90th percentile**
Mini airgun (≤ 12 in^3)	4; 5	15 - 45	0.2 - 0.6	0.5	0.6
Single airgun or array ≤ 1,200 in^3	11; 24	8 - 55	0.2 - 4.6	1.3	3.3
Airgun array > 1,200 in^3	6; 9	20 - 70	5.4 - 18.6	9.5	14.5

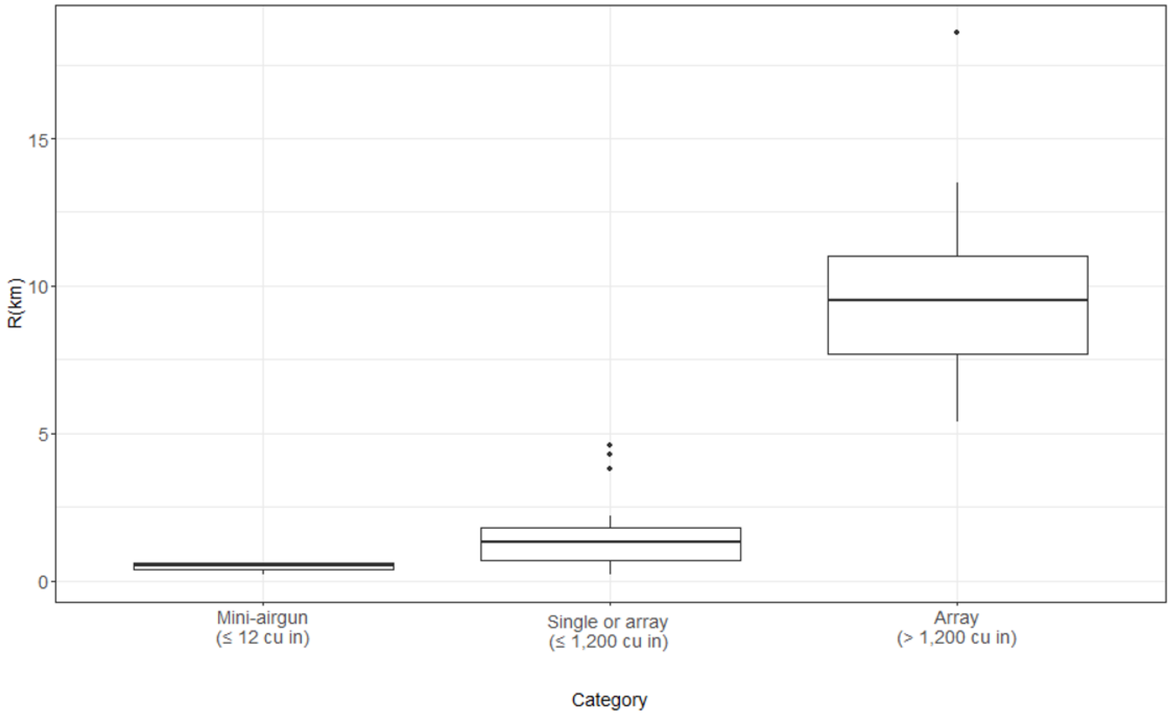

Figure 3. Boxplots of distances to SPL_{rms} 160 dB re 1 μPa threshold levels among selected studies reviewed in Jiménez-Arranz *et al.* (2020) estimated from their reported best fit regression equations, grouped by airgun size category. Horizontal black lines = median; box = interquartile range; whiskers = min and max values, excluding outliers; dots = outliers.

5.4.2.2. Hermannsen *et al.* (2015) - Single airguns in shallow water

Hermannsen *et al.* (2015) investigated the characteristics and propagation of airgun pulses in shallow water and their implications for small marine mammals. Data collection occurred in a uniform sandy-bottomed habitat with a water depth of 15 m (± 0.2 m) in Aarhus Bay, Denmark.

The seismic survey employed a single airgun with three volume settings: 10 in^3, 25 in^3, and 40 in^3. Airgun pulses were recorded at six distances between 6–1,300 m using calibrated hydrophones and acoustic data recorders. Source levels for the airgun @ 1m were estimated at SPL_{pk-pk} 212–221 dB re 1 µPa, SEL_{SS} 186–192 dB re µPa²s and SPL_{rms} 195–200 dB re 1 µPa (averaged over 125 ms duration), depending on airgun size and firing pressure. Sound level recordings at a range of 120 m indicates that received SPL_{pk-pk} ranged from 176–188 dB re 1 µPa, while SEL_{ss} ranged from 151–160 dB re 1 µPa²s, and SPL_{rms} ranged from 159–168 dB re µPa. Higher values were observed for airguns with larger volumes and higher pressures.

At a range of 1,300 m from the airgun, the recorded sound levels were approximately 60 dB lower, with SPL_{pk-pk} ranging from 152–167 dB re 1 µPa, SEL ranging from 123–133 dB re 1 µPa²s and SPL_{rms} ranging from 132–143 dB re 1 µPa. The recorded airgun pulses exhibited the highest energy at low frequencies, peak frequencies ranging from 5 to 90 Hz. Considerable energy was also detected at frequencies exceeding 10 kHz, even at a distance of 1,300 m, the farthest recording range in this study.

In the analysis of avoidance responses of harbour porpoises to pile-driving noise, the author cited Tougaard *et al.* (2015) and reaction thresholds between SPL_{rms} 141–149 dB re 1 µPa. The study suggested that porpoises could exhibit fleeing response at distances of several kilometres from even a single 40 in³ airgun, although no specific distances were presented.

Interpreting results for inferred response ranges

In this review we used the graphreader online tool to interpolate the distance to SEL 145 dB re 1 µPa²s (Lucke *et al.* 2009) using unweighted SELs for recorded broadband pulses from a 40 in³ airgun. A screenshot of Figure 5 in the Hermannsen *et al.* (2015) was uploaded to graphreader, and data points were manually marked on crosses representing unweighted SELs at high output pressure. The sampled curve data were exported as a CSV file, and the curve equation was used to calculate received levels at various distances. The resulting distance to the Lucke *et al.* (2009) 145 dB re 1 µPa²s threshold was estimated at approximately 1.6 km.

5.4.2.3. Seismic survey in Ionian Sea (Confidential, 2020b)

For this review, results were obtained from a noise measurement campaign associated with a seismic survey in the Ionian Sea (Confidential 2020b). The survey area covered water depths ranging from 750 to 1,200 m. The survey consisted of both 2D and 3D data acquisition methods. The 2D survey employed a single airgun source with a 5,000 in³ volume, while the 3D survey uses two airgun sources, each with a 3,500 in³ volume. Measurements were provided for a total of four days of survey, although the exact array configuration operating at any time was not specified. The study measured SPL_{rms} and SPL_{pk} levels at distances ranging from 7.2–47.4 km from the airguns.

Interpreting results for inferred response ranges

Raw acoustic measurements were provided by the data owners (Confidential 2020) and were plotted against distance from the seismic sound source. A line of best fit was added to each set of measurements using the transmission loss coefficients (aka regression equation) derived by the data owner. The lines of best fit were then used to identify the distance from the sound source at which the following behavioural thresholds were exceeded:

- SPL_{rms} 160 dB re 1 µPa ('Level B harassement', NOAA 2005); for this metric, the source level was adjusted by subtracting 20 dB from the SPL_{pk} source level, whilst keeping the transmission loss coefficient ($20*\log_{10}$(range)) and absorption coefficient (0.00025*range) the same as in the formula provided by the data owner for SPL_{pk}.
- SPL_{pk} 168 dB re 1 µPa (Lucke *et al.* 2009); see Appendix 1 for more details about how this threshold was derived.

To estimate disturbance ranges, the lines of best fit for each metric were used to identify the distance from the sound source at which the above thresholds were exceeded. This provided an estimated distance of 14.7 km within which the SPL_{pk} 168 dB re 1 μPa threshold was exceeded (Figure 4), and a distance of 4.9 km within which the SPL_{rms} 160 dB re 1 μPa threshold was exceeded (Figure 5). It is noted that while the fit to the SPL_{pk} was good, the fit extrapolated to SPL_{rms} measurements was poor at distances less than approx. 20 km and the threshold distance of 4.9 km is likely to be an over-estimate.

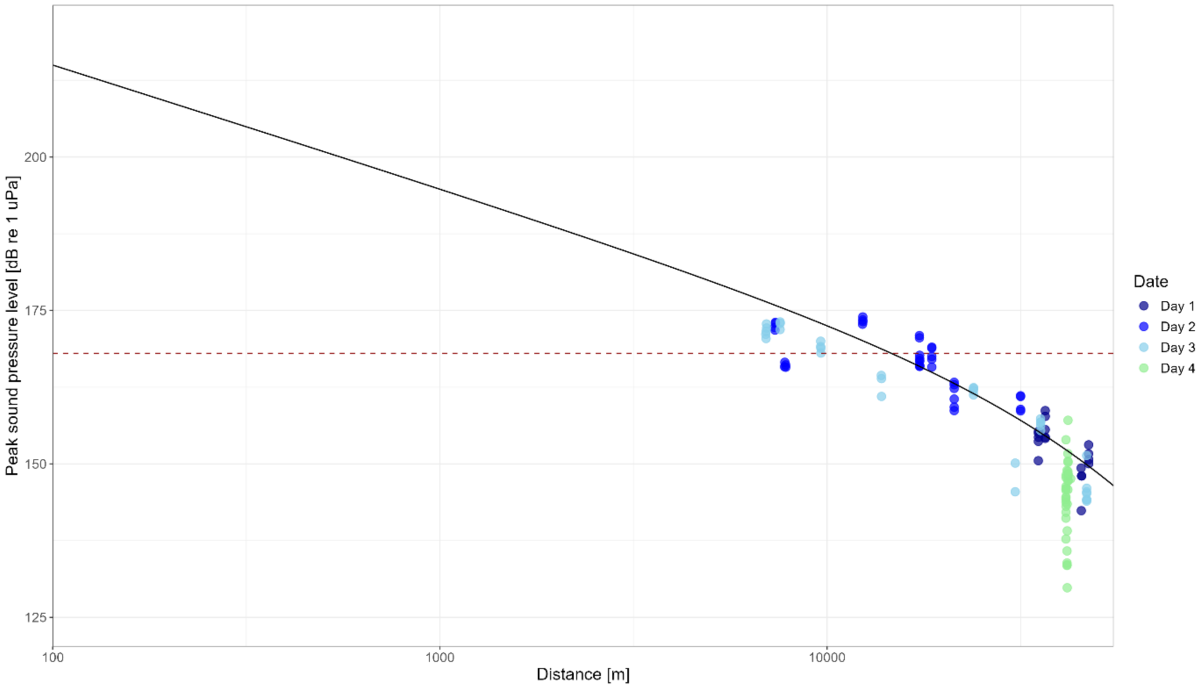

Figure 4. SPL_{pk} measured in the field (coloured dots by the date of the acoustic survey) and line of best fit (black solid line) for seismic airgun surveys in the Ionian Sea monitored from various distances relative to the sound source. The Lucke *et al.* (2009) threshold of SPL_{pk} 168 dB re 1 μPa (horizontal red dashed line) was exceeded by the fitted line at 14.7 km.

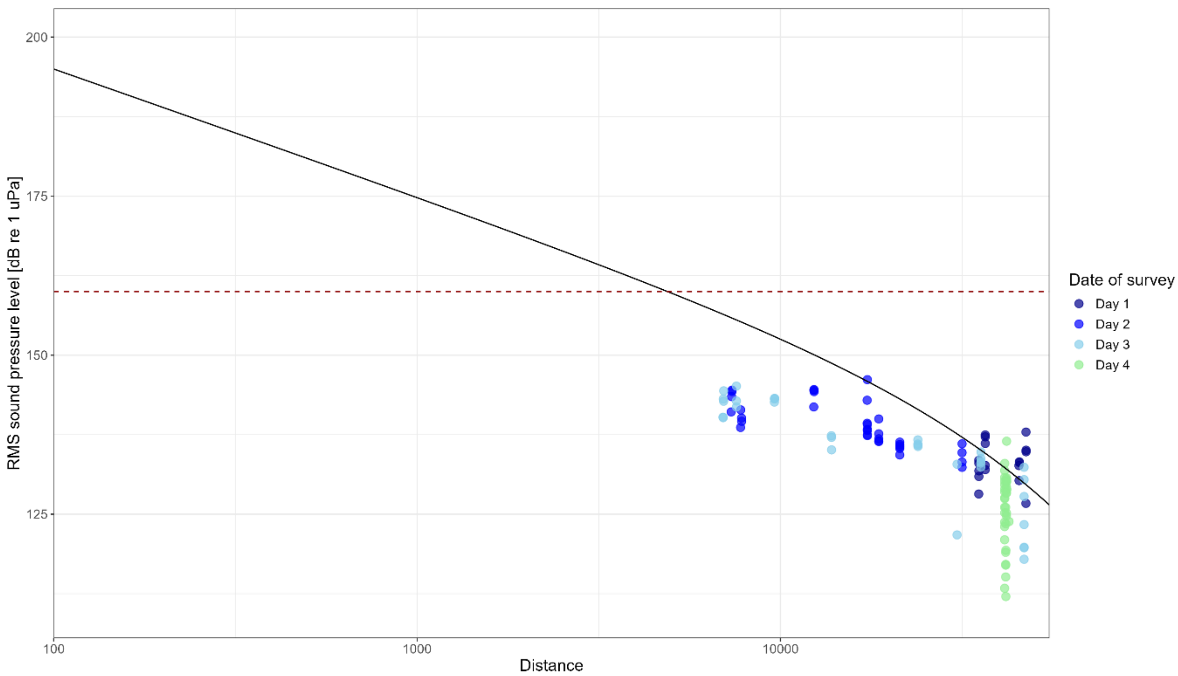

Figure 5. SPL_{rms} measured in the field (coloured dots by the date of the acoustic survey) and line of best fit (black solid line) for seismic airgun surveys in the Ionian Sea monitored from various distances relative to the sound source. The threshold of SPL_{rms} 160 dB re 1 µPa (horizontal red dashed line) was exceeded by the fitted line at 4.9 km.

5.4.3. Modelling studies

In the UK seismic surveys are mostly used by the offshore oil and gas industry. As such, all modelling studies presented in this section are based on the Appropriate Assessments (AA) in the form of the Habitat Regulations Assessments (HRA) found on the OPRED website.

5.4.3.1. Airgun arrays below 1,200 in^3

The AA for the BC41 Seismic Survey outlined surveys planned to take place in the North Sea, England over five days in July 2024 (OPRED 2024). The exact minimum and maximum depths at which the surveys were planned to take place within were not provided. Similarly, the exact equipment to be used was unspecified, but the airgun volume was provided as 160 in^3, with a source level of 245.5 dB re 1µPa and SPL_{pk-pk} 250.3 dB re 1µPa. Potential disturbances to marine mammals from the seismic survey have been estimated using the NMFS Level B harassment threshold of SPL_{rms} 160 dB re 1 µPa and the Tougaard (2016) threshold (authors do not specify whether they used SEL_{ss} 145 dB re 1 µPa^{2}s or SPL_{pk-pk} 130 dB re 1 µPa threshold, both reported in this publication). The resulting behavioural disturbance ranges are 3 km and 7 km, respectively for NMFS Level B harassment and the Tougaard (2016) threshold.

Another AA for the BP Endurance Field Integrated Site Survey (OPRED 2020a), outlines seismic surveys planned to take place in the North Sea, England. Similar to the BC41 project, the minimum and maximum depths were not provided. The equipment to be used was described as a 2D high-resolution (2D HR) seismic system with an airgun volume of 160 in^3. The peak frequency of the 2D HR survey was provided as 90 Hz with a source level of SPL_{pk} 245.5 dB re 1µPa and SPL_{pk-pk} 251 dB re 1µPa. The AA also included a 4D Test Line survey of a total volume of 320 in^3 (OPRED 2020a). The peak frequency of the 4D survey was described as 60 Hz with a source level of SPL_{pk} 251.5 dB re 1µPa and SPL_{pk-pk} 257.5 dB re 1µPa. The study estimated behavioural disturbance ranges based on 145 dB re 1 µPa criteria but did not provide a source of this threshold. The results from the modelling indicate that there is a risk of behavioural effects within the range of 5 km based on the use of the 160 in^3 2D HR survey and within the range of 8.5 km for 320 in^3 for the 4D Test Line survey.

The AA for the Hewett Seismic Survey outlined surveys to take place in the North Sea region of England over 130 days between June to October 2023 (OPRED 2023). The minimum and maximum depth at which surveys were planned to be conducted was not specified. The equipment to be used included a seismic survey system with a total volume of 585 in^3 and with a source level of SPL_{pk} 247 dB re 1µPa. Although modelling undertaken for this project is not explained in detail, behavioural disturbance range was estimated out to 1.5 km based on a threshold of SPL_{rms} 160 dB re 1 µPa.

These projects demonstrate the variations in seismic survey methodologies and their potential impact on marine life, with predicted behavioural response distances ranging from 1.5–8.5 km depending on the equipment (and associated source levels), modelling approach and metric.

5.4.3.2. Airgun arrays above 1,200 in^3

Spectrum Seismic Survey (4,000 in^3)

The AA for the Spectrum Seismic Survey project outlined the 3D seismic survey planned to take place in the North Sea region of England over 160 days between April and October 2019 (OPRED 2019). The exact equipment to be used was unspecified, but the airgun volume was 4,200 in^3, with a source level up to SPL_{pk} 257.0 dB re 1µPa. The study estimated behavioural disturbance ranges based on SPL_{rms} 160 dB re 1 µPa criteria with risk of behavioural effects to harbour porpoise up to approximately 12.4 km. However, the reports also highlights that based on another study (BEIS 2018) for a smaller airgun (3,000 in^3) but with larger SPL (SPL_{pk} 261 dB re 1 µPa), the behavioural disturbance to harbour porpoise can extend up to a distance of 34 km.

ION Seismic Surveys (3,390, 4,240 and 8,000 in^3)

The AAs for all ION seismic surveys outlined surveys to be carried out in the North Sea region of England. The exact minimum and maximum depths at which the surveys were supposed to take place were not recorded.

The AA for the ION 3D seismic survey outlined surveys planned to take place between April and October 2020 over 165 days (OPRED 2020b). The exact equipment to be used was unspecified, with three options provided as 3,070 in^3, 4,240 in^3 and 8,000 in^3. However, behavioural impact range was provided only for the 4,240 in^3 airgun (source level up to SPL_{pk} 260.0 dB re 1µPa). The study estimated behavioural disturbance at levels of 145 dB re 1 µPa but did not provide a source of this threshold. The details about the modelling are not provided in the report but the study indicated that there is a risk of behavioural effects to harbour porpoise up to 12 km.

The AA for the ION spectrum seismic survey outlined the surveys planned to take place in the southern North Sea, England over 165 days in between April and October 2021 (OPRED 2021b). The exact equipment to be used awas unspecified, but the airgun volume was described as 3,390 in^3, with a source level up to SPL_{pk} 255.0 dB re 1µPa and SEL 233 dB re 1µPa^2s. In the same AA, a seismic survey of a total volume of 8,000 in^3 was also modelled. The source level of 8,000 in^3 survey was described as SPL_{pk} 243 dB re 1µPa and SEL 223 dB re 1µPa^2s. This noise assessment defined mild behavioural disturbance at levels of SEL_{ss} 145 dB re 1 µPa^2s although it did not provide a source of this threshold. The details about the modelling are not provided in the report but the study indicated that there is a risk of mild behavioural effects to harbour porpoise up to 2.4 km for the 8,000 in^3 airgun array.

The AA for the ION MNSH Phase 2B Seismic Survey relates to another seismic survey planned to be conducted in the North Sea region of England over up to 51 days between September to November 2021 (OPRED 2021a). The airgun volume was described as 3,390 in^3, with a source level up to SPL_{pk} 254.0 dB re 1μPa. Similarly to previous OPRED report, the noise assessment defined mild behavioural disturbance at levels of SEL_{ss} 145 dB re 1 $μPa^2s$ but it did not provide a source of this threshold. The details about the modelling are not provided in the report but it indicated that there is a risk of behavioural effects to harbour porpoise up to 1.1 km.

It is not possible to scrutinise the underwater noise modelling technology based on the AA reports (the underwater noise modelling reports referenced in the respective AA were not available in the public domain), however, there seems to be a discrepancy between the results for different array volumes (Table 8). Overall, there does not appear to be a clear linear relationship between airgun volume and behavioural disturbance range. Additionally, modelling methodologies may significantly influence the reported impact distances.

Table 8. Summary of estimated effects ranges for various air gun arrays across ION seismic surveys.

Survey Name	Reference	Total volume (in^3)	Source Level (SPL_{pk})	Criteria	Behavioural response ranges
ION 3D	OPRED (2020b)	4,240 in^3	260.0 dB re 1μPa	SPL_{rms} 145 dB re 1 μPa	12 km
ION 3D	OPRED (2019, 2021b)	3,390 in^3	255.0 dB re 1μPa	SPL_{rms} 160 dB re 1 μPa	12.4 km
ION Spectrum	OPRED (2021b, 2021a)	8,000 in^3	243 dB re 1μPa	SEL_{ss} 145 dB re 1 $μPa^2s$	2.4 km
ION MNSH Phase 2B	OPRED (2021a)	3,390 in^3	254.0 dB re 1μPa	SEL_{ss} 145 dB re 1 $μPa^2s$	1.1 km

5.4.3.3. Modelling studies conclusion

The modelling studies described above present significant inconsistencies in estimating harbour porpoise disturbance ranges due to a variety of methodological and data limitations. One of the primary issues identified in the AA is lack clarity regarding the specific modelling methods used to estimate disturbance distances as well as uncertainties regarding the source and metric of used thresholds. The underwater noise modelling reports cross-referenced in some of these AA reports were not available in the public domain and without transparency in the modelling techniques, assumptions, and propagation loss calculations, the validity of the results cannot be assessed. The wide variation in results suggests potential discrepancies in the array design, propagation modelling and environmental conditions, which are not sufficiently explained in the reports which were available in the public domain. Given that these uncertainties undermine the reliability of noise modelling studies for determining accurate disturbance thresholds, these studies are not considered further in the current evidence review.

5.4.4. Tabulation of evidence relating to harbour porpoise response ranges from seismic (airgun) survey

In Table 9, we provide a tabulation of reviewed studies for seismic surveys, including features of the study areas (region, water depth), equipment characteristic (array volume, shot interval, equipment source level) and the spatial extent of effects. The empirical Pirotta *et al.* (2014) study, previously discussed in Section 5.4.1, was excluded from further review as it does not report a spatial extent of effects.

Table 9. Summary of evidence relating to harbour porpoise response ranges from seismic surveys (the spatial extent of effects include ranges reported/estimated within cited studies as well as inferred via additional analyses). N/A = Not Applicable; "-" = Not Available.

Study		**Region (Country)**	**Water depth (m)**	**Airgun array volume (in³)**	**Shot interval (s)**	**Survey duration (days)**	**Source level**	**Reported and estimated spatial extent of effect and description**
Empirical response studies	Stone (2024b)	UK-wide	< 1,000	Multiple, distance provided for > 1,200 in³	Multiple	Multiple	SPL_{pk-pk} 262 dB re 1 µPa	**1.1 km =** Mean closest distance of approach of harbour porpoise to airguns when firing.
	Sarnocińska *et al.* (2020)	North Sea (DK)	36–49	3,570	10	103	Not provided	**8–12 km =** Maximum distance within which different porpoise vocalisation metrics showed a negative correlation with distance to source.
	van Beest *et al.* (2018)	Skagerrak and Belt Sea (DK)	< 60	10	2–3	Experimental exposures of 1 minute	SPL_{pk-pk} 216 dB re 1 µPa	**0.42 km (0.21–0.63 km) =** Distance at which one harbour porpoise exhibited a measurable response (fleeing). **< 1 km =** Distance at which a proportion of harbour porpoise individuals subject to a short exposure to a mini airgun may show behavioural disturbance.

Study		Region (Country)	Water depth (m)	Airgun array volume (in³)	Shot interval (s)	Survey duration (days)	Source level	Reported and estimated spatial extent of effect and description
Empirical response studies	Thompson *et al.* (2013)	Moray Firth (UK)	50	470	5-6	10	SPL_{pk-pk} 242–253 dB re 1 µPa	**10 km =** Decrease in relative density of porpoises up to this distance and increase at greater distances. **4,15 km =** Distance to SPL_{pk-pk} 174 dB re 1 µPa threshold **3.194 km =** Distance to SPL_{rms} 160 dB re 1µPa threshold
Noise measurement studies	Jiménez-Arranz *et al.* (2020)	Various	15–45	≤ 12 in³	Various	Various	NA	**0.5, 0.6 km =** Median and maximum estimated distance to SPL_{rms} 160 dB re 1µPa threshold
			8–55	≤ 1,200 in³ (20–880 in³)				**1.3, 4.6 km =** Median and maximum estimated distance to SPL_{rms} 160 dB re 1µPa threshold
			20–70	> 1,200 in³ (1,709–4,380 in³)				**9.5, 18.6 km =** Median and maximum estimated distance to SPL_{rms} 160 dB re 1µPa threshold

Study		Region (Country)	Water depth (m)	Airgun array volume (in^3)	Shot interval (s)	Survey duration (days)	Source level	Reported and estimated spatial extent of effect and description
Noise measurement studies	Hermannsen *et al.* (2015)	Aarhus Bay (DK)	15	40	10	-	SPL_{pk-pk} 212–221 dB re 1 µPa	**1.6 km =** Distance to SEL 145 dB re 1 µPa^{2}s threshold
	Confidential (2020b)	Ionian Sea (GR)	750–1,200	3,500–7,000	10 s	Not provided	SPL_{pk-pk} 255 dB re 1 µPa	**14.7 km =** Distance to SPL_{pk} 168 dB re 1 µPa threshold **4.9 km =** Distance to SPL_{rms} 160 dB re 1µPa threshold
Noise modelling studies	OPRED (2024)	North Sea (UK)	-	160	-	5	SPL_{pk} 255.5 dB re 1µPa	**3 km =** Distance to SPL_{rms} 160 dB re 1µPa threshold
	OPRED (2020a)	North Sea (UK)	-	160	-	-	SPL_{pk} 245.5 dB re 1µPa	**5 km =** Distance to SEL 145 dB re 1 µPa^{2}s threshold
				320			SPL_{pk} 251.5 dB re 1µPa	**8.5 km =** Distance to SEL 145 dB re 1 µPa^{2}s threshold
	OPRED (2023)	North Sea (UK)	-	585	-	130	SPL_{pk} 247 dB re 1µPa	**1.5 km =** Distance to SPL_{rms} 160 dB re 1µPa threshold
	OPRED (2019)	North Sea (UK)	-	4,200	-	160	SPL_{pk} 257 dB re 1µPa	**12.4 km =** Distance to SPL_{rms} 160 dB re 1µPa threshold

Study		Region (Country)	Water depth (m)	Airgun array volume (in^3)	Shot interval (s)	Survey duration (days)	Source level	Reported and estimated spatial extent of effect and description
Noise modelling studies	OPRED (2020b)	North Sea (UK)	-	4,240	-	165	SPL_{pk} 260 dB re 1μPa	**12.0 km =** Distance to SEL 145 dB re 1 μPa^{2}s threshold
	OPRED (2021b)	North Sea (UK)	-	3,390–8,000	-	165	SPL_{pk} 255 dB re 1μPa	**2.4 km =** Distance to SEL 145 dB re 1 μPa^{2}s threshold
	OPRED (2021a)	North Sea (UK)	-	3,390	-	51	SPL_{pk} 254 dB re 1μPa	**1.1 km =** Distance to SEL 145 dB re 1 μPa^{2}s threshold

5.4.5. Estimation of EDRs from existing data

The plots of predicted effect of distance to source vessel with an active gun presented in Sarnocińska *et al.* (2020), when interpreted as a deterrence function (i.e. probability of response is assumed to be the proportional change in three different indicators), allow for an approximate estimation of an EDR according to the definition of Tougaard *et al.* (2013).

At the smallest spatiotemporal scale, porpoise acoustic activity exhibited a non-linear relationship with distance from the seismic source vessel. All three indicators of porpoise acoustic activity (CPM, PPM, and BPM/PPM, explained in Section 5.4.1.2) demonstrated a dose-response effect, with the lowest activity observed nearest to the source vessel.

