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Recommendations for assessing the risk of injury to marine mammals and fish posed by noise when using explosives in UK waters

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1. Introduction

1.1. Background

Anthropogenic underwater noise is one of the greatest pressures in the marine environment. Whether the noise is considered impulsive, such as an explosion, or non-impulsive, such as shipping, it can have an impact on marine life. Explosive operations are one source of underwater noise, and these have been undertaken for decades in the marine environment for a variety of purposes. Explosives may be used to remove existing infrastructure or to clear unexploded ordnance (UXO). The sound from explosive use falls within the hearing range of marine receptors such as marine mammals, fishes (including elasmobranchs) and is usually loud, hence it has the potential to cause acoustic impacts. The main issue of concern around explosive use is risk of death and injury to wildlife, as any disturbance effect will be of short duration and will have a low likelihood to cause longer-term changes in behaviour (JNCC *et al.* 2010; Popper *et al.* 2014).

Marine mammals are protected throughout their range in UK waters, under UK and devolved administration legislation. The Habitats Regulations (as outlined in JNCC 2025b), which transpose the European Habitats Directive into UK law, make it an offence to deliberately kill, injure, capture or disturb cetaceans. Seal species in the UK are also protected from capture, injury or killing under various legislation, including the Conservation of Seals Act (1970), the Marine (Scotland) Act 2010, and the Wildlife (Northern Ireland) Order 1985.

Certain fish and elasmobranch species are protected from injury under the Wildlife and Countryside Act (1981) or under the Habitats Regulations. Additionally, several fish and elasmobranch species are listed as species of principal importance in England (Natural Environment and Rural Communities (NERC) Act 2006, Section 41), as species of principal importance for biodiversity conservation in Scotland (Scottish Biodiversity List), and as living organisms of principal importance in Wales (The Environment (Wales) Act 2016, Section 7). Despite a lack of specific legislation for most fish species, it is important that marine users consider the impacts of explosives on all fish species, in addition to marine mammals.

Before explosives operations are undertaken in UK waters, a licence or consent is required. When applying for licences to detonate explosives in the marine environment, noise risk assessments are typically required to understand, quantify and predict these impacts, and to demonstrate that there will not be significant negative effects. These assessments are routinely underpinned by underwater noise modelling, which requires information on the sound source level of the blast, sound propagation, sound exposure, and criteria for impacts to marine life. Modelling outputs present the impacts in a quantitative way, by estimating the spatial range or area over which the impact could occur. The assessment can also be used to identify what mitigation measures are required to reduce the impacts to acceptable levels. The results of the assessment and efficacy of mitigation measures can be checked and validated through monitoring of underwater noise.

In addition to the noise risk assessment a marine mammal mitigation protocol (MMMP) is often required, summarising the key findings of the noise risk assessment and defining the measures the project will take to mitigate the risks. The residual level of risk will determine the need for any additional licences (e.g. European Protected Species (EPS) licence). Guidance on these additional documents are not included herein as they are provided elsewhere (e.g. JNCC *et al.* 2010).

1.2. Purpose of Guidance

Whilst underwater noise risk assessments have been undertaken for a long time, there are inconsistencies in the approaches being taken. Furthermore, the approach to undertaking noise risk assessments continues to evolve with the publication of new information, which should be incorporated into the assessments where appropriate. There is a need to understand and review the current approaches, in the light of evolving information, to create a common understanding of best practice for noise risk assessments considering the use of explosives in the marine environment.

As a condition of the licence or consent, there may be a requirement to undertake underwater noise monitoring. The Joint Position Statement on UXO clearance (UK Government 2025) and accompanying guidance (Defra 2025) provides some clarity around the expectations and objectives of undertaking underwater noise monitoring of UXO clearance activities. However, there is an absence of similar guidance in relation to noise monitoring of other activities that utilise explosives in the marine environment (such as decommissioning of oil and gas infrastructure).

This project, entitled “Guidance for assessing injury risk to marine mammals and fish posed by noise when using explosives in UK waters” (hereafter the Project), aims to address these gaps, through a series of four interlinked objectives. These objectives are:

1. **Objective 1**: Literature Review (Section 1).

2. **Objective 2:** Guidance for assessing the risk of injury to marine mammals and fish from explosive noise (Section 2).

3. **Objective 3:** Guidance for the verification of underwater sound fields from the use of explosives in the marine environment (separate report, East *et al.* 2026).

4. **Objective 4:** Future improvements (Section 3).

The guidance in Section 3 provides recommendations for undertaking explosive noise risk assessments for marine mammals and fish (including elasmobranchs), specifically with regards to the potential for injury. Whilst there are other effects from underwater noise, such as disturbance, this guidance focuses on the risk of auditory injury to marine mammals and lethal and sub-lethal injuries to fish. This guidance should be considered in conjunction with the JNCC guidance for minimising the risk of injury to marine mammals from explosive use and UXO clearance in the marine environment (JNCC 2025a, 2025b). The guidance in Section 3 can be adapted to assess the risk of injury to other marine species if deemed appropriate by the relevant Regulator and/or Statutory Nature Conservation Body (SNCB). This could include, for example, marine turtles, which are also protected under the Habitats Regulations.

The Project focuses on explosive use in decommissioning of oil and gas infrastructure and the clearance of UXOs, which are the main uses of explosives in the UK marine environment. Clearance of UXOs is occurring more frequently as a byproduct of increased development in the marine environment. It is acknowledged that other explosive operations occur in UK waters, including decommissioning of other infrastructure, rock blasting, drill-and-blast activities, and coastal quarry blasting. These activities may require a noise risk assessment where there are potential impacts to the marine environment. Though not explicitly covered, the recommendations put forward in this Project may be applied to other explosive operations, though this should be agreed with the relevant Regulator.

The Project has been undertaken by a consortium of APEM Ltd, SMRU Consulting and Subacoustech Environmental Ltd., and through consultation with UK Regulators, SNCBs and technical experts. Additional consultation was undertaken through the Technical Project Steering Group, which included members from Cefas, Seiche Ltd., Loughborough University, and Manta Environmental Ltd.

2. Literature Review

2.1. Introduction

Objective 1 of the Project comprises a review of key publications relating to underwater noise risk assessments for explosive operations. The outputs of this objective are presented below. The aim of this section is to summarise new findings as well as recommended methods for improving assessments of the risk of injury to marine mammals and fish from explosive noise.

While some summary information on relevant acoustic metrics is provided in this literature review, full definitions can be found in the International Standard (2017) ISO 18405:2017(E) Underwater acoustics — Terminology and Table 1 of this report. Additionally, NPL (2022) provide a Protocol for In-Situ Underwater Measurement of Explosive Ordnance Disposal for UXO. This protocol is not described here in the literature review but is considered in East *et al.* 2026, Additional recommendations for the verification of underwater sound fields from the use of explosives in the marine environment.

Table 1. Common terms and expressions used in the field of underwater acoustics used from the International Standard (2017) ISO 18405:2017(E) Underwater acoustics — Terminology.

Term	Abbreviation or symbol
Root-mean-square sound pressure level	SPL_{rms} or $L_{p,rms}$
Sound pressure level	SPL or L_p
Peak, or zero-to-peak sound pressure level	SPL_{pk} or $L_{p,pk}$ or $L_{p,0\text{-}pk}$
Sound exposure level	SEL or $L_{E,p}$
Cumulative sound exposure level	SEL_{cum} or $L_{E,p,t}$
Source level	SL or L_s

2.2. Review methods

The research papers presented in the original Project Invitation to Tender (ITT) were reviewed alongside additional studies from scientific journals and the grey literature. Additional literature sources were provided by the Technical Project Steering Group.

More than 70 papers and reports were included in the literature review; details of these are listed in *References* and in *Other papers included in the literature review* (not cited in report text). Each literature source which provided information on noise risk assessments for explosive operations was summarised for information on sound source characterisation, sound propagation modelling, and marine life sound exposure. These papers and reports were sourced through a Google Scholar search, using search terms such as, but not limited to, “underwater explosive”, “UXO”, “marine mammal”, “fish”, “impacts”, “injury”, “model”, and “noise”. This search was not exhaustive but focussed on collating papers and reports that have been published recently and that provided information on models that have commonly been used in underwater noise impact assessments to date. Additionally, the review focussed on explosive operations in terms of UXO clearance and oil and gas decommissioning activities (such as well severance) as these are currently the commonest use of explosives in UK seas. The review did not focus on other explosive operations such as rock blasting, drill and blast activities, or quarry blasting near the coast. The literature search found that while there are some published, peer-reviewed examples of detailed

underwater noise monitoring and resulting injury ranges, much of this data is in unpublished and/or non-peer reviewed reports, including underwater noise monitoring reports from UXO clearance campaigns at recent proposed offshore wind farms. Where it was known that such relevant data existed, the data were sourced through communication with the data owners.

In addition, further sources were sought and summarised on relevant guidance around the noise risk assessment process, and validation of noise risk assessments through monitoring.

2.3. Explosive use in oil and gas decommissioning

Explosives are currently used on a regular basis in oil and gas decommissioning activities including 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; Continental Shelf Associates 2004; DESNZ 2023; Zawawi *et al.* 2023). Tools that utilise explosive charges can be lowered into piles and wellheads or set externally by dive teams, although recently it has become commonplace for remote operating vehicles (ROVs) to be used instead (DESNZ 2023).

The most common charge size for explosives used in decommissioning is 40 – 50 kg but typical charges can range from 10 – 50 kg (Ainslie *et al.* 2009; DESNZ 2023). Stone (2023) reported that, based on a review of marine mammal observer reports, NEQs of up to 86 kg were reported for O&G explosive use, with 58% of reported detonations (for which information was available) using an NEQ exceeding 30 kg. A review of O&G licences that requested explosive use found that 62% of detonations would use an explosive weight of 2 kg or less; 81% of detonations within 10 m of the seabed surface (mudline) used charges greater than 59 kg (JNCC, personal communication). All bar one of the licences reviewed involved the explosive being located below the level of the seabed surface, with 37% using explosives within 100 m of the seabed surface and 20% within 10 m. The number of detonations required per operation varied, with some only requiring a single detonation while others required up to three detonations within the same well but at different depths. The size of charge varied with operation and depth and varied greatly depending on the method of explosive being applied. Down-well operations (> 10 m) usually used perforating guns (multiple detonations of very small charges), with a combined weight of < 2 kg, whereas infrastructure severance within 10 m of the seabed use much larger charge weights (45 kg or greater).

Similarly, it has been reported by Brand (2021a, 2021b) that for explosive-severance studies conducted by the US Department of the Interior's Minerals Management Service (now BOEM (Bureau of Ocean Energy Management)), charges cleared at different depths below the mudline (BML) were typically smaller (2.27 – 3.18 kg, or 5 – 7 lb) than those above the mudline (majority 22.68 – 90.72 kg, or 50 – 200 lb).

Various types of explosive charges are used during decommissioning, but they are generally classified into two main categories: bulk charges and cutting charges.

Bulk charges are most often used to sever and recover subsea wellheads and are generally made up of the high explosive materials C-4 or Composite B (Comp B) (Continental Shelf Associates 2004). The charges are lowered into pilings or well conductors and detonated with a 0.9 second delay between detonations (DESNZ 2023). Detonations are conducted in groups of eight or less with short pauses (2 - 3 minutes) in between groups (DESNZ 2023). Historically, all piles on platforms can be severed within two hours using bulk charges, including the time needed for marine mammal searches and the loading of charges (DESNZ 2023). Bulk charges can be configured into ring charges and focusing charges which are designed to concentrate more energy along the fracture lines of structures, which reduces the overall charge size required to sever piles (Continental Shelf Associates 2004).

There are two types of cutting charges: linear shaped charges (LSC) and foam clad breeching charges (sometimes referred to as cutting tape). LSCs are manufactured so that upon the detonation of explosives (often RDX or PBX) a cutting material (generally made of copper) placed in close contact with the explosives is propelled at high velocities (> 3,000 m/s) to form a jet that cuts through steel piling up to 75 mm thick (Continental Shelf Associates 2004; DESN 2023). LSCs can be placed inside or outside of targets but placing the charges externally and above the mudline reduces the overall attenuation of sound upon detonation (DESNZ 2023; Dzwilewski & Fenton 2003) provided by the seabed. 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 (Continental Shelf Associates 2004; DESNZ 2023). Although foam clad breeching charges can be used for subsea decommissioning, they are not used beyond 10m depth (DESNZ 2023).

There is an overall lack of data available in the public domain on underwater measurements of explosives used in decommissioning. A report produced by Genesis (2011) reported on a study by Nedwell *et al*. (2001), in which sound pressure levels were measured for various charge sizes (36 – 81 kg) for decommissioning of wellheads in the North Sea. Sound pressure levels were recorded from seabed mounted hydrophones at depths of 84 – 116 m, with charge depths of 2 – 3 m BML. For a 36 kg charge, the highest $L_{p,pk}$ value recorded at 650 m was 222 dB re 1 µPa and for an 81 kg charge the highest $L_{p,pk}$ value recorded at 650 m was 226 dB re 1 µPa, both of which are above the instantaneous permanent threshold shift (PTS) threshold for the LF, VHF and PCW marine mammal hearing groups at this distance.

Based on multiple reports from down-well perforations using various explosive materials of the order of 10s of kg, it appears that the recorded noise levels from these events do not pose a large threat of auditory injury to marine mammals. Underwater noise measurements were recorded during well perforations in the North Sea (Confidential 2020). Perforations occurred at 4.3, 5.2, 8.5, 73.8, 138.1, and 156.7 m below the mudline. All perforations consisted of 120 shots with 22.7 g RDX charges. Acoustic measurements were collected at 3 m above the seabed via a stationary hydrophone and at either 5 m or 10 m (away via a hydrophone attached to an ROV.

At one site, the measured $L_{p,pk}$ for the shallow detonations (< 10 m BML, but water depths of ~95 m) ranged from 204.6 – 211.0 dB re 1 µPa and the unweighted $L_{E,p}$ ranged from 175.5 – 183.7 dB re 1 µPa^{2}s. The $L_{p,pk}$ for the deeper detonations ranged from 188.3 – 193.0 dB re 1 µPa and the unweighted $L_{E,p}$ ranged from 165.4 – 169.6 dB re 1 µPa^{2}s.

At a second site, the measured $L_{p,pk}$ for the shallow detonations (< 10 m BML, but water depths of ~95 m) ranged from 198.2 – 208.7 dB re 1 µPa and the unweighted $L_{E,p}$ ranged from 171.1 – 176.7 dB re 1 µPa^{2}s. The $L_{p,pk}$ for the deeper detonations ranged from 182.2 – 193.6 dB re 1 µPa and the unweighted $L_{E,p}$ ranged from 160.8 – 169.9 dB re 1 µPa^{2}s.

The measured $L_{p,pk}$ were below the Southall *et al.* (2019) guidelines for PTS in all cases except for shallow perforations which exceed PTS levels for Very High Frequency (VHF) cetaceans. However, based on measurements from the ROV ($L_{p,pk}$ of 202.0 dB re 1 µPa at 10 m distance) noise levels were predicted to drop below these thresholds with increased distance from the perforation site, likely within 50 - 100 m. The same pattern was observed in the weighted $L_{E,p}$ measurements as shallow perforations exceeded thresholds for PTS in VHF cetaceans (160.9 dB re 1 µPa^{2}s at 10 m distance) but again, it was predicted these levels would be below the threshold within 50 – 100 m of the well perforation. In all cases, the $L_{p,pk}$ were higher for shallow perforations.

These conclusions are supported by the findings of a second report (Confidential 2018a) in which underwater noise measurements were taken during well perforations in the Southern North Sea. Perforations occurred at 193 m below the seabed using 402 g of High Melting Explosive. Fixed recorders collected noise data at 270 m and 610 m from the detonation site. The recorded noise levels during perforations did not exceed baseline ambient noise levels and noise associated with detonations were not identified on the recordings. However, noise levels were higher at 270 m compared to 610 m. Based on these findings, peak noise levels ($L_{p,pk}$) were below 120 dB re 1 µPa and the $L_{E,p}$ was below 110 dB re 1 µPa^{2}s at 270 m distance. The report concluded that there is little risk to marine mammals at 270 m from the well head.

A third report (Confidential 2018b) had similar findings based on the analysis of underwater noise measurements taken during five explosive events in the Southern North Sea. Noise levels were monitored using fixed hydrophones at distances of 270, 610, 750, and 1,500 m from the site. Modelling on peak ambient noise levels was conducted using the data from the first detonations at 750 m and a KRAKEN model (Porter 1997). The explosions took place at a depth range (BML) of 244 m to 2,734 m using either a 187.5 g TNT eq. charge with a 1 g ignitor, 52 g or 402 g of High Melting Explosive. The noise level recording during the explosive campaign, while variable, were not significantly different from those generally observed in the Southern North Sea with typical observed levels ranging from 110 to 130 dB re 1 µPa. The absence of any increases in sound pressure, L_p, and $L_{E,p}$ at the time of detonation in the recordings meant there was no indication of explosions occurring in the data. Furthermore, the modelling that was conducted based on worst-case scenarios from the recorded noise levels resulted in no effect observed across any of the marine mammal hearing group categories in both the Southall *et al.* (2019) and NMFS (2024) guidelines.

In summary, explosives at shallow depths (< 100 m) below the mudline can lead to PTS thresholds for marine mammals being exceeded, but only at short ranges (within 50 – 100 m of source). Explosives at deeper depths below the mudline (> 100 m) do not lead to PTS threshold being exceeded (though it is noted that there is limited monitoring data). In general, there is little data available in the literature to comment further, or to confidently identify limits to define when underwater noise modelling is or is not required. Further monitoring data is required for a range of charge sizes and a range of depths below the mudline.

2.4. UXO clearance

UXO clearance is the process of detecting, identifying, and removing or neutralising UXO from an area. UXO includes any military munitions (bombs, mines, grenades, shells, *etc*.) that remain intact and could still contain viable explosive material. A significant amount of UXOs are present in UK waters (Defra 2025) and once detected they typically require removal. Dedicated surveys to identify UXOs are undertaken as part of the development of marine infrastructure such as offshore wind farms and interconnectors, hence UXO clearance frequently occurs as part of these developments.

UXO clearance typically occurs at or just below the seabed as this is where the UXO has come to lie, though the clearance may occur elsewhere if the UXO is safe enough to be moved before clearance. The size of UXOs at the time of manufacture can range significantly in size, from < 1 kg to several hundred kg or even 1,000 kg. It is the amount of explosive material within the UXO that primarily determines the noise upon detonation; the greater the amount of explosive material, generally the greater the noise produced. However, the amount of viable explosive material at the time of UXO clearance, which can be decades after manufacture and affected by time spent in the marine environment, is unknown. There is more monitoring data available of the noise from UXO clearance than from explosives used in decommissioning; examples of these data are provided in Section

2.13. Generally, it can be assumed that all UXO clearance operations can lead to injury thresholds for marine mammals and fish being exceeded.

Clearance of UXOs can be undertaken using high-order or low-order methods. The high-order clearance method involves detonating an explosive donor charge next to the UXO, which in turn causes the UXO to detonate. Low-order techniques are designed to destroy the explosive material in the UXO without it detonating at its maximum value. Deflagration is a type of low-order clearance that involves burning the explosive material in the UXO at a lower sonic velocity without detonating it. Currently this process is initiated using a shaped explosive charge which creates a plasma jet that penetrates the UXO casing, causing the content to burn. This method of initiating deflagration has been proven to result in significantly lower acoustic energy when undertaken successfully (Lepper *et al.* 2024; Wang *et al.* 2026a, b). Other low-order techniques have been proposed (e.g. Lepper *et al.* 2026), and in some cases used offshore (e.g. Seiche Ltd 2021), but some have limited evidence to support their noise reduction (e.g. Alford *et al.* 2022). The UXO clearance method is relevant to the noise risk assessment as it may affect the predicted source level (see Defra 2025). Both high-order and current low-order clearance methods use explosive charges to clear the UXO. High-order clearance often uses a donor charge size in the range of one to tens of kg, whereas low-order shape-charge deflagration tools are typically a maximum of ~1 kg.

It is highlighted that in January 2025, the UK Government and relevant stakeholders produced an update to the 2021 Joint Position Statement on the clearance of UXOs in the marine environment (UK Government 2025). This updated position reinforces that low-noise methods should be the default clearance technique, with high-order clearance used only as a last resort in extraordinary circumstances, such as when UXO characteristics (e.g. level of degradation, shell thickness, or depth) exceed the capabilities of known low-noise clearance tools. It is expected that UXO clearance campaigns that retain the option of high order as a last resort will need to include this worst-case scenario in their assessment and associated modelling. For operations in Scotland, the Joint Position Statement should be read alongside the Marine Directorate (2025) Marine licensing – unexploded ordnance clearance: application guidance.

All UXO clearance operations require a noise risk assessment. However, at the time of undertaking the noise risk assessment, the size of the UXOs to be cleared may be unknown. In this case, assumptions must be made on the size of the UXOs to be cleared, and the clearance method(s) to be used. Once further detailed UXO surveys have been undertaken, these can provide information on the number, size and location of UXOs, as well as inform likely clearance methods and mitigation measures. It is acknowledged that there are many additional factors which can affect the noise produced during UXO clearance and how it propagates through the water column, however the relationship between these is poorly understood and not frequently accounted for. The modelling tends to assume the worst-case scenario that the UXO is in pristine condition, with no consideration of partial burial, location on the seabed, absorption of energy by the seabed or degradation of the explosive material over time. As such, the outputs of the modelling are generally assumed to be conservative estimates.

The number of UXO clearances (or attempts) in a day can vary; often only one occurs per day, but sometimes multiple can occur. The number per day may be restricted through operational constraints, licence conditions, etc. According to the Special Area of Conservation (SAC) Noise Management Regulators Working Group's 2024 Progress Report, as well as recent marine licence project applications (Sofia OWF, Hornsea 3 OWF and East Anglia Three OWF; MMO 2023, 2024a, 2024b), the Marine Management Organisation (MMO) may consent to a maximum of three high-order UXO clearances per campaign, with a maximum of one high-order clearance undertaken within any 24-hour period. Further high-order UXO clearances can be requested from the MMO (MMO 2023, 2024a, 2024b; Defra

2025). There may also be restrictions on the number of low-order UXO clearances that can be carried out within a 24-hour period. The MMO may consent to up to three low-order clearances per day (Hornsea 3; MMO 2024a), whereas other projects may have a lower daily allowance (East Anglia Three; MMO 2024b). Additionally, limitations may be imposed regarding the combination of low-order and high-order detonations (e.g. Hornsea 3; MMO 2024a).

Nevertheless, in most cases the clearance of UXO is treated as a single event for the purpose of modelling. Whilst it is theoretically possible for multiple UXO clearances or attempts to occur within a day, modelling this would require a series of large assumptions, particularly regarding animal movement in the intervening time, where there is likely to be a long period between these clearances or attempts.

2.5. Source level characterisation

The acoustic characteristics of explosive operations have been measured by deploying calibrated acoustic recorders and quantifying the received sound pressure levels at various distances from the sound source (e.g. Salomons *et al*. 2021; von Benda-Beckmann *et al*. 2015). Such measurements, along with older data (e.g. Cole 1948; Arons 1954), have enabled the back-calculation of the source level at a theoretical one metre away from the location of the explosive as well as the integration of field measurements into semi-empirical sound propagation models designed to predict received noise levels at greater distances and in novel conditions.

There are various acoustic metrics which can define the characteristics of a signal, and these can be categorised into instantaneous metrics (e.g. peak Sound Pressure Level (SPL_{pk} or $L_{p,pk}$)), or time-based metrics (e.g. root-mean-squared Sound Pressure Level (SPL_{RMS} or L_p) or Sound Exposure Level (SEL or $L_{E,p}$)). $L_{p,pk}$ represents the maximum amplitude measured over the duration of a signal of interest whereas metrics such as SPL_{RMS} provide an average amplitude quantified over a pre-defined time window. $L_{E,p}$ quantifies the amount of acoustic energy accumulated over a specified period (e.g. single pulse SEL, SEL_{ss} or $L_{E,p,ss}$) or following multiple exposures to transient signals ($L_{E,p,t}$). Full definitions of these metrics can be found in the International Standard (2017) ISO 18405:2017(E) Underwater acoustics — Terminology.

There have been multiple studies which involved measuring underwater sound pressure levels during explosive detonations. This includes is a wide range of charge weights (amount of explosive material, defined as Net Explosive Quantity or NEQ), types of explosive substances, depth, and position in the water column (e.g. above or below the mudline).

It is noted that models available for source level characterisation may not be able to account for all factors (e.g. charge weight, characteristics of the explosion/explosive itself) which could affect the realised source level, and commonly only the charge weight is known at the time of assessment. For example, in the case of UXO clearance, the amount of viable explosive material left in the UXO will be unknown, as it may have been affected by degradation over time. Other factors which may be unaccounted for include size, thickness, orientation and age of the explosive casing, and the amount of explosive material actually detonated, as this may be different from NEQ and can lead to lower noise levels than predicted if not all the explosive material gets denotated (i.e. residual/unconsumed explosive material left on fragments of the casing). The source level characterisation may be considered conservative if there are such factors that cannot be accounted for.

Few of the studies included in the literature review here provided information on the frequency components of explosive noise. Where they were presented, centre/predominant frequencies ranged between 0.01 - 25 kHz, and peak power frequencies ranged between

0.04 - 12.1 kHz (see Table 2), although energy is present across a much greater frequency range than this.

Table 2. Summary of manuscripts reviewed which provided information on the centre/predominant frequencies, and peak power frequencies of UXO detonations

Author/Study	Centre/Predominant frequencies (kHz)	Peak power frequencies (kHz)
Bagocius (2013)	0.187 - 1.69	0.4 - 0.157
Bagocius & Narscius (2019)	0.1 - 10	Not provided
Gaspin & Shuler (1971)	0.0125 - 1	Not provided
Lepper *et al.* (2024)	0.2 - 13	1
Salomons *et al.* (2021)	0.25 - 0.4	Not provided
Schulkin & Mercer (195)	0.1 - 2.8	Not provided
Soloway (2014)	0.1 - 1	Not provided
Soloway (2018)	0.05 - 1.6	Not provided
Soloway & Dahl (2015)	0.05 - 2.5	Not provided
Turner & Scrimger (1970)	0 - 10.2	0.32 - 0.64
Veloria *et al.* (2021)	0 - 25	12.1
Von Benda-Beckmann *et al.* (2015)	0.01 - 20	< 1
Weston (1960)	0.035 - 4.5	Not provided

2.6. Sound propagation models

Currently, there is no single model considered to be “ideal” when assessing the potential for auditory injury from explosive detonations. The model selected for use will be determined by the purpose of the modelling, activity, regulatory requirements, and anticipated level of risk. This has been reflected in the advice provided in the guidance (Section 3).

A multitude of modelling tools have been developed to estimate and predict underwater noise levels at various distances from explosive operations. These tools vary in complexity, with some examples involving mathematical formulas based primarily on the charge weight of the explosive. Other sound propagation models are based on the sonar equation or other mathematical formulas and include parameters which consider the characteristics of the sound source and the environment in which the sound travels.

The complexity of the sound propagation modelling tools can range from user-friendly spreadsheet-type files that require a user to provide a set of single-valued parameters, otherwise referred to as ‘simple’ models (EDGAR: Brand 2021a, 2021b) to more computationally intensive software which requires spatial information (e.g. bathymetry) and other site- or signal-specific characteristics (‘complex’ models). By including additional parameters or considering the fine-scale variations in characteristics in the propagation environment, more complex models have the potential to add greater accuracy to the results of modelling exercises. The more complex the model the more location-specific it generally tends to become.

Further, the models are input file driven and each requires location specific environmental data which is not always available at the planning stage of an operation. The software can include, for example, acoustic field calculation by normal modes, wavenumber integration, and ray and beam tracing. Much of this type of software is opensource and has been combined in the AcTUP package by the Centre for Marine Science and Technology at Curtin University (Duncan & Maggi 2006). The software, which works in the MATLAB platform, is available from the Ocean Acoustics Library (OALIB) website (OALIB 2024).

The underwater environment is a complex one, and there are many factors that influence the propagation of sound and contribute to the propagation loss (Robinson 2014) including:

- The geometrical spreading of the sound away from the source
- Absorption of sound by sea water and seabed
- Interactions with
    - sea surface (reflection and scattering)
    - seabed (and transmission through it)
- Refraction of sound due to the sound speed gradient
- Bathymetry (water depth) between source and receiver positions; and
- Source and receiver depth.

Most of the above factors depend on the acoustic frequency of the sound source, and a complex model will include frequency dependence explicitly within the model parameters. However, many of the above factors are highly context dependent and as such many preclude a model from being used over a wide spatial extent.

2.6.1. Simple models

It is generally the simple models that are most used in environmental impact assessments (EIAs) for explosive use. DESNZ (2023) describes three main model types that have typically been used to estimate impacts from oil and gas (O&G) decommissioning activities:

- Open water detonation models (Cole 1948; Swisdak 1978; Slifko 1967; Soloway & Dahl 2014);
- Connor (1990) models: estimates noise levels from explosive severance of piles and well conductors; and
- Brand (2021a, b) EDGAR model (Explosives use in Decommissioning – Guide for Assessment of Risk): estimates noise levels from explosive severance of piles and well conductors but can also be used to model open water explosions.

The Soloway and Dahl (2014) open water model is also commonly used to predict impact ranges for UXO clearance (both high and low order).

The simple spreadsheet-type model equations are presented here, and their validity and limitations are discussed in the next section. Many of these models consist of similitude equations coupled with specific empirical exponents and coefficients, depending on the

scenario. The models are divided into open water and confined severance models. These are outlined in detail in Appendix 1 'Simple'.

2.6.2. Complex models

The suitability of the more complex models depends on the acoustic frequency range of the sound source, water depth, computational requirements and ability to account for spatial variability in the environment (Farcas *et al.* 2016). An important physical process is assumed during an underwater explosion, including bubble generation and movement related to the interaction between the expanding high-pressure detonation product and the surrounding fluid. The bubble shape and volume in relation to the charge mass, depth and surrounding environment adds a further level of complexity while trying to estimate impact ranges (Nowak *et al.* 2023). The accuracy of model estimates therefore depends on the quality of input data and the suitability of the model used. To reduce uncertainty in modelling outputs, it is important to be transparent in the modelling approach used and what data are included to inform the model.

Current complex models have been developed based on a variety of mathematical methods such as ray theory, normal modes, multipath expansion, wavenumber integration or parabolic equation (Farcas *et al.* 2016). The most appropriate model will be dependent on the given scenario and therefore should be project specific to account for the acoustic frequencies and environment. For example, models based on ray theory (e.g. BELLHOP; Porter & Liu 1994) is a beam tracing model which handles arbitrary range-dependent environments. It works best for deep-water environments and is suitable for higher frequency sound sources, however it is limited in describing the way that sound propagates at low frequencies in shallow water (Porter 2011; Farcas *et al.* 2016). The parabolic equation method is suitable for range-dependent environments, discontinuous sound speed profiles and is commonly used in shallow or deep-water environments, however it is not the model of choice for shallow water due to the approach not being able to handle density discontinuities easily (Wang *et al.* 2014a). For further detail on the benefits and limitations of a range of common propagation models, refer to Wang *et al*. (2014a).

Whether a scenario is assessed as deep water or shallow water is not determined solely by water depth, but rather the importance of the sound interaction with the seafloor (Wang *et al.* 2014b). For example, the choice of propagation model should thus consider the extent to which seafloor conditions might influence the propagating sound. If the seafloor interaction is small or can be neglected, then the location will be assessed as deep water, whereas shallow water propagation will generally be dominated by boundary interactions (i.e. seafloor or sea surface). Table 3 summarises the applicability of various propagation models depending on the acoustic frequency and the interaction of sound with the seafloor.

Table 3. Applicability of common propagation modelling approaches according to acoustic frequency of the noise source and the interaction of sound with the seafloor. Green ([1]) = suitable, Amber ([2]) = suitable with limitations, Red ([3]) = not suitable. Source: Wang *et al*. (2014a).

Shallow water		**Deep water**	
Low frequency	**High frequency**	**Low frequency**	**High frequency**
Ray theory[3]	Ray theory[1]	Ray theory[2]	Ray theory[1]
Normal mode[1]	Normal mode[2]	Normal mode[2]	Normal mode[3]
Wave number integration[1]	Wave number integration[1]	Wave number integration[1]	Wave number integration[2]

Shallow water		Deep water	
Low frequency	**High frequency**	**Low frequency**	**High frequency**
Parabolic equation[1]	Parabolic equation[2]	Parabolic equation[1]	Parabolic equation[3]
Energy flux[1]	Energy flux[1]	Energy flux[2]	Energy flux[2]

2.6.3. Combined approach

An alternative to using only a "simple" or "complex" model is to combine model types by using a shock wave model for the zone within which it has been validated, and another model for the acoustic propagation for the zone beyond which the shock wave model was validated. For example, Hannay and Zykov (2022) conducted modelling of UXO clearance using a semi-empirical model for the shock pulse and exponential decay approximation, and an explosive waveform model alongside an acoustic propagation model that used JASCO's marine operations noise model (MONM, JASCO Applied Sciences). Likewise, to model UXO clearance, von Benda-Beckmann *et al.* (2015) used a 'two-part' model:

(1) a source model for underwater explosions in deep water (i.e. a deep-water propagation model (Weston 1960)), and

(2) a sound propagation model for shallow water (SOPRANO Model, Sertlek & Ainslie 2014).

This allowed for measurements of sound produced by several large underwater explosives in shallow water environments to be used to correct deep water source models for explosions and used in combination with a shallow water propagation model to generate maps of received sound exposure level for marine mammals (von Benda-Beckmann *et al.* 2015).

2.6.4. Model comparison

DESNZ 2023 provides a summary of the Connor (1990), EDGAR (Brand 2021a, b), Swisdak (1978) and Soloway and Dahl (2014) models, and provides a comparison of predicted impact ranges obtained when using each model for the same charge size. They provide predicted PTS impact ranges for marine mammals and mortal injury ranges for fish using high explosive (Comp-B) charge sizes between 11.3 kg and 90.7 kg. Their results for the largest charge sizes modelled are reproduced here in Tables 4 and Table 5.

These recommendations does not provide commentary on the methods used in DESNZ 2023 however, the author of the EDGAR model has highlighted they have been unable to replicate the values presented for their model (Brand, pers. comm.). This is considered likely due to:

- The auditory weighting factor adjustments for marine mammals used in DESNZ 2023 are different from those used in EDGAR.
- The formulae used by DESNZ to obtain the weighting factor adjustments are designed for use with explosions in open water with no boundaries (e.g. sea surface, seabed, etc.; Christian 1963), which are not directly applicable to confined explosions such as those used in decommissioning operations, for which EDGAR was initially designed.
- DESNZ potentially using different values of density and speed of sound to those which would have applied in the field for Connor's model data collection.

- The factor used to convert the weight of Comp B to TNT eq. (see Appendix 1).

Impact ranges using corrected parameters have been provided by the EDGAR author and included in the results tables below for comparison. The revised predictions are more aligned with those presented in DESNZ 2023 using the Conor models than previously reported and highlight the importance of clearly identifying what parameters have been applied when presenting model outputs.

It is evident from the results across the models, that the predicted PTS ranges for marine mammals can vary considerably depending on the model used. Using the $L_{p,pk}$ metric, the marine mammal PTS impact ranges are highest for VHF cetaceans, and significantly higher using the open water model compared to the other models (Table 4). Using the $L_{E,p}$ metric, the marine mammal PTS impact ranges are again highest for VHF cetaceans followed by LF cetaceans, and significantly higher using the open water models (especially Soloway & Dahl 2014) compared to the other models (Table 5).

The key issue with all three predictive models is that the measurements used to inform the models were limited to < 1 km, yet the models are extrapolating well beyond measured distances, out to tens of km in some instances. The $L_{E,p}$ metric impact ranges are described by DESNZ (2023) as being overly conservative for both the Soloway and Dahl (2014) and the Swisdak (1978) models, resulting in significant overestimates of impact ranges, especially for VHF cetaceans. A data gap exists in sound measurements at distances > 1 km that are required to verify the predictions of these models.

The model comparison presented in the DESNZ 2023 report also shows differences in predicted mortal injury ranges in fish depending on the model used. Using the $L_{p,pk}$ metric, the fish mortal injury range is highest for the open water model, while the Connor (1990) and EDGAR (Brand, 2021a, b) models predict lower but similar impact ranges (Table 5). Both the Connor (1990) and the EDGAR (Brand, 2021a, b) model were found by DESNZ 2023 to underestimate measured $L_{p,pk}$ for many noise measurements made during oil and gas decommissioning activities involving explosive. The open water model is described as potentially providing a useful upper bound to the measured data. As discussed above, empirical evidence to verify model performance at larger distances from explosive detonations is limited. Sound measurements presented in the DESNZ 2023 report were taken less than 100 m from the charges and considered by DESNZ insufficient to estimate distances where the mortal injury threshold for fish may be exceeded, particularly for larger charge sizes.

To note:

- PTS ranges presented in DESNZ 2023 (and subsequently Tables 4 and 5) are based on the Southall et al., 2019 thresholds.

- Table 4: the revised EDGAR ranges presented use a TNT eq. coefficient of 1.27 for Comp B, the b_{ED} of 0.1969, and $W^{0.1969}$ (instead of $W^{0.333}$ used by DESNZ 2023;) and the addition of +5 dB for the bubble pulse (see Appendix 1).

- Table 5: DESNZ 2023 did not present SEL impact ranges using EDGAR, so these have been added. The weighting factor adjustments used in DESNZ 2023 and those used for the revised EDGAR results are presented in Table 5b.

Table 4. Predicted marine mammal PTS range, and fish potential mortality range (in metres) for a 90.7 kg Comp B charge. Data taken from Table 4-5 and Table 4-7 in DESNZ 2023 with revised values for the EDGAR model provided by Brand (pers. comm.); original predictions using the EDGAR model from DESNZ 2023 are in square brackets for comparison.

Marine Mammal Permanent Threshold Shift (PTS; Southall *et al*. (2019) $L_{p,pk}$ thresholds**)**

Hearing group ($L_{p,pk}$ PTS thresholds)	**Connor (1990) pile severance**	**Connor (1990) well conductor severance**	**Brand (2021a, b) EDGAR pile/ conductor severance**	**Open water model**
LF cetaceans	160	180	167 [100]	1,300
HF cetaceans	90	90	77 [50]	420
VHF cetaceans	440	510	589 [330]	7,200
Phocid seals	170	190	179 [100]	1,500

Fish Potential Mortality Threshold (229 dB re 1 µPa)

Hearing group ($L_{p,pk}$ PTS thresholds)	**Connor (1990) pile severance**	**Connor (1990) well conductor severance**	**Brand (2021a, b) EDGAR pile/ conductor severance**	**Open water model**
Fish	90	90	83 [50]	460

Table 5a. Predicted marine mammal PTS range (in metres) using the Southall *et al.* 2019 $L_{E,p}$ thresholds for a 90.7 kg Comp B charge. Data taken from Table 4-8 in DESNZ 2023 plus values using the EDGAR model (provided by Brand pers. comm.). The EDGAR values use the weighting factor adjustments assumed by EDGAR with results using weighting factor adjustments values from DESNZ 2023 presented in square brackets for comparison.

Hearing group ($L_{E,p}$ PTS thresholds)	**Connor (1990) pile severance**	**Connor (1990) well conductor severance**	**Swisdak (1978) Open water**	**Soloway & Dahl (2014) open water**	**Brand (2021a, b) EDGAR**
LF cetaceans	240	250	1,500	3,100	284 [232]
HF cetaceans	70	80	210	140	51 [68]
VHF cetaceans	530	520	5,000	20,500	337 [517]
Phocid seals	130	140	540	630	183 [122]

Table 5b. Weighting factor adjustments applied when generating the results in Table 5a.

Source	LF cetaceans	HF cetaceans	VHF cetaceans	Phocid seals
DESNZ 2023 (Table 4.3)	3.1	18.6	20.4	10.1
EDGAR (A. Brand pers. comm.)	-0.06	-29.11	-37.55	-5.90

While it is interesting to compare the predicted impact ranges across the various models, what remains missing is empirical validation of the predictions to determine which model is best at predicting auditory and injury impact ranges in practice. Whilst this is currently absent from the literature, an understanding of each of the scenarios modelled, the model validation parameters used within each model, and details on the charge depths, distances and charge weights modelled across the various models could help provide guidance as to which models are best suited for predicting impact ranges in more context specific circumstances (i.e. UXO clearance activities versus well severance activities). The modelled scenarios, model validation parameters, distances and charge depths modelled across each of the Connor (1990), EDGAR (Brand 2021a, b), Swisdak (1978) and Soloway and Dahl (2014) models are summarised in Table 6.

Table 6. A summary of the Connor (1990), EDGAR (Brand 2021a, b), Swisdak (1978) and Soloway and Dahl (2014) models' validation parameters and the scenarios in which models were tested.

Model	Summary

Connor (1990)	• 35 underwater explosive severance operations of bottom-penetrating tubular members of offshore platforms in GOM
	Charges sizes: ranging from 25 – 50 lbs (11.34 – 22.68 kg)
	Charge depth: 8, 16, and 26 feet (2.4, 4.9 and 7.9 m) BML
	Water depth: 53 feet (16.2 m)
	• Scenarios:
	  ○ Direct shock pulses and bubble collapse pulses were analysed for pressure, impulse, and energy
	  ○ The influence of surface reflections, cavitation effects, and precursor pulses on underwater shock propagation was assessed.
	• Compared shock propagation in air-terminated versus water-terminated well conductors, revealing that impulse was slightly lower in water-terminated detonations.

Soloway & Dahl (2014)	Five different explosive charge tests, each with varying charge weights, depths, and distances Charge sizes: C-4 charges with TNT eq. 0.3-6.1 kg; CH-6 charges with TNT eq. 0.1 kg • Charge depth: either 9 m depth or 0.5 m from the seafloor • Water depth: 14.7 m • Distances: Vessel at 430 m from source detonation ○ Vessel at 165–950 m from source (varied between trials)

Model	Summary
Swisdak (1978)	Charge sizes: analysed charges ranging from small 0.5 kg explosive weights up to large 1,000 kg TNT charges Charge depths: explosions occurred at depths between 60 and 5,500 m • Distances: o The pressure pulse characteristics were calculated at a range of 2,000 m for a 1,000 kg TNT charge detonated at a depth of 3,000 m • Scenarios: • Deep TNT explosions: focused on understanding pressure-pulse characteristics at significant depths. • Surface Cutoff Effects: includes scenarios analysing how the surface reflection affects shock waves. • Explosions on the seabed: used to estimate energy and pressure from explosions detonated on different types of seabeds (mud and hard bottom). • Underwater plume formation: predicts the formation and size of plumes generated by underwater TNT explosions. • Line charge detonation: includes shock wave parameters for detonations of line charges in water.
Brand (2021b)	• EDGAR has been validated against datasets from several Gulf of Mexico (GOM) projects • Charge sizes: o 7 lbs (3.175 kg) of C-4, TNT, and NM explosives for scaled well casing severance and open water tests o 5 lbs (2.27 kg) of Pentolite for open water tests o 25 lbs (11.34 kg) to 200lbs (90.7 kg) of Comp B for well conductors and piles • Charge depths: o 7.5 feet (2.286 m) BML for conductor severance in the Potomac River o 14.6 m and 11.8 m BML for TAP-570 Merit Platforms o Various depths ranging from -5 ft to 30 ft BML for different test scenarios, including open-water blasts and well conductor severance o 4.57 to 7.62 m BML in the BOEM 2016-019 study sites • Distances: 1 m slant range was adopted for open-water shots o 0.1 m was used for conductors and piles • Scenarios: o Cutting of conductors at different depths below the mudline. o Cutting of piles using explosives. o Testing of explosions in open water conditions. • Effects of seabed composition, water column conditions, and explosion depth were incorporated into the model

Additional note regarding auditory weightings:

When applying weighted marine mammal auditory thresholds for SEL assessments, information for the sound source is also needed to enable the weighting (which varies with frequency) to be applied to the frequency spectrum of the total signal the animal is exposed to. However, this level of detail on the sound source is not always available. As the developer of the marine mammal auditory weighting functions, NMFS developed simple weighting factor adjustments for those who can't fully apply the auditory weighting functions associated with the SEL metric (NMFS 2018).

DESNZ 2023 is an example of where adjustments were made because the sound measurements used in the modelling were reported as broadband quantities, meaning direct application of weighted marine mammal SEL thresholds was not appropriate. Instead, unweighted SELs thresholds for PTS and TTS were calculated, produced using weighting factor adjustments based on a theoretical energy spectral density for underwater explosive signals (DESNZ 2023, Appendix C).

EDGAR also applies weighting factor adjustments and assumes the default weighting factor adjustments recommended by NMFS 2020 for seismic sources (1 kHz). This is because the first iteration of the NMFS spreadsheet (NMFS 2018) did not provide a weighting factor adjustment for explosives due to the fact '*spectra associated with underwater explosives vary with size and depth* (Urick 1983)'. It was considered (by the EDGAR author) that of the defaults provided by NMFS; an airgun represented a similar signal to explosives with both sources having a strong emphasis on low frequency signals. As most of the energy from a detonation is in the primary pulse and airgun pulses are longer in duration, use of the airgun weighting factor adjustment was considered precautionary.

Differences in the resultant adjustment factors (Table 5b) highlights the complexity of the weighting factor adjustments assumed by different modellers, and the importance of clearly reporting the values assumed for all constants and weighting factor adjustments assumed in any modelling exercise.

2.7. Sound exposure modelling

Sound propagation modelling tools have been used to estimate noise levels at various distances from the sound source and thus predict how fish and marine mammals are likely to be impacted by noise exposures relative to their distance from the source.

There have been multiple studies designed to investigate what received noise levels are likely to cause auditory effects in marine and terrestrial organisms, some of which also quantified the magnitude of the effect. These studies can be primarily split into controlled laboratory experiments (where a subject is exposed to acoustic stimuli and their behaviour/hearing is monitored during and after the exposure) and field studies (where subjects are monitored from remote stations or via animal-borne tags during acoustic exposures). Such studies have provided the data required to establish noise exposure thresholds for various species or hearing groups (i.e. categories of species understood to have similar hearing abilities). Sound exposure modelling tools therefore output estimated distances from the sound source at which specific noise exposure thresholds are exceeded, thus causing a receiver to be impacted by underwater noise exposure.

Sound exposure modelling tools vary in complexity in terms of the number of parameters used and the metrics chosen to predict hearing impact ranges. Whilst all models provide the horizontal distance from the sound source at which a given threshold is exceeded, other models account for depth-specific variations in noise levels and the placement of the receiver in the water column. Additionally, some modelling tools apply frequency-specific

filters to the acoustic measurements to finetune the received noise levels to the hearing sensitivity of a particular species or hearing group. Lastly, the movement of the receivers may be accounted for during scenarios with multiple exposures to noise over a 24-hour period by assuming that animals remain either:

(1) static throughout the whole exposure, or

(2) that they move in a stochastic manner, or

(3) directly away from the exposure location.

In most cases, the $L_{E,p}$ for UXO detonations or clearances reported in the literature exceed the widely used thresholds for injury for marine mammals and fish. This is true for both measured and modelled results. However, the spatial extent over which the thresholds are exceeded is dependent on how far from the detonation the animal is, the amount of explosive material used, as well as whether auditory weighting functions are applied. At short distances (less than 2 km) both measured and modelled results found that marine mammals experienced injury that could be debilitating or lethal (Atodiresei *et al.* 2013; Bagocius 2013; 6 Alpha, West of Orkney, 2022; DESNZ 2023; Ocean Winds 2024).