Values from the plots with the predicted effect of distance to source vessel with an active gun (Figures 3A, 3B and 3C (left) in Sarnocińska *et al.* 2020) were extracted using the graphreader online tool. For each indicator of porpoise acoustic activity, the onset of the plateau at greater distances from the vessel was used as the reference point for the baseline, if activity remains relatively constant beyond this point. The example is provided in Figure 6 for the number of porpoise clicks (CPM) indicator where the plateau started at a distance of approximately 16 km.

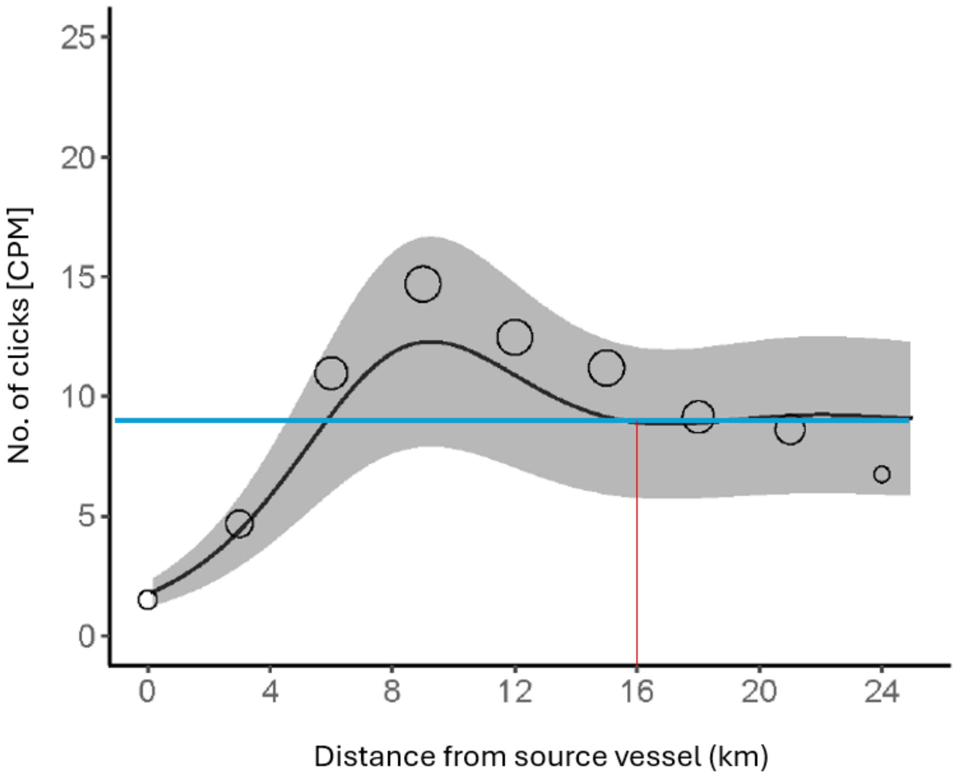

Figure 6. Predicted effect of distance to source vessel with an active airgun (3,570 in^3) using the number of porpoise clicks (CPM) indicator from Sarnocińska *et al.* (2020). Blue line represents the point at which the effects appear to plateau, with red line at 16 km indicating where the plateau started.

The sampled curves for the predicted effect as well as baseline were exported as a CSV file and, for 100 m increments of distance, the number of disturbed vs non-disturbed porpoises was estimated within the effect range (assuming a uniform density of animals). The distance at which the number of porpoises disturbed was equal to non-disturbed was then estimated using the sampled curves for three indicators and presented as an EDR in Table 10. The resulting EDRs across the three harbour porpoise response indicators are consistent, ranging from 3.9–4.3 km. Additionally, both the probability of response and the distance at which there is a 50% probability of response are comparable.

It is noted that the aforementioned exercise was also repeated for the PPM results, but assuming a 'baseline' at the peak value of PPM, at approximately 12 km. This more conservative approach, assuming a higher baseline than was apparent at more distant, assumed reference locations, resulted in an EDR of 7.8 km, where the p(response) was 0.174. The estimate of 7.8 km is considered to be unrealistically high, but it presented here for comparative purposes with other interpretations of the spatial extent of effects from Sarnocińska *et al.* (2020).

Table 10. Estimated EDRs from Sarnocińska *et al.* (2020).

Harbour porpoise response indicator	R50[1] (km)	EDR (km)	*p(response)* at EDR
Number of clicks per minute (CPM)	3.7	3.9	0.482
Porpoise positive minutes (PPM)	3.9	4.3	0.436
Ratio of minutes with high repetition rate click trains called buzzes to minutes with any click train calculated per hour (BPM/PPM)	3.8	4.0	0.462

[1] The distance at which there is a 50% proxy p(response).

5.4.6. Evidence scores

Detailed methods and results of the evidence scoring exercise are presented in Appendix 2, Table 28; a summary is provided here. Four empirical response studies, three noise measurement (including one review encompassing 14 individual studies) studies and seven noise modelling studies were reviewed and assigned scores based on specific evaluation criteria (Figure 7, Appendix 2).

All studies were assigned an initial score of 10, with penalties subsequently applied as appropriate for criteria including: the study type, the study's suitability for estimating an EDR (empirical response studies only); the relevance of the species studied, the relevance of the study area to the UK (i.e. water depth); the relevance of the activity to current and near-future UK practices; and, other study limitations (e.g. limited sample sizes, potential for biases).

For **mini airguns (≤ 12 in^3)**, the single relevant empirical study received a score of 5. There were two relevant noise measurement studies (albeit with one being a review of multiple studies) which received scores ranging from 5 to 6, with an average score of 5.5. No modelling studies specific to mini airguns were reviewed. The overall average across the two study type scores is 5.0.

For **airgun arrays of ≤ 1,200 in^3** (excluding mini airguns), the single relevant empirical study received a score of 7. There were two relevant noise measurement studies (albeit with one being a review of multiple studies) which received scores ranging from 5 to 6, with an average score of 5.5. The score assigned to all three relevant modelling studies was 3.0. The overall average across the three study type scores is 5.2.

For **airgun arrays of > 1,200 in^3**, the two relevant empirical response studies received scores of 6 and 8, averaging 7. There were two relevant noise measurement studies (albeit with one being a review of multiple studies) which received scores ranging from 5 to 6, with an average score of 5.5. The score assigned to all four relevant modelling studies was 3.0. The overall average across the three study type scores is 5.2.

5.5. Recommending default EDRs

5.5.1. Overview: evidence base

Among the evidence reviewed, only one study presented data from which an EDR could be estimated (Sarnocińska *et al.* 2020). Reported and estimated effects ranges among the seven empirical and noise measurement studies reviewed for seismic surveys are summarised in Table 11, additionally separated by airgun volume. Given the large discrepancy between distances reported in the six noise modelling studies discussed in Section 5.4.3**,** the modelling studies were not considered as appropriate for estimating reliable effect ranges and are not considered in this section.

Table 11. Summary of reported and estimated effects ranges and estimated EDRs for seismic surveys among the seven empirical and noise measurement studies reviewed.

Category	Reported effects range, km (n= number of studies)	Estimated EDR, km (n= number of studies)
All seismic (airgun arrays) surveys	0.2–18.6 km (7)	3.9–4.3 km[2] (1)
Mini airguns with a volume ≤ 12 in^3	0.2–0.6 km (3)	N/A
Arrays (or single airguns) with a total volume ≤ 1,200[1] in^3	1.3–10 km (3)	N/A
Arrays with a total volume > 1,200 in^3	0.5–18.6 km (4)	3.9–4.3 km[2] (1)

[1] ≤1,200 in^3 but > 12 in^3. [2] As described in Section 5.4.5, under highly precautionary alternative assumptions of the baseline level of porpoise activity, an EDR of 7.8 km was estimated.

Inclusion of noise measurement studies, particularly the review of Jiménez-Arranz *et al.* (2020), suggests the potential for larger response ranges to large compared to small array surveys, with the median / maximum ranges for large and small arrays being 9.5 / 18.6 km and 1.3 / 4.6 km, respectively. However, the two highest scoring empirical response studies do not support such a split. Both studies reported evidence that porpoise occurrence approximately > 10 km from the source did not appear to be reduced over apparent undisturbed conditions. The maximum estimated EDR from Sarnocińska *et al.* (2020) of 4.3 km (or 7.8 km given highly conservative assumptions) reflects that the EDR will be less than the maximum reported extent of effects. While an EDR could not be estimated for Thompson *et al.* (2013), it can be assumed that any such EDR would be less than the reported 10 km maximum extent of detectable effects.

With two highest scoring empirical response studies (7 to 8 points out of 10) that measured harbour porpoise responses at larger distances (Thompson *et al.* 2013; Sarnocińska *et al.* 2020) applying different study designs and analytical approaches, and covering surveys of very different temporal extents, direct comparisons are challenging. For example, the shorter 10-day duration of the 2D survey studied in Thompson *et al.* (2013) showed evidence of lessening responses over time, and it is possible that inclusion of data across many months in the 3D survey studied in Sarnocińska *et al.* (2020) may have contributed to smaller reported responses than might be expected in the initial days of a survey. Also, the influence of the environment, other activities in the area and prior exposure is unknown, noting that the survey in Sarnocińska *et al.* (2020) was in an area of multiple offshore platforms, with a majority of PAM stations located within 100–200 m of platforms. It is possible that responses to the seismic survey were influenced by attractive effects of these platforms (e.g. Delefosse *et al.* 2018; Fernandez-Betelu *et al.* 2022).

Although source levels for some studies are unknown, the data presented in Table 9 may suggest a positive correlation between the source level and the spatial extent of impacts. However, the results of empirical response studies should not be compared like-for-like due to different study designs. For example, van Beest *et al.* (2018) studied several tagged harbour porpoises at limited distance to the sound source (approx. 1 km) whilst Thompson *et al.* (2013) used differences in acoustic activity of unknown number of animals as a proxy for changes in density at ranges up to approximately 60 km from the survey vessel. Similarly, different thresholds were applied to underwater noise modelling studies and distances reported are not directly comparable between SPL_{rms} 160 dB re 1 µPa and SPL_{pk} 168 dB re 1 µPa. Literature to date suggest that other factors influencing the noise output include airgun design such as bandwidth, how airguns are organised in the array and how airguns are synchronised during the activation (GAMeON 2022, 2023).

There was considerable overlap between estimated distances to behavioural response thresholds from measurement studies and the responses reported in empirical studies, albeit with wide variability within the categories for small and large arrays. While the measurement studies add support to the overall assertion that an EDR is likely to fall within 10 km of small or large seismic airgun sources, there is considerable uncertainty over the applicability of the broadband SPL_{rms} 160 dB re 1 µPa threshold to harbour porpoises exposed to a low frequency dominated source such as seismic airgun surveys. van Beest *et al.* (2018) showed obvious behavioural responses, including aversive movement, to a short exposure to a mini airgun at < 1 km distance. Such responses were only reported in a proportion of the small number of individuals exposed and noise measurement data suggest that the response ranges of harbour porpoise to mini airguns is likely to be well-within the current recommended EDR of 5 km.

5.5.2. Recommended default EDRs

Recommended default EDRs are presented below. These follow consideration of all the evidence reviewed in the current study, including reported effects ranges and estimated EDRs, but also the limitations and relevance of specific evidence.

For seismic surveys of airgun arrays of any size > 12 in^3, an EDR of 5 - 10 km is recommended.

- The 5–10 km range reflects uncertainty among the results of empirical response studies. A single best precautionary estimate would be 8 km, reflecting the results of Thompson *et al.* (2013) and encompassing the largest estimated EDR from Sarnocińska *et al.* (2020) under highly precautionary assumptions. These two studies relate to airgun array volumes of 470 and 3,570 in^3 and, therefore, cover a wide range of potential airgun volumes. Nonetheless, should airgun arrays substantially larger and/or louder than these be proposed, an EDR with additional precaution may be appropriate.

- This range is well-supported by evidence from both empirical response and noise measurement studies which received scores between 7–8 and 5–6, respectively.
- Noise measurement studies generally support a gradient approach to assigning an EDR within this range according to airgun array volume; however, the evidence from empirical response studies is currently too limited to support such an approach.

For mini airguns of ≤ 12 in^3, an EDR of < 5 km is recommended, which approximately aligns with those of other high-resolution seismic sources (e.g. sparkers, boomers)

- It is noted that the empirical evidence base for mini airguns is currently inadequate to inform an EDR. The recommended EDR is supported by evidence from noise measurement studies, which received average score of 5 out of 10.
- Relying on noise measurement studies alone suggests an effect range not exceeding 1 km; however, at such distances the potential effects of disturbance arising from the vessel itself begin to become a factor, and so a precautionary EDR in the range of > 1 km and < 5 km is considered appropriate.

6. SBP and USBL

6.1. Description of activity

Sub-bottom profilers (SBPs) encompass a range of acoustic sources which are designed to collect information on the characteristics of strata below the seabed (Hartley Anderson Ltd 2020). These acoustic signals can penetrate the seabed to a range of depths, offering vertical resolutions between a few centimetres and a few meters. SBPs are categorised based on their signal type, frequency, source level, and directionality. These characteristics determine their application and performance in surveying seabed strata.

In this evidence review, SBP types will be categorised as either pulsed-waveform sources (sparker and boomer) and periodic waveform sources (pinger, chirper and parametric). The SBPs and other high-resolution geophysical sources (e.g. side-scan sonar, SSS) are often used in tandem with USBL acoustic positioning systems and therefore the potential impacts as a result of USBL use are also considered in this review. USBL acoustic positioning systems are periodic waveform sources.

It should be noted that mini airguns ≤ 12 in^3 are commonly used alongside other equipment as part of high-resolution geophysical surveys and that their current recommended EDR aligns with that of SBPs. This source is covered in the seismic airgun survey Section 5.

In the sections below, we draw upon the reviews of Hartley Anderson Ltd (2020), Jiménez-Arranz *et al.* (2020) and experiments of Crocker *et al.* (2019) for details of SBP equipment.

6.1.1. Pulsed waveform SBP sources

6.1.1.1. Sparker SBPs

Sparker SBPs are small seismic sources that produce a broadband pulsed waveform with a rapid rise time of approximately 1 millisecond. While the initial peak pressure is reached quickly, subsequent oscillations caused by the expansion and collapse of a steam bubble can extend the signal duration to around 10 milliseconds. These devices operate over a frequency range of approximately 100 Hz to 5 kHz, with most energy concentrated between 200 Hz and 3 kHz, peaking around 1 kHz. Their source levels typically range from SPL_{pk} 215–225 dB re 1 µPa @ 1m with maximum calibrated source level of SPL_{pk} 255 dB re 1µ Pa @ 1m. Sparkers are nearly omnidirectional, with energy strongest at 90 degrees from vertical. They are most commonly used for high-resolution geophysical surveys, achieving seabed penetration depths of several hundred meters below the seabed.

6.1.1.2. Boomer SBPs

Boomer SBPs utilise an electromechanical system to generate a broadband pulsed waveform with a short duration, typically between 0.5 and 1 millisecond. Their frequency range extends from approximately 100 Hz to 15 kHz, with peak energy around 1 kHz and most energy distributed between 200 Hz and 8 kHz. Source levels for boomers typically fall between SPL_{pk} 205–215 dB re 1 µPa @ 1m. These devices exhibit beam widths ranging from 46–90 degrees at -3 dB, with a typical value of approximately 75 degrees. Boomer SBPs are commonly employed in high-resolution geophysical surveys, with a maximum seabed penetration depth of about 100 m.

6.1.2. Periodic waveform SBP sources

6.1.2.1. Pinger SBP

Pinger SBPs rely on a transducer to emit controlled pulses at a single frequency. The signal duration can be configured between 0.5 and 30 milliseconds, and frequencies range from 1–40 kHz, although most applications use frequencies between 2–15 kHz. Manufacturer data suggests source levels of approximately 214 dB re 1 µPa @ 1m. Directionality depends on frequency, with beam widths of 55 degrees at 3.5 kHz, narrowing at higher frequencies. Seabed penetration depths range from a few meters to about 50 m, with vertical resolutions of approximately 10 cm.

6.1.2.2. Chirp SBPs

Chirp SBPs generate a frequency-modulated signal, sweeping across a selectable frequency band during a pulse that typically lasts between 5–40 milliseconds. Manufacturer specifications indicate bandwidths of 5–20 kHz, although the measurements showed narrower bandwidth of 2–13 kHz. Source levels for chirpers typically range from 185 to 215 dB re 1 µPa @ 1m. Their beam widths vary from 36–80 degrees at -3 dB and 80–153 degrees at -10dB. The beam can be narrower for higher frequency signals. Chirp SBPs are highly versatile and configurable, making them suitable for a wide range of high-resolution geophysical surveys. Depending on the sediment type, they can achieve seabed penetration depths of up to 100 m or more, with vertical resolutions finer than 10 cm.

6.1.2.3. Parametric (non-linear) SBPs

Parametric SBPs use a transducer to emit two high-frequency primary signals that interact non-linearly during propagation to produce a secondary low-frequency signal. The primary signals are typically in the range of 85–115 kHz, while the secondary signals are generated between 4 and 15 kHz. The source levels of the primary signals range from SPL_{rms} 238–247 dB re 1 µPa @ 1m, while secondary signals range from SPL_{rms} 200 - 206 dB re 1 µPa @ 1m. Parametric SBPs have extremely narrow beam widths, generally less than 5 degrees, with typical values around 3–4 degrees at -3 dB. This narrow focus allows for precise data collection but limits seabed coverage per survey line. These systems are capable of penetrating up to 200 m below the seabed with vertical resolutions as fine as 5 cm. They are particularly suitable for precision surveys in deep or complex sediment environments.

6.1.3. USBL

USBL acoustic positioning systems operate by emitting acoustic signals from a transceiver mounted on a surface vessel, which are then received by a transponder located on a subsea target, such as a remotely operated vehicle. The transponder responds by sending an acoustic signal back to the transceiver. The system measures the time delay between transmission and reception to calculate the range, and the angle of arrival to determine the bearing, thereby computing the target's position relative to the vessel.

There are a number of USBLs available on the market and based on a range of manufacturer specifications, the system can operate within a frequency band where transmission spans from 17–34 kHz. Manufacturer-reported source levels are generally $SPL_{rms} < 200$ but up to 206 dB re 1µPa @ 1m.

6.2. Current recommended EDRs

The SAC noise guidance (JNCC 2020) recommends an EDR of 5 km for high-resolution geophysical surveys (HRGS). This encompasses a variety of HRGS sources, ranging from lower-frequency boomer and sparker SBPs (see Section 6.1.1) to pinger and chirp SBPs (see Section 6.1.2). The guidance does not reference specific studies on porpoise responses to SBP to support this EDR. Instead, the 5 km value is a precautionary value based on the expected deterrence effects of HRGS sources being less extensive than those caused by seismic (airgun array) surveys. This assumption relies on anticipated lower noise levels (and the highly directional nature of most of these surveys) derived from available HRGS source level measurements and modelling studies. The only supporting literature cited in the guidance involves test tank source characterizations (including source levels, frequency ranges and directionality) of various HRGS sources, as documented in studies commissioned by the US Bureau of Ocean and Energy Management (BOEM) (Crocker & Fratantonio 2016; Crocker *et al.* 2019).

As for seismic surveys, SBP surveys comprise a moving sound source and the area of potential disturbance will vary depending on the location of the survey in relation to the SAC, how many line turns, etc. The MNR tool currently applies a daily disturbance footprint of 256 km^2 for planned SBP surveys, which was taken from estimated maximum daily area disturbed for the proposed geophysical surveys at Dogger and Sofia OWFs within the Southern North Sea SAC, which were the largest estimated daily disturbed footprint attributed to sub bottom profilers in published HRAs when reviewed for the ION Southern North Sea Seismic Survey 2021 (JNCC 2023a). However, the aim is for the daily disturbance footprint to be appropriately assessed using project-specific information on the average transect line length per day to which the EDR is applied (JNCC, *pers. comm.)*.

There is currently no EDR recommended specifically for USBL (JNCC 2023a).

6.3. Approach to evidence review

The overall approach to the evidence review is described in Section 2. Due to the near absence of empirical studies of harbour porpoise responses to SBP and USBL noise sources, the review is dominated by examining:

(i) studies reporting on noise levels measured during SBP and USBL surveys, and

(ii) studies undertaking modelling to estimating noise levels from SBP and USBL. Where results allow, for each of these two types of studies, ranges to the following proposed behavioural disturbance thresholds are reported:

- SEL 145 dB re 1 μPa^2s / SPL_{pk-pk} 174 dB re 1 μPa (unweighted) aversive behavioural reactions (Lucke *et al.* 2009) - adjusted to SPL_{pk} 168 dB.
- SPL_{rms} 160 dB re 1 μPa ('Level B harassement', NOAA 2005).
- Alternative thresholds as reported in individual studies (see below).

One study (Confidential 2023) reported the distance to a VHF-weighted SPL_{rms} 103 dB re 1 μPa threshold proposed by Tougaard (2021) following a review of empirical response data from piling. An additional study (Pace *et al.* 2021) reported the distance to a VHF-weighted SPL_{rms} 100 dB re 1 μPa threshold; the study did not specify the basis for this threshold, but it is close to that proposed by Tougaard (2021). One of the noise measurement studies (OSC 2025) also provided distances to the TTS-onset thresholds presented in Southall *et al.* (2019). This study was used as it also reported a distance at which the noise was not detectable above ambient noise.

As described in Section 2.4, where behavioural response ranges are not explicitly reported in studies we estimate these (where possible) from data or plots presented in reports, using the graphreader online tool to extract values from relevant plots. For studies where such analyses were carried out, this is indicated under the subheader *"Interpreting results for inferred response ranges".*

6.4. Evidence

In Section 6.4.1, we provide summary reviews of relevant empirical, measurement and modelling studies identified in our review for SBP. The relevant noise measurement and modelling studies associated with the USBL are provided in Section 6.4.2.

In Section 6.4.3 we provide a tabulation of all evidence reviewed in the current study for these noise sources, including specific features of the activities (e.g. region, water depth, SBP type) and the reported spatial extent of deterrence effects / distance to threshold levels. Results of the evidence scoring exercise for SBPs and USBL is provided in Section 6.4.5.

Exclusions

We do not review evidence relating exclusively to source characterisation experiments in test tanks (Crocker *et al.* 2019) as these do not provide information on transmission loss or results from which distances to specific noise levels can be estimated. We also do not review the assessment of acoustic survey sources provided by Ruppel *et al.* (2022), which includes elements of both noise measurement and modelling studies; however, this study is considered in Section 6.5.1 when summarising the overall evidence base.

6.4.1. Sub-bottom profilers

6.4.1.1. Empirical response studies

Stone (2024b) - Responses of porpoise to Chirp SBPs

Stone (2024b) investigated the impacts of geophysical surveys on marine mammals from a review of visual and acoustic detection data collected from the source vessel during marine mammal mitigation (details of this study are provided in Section 5.4.1.1). Limited results are provided specifically for chirp and pinger SBPs as the sample sizes were too small to explore responses for anything other than “all cetaceans combined”. Median detection rates were significantly lower when a pinger SBP was active (median detection rate per hour = zero) compared to when not active (median detection rate per hour = 0.74), but not for a chirp SBP. For chirp SBPs, data allowed an assessment for the closest approach distances to source vessels: the closest approach distance was significantly larger when a chirp SBP was active (2,000 m) compared to not active (165 m).

It is noted that values reported in this study do not meet the definition of an EDR as described in Section 2.2 and are not suitable for estimating a maximum spatial extent of effects or an EDR. The analysis in Stone (2024b) suggested that cetaceans react aversively to noise from pinger and chirper, however, distances were only reported for chirper. Therefore, a general finding of the study is that cetaceans, including harbour porpoise, appear to show an average minimum avoidance range of 2.0 km from active chirp SBPs.

Veneruso (2024) - Boomer SBP survey, North Wales, UK

Veneruso (2024) investigated fine scale spatio-temporal harbour porpoise distribution within the tidal energy zone is summers of 2017 and 2018. The study area was located off Holy Island, Wales (coastal Irish Sea) in a mean water depth of approximately 38 m. During the

PAM deployment in 2017, a research SBP survey was conducted over five days in the study area, and an analysis was conducted to model the effect of the survey on porpoise detections. The SBP survey took place aboard the *RV Prince Madog*, a 35 m research vessel operated by Bangor University. The source was a three-plate boomer SBP (Applied Acoustics S-Boom DC SBP) with two hydrophone streamers. The SBP emitted 10 kHz sound pulses with a maximum energy of 500J, producing up to 4 pings per second, with a reported source level of SPL_{pk} 210 dB re 1 µPa @ 1 m (Crocker *et al.* 2019). No data were presented on detection of acoustic signals from the boomer SBP at PAM sensors, so received levels were unknown. The use of additional acoustic survey equipment was not reported; however, it is noted that the *RV Prince Madog* is equipped with MBES and a scientific single-beam echosounder. Although the Veneruso (2024) do not indicate their use, it is common practice for HRGS to involve the simultaneous operation of an MBES and a SBP.

Continuous acoustic data were collected by an array of seven broadband recorders (SoundTraps) with a high frequency click detector to record the presence of harbour porpoise. Recorders were deployed across an area entirely overlapping the SBP survey area, albeit covering only a small proportion in its east; recorders were spaced between 500–750 m apart with a maximum distance between any two recorders of approximately 2 km. Distance between survey effort and PAM moorings was between approximately 0–9 km, although a majority of effort took place closer to the PAM moorings at distances of approximately 0–6 km.

Analysis of the acoustic data showed a significant reduction in porpoise detections coinciding with the SBP survey. Prior to the survey, daily porpoise detection rates across sites averaged 27.3% PP15M (porpoise-positive 15-minute intervals). Following the start of the survey, this rate dropped to 13.5% PP15M. Lower detection rates persisted until the end of the monitoring effort up to five days after the survey ended, albeit with some potential signs of recovery were towards the end of the recording period.

No attempt was made to model changes in detection rates as a function of distance to the survey vessel, so very limited inference can be made on porpoise responses at a sufficiently fine spatio-temporal scale to assess the spatial extent of effects. However, results demonstrated a significant reduction in porpoise acoustic activity (of approximately 50%), concurrent with a boomer SBP survey located between 0–9 km from the monitored area. These results, as currently presented, were not considered suitable for estimation of an EDR.

6.4.1.2. Noise measurement studies

Pace *et al.* (2021) - Sparker, parametric SBP, USBL, southern North Sea

Pace *et al.* (2021) reported on the results of a sound source characterisation study for a sparker, parametric SBP and USBL. Results relating to USBL are provided in Section 6.4.2. Surveys were conducted in Danish waters of the North Sea in a water depth of approximately 30 m. Underwater sound emission data was acquired using three broadband recorders arranged to measure sound levels relative to both range and direction from the sources. The recorders were deployed at distances between 0 m to 10 km from the source.

The sparker was a GSO-360 towed device with up to 360 tips and a power input of 900 K. It was operated at a frequency of 0.2–0.3 kHz and was recorded as having an effective source level of SPL_{rms} 188 dB re 1µPa. The parametric SBP was a hull-mounted Innomar SES-2000. The source was set to 80% of the maximum power. The study reported an effective source level of SPL_{rms} 237 dB re 1µPa with peak energy of the primary frequency between

85–110 kHz. The device's secondary frequencies were also detectable at 8–12 kHz at the vessel's closest point of approach.

The study concluded that the parametric SBP pulse was clearly visible with all its frequency components at the closest point of approach along the survey line; however, the secondary frequencies were barely detectable off-axis, indicative of the high directivity of the source. The signal could be detected at distances of 500 m in the survey direction and 150 m in the off-axis direction before dropping below SPL_{rms} 100 dB re 1µPa. The sparker pulses were detectable above background noise until 2 km both in the endfire and broadside directions but not at 5 and 10 km.

Plots of noise levels vs distance for the sparker and parametric SBP showed that distances to behavioural response thresholds were < 100m or even < 50 m for SPL_{pk} 168 dB re 1µPa, SPL_{rms} 160 dB re 1µPa and SEL_{ss} 145 dB dB re 1 μPa^2s.