For various explosive types (naval mines and/or torpedoes), PTS thresholds for marine mammals were exceeded up to 350 m away from the detonation (Atodiresei *et al.* 2013). Bagocius (2013) estimated that, for seals exposed to a 24 kg TNT blast, the effects would be lethal up to 100 m and dangerous out to ~ 1 km. While low-order explosives result in shorter impact ranges, they still cause injury at short distances (6 Alpha, West of Orkney, 2022; DESNZ 2023). For example, Ocean Winds (2024) predicted PTS ranges for low-order UXO clearances (0.15 - 0.25 kg donor charges) of < 1.5 km from the source for all marine mammal hearing groups. This was at least 1 km less than the minimum predicted 2.55 - 14.25 km impact ranges for equivalent high-order detonations (NEQ 6-700 kg). In addition, Veloria *et al.* (2021) characterised the acoustic properties produced from single pulse explosions using hydrophones and found that for estimated charge weights of 0.08 - 0.39 kg TNT, marine mammals within 150 m of the detonation would experience injury. For UXO detonations (1 – 200 kg), Robinson *et al.* (2022) reported modelled results indicating that PTS thresholds were exceeded from 1.6 - 7.1 km away. Worst-case scenarios based on open water detonation models estimated that PTS could occur tens of kilometres away from the detonation (DESNZ 2023). However, this finding appears to be an extremely unlikely case when compared to the results of available literature. Seemingly, the only other account of PTS onset being predicted to occur on the scale of tens of kilometres was estimated by Hannay and Zykov (2022) who found that for a 454 kg TNT charge, PTS onset could occur out to 16.1 km. These results were both the highest modelled for HF cetaceans (in reference to the terminology of NMFS, 2018; equivalent to VHF in Southall *et al*. 2019).

Like for marine mammals, the extent to which the impact thresholds for fish are exceeded is dependent on numerous factors such as how far from the detonation the animal is, and the amount of explosive material used. Other factors influencing the severity of injury effects in fish include the position of the animal in the water column and the extent to which the animal has acclimated to ambient pressure at the time of detonation, which determines the animal's susceptibility to barotrauma (Popper *et al.* 2014).

Empirical evidence on injury ranges for fish from underwater explosions is limited. Jenkins *et al.* (2022) and Smith *et al.* (2022) studied the physical effects of sound exposure from a single pulse explosion on Pacific mackerel (*Scomber japonicus*) at distances of 21 to 807 m from the detonation site and found that for a 6.2 kg TNT equivalent (TNT eq.) explosive weight, individuals within 330 m of the detonation experienced severe injury (e.g. damage to the swim bladder and kidney) above control levels. Mortality was observed out to 157 m from

the detonation site, and significant injuries to sensory hair cells in the inner ear, which may lead to TTS, were observed up to 400 m. Acoustic measurements undertaken during the studies showed that thresholds for mortality and potential mortal injury in fish ($L_{p,pk}$ 229–234 dB re 1 µPa; Popper *et al.* 2014) during the detonation of 6.2 kg TNT were exceeded within 100–200 m of the detonation (Jenkins *et al.* 2022; Bowman *et al.* 2024). For high-order UXO detonations (25–800 kg charge weight plus donor weight), Outer Dowsing Offshore Wind (2025) reported modelled results based on the Soloway and Dahl (2014) model, indicating impact ranges for mortality and potential mortal injury in fish of between 170–560 m for the unweighted 234 dB $L_{p,pk}$ threshold and of between 290–930 m for 229 dB $L_{p,pk}$. For low-order UXO deflagration (0.5 kg donor charge), using the same model, effects were modelled to be lethal at less than 50 m from the detonation for 234 dB $L_{p,pk}$ and up to 80 m for 229 dB $L_{p,pk}$. Worst-case scenarios based on open water detonation models for a 90.7 kg Comp B charge estimated that mortal injuries in fish could occur up to 460 m from the detonation (DESNZ 2023).

2.8. Impulsiveness of noise

Several studies have found that impulsive sounds are generally more hazardous to animal hearing compared to non-impulsive (continuous) sounds of similar amplitude due to the increased risk of mechanically induced auditory injuries (Henderson & Hamernik 1986, 2012; Dunn *et al*. 1991; Ahroon *et al*. 1993). However, as impulses travel further away from the sound source, their defining characteristics (fast rise time, clear amplitude peak, short signal duration) become less pronounced as the energy of the signals are being absorbed and dissipated in the environment over distance (e.g. Hastie *et al.* 2019; Martin *et al.* 2020). Impulsive sounds (including explosives) therefore lose their impulsive characteristics with increasing distance from the source and could theoretically be characterised as non-impulsive beyond a certain distance. The changes in noise characteristics generally result in the sound becoming less physiologically damaging with distance (Southall *et al.* 2007).

There are multiple ways to define impulsiveness, and there is currently no absolute definition to determine the point at which a sound transitions from impulsive or non-impulsive (Matei *et al.* 2024). Of the methods available, NMFS (2024) considers that kurtosis might be a valuable metric to help move toward a quantitative means of defining whether a sound is impulsive or not. Kurtosis values of > 40 are considered fully impulsive, whereas kurtosis values of < 3 are non-impulsive. Between these values, therefore, is a region of transition, with impulsivity reducing with distance from the source.

The following has been reported regarding impulsiveness of explosive noise with distance:

- Robinson *et al*. (2022) monitored high-order UXO clearance activities for 37 UXOs at the Neart na Goaithe (NnG) wind farm and found that at 58 km from the source, the acoustic signals were still impulsive in nature, though the pulse duration increased with range. A further 17 UXO target disposals were measured at Moray East wind farm at distances up to 58 km from the source. Estimated average charge sizes (in TNT eq.) ranged from < 0.5 kg to 295 kg, with the most common UXO type being 22 to 60 kg.

- Matei *et al.* (2024) provide an assessment of the impulsiveness of signals from the high-order detonation of UXOs monitored up to 29 km away from a detonation site. They showed that for the 38 UXO detonations examined (located in the North Sea and the Kattegat), there was evidence of a decline in impulsiveness with increasing distance from the source. However impulsive characteristics were still shown at distances from the source exceeding 20 km.

- Lee *et al*. (2022) monitored high-order UXO clearance at the Sofia wind farm, and found that with increasing range, the waveform elongated, the pulse duration increased and kurtosis values were lower. They concluded that the Southall *et al*. (2019) PTS thresholds may not be suitable for predicting auditory injury at long ranges beyond 10 km.

- Seiche Ltd. (2021) monitored clearance of three UXOs at the Seagreen OWF and found that the wave form elongated with distance and kurtosis significantly reduced with range, showing evidence of a reduction in impulsivity at long ranges.

The evidence from these sources suggest that there are aspects of impulsivity that decrease over longer ranges (i.e. tens of km); however, there is no conclusive evidence that explosive noise becomes fully non-impulsive over the monitored ranges for which data is available. Further investigation into the impulsive characteristics of different explosive sources is required to better understand the relationship between impulsiveness and distance from the sound source.

In addition, further data is required from low-order clearance of UXOs, and other smaller explosives use (e.g. during decommissioning) to better understand and characterise variation in the impulsiveness of the sound produced relative to explosive size. In the meantime, for all practical purposes, explosive noise can be considered impulsive at all ranges.

2.9. Overview of noise risk assessment process

Faulkner *et al.* (2018) outlined the guiding principles for assessing the impact of underwater noise in general. Whilst this reference is not new, it is useful to provide an overview of the process that should be undertaken in a noise risk assessment for underwater noise impacts. The process comprises three key stages. The first stage involves the scoping of receptors to identify those that may be affected, and the second stage involves a detailed assessment of noise impact pathways. Finally, the third stage integrates the noise prediction data with receptor-specific noise exposure criteria to produce an impact assessment.

The first stage identifies acoustically sensitive species that may be present within the relevant zone of influence (ZoI), and that consequently need to be scoped into the noise risk assessment of underwater noise impacts. Marine mammals and fish are routinely considered as sensitive species to underwater noise and are included in noise risk assessments, whereas other species with lower sensitivity (and very limited data for it) such as sea turtles and marine crustaceans are not typically included. The relevant noise exposure or impact criteria for the sensitive marine species are then outlined in the assessment, which should comprise the latest peer-reviewed and widely used criteria available. It should be noted that currently marine invertebrates can only be considered on a qualitative basis, as there are no criteria available by which to make an assessment, despite the increase in publications discussing impacts of underwater noise on marine invertebrates (Hawkins & Popper 2017; Carter *et al.* 2020; Wale *et al.* 2021; Solé *et al.* 2023).

The noise risk assessment should use all the relevant available metrics for their specific impact and receptor pathways; it is important that the worst-case scenario regarding impacts is presented. There are widely accepted quantitative criteria available for assessing the risk of injury in marine mammals and fish (Section 2.10). Explosive noise is treated as an impulsive noise source and therefore the impulsive noise criteria are the most appropriate to use in noise modelling and assessment (though see Section 2.8 for more detail).

The approach to the second stage, for prediction of underwater noise levels via noise impact pathways, should be proportionate to the level of impact (e.g. whether noise modelling is

required), and to what level of detail. Explosive use is one of the loudest anthropogenic noise sources in the ocean, and so typically needs to be assessed through modelling to have confidence in the magnitude of impact in the assessment. Noise modelling requires consideration of the appropriate method to determine the source level (see Section 2.5) and sound propagation model (see Section 2.6). As highlighted by Faulkner *et al.* (2018), there are many sound propagation models available, of varying levels of complexity, and no single model is likely to be applicable to all scenarios. Therefore, the choice of model must be appropriately informed. It is recommended that models are validated with field measurements to provide confidence (see Section 4.1).

The third stage is to combine the information on the noise predictions and the receptor noise exposure criteria into an impact assessment. The ZoI, or area over which the noise exposure criteria are exceeded, is presented and overlaid with biological information on the presence of the receptors (e.g. density, known important biological areas). The ZoI needs to consider all relevant noise exposure criteria (Section 2.10) and any mitigation proposed (Section 2.11). Typically, the instantaneous and 'single pulse' nature of explosive noise means that possible movement of the receptor does not require consideration, as it often does when noise sources present over a prolonged period are relevant. However, this does need to be considered in situations where there are multiple pulses (i.e. where there are multiple explosions (Section 1.1.10)). The percentage overlap between the ZoI and important biological areas, or the number of animals affected, can then be used to determine impact significance in accordance with the noise risk assessment methodology.

Faulkner *et al.* (2018) highlights the importance of appropriately assessing and mitigating for underwater noise impacts from development, but states that "at present many [assessments] for underwater noise do not apply appropriate methods and lack reference to the best available science." This finding supports the need for the guidelines on explosive noise risk assessments, which have been developed in Section 3.

2.10. Injury criteria

Effects on marine mammal hearing can be divided into categories of temporary hearing loss (where hearing sensitivity returns to baseline levels after a period following the noise exposure) or permanent hearing loss (where damage to the inner ear means that hearing sensitivity never returns to baseline levels). As hearing loss is associated with a higher threshold of audibility for sounds, temporary and permanent hearing loss have been termed Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS), respectively. The latest sources of criteria guidance identifying the point at which these effects could occur (NMFS 2024) concentrate more on TTS and "auditory injury" rather than PTS.

Injury in fish resulting from underwater explosions can be divided into categories of mortality and potential mortal injury and recoverable injury. In addition, injury to auditory structures, such as the inner ear or the swim bladder, can result in temporary loss of hearing sensitivity, TTS.

2.10.1. Auditory injury for marine mammals

2.10.1.1. Defining auditory injury

Marine mammals in UK waters are protected by various legislation, including the European Union (EU) Directive 92/43/EEC, which was transposed into UK law prior to departure from the EU, and has remained following UK exit from the EU. This directive provides consistency in marine mammal protection in shared EU/UK waters. Nevertheless, there is a lack of legal and regulatory consensus across countries regarding the definition of 'auditory injury'. Specifically, there is uncertainty about whether mitigation should address the onset of PTS

alone, or both PTS and TTS. Most countries (including the UK) consider auditory injury to include PTS only, while some countries (e.g. Germany and Ireland) classify TTS as auditory injury:

- The UK (England, Scotland, Wales): PTS is considered an injury that requires mitigation, as stated in JNCC *et al*. (2010) (in the context of an offence to European Protected Species (EPS)), and advised by UK Regulators and Statutory Nature Conservation Bodies (SNCBs). TTS was often referred to as the 'onset of fleeing response' and might have been considered a proxy for disturbance from some noisy activities (e.g. UXO clearance) in the absence of dedicated disturbance criteria but was not considered an injurious effect that would have required mitigation.

- Denmark: PTS is considered an injury that requires mitigation. TTS does not constitute a significant injury and does not require mitigation (Skjellerup *et al.* 2015).

- Germany: Under the German regulations, injury includes impairment of an animal's physical integrity and thus TTS is classified as injury, and mitigation must apply once the TTS threshold has been exceeded (ASCOBANS 2014).

- USA (while outside of the EU waters, it is relevant in terms of thresholds): Under the Marine Mammal Protection Act, National Marine Fisheries Service (NMFS) has defined injury as "destruction of tissue" (Houser 2021). Therefore, PTS constitutes an injury offence as it is permanent damage to tissue in the auditory system (e.g. disarticulation of the middle ear bones, loss of hair cells). However, TTS is a fully recoverable form of auditory fatigue and thus does not constitute injury. Under the Marine Mammal Protection Act, National Marine Fisheries Service (NMFS), TTS is considered as a Level B harassment along with behavioural disturbance.

As PTS is considered an (auditory) injury in England, Scotland and Wales, the relevant jurisdictions for this guidance, PTS (or "auditory injury", as per NMFS 2024) has been the focus of this literature review hereafter. Where injury or auditory injury is referred to this document in the context of marine mammals, it is referring to PTS specifically.

2.10.1.2. Auditory injury criteria

Thresholds for the assessment of auditory injury to marine mammals were provided for different hearing groups in Southall *et al.* (2007) and subsequently updated in NMFS (2018), Southall *et al.* (2019) and most recently NMFS (2024).

Explosives are categorised as "impulsive" sound sources, alongside airguns and impact pile driving. The auditory injury thresholds for marine mammals are provided as dual metrics: weighted cumulative sound exposure level ($L_{E,p,t}$) and peak sound pressure level ($L_{p,pk}$). Whichever metric is exceeded first or at the greatest distance should be used as the injury criterion. Impulsive sound sources can be sub-divided into single pulses (e.g. a single explosion) and multiple pulses (pile driving, airguns, multiple explosions in a 24-hour period). This results in the differentiation between the single pulse SEL ($L_{E,p,ss}$) and the $L_{E,p,t}$ although the injury threshold is the same for both. With regards to explosives, if one detonation were to occur in a 24-hour period then the assessment would be based on the $L_{p,pk}$ and single pulse SEL metrics, whereas if multiple detonations occur closely together (there is no consensus on how close, but any subsequent exposures would need to be sufficiently loud to lead to a material increase in the $L_{E,p,t}$) within 24-hours then the assessment could be based on the $L_{p,pk}$ and $L_{E,p,t}$ metrics. There are times when the impact ranges for the $L_{p,pk}$ metric will exceed those for single pulse SEL metric and visa-versa. Thus, both metrics must be modelled for explosives.

Knowledge of PTS in marine mammals is very limited since it is not ethical to intentionally cause auditory injury. Thus, thresholds for PTS are derived from thresholds for TTS. For the $L_{E,p,t}$ metric, PTS is assumed to occur at 15 decibels above the TTS onset criteria. For the $L_{p,pk}$ metric, PTS is assumed to occur at 6 decibels above the TTS onset criteria. The most recent PTS dual metric thresholds for marine mammals are provided in Table 7. The $L_{p,pk}$ metric is unweighted, whereas the $L_{E,p}$ metric is weighted by marine mammal auditory weighting functions which reflect species-dependent changing hearing sensitivity at specific frequencies.

Thresholds for the assessment of effects (auditory injury/PTS and TTS) to marine mammals are provided for different hearing groups or categories in Southall *et al*. (2019) and NMFS (2024). The more recent NMFS (2024) provides updated, generalised hearing ranges for each of the marine mammal hearing groups (Table 8) and are described as follows:

- Low-Frequency Cetaceans (Group LF) - “The LF cetacean group contains the mysticetes (baleen whales). Although there have been no direct measurements of hearing sensitivity in any mysticete, an audible frequency range of approximately 10 Hz to 30 kHz has been estimated from measured vocalization frequencies, observed reactions to playback of sounds, and anatomical analyses of the auditory system. [...] A single species group is used for all mysticetes.”

- High-Frequency Cetaceans (Group HF) - “The HF cetacean group contains most delphinid species (e.g. bottlenose dolphin, common dolphin, killer whale, pilot whale). [...] Hearing sensitivity has been directly measured for several species within this group using psychophysical (behavioural) or auditory evoked potential (AEP) measurements.”

- Very High-Frequency Cetaceans (Group VHF) - “The VHF cetacean group contains the porpoises, river dolphins, pygmy/dwarf sperm whales, *Cephalorhynchus* species, and some *Lagenorhynchus* species. Hearing sensitivity has been measured for several species within this group using behavioural or AEP measurements. VHF cetaceans generally possess a higher upper-frequency limit and better sensitivity at higher frequencies compared to the HF cetacean species.”

- Phocid Carnivores (Group PCW (Phocids in water)/PCA (Phocids on land)) - “This group contains all earless seals or “true seals,” including [...] harbour or common seals [and] grey seals [...]. Weighting functions and TTS/injury thresholds are included for both airborne (group PCA) and underwater exposure (group PCW).”

It is expected that “Outside the generalized hearing range[s], the risk of auditory impacts from sounds is considered highly unlikely or very low (the exception would be if a sound above/below this range has the potential to cause physical injury, i.e. lung or gastrointestinal tract injury from underwater explosives)”.

The range of frequencies produced by explosives overlaps most with the Low Frequency (LF) cetacean hearing group, although explosives produce sound at a very wide range of frequencies perceptible to all relevant species in the UK. It is important to note that the information on the LF cetacean hearing group in NMFS (2024) was extremely limited, relying on assumptions of hearing sensitivity based on vocalisation frequencies, anatomical models, behavioural reactions, and extrapolation from other marine mammals (Houser *et al.* 2024). However, since then the first direct hearing measurements from a baleen whale have been recorded. Houser *et al*. (2024) showed that minke whales are sensitive to frequencies much higher than previously believed, with auditory brain stem responses detected at 45 – 90 kHz. This new data suggests that baleen whales may not be solely sensitive to relatively low-frequency sounds. It should be noted that in NMFS (2024), the data collected by Houser *et*

al. (2024) have implications for not only the generalised hearing range for low-frequency cetaceans but also on their weighting function. Therefore, NMFS expects to update the information on low frequency hearing groups in due course.

Table 7. Auditory injury (PTS) onset thresholds for the key UK marine mammal functional hearing groups: comparison of Southall *et al*. (2019) and NMFS (2024).

Hearing Group	Species groups	Single pulse $L_{E,p}$ or $L_{E,p,t}$ dB re 1 µPa^{2}s (weighted)		$L_{p,pk}$ dB re 1 µPa (unweighted)	
		Southall	NMFS	Southall	NMFS
(LF) Low Frequency cetacean	Baleen whales	183		219	222
(HF) High Frequency cetacean	Dolphins, toothed/ beaked/ bottlenose whales	185	193	230	
(VHF) Very High Frequency cetacean	Porpoise	155	159	202	
(PCW) phocid carnivores in water	Seals	185	183	218	223

Table 7 includes both Southall *et al.* (2019) and NMFS (2024) thresholds for comparison purposes only, as at the time of writing, both sets of guidance were in use and many of the documents referred to in this report have used the Southall *et al*. (2019) thresholds. However, the NMFS 2024 thresholds should now be used in impact assessments. If these are updated again, discuss with the appropriate SNCB to confirm which thresholds to apply.

Table 8. Generalised hearing range for the key UK marine mammal hearing groups (from NMFS 2024).

Hearing Group	Species groups	Generalised hearing range
LF	Baleen whales	7 Hz to 36+ kHz
HF	Dolphins, toothed whales, beaked whales, bottlenose whales	150 Hz to 160 kHz
VHF	Porpoise	200 Hz to 165 kHz
PCW	Seals	40 Hz to 90 kHz

2.10.2. Injury criteria for fish

Thresholds for the assessment of injury (mortality and potential mortal injury, recoverable injury, and TTS) in fish are provided for different hearing groups in Popper and Hawkins (2019, Table 7; following Popper *et al.* 2014), with fish species being broadly characterised into four groups based on their hearing abilities, plus an additional group for fish eggs and larvae:

- Group 1 – Fishes lacking swim bladders and other gas-filled cavities that are sensitive only to sound particle motion and show sensitivity to only a narrow band of frequencies

(e.g. flatfishes, *Pleuronectiformes*; sharks skates and rays, *Chondrichthyes*). Some barotrauma may occur from the exposure to sound pressure.

- Group 2 – Fishes with a swim bladder or other gas-filled chambers where that organ does not appear to play a role in hearing. These fish are sensitive only to particle motion and show sensitivity to only a narrow band of frequencies. Some barotrauma may occur from the exposure to sound pressure. This group includes salmonids (*Salmonidae*) and some tunas and mackerels (*Scombridae*), but many other species are likely to fit into this category as well.

- Group 3 – Fishes with swim bladders that are close, but not intimately connected, to the ear. These fishes are sensitive to both particle motion and sound pressure and show a more extended frequency range than groups 1 or 2, extending up to about 500 Hz. These species are susceptible to barotrauma. This group includes cod fishes (*Gadidae*), eels (*Anguillidae*), some drums and croakers (*Sciaenidae*), and perhaps other fishes.

- Group 4 – Fishes that have special structures mechanically linking the swim bladder to the ear. These fishes are primarily sensitive to sound pressure, although they also detect particle motion. They have a wider frequency range, extending to several kHz and generally show higher sensitivity to sound pressure than fishes in groups 1, 2, or 3. These species are susceptible to barotrauma. The group includes some of the squirrel fishes (*Holocentridae*), drums and croakers (*Sciaenidae*), herrings (*Clupeidae*) and the large group of otophysan fishes.

- Group 5 – Fish eggs and larvae - These are also considered to be receptors of concern by Popper *et al*. (2014), due to their vulnerability, small size and reduced mobility.

Severe injuries to fish that can result from high-intensity underwater explosions and that are likely to result in immediate or delayed mortality include internal haemorrhaging, rupture of the swim bladder and rupture or damage to other organs and soft tissues (Bowman *et al.* 2024). Such injuries result from sudden pressure changes (barotrauma) during sound exposure, which cause gas-filled chambers like the swim bladder to expand and contract rapidly, leading to the damage of surrounding tissues and organs or the rupture of the swim bladder itself (Popper *et al.* 2014). Less severe injuries from which an individual may recover over time include internal and external bruising or haematomas and external haemorrhaging (Popper *et al.* 2014). Injury to auditory structures following the exposure to intensive sound can cause a temporary reduction in hearing sensitivity (i.e. TTS). Popper *et al.* (2014) have defined TTS in fish as any reduction in hearing threshold of six decibels or greater in terms of sound pressure or particle motion. TTS has been demonstrated in some fishes, resulting from the damage or loss of sensory hair cells in the inner ear and/or damage to auditory nerves. However, fish are known to have the ability to regenerate sensory hair cells that have been damaged (Smith *et al.* 2016). Normal hearing ability returns following cessation of the noise causing TTS, though the recovery period is variable. When experiencing auditory and other injuries fish may have decreased fitness due to a reduced ability to communicate, detect predators or prey, and/or assess their environment.

When assessing the potential impacts from explosive noise sources, quantitative thresholds for assessment are only available for mortality and potential mortal injury of different hearing groups in Popper *et al*. (2014). These thresholds are presented in Table 9 below. Effects such as recoverable injury and TTS require a qualitative assessment, based on empirical data on non-lethal effects from explosive noise (Popper *et al.* 2014). Popper *et al*. (2014) provided qualitative thresholds whereby the relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N, of the order

of tens of metres), intermediate (I, of the order of hundreds of metres), and far (F, of the order of thousands of metres) from the source. It should be acknowledged that the Popper *et al*. (2014) criteria primarily focus on the impact of a single, small-charge explosion, such as dynamite. Larger detonations or repeated exposures may have greater cumulative effects, necessitating careful evaluation of the impacts to fish in noise risk assessments.

It is important to note that the Popper *et al.* (2014) onset thresholds for mortal injuries in fish from explosions are based on upon single explosions from relatively small charge sizes and a small number of studies on a limited number of species. Any limitations to existing thresholds should be acknowledged when reporting predicted injury ranges, particularly for operations that involve large or multiple explosions. Moreover, the latest scientific evidence (e.g. Jenkins *et al.* 2022; Smith *et al.* 2022; Bowman *et al.* 2024) should be considered when predicting potential explosive effects on fish. More information and guidance on how to approach this is provided in Section 3.

Table 9. Mortality and potential mortal injury, recoverable injury and TTS impact thresholds for fish, as given by Popper *et al*. (2014) and Popper and Hawkins (2019) in relation to explosions. Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N; tens of metres), intermediate (I; hundreds of metres), and far (F; thousands of meters) from the source.

Fish grouping	Mortality and potential mortal injury	Recoverable injury	Temporary Threshold Shift
Group 1	229 - 234 dB re 1 µPa $L_{p,pk}$	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low
Group 2	229 - 234 dB re 1 µPa $L_{p,pk}$	(N) High (I) High (F) Low	(N) High (I) Moderate (F) Low
Groups 3 and 4	229 - 234 dB re 1 µPa $L_{p,pk}$	(N) High (I) High (F) Low	(N) High (I) High (F) Low
Group 5 (Eggs and larvae)	> 13 mm s^{-1} peak velocity	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low

2.11. Consideration of mitigation in noise risk assessments

A suite of mitigation measures has been used for explosive operations, which reduce the risk of acoustic impacts to noise-sensitive species. Existing mitigation measures are primarily aimed at marine mammals; mitigation measures for fish for explosive operations are limited. Some measures may provide mitigation by either reducing the sound source levels or restrict sound propagation through the water column. These can provide mitigation to both marine mammals and fish. Other measures may introduce low levels of noise aimed to provide a "warning" to mobile species, to discourage them from the immediate vicinity of the explosive operation, though these are only considered effective for marine mammals.

To note, scare charges are not appropriate as mitigation for marine mammals (JNCC 2025a, b). Scare charges are also not advised for fish in England and Wales (Natural England &

Natural Resources Wales, pers. comm.), and in Scotland they may be considered on a case-by-case basis though there is a lack of evidence on their effectiveness (NatureScot, pers. comm.). Therefore, scare charges are not considered further in this report and following guidance (Section 3).

2.11.1. Acoustic deterrent devices

Acoustic deterrent devices (ADDs) are underwater units which emit bursts of audio signals across a range of frequencies. The signals are intended to discourage marine mammals from entering, or encourage them to leave, the immediate vicinity around the explosive operation. However, they require additional sound to be introduced into the marine environment.

In the UK, it is standard practice to use ADDs for the mitigation of noise effects in marine mammals from UXO clearance. This is because of the large auditory injury ranges associated with UXO clearance, particularly using high-order techniques. JNCC (2025b) recommends the usage of ADDs proven to be effective for such mitigation measures during explosive use when injury ranges are predicted to be greater than 1 km.

McGarry *et al.* (2022) have provided an evidence review of ADDs as marine mammal mitigation. This report highlights that ADDs can operate across a wide range of frequencies (as low as 200 Hz up to 500 kHz), though most are focussed on a narrower band of frequencies. Similarly, the sound pressure level (L_p) output can range from 132 to 196 dB re 1 µPa @1m. This range of frequencies and sound outputs highlights the variety of ADDs available, and that the specific ADD to be used will determine the effects on species that could occur. The frequency will determine the audibility of the device to specific marine mammal hearing groups (see Section 1.1.5.2) or fish, and the sound level will (simplistically) correspond to the level of effect. The planned duration of ADD activation would also affect the nature of acoustic impacts.

McGarry *et al*. (2022) explored the potential for ADDs to cause hearing damage (i.e. auditory injury or PTS) in marine mammals. They found that the NMFS (2018) PTS onset threshold, using the frequency weighted $L_{E,p,t}$ for all marine mammal hearing categories, was not exceeded beyond a range of 100 m for all devices that have been used for marine developments, and so are relevant to explosive operations. The authors of the report therefore concluded that "*the risk of injury due to ADD deployment is likely low for all devices*". Similarly, Boisseau *et al.* (2021) showed that minke whales starting over 25 m from the ADD and moving at a speed of 3.4 km/h did not risk injury.

Reflecting these reports, JNCC have recently updated their guidelines on mitigation for UXO (JNCC 2025a) and explosives use (JNCC 2025b). The guidelines now state that "*A 30-minute visual search should be undertaken prior to activating the ADD to ensure there are no marine mammals in the immediate vicinity. Should a mammal be detected within 100 m of the ADD during this search, ADD activation should be delayed until the animal has moved further away (i.e. to more than 100 m from the device) to reduce the possibility of auditory injury from the device*." With these measures in place, it can be concluded that ADDs should not pose a risk of injury to marine mammals. Whilst ADDs may contribute to the total sound received by an animal, it is considered very small when compared to the received sound from an explosive detonation and is unlikely to measurably contribute to the overall exposure.

There have been operations where the ADD noise has been included in underwater noise modelling (e.g. prior to piling, for Mona Offshore Wind Farm; RPS 2024). Here, it was assumed that the ADD itself does not contribute towards any injury to marine mammals, but is expected to trigger disturbance behaviours, promoting individuals to move away from

predicted injury zones. The inclusion of the displacement effect of ADDs in the quantitative noise modelling for injury resulted in a smaller effective $L_{E,p,t}$ PTS range (RPS 2024). This is because it was be assumed that marine mammals will be at a greater distance from the source when the noisy operation (e.g. explosive use) occurs. Hence, not including the displacement effect of ADDs in the quantitative noise modelling leads to more precautionary estimates of injury range and will be the worst-case scenario.

2.12. Noise abatement

Noise abatement systems (NAS) are used to reduce the propagation of sound through the water column from noisy sources. The only known NAS to have been used during explosive use, specifically during UXO clearance, is bubble curtains. Whilst the authors are not aware of NAS or bubble curtains being used in oil and gas decommissioning, it is noted that recent JNCC (2025b) guidance does include the use of noise abatement as a measure. NAS are advised to be used when the injury ranges for marine mammals are too large to be effectively mitigated using visual observers, acoustic monitoring and ADDs (JNCC 2025a, b). NAS may be used in conjunction with other mitigation measures. There are also environmental conditions which may limit the use of certain NAS for explosive operations.

The extent to which bubble curtains have been included in noise risk assessments for explosive use has varied between projects. Some projects have not factored in a reduction in sound levels from bubble curtains in their underwater noise modelling, instead referring to the potential reduction in a qualitative way (i.e. that the realised noise levels and injury ranges would be much smaller than the presented worst-case). Others have assumed a blanket 10 decibel reduction in the source level (e.g. in the Dogger Bank B Marine Mammal Mitigation Protocol; Dogger Bank Offshore Windfarm 2023). A more refined approach could be taken to model the variation in noise reduction by bubble curtains across the frequency spectrum, which could then be considered when calculating the impact range for each marine mammal hearing category. However, this is likely to require significant work that may be disproportionate to the level of risk from the explosive operation.

2.12.1. Noise reduction from using abatement

Whilst bubble curtains have been used to mitigate acoustic impacts from explosive operations, there has been limited monitoring to evidence realised noise reductions, and the available evidence is not conclusive on the level of noise reduction offered. This may be in part due to differences in experimental conditions, and direct comparison between studies should be treated with caution. Croci *et al.* (2014) investigated the transmission of a shock wave (meant to simulate the shock wave of a high order detonation) through a bubble curtain. The modelled results found that the attenuation by the bubble curtain was ~20 decibels for sound exposure level and ~13 decibels for peak sound pressure level. Cheong *et al.* (2023) utilised a small bubble curtain around small UXOs of known charge sizes (45 g, 250 g and 465 g) and found that the attenuation by the bubble curtain was 13 – 17 decibels in terms of peak sound pressure level, and 7 – 8 dB in terms of sound exposure level. Grimsbo and Kvadsheim (2018) measured the noise levels of four 500 kg TNT detonations. They recorded 6.2 decibel to 12.4 dB lower peak sound pressure levels when using a bubble curtain, compared to the unmitigated detonation. Bellmann (2021; cited within Hannay & Zykov 2022) reported results of attenuation of UXO acoustic levels by big bubble curtain of up to 18 dB for SPL (L_p) and 11 dB for broadband $L_{E,p}$, although the specifics of charge sizes and environmental parameters were not provided. These reports highlight how the evidence varies on realised reduction of noise levels from explosive operations when using a bubble curtain. While they support the use of bubble curtains as an effective noise reduction tool during UXO clearance, the evidence suggests that a blanket noise reduction of at least 10 decibel is not always realised, in contrast to the use of bubble curtains during piling activities (Verfuss *et al.* 2019).

Attenuation by bubble curtains of any noise, including explosive noise, is expected to be frequency-dependent, however direct evidence on frequency-dependent attenuation of explosive noise in the marine environment is limited. One source is Schmidtke *et al.* (2009), who reported attenuations of 2 decibels at 100 Hz to 6 decibels at 10 kHz for a large mine, whereas they reported a 16 decibel attenuation at all frequencies greater than 1 kHz for the small charge. It is not clear whether the bubble curtain used in Schmidtke *et al.* (2009) was optimised to maximise the frequency-dependent attenuation characteristics (Hannay & Zykov 2022), which can be undertaken. However, an additional complication is that the frequency-dependent energy from explosive operations is not well understood. Smaller charges contain relatively more high-frequency energy than larger charges (Hannay & Zykov 2022). Hannay and Zykov (2022) report that the maximum spectral levels of all charges is less than 10 Hz, however the maximum decidecade L_E band levels occur above a few hundred Hz. The explosive characteristic of large charges (e.g. 454 kg) suggests that the shock pulse peak pressure is dominated by high frequencies that are likely much higher than 500 Hz (Hannay & Zykov 2022). Given that assessments include frequency-dependent metrics (SELs), it is important to consider both the likely frequency spectra of the explosive source and the frequency-specific attenuation of the noise abatement.

Various parameters appear to have an influence on the efficacy of bubble curtains in mitigating noise from explosive operations. The German Federal Armed Forces Underwater Acoustics and Marine Geophysics Research Institute (FWG) conducted a series of controlled tests to understand the efficacy of bubble curtains as a noise mitigation tool during mine explosions. The first test involved testing the difference in noise reduction when using one to three concentric semicircle bubble curtains (7.5 to 11.5 m) with a constant airflow of 20 m³/min when detonating 1 kg charges at 13 m water depth (Schmidtke *et al.* 2009). This resulted in an attenuation by the bubble curtain of between 10 and 16 decibels in SPL_{pk}. In a second test, a standard mine of 300 kg explosive with 45% TNT was detonated at 20 m water depth with one bubble curtain circle of 22 m diameter around the detonation site. This resulted in a 4 decibel reduction in SPL_{pk}. Schmidtke *et al* (2009) concluded that larger sea mine charges contain ingredients that generate significantly more gas than TNT, leading to increased water displacement and pressure that air bubbles cannot effectively dampen, and thus suggest a larger air bubble curtain to better mitigate the influence of displaced water flow. Schmidtke (2010) followed by increasing the radius of the bubble curtain to 70 m in their experiments and testing a bubble curtain semicircle open to the coastline. They detonated a 300 kg mine at a water depth of 12 m, with an air volume flow of the bubble curtain of 1 m³/min/m. A noise reduction of 16 to 19 dB in SPL_{pk} was recorded for two explosions. Schmidtke (2012) then investigated the influence of the air volume flow on the efficacy of the semicircle bubble curtain with 70 m radius. The attenuation of the peak sound pressure level of 20 g test explosives was 24 dB on average, with the volume of air flow (0.5 or 1.0 ³/min/m) having no influence on efficacy.

Hannay and Zykov (2022) modelled the underwater noise produced for UXO clearance with and without mitigation (i.e. noise abatement) measures for the Revolution Wind project lease area, in the Atlantic Ocean off the Massachusetts coastline. Hannay and Zykov (2022) used a semi-empirical model for the shock pulse and exponential decay approximation, and an explosive waveform model alongside an acoustic propagation model that used JASCO's marine operations noise model (MONM, JASCO Applied Sciences). Hannay and Zykov (2022) reviewed the available evidence base on noise attenuation for bubble curtain systems. That report acknowledged that smaller attenuations in noise have been reported (e.g. in Schmidtke *et al.* 2009), linked to the small size of the bubble curtain relative to the large detonation charge size. "Hannay and Zykov (2022) state attenuations by bubble curtains for explosive noise are expected to be like that for piling noise "*if the bubble curtain radius is large enough to avoid nearfield effects of the explosive detonations*." The authors conclude that modern bubble curtains should be effective at attenuating both peak pressure and $L_{E,p}$, in the frequency bands dominating explosive detonation, by greater than 10 dB

Hence this value was used in their modelling. This 10 dB value has also been used in other environmental assessment reports (e.g. Marine Mammal Mitigation Protocol (MMMP) for UXO Clearance at Dogger Bank B OWF). Though other assessments have used a more conservative 4 dB reduction (for SPL_{pk}), and SEL reduction values specific to a particular UXO assumed frequency spectrum and to the hearing weightings being used (Stephenson, S., pers. comm).

Whilst an assumed noise reduction will reduce the impact ranges, the extent of this reduction will vary depending on the approach taken and will also vary between noise-sensitive receptor group. This can be seen when reviewing the impact ranges from mitigated explosive operations in licence support documents (e.g. Dogger Bank OWF MMMP; Hannay & Zykov 2022). These are sometimes presented alongside the impact ranges from unmitigated explosive operations, which allows for comparison and understanding of the relative reduction in impact ranges (e.g. Hannay & Zykov 2022). These reports both assumed a 10 dB attenuation from the use of a bubble curtain. In most modelled scenarios, the reduction in impact ranges across marine mammal hearing categories was over 50% (i.e. the predicted impact range was at least halved). This result has been drawn out to demonstrate that the inclusion of NAS can significantly improve the predicted impact ranges, which in turn would affect the mitigation advised for the project (e.g. ADD duration). It is therefore important that the approach taken is robust, precautionary, and validated through monitoring.

2.13. Noise validation through monitoring

This section focuses on the validation of predicted UXO clearance noise through monitoring, for which some data from the literature is available. There is a lack of data available in the public domain on underwater noise measurements of explosives used in decommissioning. This lack of findings in the literature review was confirmed by the experience of the technical PSG. Therefore, it is strongly recommended that monitoring is conducted going forwards.

2.13.1. Measured vs modelled

In most underwater noise monitoring reports available and reviewed here, the received levels at a range of distances are provided, but often the reporting lacks the following step of estimating the auditory injury ranges interpolated from the monitored data to compare against the modelled ranges in the associated impact assessments.

All modelled values presented in the tables below have been modelled by the project team, using the Soloway and Dahl (2014) model. The Soloway and Dahl (2014) model has been used extensively to predict auditory impact ranges for UXO clearance in recent offshore wind farm EIAs, which is why it was selected here to compare to monitored data. As it does not directly account for the frequency weightings required by Southall *et al.* (2019), the calculation was augmented using suitable UXO explosive frequency spectra so that this comparison could be included. The underwater noise modelling reports reviewed rarely present the modelled ranges or compare modelled to measured auditory injury ranges to allow a direct comparison.

The following high-level conclusions can be drawn from the following measured versus modelled section:

- The Soloway and Dahl (2014) model (based on Cole *et al.* 1948; Arons 1954) can substantially under-predict SEL auditory injury ranges for marine mammals, especially for VHF cetaceans (e.g. harbour porpoise).

- The Soloway and Dahl (2014) model is better at predicting $L_{p,pk}$ auditory injury ranges for marine mammals.

- Low-order clearance noise is dependent on the deflagration tool/charge, not the UXO size (provided that the UXO does not accidently detonate high-order).

- High-order UXO clearance modelling assumes the UXO is in perfect condition – this does not take into consideration factors that may lead to lower noise levels such as location on the seabed, degradation of the UXO over time, etc.

The following comparison of measured impact ranges with impact ranges predicted from modelling focusses exclusively on marine mammals, as marine mammals are typically the focus of monitoring efforts to validate injury ranges. Measured injury ranges in fish are rarely reported. However, it is recommended that where underwater noise monitoring is required (see East *et al.* 2026), impact ranges based on measured noise levels are calculated for both marine mammals and fish to validate the findings of the noise risk assessment for both receptor groups. More information on monitoring and guidance on how to approach this is provided in East *et al.* (2026).

2.13.1.1. UXO (high order) in Dutch waters (von Benda-Beckmann *et al.* 2015)

Modelled and measured $L_{E,p}$ from UXO clearance were presented in von Benda-Beckmann *et al.* (2015), where information from the Dutch MoD was used to produce sound exposure maps and estimates of exposure predicted to cause PTS in harbour porpoise.

Cleared UXO charge weights ranged from 10 – 1,000 kg (with most ranging between 125 – 250 kg), and a total of 88 explosions were modelled. The model consisted of a 'two-part' model: (1) a source model for underwater explosions in deep water (i.e. a deep-water propagation model (Weston, 1960)); and (2) a sound propagation model for shallow water (SOPRANO Model, Sertlek and Ainslie, 2014). Measured data of $L_{E,p}$ were obtained for seven aerial bombs (263 kg equivalent charge weight) and one TNT (121kg equivalent charge weight) using hydrophones at varying depths (4 – 25 m) and distances (100 m – 2 km). Adopting the deep water model from Weston (1960) led to an overestimation in the modelled broadband $L_{E,p}$ by ~8 dB at frequencies above 200 Hz. To adjust for the overprediction in $L_{E,p}$, a correction factor was applied (the power mean over each decidecade band was subtracted from the modelled $L_{E,p}$). Following these applications, the modelled broadband $L_{E,p}$ agreed within 0.1 decibel from the measured broadband $L_{E,p}$.

For measured $L_{E,p}$ at < 6 m water depth (from a 263 kg charge mass), $L_{E,p}$ ranged from ~190 – 211 dB re 1 μPa^2s and for water depths > 22 m (from a 263 kg charge mass), $L_{E,p}$ ranged from ~198 – 209 dB re 1 μPa^2 s. Modelled estimates of $L_{E,p}$ as a function of modelled distances appeared to underestimate broadband $L_{E,p}$ measurements from the 'two-part' model for the near surface, whilst modelled estimates of $L_{E,p}$ for the near bottom were in closer agreement with the $L_{E,p}$ measured in the field. This may be attributed to the difficulty in predicting the generation and propagation of underwater shock waves in shallow water, at large distances (von-Benda Beckmann *et al.* 2015). Further, for both modelled and measured scenarios, $L_{E,p}$ were greater for detonations in the 'near bottom' than in the 'near surface' throughout the range of distances presented. This may occur due to the fact that the models used in this study were informed by a better understanding of radiated energy at depth versus in shallower waters (Weston 1960; Sertlek & Ainslie 2014; von-Benda Beckmann *et al.* 2015), thus observed $L_{E,p}$ in the 'near-bottom' was closer for the modelled and measured scenarios when compared with the 'near-surface'.

2.13.1.2. UXO (high-order and low order deflagration) sea trial (Lepper *et al.* 2024)

Measured unweighted L_p and measured auditory weighted $L_{E,p}$ for two types of UXO were used to estimate the potential minimum distances of PTS, for each marine mammal hearing group. The measured data used in estimating PTS impact ranges were obtained from a high-order clearance (10 kg donor charge) of a 170 kg (TNT eq.) mine at 18.5 m water depth, and low-order deflagration (0.25 kg charge) of a 430 kg (TNT eq.) mine at 17.5 m water depth. Measured data were first combined with both $L_{E,p}$ and L_p propagation loss profiles (propagation loss versus range) to estimate $L_{E,p}$ and L_p received levels versus range for the low-order and high-order clearances, before the measured $L_{E,p}$ was scaled for each hearing group (Lepper *et al.* 2024). $L_{E,p}$ propagation loss profiles were then fitted through each of the weighting adjusted data points to estimate PTS impact ranges (Lepper *et al.* 2024).

Measured PTS impact ranges for both unweighted L_p and weighted $L_{E,p}$ from Lepper *et al.* (2024) were generally greater than those modelled under Soloway and Dahl (2014; Table 10), particularly when considering PTS impact ranges under the auditory weighted $L_{E,p}$ criteria for VHF and PCW hearing groups. The variation in PTS impact ranges between the modelled equivalent TNT charge masses based on the acoustic levels compared to the estimated actual physical UXO charge mass may be due to a variety of causes. These can include uncertainty in the models used in shallow water as discussed by various authors (von Benda-Beckmann *et al.* 2015; Soloway & Dahl 2014; Favretto Cristini *et al.* 2022a, b; Robinson *et al.* 2022), uncertainty in the remaining UXO charge mass, typically estimated by visual inspection and uncertainty in the UXO's explosive material viability due to chemical degradation over time and potential long-term exposure to the marine environment (Lepper *et al.* 2024).

Table 10. Comparison of modelled (Soloway & Dahl 2014) PTS impact ranges with estimated PTS ranges using measured data for UXO clearance (Lepper *et al.* 2024)[a].

Charge size (kg TNT eq.)	Modelled PTS L_p range (m)	Modelled PTS $L_{E,p}$ range (m)	Estimated PTS L_p range (m) interpolated from measurements	Estimated PTS $L_{E,p}$ range (m) interpolated from measurements
28	LF: 850 HF: 270 VHF: 4,800 PCW: 940	LF: 2,300 HF: 12 VHF: 590 PCW: 400	LF: 1,500 HF: 600 VHF: 4,000 PCW: 1,600	LF: 2,100 HF: 300 VHF: 4,700 PCW: 1,000
0.26	LF: 170 HF: 58 VHF: 1,000 PCW: 190	LF: 230 HF: 1 VHF: 82 PCW: 41	LF: 210 HF: 30 VHF: 1,160 PCW: 290	LF: 260 HF: 20 VHF: 1,030 PCW: 100

2.13.1.3. UXO (high order) in the North Sea (Robinson *et al.* 2022)

Acoustic measurements of UXO were made for charge masses ranging between < 1 – 295 kg TNT eq. whereby measured L_p and $L_{E,p}$ were compared to data from modelling using a shallow-water propagation model (Robinson *et al.* 2022; Table 11). This allowed for estimations of PTS impact ranges to be made. Measured PTS impact ranges for unweighted L_p from Robinson *et al.* (2022) were largely in agreement with those modelled under Soloway and Dahl (2014) at smaller charge weights for all marine mammal hearing groups. However, while the bubble curtain could explain the reduction in noise levels for the 2.5 kg charge, the same pattern was not observed for the 220 kg airdropped bomb. As the bomb

also used a bubble curtain, the authors concluded that it was ineffective at reducing SEL but could not explain why.

Table 11. Comparison of modelled (Soloway & Dahl 2014) PTS impact ranges with estimated PTS ranges using measured data for high-order UXO clearance in the North Sea (Robinson *et al.* 2022).

Charge size (kg TNT eq.)	Modelled PTS L_p range (m)	Modelled PTS $L_{E,p}$ range (m)	Estimated PTS L_p range (m) interpolated from measurements	Estimated PTS $L_{E,p}$ range (m) interpolated from measurements
1	LF: 280 HF: 91 VHF: 1,500	LF: 450 HF: 2 VHF: 150	LF: 300 HF: 80 VHF: 1,600	LF: 300 HF: 60 VHF: 2,100
5	LF: 470 HF: 150 VHF: 2,700	LF: 990 HF: 5 VHF: 300	LF: 600 HF: 200 VHF: 2,500	LF: 1,000 HF: 80 VHF: 4,100
10	LF: 600 HF: 190 VHF: 3,400	LF: 1,400 HF: 7 VHF: 400	LF: 600 HF: 200 VHF: 2,900	LF: 1,300 HF: 100 VHF: 5,200
100	LF: 1,300 HF: 420 VHF: 1,400	LF: 4,200 HF: 23 VHF: 900	LF: 1,400 HF: 500 VHF: 5,700	LF: 4,500 HF: 300 VHF: 9,900
200	LF: 1,600 HF: 530 VHF: 9,200	LF: 6,000 HF: 32 VHF: 1,100	LF: 1,700 HF: 600 VHF: 7,100	LF: 6,100 HF: 400 VHF: 10,200

2.13.1.4. UXO (high order) at Neart na Gaoithe (NnG) OWF (Bellmann *et al.* 2021)

Following analysis of noise measurements during the UXO clearance campaign at NnG OWF, Bellmann *et al.* (2021) identified that the measured project-specific, frequency-unweighted transmission loss (24.6 log distance) differed from that proposed in Thiele and Schellstede (1980) and Soloway and Dahl (2014) – the latter being used to predict impact ranges at NnG OWF. Nonetheless, when examining unweighted $L_{p,pk}$ marine mammal PTS-onset impact ranges for UXO detonation at NnG OWF, measured impact ranges were generally very similar to model predictions based on the donor charge weight only (Table 12). This indicated that almost all detonation events did not result in any detonation of the original explosive material within the target UXO, and that the model was generally a good predictor of noise levels. It is noted that this is not typical of all high-order UXO clearance, where noise levels have been shown to be highly variable and proportional to detonation of the donor charge plus varying proportions of the UXO's original explosive material (e.g. Robinson *et al.* 2022; Lepper *et al.* 2024).