The study used, at the Client's request, a threshold of a VHF weighted SPL_{rms} 100 dB re 1 µPa (VHF weighted) for estimating harbour porpoise sensation levels and potential disturbance. The estimated distance to this threshold from the parametric SBP was 597 m (best fit) with the 90% CI extending to 731 m. The estimated distance to this threshold from the sparker was 1.7 km (best fit) with the 90% CI extending to approximately 2.2 km.

Confidential (2018b) - parametric SBP sound source verification, US Atlantic

Confidential (2018b) carried out a sound source verification exercise of an Innomar SES-2000 parametric SBP off the coast of southern New Jersey (US), at a water depth of 32 m. The survey aimed to measure underwater acoustic levels from both baseline vessel noise and the SBP. Acoustic data were collected using two hydrophones, positioned 1 meter from the seabed (sea bottom) and 16 meters above it (midwater), while the vessel ran transects at 100, 250, 500, and 1,000 meters from the hydrophones.

Recorded noise levels were higher at seabed positions compared to mid-water. Seabed measurements at 100 m were SPL_{pk} 168.9 dB re 1 µPa and SPL_{rms} 129.2 dB re 1 µPa, with an estimated effective source level at the seabed of SPL_{pk} 215 dB re 1 µPa and SPL_{rms} 169.1 dB re 1 µPa. It was commented that noise levels decreased rapidly with range such that the noise from the SBP could not be easily identified above background noise at 1 km distance, likely due to its highly directional nature. For both seabed and midwater positions, distances to NMFS Level B harassment threshold of SPL_{rms} 160 dB re 1 µPa were < 10 m for both sea bottom and midwater hydrophone positions.

Confidential (2023) - Sparker and parametric SBP measurements, Baltic Sea

For this review, results were obtained for a measurement campaign associated with a sparker and parametric SBP in the western Baltic Sea (Danish waters), in a water depth of approximately 30 m. The sparker was a Dura-Spark UHD 400+400 with a source level of up to SPL_{pk} 226 dB re 1 µPa @ 1m, frequency range of 300 Hz to 1.2 kHz, pulse length of 0.5–1.5 ms, and a pulse rate of approximately 1 per second. The parametric SBP was an Innomar Medium 100, with a primary source level of SPL_{rms} 247 dB re 1 µPa @ 1m, a primary operating frequency of 100 kHz (bandwidth: 85–115 kHz), secondary frequencies of 4, 5, 6, 8, 12, and 15 kHz (bandwidth: 2–22 kHz), and a pulse rate of up to 40 per second.

Interpreting results for inferred response ranges

Measurements were made at varying distances from the sources from directly beneath the operational equipment up to a range of 5–10 km. The coefficients of the transmission loss formula (source level, propagation loss coefficient, absorption coefficient) were provided by the data owner for a variety of unweighted and auditory frequency weighted acoustic metrics, allowing estimation of distance to several potential behavioural disturbance thresholds. Results are presented in Table 12. For the majority of thresholds, estimated impact ranges were < 100 m. Distances to the VHF weighted threshold proposed by Tougaard (2021) extended up to 0.8 km for the sparker and 0.7 km for the parametric SBP. The authors noted that both sources were clearly detectable up to 1 km from the source, and just detectable at 2 km but within the background noise at this distance, and not detected beyond (Confidential 2023).

Table 12. Estimated distances to behavioural disturbance thresholds based on noise measurements for a sparker and parametric SBP.

Behavioural disturbance threshold	Estimated distance to threshold (km)	
	Sparker	Parametric SBP
SPL_{pk} 168 dB re 1 µPa	< 0.1	< 0.1
SEL_{SS} 145 re 1 µPa^{2}s	< 0.1	< 0.1
SPL_{rms} 160 dB re 1 µPa	< 0.1	< 0.1
VHF-weighted SPL_{rms} 103 dB re 1 µPa[1]	0.8	0.7

[1] From Tougaard (2021)

OSC (2025) - Chirp SBP (North Sea), parametric SBP (Kattegat, Danish waters)

Acoustic recordings of SBP operations were conducted opportunistically during geophysical surveys in the North Sea and Kattegat (inner Danish waters). Sound recordings were taken of a hull-mounted chirp SBP (EdgeTech 3300) in the North Sea, at a water depth of 90 m. The source had nominal source levels of $SPL_{pk\text{-}pk}$ 219 dB re 1 µPa and SPL_{rms} 210 dB re 1 µPa, a frequency range of 1–10 kHz, a pulse duration of 10 ms, and a pulse rate of 4 pulses per second. It should be noted that in addition to the SBP, the vessel was also operating a MBES and a USBL system with a potential source level of SPL_{rms} 206 dB re 1 uPa. The precise operational configuration of the MBES and USBL were not stated prior to data analysis. A total of 30 minutes of acoustic data were collected, including minutes where only the SBP was operational, and minutes with both the SBP and MBES active. The USBL system was active during all recordings, but no results or discussion of its noise levels are presented.

A hydrophone was deployed over the side of the vessel, outside of the main beam and an estimated 42 m horizontal distance to the chirp SBP source. While noise from the chirp SBP was readily detected by the hydrophone, particularly when a 1–10 kHz bandpass filter was applied to isolate central frequencies of the device, broadband noise levels were within a few dB of ambient. Even at such close proximity to the source, mean recorded noise levels were SPL_{pk} 166.6 dB re 1 µPa and SPL_{rms} 146.3 dB re 1 µPa, which were below both the Lucke *et al.* (2009) aversive response and the NMFS Level B harassment threshold.

Sound recordings were also taken of a hull-mounted parametric SBP (Innomar SES-2000) in the Kattegat by an over-the-side hydrophone nearshore in a water depth of 11 m and from a towed hydrophone array in open water at a water depth of 20–30 m. The parametric SBP operated at a nominal source level of SPL_{rms} 247 dB re 1 µPa, a primary frequency of approximately 100 kHz, and emitted 10 pulses per second. The nominal secondary frequency was varied between 4 kHz, 6 kHz, 8 kHz, and 10 kHz. The most relevant results are for the open water recordings, where the hydrophones were 56 m horizontal distance to the source (only 7 m distance in the nearshore recordings). Pulses from the SBP were readily identified in the primary frequencies of between 75–125 kHz, but secondary signals (< 10 kHz) could not be identified. Even at this close proximity to the source, mean recorded broadband noise levels were SPL_{pk} 143.5 dB re 1 µPa and SPL_{rms} 122.9 dB re 1 µPa, which were below both the Lucke *et al.* (2009) aversive response and NMFS Level B harassment threshold.

Propagation models applied to the measurement data estimated that, for both SBP sources, noise would drop below ambient background levels within 600 m of the source even under worst-case propagation assumptions.

Hannay and Warner (2009) - Pinger SBP

Hannay and Warner (2009) describe open water noise measurements from geophysical survey equipment in the Beaufort Sea in water depths of 20–50 m, including a pinger SBP. Measurements were taken as survey vessels approached, to provide measurements between approximately 200 m and up to 10 km range of the source. Within 500 m of the source, measured SPL_{pk} was 175 dB re 1 µPa. A level of SPL_{rms} 160 dB re 1 µPa (Level B harassment) was recorded at an estimated 140 m of the pinger SBP (extrapolated from a level of < 160 dB re 1 µPa at the minimum measurement distance of 190 m).

Halvorsen and Heaney (2018) - Categorising various acoustic survey sources based on source level measurements and other factors

The test-tank measurements of a variety of sources reported in Crocker and Fratantonio (2016) and Crocker *et al.* (2019) were followed by measurements in shallow (≤ 100 m depth) open-water environments to investigate sound propagation (Halvorsen & Heaney 2018). While it is acknowledged that these results suffered from challenges in data collection and are incompletely calibrated (Labak 2019), it is worth noting some general patterns observed from the open-water tests, as were summarised in Hartley Anderson Ltd (2020). Broadband received levels from all chirp and boomer SBPs tested (in addition to MBES and SSS) were rapidly attenuated with distance from source in all test environments, including particularly pronounced fall-off for directional sources when the receiver was outside of the source's main beam (Halvorsen & Heaney 2018). Acoustic signals from a sparker SBP and mini airgun showed slightly greater propagation, as would be expected from the lower-frequency and higher-amplitude impulsive signals produced by these sources. The greatest propagation was generally observed at the deepest test site (100 m water depth) from sources generating low frequencies (< 10 kHz) including sparkers and boomers, whilst some of the highest frequency sources (> 50 kHz) were only weakly detectable or undetected by recording equipment located a few hundred metres from the source. In all open-water test environments, broadband received levels did not exceed the Level B harassment threshold of SPL_{rms} of 160 dB re 1µPa beyond a mean distance of 338 from any SBP, echo-sounder or SSS device tested, with sparkers responsible for the largest distances (Halvorsen & Heaney 2018). For comparison, such levels extended between several hundred metres and approximately 1 km for the mini airgun tested.

6.4.1.3. Modelling studies

A total of five noise modelling studies were reviewed to collate estimated disturbance ranges across a variety of SBP sources including sparker, boomer, parametric and pinger SBPs (Xodus Group Ltd 2022; MarineSpace Ltd 2023; RPS 2023a, b; Xodus Group Ltd 2023a). Four out of five reports analysed are examples of European Protected Species (ESP) Risk Assessments (RAs) for offshore wind industry. Detailed information about these assessments and equipment modelled is provided in Table 14.

All modelling studies used the SPL_{rms} 160 dB re 1 µPa threshold to estimate the range of potential behavioural disturbance effects. The ranges estimated for sparker and boomer SBPs were between 83–510 m and 400–510 m, respectively. The distances to behavioural disturbance threshold for parametric SBP ranged between 74–1,348 m. One study estimated a range to behavioural response threshold for pinger SBP as 87 m. Generally, across all sources, estimated disturbance ranges were between 73 m and 1.3 km, with the majority being < 100 m or between 400–510 m.

There was no clear pattern between source type and disturbance range, with the parametric SBPs accounting for some of the smallest and the largest estimated ranges. Estimated disturbance ranges appeared to be sensitive to modelling assumptions.

6.4.2. USBL

6.4.2.1. Noise measurement studies

Pace *et al.* (2021)

As previously discussed in Section 6.4.1.2, the USBL system was used for acoustic positioning of SSS during surveys in the North Sea. The study estimated an effective source level of SPL_{rms} 184 dB re 1µPa. The USBL source had a distinct signature at 25 kHz and emitted a regular ping approximately every 1 s that could be detected above the ambient for the entire monitoring range up to 2 km from the source both on and off axis. The study concluded that the USBL source appears to be omnidirectional. The signal of the SSS was undetectable in the recordings as its operating frequency was above the bandwidth of the hydrophone.

The study used, at the Client's request, a threshold of SPL_{rms} 100 dB re 1 µPa (VHF weighted) for estimating harbour porpoise sensation levels and potential disturbance. The estimated distance to this threshold for the USBL was 2.7 km.

Confidential (2023) - USBL measurements, Baltic Sea

For this review, results were obtained for a measurement campaign associated with a USBL in the western Baltic Sea (Danish waters), in a water depth of approximately 30 m. The tested USBL was a Kongsberg HiPAP 351P and cNODE MiniS system, with an operating frequency of 26.4 ±2 kHz and a manufacturer-stated maximum source level of up to SPL_{rms} 207 dB re 1 µPa @ 1m and a pulse/ping rate configured to 1s.

Interpreting results for inferred response ranges

Measurements were made at varying distances from the sources from directly beneath the operational equipment up to a range of 5–10 km. The coefficients of the transmission loss formula (source level, propagation loss coefficient, absorption coefficient) were provided by the data owner for a variety of unweighted and auditory frequency weighted acoustic metrics, allowing estimation of distance to several potential behavioural disturbance thresholds. Results are presented in Table 13, selecting the maximum distances among the seabed vs midwater and low vs high vs max USBL settings. For the majority of thresholds, estimated impact ranges were < 100 m. Distances to the VHF weighted threshold proposed by Tougaard (2021) extended up to 4.2 km. The authors noted that the USBL on all power settings was clearly detectable up to 1 km from the source, and just detectable at 5 km but within the background noise at this distance, and not detected at the 10 km measurement distance (Confidential 2023).

Table 13. Maximum estimated distances to behavioural disturbance thresholds based on noise measurements for a USBL system.

Behavioural disturbance threshold	Maximum estimated distance to threshold (km)
SPL_{pk} 168 dB re 1 µPa	< 0.1
SEL_{SS} 145 re 1 µPa^{2}s	< 0.1
SPL_{rms} 160 dB re 1 µPa	< 0.1
VHF-weighted SPL_{rms} 103 dB re 1 µPa[1]	4.1

[1] From Tougaard (2021)

6.4.2.2. Noise modelling studies

A total of four noise modelling studies were reviewed to collate estimated disturbance ranges across a variety of USBL sources (RPS 2023a; SMRU Consulting 2023; Xodus Group Ltd 2023b; Unknown). The reports analysed are examples of European Protected Species (EPS) RAs for offshore wind industry and interconnector cables. Detailed information about these assessments and equipment modelled is provided in Table 15.

All modelling studies used the SPL_{rms} 160 dB re 1 µPa threshold to estimate the range of potential behavioural disturbance effects. The estimated disturbance ranges for different USBL types were between 182 m and 1.6 km. There was no clear pattern between source level and disturbance range, with estimated disturbance ranges appearing to be sensitive to modelling assumptions.

6.4.3. Tabulation of evidence relating to harbour porpoise response ranges from SBPs and USBL

In Table 14 and Table 15, we provide a tabulation of reviewed studies for SBP and USBL sources, respectively, including features of the study areas (region), equipment characteristic (type, frequency, equipment source level) and where available, the spatial extent of effects.

Table 14. Summary of evidence relating to harbour porpoise response ranges from SBP surveys (the spatial extent of effects include ranges reported/estimated within cited studies as well as inferred via additional analyses). N/A = Not Applicable; "-" = Not Available.

Study		Region	Water depth	Equipment used	Survey duration	Reported source level	Reported and estimated spatial extent of effect and description
Empirical response studies	Stone (2024b)	UK-wide	< 1,000	Chirp SBP	Multiple	SPL_{rms} 212–215 dB re 1μPa	**2.0 km =** Mean closest distance of approach of harbour porpoise to chirp when active.
	Veneruso (2024)	Irish Sea	38 m	Boomer (Applied Acoustics S-Boom)	5 days	222 dB re 1 μPa [1]	Distance not available, but a significant (50%) decrease in harbour porpoise presence (PP15M) was noted after the survey began and to several days after the survey was completed.
Noise measurement studies	Confidential (2018b)	US Atlantic Ocean	32 m	Parametric SBP (Innomar SES-2000)	-	247 dB re 1 μPa [1] SPL_{pk} 198 dB re 1μPa (midwater) [2] SPL_{pk} 215 dB re 1μPa (sea bottom) [2]	**0.1 km =** Distance to SPL_{rms} 160 dB re 1μPa threshold
	Pace *et al.* (2021)	North Sea	30 m	Parametric SBP (Innomar SES-2000)	2 days	SPL_{rms} 237 dB re 1μPa	**< 0.1km** = Distance to SPL_{rms} 160 dB re 1μPa threshold **0.6 km =** Distance to SPL_{rms} 100 dB re 1 μPa (VHF-weighted) threshold

Study		Region	Water depth	Equipment used	Survey duration	Reported source level	Reported and estimated spatial extent of effect and description
Noise measurement studies	Pace *et al.* (2021)	North Sea	30 m	Geo-360 sparker	2 days	SPL_{rms} 188 dB re 1µPa	**< 0.1km =** Distance to SPL_{rms} 160 dB re 1µPa threshold **2.2 km** = Distance to SPL_{rms} 100 dB re 1 µPa (VHF-weighted) threshold
	Confidential (2023)	Baltic Sea	30 m	Dura-Spark UHD 400+400 (sparker)	-	226 dB re 1 µPa	**< 0.1 km =** Distance to SPL_{pk} 168 dB re 1 µPa, SEL 145 dB re 1 µPa^{2}s and SPL_{rms} 160 dB re 1 µPa thresholds **0.8 km =** Distance to SPL_{rms} 103 dB re 1 µPa (VHF-weighted) threshold
				Parametric SBP (Innomar SES-2000)		> 247 dB re 1 µPa	**< 0.1 km =** SPL_{pk} 168 dB re 1 µPa, SEL 145 dB re 1 µPa^{2}s and SPL_{rms} 160 dB re 1 µPa thresholds **0.7 km =** Distance to SPL_{rms} 103 dB re 1 µPa (VHF-weighted) threshold
	OSC (2025)	North Sea and Kattegat	5–22 m	EdgeTech 3300 (chirper)	-	$SPL_{pk\text{-}pk}$ 219 dB re 1 µPa [1] SPL_{pk} 181 dB re 1 µPa [2]	Individual pulse would not exceed TTS-onset thresholds (SPL_{pk} and SEL). Cumulative exposure at the source would exceed TTS-onset threshold if harbour porpoise would stay next to the source for 1.7 hrs. Noise dropped below ambient background noise levels within 600 m.

Study		Region	Water depth	Equipment used	Survey duration	Reported source level	Reported and estimated spatial extent of effect and description
Noise measurement studies	OSC (2025)	North Sea and Kattegat	5–22 m	Parametric SBP (Innomar SES-2000)		SPL_{pk-pk} 247 dB re 1 µPa [1] SPL_{pk} 161.2 dB re 1 µPa [2]	Individual pulse would not exceed TTS-onset thresholds (SPL_{pk} and SEL). Cumulative exposure at the source would exceed TTS-onset threshold if harbour porpoise would stay next to the source for 3.7 seconds. Noise dropped below ambient background noise levels within 600 m.
Noise modelling studies	Xodus Group Ltd (2022)	North Sea	10–95 m	Innonmar Medium 100 (85–115 kHz)	-	SPL_{rms} 247 dB re 1µPa	**0.46 km** at 95m depth **=** Distance to SPL_{rms} 160 dB re 1 µPa threshold
				GeoSource 200 (Sparker, 1.5kHz)		SPL_{rms} 228 dB re 1µPa	**< 0.1 km** (91 m) at 95m depth **=** Distance to SPL_{rms} 160 dB re 1 µPa threshold
				Innonmar SES2000 (80–10 kHz)		SPL_{rms} 238 dB re 1µPa	**< 0.1 km** (74 m) at 10m depth **=** Distance to SPL_{rms} 160 dB re 1 µPa threshold
				Applied Acoustics AA200 (Boomer, 12 kHz)		SPL_{rms} 214 dB re 1µPa	**0.4 km** at 10m depth **=** Distance to SPL_{rms} 160 dB re 1 µPa threshold
	MarineSpace Ltd (2023)	North Sea	Not specified but < 200 m	Innomar Medium 100 (85–115 kHz)	-	243 dB re 1 µPa	**0.169 km =** Distance to SPL_{rms} 160 dB re 1 µPa threshold
				Innomar Deep 36 (30–42 kHz)		> 246 dB re 1 µPa	

Study		Region	Water depth	Equipment used	Survey duration	Reported source level	Reported and estimated spatial extent of effect and description
Noise modelling studies	RPS (2023b)	Co. Clare (North Atlantic Ocean)	< 60m	Edgetech 3100, Edgetech 3300, Geopulse 5430A, 400 Joule Generic (sparker), 350 Joule Generic (boomer); 0.6–12 kHz	-	SPL_{rms} 188 dB (off-axis) / SPL_{pk} 220 dB (on-axis)	**0.51 km =** Distance to SPL_{rms} 160 dB re 1 µPa threshold
				All the above plus Innomar parametric (dual frequency, 1–4 kHz and 85–11 kHz)		SPL_{rms} 197 dB (off-axis) / SPL_{pk} 247 dB (on-axis)	
	RPS (2023a)	North Sea	50–100 m	Innomar SES2000 (85–115 kHz)	-	SPL_{rms} 248 dB re 1 µPa	**1.34 km =** Distance to SPL_{rms} 160 dB re 1 µPa threshold
				GSO 360 Sparker (frequency not provided)		SPL_{pk-pk} 229 dB re 1µPa	**< 0.1 km** (83 m) **=** Distance to SPL_{rms} 160 dB re 1 µPa threshold
	Xodus Group Ltd (2023a)	North Sea	< 100 m	GeoAcoustics GeoPulse (pinger, 2–8 kHz)	-	SPL_{pk} 223.5 dB re 1µPa	**< 0.1 km** (87 m) **=** Distance to SPL_{rms} 160 dB re 1 µPa threshold

Notes: [1] Reported by the manufacturer. [2] Based on field measurements.

Table 15. Summary of evidence relating to harbour porpoise response ranges from USBL (the spatial extent of effects include ranges reported/estimated within cited studies as well as inferred via additional analyses). "-" = Not Available.

Study		Region	Water depth	Equipment used	Survey duration	Reported Source Level	Reported and estimated spatial extent of effect and description
Noise measurement study	Pace *et al.* (2021)	North Sea	-	Omnidirectional USBL (25 kHz)	2 days	SPL_{rms} 184 dB re 1μPa	**< 0.1 km =** Distance to 160 dB re 1 μPa SPL_{rms} threshold **Up to 2.7 km =** distance to SPL_{rms} 100 dB re 1 μPa (VHF-weighted) threshold
	Confidential (2023)	Baltic Sea	30 m	Kongsberg HiPAP 351P (26 ±2 kHz)	-	SPL_{rms} 207 dB re 1 μPa	**< 0.1 km =** Distance to SPL_{pk} 168 dB re 1 μPa, SEL 145 dB re 1 μPa^{2}s and SPL_{rms} 160 dB re 1 μPa thresholds **Up to 4.1 km =** distance to for SPL_{rms} 103 dB re 1 μPa (VHF-weighted) threshold
				cNODE MiniS (26 ±2 kHz)		SPL_{rms} 206 dB re 1 μPa	
Noise modelling study	RPS (2023a)	North Sea	50–100 m	Kongsberg μPAP 201-3 (20-30 kHz)	-	SPL_{rms} 190 dB re 1 μPa	**1.59–1.64 km =** Distance to SPL_{rms} 160 dB re 1μPa threshold
	Xodus Group Ltd (Unknown); Xodus Group Ltd (2023b)	Orkney, North Sea; Outer Hebrides, North Atlantic Ocean	10–100 m	1000 Series Mini Beacon, Applied Acoustics (24-33.5 kHz)	-	SPL_{rms} 200 dB re 1μPa	**0.182 km** at 100m water depth, **0.207 km** at 10 m water depth = Distance to SPL_{rms} 160 dB re 1μPa threshold

Study		Region	Water depth	Equipment used	Survey duration	Reported Source Level	Reported and estimated spatial extent of effect and description
Noise modelling study	SMRU Consulting (2023)	Firth of Forth, North Sea	-	Kongsberg HiPAP 501 (20–32 kHz)	-	SPL_{rms} 190 - 206 dB re 1 µPa	**0.5–1 km =** Distance to SPL_{rms} 160 dB re 1µPa threshold
				Sonardyne Ranger HPT 3000 (19–34 kHz)		SPL_{rms} 194 dB re 1 µPa	
				Sonardyne Compatt 6 (19–34 kHz)		SPL_{rms} 187 - 202 dB re 1 µPa	
				Kongsberg cNODE Modem MiniS (21–31 kHz)		SPL_{rms} 182 - 197 dB re 1 µPa	

6.4.4. Estimation of EDRs from existing data

No studies were assessed as suitable for estimation of EDR for SBP and USBL.

6.4.5. Evidence scores

Detailed methods and results of the evidence scoring exercise are presented in Appendix 2, Table 29**;** a summary is provided here. In total, for SBP and USBL, four noise measurement and eight noise modelling studies were reviewed and assigned scores based on specific evaluation criteria (Appendix 2, Figure 7). One empirical study available did not provide distances at which harbour porpoise may respond to the SBP noise and therefore it was not scored.

The studies were assigned an initial score of 10, with penalties subsequently applied as appropriate for criteria including: the study type, the relevance of the study area to the UK (i.e. water depth); the relevance of the activity to current and near-future UK OWF construction and other study limitations (e.g. unclear methodology).

For **all SBPs**, there were four relevant noise measurement studies which received scoring ranging from 4 to 6, with an average score of 5.0. The score assigned to all modelling studies was 3.0. The overall average across the two study type scores is 4.0.

For **pulsed waveform SBP sources (sparker, boomer)** there was one relevant noise measurement study which received a score of 6.0 (sparker). The score assigned to all modelling studies was 3.0. The overall average across the two study type scores is 4.0.

For **periodic waveform SBP sources (pinger, chirp, parametric SBP)** there were four relevant noise measurement studies which received scoring ranging from 4 to 6, with an average score of 5.0. The score assigned to all modelling studies was 3.0. The overall average across the two study type scores is 4.0.

For **USBL,** there were two relevant noise measurement studies which received scoring of 4 and 6, with an average score of 5.0. The score assigned to all modelling studies was 3.0. The overall average across the two study type scores is 4.0.

6.5. Recommending default EDRs

6.5.1. Overview: evidence base

A summary of reported and estimated effects ranges for SBP and USBL are presented in Table 16. Across all such sources, reported distances to proposed behavioural response thresholds are small. These are all < 1 km based on noise measurement data, and ≤ 1.69 km based on modelling studies. When including the limited empirical response results from Stone (2024b) for chirp SBPs, the reported effects range increases to 2 km.

Table 16. Summary of reported and estimated effects ranges and estimated EDRs for SBP and USBL among the 13 studies reviewed.

Category	Reported effects range, km (n= number of studies) [1]	Estimated EDR, km (n= number of studies)
All SBPs	< 0.1–2.0 (11)	Data from the reviewed studies did not allow for EDR estimation
Pulsed waveform SBP sources (sparker, boomer)	< 0.1–0.51 (5)	
Periodic waveform SBP sources (pinger, chirp, parametric)	< 0.1–2.0 (10)	
USBL	< 0.1–1.64 (6)	

[1] Excluding reported effects ranges for the VHF-weighted SPL_{rms} 100 or 103 dB re 1 μPa threshold proposed by Tougaard (2021).

It is worth noting the findings of Ruppel *et al.* (2022) in the context of SBPs - a study which is relevant but does not fall into either of the categories of evidence considered above. Drawing heavily on the calibrated test-tank source level measurement results of Crocker *et al.* (2019), Ruppel *et al.* (2022) provide a comprehensive assessment of the potential for active acoustic sources, including high-resolution geophysical sources such as SBPs, to result in incidental take of marine mammals (behavioural disturbance / 'Level B harassment', as per NMFS exposure criterion of SPL_{rms} 160 dB re re 1 μPa). The authors assess physical criteria of the sources beyond sound levels alone, such as transmission frequency, directionality, beamwidth, and pulse repetition rate, and conclude that most HRG sources can be classed as *de minimis* (i.e. unlikely to result in incidental take of marine mammals according to US legislation). This covers pulsed waveform SBPs including chirp, pinger and parametric SBPs. However, it was found that pulsed waveform HRG seismic sources (including some boomers, sparkers) had insufficient data to support thorough analysis. The authors noted that certain configurations were likely to be classified as *de minimis* with more information, but all such sources were classified between low-energy airguns (where incidental take could be possible) and *de minimis* sources.

6.5.2. Recommended default EDRs for SBP and USBL

For all types of SBPs and USBL, an EDR in the range of 2–3 km is recommended.

This is considered to be a precautionary EDR given the reported effects ranges from measurement and modelling studies, which received scores between 4–6 and 3, respectively. It acknowledged that empirical response data are very limited but do provide some evidence of displacement of animals to both pulsed and periodic waveform SBP sources within the suggested range.

7. ADDs

7.1. Introduction

ADDs are widely used as a tool to deter marine mammals from zones of potential injury around impulsive noise sources such as impact piling and UXO clearance. They do not currently have a recommended default EDR (JNCC 2020, 2023a) as they are not employed in isolation (at least not in harbour porpoise SACs of England, Wales and Northern Ireland) but, rather alongside louder noise sources. However, the reported wide-ranging deterrence effects of ADDs (e.g. Brandt *et al.* 2013c) have raised discussions over the relative contribution of ADDs and piling noise to disturbance effects (Dähne *et al.* 2017) and the need to balance risks of injury and disturbance (Thompson *et al.* 2020). Such considerations are pertinent as the noise generated by piling and UXO clearance is reduced (i.e. with the use of NAS and low-order methods, respectively). As such, an examination of the evidence relating to disturbance ranges associated with ADD use is of importance.

7.2. Description of activity

Anthropogenic noise in coastal and offshore waters has the potential to cause injury to marine mammals. In particular, the clearance of historic UXO and piling activities during the development of OWFs, and the use of explosives in decommissioning. In order to reduce these risks, mitigation measures include the use of visual observations and PAM to monitor for marine mammals prior to commencing activities. Where the risk of injury cannot be mitigated to negligible levels solely through the use of visual observations and PAM, ADDs may be recommended to deter marine mammals from the area of impact (or mitigation zone). The purpose of pre-UXO clearance and/or pre-piling ADD activation is to deter marine mammals out of the mitigation zone prior to the start of activity. The use of ADDs is accepted by Natural England, the MMO, NatureScot and NRW and they have been extensively used as a pre-piling mitigation method in England, Wales, Scotland and other European jurisdictions (e.g. Germany) over the last decade. However, guidance for piling as well as explosives use states that ADDs should be considered, but only used in conjunction with visual and/or acoustic monitoring (JNCC 2010, 2025c).

While a variety of different ADDs exist, the most common ADD used in association with impact piling and UXO clearance in the UK is the Lofitech AS seal scarer (Stone 2023a, b), which has also been widely used prior to piling in Europe (see Section 7.4). This ADD has been shown to have the most consistent and far-reaching deterrence effects on harbour porpoise, with pronounced deterrence effects also reported for minke whales and seals (see review in McGarry *et al.* 2022). The Lofitech device emits short pure tone pulses (500 ms) at variable intervals (0.5–90 s), at frequencies between 10–20 kHz (typically 14 kHz) and a source level of SPL_{rms} 189 dB re 1 μPa @ 1 m.

An overview of ADD use associated with piling and explosives in UK waters from 2011–2021 is provided by Stone (2023a) and Stone (2023b). ADDs were used in advance of piling for OWF projects, UXO clearance as well as during decommissioning projects for oil and gas industry. For piling, wherever the ADD type was specified, it was the Lofitech device. One project used two devices simultaneously. ADDs were activated prior to piling, for durations of between 15-30 minutes, and deactivated within a few minutes of the start of piling Stone (2023b). Among ten decommissioning projects and 11 UXO clearance projects, the Lofitech device was also the most commonly used where specified. Two decommissioning projects used an Aquamark 210 device, which emits pulses at frequencies of 5–150 kHz with a source level of SPL_{pk} 150 dB re 1 μPa @ 1m (McGarry *et al.* 2017; McGarry *et al.* 2022). Most projects using ADDs used just one device; 22% of decommissioning projects and 33% of UXO clearance projects using ADDs used two devices simultaneously. Not all licences specified a duration for ADD deployment – all those where a duration was specified were for UXO clearance projects. Licences specified durations of between 15–80 minutes. However, it was noted that compliance was poor, with ADD durations typically longer than licences specified, particularly where specified durations were shorter. While reported durations were up to 121 minutes, 90% were < 40 minutes. It is noted that ADD durations for low-order clearance are typically 10–20 minutes, depending on the size of the charge being used (see Section 3). Typical ADD durations can also vary between countries within the UK, where different regulators and their advisors have different expectations in terms of the metrics for auditory injury upon which mitigation and deterrence should be based (i.e. instantaneous (based on the SPL_{pk} metric) vs cumulative (based on frequency-weighted SEL metric).

While the Lofitech Seal Scarer has been the predominant ADD used in the UK, this type of ADD has also been used across Europe (Brandt *et al.* 2012; Brandt *et al.* 2013a; Elmegaard *et al.* 2023). However, seal scarers have led to decreased porpoise detection rates in much larger distances than intended during mitigative activities, and thus, devices specifically designed for harbour porpoise mitigation purposes have been prescribed in Germany (Voss *et al.* 2023). This has led to the development of the FaunaGuard Porpoise Module, which generates a lower source level and signals at higher frequencies than the Lofitech sea scarer, aiming to keep the animals away from offshore construction sites but without inducing large-scale disturbance (Voss 2021; Voss *et al.* 2023). This device has since been used at various German OWF project sites (Rose *et al.* 2019; de Jong *et al.* 2022; Rose *et al.* 2024).

7.2.1. Other ADD types

Acoustic devices have been applied across a broad spectrum of marine industries and the diversity in application has resulted in a wide array of devices available on the market. Although most devices operate within the medium to high frequency range, their acoustic properties vary significantly in terms of sound pressure levels, frequency ranges, temporal patterns (duty cycles), and harmonic content. Deployment methods and operational functionalities also differ among devices.

McGarry *et al.* (2022) presented an overview of various ADDs designed to mitigate the risk of injury or mortality to marine mammals. The study categorised ADDs by target species and associated hearing groups, identifying several types considered effective for deterring harbour porpoise. For instance, the report indicates that Aquatec's Aquamark 100 and 200 models can displace porpoises at distances between 0.1 km and approximately 0.5 km. Similarly, devices from Terecos Ltd and the Airmar dB plus II have demonstrated deterrent ranges of approximately 0.3–1.2 km and 0.2–3.5 km, respectively.

While the current study also reviewed a few additional ADD types, empirical evidence supporting deterrence at larger ranges remains limited. Consequently, devices other than Lofitech and FaunaGuard are considered outside the scope of this review.

7.3. Approach to evidence review

In Section 7.4 below, we provide summary reviews of relevant empirical studies reporting harbour porpoise responses to various deterrent devices. These studies utilise tracking, PAM data and aerial survey data to assess harbour porpoise responses, and we focus our review on how porpoise respond as a function of distance to acoustic deterrent, rather than received noise levels, as it is empirical evidence of response ranges which are currently favoured in harbour porpoise SAC noise management (JNCC 2020).

It is noted that modelled predictions of porpoise responses to the Lofitech ADD generally assume a fleeing response with animals moving directly away from the source while it remains active at a net swim speed of 1.4–1.5 m/s. For example, based on the latter swim speed, in the noise modelling assessments (e.g. to inform EPS RAs for offshore wind industry), the estimated disturbance range is proportional to the duration of ADD activation (e.g. 1.4, 2.7 and 4.1 km for ADD durations of 15, 30 and 45 minutes respectively). Considering the above and given that there are several empirical studies available in the public domain on responses of porpoises to ADD use, this review did not consider studies which estimated response ranges from noise measurements or predictive modelling.

As described in Section 2.3, where possible, we estimated EDRs from existing data through the examination/ interpretation of deterrence functions (magnitude/ probability of response vs distance to noise source) within published studies (see Section 7.4.3).

For the purpose of this review, the "seal scarer" and ADD are used interchangeably because these two terms are used in various studies and refer to the same equipment (e.g. Lofitech).

7.4. Evidence

A number of empirical studies that report behavioural response of harbour porpoise to acoustic deterrents were identified. This review is focussed on the large-scale displacement, which are reviewed in detail in Section 7.4.1. A summary of findings from more local-scale responses is provided in Section 7.4.1.6.

In Section 7.4.2 we provide a tabulation of all evidence reviewed in the current study for this noise source, including specific features of the activities (e.g. region, water depth, ADD type) and the reported spatial extent of deterrence effects / distance to threshold levels. Section 7.4.3 describes estimation of EDRs for studies that met criteria discussed in Section 2.3.

Results of the evidence scoring exercise for ADD is provided in Section 7.4.4.

7.4.1. Empirical response studies

7.4.1.1. Elmegaard *et al.* (2023)

Elmegaard *et al.* (2023) carried out a study investigating the behavioural and physiological responses of harbour porpoises to ADDs. The authors tagged six harbour porpoises in Danish waters with suction-cup-attached DTAGs recording sound, 3-D movement, GPS and electrocardiogram.

The harbour porpoises were tagged in 2018 and 2019 after incidental capture in pound nets by fishermen. After release, porpoises were exposed to a Lofitech ADD for 15 minutes. In 2018, the exposures were carried out 16–17 minutes after release of the porpoises with the aim of exposing the animals at an initial distance of approximately 1 km. In 2019, a variable amount of time was allowed to elapse after release (90–202 minutes) to achieve longer exposure ranges. Harbour porpoises were therefore initially exposed to the ADD at distance ranging between 0.9–7 km. Tagging data indicate that exposed porpoises were generally in water depths of 4–20 m.

Detection of feeding buzzes were used as a proxy for return to baseline behaviour after tagging. For each 15-minutes exposure, a pre-exposure interval immediately before the exposure was used as a control. Click counts were then compared during the 15-minutes window before exposure and the 15-minutes window during ADD exposure.

All porpoises up to an initial exposure range of 7 km reacted with a mixture of acoustic startle responses, fleeing, altered echolocation behaviour and unusual tachycardia while diving. Four of the six harbour porpoises exhibited an acoustic startle response as their first response to the ADD exposure and five out of the six animals increased their distance to the ADD. The single harbour porpoise which did not flee made a deep U-shaped dive immediately after the ADD exposure started. GPS tracks were available for three of the porpoises, which showed that the porpoises headed away from the ADD with a 15-minutes mean horizontal travel speed of 1.4, 1.8 and 1.9 m/s during the exposure.

The authors also carried out a separate experiment to control for the effect of tagging in which porpoises were exposed to ADD playbacks without tagging and filmed using a drone to observe the behavioural effects of ADD playback. To accommodate the limited range (< 500 m) of the drone, the playback consisted of a recording of a 500 ms ping from a Lofitech taken at 1 km (source level 158 dB re 1 µPa rms @ 1 m). Similar sound files with ping sound pressure reduced by 80 dB (i.e. only detectable within a few metres from the source) were used for control playbacks. Untagged porpoises were observed during five control trials for an average of 308 s and during one exposure trial for 371 s, in which a group of seven porpoises were exposed. All harbour porpoises reacted by fast swimming in different directions generally away from the sound source, and the focal porpoise during the exposure swam away from the sound source at more than doubled swimming speed (an average speed of 4 m/s during the first 30 seconds of the exposure compared to an average speed of 1.6 m/s in the preceding 30 seconds). In contrast, harbour porpoises did not exhibit any apparent avoidance of the sound source, or any flee response during the control playbacks and their average swimming speed varied between 0.7 and 1.1 m/s.

It is noted that values reported in this study do not meet the definition of an EDR as described in Section 2.2. Tagged porpoises responded to a 15-minutes Lofitech ADD exposure at initial distances up to 7 km, and as this was the furthest initial distance measured, it is possible that the response could have extended further. Therefore, porpoise were reported to show behavioural responses to at least 7 km from the ADD. These results, as currently presented, were not considered suitable for estimation of an EDR.

7.4.1.2. Voss *et al.* (2023)

Voss *et al.* (2023) analysed a dataset of harbour porpoise detection rates collected at four offshore windfarms constructed in 2018 and 2019 in the German Bight, North Sea. The aim of the study was to assess harbour porpoise responses to Acoustic Porpoise Deterrents (APDs) and subsequent piling. APDs are devices that emit acoustic signals at higher frequencies compared to seal scarers and are designed to have a smaller scale of impact. In this case, the authors used the FaunaGuard porpoise module (SPL_{rms} 172 dB re 1 µPa @ 1 m, 60–150 kHz).

A total of 16 monitoring stations equipped with CPODs were set up to 10 km from the piling locations from at least 4 days before piling until 1 day after the last piling. Additionally, mobile CPODs were deployed for durations of a few hours during pile-driving of 187 monopiles at fixed distances of 750 m to 1.5 km from the construction sites to monitor the effectiveness of the deterrent measures. All CPODs were maintained at a water depth 5–10 m above the seafloor.

Harbour porpoise response was assessed in terms of number of minutes with porpoise click trains ("Detection Positive Minutes", DPM) and standardized to %DPM/phase to account for the differing durations of APD and piling phases. Harbour porpoise detection rates were compared across five phases. Phase 1 (before APD operation) covered an average of 6 h. Phase 2 consisted of the time between start of the APD and start of the piling. Phase 3 was the pile driving time. Phase 4 consisted of the time after the piling activity and before recovering the device, which was on average 3 h for mobile CPODs. Additionally, there was a reference phase for stationary CPODs combining the periods from 48-h to 72-h after last piling as well as 48-h to 24-h before deterrence of the next piling.

Bayesian proportion tests and Boosted Regression Tree (BRT) models were created to evaluate short-term differences in detection rates among phases for all OWFs combined as well as individual wind farms, and a Generalised Additive Model (GAM) was conducted to analyse the overall effect range of the APD in the following distance classes: 0–2.5 km, > 2.5–5 km, > 5–7.5 km and > 7.5–10 km. Harbour porpoise detection rates decreased by 30–100% at 750 m distance and by 25–60% at 1.5 km during APD operation. The range of APD activity durations available for modelling in the GAM were one to 43 minutes. The results from the GAM demonstrated a reduction in harbour porpoise detection rates up to a distance of approximately 2.5 km during APD operation, even when the APD was switched on for over 40 minutes.

The authors also had the opportunity to directly compare APDs with a Lofitech seal scarer ADD when the APD at one of the four windfarms did not function correctly. A seal scarer was used instead and differences in the %DPM/phase between the APD and the seal scarer were explored at distances of 5–10 km form the construction sites (mean of available distances = 8 km). The detection rates of harbour porpoises only decreased by 12% during APD operation, compared to the 94% decrease when the seal scarer was used. However, the APD to seal scarer comparison was limited due to a low number of observations and a lack of data for other distance classes.

It is noted that values reported in this study do not meet the definition of an EDR as described in Section 2.2; rather, these represent the distance at which porpoise detections were predicted to be lower during APD operations than reference phase and are therefore akin to the maximum distance of detectable effect. These results, as currently presented, were not considered suitable for estimation of an EDR.

7.4.1.3. Thompson *et al.* (2020)

Thompson *et al.* (2020) used a large CPOD array in the Moray Firth to investigate harbour porpoise responses to a 15-minutes Lofitech ADD exposure at distances of up to 60 km from the exposure site. The water depth within the study area varied between 35–45 m. The ADD was deployed from a survey vessel at a depth of approximately 20 m. Source level was estimated based on field measurements (out to 2 km range) as SPL 187–188 dB re 1 μPa @ 1 m.

Changes in porpoise occurrence at various CPOD locations were investigated in the 3-, 6- and 12-h periods after a 15 minutes Lofitech ADD exposure, relative to the baseline occurrence (48 h before the exposure). Porpoises were considered to have responded to the ADD when the proportional decrease in occurrence defined by detection positive hours (DPH) was greater than 0.5 (the 99th percentile of a baseline distribution - see Brown *et al.* (2025). The probability that porpoise occurrence did (1) or did not (0) show a response to ADD was then modelled in relation to distance from the ADD as a binomial response.

Within the 3-h period following the ADD playback, there was a > 50% chance of porpoise response at distances up to 21.7 km. The spatial extent of responses diminished with increasing length of period after ADD exposure, to > 50% chance of porpoise response at 13.8 km in the 6-h period after ADD exposure, and 3.9 km in the 12-h period after ADD exposure. Close inspection of results for the 3-h period indicates that the closest data point classified as no response was at approximately 10 km distance to the ADD source (see Figure S7 in Thompson *et al.* 2020).

It is noted that values reported in this study do not meet the definition of an EDR as described in Section 2.2; rather, these represent the distance at which 50% of porpoise were predicted to respond to the ADD exposure. In Section 7.4.3, we revisit these results with a view to estimating a corresponding EDR.

7.4.1.4. Dähne *et al.* (2017)

Dähne *et al.* (2017) used PAM to study porpoise responses to acoustic deterrent measures and piling at the DanTysk wind farm in the German North Sea. Acoustic deterrence measures used included the Lofitech seal scarer and a broadband pinger Aquamark 100 (source SPL_{rms} of 145 dB re 1 µPa @ 1m) activated for 37–235 minutes (median 66 minutes) prior to commencing piling. The study suggested that both were used simultaneously up until the start of piling, but it is not clear if this was the case at all piling events.

Twelve monitoring stations were deployed along three transects oriented west, east, and south, with each transect containing four stations. These stations were positioned at distances ranging from 1–31 km from the monopiles. Each station was equipped with a CPOD, anchored approximately 2 m above the seabed.

The CPOD time series was divided into four periods to assess the effects of pile driving and the seal scarer. The "before" period (3 h prior to seal scarer activation) served as a reference, although noting there was increased background noise associated with other construction activities. The "deterrence" period covered the variable duration of seal scarer activity before piling. The "pile driving" period varied in length, while the "after" period spanned 24 hours post-piling, divided into 1-h intervals. Overlapping periods from subsequent installations were excluded. In cases where the deterrence phase for a subsequent foundation installation began within 24 h of the previous piling event, the overlapping time intervals were excluded from the "after" period. Porpoise positive minutes (%PPM) were calculated for 80 foundations, and data were analysed using a generalized linear mixed-effects model. Data were aggregated into distance groups, specifically 1.5–3 km, 3–6 km, and successive intervals up to 15–18 km from the monopile.

Relative to a baseline period, acoustic activity was significantly reduced during ADD activation at almost all measured distances, including the furthest 15–18 km distance category. The largest decrease was recorded at closest range, where %PPM fell to approximately 0.5% (1.5–3 km). The authors noted that the observed reactions to the seal scarer were comparable to or even exceeded the reaction to the subsequent noise abated pile driving.

It is noted that values reported in this study do not meet the definition of an EDR as described in Section 2.2; rather, these represent the maximum distance at which porpoise detections were significantly lower during ADD activation compared to the period before activation. In Section 7.4.3, we revisit these results with a view to estimating a corresponding EDR.

7.4.1.5. Brandt *et al.* (2013c)

Brandt *et al.* (2013c) conducted a study consisting of five months of monitoring in the German North Sea with the objective of determining the spatial extent of the deterrence effects of a seal scarer on harbour porpoises. The authors deployed 16 C-PODs in a star-like configuration within a 180 km^2 study area. A single C-POD was located in the centre of the configuration (0 km) and the remaining PODs were located at 0.75, 1.5 km, 3 km and 7.5 km distances. CPODs were deployed 1.5 m above the seabed.

Ten trials with an active Lofitech seal scarer were conducted, where a boat would drive to the central POD position and deploy the seal scarer sound head at 7–10 m depth in the water column. During days when the seal scarer was activated, it was switched on for 4 hours continuously. Each seal scarer exposure trial was separated by at least four days from other trails. CPODs recorded the responses of harbour porpoises to the seal scarer and porpoise activity was analysed in terms of ‘porpoise positive minutes per hour’ (PPM/H). All hours between 7-h before and 12-h after seal scarer activity were used, and these hours were then grouped into 3-h blocks and numbered relative to the start of the seal scarer. The hour directly before the start of the seal scarer and the first hour after the start of the seal scarer were excluded to account for potential effects from the vessel deploying the seal scarer and to allow enough time for porpoises to leave the study area after activation of the seal scarer.

The PPM for the 3-h block before and during seal scarer operation were compared by performing the Wilcoxon test for two dependent samples. There was a statistically significant decrease in porpoise activity observable up to 7.5 km (the furthest distance measured), where there was a decrease from an average of 3.1% - 0.1% PPM. Statistically significant decreases in porpoise activity occurred at all distances from the seal scarer except at 1.5 km and 5 km, although the authors note that the decrease at 5 km likely resulted from the very limited power to detect significant changes due to porpoise activity being low before the seal scarer was activated. The significant difference in porpoise activity compared to the time before seal scarer activation was found to extend up to a maximum of 4–6 h after seal scarer activity. The additional acoustic measurements indicated that at the maximum distance where a significant reduction in harbour porpoise activity was observed (7.5 km), the sound pressure level was still approximately SPL_{rms} 113 dB re 1 µPa.

Two aerial surveys were also conducted on 10 August 2009, one before and one during seal scarer operation. A line-transect distance sampling method was applied to calculate porpoise densities. Porpoise density was calculated per transect for both aerial surveys and the difference in porpoise densities between surveys before and after seal scarer activity was tested. The aerial survey revealed a porpoise density of 2.4 harbour porpoises per km^2 over the entire study before seal scarer activity, and a decrease in density during seal scarer activation to 0.3 harbour porpoises per km^2. This was a statistically significant decrease and porpoise density during seal scarer activity was only 11% of that before seal scarer activation.

It is noted that values reported in this study do not meet the definition of an EDR as described in Section 2.2. Rather, they illustrate that harbour porpoises are deterred by the Lofitech seal scarer up to at least a distance of 7.5 km, and potentially further since this was the maximum distance at which CPODs were deployed in the study. These results, as currently presented, were not considered suitable for estimation of an EDR.

7.4.1.6. Local-scale response studies

Using land-based observations, two studies reported temporary avoidance responses in harbour porpoise up to 2.6 km from a 4-h exposure to a Lofitech seal scarer (Brandt *et al.* 2013b), and up to 1.7 km from a 15 minutes exposure to a playback of similar signals to a seal scarer but at a reduced source level (Mikkelsen *et al.* 2017). A number of additional studies have documented adverse responses of harbour porpoises to ADDs and increases in avoidance behaviour and deterrence (Northridge *et al.* 2010; Kindt-Larsen *et al.* 2019).

Hiley *et al.* (2021) and Brennecke *et al.* (2022) carried out studies assessing the behavioural response of harbour porpoises to devices other than standard commercial ADDs. In the case of Brennecke *et al.* (2022), the authors tracked wild porpoises with a drone and recorded behaviour before and during exposure to a Fishtek banana pinger suspended at 5–10 m depth, emitting 50–120 kHz signals with a source level of SPL_{rms} 144 dB re 1 µPa @ 1 m. Of the 16 wild porpoises that were tracked, eight were lost from the drone's field of view as soon as the pinger playback started (indicating deep diving or speeding away from the pinger), four animals did not respond to the pinger sounds, and four animals reacted with strong avoidance behaviour including increased swim speed in the direction away from the pinger. These four porpoises were between 199–521 m away from the pinger when it was activated and avoidance behaviour occurred.

Hiley *et al.* (2021) tested a startle-eliciting sound exposure system with a lower sound level and duty cycle than those produced by currently available commercial ADDs. The sound exposure system consisted of an underwater transducer, a power amplifier, and an audio player. This system emitted 0.2 s long band-limited signals with a peak frequency of approximately 10.5 kHz and a broadband source level set at 180 dB re 1 µPa for each individual signal. Visual observers tracked a group of harbour porpoises during a 15-minutes sound exposure or control observation period and 90 minutes of post-exposure tracking (or until the animals were out of sight). The study found that porpoises showed a significant avoidance reaction during exposure, travelling a mean distance of 1.78 km, and left the area within 1 km of the sound source in all exposure trials within the first 15 minutes after the start of the exposure. Modelling using a mean distance Generalised Linear Mixed Model (GLMM) and a Generalised Additive Mixed Model (GAMM) using distance to the exposure vessel as a function of time indicated a maximum deterrence range between 1.65 km (GLMM) and over 2.07 km (GAMM) either within the exposure or during the first 15 minutes after the exposure stopped.

7.4.2. Tabulation of empirical response studies relating to ADDs, including the reported spatial extent of deterrence effects

In Table 17, we provide a tabulation of all reviewed empirical response studies, including features of the study areas (region), acoustic deterrent characteristic (type, activation protocol, frequency, equipment source level) and the reported spatial extent of deterrence effects.

Table 17. Summary of empirical evidence relating to harbour porpoise response ranges from ADDs (the spatial extent of effects include ranges reported/estimated within cited studies as well as inferred via additional analyses).

Study	Region	Type of ADD	ADD duration	Frequency	ADD source level (SPL_{rms})	Reported and estimated spatial extent of effect and description
Elmegaard *et al.* (2023)	Denmark	Lofitech	15 minutes exposure	14 kHz [1]	189 dB re 1 µPa [1]	**7 km** = This is the maximum range at which a porpoise was exposed to the ADD and reacted, therefore not a true maximum distance of behavioural reaction.
Voss *et al.* (2023)	German North Sea	FaunaGuard Porpoise Module	Up to 43 minutes	60–150 kHz	172 dB re 1 µPa	**2.5 km =** Distance to which detection rates were reduced relative to baseline based on GAM using % DPM.
		Lofitech seal scarer	Not reported	14 kHz [1]	189 dB re 1 µPa [1]	**5–10 km** = Distance bin (maximum monitored) in which 94% decrease in %DPM during ADD activation compared to baseline. (The equivalent result for the Faunaguard was a 12% decrease.)
Thompson *et al.* (2020)	Moray Firth, NE Scotland	Lofitech seal scarer	15 minutes	12.84 kHz [2]	187.2 dB re 1 µPa [2]	**21.7, 13.8, 3.9 km =** Distance where $\geq$ 50% chance of harbour porpoises responding to the ADD playback in the 3-h, 6-h or 12-h (respectively) period following the playback (using data to 60 km).

Study	Region	Type of ADD	ADD duration	Frequency	ADD source level (SPL_{rms})	Reported and estimated spatial extent of effect and description
Dähne *et al.* (2017)	German North Sea	Aquamark 100 Pinger	37–235 minutes exposure (median 66 minutes) prior to impact piling	20–160 kHz	145 dB re 1 µPa	**15–18 km** = Maximum distance with statistically significant decrease in % PPM due to acoustic deterrence.
		Lofitech seal scarer		14 kHz [1]	189 dB re 1 µPa [1]	
Brandt *et al.* (2013c)	German North Sea	Lofitech seal scarer	4 h exposure	14 kHz [1]	189 dB re 1 µPa [1]	**7.5 km =** Statistically significant decrease in porpoise activity (PPM / hour; this was the furthest distance measured and therefore not a true maximum distance of behavioural reaction).

Notes: [1] Reported by the manufacturer. [2] Based on field measurements.

7.4.3. Estimation of EDRs from existing data

Two studies were identified as suitable for estimation of EDR for ADDs (Dähne *et al.* 2017; Thompson *et al.* 2020).

7.4.3.1. Thompson *et al*. 2020

Details of the study approach and results presented in Thompson *et al.* (2020) are provided in Section 7.4.1.3. The plots of probability of response by distance presented in Thompson *et al.* (2020), when interpreted as a deterrence function (i.e. probability of response is assumed to be the proportional reduction in relative density), allow for an approximate estimation of an EDR according to the definition of Tougaard *et al.* (2013).

With the time-area thresholds calculated on a daily basis, the results for 12-h after exposure (the longest-duration presented) are considered most appropriate from an EDR perspective given the short ADD activation period (15 min) and the 24-h period over which EDRs are implemented. For comparison, also 6-h after exposure is presented. A plot with the probability of a harbour porpoise response 12-h and 6-h post-ADD exposure (60 km truncation distance; Figure 7 in Thompson *et al.* (2020)) was used in the graphreader online tool. The sampled curve data were exported as a CSV file and for 200 m increments of distance, the number of porpoises disturbed vs non-disturbed was estimated (assuming a theoretical uniform density of animals). The distance at which the number of porpoises disturbed was equal to non-disturbed has been then estimated using the sampled curve and presented as an EDR in Table 18. Following the same methodology, an EDR for a 12-h and 6-h response and 40 km truncation distance was estimated (Table 18) based on Figure S7b and S7c presented in the supplementary material from Thompson *et al.* (2020).

For the respective truncation distances, the resulting EDRs at 12-h post-exposure are smaller than those at 6-h post-exposure. This outcome is expected, as some individuals may have begun to return to the study area over the extended period. As outlined earlier, given that time-area thresholds are evaluated daily, the 12-h post-exposure results are deemed more appropriate for assessment and are therefore considered further.

While the distance at which a > 50% probability of response (‘R_{50}’, hereafter) in a 12-h period after exposure is 3.9 km, the corresponding EDR is much larger, at c. 14.2 km. It is important to note that these results correspond to a deterrence function which extends to the maximum range at which the PAM network could monitor, that is, 60 km from the ADD source, where the modelled probability of response reaches almost zero. Thompson *et al.* (2020) highlight that they detected a few significant responses at > 40 km, which were unlikely to be a result of ADD exposure as harbour porpoise are unlikely to detect ADD signals above background noise at these distances. While truncating data to 40 km made little difference to the modelled relationship at closer distances and yielded approximately the same R_{50} value, the corresponding estimate of EDR for a 12-h period is much smaller (8.0 km). This highlights the sensitivity of EDR estimates to decisions around the distance at which data are truncated and/or responses are assumed to be zero, at least from this modelling approach.