One UXO cleared at NnG OWF (identified as "UXO 17") showed notably higher larger impact ranges than predicted for its 5 kg donor charge alone, albeit smaller than would be expected for a full detonation of its estimated 102 kg NEQ. Suggested potential reasons for higher noise levels from this specific UXO were the position of the UXO (if half buried) on the seabed, sediment type, possible partial explosion of the original NEQ or other unknown factors (Bellmann *et al.* 2021).

Assessing the accuracy of model-predictions for frequency-weighted $L_{E,p}$ (based on a proprietary, frequency dependent adaptation of the transmission loss from Soloway & Dahl

2014) was more challenging, as the smallest charge size used in model predictions was larger (10 kg) than those used in the clearance campaign. However, results suggested that the model had a general tendency to under-predict $L_{E,p}$ impact ranges, particularly for lower-frequency groups such as LF cetaceans and PCW.

Table 12. Comparison of modelled (Soloway & Dahl 2014) PTS-onset impact ranges for donor charges with estimated PTS ranges using measured data for high-order UXO clearance at the NnG OWF (Bellmann *et al.* 2021).

Charge size	Modelled PTS L_p range (m)	Estimated PTS L_p range (m) interpolated from measurements
5 kg donor charge	LF: 470 HF: 150 VHF: 2,700 PCW: 530	LF: 550–600 [1,140] HF: 200–220 [410] VHF: 2,720–2,960 [5,580] PCW: 610–660 [1,250]
2.5 kg donor charge	LF: 380 HF: 120 VHF: 2,100 PCW: 420	LF: 500 HF: 180 VHF: 2,470 PCW: 550
1 kg donor charge	LF: 280 HF: 91 VHF: 1,500 PCW: 310	LF: 170 HF: 60 VHF: 850 PCW: 190

Furthermore, “soft start” charges were used at NnG for larger charges (> 50 kg), which allowed for comparison between modelled and measured charges of known weight. This showed that there was good agreement between the modelled source levels using Soloway and Dahl (2014) and the measured source levels.

The measured transmission loss from the NnG OWF UXO clearance monitoring results were also of interest. The transmission loss for both the $L_{E,p}$ and L_p values clearance were unusually high in comparison to values derived from comparable water depths. The high transmission loss was not the result of the UXO being partially buried or resting on the seabed, as the “soft start” charges (which were detonated in the water column) also showed a high transmission loss. This markedly high transmission loss is therefore likely to be a result of the sediment type and layering in this area.

2.13.1.5. UXO (high order) at Sofia OWF (Lee *et al.* 2022)

At the Sofia OWF, two high-order UXO detonations with a bubble curtain were monitored, one with an estimated NEQ of 220 kg and one with an estimated NEQ of 328 kg (Table 13). The measured sound levels for the 220 kg UXO were significantly higher than the measured sound levels of the 328 kg UXO, which the authors suggested was most likely due to the degradation of the explosive material in the 328 kg UXO (Lee *et al.* 2022).

When comparing the predicted and measured noise levels and unweighted $L_{E,p}$, results indicated that the measured levels were 10 to 15 decibels lower for the 2.5 kg donor charge used. For the 0.03 kg low-order charges and 220 kg airdropped bomb, predicted levels are only about 5 decibels lower. The measured $L_{E,p}$ was comparable to predicted levels for the 0.03 kg low-order charges and 220 kg airdropped bomb. Authors attributed the discrepancies between measured and modelled values to a variety of potential factors

including the model being semi-empirical, parameters like bathymetry and bottom condition not being included in the model, and the attenuation from the bubble curtain not being considered in the models. However, while the bubble curtain could explain the reduction in noise levels for the 2.5 kg charge, the same pattern was not observed for the 220 kg airdropped bomb. As clearance of the airdropped bomb also used a bubble curtain, the authors concluded that it was ineffective at reducing $L_{E,p}$ but could not explain why. The authors have since suggested that bubble curtains may be less effective for larger explosions (S Stephenson, pers. comm.).

Table 13. Comparison of modelled (Soloway & Dahl 2014) PTS impact ranges with estimated PTS ranges using measured data for UXO clearance at the Sofia OWF (Lee *et al.* 2022).

Charge size	Modelled PTS L_p range (m) (no bubble curtain)	Modelled PTS $L_{E,p}$ range (m) (no bubble curtain)	Estimated PTS L_p range (m) interpolated from measurements	Estimated PTS $L_{E,p}$ range (m) interpolated from measurements
328 kg NEQ + 2.5 kg donor charge (high order with bubble curtain)	LF: 1,900 HF: 630 VHF: 10,900 PCW: 2,10	LF: 7,600 HF: 41 VHF: 1,200 PCW: 1,300	LF: 49 HF: 14 VHF: 368 PCW: 56	LF: 547 HF: < 10 VHF: 399 PCW: 68
220 kg NEQ + 2.5 kg donor charge (high order with bubble curtain)	LF: 1,600 HF: 550 VHF: 9,500 PCW: 1,800	LF: 6,300 HF: 34 VHF: 1,100 PCW: 1,100	LF: 1,055 HF: 303 VHF: 7,250 PCW: 1,181	LF: 10,400 HF: 893 VHF: 12,500 PCW: 3,274

2.13.1.6. UXO (low order deflagration) at Moray West OWF (Ocean Winds 2024)

A total of 81 UXOs (NEQ ranging from 6 – 700 kg) were cleared using low-order methods using the Alford Technologies disposal tool. The NEQ of the shaped charges used by the disposal tool ranged between 100 – 250 g. The report found that the measured $L_{p,pk}$ for all the 250 g charge UXO detonations were below the predicted received levels (Table 14). The measured levels were also much lower than the predicted levels for high-order UXO detonations (NEQ of 20.7 kg). For example, the predicted impact ranges for high-order detonations were 2.55 - 14.25 km but all the measured impact ranges for low-order UXO detonations were less than 1.5 km. Authors attributed the consistent high estimates to the fact that the model assumes a mid-water detonation and therefore overlooks early interactions of sound propagation and the seabed. Authors ultimately concluded that the noise produced by low-order detonations is determined by the disposal tool size rather than UXO NEQ.

Table 14. Comparison of modelled (Soloway & Dahl 2014) PTS impact ranges with estimated PTS ranges using measured data for UXO low-order clearance at the Moray West OWF (Ocean Winds 2024).

Charge size	Modelled PTS $L_{E,p}$ range (m)	Estimated PTS $L_{E,p}$ range (m) interpolated from measurements
0.25 kg	VHF: 81	VHF: 1,500

2.13.1.7. UXO (low order deflagration) at East Anglia (EA) 3 OWF (Midforth 2024)

A total of 19 low-order UXO clearance events for 12 UXO were monitored at EA3 OWF. The monitoring report found that the estimated source levels from the clearance events were not correlated with the NEQ of the target UXOs, which ranged from 16.4 kg to 226 kg. This suggests that, in a similar fashion to other measured low-order deflagration clearances reported here, the source levels are related to the size of the deflagration charge weights (0.15 kg, 0.20 kg and 0.25 kg), rather than the NEQ of the target UXO. The estimated source levels ($L_{p,pk}$, dB re 1 µPa) was 255 decibels for the UXO cleared using a 0.25 kg deflagration charge; 251 – 253 decibels for the UXOs cleared using the 0.20 kg deflagration charge; and 238 – 252 decibels for the UXOs cleared using the 0.15 kg deflagration charge. The report did not present a table of the PTS ranges interpolated from measured data, instead presenting this on graphs, and it was not possible to extract this information (therefore, the comparisons are not presented).

2.13.1.8. UXO (low yield) at Seagreen OWF (Seiche Ltd. 2021)

At the Seagreen OWF, three UXOs were cleared using a low yield technique (HYDRA-Jet Disrupter system) which used 2x 750 g explosive charges - 1.0125 kg TNT eq. SEMTEX charge. Measured peak sound pressure levels were ~4 – 7 decibel higher than predicted for a 1.0125 kg TNT eq. charge using Soloway and Dahl (2014) at 500 m range and 7 – 8 decibel higher than predicted at 1.5 km range (Table 15). Measured $L_{E,p}$ values were ~6 – 7 decibel higher than predicted at 500 m range and 7 – 8 decibel higher than predicted at 1.5 km range. The authors suggested that the discrepancy could be due to: "*limitations in the prediction methodology (e.g. because it is a semi-empirical method and does not take into account bathymetry, bottom conditions, etc.); and differences in sound produced by the explosive due to the configuration of the HYDRA-Jet (e.g. since the prediction model is based on detonation of a freely suspended charge in open water)".* Although the prediction methodology limitations will apply to all impact assessments which use the same approach.

Table 15. Comparison of modelled (Soloway and Dahl, 2014) PTS impact ranges with estimated PTS ranges using measured data for low yield UXO clearance at the Seagreen OWF (Seiche Ltd 2021).

Charge size	Modelled PTS L_p range (m)	Modelled PTS $L_{E,p}$ range (m)	Estimated PTS L_p range (m) interpolated from measurements	Estimated PTS $L_{E,p}$ range (m) interpolated from measurements
2x 1.0125 kg TNT eq. SEMTEX charge	LF: 356 HF: 116 VHF: 2,010 PCW: 395	LF: 227 HF: 8 VHF: 730 PCW: 43	LF: 496 HF: 128 VHF: 3,990 PCW: 560	LF: 1,091 HF: 22 VHF: 2,314 PCW: 156

2.13.1.9. UXO (low order deflagration) on NeuConnect Interconnector (Seiche Ltd. 2024)

During the disposal process, the total NEQ used was 25 kg (main charge + 150 g disposal charge, low-order disposal tool not reported). The report did not present a table of the PTS ranges interpolated from measured data, instead presenting the received level at the monitoring locations and stating if these were above the auditory injury thresholds. PTS thresholds were not exceeded at the closest monitoring station (1 km away). The authors presented a comparison between the modelled (Soloway & Dahl 2014) and measured

unweighted $L_{p,pk}$ and showed that the measured values were significantly lower than would have been predicted for a high-order disposal of the UXO with a 25 kg NEQ, and lower than for the disposable tool charge (150 g). They suggested that water depth likely had a significant effect in the results as the UXO was cleared in very shallow depths (5.5 m) which would have restricted low-frequency sound wave transmission.

A second UXO was cleared, the first low-order clearance attempt was unsuccessful. A second attempt was made, but the data suggest the UXO detonation was high order. The second attempt resulted in the PTS threshold being exceeded at 1 km for LF, VHF cetaceans and seal hearing categories. The authors presented a comparison between the modelled (Soloway & Dahl 2014) and measured unweighted $L_{p,pk}$ and showed that the measured values were of a similar magnitude to those expected for a high-order detonation for a 162 kg NEQ. The authors do not provide any information on why the second low-order attempt resulted in a high-order detonation.

2.13.1.10. UXO (low order deflagration) at Hornsea 3 OWF (Seiche Ltd. 2025)

A total of 38 UXO clearance events were monitored at Hornsea 3 OWF. All bar four attempts were initiated using a 0.25 kg deflagration shape charge, with two using 0.1 kg and two 0.2 kg. Measured sound levels were in line with those expected for low order clearance techniques for most devices cleared, and no accidental high order detonations were reported.

Measured sound levels were compared with PTS thresholds (NMSF 2024). The Lp,0-pk threshold was only exceeded at 1 km for very high frequency cetaceans. The loudest estimated source level reported at 1 km was 212 decibels ($L_{p,pk}$, dB re 1 µPa,), measured during four clearance attempts using a 0.15 kg deflagration charge; three of these attempts were on the same UXO device.

The weighted SEL PTS threshold for low frequency cetaceans (dB re 1 μPa^2s) was exceeded at 1 km for two clearance attempts, while the PTS threshold for high frequency cetaceans and pinnipeds was not exceeded at 1 km for any. For very high frequency cetaceans, the weighted SEL PTS threshold was exceeded at 1 km for 11 clearance attempts, with the loudest SEL estimated at 168 dB re 1 μPa^2s.

2.13.2. Number of clearance attempts per day

The UXO monitoring data that have been reviewed have also been reviewed to inform the likely number of clearance attempts that realistically can occur in a day, to understand how to best reflect this in the noise modelling.

Low-order deflagration was attempted by three of the projects reviewed (East Anglia Three (EA3), Moray West and Sofia) and was successfully used to clear UXOs by two of these projects (EA3 and Moray West) (Lee *et al.* 2022; Ocean Winds 2024; Midforth 2024). Low-order deflagration was attempted at Sofia Offshore Wind Farm for one of two UXOs on the 12 and 19 August 2022 (but didn't pierce the UXO casing) prior to a high-order clearance on the 24 August 2022 (Lee *et al.* 2022). For EA3, a total of 12 UXOs were disposed of using low-order deflagration, across 19 attempts (Midforth 2024). These occurred across three phases between 8 July 2024 and the 27 July 2024, on a total of 10 days. Of these, four days had a single UXO clearance attempt; five days had two UXO clearance attempts; and one day had five UXO clearance attempts, although three of these are understood to be misfires. In general periods of slack tide were targeted for ROV operation limitations. Where two clearance attempts occurred on a day, this was attempting to clear one or two UXOs. The day where five UXO clearance attempts occurred, three UXOs were the targets of the clearance operation. Details of the exact dates on which low-order clearance was attempted

was not included in the report for Moray West Offshore Wind Farm (Ocean Winds 2024). Whilst these data are limited, it can be concluded that multiple low-order UXO clearance attempts can occur in a day; two events may occur occasionally; more than this is expected to be exceptional.

High-order detonation for UXO clearance has been carried out within two of the projects reviewed. Sofia OWF undertook two high-order detonations, with the use of a bubble curtain within their campaign (Lee *et al.* 2022). The first occurred on the 16 August 2024, while the second was carried out on the 24 August 2024 following two unsuccessful attempts of low-order deflagration. NnG OWF performed four high-order detonations, with no noise abatement technique during their campaign from 14 to 17 May 2020 (itap 2021). Two high-order detonations were carried out in one day on the 15 May 2020, at 10:30 and 17:30. High-order detonations were also carried out by Moray East OWF, however, details of the exact dates on which high-order clearance was attempted are not available (Robinson *et al*. 2022). It is therefore logistically possible to undertake multiple high-order clearances per day.

3. Guidance for assessing the risk of injury to marine mammals and fish

3.1. Introduction

Objective 2 of the Project comprises guidance for the stages involved with the noise risk assessment and associated underwater noise modelling. The aim of the objective is to outline key considerations and required information when assessing the risk of injury to marine mammals and fish from explosives.

This guidance is focussed on the standalone explosive licence application process, and the required supporting information. For guidance on the high-level assessment that may be required in the application for the larger marine development (e.g. for DCOs), guidance from the relevant Regulator or SNCB should be consulted (such as Natural England's Best Practice Advice for Offshore Wind; Parker *et al.* 2022).

3.1.1. Exempt operations

Almost all explosive operations are expected to lead to a risk of auditory injury in noise-sensitive species (i.e. risk cannot be excluded based on the absence of receptors) and so a noise risk assessment for auditory injury would be required. However, JNCC (2025b) state that the risk of injury to marine mammals from explosive operations at greater than 100 m below the seabed surface (referred to as below the mudline, BML) is negligible. This statement is expected to apply to other noise-sensitive species. Therefore, explosive operations of this nature do not require a noise risk assessment for injury.

If a prospective applicant considers that their project should be exempted from the requirement of the noise risk assessment (e.g. because of its depth BML) it is recommended that they consult the relevant Regulator.

3.1.2. Noise risk assessment

An overview of the noise risk assessment process, from Faulkner *et al*. (2018), is provided in Section 2. The workflow and stages of the noise risk assessment are summarised in Figure 1 and are adapted from Faulkner *et al*. (2018).

The noise risk assessment must include robust technical approaches to determining the level of risk. It should in most cases be supported by underwater noise modelling of a level of detail appropriate to the situation. The noise risk assessment and associated noise modelling is the responsibility of the prospective applicant and is usually undertaken by technical specialists. The noise risk assessment should summarise any noise modelling that was undertaken in a way that is comprehensible by a non-technical specialist. It will be reviewed by the relevant Regulator and SNCB(s) (and technical advisors, if applicable), and must provide sufficient information that allows the authorities to best assess the application and the need for any licence conditions (UK Government 2025).

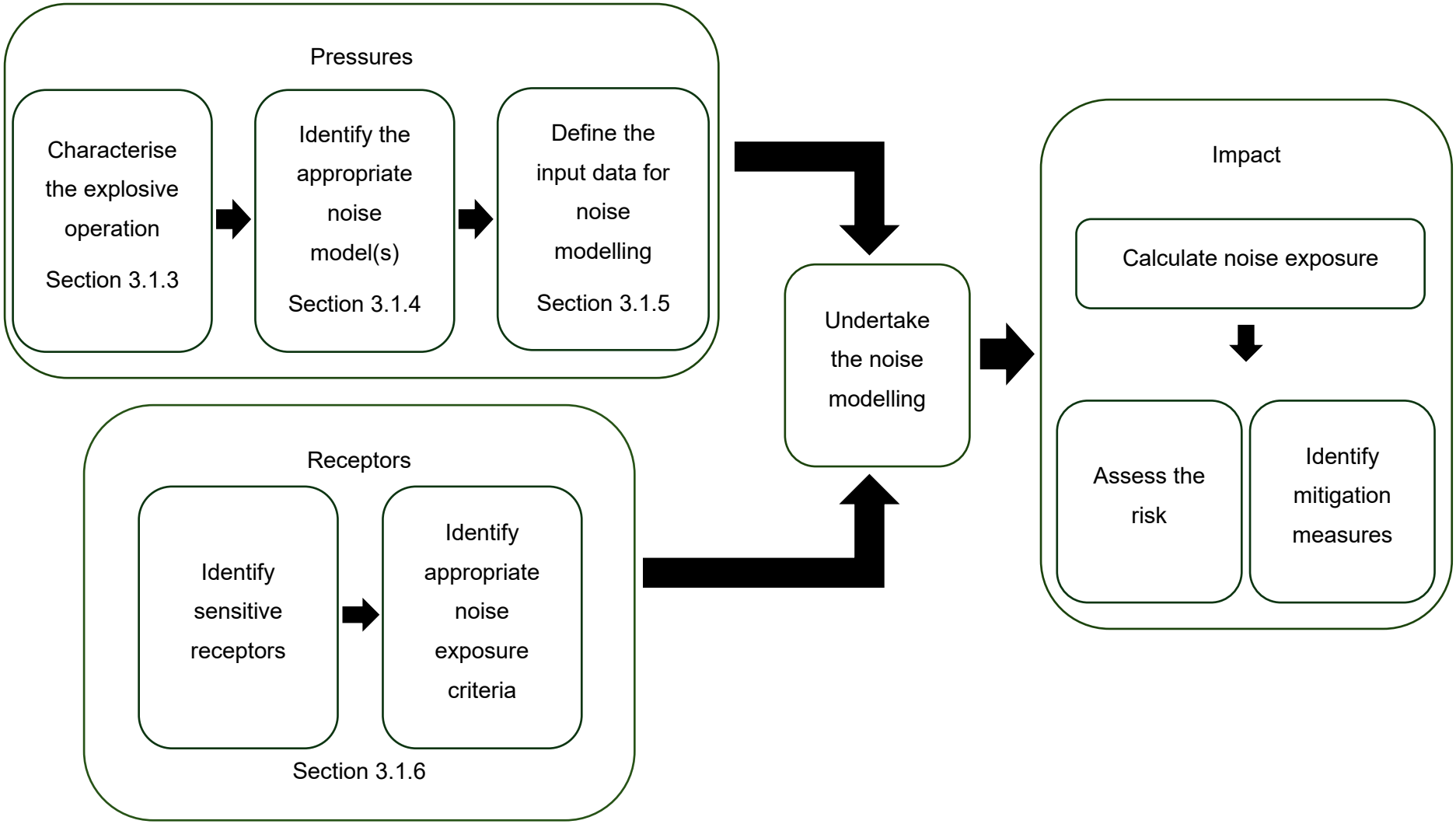


Figure 1. Flow diagram illustrating the proposed noise risk assessment workflow.

3.1.3. Characterise the explosive operation

The key characteristics of an explosive operation must be defined in the noise risk assessment. These are:

- The type of explosive operation (e.g. UXO clearance, decommissioning), alongside an explanation as to why the operation is necessary.
- The location(s) of the operation, in terms of:
    - Geographical location(s) of detonation, highlighting distance to sensitive features and/or MPAs.
    - Location(s) of detonation in the water column or if below the surface of the seabed.
    - Environmental conditions.
- For explosive decommissioning, the mass(s) of the explosive charge that will be detonated.
- For UXO clearance:
    - Identify the type(s) of UXO device(s) to be cleared and their explosive mass when new. If the types of UXO to be cleared is not confirmed, presenting a range of likely types is recommended in addition to the worst case.
    - Identify the low-order clearance method being used and whether a high-order contingency is also being applied for (see Glossary for definitions; see also UK Government 2025; JNCC 2025a).
    - In the case of low-order methods, the name of the tool to be used (where known) should be identified with evidence to support claims of noise reduction, in line with requirements in the Joint UXO position statement (UK Government 2025).
    - Where contingency high order clearance is requested, present the explosive mass within the device plus the donor charge to be used.
    - If requesting low noise and high order contingencies in the same application, separate worst-case scenarios should be identified for each. For low order deflagration, this can be based on the explosive mass contained within the disposal tool. For high order clearance this should be based on the explosive mass of the donor charge plus that in the UXO.

There are several cutting methods available which use explosives that can be applied for O&G decommissioning, each with their own terminology. The information provided in the noise risk assessment describing the proposed operations should be clear and aligned with industry standards for the proposed operation. The size of charge to be detonated should be clearly stated, with an NEQ equivalent weight provided. When using cutting tape with explosives or similar (e.g. TCP guns), state the size of each individual charge (in grams) and the total combined volume of explosives for each cut. Also provide the NEQ equivalent mass of the total volume to be detonated during a single cut to enable comparisons with other operations.

The location(s) of the operation (UXO clearance and decommissioning) must be stated, both geographically and in terms of location in the water column, if known. Specify the distance from the detonation to all sensitive features and to nearby MPAs. Clarify whether the detonation will be mid water (specifying the depth relative to the seabed surface), on the seabed surface or the depth BML. UXO clearance typically occurs on the seabed whereas for O&G decommissioning operations, the detonation is often below the seabed surface. For the latter, the depth BML should be stated as accurately as possible.

The water depth at the detonation location is the key environmental condition that should be provided. The water depth may be used to inform model selection (see Section 2 on suitability of models for “shallow” and “deep” water). The need to define other physical environmental parameters at the operation location will depend on the modelling approach taken (i.e. whether they are required inputs).

There may be some operations where the use of explosives is an option, and that other non-explosive methods may be attempted first (e.g. relocation of a UXO will be considered first) or it is a contingency if a non-explosive method does not complete the required task (e.g. mechanical cutting). In this case, the need for explosives and their specific use must still be clearly outlined in the application and a noise risk assessment undertaken.

3.1.3.1. Explosive weight standardisation

While attempts have been made to standardise how explosive weight is presented in impact assessments, there is some variation in the terminology applied. For example, Net Explosive Quantity is often quoted for UXOs, but relative energy and TNT equivalence have all been referred to (for all explosives use). However, there are nuances between these metrics which introduce variability to the process and make direct comparisons between explosive operations difficult. These metrics can be explained as:

- Net Explosive Quantity (NEQ) is the actual weight of an explosive material, excluding any packaging, casing or other non-explosive components.

- Relative Effectiveness (RE) Factor compares the explosive power of a substance to TNT, indicating how much TNT would be needed to produce an equivalent explosive effect. The higher the factor, the more powerful the explosive.

- TNT equivalence compares the energy released by an explosion to the energy released by a specific amount of TNT (usually 1 kg). A The energy from a metric ton of TNT is equal to 4.184 GJ.

The NEQ can also be referred to as net explosive content, and while it commonly understood both these refer to mass there is scope for different interpretations meaning they could be taken to mean volume. As a result, the term net mass can also be used to avoid any scope for confusion.