While not meeting the definition of an EDR, it is also useful to consider the maximum distance at which a response to the ADD was recorded, as indicated by the actual values plotted over the deterrence functions (and provided in the supplementary data) presented in Thompson *et al.* (2020). As every ‘positive’ response represents a change greater than the 99th percentile of changes among baseline data, there is a high degree of certainty that these are not a stochastic change unrelated to the ADD activity. These values, therefore, show that the maximum recorded distance to a response was 11.0, 15.5 and 24.5 km for the 12-h, 6-h and 3-h response periods, respectively (with data truncated to 40 km).

Table 18. Estimated EDRs from Thompson *et al.* (2020) study.

Scenario	R50[1] (km)	Maximum distance to a recorded response (km)	EDR (km)	*p(response)* at EDR
12-h after exposure, 60 km truncation distance	3.9	45	14.2	0.159
12-h after exposure, 40 km truncation distance	4.0	11	8.0	0.208
6-h after exposure, 60 km truncation distance	13.7	50	21.6	0.268
6-h after exposure, 40 km truncation distance	11.5	16	13.5	0.336

[1] The distance at which there is a 50% proxy p(response).

7.4.3.2. Dähne *et al.* (2017)

Details of the study approach and results presented in Dähne *et al.* (2017) are provided in Section 7.4.1.4. The paper includes a figure (Figure 2) which plots the %PPM during a baseline period (3 h prior to ADD activation), during the ADD activation, during piling, and in 1-h bins for 24 h post-piling. A plot is provided for each of six distance bins starting at 1.5–3 km and up to 15 - 18 km from the ADD/piling location. Using the graphreader online tool, values of %PPM were extracted for the baseline and ADD activation periods for each of the six plots. We then calculated the proportional reduction in %PPM between the baseline and ADD activation period for each of the distance bins as a proxy for the probability of response, p(response). Values of p(response) were plotted vs distance to piling, taking the mid-point of each distance bin (e.g. 4.5 km for the 3–6 km bin). Two additional data points were plotted to complete the deterrence function: a p(response) of 1.0 at 0 km distance to account for the assumption that all animals were deterred from the immediate vicinity of the ADD; and a p(response) of zero at 19.5 km based on the assumption that animals were not responding to the noise source at this range. The latter assumption may slightly underestimate the maximum extent of responses to the ADD as there was a significant reduction in %PPM for the 15–18 km distance bin, although not in the 12–15 km distance bin.

A non-linear least squares model was fit to these data using the ‘nls’ package in R (R-Core-Team 2023), with the model fit digitised in graphreader. The model did not fit exactly through the added values at 0 km and 19.5 km, and adding a weighting to these values to force a fit resulted in a compromise to the fit to the other values. Therefore, to avoid abrupt step changes in the deterrence function at 0 and 19.5 km, we assumed a linear function between the model fit and the added values between 0–2.25 km and 16.5–19.5 km. From the resulting deterrence function, an EDR of 11.1 km was estimated. The distance to the 50%

probability of response (R50) was 6.6 km (Table 19). It is noted that this EDR is smaller than the reported maximum extent of effect (statistically significant decline at 15–18 km), and very similar to the 10.5 km EDR estimated during piling (see Brown *et al.* (2025)).

Table 19. Estimated EDRs from Dähne *et al.* (2017) study.

Scenario	R50[1] (km)	EDR (km)	*p(response)* at EDR
Change in %PPM during ADD operation compared to baseline	6.6	11.1	0.297

[1] The distance at which there is a 50% proxy p(response).

7.4.4. Evidence scores

Detailed methods and results of the evidence scoring exercise are presented in Appendix 2, Table 30; a summary is provided here. Five empirical response studies were reviewed and assigned scores based on specific evaluation criteria (Figure 7, Appendix 2).

All studies were assigned an initial score of 10, with penalties subsequently applied as appropriate for criteria including: the study type, the study's suitability for estimating an EDR; the relevance of the species studied (no penalties applied in this instance), the relevance of the study area to the UK (i.e. water depth); the relevance of the activity to current and near-future UK OWF construction (e.g. ADD duration and type); and, other study limitations (e.g. limited baseline data, limited sample sizes, potential for biases).

The five studies received scores from 6–7, with an average score of 6.8. Common penalties included a lack of ability to estimate an EDR, limited sample size and/or spatial extent of monitoring and ADD durations longer-than-typical for the UK.

7.5. Recommending default EDRs

7.5.1. Overview: evidence base

Reported effects ranges and estimated EDRs among the five studies reviewed are summarised in Table 20, separated by deterrence types/device. These were all empirical response studies with monitoring extending to multiple kilometres from the ADD source.

All five studies included results associated with the Lofitech seal scarer ADD; three exclusively, one where this device was used alongside an Ace Aquatec pinger, and one where data for the Lofitech were contrasted with a FaunaGuard deterrent. Effects ranges reported in studies ranged from 3.9–21.7 km for the Lofitech, and 2.5 km for the FaunaGuard. Two studies presented results from which an EDR could be estimated for the Lofitech ADD, with values of 8.0 and 11.1 km estimated. While these two estimated EDRs might appear approximately similar in size, they are very different in terms of the context and duration of exposures and the analytical approach of the studies. The latter, which applies to all the studies reviewed, complicated comparisons between results.

A challenge when interpreting the evidence relative to current practices in the UK is that several studies involved long (> 60 minutes) ADD durations or did not report this information. However, pronounced responses to shorter exposures were also observed (Thompson *et al.* 2020; Elmegaard *et al.* 2023), as has also been reported in minke whales (Boisseau *et al.* 2021), albeit with only one such study assessing the magnitude of responses over a prolonged recovery period (Thompson *et al.* 2020).

Table 20. Summary of reported effects ranges as well as estimated EDRs for acoustic deterrents among the five studies reviewed.

Category	Reported effects range, km (n= number of studies)	Estimated EDR, km (n= number of studies)
Lofitech [1]	3.9–21.7 (5)	8.0–11.1 (2)
Faunaguard	2.5 (1)	-

[1] Noting that Dähne et al. (2017) analysed a subset of data from various OWFs where pingers were also used and could therefore contribute to deterrence.

7.5.2. Recommending default EDRs

Recommended default EDRs are presented below. These follow consideration of all the evidence reviewed in the current study, including reported effects ranges and estimated EDRs, but also the limitations and relevance of specific evidence.

Due to the limited empirical evidence regarding disturbance ranges for harbour porpoises associated with ADDs other than Lofitech and FaunaGuard (as discussed in Section 7.2.1), EDRs should be assessed on a case-by-case basis, informed by modelling provided by the project proponent.

For use of the Lofitech seal scarer ADD for short durations, the evidence, while limited, suggests an EDR of up to 8 km.

- This is based on a single empirical study and single exposure event of a 15 minute duration, which received a score of 7 out of 10 (Thompson *et al.* 2020). This EDR is based on the response of animals averaged over a 12-h period; it can be expected that an average response to a single short exposure over 24-h would be less, although potentially not in the context of other noise-generating activities or multiple exposures within 24-h.
- Additionally, results from Elmegaard *et al.* (2023), a study with the same score of 7 out of 10, also reported pronounced responses to exposures of 15 minutes ADD duration at 7 km distance.

For use of the Lofitech seal scarer ADD for long durations, the evidence, while limited, suggests an EDR of 11 km.

- This is based on a single study (score 7 out of 10) across multiple exposures of average 66 minutes duration (range 37–235 minutes) in advance of impact pile driving with noise abatement (Dähne *et al.* 2017). However, results from other studies of longer exposures of > 60 minutes (Brandt *et al.* 2013c, and likely Voss *et al.* 2023) report near-complete deterrence to 5–10 km, such that responses can be expected to extend beyond this distance (these studies scored 6–7 out of 10).

For the use of the FaunaGuard for any duration the evidence, while limited, suggests an EDR of up to 2.5 km.

- This is based on a single study (score 7 out of 10) across multiple exposures of up to 43 minutes in advance of impact pile driving with noise abatement (Voss *et al.* 2023). However, results show that deterrence is of a far smaller magnitude to that observed following exposure to a Lofitech ADD.

8. MBES

8.1. Description of activity

Echo-sounders produce directional acoustic signals pointing towards the seafloor to collect information on bathymetry, seabed characteristics and objects present in the water column (e.g. seabed infrastructure). Single-beam echo-sounders (SBES) emit a pulse of sound in a single narrow cone directed at the seabed which ensonifies a very small volume of the water column. They generate a periodic waveform (as per pinger, chirp and parametric SBPs), not pulsed waveform (as per sparkers, boomer, airguns) (see Section 6.1 for further info). Multi-beam echo-sounders (MBES) use multiple beams elongated in the across-track direction to cover a fan-shaped sector (or swath) of the water column. MBES are usually mounted to the hull of the survey vessel and are used for high-resolution seabed mapping, which can inform geological, oceanographic, or archaeological research, as well as seabed cable routing, and offshore oil and gas exploration. The beams of MBES signals are narrow along the track of the vessel (usually between 1.5–3°) and wide across the track (e.g. 150–160° 3 dB beam widths) (Hartley Anderson Ltd, 2020).

There is a range of MBES systems operating at frequencies as low as approximately 12 kHz but more commonly in the ultrasonic range, having central operating frequencies of over 100 kHz. MBES source levels typically range between SPL_{rms} 210–240 dB re 1 µPa @ 1 m, depending on the system configuration, with the highest levels corresponding to the lowest frequency systems such as the 12 kHz system, often called ‘high-power’. For collecting information on the seabed, lower frequency systems (typically 10–50 kHz) are designed for deep waters, medium frequency systems (typically 70–150 kHz) are generally designed for continental shelf depth, while high-frequency systems (> 200 kHz) are designed for shallower shelf depths (to tens of metres), or an equivalent distance above the seafloor if deployed at depth (Lurton 2016).

Only MBES systems with a central frequency of ≤ 12 kHz require inclusion into the Marine Noise Registry (JNCC 2016), as are considered to fall into the MNR’s scope of loud, low- to medium-frequency impulsive noise. Compared to higher-frequency devices, echosounders of ≤ 12 kHz have been identified as having the greatest potential for impacts to marine mammals (e.g. Cholewiak *et al.* 2017). Such activities are uncommon in UK waters and are typically restricted to deeper waters beyond the shelf habitats of harbour porpoise. MNR records for 2020 to 2024 were downloaded and included only eight completed MBES activities over the five-year period. Of these, only five included information on the operating frequency which did not appear to be erroneous (one activity was listed as 300 Hz which was likely either 300 kHz or not MBES).

8.2. Current recommended EDRs

The SAC noise guidance (JNCC 2020) recommends an EDR of 5 km for HRGS. This encompasses a variety of HRGS sources, including MBES and SBPs (see Section 6). The guidance does not reference specific studies on porpoise responses to MBES to support this EDR. Instead, the 5 km value is a precautionary value based on the expected deterrence effects of HRGS sources in general being less extensive than those caused by seismic (airgun) surveys, given source characterisations (Crocker *et al.* 2019). A recommended default EDR of 5 km is specifically assigned to MBES in the MNR disturbance tool (JNCC 2023a), with this only applied to MBES activities with a central operating frequency of ≤ 12 kHz, given the upper frequency limit of MBES data accepted in the MNR (JNCC 2023a).

As for seismic and SBP surveys, MBES surveys comprise a moving sound source and the area of potential disturbance will vary depending on the location of the survey in relation to the SAC and the number of line turns, etc.

8.3. Approach to evidence review

As described above, the EDR for MBES is currently applied only to activities with a central operating frequency of ≤ 12 kHz, and these are the focus of our review. However, due to the paucity of evidence relating to harbour porpoise and MBES of any type, the scope of our review has been expanded to include:

(i) empirical response studies on other species of cetacean to both MBES and SBES, and

(ii) (ii) limited consideration of measurement and modelling studies of MBES with a central operating frequency of ≤ 200 kHz with the potential for overlap with the hearing range of harbour porpoise.

Studies only measuring sound levels within a few metres of the source (e.g. Risch *et al.* 2017; Cotter *et al.* 2019; Crocker *et al.* 2019) are not included.

Where results allow, for each of the studies undertaking modelling, ranges to the Level B harassment threshold for impulsive noise (SPL_{rms} 160 dB re 1 µPa) are reported.

8.4. Evidence

In Sections 8.4.1 to 8.4.3, we provide summary reviews of relevant empirical, as well as noise measurement and modelling studies identified in our review for MBES.

In Section 8.4.4 we provide a tabulation of all evidence reviewed in the current study for this noise source, including specific features of the activities (e.g. region, water depth, MBES type) and the reported spatial extent of deterrence effects / distance to threshold levels. Results of the evidence scoring exercise for MBES is provided in Section 8.4.6.

8.4.1. Empirical response studies

8.4.1.1. Kates Varghese *et al.* (2021) - Beaked whale responses to MBES surveys (12 kHz)

Kates Varghese *et al.* (2021) assessed the spatial foraging effort of goose-beaked whales (*Ziphius cavirostris*) during two MBES surveys conducted in deep water (> 800 m) off San Clemente Island, California, USA. Monitoring was conducted by a large array of 89 hydrophones covering an area of approximately 1,800 km^2. The MBES was a Kongsberg EM 122 with a 12 kHz centre operating frequency and an estimated source level of SPL_{rms} 239–242 re 1 µPa @ 1m. During the first survey, foraging activity occurred in the same general areas during all analysis periods (before, during and after the MBES survey). In the second survey, two years later, the foraging hotspot shifted between the before, during and after periods. While the authors could not confirm whether the change detected in second survey was a result of MBES activity or some other environmental factor, they concluded that the results strongly suggest that the level of detected foraging during either MBES survey did not change at a broad scale and mostly remained in historically well-utilised foraging locations in the area. These results do not allow estimation of an EDR or quantification of the extent of avoidance.

8.4.1.2. Cholewiak *et al.* (2017) - Beaked whale responses to a scientific SBES survey (18–200 kHz)

Cholewiak *et al.* (2017) conducted visual and acoustic cetacean assessment surveys in the deep waters (shelf break and abyssal) of the western North Atlantic in which multiple scientific SBES were used to characterize the distribution of prey along survey tracklines. The echosounders were Simrad EK60s operating simultaneously at the frequencies of 18, 38, 70, 120 and 200 kHz. Echosounders were alternated daily between active and passive mode, to determine whether their use affected visual and acoustic detection rates of beaked whales. Across all data, the average radial distances to beaked whale sightings were similar between active and passive mode (no significant difference); however, radial distances were significantly smaller (mean 3.5 km when active vs 2.7 km when passive; only when data from two days of extremely high numbers of sightings were removed as a part of the sensitivity analysis). Regression analyses using GLMs found that sea state and region were primary factors in determining visual sighting rates, while echosounder state was the primary driver for acoustic detections, with significantly fewer detections (only 3%) occurring when echosounders were active. The authors concluded that beaked whales both detect and change their behaviour in response to commercial echosounders, suggesting that this could indicate interruption of foraging activity or vessel avoidance. As monitoring did not extend beyond the limit of visual or acoustic detections, an EDR or maximum extent of avoidance cannot be estimated from these results.

8.4.1.3. Quick *et al.* (2016) - Pilot whale responses to a scientific SBES (38 kHz)

Quick *et al.* (2016) exposed five tagged short-finned pilot whales (*Globicephala macrorhynchus*) to a scientific SBES in deep water (> 200 m) off Cape Hatteras, USA. The device was a Simrad EK60 operating at 38 kHz with an estimated source level of SPL_{rms} 224 dB re 1 µPa @ 1m. The maximum received noise level of exposed animals was between SPL_{rms} 119–125 dB re 1 µPa. A model to characterise diving states provided no evidence for a change in foraging behaviour associated with exposure, however whales did change their heading more frequently when the SBES was active, which could represent increased vigilance. The study did not report the distance between the SBES and tagged animals, but the experimental design (small vessels and animals within visual sight when exposed) suggests that it was likely to be of the order of no more than hundreds of metres. These results indicate a subtle change in behaviour associated with exposure to SBES, but do not allow estimation of an EDR or quantification of an extent of avoidance.

8.4.2. Noise measurement studies

8.4.2.1. Halvorsen and Heaney (2018) - Measurements of 200 kHz MBES and 38 kHz SBES

Halvorsen and Heaney (2018) build on calibrated source level measurements of a variety of high-resolution geophysical sources (Crocker *et al.* 2019) with measurements in shallow (≤ 100 m depth) open-water environments to investigate sound propagation (Halvorsen & Heaney 2018). While it is acknowledged that these results suffered from challenges in data collection and are incompletely calibrated (Labak 2019), it is worth noting some general patterns observed from the open-water tests. Tested devices included two MBES with a centre operating frequency of 200 kHz (Reason 711, 7125) and a SBES with a peak frequency of 38 kHz (EK60). In all open-water test environments, distances to the SPL_{rms} 160 dB re 1µPa threshold were < 200 m from the source for all three devices.

8.4.3. Noise modelling studies

8.4.3.1. Ruppel *et al.* (2022)

Building upon the calibrated test-tank measurement results presented by Crocker *et al.* (2019), Ruppel *et al.* (2022) conducted a comprehensive evaluation of the potential for active acoustic sources, including MBES, to cause incidental take of marine mammals. This assessment specifically considered Level B harassment under the NMFS exposure criterion (SPL_{rms} 160 dB re 1 µPa threshold). The authors concluded that even in the worst-case scenario for MBES systems, for example lowest operational frequency (12 kHz), highest source levels (SPL_{rms} 245 dB re 1 µPa), largest along-track beamwidth, and stationary animal located only 100 m below the ship, the combination of factors that make up the degree of exposure (radiated power; exposure duration; the number of pings exceeding the threshold; typical animals densities in US waters) indicate that MBES systems have such minimal impact that they are unlikely to result in incidental take and could be considered *de minimis* with respect to SPL_{rms} 160 dB re 1 µPa criterion.

8.4.3.2. NMFS (2020) Tool

The US NMFS provide recommendations for estimating sound propagation from HRGS sources. This is accompanied by a tool for users to estimate horizontal ranges to the SPL_{rms} 160 dB re 1 µPa (Level B harassment) threshold based on input values of: source level, frequency, beamwidth and water depth. This tool was used to estimate horizontal distances for a selection of water depths for an example 12 kHz MBES system with a source level of SPL_{rms} 240 dB re 1 µPa and a beamwidth of 130 degrees, which are indicative of a high-power MBES system. Water depth is an important consideration as at shallower depths the seabed footprint of the swath and horizontal propagation is limited. The tool estimated the horizontal distances to the Level B harassment threshold (SPL_{rms} 160 dB re 1 µPa) as 0.45 km, 2.1 km, and 3.6 km for water depths of 200 m, 1,000 m, and 2,000 m, respectively.

8.4.3.3. Lurton (2016)

Lurton (2016) analysed the MBES radiation characteristics (pulse design, source level, radiation directivity pattern) in the context of their potential impacts on marine mammals. The authors modelled the sound fields radiated by three generic types of MBES systems, noting that although none of them are strictly an actual commercial system, their characteristics are representative of models operated across marine industries. The first MBES system operated at high frequency (100 kHz), with an assumed source level of SPL_{rms} 220 dB re 1 µPa @ 1 m and a modelled water depth of 200 m. The second was a medium-low frequency (30 kHz) system, with an assumed source level of SPL_{rms} 230 dB re 1 µPa @ 1 m and a modelled water depth of 2,000 m. The third MBES was a multi-sector low-frequency system (12 kHz) with an assumed source level of SPL_{rms} 240 dB re 1 µPa @ 1 m and a modelled water depth of 5,000 m.

Visual interpretation of the modelled sound fields in the across-track plane (see Figures 9, 10, 11 and 17 of Lurton (2016)) showed estimated horizontal distances to a Level B harassment threshold (SPL_{rms} 160 dB re 1 µPa) of approximately 0.2, 1 and 4 km for the 100, 30 and 12 kHz MBES systems, respectively.

8.4.3.4. LGL Limited (2014) - 30 kHz MBES off Nova Scotia

An environmental assessment was conducted to assess the effects of MBES surveys within the southwest Scotian Slope region off Nova Scotia on marine mammals (LGL Limited 2014). Water depths around the project area range from 339–3,145 m. As part of the assessment, it was assumed that the MBES will be hull mounted at a depth of approximately

3–7 m and that the operating frequency will be 30 kHz. Underwater noise propagation modelling was conducted by Jasco Applied Sciences using a representative MBES (model Kongsberg EM 302) and the following characteristics were assumed during modelling: source level of SPL_{rms} 228 dB re 1 µPa @ 1 m (1 second), ping duration of 200 ms, MBES depth of 5.5 m, and a 2°x 2° beamwidth. A wider along-track beamwidth of 2°x 150°equi-angled swath was selected for modelling to account for the larger radii. Moreover, the acoustic signature for one swath was duplicated to take into account the ability of the EM 302 model of surveying with two swaths. To account for variations in sound speed profiles, two different sets of modelling results were produced for the months of May and July. By using the Level B harassment threshold (SPL_{rms} 160 dB re 1 µPa), it was predicted that the distance where responses would likely occur would be up to 2 km from the sound source.

8.4.4. Tabulation of evidence relating to harbour porpoise response ranges from MBES survey

In Table 21, we provide a tabulation of reviewed studies for MBES, including features of the study areas (region, water depth), equipment characteristic (equipment model, operating frequency, and source level) and the spatial extent of effects. Please note that the Kates Varghese *et al.* (2021) and Quick *et al.* (2016) studies are not included in the table as these did not provide distances between the sound source and exposed animals. Similarly for Ruppel *et al.* (2022), given that the distances to Level B harassment threshold were not explicitly quantified and assessed as *de mimis,* it is not included in Table 21.

Table 21. Summary of evidence relating to harbour porpoise and other cetacean species response ranges from SBES/MBES. "-" = Not Available; "N/A" = Not Applicable.

Study		Region	Water depth	Equipment used	Survey duration	Equipment frequency	Equipment source level (SPL_{rms})	Reported and estimated spatial extent of effect and description
Empirical response studies	Cholewiak *et al.* (2017)	North-west Atlantic	100 m to > 2,000 m	Multiple Simrad EK60s SBES	63 days across 2 years (2011, 2013)	18–200 kHz	Not reported	**3.5 km** = Average radial distance to beaked whale sightings when SBES active (significantly larger than the 2.7 km when not active).
Noise measurement studies	Halvorsen and Heaney (2018)	North-west Atlantic	≤ 100 m	Simrad EK60 SBES, Reason 7111, 7125 MBES	N/A	38 kHz, 200 kHz	Up to 229 dB re 1 µPa	**< 0.2 km** = Average distance to SPL_{rms} 160 dB re 1 µPa threshold.
Noise modelling studies	NMFS (2020) tool	N/A	200 m	N/A (MBES with 130 degree beam width)	N/A	12 kHz	240 dB re 1 µPa	**0.45 km** = Horizontal range to SPL_{rms} 160 dB re 1 µPa threshold.
			1,000 m					**2.1 km** = Horizontal range to SPL_{rms} 160 dB re 1 µPa threshold.
			2,000 m					**3.6 km** = Horizontal range to SPL_{rms} 160 dB re 1 µPa threshold.
	Lurton (2016)	N/A	5,000 m	-	-	12 kHz	240 dB re 1 µPa	**~4 km** = Maximum distance to SPL_{rms} 160 dB re 1 µPa threshold.

Study		Region	Water depth	Equipment used	Survey duration	Equipment frequency	Equipment source level (SPL_{rms})	Reported and estimated spatial extent of effect and description
Noise modelling studies	Lurton (2016)	N/A	5,000 m			30 kHz	230 dB re 1 µPa	**~1 km** = Maximum distance to SPL_{rms} 160 dB re 1 µPa threshold.
						100 kHz	220 dB re 1 µPa	**~0.2 km** = Maximum horizontal distance to SPL_{rms} 160 dB re 1 µPa threshold.
	LGL Limited (2014)	Nova Scotia, Canada	339–3,145 m	Kongsberg EM® 302 MBES	Up to 20 days	30 kHz	221 dB re 1 µPa	**2 km** = Maximum distance to SPL_{rms} 160 dB re 1 µPa threshold.

8.4.5. Estimation of EDRs from existing data

No studies were assessed as suitable for estimation of EDR for MBES.

8.4.6. Evidence scores

Detailed methods and results of the evidence scoring exercise are presented in Appendix 2, Table 31; a summary is provided here. One empirical response study, one noise measurement and three noise modelling studies were reviewed and assigned scores based on specific evaluation criteria (Figure 7, Appendix 2).

All studies were assigned an initial score of 10, with penalties subsequently applied as appropriate for criteria including: the study type, the study's suitability for estimating an EDR (empirical response studies only); the relevance of the species studied, the relevance of the study area to the UK (i.e. water depth); relevance of the activity to the UK waters and other study limitations (e.g. study design).

The one empirical response study was assigned a score of 4, with penalties applied for the lack of EDR estimation, a non-porpoise species, and deeper waters and higher frequencies than considered in UK harbour porpoise SAC management. The single noise measurement study received a score of 5, with a penalty for only including equipment with frequencies > 12 kHz. The three noise modelling studies received scores between 2 and 4, with an average of 3. The average score across all three study types was 4.

8.5. Recommending default EDRs

8.5.1. Overview: evidence base

A summary of reported and estimated effects ranges for SBES and MBES are presented in Table 22.

Table 22. Summary of reported and estimated effects ranges and estimated EDRs for SBES and MBES.

Category	Reported effects range, km (n= number of studies)	Estimated EDR, km (n= number of studies)
SBES	3.5 (1)	Data from the reviewed studies did not allow for EDR estimation
MBES	< 0.2–4 (4)	
SBES and MBES	< 0.2–4 (5)	

It should be noted that there is no empirical evidence of harbour porpoise response to SBES and MBES. The only empirical study identified for this review reported average radial distance to beaked whale sightings when SBES active compared to inactivity periods (3.5 km vs 2.7 km) (Cholewiak *et al.* 2017). However, there is uncertainty whether harbour porpoises would respond to this noise source at the same distances. The noise measurement study in water depths comparable to the ones within the UK SACs reported an average distance to the level B threshold of approximately 0.2 km (Halvorsen & Heaney 2018). The noise modelling studies reported up to a distance of 4 km to the 160 dB re 1 μPa threshold for MBES using a 12 kHz frequency (LGL Limited 2014; Lurton 2016; NMFS 2020). It should be noted that the reported distances for the noise measurement and noise modelling studies assume that the animal receiving the sound is within the main beam of the source signal, with lower levels of exposure off-axis.

8.5.2. Recommended default EDRs

There is an absence of empirical data on the responses of free-ranging harbour porpoises to low-frequency MBES and limited evidence of reported responses among beaked whales to an array of SBES (this review identified one study which received a score of 4 out of 10). Further, noise measurement studies are lacking for equipment operating at ≤12 kHz, and so low-scoring (2 to 4 points out of 10) modelling studies which all use similar assumptions dominate the evidence base. Given these limitations, there is a high degree of uncertainty in any recommendations for a default EDR.

Despite the limited evidence base, reported effects ranges are all ≤ 4 km. Values closer to 4 km relate to a complex multiple SBES array or MBES use in deep water (> 1,000 m) and for the lowest frequencies. Even at 12 kHz and high source levels, the beam pattern of MBES is such that distances to assumed response thresholds are estimated to be < 500 m.

Suggested options for precautionary recommended default EDRs include:

- **5 km** for multiple-transducer SBES or MBES with an operating frequency of ≤ 12 kHz operating in waters > 200 m depth.
- **3 km** for multiple-transducer SBES or MBES with an operating frequency of ≤ 12 kHz operating in waters ≤ 200 m depth.

While the 5 km and 3 km suggestions above may seem overly-conservative, they reflect the uncertainty among the evidence base, particularly the applicability of the Level B harassment threshold (SPL_{rms} 160 dB re 1µPa) in the context of echo-sounder signals, harbour porpoise, and how this relates to average habitat loss. Until empirical response data specific to harbour porpoise are available, such a precautionary approach is advised.

It is emphasised that the suggested EDRs apply only to complex multi-transducer SBES or MBES with an operating frequency of ≤ 12 kHz, to align with current MNR reporting requirements. However, it is possible that other devices operating within the lower end of the harbour porpoise hearing range may also require consideration from a disturbance perspective, particularly when operated in deeper waters - such activities should not be disregarded from future opportunities for empirical response studies.

9. Military sonar

9.1. Description of activity

Sonar (Sound Navigation and Ranging) is a technology used primarily for underwater detection, navigation and communication. Active sonar operates by emitting sound waves into the water and analysing the returning echoes that reflect off objects. Military sonars typically comprise an array of transducers mounted on the hull of a vessel or deployed from a vessel or helicopter (dipping sonar) and their primary application is submarine detection and tracking. Most systems are broadly categorised as low-frequency or mid-frequency active sonar (LFAS, MFAS). LFAS operates at < 1 kHz and typically between 100–500 Hz, while MFAS operates between 1–10 kHz and most typically with centre frequencies between 3.5–8 kHz (Hartley Anderson Ltd 2020). Source levels can be in the range SPL_{rms} 230–240 dB re 1 µPa @ 1m (Finneran & Jenkins 2012). Conventional military sonar generates a periodic signal of approximately 1–2 s duration followed by a long listening time, whereas continuous active sonar (CAS) emits much longer signals (e.g. 18–19 s) with short breaks of no more than a couple of seconds between signals (Hartley Anderson Ltd 2020). Energy is primarily directed horizontally. The majority of reported military sonar use in UK waters relates to MFAS for testing and training exercises.

Military sonar is known to negatively affect cetaceans, disrupting behaviours like feeding, resting, and communication (Harris *et al.* 2018). High-intensity exposure can cause auditory injuries and severe flight responses, sometimes leading to stranding and death (D'Amico *et al.* 2009). This has led navies to prioritise behavioural response studies (BRS) to investigate if an empirical relationship can be established between sonar and behavioural disruption in cetaceans. Most military sonar BRS studies have been conducted on beaked whales as they are well known for stranding in response to this sound source, therefore the responses of other species are still underrepresented in the literature.

Military sonar do not currently have a recommended default EDR (JNCC 2020, 2023a).

9.2. Approach to evidence review

In Section 9.3.1 below, we provide summary reviews of relevant empirical studies reporting the responses of marine mammals to military sonar. These studies utilise acoustic, movement and GPS tags to assess the responses of free-ranging cetaceans to experimental military sonar exposures. Additionally, one noise modelling study (Section 9.3.2) is considered which assessed the behavioural response zone for harbour porpoises using three thresholds, depending on signal characteristics (Kastelein *et al.* 2015a; Andersson & Johansson 2016).

9.3. Evidence

There are currently no studies within the literature that report behavioural responses of free-ranging harbour porpoise to military sonar. Therefore, we have considered empirical studies carried out on other odontocete species such as beaked whales and focussed on those which report distances from sound sources at which animals responded (Section 9.3.1). Several empirical studies were also identified which focused on the received sound levels at which animals responded but did not report response distance; these are summarised in Section 9.3.1.6. Additionally, harbour-porpoise specific studies in experimental settings are discussed in Section 9.3.1.7. One noise modelling study has been identified as relevant for this review and is discussed in Section 9.3.2.

In Section 9.3.3 we provide a tabulation of all evidence reviewed in current review for military sonar, including specific features of the activities (e.g. region, water depth, sonar type) and the reported spatial extent of deterrence effects / distance to threshold levels. Results of the evidence scoring exercise for military sonar is provided in Section 9.3.5.

9.3.1. Empirical response studies

9.3.1.1. Wensveen *et al.* (2025) - Sperm whales

Wensveen *et al.* (2025) conducted Controlled Exposure Experiments (CEEs) using acoustic, movement and GPS tags (mixed-DTAGs) to measure behavioural responses of sperm whales (*Physeter macrocephalus*) to LFAS in deep waters of the Norwegian Sea. Nine experiments were conducted on 14 tagged individuals, all assumed to be male. Whales were exposed to a range of signal types from one of two different types of LFAS, operating at a frequency of 1.3–1.9 kHz and source levels of up to SPL_{rms} 206–220 dB re 1 µPa. Exposures were started at either 7.4 or 14.8 km from focal whales and approached at an angle of 45 degrees to their path. Sonar source levels were increased stepwise over the 20 minutes exposure period. Control sessions followed the same approach but with sonar not active. Statistical models were developed to explore the effects of distance, received level and other covariates on whales' behaviour. The probability of occurrence of non-foraging active behaviour was affected by received level, source distance and session order, with decreased foraging effort at higher received levels and shorter distances to source, and during subsequent sessions (indicating short-term sensitisation). There was 95% confidence that the probability of the non-foraging active state was increased above baseline levels to a maximum distance of 13 km (at the highest received levels of approx. $SPL_{rms} \geq 160$ dB re 1 µPa). The authors concluded that, similar to what has been suggested for some populations of blue whales (*Balaenoptera musculus*) and beaked whales regularly exposed to navy sonar, but unlike northern bottlenose whales in more pristine waters, source distance affected sperm whale behavioural responses to LFAS on a high-latitude foraging ground (Wensveen *et al.* 2025).

9.3.1.2. Southall *et al.* (2024) - Common dolphins

Southall *et al.* (2024) conducted CEEs using drone-based photogrammetry, acoustic recorders and visual observations to measure behavioural responses of long-and short-beaked common dolphins (*Delphinus delphis*) to MFAS (3–4 kHz) using simulated and actual Navy sonar sources. Initial exposure ranges to focal groups were between 0.6–6.9 km of sonar sources, with animals experiencing maximum received levels typically in the range of SPL_{rms} 140–160 dB re 1 µPa. Changes in subgroup movement and aggregation parameters were commonly detected during MFAS CEEs but not control CEEs. Responses were more evident in short-beaked common dolphins (n = 14 CEEs), and a direct relationship between response probability and received level was observed. Long-beaked common dolphins (n = 20) showed less consistent responses, although contextual differences may have limited which movement responses could be detected. This study provides evidence that common dolphins exhibit behavioural responses to MFAS when exposed to the aforementioned noise levels and within ranges of < 7 km. However, results do not allow estimation of a maximum response range, and it is noted that the observed responses were less pronounced than those reported from some studies of beaked whale responses to sonar exposure.

9.3.1.3. Wensveen *et al.* (2019) - Northern Bottlenose whales

Wensveen *et al.* (2019) investigated the behavioural responses of tagged northern bottlenose whales (*Hyperoodon ampullatus)* to navy sonar signals in a remote area north of Iceland near the island of Jan Mayen, Norway. The study area is in deep water and the experimental exposures occurred over depths of 1,000–1,500 m. The whales in this area are unlikely to be habituated to sonar, making their responses more pronounced than animals in areas where sonar and other anthropogenic noise is more common.

The authors tagged twelve northern bottlenose whales in total with two types of tags; suction-cup attached DTAGs and position and depth-transmitting satellite tags. The whales were exposed to simulated naval sonar signals using different sonar transmission protocols in three experiments conducted across 2015 (*n* = 2, close range exposures) and 2016 (*n* = 1, distant exposure).

In the close-range exposures in 2015, the sound source deployed was a drifting speaker deployed from a sailing research vessel at a source depth of 8 m and was comprised of a series of simulated sonar pulses designed to be representative of military active sonars. The signal type was a tonal hyperbolic upsweep with a source level of 122 dB re 1 µPa and 185 dB re 1 µPa, a frequency band of 1–2 kHz, a pulse duration of 1 second and a pulse interval of 20 seconds. The focal whales were ≤ 1 km from the sound source at first exposure and the duration of exposure was 15 minutes. Behavioural responses were reported in the focal whale fitted with a DTAG during both low and high source level exposures. Extreme avoidance was reported in response to the higher source level exposure, with the whale continuing to move away from the source for 6.5 hours without resuming foraging. Avoidance behaviour was not apparent in two other tagged animals.

In the distant exposure experiment in 2016, the sound source was a drifting speaker deployed from a drifting sailing research vessel at a source depth of 17 m. The signal type was a compound signal (500 ms linear upsweep from 3,350–3,450 Hz, followed by 500 ms tones at 3,600 Hz and 3,900 Hz) with a source level of SPL_{rms} 154–214 dB re 1 µPa, a frequency band of 3.4–3.9 kHz, a pulse duration of 1.5 seconds and a pulse interval of 25 seconds. The duration of exposure was 20 minutes for both. A total of seven whales were tagged, with one focal whale fitted with a DTAG and the remaining six whales fitted with satellite tags. The focal whale was 17 km from the sound source at first exposure and showed an immediate behavioural response with an atypically long deep dive, displayed avoidance behaviour for at least 7.5 hours and moved 37 km away from the exposure site. The satellite tagged whales were at distances ranging from 14.6–28.1 km from the sound source at first exposure and showed a behavioural response at a received SPL range of 117–129 dB re 1 µPa.

In summary, tagged whales initiated avoidance of the sonar sound source over a wide range of distances (0.8–28 km), with responses characteristic of beaked whales. Received noise levels were a better predictor of responses than distance.

9.3.1.4. Joyce *et al.* (2019) - Blainville's Beaked Whales

This study sought to document behavioural responses to MFAS exposure by using opportunistic observational data from medium-duration satellite tags deployed on Blainville's beaked whales (*Mesoplodon densirostris*) between 2009 and 2015 in the Tongue of the Ocean region of the Bahamas. Individuals were exposed to MFAS during naval sonar exercises at the Atlantic Undersea Test and Evaluation Center (AUTEC) over the course of several multi-ship MFAS exercises involving up for four surface ships and accompanying helicopter dipped sonar units. The whales were exposed to modelled received sound levels ranging from an initial maximum of SPL_{rms} 145–172 dB re 1 µPa, which declined to 70–150 dB re 1 µPa as the whales moved away from the sonar sources. Whales were tracked in real time using the AUTEC bottom mounted hydrophone array. The initial distance at which each individual was exposed to the sound source is unknown; however, the distances from the AUTEC hydrophone array are provided.

Five of the seven individuals exhibited a behavioural response of a clear and sustained displacement from their pre-exposure locations by moving away from the sonar source. The whales which responded were initially located at distances of < 2 km, 10 km and 29 km. Displacements ranged from 27–68 km, with an average maximum displacement of 44 km from their initial locations. Some individuals returned to AUTEC within days, while others remained displaced. Behavioural responses, including avoidance, occurred at received levels of SPL_{rms} 150 dB re 1 µPa or higher. One individual, which had been consistently seen at AUTEC for five years, did not exhibit displacement despite being exposed to sonar levels at or slightly below 150 dB, suggesting potential habituation or inter-individual variability in response.

9.3.1.5. DeRuiter *et al.* (2013) - Beaked Whales

This study aimed to measure direct behavioural responses of goose-beaked whales to MFAS during the Southern California Behavioural Response Study. The specific sonar used was a simulated MFAS with signals in the 3–4 kHz range. The maximum source level was achieved by a ramp up procedure which gradually increased by 3 dB per transmission from the initial (SPL_{rms} 160 dB re 1 µPa @ 1m) to the maximum (SPL_{rms} 210 dB re 1 µPa @ 1m).

In 2010 and 2011, two whales were tagged with DTAGs which recorded received sound exposure levels and behavioural responses. CEEs were then conducted on both whales with a 1.6-second simulated MFAS signal repeated every 25 seconds for 30 minutes at a distance of 3.4–9.5 km. A strong behavioural response occurred for both whales during the CEEs with received levels as low as SPL_{rms} 89–90 dB re 1 µPa, when both whales paused fluking. Whale 1 ceased echolocation at 98 dB, whereas Whale 2 remained silent throughout the CEE. Avoidance behaviour was triggered at lower levels for Whale 1 (98 dB SPL) compared to Whale 2 (127 dB SPL), but both sustained high-speed swimming (2.6 m/s and 3.1 m/s, respectively) for over an hour post-exposure. Both whales exhibited extended dive durations, with normal deep diving resuming after 6.6–7.6 hours. The whale tagged in 2011 was also exposed to incidental naval sonar from distant exercises (approximately 118 km away). The same SPL levels from the distant naval exercise (78–106 dB SPL) did not elicit a strong response from the second whale, as it continued its normal behaviour.

In summary, tagged beaked whales responded to a 30-minute sonar exposure at distances up to 9.5 km at received levels of SPL_{rms} 98–127 dB re 1 µPa. As this was the furthest initial distance measured it is possible that the response could have extended further.

9.3.1.6. Received Sound Levels Studies

During this review, we identified several studies that did not explicitly report the specific distances at which the animal was located relative to the sonar sound source at the time of the behavioural response. Since these studies do not permit distance estimation, only a selection of them is briefly summarised in this section.

Miller *et al.* (2012) studied behavioural responses of wild killer whales (*Orcinus orca*), long-finned pilot whales (*Globicephala melas*), and sperm whales to naval sonar exposure as part of the 3S project, during which 14 controlled exposure experiments were conducted in Norwegian waters. DTAGs were used to measure sound exposure levels and subsequent movement responses of animals. The source vessel aimed to start sonar exposure at 6–8 km from the tagged whale in each species group and moved towards it gradually. By the end of each of the 30-minute exposure sessions, the sonar source was 100 m away from the focal killer whale, 154 m away from the focal pilot whale, and 150 m away from the focal sperm whale. However, specific distances of behavioural response not recorded for each species, with responses at received levels reported instead. Killer whales exhibited the highest sensitivity to sonar exposure, with behavioural responses initiating at lower received levels (approximately SPL_{rms} 139 dB re 1 µPa, SEL_{cum} 144 dB re 1 µPa^{2}s). Responses included increased speed, altered movement patterns, and prolonged avoidance, with individuals moving 28–30 km from the source within 4–5 hours post-exposure. Sperm whales showed strong behavioural reactions such as increased dive depth (800–1,200 m) and longer dive duration (by up to 90 minutes), particularly to LFAS (1–2 kHz) over MFAS (6–7 kHz). At higher levels (SPL_{rms} ~150–160 dB), they shifted to horizontal movement and moved several kilometres away, with some ceasing vocal foraging. Other responses included increased dive depth and extended submersion (up to 90 minutes), possibly as an anti-predator strategy. Pilot whales exhibited the least sensitivity, showing moderate avoidance and altered group cohesion, with avoidance occurring at SPL_{rms} 150 dB and SEL_{cum} 168 dB.

Southall *et al.* (2012) analysed the data from the Southern California Behavioural Response Study which took place in areas of the Southern California Bight. Three different species of marine mammals were tagged (goose-beaked whales, Risso's dolphin (*Grampus griseus*) and blue whale) and then exposed to real and simulated MFAS as part of a CEE. The sound output was only permitted once the source vessel was ~ 1,000 m from the focal animal or group for all species and this was the 'target range' as per the methodology to meet the specified received level objectives for each species group (SPL_{rms} 110–130 dB for beaked whales; SPL_{rms} 120–150 dB for all other species). The specific distances at which animals exhibited behavioural disturbance were not specified and the study focused on the received noise levels. Goose-beaked whales were exposed to the received levels which ranged from SPL_{rms} 100–140 dB and a strong behavioural response was observed as the animals stopped vocalising, ceased foraging, moved horizontally away from the sound source and changed deep-diving patterns. Risso's dolphins were also exposed to the received levels which ranged from SPL_{rms} 100–140 dB and a mild behavioural response was observed, as the animals increased their vocalizations, and some individuals tightened group cohesion. Blue whales were exposed to the received levels ranged from SPL_{rms} 100–160 dB and a moderate behavioural response was observed as some individuals stopped feeding or altered their foraging behaviour, some individuals increased their swimming speeds and altered their dive patterns.

In summary, the studies described above illustrate that a variety of cetacean species respond to military sonar signals at distances within 10 km, although the nature of responses and corresponding received noise levels is highly variable between species and even individuals. As such, it is difficult to generalise a noise level at which animals will respond and make predictions of the distance at which such noise levels will be experienced.

9.3.1.7. Harbour porpoise captive facility studies

Empirical studies on the behavioural responses of harbour porpoises to military sonar are limited to those performed on animals in captive facilities. The majority of studies examining the behavioural responses of harbour porpoise have been carried out at the SEAMARCO research unit in the Netherlands. All studies were conducted in a pool that was 12 m × 8 m and 2 m deep and therefore do not allow estimation of response distances. However, they can provide evidence that harbour porpoise show responses to the type of signals associated with military sonar and therefore add support to the use of studies on other cetacean species as proxies.

Kastelein *et al.* (2019) investigated the behavioural response of harbour porpoise to a series of four different simulated low-frequency sounds to mimic those emitted from LFAS systems deployed from navy helicopters. All sounds had the same duration (1.25 s), source level (107 dB re 1 µPa) and were produced in a series with regular inter-pulse intervals (14.4 s; duty cycle: 8%). The mean received SPL in the pool was ~97 ±6 dB re 1 µPa for all exposures. The distance at which harbour porpoise was located prior to the sonar activation was not provided. During test sessions with each of the four sounds, the harbour porpoises mean distance to the transducer remained the same (5.9 m, SD ± 0.2 m, n = 30), and the swimming speed and number of surfacing (respirations) were only slightly higher than during baseline periods.

In the study by Kastelein *et al.* (2015b), the focus was on examining the effects of both intermittent and continuous 6–7 kHz sonar sweeps on the hearing and behaviour of a captive harbour porpoise. The porpoise was exposed to sequences of one-second down-sweeps, with the number of sweeps in a sequence varying from 10–200. The average received SPL during these exposures was recorded at 166 dB re 1 µPa. Under control conditions, the porpoise swam an average distance of 7.9 meters (SD ± 0.9 m) away from the transducer and had a respiration rate of 285 breaths per hour (SD ± 649). When exposed to a 10% duty cycle, there was a slight increase in the average distance to 9.5 meters (SD ± 60.8 m), while the respiration rate remained unchanged. With exposure on a 100% duty cycle, the increase in distance was modest, averaging an additional 1.5 meters, and the respiration rate increased marginally to 288 breaths per hour (SD ± 60.0). As with the previous study, the initial distance of the porpoise relative to the transducer before exposure was not reported.

Kastelein *et al.* (2012) investigated whether frequency-modulated up-sweeps and down-sweeps from mid-frequency and low-frequency sonar systems would elicit a startle response in harbour porpoises, which was defined as a sudden change in swimming speed or direction. The study involved exposing the animals to three paired sets of sweeps: a 1–2 kHz up-sweep paired with a 2–1 kHz down-sweep with harmonics, a 1–2 kHz up-sweep paired with a 2–1 kHz down-sweep without harmonics, and a 6–7 kHz up-sweep paired with a 7–6 kHz down-sweep without harmonics. The 50% startle response rate was observed at different received SPL thresholds for the different stimuli: 133 dB re 1 µPa for the 1–2 kHz sweeps without harmonics, 99 dB re 1 µPa for the 1–2 kHz sweeps with strong harmonics, and 101 dB re 1 µPa for the 6–7 kHz sweeps without harmonics.

Collectively, these studies demonstrate that harbour porpoises exhibit measurable behavioural responses to sonar exposures, with the magnitude and type of response varying by the acoustic stimulus and received SPL.

9.3.2. Modelling Study

Andersson and Johansson (2016) is the only modelling study identified as suitable for this review. This study estimated the scale of negative effects on marine mammals, including harbour porpoise, by estimating impact zones from active sonar systems commonly used in the shallow brackish waters of the Baltic Sea and the Skaggerak. By impact zones, the authors refer to a zone around the sound source such that if an animal is within this zone, it risks behavioural disturbance or injury. The calculations used in this study are based on the sound propagation characteristics of the Baltic Sea combined with information on sound level thresholds for physical and behavioural effects.

This study uses a variable depth sonar (VDS) typically used for anti-submarine warfare, that can transmit a variety of pulses at frequencies around 25 kHz and a source level up to 220 dB re 1 µPa @ 1 m. The modelling used three different pulses (all with a center frequency 25 kHz) of which would be appropriate for operational use; a 50-ms frequency-modulated sweep from 24.5–25.5 kHz (FM), a 600-ms amplitude- modulated tone (CW), and a 900-ms combination of a FM part and a tone (Combo). A combination of thresholds based on Kastelein *et al.* (2015a) was used to inform the behavioural reaction zones for harbour porpoise (125 dB re 1 µPa (Combo), 140 dB re 1 µPa (FM), and 155 dB re 1 µPa (CW) depending on signal characteristics.

In the Baltic Sea, impact zones for significant behavioural reactions in harbour porpoise were estimated to extend from 1–20 km around a VDS transmitting at a source level of SPL_{rms} 220 dB re 1 µPa @ 1 m, depending on the threshold and transmission loss assumptions. The extent of the impact zone depended on pulse type and transmission loss, with the Combo pulse having the greatest impact zone. In the Skagerrak (a more saline waterbody) the impact zones became smaller at 0.8–7 km. If the source levels were to be decreased to 200 dB re 1 µPa @ 1 m, the impact zones for behavioural effects for harbour porpoise in the Baltic Sea are decreased to 0.3–10 km and below 4 km in the Skagerrak. The authors noted that the modelled sound source, at 25 kHz, was higher frequency than typical MFAS, and so propagated noise levels and impact zones would be larger for such sources.

9.3.3. Tabulation of empirical response studies relating to military sonar, including the reported spatial extent of deterrence effects

In Table 23, we provide a tabulation of all reviewed empirical response and noise modelling studies, including features of the study areas (region), military sonar characteristics (type, activation protocol, frequency, equipment source level) and the spatial extent of military sonar effects (where reported).

Table 23. Summary of evidence relating to harbour porpoise and other cetacean species response ranges from military sonar. “N/A” = Not Applicable.

Study		**Study species, region (water depth)**	**Type of sonar**	**Exposure duration**	**Frequency (kHz)**	**Sonar source level (SPL_{rms})**	**Reported and estimated spatial extent of effect and description**
Empirical response studies	Wensveen *et al.* (2025)	Sperm whales, Norwegian Sea (deep >> 200 m)	LFAS (SOCRATES or CAPTAS-Mk2)	Up to 21 minutes	1.3–1.9 kHz	206 - 220 dB re 1 µPa	**13 km** = Maximum distance at which there was 95% confidence that the probability of the non-foraging active state was increased above baseline levels.
	Southall *et al.* (2024)	Common dolphins, Southern California, USA (slope > 200 m)	MFAS and simulated sonar	10 minutes	3–4.25 kHz (MFAS) 3.5–4 kHz (simulated)	215 dB re 1 µPa (MFAS) 212 dB re 1 µPa (simulated)	**≤ 6.9 km** = Maximum initial distance between source and dolphins at start of sonar exposure, to which changes in subgroup movement and aggregation parameters were measured.
	Wensveen *et al.* (2019)	Northern bottlenose whales, Arctic, north of Iceland (deep >> 200 m)	Simulated sonar (hyperbolic upsweeps)	15 minutes	1–2 kHz	122 - 185 dB re 1 µPa	**< 1 km** = Distance of the animal from the sound source; immediate behavioural response and movement away from the sound source was observed.
			Simulated sonar (compound signals)	20 minutes	3.4–3.9 kHz	154 - 214 dB re 1 µPa	**17 km** = Distance of the animal from the sound source; immediate behavioural response and movement away from the sound source was observed.

Study		Study species, region (water depth)	Type of sonar	Exposure duration	Frequency (kHz)	Sonar source level (SPL_{rms})	Reported and estimated spatial extent of effect and description
Empirical response studies	Joyce *et al.* (2019)	Blainville's beaked whales, The Bahamas (AUTEC) (deep >> 200 m)	MFAS	Various	3–8 kHz	Not reported	**< 2 km, 10 km, 29 km** = Distances of the animals from the AUTEC array; immediate behavioural response and movement away from the sound source was observed.
	DeRuiter *et al.* (2013)	Goose-beaked whale, Southern California, USA (deep >> 200 m)	MFAS	30 minutes	3–4 kHz	210 dB re 1 µPa	**9.5 km** = Maximum distance of the animals from the sound source; immediate behavioural response was observed (paused fluking, stop echolocating, avoidance, extended dive duration).
Noise modelling studies	Andersson and Johansson (2016)	Harbour porpoise, Baltic Sea, Skaggerak (no depth parameters specified, but environments considered were shallow < 200 m)	Variable depth sonar	N/A	25 kHz	200 - 220 dB re 1µPa	Threshold used (depending on signal characteristic): • 125 dB re 1 µPa (Combo), • 140 dB re 1 µPa (FM), • 155 dB re 1 µPa (CW). **1-20 km (Baltic Sea), 0.8-7 km (Skagerrak)** = Extent of behavioural reaction zone based on source level of SPL_{rms} of 220 dB re 1 µPa

Study		Study species, region (water depth)	Type of sonar	Exposure duration	Frequency (kHz)	Sonar source level (SPL_{rms})	Reported and estimated spatial extent of effect and description
Noise modelling studies	Andersson and Johansson (2016)	Harbour porpoise, Baltic Sea, Skaggerak	Variable depth sonar	N/A	25 kHz	200–220 dB re 1µPa	**0.3-10 km (Baltic Sea), < 4 km (Skagerrak)** = Extent of behavioural reaction zone based on source level of 200 dB re 1 µPa

9.3.4. Estimation of EDRs from existing data

No studies reported a gradient of responses vs distance to source in isolation to received sound level. Therefore, none were assessed as suitable for estimation of EDR for military sonar.

9.3.5. Evidence scores

Detailed methods and results of the evidence scoring exercise are presented in Appendix 2, Table 32; a summary is provided here. Five empirical response studies and one noise modelling study were reviewed and assigned scores based on specific evaluation criteria (Figure 7, Appendix 2).

All studies were assigned an initial score of 10, with penalties subsequently applied as appropriate for criteria including: the study type, the study's suitability for estimating an EDR (empirical response studies only); the relevance of the species studied, the relevance of the study area to the UK (i.e. water depth); relevance of the activity to the UK waters and other study limitations (e.g. study design).

The five empirical response studies were each assigned a score of between 3 and 5, with an average score of 3.6. This low score reflects several limitations: the studies did not permit estimation of the EDR, they focused on behavioural responses in species other than the harbour porpoise, and they were all conducted in deep water. Additionally, these studies generally only reported the distance at which the animal was located at the time of sonar exposure and the subsequent behavioural response, rather than recording measurements at regular intervals that would allow estimation of the maximum range of responses. The single noise modelling study received a score of 4, with point deductions primarily related to the study type but also its relevance to UK activities (a higher frequency sonar was assumed with much higher transmission loss than typical MFAS). The average scores across both study types was 3.8.

9.4. Recommending default EDRs

9.4.1. Overview: evidence base

A summary of reported and estimated effects ranges for military sonar are presented in Table 24.

Table 24. Summary of reported and estimated effects ranges for military sonar among six studies reviewed.

Category	Reported effects range, km (n= number of studies)	Estimated EDR, km (n= number of studies)
Sonar (all studies)	< 1–29 (6)	Data from the reviewed studies did not allow for EDR estimation
Sonar (empirical studies based on responses from other odontocetes)	< 1–29 (5)	
Sonar (noise modelling study based on harbour porpoise specific threshold)	0.8–7[1] (1)	

Notes: [1] Only including results for the Skaggerak, as Baltic Sea parameters (salinity) are not relevant to UK porpoise SACs.

Across the five empirical studies, the reported effect ranges correspond to the distances at which animals were present at the time of exposure to the sound source, representing a minimum response range. The study designs did not allow for the estimation of the maximum distance at which animals may exhibit behavioural responses. However, it should be noted that Joyce *et al.* (2019) reported that animals located 27 km and 73 km from the AUTEC array did not exhibit avoidance behaviour. It is important to note that these distances refer to the AUTEC range, within which the sound source was located, rather than the precise distance to the sound source itself. Consequently, the values reported in this study (2 km, 10 km, and 29 km) should be interpreted with caution.