Both TNT equivalence and Relative Effective factor represent a ratio of the explosive to be used with that of a known quantity of TNT to achieve the same effect. Both are used in the literature with the RE generally used for demolition and the TNT equivalence for safety evaluations (Fuchs *et al* 2018). There are experimental and theoretical methods available to generate these values. However, the detonation process is complex meaning none of these methods are perfect or represent the complete picture (for example see Cooper 1994; Locking 2011; Fuchs *et al*. 2018; Jaansalu *et al*. 2020).

For noise assessments to support licence applications, it is recommended that all assessments involving explosives present the following:

- Net mass (in kg): to represent the actual weight of explosive material to be detonated minus any casing or other non-explosive material.

- TNT equivalence: to enable comparisons of predicted injury ranges between activities using different types or quantities of explosive material.

The TNT equivalence is to be provided to enable comparisons between operations and is not always used in the modelling process (which focus on mass). To obtain a TNT equivalence value, the net mass of the explosive to be used can be multiplied by a conversion factor. The factor or ratio used to calculate the equivalence should be explicitly stated and referenced in the assessment. Where explosives with mixed composition are used, a weighted average can be applied which considers the relative mass of each component.

Note: For UXOs, when citing the net mass this should represent the mass of explosive material when new and not be estimated based on the status of the device when found.

3.1.3.2. Additional note regarding UXO clearance

If, at the time of application, the contractor who will undertake the UXO clearance is not known, it will not be possible to confirm the mass of explosive to be contained within the disposal tool. If a deflagration tool, care is recommended when determining the mass to assess, as subsequent predictions will be used to determine mitigation requirements and this explosive mass should not be exceeded in the subsequent operations, should the licence be awarded. A balance is recommended which allows flexibility when awarding the contract but does not result in over precautionary mitigation.

3.1.4. Identify the appropriate model(s)

Several modelling approaches have been developed to estimate and predict underwater noise levels at various distances from explosive operations. A non-exhaustive list of some of these models is provided in Section 2. There is no single “ideal” model, therefore an appropriate model must be determined for the operational scenario, usually by a technical specialist, taking account of the points below.

The model must be appropriate for the type of operation. For UXO clearance, open water detonation models are considered the most appropriate. Examples include Cole (1948) and Swisdak (1978), among others. These may also be used for explosive operations within 10 m of the mud line. Confined severance models may be used for down-well operations (e.g. well pipe decommissioning, wellhead severance).

The model selected must be sufficiently valid for the operational scenario(s) of the explosive operations. The noise risk assessment must present information on how the model was selected and why it is sufficiently valid. The following factors need to be considered and commented on in the noise risk assessment:

- Whether the model has been validated for scenarios that are aligned with the proposed explosive operations (e.g. water depths, location of device in water column, charge sizes) and the predicted impact ranges; and

- Whether there is good agreement between the measured noise level and predicted noise level. This needs to consider propagation of both $L_{p,pk}$ and $L_{E,p,}$ across ranges that are representative of the likely or predicted impact ranges.

Note that, following the exercise undertaken in Section 2, this guidance advises caution in the use of Soloway and Dahl (2014) as the basis for estimating weighted SEL auditory injury for marine mammals, as it may underestimate impact ranges.

The model should predict the maximum impact ranges with confidence. However, the model should not significantly over-estimate impact ranges, as that could result in extensive mitigation measures that are not proportionate to the true impact ranges.

The model(s) selected must use the appropriate noise metrics. For marine mammals, both $L_{p,pk}$ and $L_{E,p}$ metrics must be modelled and provided as outputs. The $L_{p,pk}$ metric is an unweighted measure of peak pressure, whereas the $L_{E,p}$ metric accounts for exposure over time and is weighted using marine mammal auditory weighting functions. These weighting functions adjust for species-specific hearing sensitivities of marine mammals. The terminology used in the noise risk assessment must follow the International Standard (2017) ISO 18405:2017(E) Underwater acoustics.

For fish, Popper *et al.* (2014) provides quantitative onset thresholds for mortality and potential mortal injury from explosions using unweighted peak pressure $L_{p,pk}$ for juvenile and adult fish and peak particle velocity for eggs and larvae. As a minimum, $L_{p,pk}$ must be modelled and provided as an output in the noise risk assessment.

Some explosive operations involve the detonation of multiple devices per day (see Section 3.1.5.3). If multiple explosive operations are proposed in a 24-hour period, then modelling with a time integration function should be considered (see Section 2). For example, there is a specific function for this in EDGAR, and with the other methods (e.g. Soloway & Dahl 2014), the $L_{E,p}$ equations can be modified with a time element to account for the number of pulses. Only the $L_{E,p}$ metric would be affected by multiple detonations per day. Modelling of multiple operations would be appropriate when they occur in relatively quick succession (e.g. up to tens of minutes apart) and in proximity to each other (e.g. up to a few kilometres apart). For UXO clearance, it is more likely that the operations will occur one or more hours apart, given all the setup needed and the required mitigation pre-watches. Therefore, a decision should be made whether multiple noise events need to be modelled.

The complexity of sound modelling tools for explosive operations can range from “simple”, user-friendly spreadsheet-type files which require a user to provide a single set of parameters, to “more complex” computationally intensive software models which require spatial information (e.g. water depth) and other site- or signal-specific characteristics. Simple models do not typically provide location-specific, spatially explicit results. Whilst more complex models have the potential to add more realism to the results of the modelling exercise, the more complex the models are, the more location-specific it will be. Examples of some simple and more complex models, as well as their limitations, are provided in Section 2. Modelling approaches have been described in this way to also reflect the level of modelling effort, to support a proportionate approach to modelling based on risk. Section 3.1.4.1 of this guidance suggests an approach to model selection based on uncertainty and risk, should a simple model be used.

A technical specialist may consider that an explosive operation does not need project-specific underwater noise modelling because there is already robust evidence (e.g. previous modelling and/or monitoring of similar explosive operations) that demonstrates that the proposed explosive operation is low risk (e.g. injury ranges < 1 km), and industry-standard mitigation has been committed to. In this case, it is recommended to discuss and confirm with the relevant Regulator and SNCB(s).

3.1.4.1. Suggested approach to model selection

From a noise risk assessment perspective, it is vital that the modelling approach will determine maximum realistic impact ranges with confidence. This is needed to understand the maximum impact to the receptors and inform appropriate mitigation measures to reduce the risk of injury, as required.

Considering the points in Section 3.1.3, this guidance recommends the following approach to selecting an appropriate model for explosive noise.

1. Use an appropriate model for the operational scenario. This may be “simple” or “more complex”.

The technical specialist should determine an appropriate model, using the information outlined in Section 3.1.3. It is acknowledged that a proportionate approach is preferred, hence a simple model can be used in the first instance, if relevant to the operational scenario.

2. If a simple model was used, and:

    a) there is low confidence in the robustness of the predicted impact ranges; and/or,

    b) the predicted impact ranges are close to or beyond that which can be mitigated

then a more complex model should also be used to predict impact ranges. This is considered appropriate for such “higher uncertainty/risk projects”.

It is recognised that there are limitations to simple models (see Section 2). The predicted ranges can be reviewed by a technical specialist who will consider whether the predicted ranges are greater than those over which the model has been validated, the change in environment over the injury ranges, and whether the predicted injury ranges align with monitored impact ranges. Details of this technical review must be presented in the noise risk assessment in terms that can be understood by a non-technical specialist. In addition, the level of risk to receptors needs to be considered; more information and guidance on how to approach this is provided in Section 3.1.6.

It is acknowledged that explosive operations may include a range of scenarios (including charge weights, water depths, depth BML, clearance methods, and mitigation measures), each with their own predicted injury range. It may be that the largest injury ranges are for activities which form only a small part of the operations (e.g. high-order contingency for UXO clearance; only a small amount of explosive decommissioning within 10 m BML). If that is the case, and a simple model has been used, then it is recommended to seek advice from the Regulator (and SNCB) on how to apply the above suggested approach.

One purpose of undertaking an additional more complex modelling approach is to compare these model outputs to that of the simple model outputs. Using this approach, the maximum impacts can be determined with greater confidence, and thus greater confidence in the mitigation measures applied.

3.1.4.2. Higher risk projects

A flow chart has been provided (Figure 2) to guide prospective applicants in understanding whether their project could be considered higher risk to marine mammals, and if more

complex modelling should be undertaken. It follows a two-question process, with each question being a yes or no answer, and the answer determining the next step. What to consider when answering the two questions is provided in the text below.

A process to determine higher risk projects to fish has not been provided because of the differing approaches to determining sensitivity and mitigation for explosive operations.

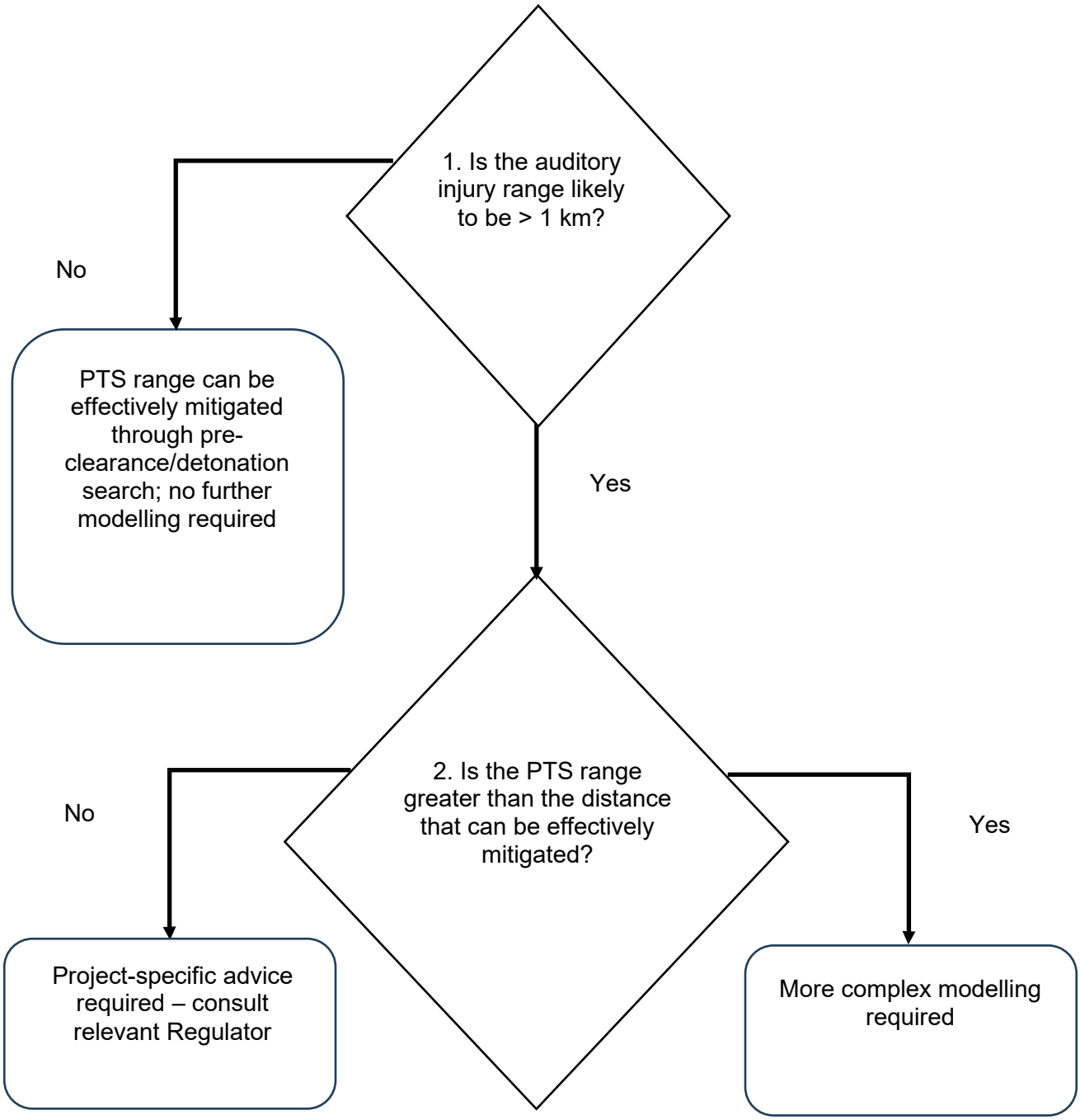


Figure 2. Flow diagram illustrating a process when considering questions to support determining whether a project or operation could be considered higher risk to marine mammals.

Question 1. Is the PTS range > 1 km?

When answering this question, the assessment should consider, and clearly present:

- The worst-case scenario (WCS) for all relevant project parameters
- The impact ranges for all the relevant acoustic metrics ($L_{p,pk}$, $L_{E,p}$)
- The impact ranges for each marine mammal hearing group that could occur in the project area and
- Whether measures to reduce the impact ranges (e.g. NAS, low-order methods) will be undertaken in accordance with latest JNCC Guidelines (currently JNCC 2025a, b).

This question should be answered with the outputs of the simple modelling (or in low-risk cases, robust evidence from the literature).

Question 2. Is the auditory injury range greater than the distance that can be effectively mitigated?

When answering this question, the assessment should consider and clearly present all the above information, plus:

- Whether an ADD is being proposed, and the duration of ADD activation proposed. Evidence on the effectiveness of the chosen ADD at displacing marine mammals beyond the predicted injury ranges should also be presented; and
- Whether additional noise abatement is proposed, such as bubble curtains, and whether/how these have been factored into the assessment alongside the evidence to support the predicted noise reduction in the assessment.

3.1.5. Define input data for noise modelling

An explosive operation must be defined in terms of the parameters and input data required for the specific modelling approach selected. These should be presented in a table in the noise risk assessment. This table should capture the range of parameters which will or may be realised for the project, as well as the maximum or worst-case input parameters. These are the inputs that will lead to the WCS for risk to the receptor. The input parameters should be as refined and realistic as possible; excessive uncertainty may increase the WCS or the potential difference between the WCS and realised impacts, making the consenting process more complicated and mitigation requirements over precautionary.

The input parameters detailed here are not exhaustive, additional ones may be required depending on the model selected. If a more complex model is being used, then the physical environment input data should also be presented in terms of range and WCS. This will need to consider the effects of water depth and sediments, at the location and along propagation ranges, which can interact to affect the WCS.

3.1.5.1. Explosive charge size

All explosive operation noise risk assessments should be informed by the explosive charge explosive mass(s) that will, or is likely to, be utilised and/or detonated.

At a minimum, the explosive charge mass(s) should be presented in terms of their actual charge weight (kg) and their TNT equivalent (TNT eq.; kg). If many explosive charge size(s)

are proposed, then at least the maximum and a representative range should be presented, in a table format.

Note, subsequent operations at sea (if licenced) must not use and/or detonate an explosive charge size that is greater than those assessed during the application process. If a larger explosive charge size needs to be used and/or detonated, then a variation to the licence will be required.

There are additional specific considerations regarding UXO clearance operations and assessed explosive charge sizes. Where investigative surveys to confirm UXOs have occurred, the noise risk assessment should clearly state the size of known UXO devices requiring clearance in terms of:

- Physical size (typically included in the name of the item)
- Net explosive mass (kg)
- For UXO clearance, disposal tool or (where appropriate) donor charge explosive mass (kg)
- For high order clearance, total of the above (kg) and
- TNT equivalent (see Section 3.1.3.1) (kg).

This clarity will reduce risk of confusion around the different sizes often presented for UXO clearance. Where investigative surveys have not been undertaken, a likely range of UXO and disposal/donor charge sizes should be stated, following the same format as the bullet point list above.

For low-order deflagration clearance, assuming a tool is proposed which is supported by robust evidence that it will result in reduced noise levels, only the size (charge weight) of the disposal tool needs to be assessed (Defra 2025). The size of the disposal tool is expected to be < 1 kg; ideally, the precise size will be known at the time of undertaking the noise risk assessment and associated noise modelling and so can be inputted. It is acknowledged that there is a risk of accidental high-order detonation resulting from low-order methods, however it would add a disproportionate burden on mitigation to assume this could happen every time low order methods are used. Furthermore, the growing pool of data for deflagration tools suggest that the risk of accidental high order is very low. Hence this scenario (in terms of using UXO charge weight rather than low-order tool size) does not explicitly need to be modelled. It may be possible in the future to apply this approach to other low-order methods that may come to market but will depend on the supporting evidence and level of noise reduction demonstrated.

For high-order clearance, the weight of the UXO and donor charge should be summed, to create a single TNT eq. (kg). The maximum TNT eq. (kg) must be modelled, as this will generate the worst-case impact ranges, however a range of devices is recommended to be modelled also (see Defra 2025b) if multiple devices are expected to need to be detonated. It should also be assumed that no degradation of the explosive material in the UXO has occurred, hence upon clearance the UXO will detonate at the intended full power.

The size of explosive charges used in decommissioning are expected to be known prior to undertaking the noise risk assessment. The charge weight, together with the explosive material being used, will determine the TNT eq. (kg). The charge weight should be presented in both TNT eq. and unadjusted, with information on the conversion between the

two. The model selected will determine which charge weight value should be inputted (i.e. unadjusted or TNT eq.); the value that is inputted to the model must be specified.

3.1.5.2. Depth of explosive operations

Depth of the explosive operation relative to the seabed is not an input parameter used in open water models. Therefore, UXO clearance and explosive operations < 10 m BML, which are recommended to use open water models, do not need to consider this parameter.

Depth of the explosive operation BML is relevant for explosive operations for decommissioning where the detonation occurs between 10 m and 100 m BML (as below 100 m, no injury is expected, therefore no modelling is required for detonations at these depths). When using models that account for depth BML, this parameter must be specified. It is understood that a range of depths, as well as charge weights, may be used during explosive operations. As a minimum, the worst-case scenario should be modelled. It is expected that this will be the detonation at the shallowest depth BML, though if there is uncertainty as to the parameters that will lead to the worst-case (e.g. larger charges will be used at lower depths), then a representative range should be modelled.

The need to input data on water depth will depend on the model selected. Whilst not a parameter in the models reviewed in Section 2, water depth between source and receiver positions would be required for range-dependent models, which are a more complex model type that take into account difference in propagation through water (and so are less relevant to explosive decommissioning operations), and may be used for explosive operations of higher risk.

3.1.5.3. Number of explosive operations

The WCS should be defined in terms of number of detonations simultaneously, maximum number of detonations per day (within limited time and geographical constraints noted below), and maximum number of detonations during the proposed operation.

The number of explosives used within an oil and gas decommissioning operation will be project specific and likely be known at the licence application stage. For down-well explosive severance, the time between explosive operations correlates to the depth of the operations, due to the time taken to run explosives down to the required depth. The shallower the operations, the more operations that can be achieved per day.

The maximum number of UXO clearances that can realistically be achieved per day should be considered, noting there may be restriction on this by the regulator depending on where clearance is to occur (e.g. if in an MPA). This should reflect clearances occurring at discrete UXO locations, but not as multiple, accumulative UXO clearance attempts on a given day, unless this is likely to occur within 1 km and within 20 minutes of the previous clearance. It does not need to include a combination of clearance methods, provided that the worst case is included (e.g. if high-order methods are to be retained as an option, see Defra 2025).

3.1.5.4. Mitigation measures

There are industry-standard mitigation measures for explosive operations (JNCC 2025a, b; Defra 2025) which may be embedded into the project design and can affect the noise modelling results.

Based on Section 2, the current guidance does not recommend including the use of an acoustic deterrent device (ADD) in the underwater noise modelling. Modelling without the inclusion of ADDs will lead to more precautionary impact ranges and so will comprise the

worst-case scenario that must be modelled. In addition, scare charges are not recommended for marine mammal mitigation (JNCC 2025a, b), nor for fish (see Section 2).

The use of NAS, where proposed, should be considered quantitatively in the noise modelling. Modelling with and without NAS will demonstrate the benefit of the assumed noise reduction in reducing overall risk. The operational scenarios and outputs of the noise risk assessment may lead to specific regulatory advice on when NAS must be used (Defra 2025). The noise risk assessment should review the available evidence base for noise reduction from NAS, such as modelling, empirical evidence or both, and present an appropriate expected reduction for the operational scenario that is supported by evidence and achievable in practice. Consideration should be given to frequency-related performance also, as different NAS may attenuate different parts of the frequency spectrum of explosive noise better.

If high-order UXO clearance is proposed, then NAS is expected (Defra 2025). The scenarios in which NAS will be used (e.g. device charge weight, environmental conditions) need to be considered in the noise risk assessment.

To date, applications for decommissioning explosive operations have only used ADDs for active mitigation, which do not need consideration in the modelling. It is therefore expected that the underwater noise modelling of decommissioning explosive operations will not need to factor in any mitigation measures (i.e. that the modelling will reflect a no-mitigation scenario). However, in the future, decommissioning explosive operations may require the use of NAS, if there is a higher level of risk from the proposed operations. If NAS is required, then it will need to be assessed and included in the noise modelling.

If NAS is not proposed for all operational scenarios, underwater noise modelling should be undertaken for each operational scenario. Importantly, modelling must be undertaken for the WCS (i.e. the lowest level of mitigation).

3.1.6. Combine modelling outputs with receptor thresholds and data

The receiving biological environment needs to be considered when determining what noise-sensitive biological receptors or species may be present, and therefore how to calculate their exposure to the predicted noise. If there is variation in the receiving environment due to uncertainty in the location of the explosive operation, a range of locations and/or the worst-case location needs to be determined.

3.1.6.1. Identify sensitive receptors

The presence of noise-sensitive species within an appropriate area around the explosive operations must be determined. This is known as baseline characterisation, which should use the latest available evidence for the specific project area and species likely to be present.

The appropriate area over which the baseline will be characterised must be defined. A generic buffer distance around the operation could be used, or a wider area to reflect the mobile nature of noise-sensitive species, if the location of the operation is unknown or if there are multiple locations. Once the underwater noise modelling has been undertaken, and impact ranges predicted, these should be checked to ensure that they are within the appropriate area.

The location and timing of the explosive operations will need to be considered when determining species likely to be present and overlap with key life stages (e.g. spawning or migration periods).

The review, 'Identification of Key Species in the UK, with a focus on English Waters, Sensitive to Underwater Noise – ME5605' (Williams *et al.* 2021), provides key information on the protected and commercial species that are sensitive to underwater noise in UK waters, and should be used in the noise risk assessment.

The presence of designated sites for noise-sensitive species within the appropriate range should be identified, using sources such as the JNCC MPA mapper (Marine Protected Area Mapper | JNCC - Adviser to Government on Nature Conservation). For decommissioning activities involving explosives, a range of 40 km from the operation site is usually sufficient for these sites.

Marine mammals

All marine mammal species are considered noise-sensitive species that would be able to detect, and be impacted by, the noise from explosive operations. More information on hearing abilities of marine mammals can be found in Section 2, and the sources referenced therein.

IAMMWG outline the seven most common cetacean species found in UK waters (most recently in IAMMWG 2023). There are also two resident seal species in UK waters, harbour seal (*Phoca vitulina*) and grey seal (*Halichoerus grypus*). However, the species present at a given location will vary, and so the baseline characterisation will be used to identify those which are at most risk (i.e. those that may be present in the area of impact around the location of the explosive operation). Appendix 4 lists key sources of information on marine mammal species distribution in UK waters at the time of writing, which can be considered in the baseline characterisation.

Note: some applications may require a broader noise risk assessment which involves estimation of the number of potentially impacted individuals for each species/population. This is not covered by the current guidance. To complete this component of the assessment, the most up-to-date data sources for species densities and abundances should be used, though any uncertainty on which sources to use should be discussed in consultation with the relevant regulators.

Fish

The baseline should characterise fish and elasmobranch species that are of conservation, commercial and/or recreational importance. This should include species known to have nursery and/or spawning grounds within the area, together with species of commercial or conservation interest, including species known to migrate through the area or that have a generally restricted geographical distribution but are locally abundant.