While there is evidence from empirical studies on species other than harbour porpoise that distance as well as received level is an important determinant of responses (e.g. Southall *et al.* 2016; Wensveen *et al.* 2025), received level is generally the focus of studies and it is uncommon studies test either factor in isolation. As illustrated in Section 9.3.1 and in the reviews provided by Southall *et al.* (2016) and Southall *et al.* (2021), animals exposed to sonar have shown wide variability in the received levels at which responses have been observed, with a variety of context and species-specific factors likely to be of importance. Numerous field studies have observed responses at received levels substantially lower than the SPL_{rms} 160 dB Level B harassment threshold for impulsive sounds, with the target SPL_{rms} 140–160 dB received levels tested for common dolphins in Southall *et al.* (2024) encompassing many of the reported received levels at which measurable responses have been reported. Additionally, research on captive harbour porpoise indicates that received sound level is not the sole determinant of behavioural responses; other factors, such as the sound spectrum (including harmonics) and duty cycle may also influence behavioural reactions (Kastelein *et al.* 2015b, Kastelein *et al.* 2019).

The applicability of findings from studies of other odontocetes to harbour porpoise is unknown. The hearing capabilities differ between species, with harbour porpoise hearing sensitivity peaking at much higher frequencies than those of MFAS or LFAS, or other odontocete species. However, harbour porpoise hearing is sensitive, with the species known to readily respond to anthropogenic noise sources of a variety of types and frequencies, including simulated military sonar (e.g. Kastelein *et al.* 2015b). As described by Miller *et al.* (2022) following sonar CEE on several species, the different hearing sensitivity of each species was not sufficient to explain the observed difference in responses, and it was suggested that the species that are less vulnerable to killer whale predation were also less responsive to sonar.

A noise modelling study assessed behavioural disturbance thresholds for harbour porpoises in response to different sonar signal characteristics. The study estimated larger effect ranges, including up to 20 km in the Baltic Sea assuming very low salinity, but up to 7 km for the Skagerrak, which is more representative of UK porpoise SACs than the Baltic. However, it is noted that the sonar source used in this study (25 kHz) was much higher frequency than the MFAS (3.5–8 kHz) understood to be most commonly used in UK waters (Hartley Anderson Ltd 2020); therefore, equivalent impact zones for MFAS would be larger.

9.4.2. Recommended default EDRs

There is an absence of empirical data on the responses of free-ranging harbour porpoises to sonar, wide variability in reported responses among other species, and limitations to the evidence from other species in terms of estimating effects ranges. As such, the evidence base is limited and scored low (scores between 3–5 out of 10) in the context of estimating harbour porpoise EDRs. Given these limitations, there is a high degree of uncertainty in any recommendations for a default EDR.

Based on distances reported for other species and limited noise modelling results (recognising that the modelling study would underestimate responses ranges for typical MFAS use in UK waters), it can be expected that harbour porpoise may respond behaviourally to military sonar to **at least 10 km** from the sonar sound source. However, given the uncertainty of the evidence, that avoidance responses among other species have been reported beyond 10 km, and the known sensitivity of harbour porpoise to a variety of anthropogenic noise sources, it is recommended that a precautionary approach to assigning an EDR for military sonar is adopted. For example, one such precautionary option would be to adopt an EDR for military sonar consistent with the largest EDR of other impulsive noise sources recommended in the current review (i.e. high-order UXO clearance and/or unabated impact piling).

10. Recommended priorities for filling evidence gaps

10.1. UXO clearance

The past few years have seen a substantial increase in the understanding of noise levels associated with UXO clearance, including both high-order and low-order clearance activities. However, in terms of how harbour porpoise respond to these activities and the estimation of appropriate EDRs, the evidence base is very limited. The following are suggested as priorities for filling evidence gaps:

- **Empirical studies of responses to UXO clearance of any type, with low-order clearance a top priority.** While low-order clearance can be expected to result in smaller disturbance ranges than high-order clearance without abatement, this is currently not supported by any empirical response data. As low-order is now the recommended clearance method (Defra *et al.* 2025; JNCC 2025c), collecting empirical data on porpoise responses to this activity should be a priority. It is noted that such data were collected during the East Anglia THREE OWF low-order UXO clearance campaign in 2024, which was concurrent to a long-term PAM array (Scala 2023).
- **Explore the potential of existing datasets for assessing empirical responses to high-order UXO clearance.** There is the potential for porpoise responses to UXO clearance to be assessed opportunistically from existing data where spatio-temporal overlap exists between static PAM networks and UXO clearance activity. UK examples to be explored include surveys associated with OWFs in the Forth and Tay region and the Moray Firth (east Scotland). Studies utilising static PAM data in Belgian, Dutch, Danish and German waters may also have the potential to investigate porpoise responses to UXO clearance where such activities overlap in time.
- **Collect additional noise measurement data on UXO clearance with noise abatement (high- and low-order).** Such data (in the public domain) are very few at present and are necessary to understand the noise reductions which can be achieved and appraise the effectiveness of abatement systems where they are to be relied-up to mitigate effects of last-resort high-order clearance.

10.2. Explosives in decommissioning

The following are suggested as priorities for filling evidence gaps for use of explosives in decommissioning:

- **Empirical studies of harbour porpoise responses to use of explosives below the mudline.** While use of explosives below the mudline can be expected to result in smaller harbour porpoise disturbance ranges than use of explosives in open water, this hypothesis is not currently supported by empirical evidence.
- **Analysis of existing and collection of additional noise measurement data related to explosives use in decommissioning.** Although explosives have been employed in decommissioning activities across various industries for several decades, publicly available underwater noise measurement data remains limited. In this review, we analysed available data concerning the use of explosives involving relatively large UXO charge weights at shallow depths below mudline, as well as multiple smaller charges detonated at varying depths. However, the dataset for smaller charges was constrained by the limited spatial distribution of noise monitoring stations, often located no further than 10 metres from the detonation site. To improve understanding of underwater noise propagation resulting from explosive use at intermediate burial

depths (between 5–100 metres below the mudline) further analysis of existing underwater noise monitoring or collection of new data is recommended.

10.3. Seismic (airgun) surveys

The following are suggested as priorities for filling evidence gaps for seismic (airgun) surveys:

- **Empirical studies of harbour porpoise responses to seismic (airgun) surveys for a range of different survey volumes to allow comparison.** Empirical studies examining animal responses are currently limited, particularly those designed to facilitate comparison across different survey volumes and designs. A notable gap relates to airgun volumes from mini guns up to a few hundred cubic inches. Future monitoring programmes should aim to collect and analyse data using standardised methodologies that enable the derivation of deterrence functions. Data should be reported in a format that supports the estimation of an EDR.
- **Underwater noise measurement data collection that would allow to estimate distances to weighted disturbance thresholds**. While numerous acoustic measurement studies exist, few incorporate frequency-weighted metrics relevant for assessing auditory and behavioural response impacts.

10.4. SBP and USBL

The following are suggested as priorities for filling evidence gaps for SBP surveys and USBL positioning systems:

- **Empirical studies of harbour porpoise responses to SBP surveys, including different devices.** Empirical studies of harbour porpoise responses to SBP surveys are currently lacking, despite widespread use of these technologies across offshore industries. Targeted response studies are needed to better understand behavioural effects and facilitate comparisons across SBP systems. As mentioned above for UXO clearance, there is the potential for porpoise responses to SBP surveys to be assessed opportunistically from existing data where spatio-temporal overlap exists between static PAM networks and SBP surveys.
- **Investigate the potential for disturbance from USBL positioning systems**. While USBL is typically not considered a risk for injury and is therefore often excluded from impact assessments, there is evidence that USBL signals may propagate over greater ranges than many SBP sources, despite the lower source levels. This warrants further empirical investigation to determine potential behavioural effects on harbour porpoise.

10.5. ADDs

The following are suggested as priorities for filling evidence gaps for ADDs:

- **Empirical studies of harbour porpoise responses to ADDs.** Conduct empirical studies on harbour porpoise responses to short-term exposures of the Lofitech ADD, employing methodologies such as PAM arrays that can characterise the full spatial extent of responses and assess average behavioural changes over a 24-hour period. Apply similar study designs to low-order UXO clearance scenarios to estimate EDRs and determine whether observed spatial responses are primarily influenced by the clearance noise itself or the associated use of ADDs (see Section 10.1 for UXO recommended priorities).

- **Validation of other ADD types.** It is recommended to undertake further validation studies on the FaunaGuard ADD, along with other devices reviewed in McGarry *et al.* (2022) to determine harbour porpoise deterrence ranges and assess whether other (than Lofitech) devices could provide sufficient deterrence to mitigate the risk of injury.
- **Assess ADD effectiveness for other marine mammal species.** Although this review is focused on EDRs for harbour porpoise, ADDs are often relied upon to deter multiple marine mammal species from zones of potential injury (primarily seals and minke whales) in UK waters, including harbour porpoise SACs. Therefore, relying on an ADD other than the Lofitech, to reduce the potential for excessive porpoise disturbance, requires reliable evidence of the device's effectiveness on other species. As such, empirical research on the effectiveness of FaunaGuard and other (than Lofitech) ADD devices for species other than harbour porpoise is required to evaluate their broader applicability as mitigation tools in place of the Lofitech ADD.

10.6. MBES

MBES or SBES of the type considered in this review (≤ 12 kHz) is not widely used in and around UK harbour porpoise SACs, and the evidence, while limited, suggests a limited potential for disturbance to harbour porpoise. Therefore, relative to other noise sources, data gaps for MBES can be considered a lower priority. Nonetheless, the following are evidence gaps which require addressing to provide more confidence in the evidence to support EDRs:

- **Empirical studies of harbour porpoise responses to MBES.** Empirical studies on harbour porpoise responses to MBES are currently lacking. Despite the widespread use of multibeam systems across offshore sectors, there is limited empirical evidence on behavioural responses of harbour porpoises to these sources. While lower frequency MBES are considered the MBES source type with the greatest potential for disturbance, opportunities to assess porpoise responses to MBES at higher frequencies which overlap the porpoise hearing range should not be overlooked, as data for these are also lacking.
- **Underwater noise measurement data collection that would allow estimation of noise levels at different positions with respect to the main beam of the source signal**. Collection of underwater noise measurement data is needed to estimate received levels at varying positions relative to the main beam of the acoustic source. The directional characteristics of MBES (e.g. narrow beams along the vessel track and wider beams across the track), mean that the spatial position of a receiver (animal or sensor) relative to the survey path may significantly influence exposure levels. Consequently, factors such as water depth and MBES frequency should be carefully considered in the design of monitoring studies.

10.7. Military sonar

The following is suggested as a priority for filling evidence gaps for military sonar:

- **Empirical studies of harbour porpoise responses to military sonar.** Despite a substantial evidence base relating to the responses of other odontocetes to military sonar, empirical studies on the behavioural responses of harbour porpoises to military sonar are currently lacking. In contrast to the controlled exposure experiments widely used on other species, studies on harbour porpoise should be designed to determine a gradient of responses over distance including monitoring to a sufficient distance to capture the maximum extent of responses. A design comparable to those implemented for OWF construction would be suitable and allow greater comparison with this noise source.

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Glossary

Table 25. Glossary of terms, acronyms and abbreviations.

Term	Definition
AA	Appropriate Assessment
ADD	Acoustic Deterrent Device. A device that emits pulses of high frequency sound to deter marine mammals from an area.
APD	Acoustic Porpoise Deterrent
ARU	Autonomous Recording Units
AUTEC	Atlantic Undersea Test and Evaluation Centre
BBC	Big Bubble Curtain
BOEM	Bureau of Ocean and Energy Management (US)
BRS	Behavioural Response Studies
BRT	Boosted Regression Tree
CAS	Continuous Active Sonar
CPM	Clicks per minute
CPOD	Cetacean Porpoise Detector
CW	Amplitude- modulated tone Continuous Wave
DCS	Dutch Continental Shelf
Defra	Department for Environment Food and Rural Affairs
DPH	Detection Positive Hours
DPM	Detection Positive Minutes
EDR	Effective Deterrence Range. A radius from a source of disturbance (i.e. noise source), with the associated area representing the overall estimated loss of habitat to animals. If all animals vacated the circle of radius EDR around the noise source, then this would be equivalent to the mean loss of habitat per animal (Tougaard *et al.* 2013).
EIA	Environmental Impact Assessment. A statutory process by which certain planned projects must be assessed before a formal decision to proceed can be made. It involves the collection and consideration of environmental information, which fulfils the assessment requirements of the EIA Directive and EIA Regulations, including the publication of an Environmental Statement (ES) or Environmental Impact Assessment Report (EIAR).

Term	Definition
EPS	European Protected Species
FCS	Favourable Conservation Status
FM	Amplitude- modulated tone Frequency Modulation
GAM	Generalised Additive Model
GAMM	Generalised Additive Mixed Model
GLMM	Generalised Linear Mixed Model
HR	High-resolution
HRA	Habitats Regulation Assessment
HRGS	High-resolution Geophysical Surveys
Impulsive noise	Noise characterised by a short duration and steep rise in sound pressure, such that the majority of the energy is delivered in a very short period of time. Examples of underwater impulsive noise sources include explosions, airgun pulses and impact pile-driving. For a given sound energy level, impulsive noise is more injurious to marine life than non-impulsive noise.
JNCC	Joint Nature Conservation Committee
LFAS	Low-Frequency Active Sonar
LSC	Linear Shaped Charges
MBES	Multi-Beam Echosounder
MFAS	Mid-Frequency Active Sonar
MNR	Marine Noise Registry. The UK MNR is a resource managed by the JNCC which documents reported low-frequency impulsive noise from licenced activities in UK waters, generally at the scale of UK Oil and Gas Licensing Blocks or as points for point noise sources (such as piling or explosions).
Mitigation measures	Measure implemented to reduce impacts associated with activities. Typically embedded within the assessment at the relevant point in the EIA and specified in consent conditions.
MU	Management Unit
NEQ	Net Explosive Quantity. The total mass of explosive material within an object, excluding non-explosive components or casings.
NMFS	National Marine Fisheries Service (US)

Term	Definition
NnG	Neart na Gaiothe offshore wind farm
NAS	Noise abatement system. Systems designed to reduce the propagation of noise into the marine environment from a noise source.
NRW	Natural Resources Wales
OBS	Ocean-bottom seismic survey
OPRED	Offshore Petroleum Regulator for Environment and Decommissioning
OWF	Offshore wind farm
PAM	Passive acoustic monitoring
PPM	Porpoise Positive Minutes
PTS	Permanent Threshold Shift
RA	Risk Assessment
R_{50}	The distance at which there is a 50% probability of response
SAC	Special Area of Conservation
SBES	Single-Beam Echosounder
SEL	Sound Exposure Level
SEL_{cum}	Accumulated sound exposure level (across multiple pulses)
SEL_{SS}	Single strike sound exposure level (in contrast to a measure of accumulated sound such as SEL_{cum}).
SNCB	Statutory Nature Conservation Bodies
SAC	Special Area of Conservation. Protected sites designated under Article 3 of the Habitats Directive for habitats listed on Annex I and Animals listed on Annex II of the Directive.
SPL	Sound pressure level
SPL_{pk}	Peak (or zero-to-peak) sound pressure level
SPL_{pk-pk}	Peak-to-peak sound pressure level
SPL_{rms}	Root-mean-squared sound pressure level.
Sonar	Sound Navigation and Ranging
SSS	Side-Scan Sonar
TNT equivalent	Trinitrotoluene. A high explosive.

Term	Definition
TTS	Temporary Threshold Shift
UXO	Unexploded ordnance. Explosive weapons (e.g. bombs, shells, mines) that did not explode when they were employed and still pose a risk of detonation. Numerous UXO associated with WWI and WWII are present on the seabed in the North Sea, which may require disposal to ensure the safe construction of offshore infrastructure.
USBL	Ultrasonic Baseline
VDS	Variable Depth Sonar
VSP	Vertical-seismic Profiling

Appendix 1 – Summary of thresholds used for noise measurement and modelling studies

Where sufficient data were available, fixed noise thresholds were applied in this review to estimate the distance between the noise source and the onset of behavioural reactions. These thresholds are based on sound levels, assuming all animals exposed to noise reaching/exceeding a specified level experience disturbance.

TTS onset as a proxy for disturbance (Southall *et al.* 2007)

Southall *et al.* (2007) stated that in the absence of data on the behavioural responses to impulsive noise, the TTS-onset threshold *could* be used as a proxy for a behavioural threshold for single pulses. Specifically: "*Even strong behavioural responses to single pulses, other than those that may secondarily result in injury or death (e.g. stampeding), are expected to dissipate rapidly enough as to have limited long-term consequence. Consequently, upon exposure to a single pulse, the onset of significant behavioural disturbance is proposed to occur at the lowest level of noise exposure that has a measurable transient effect on hearing (i.e. TTS-onset). We recognize that this is not a behavioural effect per se, but we use this auditory effect as a de facto behavioural threshold until better measures are identified. Lesser exposures to a single pulse are not expected to cause significant disturbance, whereas any compromise, even temporarily, to hearing functions has the potential to affect vital rates through altered behaviour.*"

Given the lack of guidance on behavioural thresholds for UXO, TTS-onset thresholds have been widely used in the UK as a proxy for disturbance to harbour porpoise and other marine mammals in assessments of potential disturbance to UXO clearance (e.g. European Protected Species risk assessments, Environmental Impact Assessment). The TTS-onset thresholds applied in the current review are based on the most recent recommendations in Southall *et al.* (2019) for VHF cetaceans: unweighted **SPL_{pk} at 196 dB re 1 µPa** and frequency-weighted **SEL at 140 dB re 1 µPa^{2}s**. It should be noted that the updated NMFS (2024) guidance increased the VHF-weighted threshold to 144 dB re 1 µPa^{2}s. However, as this guidance was released after work on this review had commenced, and all the evidence reviewed had been published, it has not been incorporated into the current assessment. The use of the **140 dB re 1 µPa^{2}s** threshold is therefore retained, representing a more precautionary approach.

Aversive behavioural responses to a single airgun pulse (Lucke *et al.* 2009)

A study conducted by Lucke *et al.* (2009) on a harbour porpoise in a captive facility detailed behavioural responses to an airgun source. The study found that the porpoise showed an aversive behavioural reaction to the stimuli at received **$SPL_{pk\text{-}pk}$ of 174 dB re 1 µPa** or an **SEL of 145 dB re 1 µPa^{2}s**, with the SEL being cumulated over one airgun impulse (single strike SEL). The approximate equivalent of this threshold for the SPL_{pk} (zero-to-peak) metric, which is more widely reported in noise measurement studies, is a threshold of **168 dB re 1 µPa**. This threshold was derived by subtracting 6 dB from the $SPL_{pk\text{-}pk}$ 174 dB re 1µPa. This adjustment was made on the assumption that the signal waveform is symmetrically distributed in positive and negative pressure. While this study was based on a single captive porpoise, various field studies have shown support for this threshold when applied to exposure to multiple pulses: for example, Brandt *et al.* (2016) found onset of a behavioural reaction at SEL values in the range of 140–152 dB re 1 µPa^{2}s from pile driving and Thompson *et al.* (2013) observed similar avoidance at levels of 145–151 dB re 1 µPa^{2}s for a seismic airgun (Sinclair *et al.* 2023).

Level B harassment (NMFS 2005)

Additionally, a threshold of SPL_{rms} **160 dB re 1µPa** from an impulsive sound source has been applied in this review (NMFS 2005). This threshold is also referred to as "Level B harassment" and is defined as "*any act of pursuit, torment or annoyance which has the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioural patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering but which does not have the potential to injure a marine mammal or marine mammal stock in the wild*" by the 1994 Amendments to the Marine Mammal Protection Act in the US.

Appendix 2 - Evidence scoring

Introduction

An evidence-scoring methodology was developed so that recommended default EDRs could be accompanied by a measure of confidence associated with the robustness, relevance to harbour porpoise in UK waters and volume of underlying evidence. This process involves two key steps:

(i) evaluating individual studies across various criteria, and

(ii) aggregating these scores across all studies.

The scoring framework follows a decision-tree approach (Figure 7), where all studies are initially assigned a baseline score and penalties can be subsequently applied under each criterion.

Differentiating empirical response, noise measurement and modelling studies

At the first stage, studies are scored according to the type of data they include. Empirical studies of animal responses, be it through direct observation (e.g. aerial surveys) or acoustic detections, provide direct data on animals' responses to activities; therefore, they are the most robust category of evidence available, and no penalties are applied.

The alternative to empirical studies of animal responses are those which make inferences about how animals may respond, using fixed response thresholds applied to either measured noise levels or model-predicted noise levels (see Appendix 1 for the list of considered thresholds). This type of evidence is included where empirical studies of responses are limited or lacking. Both noise measurement and modelling studies carry a substantial penalty over empirical response studies due to the uncertainty over how animals may respond.

Noise measurement studies refer to those that directly recorded real-world underwater noise levels during activities, where noise levels at different distances to the source were measured and the range to behavioural effect thresholds could be estimated. While all behavioural effect thresholds are subject to considerable uncertainty, and no universally accepted criteria exist, when applied to field noise measurements there is at least greater confidence in the noise levels which animals will experience. No further penalties are applied to noise measurement studies at this stage in the decision-tree.

By contrast, modelling studies rely on computational simulations using input parameters and assumptions to predict noise levels and estimate distances to behavioural effect thresholds. As noise measurement and modelling studies are associated with greater uncertainty in estimating distances to fixed thresholds, they incur a penalty.

Empirical response studies scoring

Empirical studies receive additional scoring adjustments based on their capacity to estimate EDR and the relevance of species studied. Given that this review aims to identify EDRs (which differ from the maximum observed behavioural response distances), studies are scored as follows:

- No penalty if the study directly estimates EDR.
- A minor penalty if the study provides data from which EDR can be extracted.

- A major penalty if the data cannot be used to extract EDR.

Additionally, as the primary focus is on harbour porpoise responses, data collected for other species receive lower scores (Figure 7).

Consideration of environmental characteristics

As noise propagation varies with bathymetry, studies are scored based on their relevance to the bathymetric conditions typical of UK harbour porpoise SACs. The average site depths in the UK SACs range from 10 to 50 meters, with a maximum depth in the Southern North Sea of 75 meters. Studies conducted in similar bathymetric environments do not lose points.

Relevance to Activity Parameters

A further scoring criterion assesses the relevance of the study to the specific activity under review. The key consideration is how closely the study parameters align with current and near-future UK activities, such as pile type, diameter, piling duration, ADD activation duration, and other operational factors (e.g. most common parameters were verified using Stone (2023a, 2023b, 2024a) and Marine Noise Registry data). Scoring is adjusted as follows:

- Studies closely matching recent UK parameters score highest.
- Points are deducted for studies with significantly different parameters (e.g. ADD duration exceeding 60 minutes).
- Studies using proxy noise sources receive penalties (UXO clearance used as a proxy for decommissioning explosives).

We note that scores are assigned on an activity-specific basis, meaning that a single study may have different scores depending on the activity reviewed. For example, if evaluating an EDR for a seismic array larger than 500 in^3, a study reporting behavioural distances for an array smaller than 500 in^3 would score lower than if it were considered with respect to array size > 500 in^3.

Other limiting factors

Further minor penalties may be applied if studies had other limiting factors, such as limited datasets or a lack of statistical analysis.

Summarising scores

To account for differences in the number and type of studies (empirical, noise measurement and modelling), scores are averaged by study type. In addition to providing average scores by study type, an overall score is also presented which represents the mean of each of the study-type average scores.

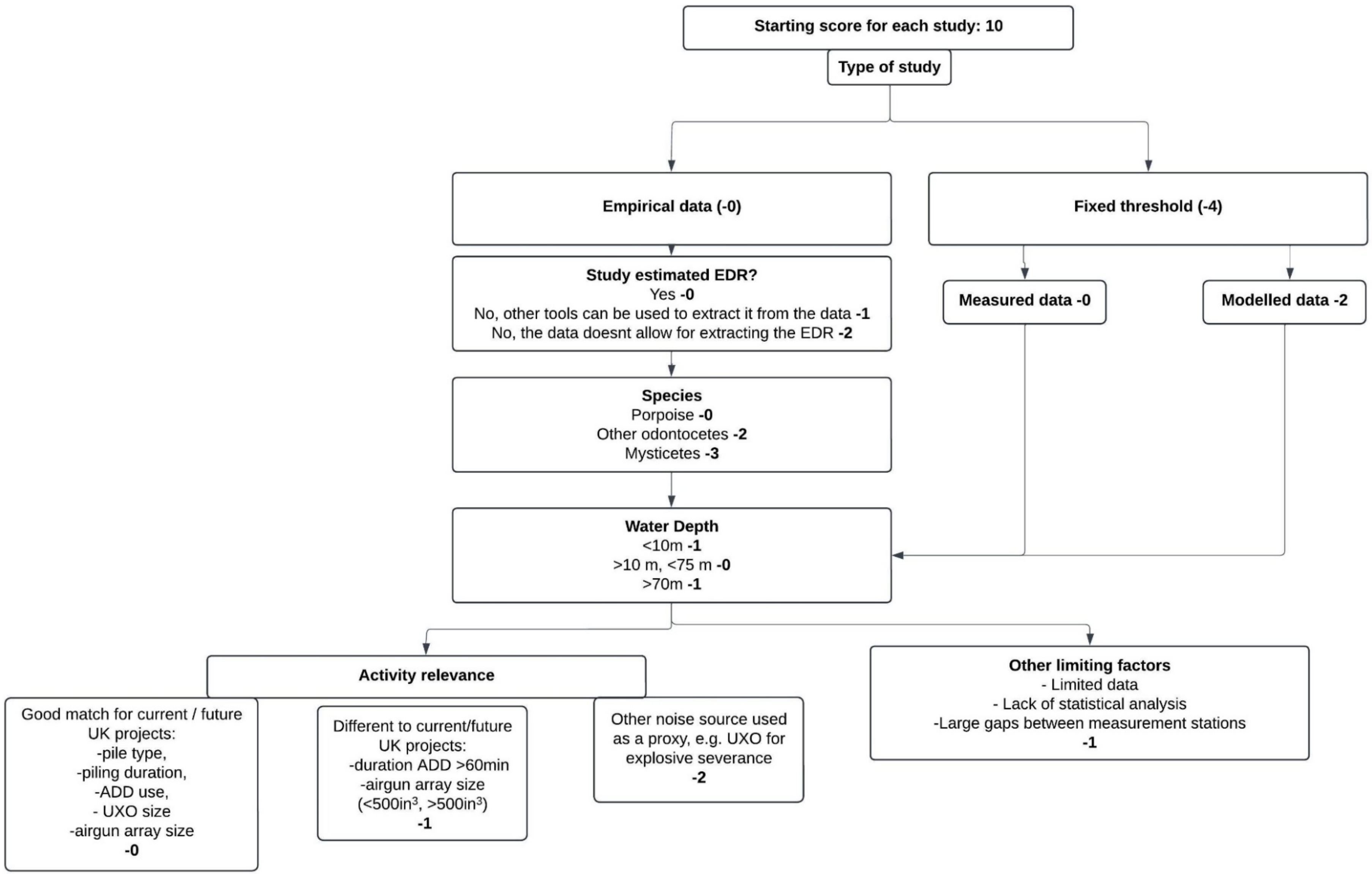


Figure 7. Decision tree used to score individual studies within this evidence review.

Study-specific scores for UXO clearance

Table 26. Scores assigned to UXO clearance studies. HO = high-order; LO = low-order. NAS = Noise abatement system. BC = Bubble curtain. Y = Yes, penalty points received (the number of points deducted indicated in brackets); N = No penalty received in this category.