Further consideration should be given to species that use vocalisation during spawning, such as Atlantic cod (*Gadus morhua*), and species that have defined spawning grounds or exhibit substrate specific requirements for spawning, such as Atlantic herring (*Clupea harengus*) and sandeel (*Ammodytes* spp.), as these can be most impacted by explosive noise. Site-specific Particle Size Analysis (PSA) data can be used to determine the presence of suitable spawning habitats for these species. Published guidance by Kyle-Henney *et al.* (2024) and Reach *et al.* (2024; Appendix 4 presents the most relevant resources on fish at the time of writing but note that new publications are frequent and/or data sets are updated regularly. To complete this component of the assessment, it is recommended that the most up-to-date data sources for species distributions and spawning and nursery grounds are confirmed in consultation with the relevant regulators. detail methodologies for the identification and mapping of herring and sandeel spawning habitats. The distribution and/or densities of the fish receptors at all life stages (eggs, larvae, juveniles and adults) should be

detailed together with the potential for a temporal overlap of the proposed explosive operations with key life events (such as spawning periods or migratory periods). It is also recommended to present the status of the fish populations likely to be affected (e.g. using the most recent ICES advice) to inform the noise risk assessment.

Appendix 4 presents the most relevant resources on fish at the time of writing but note that new publications are frequent and/or data sets are updated regularly. To complete this component of the assessment, it is recommended that the most up-to-date data sources for species distributions and spawning and nursery grounds are confirmed in consultation with the relevant regulators.

Popper *et al.* (2014) categorised fish into hearing groups depending on their sound detection mechanism and sensitivity to noise. Fish species that have a swim bladder closer to the ear or involved in hearing are generally more sensitive to noise due to having a greater ability to detect sound pressure in addition to particle motion. In addition, species with a swim bladder or other gas-filled cavities are more likely to suffer barotrauma injuries following underwater explosions compared to species that lack gas chambers. More information on hearing categories or groups of fish can be found in Section 2, and the sources referenced therein.

3.1.6.2. Identify appropriate noise exposure criteria

The latest appropriate noise exposure criteria for noise-sensitive species should be used in the noise risk assessment. At the time of writing, these are given by NMFS (2024) for marine mammals, and Popper *et al.* (2014) for fish. These criteria are presented in Section 2.

While the latest thresholds should be used, when new thresholds are published, there may be a period during which both old and new thresholds need to be used, so the results can be presented side-by-side for comparison and context until the new thresholds are fully adopted by the relevant Regulator and SNCBs.

The ranges at which all relevant metrics are breached should be presented in the noise risk assessment. In the UK, auditory injury to marine mammals is defined as PTS onset, which can be either instantaneous or cumulative. Both dual criteria metrics, of L_p and $L_{E,p}$, must be modelled.

Note: if weighted thresholds ($L_{E,p}$) are adjusted, e.g. because source data does not contain sufficient detail on frequencies, how the adjustments have been made should be clearly identified, specifying any weighting factor adjustments, or equivalent, applied.

Lethal injury to fish includes both immediate and delayed mortality and can be modelled using $L_{p,pk}$ for juvenile and adult fish and peak particle velocity for eggs and larvae. Auditory impacts to fish receptors include recoverable injury to auditory structures and TTS, both of which are assessed through qualitative thresholds. These qualitative thresholds provide standardised approximate ranges of relative impact risk, which can be used in the noise risk assessment (see Section 2). Relevant metrics and qualitative thresholds must be presented for each of the hearing groups or categories of marine mammals and fish species.

For fish it should be recognised that whilst the Popper *et al.* (2014) thresholds should be used in the noise risk assessment, there are limitations to these thresholds (see Section 2.10.2). Therefore, it is also recommended to review and present the latest literature when assessing the risk of underwater explosions to fish. Any limitations of the assessment approach should be presented, for example, if predicted injury ranges differ from those validated in the field.

There is currently no scientific consensus on the specific range at which sound transitions from impulsive to non-impulsive. However, this transition is generally expected to occur far away from the source for explosive noise (tens of kilometres away, see Section 2.8). The application of thresholds is based on the characteristics of the noise at the source, which for explosives, is impulsive. Hence, only metrics based on impulsive noise should be presented in the noise risk assessment.

3.1.7. Calculate noise exposure

Noise modelling will be used to determine the range at which the relevant species-specific thresholds are exceeded, and thus the range over which noise-sensitive species are predicted to experience injury.

Impact ranges should be presented for each of the modelled scenarios (e.g. range of TNT eq. or unadjusted weights) for each species or species/hearing group. If mitigation is incorporated into the noise modelling, then impact ranges for the mitigated scenarios should be presented alongside unmitigated scenarios. These ranges should be presented in table(s). A comparison of mitigated and unmitigated injury ranges will provide context to the realised benefits of the use the mitigation (e.g. as shown in Section 2).

Where more complex modelling has been undertaken, this may result in injury contours being presented on plots. The contours may take account of the variations in sound propagation due to environmental conditions such as water depth and sediment. If contours are produced, the maximum range as derived from the contours should be presented. Other metrics (e.g. median range) may also be presented.

The injury range and/or contour should also be overlain with a spatial layer of the presence of protected sites and important biological areas for noise-sensitive species to determine overlap. If there is overlap, then a specific assessment for that site may be required. Overlap may also mean that further mitigation is required.

Specifically for fish receptors, predicted acoustic impact ranges need to be overlain with key biological spatial layers to determine the risk level from a project. This should include any spatial overlap of impact ranges with sensitive receptors spawning and nursery grounds, taking into consideration any temporal overlaps in explosive operations with key sensitive periods such as peak spawning season. Consideration should also be given to species of conservation interest, including migratory species that may be present in the area during explosive operations. Expert judgement and available evidence should then be used to assess the risk that any spatial interaction with injury ranges may pose for sensitive fish receptors (during sensitive periods, if applicable). If there is potential for population effects, it is recommended to seek advice from the relevant Regulator and SNCB to discuss the assessment and the need for additional mitigation specifically for fish receptors.

Please refer to the checklist for the information that needs to be presented in the noise risk assessment to determine the level of risk to fish receptors.

Cumulative exposure

If multiple explosive operations are proposed in a 24-hour period, in relatively quick succession (e.g. less than 20 minutes apart), then the cumulative exposure should also be considered. Cumulative exposure can be calculated through time integration in the modelling. For marine mammals, the cumulative exposure should then be compared to the relevant auditory injury threshold using $L_{E,p}$. For fish, there are currently no exposure thresholds available for multiple explosions. However, as for marine mammals, cumulative exposure can be calculated through time integration in the modelling, and the cumulative

exposure levels could then be compared to the $L_{E,p,t}$ cumulative sound exposure thresholds for piling driving operations in Popper *et al.* (2014), as a proxy for explosives. Calculation of impact ranges should be undertaken and presented for each event individually first, and only then in combination.

If explosive operations occur with an appreciable separation in time between blasts (e.g. more than 1 minute apart), then a fleeing response for marine mammals could be considered. Marine mammals are typically assumed to flee away from a harmful noise source. A simplistic approach often used is to assume that an animal flees directly away from the source at a constant fleeing speed. An appropriate fleeing speed should be determined using the evidence base, though standard speeds are typically used in each jurisdiction.

The fleeing response of fish to underwater noise is poorly documented, but it is typically assumed that the capability to leave an area during noise exposure differs between species and will for some species also vary seasonally. For example, herring are considered more vulnerable to underwater noise during spawning, when they are less mobile, therefore increasing their theoretical exposure to underwater noise. Moreover, there is little research to suggest that fleeing responses in fish are prolonged following exposure to brief noise events such as underwater explosions. Therefore, fish should be considered as a stationary receptor when assessing cumulative exposure from multiple explosive operations that are carried out in quick succession.

3.1.8. Additional estimations

For marine mammals, the predicted noise level (SPL_{pk} ($L_{p,pk}$) and SEL ($L_{E,p}$)) at 1 km should be presented in all noise risk assessments in addition to other estimations of biologically relevant ranges. This is to allow for comparison against any noise monitoring data collected, as NPL (2020) requires that a measurement should be made at 1 km distance wherever possible.

3.2. Checklist

The checklist below (Table 16) provides a list of information that must be in the noise risk assessment and accompanying or integrated underwater noise modelling report. It is recommended that a summary of the key information from modelling is presented in the assessment, with further details of the modelling provided as an annex or appendix. It also provides a list of recommended scenarios where a prospective applicant should seek additional information from the Regulator and, if relevant, SNCB or technical advisor. Discussing proposed operations with the relevant Regulator and SNCB(s), ahead of submitting an application, can help prevent delays to subsequent application determination.

It is recommended that, at every stage of the noise risk assessment and associated modelling, information on assumptions, limitations, caveats, *etc*. are presented. The technical experts may wish to present the confidence in the outcomes of the noise risk assessment. It may also be relevant to present a range of outcomes. In this case, information on how to interpret the range of outcomes would be needed.

In addition to the checklist below, it is also recommended that the assessment data should be in a format that can be used for comparison with the monitoring data. Further guidance on how to gather monitoring data is provided in NPL (2020) and East *et al*. (2026). Any mandatory information in monitoring reports (see Section 5, East *et al.* 2026), that is known and available at the noise risk assessment stage, should ideally be presented in the noise risk assessment.

Table 16. Checklist of required information for noise risk assessments and underwater noise modelling reports, including recommended scenarios for seeking additional guidance.

Noise Risk Assessment stage	Information that must be presented		When to discuss with Regulator (recommended)
Characterise the explosive operation	Type of operation.		• Explosive operation is for purpose other than those covered by this guidance. • If prospective applicant considers their operation should be exempt from noise risk assessment or noise modelling.
	Exempted operations (*if relevant*).		
	Location of operation.		
	Water depth and depth BML where applicable.		
	Charge size (TNT eq. and/or unadjusted) and type of explosive material where known; a range of likely charge sizes where unknown.		
Identifying appropriate noise model(s) Identifying appropriate noise model(s)	Which model(s) are being used and for what purpose.		• If there is uncertainty on the level of risk and/or appropriate model to use (e.g. “simple” or “more complex” model). • There is uncertainty on the outputs from the complex model, or which output the mitigation measures should be applied to. • If a different approach is used.
	Justification for the model selected with consideration to both the operation and environment.		
	Why the model selected is sufficiently valid, with associated references.		
	Whether multiple pulses are being modelled.		
	If no modelling is proposed, justification for this plus robust evidence that demonstrates predicted impact ranges.		
	How confidence in the model outputs has been determined.		
	Whether the impact ranges are mitigatable or whether there is residual risk.		
	If a simple model is used, an overall assessment of whether the operations are considered “high uncertainty/risk”.		
Input data for noise modelling	Table of all input parameters/data used in the model, with associated references.		• The WCS is not being modelled.

Noise Risk Assessment stage	Information that must be presented		When to discuss with Regulator (recommended)
Input data for noise modelling	Parameters of worst-case scenario.		• Uncertainty over appropriate parameters. • The parameters are not known, and guidance is needed on appropriate assumptions. • Uncertainty over the need to model multiple explosions. • Uncertainty over what mitigation will be needed. • Low-order tool that have no or limited at-sea data available. • NAS other than bubble curtain proposed. • Uncertainty on best approach to incorporate NAS or combined mitigation measures.
	Representative range of parameters (*if relevant*).		
	References for any/all constants and coefficients used in the model.		
	Charge size (TNT eq. and unadjusted, and information on conversion).		
	For UXO clearance, donor charge or disposal tool size.		
	Number of explosive operations (simultaneous, per day, total).		
	How mitigation measures are being included in the model.		
Combine modelling outputs with receptor thresholds and data	Appropriate area used for baseline characterisation.		• Latest literature not being used, or uncertainty over what to use or species to include. • Recently published literature (e.g. noise exposure criteria) which may need side-by-side comparison. • Not all metrics modelled or deviation from guidance on metrics is desired.
	List of species likely to be present and their hearing groups.		
	Temporal overlap with key life stages (e.g. spawning and migration periods), where known.		
	Noise exposure criteria used.		
	Impact ranges for all metrics and hearing groups.		
	Impact ranges with and without mitigation measures.		
	Movement assumptions for fish and marine mammal receptors between pulses, such as flee speeds (*if relevant*).		
	Predicted noise levels at 1 km.		

4. Future improvements

The following are key areas identified from the literature review (Section 1) as areas that either require additional data to support noise assessments (evidence gaps) or where improvements could be made to either the assessment process or how it is reported.

4.1. Increased monitoring

There is a clear lack of data available in the public domain on underwater noise measurements of explosives used in the decommissioning of offshore structures. Therefore, it is strongly recommended that noise monitoring is conducted going forwards to allow for the collation of such data to improve assessments and de-risk future projects. How this is implemented is down to the specific regulator and SNCBs to decide. For example, it could be made a standard consent condition that underwater noise monitoring is conducted for decommissioning explosives use until sufficient data has been collected covering a range of charge sizes, water depths, depths BML, etc. This would be particularly useful to allow the regulators to refine their advice on when an impact assessment is required (e.g. relative to charge size and depth BML).

As different low-order UXO clearance methods and tools develop, it is recommended that they should be validated in controlled experiments to include noise monitoring before being used in offshore operations, to understand the levels of underwater noise they are expected to produce. This aligns with the advice provided in the Joint Position Statement on UXO clearance (UK Government, 2025) and accompanying guidance (Defra 2025).

4.2. Improved reporting

To improve our understanding of risk of auditory injury from explosives, it is essential that there is communication between the underwater noise modelling company and the underwater noise monitoring company. This feedback loop is often lacking, and thus the available monitoring literature generally lacks a comparison of modelled versus measured auditory injury ranges for marine mammals. This step is essential, so that increased information is available to assess the difference between what was modelled and what was found in practice, to assess whether assumptions in the impact assessment were correct and the validity of the model to similar situations in the future. At present, it is usually not included in underwater monitoring reports as it is not specifically an objective of the reports to do so. It is strongly recommended that data from monitored (measured) underwater noise levels are reported and used to validate and (if required) update the models used in the assessment, to ensure that the MMMP is fit for purpose.

Many underwater noise monitoring reports that have been produced and submitted to the Regulators are not easily available in the public domain. It is strongly recommended that all compliance monitoring reports should be made public if the monitoring was required as a licence condition. This would help fill evidence gaps and support future applications by informing areas of excessive precaution in the noise risk assessment and subsequent mitigation plans.

It is currently unclear whether the lack of available monitoring reports is due to them not being publicly available, or there being no consent requirement to undertake monitoring. This therefore severely limits the data available in the public domain for the scientific community, the industry and the regulators to learn from. As such it is also strongly recommended further monitoring is undertaken as part of licence conditions where applicable, given the paucity of existing data.

It was noted that the Marine Noise Registry contains little data on explosives that could be used to support or improve noise assessments, with most records simply stating the TNT eq. charge size, but nothing on modelled or measured L_p or $L_{E,p}$. To improve the usefulness of this tool, it is recommended that more information is required of data providers (such as estimated PTS ranges, source level, clearance method, donor charge size, etc.).

4.3. Noise abatement

Increased understanding of the level of achievable noise reduction using methods such as bubble curtains needs to be prioritised. Currently, modellers tend to assume that using a bubble curtain will result in a 10 dB noise reduction as standard, noting this is also the approach taken for piling operations. However, studies on explosive detonations have shown that the level of noise reduction will differ depending on charge size and that the level of noise reduction will be frequency dependent (e.g. Schmidtke *et al.* 2009; Hannay & Zykov 2022).

What is needed is clear evidence of the achievable noise reduction levels at different frequencies for a variety of charge sizes, at a variety of depths and in a range of environmental conditions. Initial work has been conducted by Cheong *et al.* (2023) for low-order clearance methods in controlled experimental trials in a quarry facility (charge size 45 – 465 g), which has demonstrated that bubble curtains can achieve a reduction in noise. However, the authors note some clear limitations of this trial:

- A controlled quarry trial is not representative of what will occur in an offshore environment (i.e. does not account for the influence of tidal flow).
- The charge was in the mid-water column rather than on the seafloor as would be the case of UXOs.
- Only one bubble curtain configuration was tested (two bubble layers a few meters apart) and the results cannot be easily extrapolated to other scenarios.
- Different hose and hole size configurations need to be tested.

Once additional experiments are conducted using different configurations and hose specifications (and other operational factors that could be relevant such as air flow), and in a variety of different offshore environments, then predicted noise reduction can be incorporated more accurately into future modelling.

4.4. Understanding impulsiveness

The evidence available suggests that there are aspects of impulsivity that decrease over larger distances (i.e. 10s of km), however there is no conclusive evidence that explosive noise becomes fully non-impulsive over existing monitored ranges. Further investigation into the impulsive characteristics of different explosive sources is required to better understand the relationship between impulsiveness and distance from the sound source.

In addition, further data is required from low-order clearance of UXOs and the use of other smaller explosives (e.g. during decommissioning) to better understand and characterise variation in the impulsiveness of the sound produced relative to explosive size. If this relationship is better understood, then there may be ways in which to incorporate this into acoustic propagation models to make them more accurate going forwards.

It is strongly recommended that all underwater noise monitoring reports for explosives include an assessment of the impulsiveness of the sound with distance, using metrics such

as crest factor, kurtosis, rise time, signal duration, and waveform elongation, to assess the reduction in impulsivity with distance.

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Chapman	1988	Source levels of shallow explosive charges
Dahl *et al.*	2020	Physical effects of sound exposure from underwater explosions on Pacific sardines
Denmark Guidelines	2022	Guideline for underwater noise
Dinjens	2024	Environmental effects of UXO clearances: The exploration of the effects of unexploded ordnances for offshore windfarms Rijkswaterstaat
DoN Critera	2024	Criteria and thresholds for U.S. Navy acoustic and explosive effects analysis (Phase 4)
dos Santos *et al.*	2010	Monitoring underwater explosions in the habitat of resident bottlenose dolphins
Dzwilewski & Fenton	2003	Shock wave/sound propagation modelling results for calculating marine protected impact zones during explosive removal of offshore structures
Finneran *et al.*	2000	Auditory and behavioral responses of bottlenose dolphins (*Tursiops truncatus*) and a beluga whale (*Delphinapterus leucas*) to impulsive sounds resembling distant signatures of underwater explosions
Gaspin	1979	The determination of acoustic source levels for shallow underwater explosions
Gaspin & Shuler	1971	Source levels of shallow underwater explosions
Goertner	1978	Dynamical model for explosion injury to fish
Goertner	1994	Effects of underwater explosions on fish without swim bladders
Hawkins *et al.*	2014	Sound exposure guidelines for fishes and sea turtles: A technical report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI
Jasco	2023	Underwater acoustic modelling of detonations of Unexploded Ordnance (UXO) for Orsted Wind Farm Construction, US East Coast
Keevin & Hempen	1997	The environmental effects of underwater explosions with methods to mitigate impacts
Ketten	1995	Estimates of blast injury and acoustic trauma zones for marine mammals from underwater explosions

Authors	Year	Title
Ketten	2006	Experimental measures of blast and acoustic trauma in marine mammals
Koschinski	2011	Underwater noise pollution from munitions clearance and disposal, possible effects on marine vertebrates, and its mitigation
Koschinski & Kock	2009	Underwater unexploded ordnance - methods for a cetacean-friendly removal of explosives as alternatives to blasting
Le Prell *et al*.	2012	Noise-Induced Hearing Loss: Scientific Advances. Springer New York, New York, NY. ISBN: 978-1-4419-9522-3 (Hardcover), 978-1-4419-9523-0 (eBook).
Marsh & Schulkin	1962	Shallow-water transmission
Menzel *et al.*	2019	Mobilization of UXO, caused by hydrodynamics
Nedwell & Howell	2004	A review of offshore windfarm related underwater noise sources
Robinson *et al.*	2020	Underwater acoustic characterisation of unexploded ordnance disposal using deflagration
Salomons *et al*.	2021	Noise of underwater explosions in the North Sea. A comparison of experimental data and model predictions
Schulkin & Mercer	1985	Colossus Revisited: LD A review and extension of the Marsh-Schulkin shallow water transmission loss model (1962)
Siebert *et al.*	2022	Blast injury on harbour porpoises (*Phocoena phocoena*) from the Baltic Sea after explosions of deposits of World War II ammunition
Slifko	1967	Pressure-pulse characteristics of deep explosions as functions of depth and range
Soloway	2014	Noise from shallow underwater explosions
Soloway	2018	Environmental noise from underwater explosions and the impact of the seabed on the received levels
Soloway & Dahl	2015	Noise source level and propagation measurement of underwater detonation training at the silver strand training complex, Coronado CA
Turner & Scrimger	1970	On the depth variation in the energy spectra of underwater explosive charges
Viada *et al.*	2008	Review of potential impacts to sea turtles from underwater explosive removal of offshore structures
Wang *et al.*	2014	Investigation of the shock wave propagation characteristics and cavitation effects of underwater explosion near boundaries
Weston	1960	Underwater explosions as acoustic sources

Authors	Year	Title
Yelverton & Richmond	1981	Underwater explosion damage risk criteria for fish, birds, and mammals

Glossary

Term	Definitions
Blast impulse	The time integral of the overpressure exerted by a blast wave.
Blast wave	A shock front with an area of high pressure behind it, followed by a rarefied zone.
Blast	A supersonic longitudinal wave produced in the surrounding atmosphere by an explosion.
BML	Below the Mudline. Refers to explosives that are detonated beneath the seabed.
Charge	A bagged, wrapped or cased quantity of explosive without its own integral means of ignition.
Cumulative PTS	PTS resulting from the accumulated sound energy an animal receives across a 24-hour period, which can be expressed as single event or cumulative Sound Exposure Level or $L_{E,p}$..
Deflagration tool or charge	Small, shaped charge used to initiate low-order deflagration.
Deflagration	Deflagration is a method of low-order clearance. Reaction where materials decompose at a rate much below the sonic velocity of the material without any excess of atmospheric oxygen being required. It is propagated by the liberated heat of reaction. Hazards produced are fireball, thermal radiation and jets of flame.
Donor charge	Bulk charge placed to cause a sympathetic detonation.
Down well	An explosive detonation that occurs within a borehole. The explosive charge results in a shock wave that beaks or cracks the rock around the borehole. Used in borehole decommissioning activities.
HF	High frequency cetacean – marine mammal hearing group used in Southall *et al.* (2019) and NMFS (2024).
High order detonation	Detonation at a velocity approaching the maximum stable velocity of detonation for the system. when a high order explosion is initiated, a very rapid exothermic chemical reaction occurs. High order explosives have a strong supersonic pressure wave, known as the blast wave or shock wave.
Injury	Physical harm to a marine mammal, including hearing damage (e.g. Permanent Threshold Shift).
Instantaneous PTS	PTS received from a single noise pulse, commonly referred to as peak Sound Pressure Level (SPL).
$L_{E,p}$	The amount of acoustic energy accumulated over a specified period. Can be expressed as single pulse or cumulative (following multiple exposures to transient signals.
LF	Low frequency cetacean – marine mammal hearing group used in Southall *et al*. (2019) and NMFS (2024).

Term	Definitions
Low order detonation	A detonation in which the charge is completely consumed but the velocity of detonation is well below its maximum value, and therefore its effect is lessened.
$L_{p,0\text{-}pk}$	The maximum amplitude measured over the duration of a signal of interest. Also denoted as peak Sound Pressure Level.
$L_{p,rms}$	Average amplitude quantified over a pre-defined time window. Also denoted as root-mean-squared Sound Pressure Level.
Mass	The terms 'net explosive content' and 'net explosive quantity' are commonly used in the industry to refer to the weight of the explosive contained within an article (i.e. less packaging, casing, *etc*., but including explosives in fuses and propelling charges, *etc*.). Although these terms are commonly understood to refer to mass there is scope for different interpretations of 'content' and 'quantity' in that these could be taken to refer to volume. The term 'net mass' is used for the sole reason of avoiding any scope for confusion or misinterpretation.
"More complex" model	Computationally intensive software models which require spatial information (e.g. water depth) and other site- or signal-specific characteristics.
NEQ	Net Explosive Quantity. The weight of an explosive material, excluding any packaging, casing or other non-explosive components.
PCW	Phocid Carnivore in Water – marine mammal hearing group used in Southall *et al* (2019) and NMFS (2024).
Permanent hearing loss	Permanent hearing loss results when parts of the inner ear experiences irreversible damage, leading to a lasting decrease in sensitivity at affected frequencies.
PTS	Permanent Threshold Shift. Hearing loss is irreversible.
SEL	Sound Exposure Level (also detonated as $L_{E,p}$). The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound- pressure-squared level. $L_{E,p}$ is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
SEL_{cum}	Cumulative Sound Exposure Level (also detonated as $L_{E,p,t}$). Single value for the collected, combined total of sound exposure over a specified time or multiple instances of a noise source.
Shock front	A discontinuous change in the pressure propagating through a medium at supersonic speed.
Shock wave	A shock front, together with its associated phenomena (e.g. blast, elevated temperature).