Study characteristics					Score penalties							Notes
Study		Region (country); water depth	Clearance type	NAS	Study type	Estimated EDR?	Species	Water depth	Relevance	Other limitations	Final score	
Empirical response studies	Van Geel *et al.* (2024) - East Anglia ONE OWF	Southern North Sea (UK) 30–40 m	HO	None	N	Y (2)	N	N	Y (1)	Y (1)	6	The data presented in the report did not allow for EDR quantification; long (80 minutes) ADD duration and scarer charges; large gap in distances between monitoring equipment, small sample size; no information on noise levels.
Noise measurement studies	Lepper *et al.* (2024)	The Great Belt (DK) 10–20 m	HO, LO	None	Y (4)	-	-	N	Y (1)	N	5	Larger donor charges (10 kg) than typically used in UK; water depths on the shallow end of those in UK SACs
	Midforth (2024) - East Anglia THREE OWF	Southern North Sea (UK) 30–46 m	LO	None	Y (4)	-	-	N	N	N	6	N/A

Study characteristics					Score penalties							Notes
Study		**Region (country); water depth**	**Clearance type**	**NAS**	**Study type**	**Estimated EDR?**	**Species**	**Water depth**	**Relevance**	**Other limitations**	**Final score**	
	Abad Oliva *et al.* (2024) - Moray West OWF	Moray Firth (UK) 35–55 m	LO	None	Y (4)	-	-	N	N	Y (1)	5	Some results presented for VHF frequency-weighted SEL appear to be erroneous (likely due to high-frequency internal electrical noise from the hydrophone pre-amp or recorder)
	Donaghy and Lee (2024a) - NeuConnect interconnector	Outer Thames Estuary (UK) 5–10 m	LO	None	Y (4)	-	-	Y (1)	N	Y (1)	4	Very shallow water (5–10 m); small sample size (n = 2)
	Donaghy and Lee (2024b) - NeuConnect interconnector	Southern North Sea (UK) 40–50 m	LO, HO	None	Y (4)	-	-	N	N	Y (1)	5	Small sample size (n = 1 for each of LO and HO).
	Lee *et al.* (2022) - Sofia OWF	North Sea (UK) 21–37 m	LO, HO	BC (HO)	Y (4)	-	-	N	N	Y (1)	5	Small sample size (n = 1 for LO, 2 for HO but only 1 with effective BC).

Study characteristics					Score penalties							Notes
Study		Region (country); water depth	Clearance type	NAS	Study type	Estimated EDR?	Species	Water depth	Relevance	Other limitations	Final score	
	Robinson *et al.* (2022) - Moray East and Neart na Gaiothe OWFs	Moray Firth, Firth of Forth (UK) 40–50 m	HO	None	Y (4)	-	-	N	N	N	6	N/A
	Bellmann *et al.* (2021) - Neart na Gaiothe OWF	Firth of Forth (UK) 50 m	HO	None	Y (4)	-	-	N	N	N	6	N/A
	Salomons (2021)	Southern North Sea (NL) 20 m	HO	None	Y (4)	-	-	N	Y (1)	Y (1)	4	Larger donor charges (10 kg) than typically used in UK; small sample size (n =2).
	Mason *et al.* (2020)	North Sea (UK) 22.4–27.6 m	HO	BBC	Y (4)	-	-	N	N	Y (1)	5	Donor charge not reported.
	von Benda-Beckmann *et al.* (2015)	North Sea (NL) 26–28 m	HO	None	Y (4)	-	-	N	N	Y (2)	4	Measurements not collected beyond approx. 2 km range; UXOs were re-located from land; donor charge size not reported.

Study characteristics					Score penalties							Notes
Study		Region (country); water depth	Clearance type	NAS	Study type	Estimated EDR?	Species	Water depth	Relevance	Other limitations	Final score	
Noise modelling studies	Subacoustech (2024a, b, c)	Southern North Sea (UK) 20–50 m	LO, HO	None	Y (6)	-	-	N	N	N	4	N/A

Study-specific scores for explosives in decommissioning

Table 27. Scores assigned to studies relevant to the use of explosives in decommissioning. NAS = Noise abatement system. Y = Yes, penalty points received (the number of points deducted indicated in brackets); N = No penalty received in this category.

Study characteristic					Score penalties							Notes
Study		Region (country); water depth	Charge type	NAS	Study type	Estimated EDR?	Species	Water depth	Relevance	Other limitations	Final score	
Noise measurement studies	Nedwell *et al.* (2001)	North Sea (UK); 32–116 m	Bulk	None	Y (4)	-	-	N	N	Y (1)	5	Limited spatial extent of measurements.
	Confidential (2020a)	North Sea (UK); 93–95m	Small cutting charges	None	Y (4)	-	-	Y (1)	N	Y (1)	4	Measurements limited to very close proximity to detonation site.
Noise modelling studies	Subacoustech (2024a, b, c)	Southern North Sea (UK); 20–50 m	Various	None	Y (6)	-	-	N	N	N	4	N/A

Study-specific scores for seismic surveys

Table 28. Scores assigned to studies relevant to seismic (airgun) surveys. Y = Yes, penalty points received (the number of points deducted indicated in brackets); N = No penalty received in this category.

Study characteristic				Score penalties							Notes
Study		Region (country); water depth	Airgun array volume (in^3)	Study type	Estimated EDR?	Species	Water depth	Relevance	Other limitations	Final score	
Empirical response studies	Thompson *et al.* (2013)	Moray Firth (UK), 50 m	470	N	Y (2)	N	N	N	Y (1)	7	The data presented in the report did not allow for EDR estimation; choice of response variable (waiting times) and challenges in identifying an extent of spatial effect from acoustic data.
	Stone (2024b)	UK-wide; < 1,000 m	> 1,200	N	Y (2)	N	N	N	Y (2)	6	The data presented in the report did not allow for EDR estimation; while some data are likely to be from surveys deeper than most relevant to porpoise SACs, a large proportion of effort is anticipated to be over shelf waters; the study was limited to the spatial extent of visual observations from the source vessel; sample sizes were small.

Study characteristic				Score penalties							Notes
Study		Region (country); water depth	Airgun array volume (in^3)	Study type	Estimated EDR?	Species	Water depth	Relevance	Other limitations	Final score	
Empirical response studies	Sarnocińska *et al.* (2020)	North Sea (DK), 15 m	3,570	N	Y (1)	N	N	N	Y (1)	8	The study did not report EDR, but other tools were used to estimate it; in the EDR estimating exercise, a reference baseline needed to be assumed at the point the effects appeared to plateau.
	van Beest *et al.* (2018)	Skagerrak and Belt Sea (DK) < 60 m	10	N	Y (2)	N	N	Y (1)	Y (2)	5	The data presented in the report did not allow for EDR estimation; very short (1 minutes) exposure period; limited sample size; nature of study did not allow for estimation of a maximum spatial extent of disturbance.
Noise measurement studies	Jiménez-Arranz *et al.* (2020)	Various, 8–70 m	10–4,380	Y (4)	-	-	N	N	N	6	Large sample size as a review of many individual studies (n = 14 considered relevant here).
	Hermannsen *et al.* (2015)	Aarhus Bay (DK), 15 m	10–40	Y (4)	-	-	N	N	Y (1)	5	The study did not present any specific distances at which behavioural response may be anticipated, except “several kilometres”.

Study characteristic				Score penalties							Notes
Study		**Region (country); water depth**	**Airgun array volume (in³)**	**Study type**	**Estimated EDR?**	**Species**	**Water depth**	**Relevance**	**Other limitations**	**Final score**	
Noise measurement studies	Confidential (2020b)	Ionian Sea (GR), 750–1,200 m	3,500–7,000	Y (4)	-	-	Y (1)	N	N	5	Water depths are deeper than those in UK SACs
	OPRED (2024)	North Sea (UK)	160	Y (6)	-	-	Y (1)	N	Y (1)	3	Underwater noise modelling methodology not presented; unknown water depths.
	OPRED (2020a)	North Sea (UK)	160–320	Y (6)	-	-	Y (1)	N	Y (1)	3	Underwater noise modelling methodology not presented; unknown water depths.

Study characteristic				Score penalties							Notes
Study		Region (country); water depth	Airgun array volume (in^3)	Study type	Estimated EDR?	Species	Water depth	Relevance	Other limitations	Final score	
Noise modelling studies	OPRED (2023)	North Sea (UK)	585	Y (6)	-	-	Y (1)	N	Y (1)	3	Underwater noise modelling methodology not presented; unknown water depths.
	OPRED (2019)	North Sea (UK)	4,200	Y (6)	-	-	Y (1)	N	Y (1)	3	Underwater noise modelling methodology not presented; unknown water depths.
	OPRED (2020b)	North Sea (UK)	4,240	Y (6)	-	-	Y (1)	N	Y (1)	3	Underwater noise modelling methodology not presented; unknown water depths.
	OPRED (2021b)	North Sea (UK)	3,390–8,000	Y (6)	-	-	Y (1)	N	Y (1)	3	Underwater noise modelling methodology not presented; unknown water depths.
	OPRED (2021a)	North Sea (UK)	3,390	Y (6)	-	-	Y (1)	N	Y (1)	3	Underwater noise modelling methodology not presented; unknown water depths.

Study-specific scores for SBP and USBL

Table 29. Scores assigned to SBP and USBL studies.Y = Yes, penalty points received (the number of points deducted indicated in brackets); N = No penalty received in this category.

Study characteristics				**Score penalties**							
Study		**Region (country); water depth**	**Equipment type**	**Study type**	**Estimated EDR?**	**Species**	**Water depth**	**Relevance**	**Other limitations**	**Final score**	**Notes**
Noise measurement studies	Confidential (2018b)	Atlantic Ocean (US), 32 m	Parametric SBP	Y (4)	-	-	N	N	N	6	N/A
	Pace *et al.* (2021)	North Sea (UK), unknown depth	Parametric SBP, USBL	Y (4)	-	-	Y (1)	N	Y (1)	4	Unknown water depth, low behavioural threshold used
	Confidential (2023)	Baltic Sea (DK), 30 m	Parametric SBP, sparker, USBL	Y (4)	-	-	N	N	N	6	N/A
	OSC (2025)	North Sea (UK), Baltic Sea (DK), 5–20 m	Parametric SBP, chirper	Y (4)	-	-	Y (1)	N	Y (1)	4	Water depth < 10 m, only distances to TTS-onset thresholds are provided, unclear how the source was modelled in the propagation modelling.

Study characteristics				Score penalties							Notes
Study		Region (country); water depth	Equipment type	Study type	Estimated EDR?	Species	Water depth	Relevance	Other limitations	Final score	
Noise modelling studies	Xodus Group Ltd (Unknown)	North Sea (UK), 10–100 m	Parametric SBP, chirper, USBL	Y (6)	-	-	Y (1)	N	N	3	Depth up to 100 m
	Xodus Group Ltd (2022)	North Sea (UK), 10–95 m	Parametric SBP, sparker	Y (6)	-	-	Y (1)	N	N	3	Water depth up to 95 m
	MarineSpace Ltd (2023)	North Sea (UK), < 200m	Parametric SBP	Y (6)	-	-	Y (1)	N	N	3	Water depth up to 200 m
	RPS (2023b)	Atlantic Ocean (IRE), < 60 m	Various	Y (6)	-	-	Y (1)	N	N	3	Water depth not specified (can be less than 10 m)
	RPS (2023a)	North Sea (UK), 50–100 m	Parametric SBP, sparker, USBL	Y (6)	-	-	Y (1)	N	N	3	Water depth up to 100 m

Study characteristics				Score penalties							Notes
Study		**Region (country); water depth**	**Equipment type**	**Study type**	**Estimated EDR?**	**Species**	**Water depth**	**Relevance**	**Other limitations**	**Final score**	
Noise modelling studies	Xodus Group Ltd (2023a)	North Sea (UK), < 100 m	Pinger	Y (6)	-	-	Y (1)	N	N	3	Water depth up to 100 m
	Xodus Group Ltd (2023b)	Atlantic Ocean (UK), 10–100 m	Parametric SBP, USBL	Y (6)	-	-	Y (1)	N	N	3	Water depth up to 100 m
	SMRU Consulting (2023)	North Sea (UK), unknown depth	USBL	Y (6)	-	-	Y (1)	N	N	3	Water depth not specified

Study-specific scores for ADDs

Table 30. Scores assigned to ADD studies. Y = Yes, penalty points received (the number of points deducted indicated in brackets); N = No penalty received in this category.

Study characteristics			**Score penalties**							**Notes**
Study	**Region**	**ADD type**	**Study type**	**Estimated EDR?**	**Species**	**Water depth**	**Relevance**	**Other limitations**	**Final score**	
Elmegaard *et al.* (2023)	Denmark	Lofitech	E	Y (2)	N	N	N	Y (1)	7	The data presented in the report did not allow for EDR quantification; study design was such that the maximum extent of porpoise responses could not be estimated; limited sample size.
Voss *et al.* (2023)	German North Sea	FaunaGuard Porpoise Module	E	Y (2)	N	N	N	Y (1)	7	The data presented in the report did not allow for EDR quantification; ADD duration not reported for Lofitech; monitoring likely did not extend far enough to capture full extent of Lofitech effects.
Thompson *et al.* (2020)	Moray Firth, NE Scotland	Lofitech seal scarer	E	Y (1)	N	N	N	Y (2)	7	The study did not report EDR, but other tools were used to estimate it. Rigorous approach but high threshold for assigning a positive response may underestimate lower-level responses; estimation of EDR appears sensitive to truncation distance and shape of deterrence function; results relate to a single exposure only and not in the context of other activity (i.e. piling or UXO clearance).

Study characteristics			Score penalties							Notes
Study	**Region**	**ADD type**	**Study type**	**Estimated EDR?**	**Species**	**Water depth**	**Relevance**	**Other limitations**	**Final score**	
Dähne *et al.* (2017)	German North Sea	Aquamark 100 Pinger, Lofitech seal scarer	E	Y (1)	N	N	Y (1)	Y (1)	7	The study did not report EDR, but other tools were used to estimate it; long ADD duration and two devices used concurrently; it is likely that other activities close to the start of piling concurrent with ADD use may also have induced some responses.
Brandt *et al.* (2013c)	German North Sea	Lofitech seal scarer	E	Y (2)	N	N	Y (1)	Y (1)	6	The data presented in the report did not allow for EDR quantification; long ADD duration; limited distance at which porpoise responses were recorded.

Study-specific scores for MBES

Table 31. Scores assigned to MBES studies.Y = Yes, penalty points received (the number of points deducted indicated in brackets); N = No penalty received in this category.

Study characteristics				Score penalties							Notes
Study		Region (country); water depth	Equipment type (frequency)	Study type	Estimated EDR?	Species	Water depth	Relevance	Other limitations	Final score	
Empirical response studies	Cholewiak *et al.* (2017)	North-west Atlantic (US); 100 m to > 2,000 m	Multiple Simrad EK60s (18-200 kHz)	N	Y (2)	Y (2)	Y (1)	Y (1)	N	4	The data presented in the report did not allow for EDR estimation; beaked whales were studied; study largely conducted in waters deeper than UK harbour porpoise SACs; higher equipment frequency than 12 kHz considered in UK impulsive noise management.
Noise measurement studies	Halvorsen and Heaney (2018)	North-west Atlantic (US); ≤ 100 m	Simrad EK60, Reason 7111, 7125 (38 kHz, 200 kHz)	Y (4)	-	-	N	Y (1)	N	5	Higher equipment frequency than 12 kHz usually used in UK waters.

Study characteristics				Score penalties							Notes
Study		Region (country); water depth	Equipment type (frequency)	Study type	Estimated EDR?	Species	Water depth	Relevance	Other limitations	Final score	
Noise modelling studies	NMFS (2020) tool	N/A	MBES, 12 kHz	Y (6)	-	-	N	N	N	4	N/A
	Lurton (2016)	N/A	MBES example (12 kHz)	Y (6)	-	-	Y (1)	N	N	3	Study considered waters deeper than UK harbour porpoise SACs.
	LGL Limited (2014)	Nova Scotia (Canada); 339–3,145 m	Kongsberg EM® 302 (30 kHz)	Y (6)	-	-	Y (1)	Y (1)	N	2	Study conducted in waters deeper than UK harbour porpoise SACs; higher equipment frequency than 12 kHz considered in UK impulsive noise management.

Study-specific scores for military sonar

Table 32. Scores assigned to military sonar studies.Y = Yes, penalty points received (the number of points deducted indicated in brackets); N = No penalty received in this category.

Study characteristic				Score penalties							Notes
Study		Study species, region (water depth)	Equipment	Study type	Estimated EDR?	Species	Water depth	Relevance	Other limitations	Final score	
Empirical response studies	Wensveen *et al.* (2025)	Sperm whales, Norwegian Sea (deep >> 200 m)	LFAS (SOCRATES or CAPTAS-Mk2)	N	Y (2)	Y (2)	Y (1)	Y (1)	N	4	The data presented in the report did not allow for EDR quantification; other odontocete study species; deep water; LFAS less-commonly used in UK shelf waters.
	Southall *et al.* (2024)	Common dolphins, Southern California, USA (slope > 200 m)	MFAS and simulated sonar	N	Y (2)	Y (2)	Y (1)	N	N	5	The data presented in the report did not allow for EDR quantification; other odontocete study species; deep water.
	Wensveen *et al.* (2019)	Northern bottlenose whales, Arctic, north of Iceland (deep >> 200 m)	Simulated naval sonar	N	Y (2)	Y (2)	Y (1)	Y (1)	Y (1)	3	The data presented in the report did not allow for EDR quantification; other odontocete study species; deep water; LFAS less-commonly used in UK shelf waters; limited range of exposure distances (1 km and 17 km).

Study characteristic				Score penalties							Notes
Study		Study species, region (water depth)	Equipment	Study type	Estimated EDR?	Species	Water depth	Relevance	Other limitations	Final score	
Empirical response studies	Joyce *et al.* (2019)	Blainville's beaked whales, The Bahamas (AUTEC) (deep >> 200 m)	MFAS	N	Y (2)	Y (2)	Y (1)	Y (1)	Y (1)	3	The data presented in the report did not allow for EDR quantification; other odontocete study species; deep water; distances to monitoring array reported, not source, therefore uncertainty in reported distances.
	DeRuiter *et al.* (2013)	Goose-beaked whales, Southern California, USA (deep >> 200 m)	MFAS	N	Y (2)	Y (2)	Y (1)	Y (1)	Y (1)	3	The data presented in the report did not allow for EDR quantification; other odontocete study species; deep water; study design was such that the maximum extent of individual responses could not be estimated.
Noise modelling studies	Andersson and Johansson (2016)	N/A	Variable depth sonar	Y (4)	N	N	N	Y (1)	Y (1)	4	Sonar was higher frequency (25 kHz) than that understood to be most commonly used in UK waters; wide range of effects ranges reported without clear details of transmission loss parameters.

Appendix 3 - *Graphreader* validation exercise

This section presents a brief validation exercise using the graphreader online tool, which was employed in this review to extract numerical values from plots in published studies (see Sections 2.3 and 2.4).

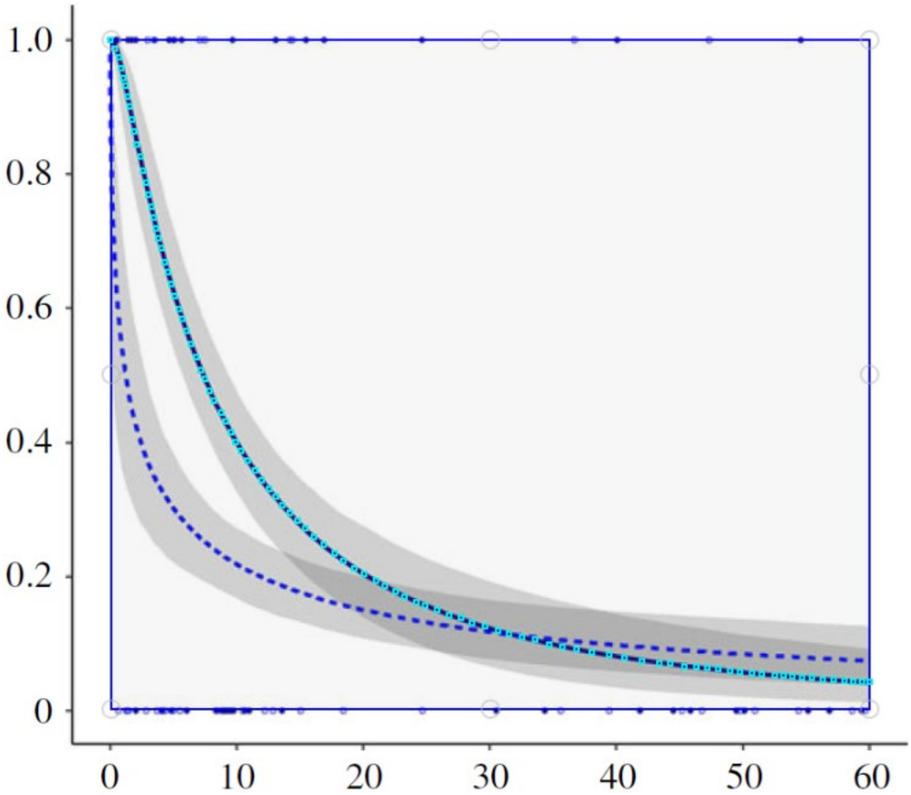
For this validation, a plot from Graham *et al.* (2019) was used. While these data relate to impact piling, and not the noise sources considered in the current review, they are appropriate for the objective of the exercise: to indicate that the graphreader tool can extract values from plots with an appropriate level of accuracy to inform the evidence review.

The selected plot was the probability of a harbour porpoise response (24 hours post-piling) as a function of distance from the piling location for both the 1st and final (86th) piling locations, using a truncation distance of 60 km. The dose-response plots for these locations are represented in Figure 6a of Graham *et al.* (2019) by a solid navy line (1st location) and a dashed blue line (86th location). A screenshot of Figure 6a was uploaded to graphreader, and data points were manually marked on both curves (Figure 8). In the graphreader tool, the axis limits were set to 0–1 on the y-axis and 0–60 km on the x-axis. The minimum sampling interval was constrained to 150 m due to the tool's limit of 500 sampling points.

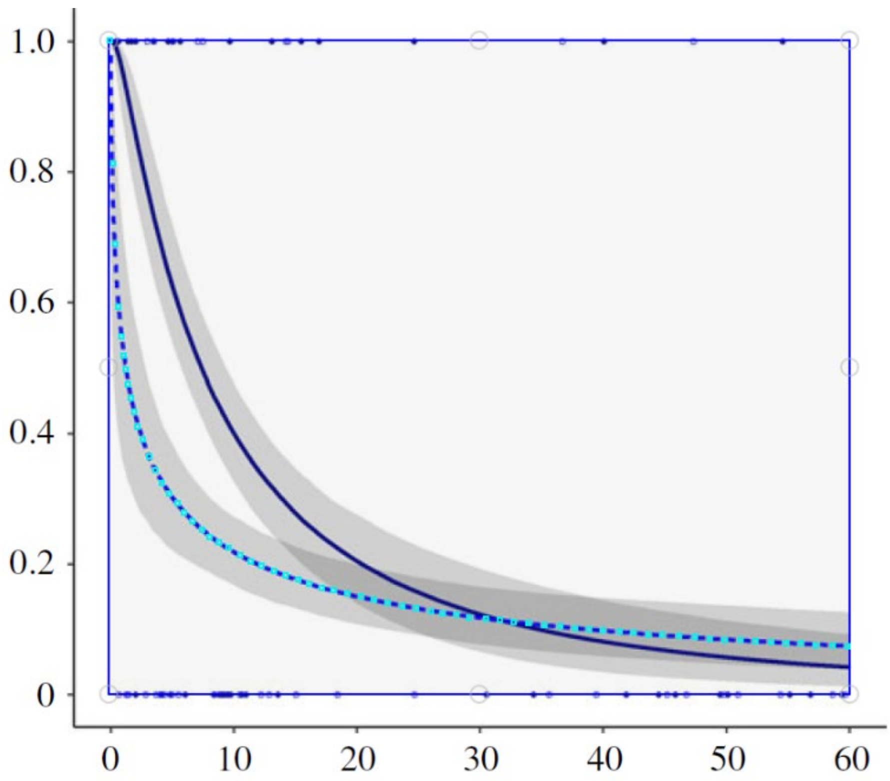
Figure 9 shows two curves (for the 1st and 86th locations) based on extracted graphreader points. The sampled curve data were exported as a CSV file. For 150 m increments of distance, the number of porpoises disturbed vs non-disturbed was estimated (assuming a theoretical uniform density of 0.8 animals per km^2). The distance at which the number of porpoises disturbed was equal to non-disturbed has been then estimated using the sampled curve and presented as an EDR in Table 33. The resulting EDR values using the graphreader tool are presented alongside those derived from the original study data (for 24-hour response and 60 km truncation distance for 1st and 86th location). The observed deviations are minimal and are likely attributable to differences in sampling resolution, as graphreader samples at 150 m intervals, whereas the original study used a 5 m interval.

Table 33. Validation exercise - EDR values estimated using the graphreader tool and the original study data for the 1st and 86th piling location at BOWL.

Piling location	**EDR value (km)**	
	Graphreader tool	**Original study data**
1st location	19.80	20.00
86th (last) location	19.65	19.74



a)



b)

Figure 8. Points marked on the probability of harbour porpoise response in relation to distance from piling for a) 1st location and b) 86th (last) location, using the graphreader tool.

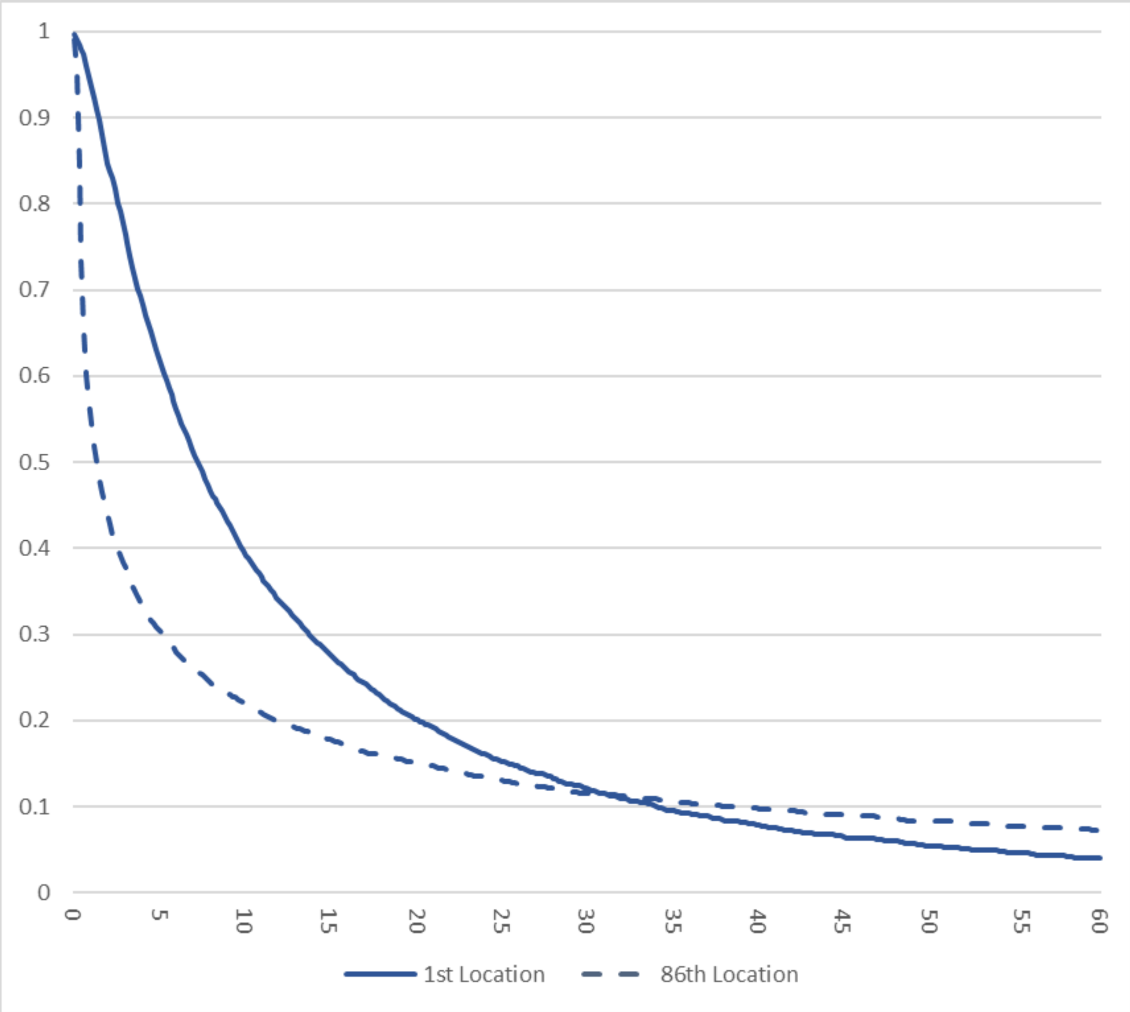


Figure 9. The probability of harbour porpoise response (24 h) in relation to distance from piling for the 1st location and 86th location using data points extracted in the graphreader tool.