Term	Definitions
“Simple” model	A user-friendly spreadsheet-type model which require a user to provide a single set of parameters.
Single pulse SEL, SEL_{ss}, SEL_{sp}	Single Pulse Sound Exposure Level. Calculation of the sound exposure level representative of a single noise impulse (e.g. a single explosion).
SPL	Sound Pressure Level (also detonated as L_p). The sound pressure level is an expression of sound pressure using the decibel (dB) scale; the standard frequency pressures of which are 1 µPa for water and 20 µPa for air.
SPL_{pk}	Peak Sound Pressure Level (also detonated as $L_{p,pk}$). The highest (zero-peak) positive or negative sound pressure, in decibels.
Temporary hearing loss	Temporary hearing loss occurs when exposure to loud sounds causes a reduction in hearing sensitivity, but the auditory system gradually recovers, returning to baseline levels after a period.
TNT	Trinitrotoluene (explosive material) 2,4,6-Trinitrotoluene.$CH_3C6H_2(NO_2)_3$
TTS	Temporary Threshold Shift. Hearing loss recovers over time.
UXO	Unexploded Ordnance. Explosive weapons (e.g. bombs, shells, mines), which did not detonate when deployed and still pose a risk of explosion.
Velocity of detonation	The speed at which the detonation wave progresses through an explosive. When it attains a value that it will continue without change, it is called the stable velocity of detonation.
VHF	Very High frequency cetacean – marine mammal hearing group used in Southall *et al* (2019) and NMFS (2024).
Water column	The expanse of water between the surface and floor of the water body.
GUI	Graphical User Interface.
EDGAR	Explosives use in Decommissioning – Guide for Assessment of Risk.
EFD	Energy flux density is defined as the transmitted shock wave energy at a specific location in the focal plane, determined by the temporal pressure of the shock wave and characterized by the integral of the pressure squared over time in relation to the acoustic impedance of the transmission medium.
TNT_{eq}	TNT-equivalence. Compares the energy released by an explosion to the energy released by a specific amount of TNT, usually 1 kg.
Integration time window	The length of time over which the pressure or other signals are determined.
PE	Plastic Explosive: A hand mouldable explosive which includes Semtex and C-4, used in demolition operations.

Term	Definitions
Pentolite	A mixture of roughly equal amounts of pentaerythritol tetranitrate (PETN) and trinitrotoluene (TNT).
RDX	Research Department Explosive", an explosive nitroamine.
Composition C-4 (Comp C-4)	Explosive compound: 91% RDX and a non-explosive plasticizer (9%).
Composition CH-6 (Comp CH-6)	Explosive compound: 97.5% RDX, 1.5% calcium stearate, 0.5% polyisobutylene, and 0.5% graphite.
Composition B (Comp B)	Explosive compound: 63% RDX, 36% TNT, 1% wax.

Abbreviations and acronyms

Term	Definitions
ADD	Acoustic deterrent device
ASCOBANS	Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas
BML	Below the mud line
BOEM	Bureau of Ocean Energy Management
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CCUS	Carbon capture, utilisation and storage
DAERA	Department of Agriculture, Environment and Rural Affairs
DCO	Development Consent Order
EIA	Environmental Impact Assessment
EPS	European Protected Species
EU	European Union
FWG	The German Federal Armed Forces Underwater Acoustics and Marine Geophysics Research Institute
GOM	Gulf of Mexico
GUI	Graphical user interface
HF	High frequency
HRA	Habitat Regulation Assessment
IAMMWG	Inter-Agency Marine Mammal Working Group
ICES	International Council of the Exploration of the Sea
ITT	Invitation to tender
JNCC	Joint Nature Conservation Committee
LF	Low frequency
LSC	Linear shaped charges
MD-LOT	Marine Directorate - Licensing Operations Team
MCAA	Marine and Coastal Access Act
MMO	Marine Management Organisation
MPA	Marine Protected Area
NAS	Noise abatement system
NEQ	Net explosive quantity
NMFS	National Marine Fisheries Service
NRW	Natural Resources Wales
OALIB	Ocean acoustics library
O&G	Oil and gas

Term	Definitions
OPRED	Offshore Petroleum Regulator for Environment & Decommissioning
OWF	Offshore wind farms
PAM	Passive acoustic monitoring
PBX	Polymer-bonded explosive
PCW	Phocid carnivore in water
PDE	Project design envelope
PSA	Particle size analysis
PTS	Permanent threshold shift
SAC	Special Area of Conservation
SCOS	Special Committee on Seals
SEL	Sound exposure level
SEPA	Scottish Environment Protection Agency
SMRU	Sea Mammal Research Unit
SNCB	Statutory Nature Conservation Body
SPL	Sound pressure level
TAP	Technical Assessment Project
UWC	Under Water Calculator
RDX	Royal demolition explosive
ROV	Remote operating vehicle
TAP	Technical Assessment Project
TNT (eq.)	Trinitrotoluene (equivalent)
TTS	Temporary threshold shift
UK	United Kingdom
UWC	Under water calculator
UXO	Unexploded ordnance
VHF	Very high frequency
WCS	Worst-case scenario
WFD	Water Framework Directive
ZoI	Zone of influence

Appendix 1: 'Simple' sound propagation models

Less sophisticated sound propagation models have been built on the work of Cole (1948) who suggested Power law relationships. Also known as Similitude Equations, these relationships involve explosive charge weight, distance from the source of the explosion and various shock wave characteristics. These characteristics vary with the type and shape of explosive, the type of explosion (open water or Below Mud Line (BML)/ confined), the environmental conditions, and the length of time and distance over which the characteristics are determined.

A1.1 Similitude equation-based models for open water explosions

In the very near-field, the shock pulse pressure of an explosion, given as a function of time $p(t)$, in Pa, consists of a near-instantaneous increase in pressure followed by an exponential decay (Cole 1948):

$$p(t) = p_0\, exp(-t/t_0)$$

where p_0 is the peak pressure (Pa) associated with the shock front and t_0 is a time constant for exponential decay (s). peak pressure and time constant in terms of the charge weight and range from the detonation position.

Shock waves from high explosives have certain characteristics, peak pressure, $p_0(r)$ (Pa), time constant, $t_0(r)$ (often given as θ) (s), impulse, I (Pa s) and energy flux density, J (Pa m). Near an underwater detonation, the 'near-field', explosion shock theory has proposed that specific relationships for these parameters can be modelled by the following similitude/ power law equations (Arons 1954; Cole 1948):

$$p_0(r) = K_p\left(\frac{W^{\frac{1}{3}}}{r}\right)^{\alpha_p},\ t_0(r) = K_t W^{\frac{1}{3}}\left(\frac{W^{\frac{1}{3}}}{r}\right)^{\alpha_t},\ I = K_i W^{\frac{1}{3}}\left(\frac{W^{\frac{1}{3}}}{r}\right)^{\alpha_i},\ J = K_j W^{\frac{1}{3}}\left(\frac{W^{\frac{1}{3}}}{r}\right)^{\alpha_j}$$

where W is the explosive charge weight in kilograms (kg), r is the measurement distance "slant range" in metres (m) (Figure A1.1), α is an empirical exponent and K is an empirical coefficient. All parameters and variables for the relationships given in the Appendix are summarised in Table A1.3. Note that traditionally "weight" has been used to describe the amount of explosive charge, technically the quantity is its mass in kg, as weight is measured in Newtons (N).

The empirical coefficients (K) and exponents (α) vary with the characteristic being determined, type and shape of explosive, type of explosion (open water or Below Mud Line (BML)/ confined) and the environmental conditions.

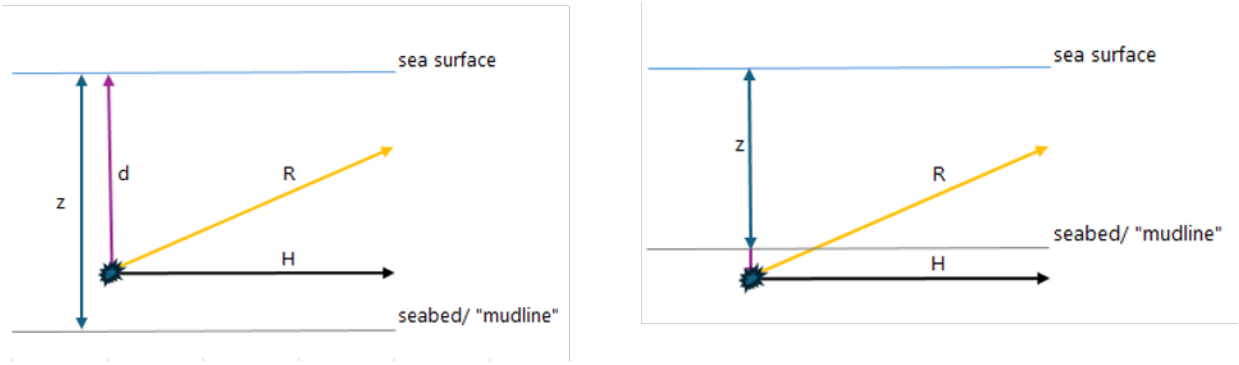


Figure A1.1. Geometry for underwater noise models distances showing water depth z (m), charge depth d (m), and the difference between the slant range R (m) and horizontal range H (m).

A1.1.1 Type of explosive

Following experimental work using spherical charges of TNT and pentolite with loading densities of 1.52 and 1.60 kg m^{-3}, respectively, Cole (1948) proposed values for K and α. Table A1.1. Table A1.1 summarises for K and α reported by Cole and other authors.

Cole (1948) noted that departures from a spherical charge shape and differences in explosive loading density resulted in changes to the shock wave parameters. He also noted that the relationships were valid for an integration time window of $6.7t_0(r)$ (Cole 1948). Swisdak (1978) stated a validity range of 3.4 to 138 MPa for TNT and pentolite.

Arons (1954) reported on experimental observations which extended the previous range of validity for spherical charges of TNT and pentolite of $r \cong 23W^{\frac{1}{3}}$ to $r \cong 1537W^{\frac{1}{3}}$, where r is range in m and W is charge weight in kg.

Table A1.1. Examples of the variability in the parameters of shock wave similitude curves for spherical explosive charges of different explsive types. Sources: [a]Cole (1948); [b]Swisdak (1978); [c]Reid (1996); [d]Slifko (1967); [e]Silfko and Farley (1959) as given in Bjørnø and Levin (1976); [f]Arons (1954); [g]Chapman (1985).

Explosive type	$p_0(r)$ (Pa)		$t_0(r)/W^{\frac{1}{3}}$ (s kg$^{-1/3}$)		$I/W^{\frac{1}{3}}$ (Pa s kg$^{-1/3}$)		$J/W^{\frac{1}{3}}$ (Pa m kg$^{-1/3}$)	
	10^7K_p	α_p	$10^{-5}K_t$	α_t	10^3K_i	α_i	10^4K_j	α_j
TNT	5.24[a, b, f] 5.212[c] 5.04[d] 4.94[e]	1.13[a, b, d, f] 1.18[c] 1.1[e]	8.4[b] 9.2[c] 9.25[f] 8.12[g]	-0.23[b] -0.185[c] -0.22[f] -0.14[g]	5.75[a, b] 6.52[c]	0.89[a, b] 0.98[c]	8.46[a] 8.44[b] 9.434[c]	2.05[a] 2.04[b] 2.155[c]
Pentolite	5.46[a] 5.65[b] 5.621[c]	1.13[a] 1.14[b] 1.194[c]	8.4[b] 8.6[c] 9.25[f]	-0.23[b] -0.257[c] -0.22[f]	7.41[a] 5.73[b] 6.518[c] 6.70[f]	1.05[a] 0.91[b] 0.903[c] 0.94[f]	10.50[a] 9.20[b] 10.311[c] 9.76[f]	2.12[a] 2.04[b] 2.094[c] 2.08[f]

A1.1.2 TNT equivalency

The peak pressure for other forms of explosives can be predicted through use of explosive dependent coefficients, such as 1.34 for Composition C-4 and 1.50 for Composition CH-6 explosives, that are used to scale W to give a TNT-equivalent weight (Soloway & Dahl 2014). However, TNT-equivalence (TNT eq.) is a minefield as different values have been quoted in the literature for the same explosive. This is because TNT-equivalence depends on several variables, including density, heat of detonation, detonation velocity and detonation pressure of explosives. For example, values for the TNT eq. for Comp B range from 1.09 (Dobratz 1981) to greater than 1.3, depending on the method of calculation and the values used (Locking 2022).

A1.1.3 Charge shape

When an explosive charge is fired, the nature and mass of the explosive are the only parameters of importance usually considered. The shape, however, also plays a major role in the explosive effect of an explosive charge. Heathcote (n.d.) used charges packed into wellhead casings in the Technical Assessment Project (TAP) TAP-025 project and noted that a charge shape effect was introduced by the length to diameter ratio of the charge deviating from a nominal ratio of 1.0. This together with the dispersion of measurement gauges away from a common charge-gauge plane precluded the establishment of valid similitude equations for the explosives. However, the shape effect is only significant within a certain range from the charge. At longer distances, the produced blast wave tends to be spherical.

A1.1.4 Integration time window

There is no accepted standard for the definition of the integration time window (i.e. the length of time over which the pressure or other signals are determined). The integration period should be determined by the purpose and intent of the explosive event (Dzwilewski & Fenton 2003). The multiplier on the time constant is a matter of choice based on the explosive event geometry.

The integration interval is usually some multiplier or integration factor of $t_0(r)$, typically 5, (Barkaszi 2016; Swisdak 1978), or 6.7 (Poe *et al.* 2009; Cole 1948). The time window was extended to the time at which surface cut-off occurred for TAP-118 (Exxon West Delta Platform (WD30); Connor, 1990), and energy time integrals were taken to 1 ms for TAP-025 (Heathcote, n.d.) and 50 ms (Blackstock *et al.* 2018).

Bebb (1951) conducted trials with small (< 1 kg) cylindrical TNT and spherical plastic explosive (PE) charges. He reported a lower K_p of 41.14 x 10^6 with an α_p of 1.1 for the cylindrical TNT charges. He also noted that large pressures encountered with underwater shockwaves do not vary inversely with distance as do small-amplitude sound waves, and this becomes noticeable at ranges closer than about 13 charge radii where the pressure varies inversely as distance to the power of approximately 1.5. Consequently, he suggested two peak pressure, $p_0(r)$ (Pa) relationships, for the spherical PE charges with:

$$p_0(r) = \begin{cases} 4.041 \times 10^7 \left(\dfrac{W^{\frac{1}{3}}}{r} \right)^{1.45}, & \dfrac{r}{r_0} \lesssim 13 \\ 4.619 \times 10^7 \left(\dfrac{W^{\frac{1}{3}}}{r} \right)^{1.15}, & \dfrac{r}{r_0} \gtrsim 13 \end{cases}$$

where r is range in m, r_0 is the charge radius in m, and W is charge weight in kg.

A1.1.5 Range dependence

Liu *et al.* (2019; 2018) revisited Cole's (1948) TNT experimental data and suggested that peak pressure, $p_0(r)$ (Pa), is range dependent.

$$p_0(r) = \begin{cases} 4.41 \times 10^7 \left(\frac{W^{\frac{1}{3}}}{r}\right)^{1.5}, & 6 \leq \frac{r}{r_0} \leq 12 \\ 5.227 \times 10^7 \left(\frac{W^{\frac{1}{3}}}{r}\right)^{1.13}, & 12 \leq \frac{r}{r_0} \leq 240 \end{cases}$$

where r is range in m, r_0 is the charge radius in m, and W is charge weight in kg.

The similitude equations for peak pressure and the time constant have been generally found to be valid in the near field (Gaspin 1983), up to a limit of:

$$r_0 = 4.76W^{1/3} \text{ m.}$$

Beyond this limit, the theory of weak shock propagation is appropriate. Rogers (1977) proposed the following modifiers for the peak pressure and time constant:

$$p_0(r) = p_0(r_0)\left\{\left[\left(1 + 2\frac{r_0}{L_0} ln\left(\frac{r}{r_0}\right)\right)^{0.5} - 1\right] \Big/ \left(\frac{r}{L_0} ln\left(\frac{r}{r_0}\right)\right)\right\}$$

$$t_0(r) = t_0(r_0)\left(1 + 2\frac{r_0}{L_0} ln\left(\frac{r}{r_0}\right)\right)^{0.5}$$

where the characteristic distance, L_0, (m) is:

$$L_0 = \frac{\rho_w {c_w}^3 t_0(r_0)}{p_0(r_0)\beta}$$

ρ_w is the density of seawater (kg m^{-3}), c_w is the speed of sound in seawater (m s^{-1}), a dimensionless acoustic nonlinearity parameter for water, β = 3.5, and $p_0(r_0)$ (Pa) and $t_0(r_0)$ (s) are computed from the appropriate near-field similitude equations.

As the shockwave propagates, its peak pressure declines, and its exponential decay becomes more gradual.

A1.2 EDGAR SPL model

Whilst the similitude relationships discussed in Section A1.1 can provide excellent fits to data, a simple, user friendly and transparent model for the determination of SPLs resulting from explosive blasts, which requires minimal user inputs, was needed. It is important to note that no model is 100% accurate, especially when applied to a scenario that it was not built for. EDGAR was designed as a one stop ballpark determination tool that has its roots in the similitude equations but avoids the confusion of which coefficients, (e.g. K, α, and TNT eq.) to choose (Brand 2021a). Figure A1.2 illustrates the EDGAR model concept.

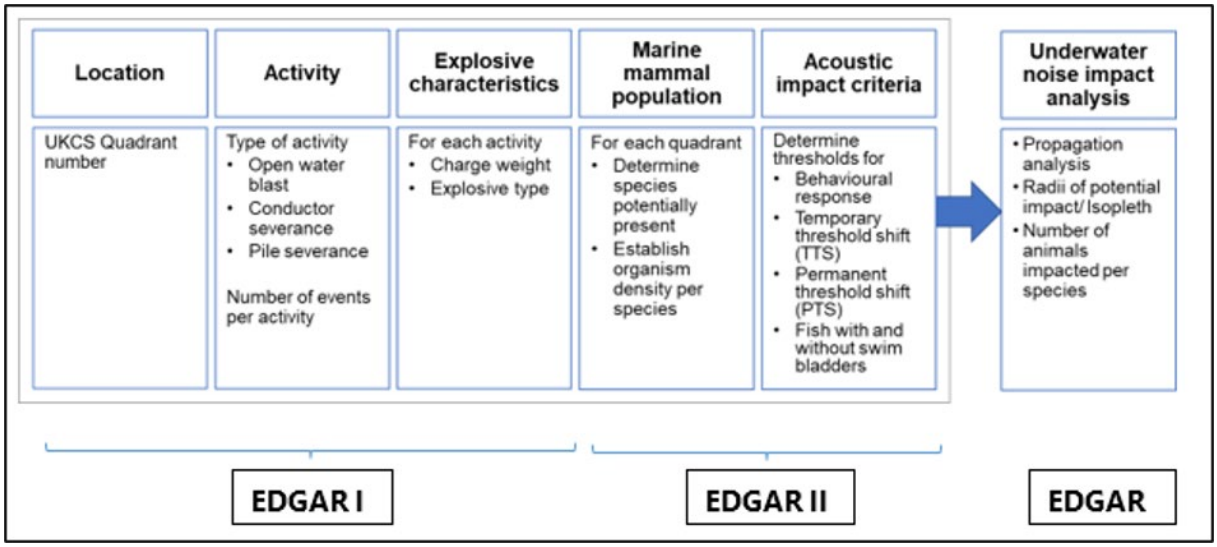


Figure A1.2. EDGAR Model concept diagram illustrating inputs for EDGAR Part I (EDGAR 1; SPL) and EDGAR II (SEL) and EDGAR outputs for underwater noise impact analysis.

A1.3.1 Determination of SPL

The EDGAR underwater noise model for SPL, $L_{p,pk}$, determination originated from an initial study which compared the results of underwater sound propagation using the several similitude models including ARA v1 (Dzwilewski & Fenton 2003) and Connor (1990).

Power relationships were fitted to plots of the SPL zero-peak, $L_{p,pk}$, against slant range (m) for a notional 1kg TNT charge for simulations using Connor (1990) and ARA. It was observed that the power relationships were of the form:

$$L_{p,pk} \approx L_s r^{-m_x/10^3}$$

where L_s is the source level (in dB re 1 µPa m), r is the impact radius (m) and m_x is a dimensionless gradient factor.

To optimise the model an adjustment was made to the source level to minimise divergence from the other models when r > 50m. In its final form the EDGAR model for $L_{p,pk}$ is given by:

$$L_{p,pk} = \left(\frac{L_s + A_{ED} W^{b_{ED}/3}}{r^{m_x/10^3}}\right) \qquad m_x = 44, \text{ for open water}$$

The adjustment is given by $A_{ED} W^{b_{ED}/3}$ for open water blasts, where W is the charge weight in kg, and A_{ED}= 4.8256 and b_{ED}= 0.1969 are constants.

Note that the slant range is used in EDGAR for the impact radius, rather than the radial range, as it is a more conservative measure. The slant range from the charge to the gauge is equivalent to the length of the hypotenuse of the triangle formed by the horizontal distance between the charge and each gauge line, and the vertical distance between the charge depth below the mudline and the height of each gauge above the mudline.

Additionally, the only inputs required for estimation of the $L_{p,pk}$ by EDGAR are the type of operation and the weight of explosive charge (unadjusted for TNT-equivalence).

A1.3.2 Source level determination for explosives

The value of the source level can be the sound pressure that would exist at a nominal range of 1 m from the acoustic centre of an equivalent monopole source (Robinson *et al.* 2014).

For a chemical charge, the source level (L_s, zero-to-peak (peak) in dB re 1 µPa m) of the initial shock wave for a large component of the energy is given by:

$$L_s = 269 + 7.533\ log_{10}(0.4536W_{TNTeq})$$

where W_{TNTeq} is the TNT eq. charge weight in kg (Ulrick, 1983).

The energy resulting from the bubble pulses will act cumulatively with the energy from the initial shock wave contributing ~5 dB to the source level (Hildebrand 2009; 2005), giving:

$$L_s = 269 + 5 + 7.533\ log_{10}(0.4536W_{TNTeq})$$

and there will be an almost constant frequency content between 10 and 200 Hz. The sounds from an explosion propagate equally in all directions.

A1.3 Confined below mudline severance models

Underwater noise models for the severance of oil and gas structures BML/ in a confined space (i.e. within well conductors or to cut piles were developed based on decommissioning projects in the Gulf of Mexico (GOM)) (Table A1.2).

Table A1.2. Gulf of Mexico decommissioning projects using explosive severance. Adapted from Brand (2021a).

Project Number	Project Title
TAP-025	Overpressures Developed by Shaped Explosive Charges Used to Remove Wellheads (Heathcote, n.d.)
TAP-118	Blast Effects Upon the Environment from the Removal of Platform Legs by Explosives (Connor 1990)
TAP-429	Oil Platform Removal Using Engineered Charges: In Situ Comparison of Engineered and Bulk Explosive Charges (Saint-Arnaud *et al*. 2004)
TAP-570	Measurement of the Effect of Depth Below Mudline of Charge Placement During EROs (Poe *et al.* 2009)
OCS Study MMS 2003-059	Shock Wave/Sound Propagation Modeling Results for Calculating Marine Protected Species Impact Zones During Explosive Removal of Offshore Structures (Dzwilewski & Fenton 2003)
OCS Study MMS 2003-013	Structure-Removal Operations on the Gulf of Mexico Outer Continental Shelf (U.S. Dept. of the Interior. Minerals Management Service 2005)
OCS Study BOEM 2016-019	Pressure Wave and Acoustic Properties Generated by the Explosive Removal of Offshore Structures in the Gulf of Mexico (Barkaszi *et al.* 2016)

The EDGAR severance BML/ confined space model evolved from the GOM work with an aim to simplify calculations by avoiding confusion of which coefficients to choose for the similitude equations (Brand 2021a, b).

A1.3.1 Connor model

The TAP-118 project investigated the underwater shocks produced during the explosive removal of a hydrocarbon production platform from the Gulf of Mexico. Two types of tubular members were explosively severed below the mudline, jacket leg and skirt piles, and well conductors (terminating above and below the sea surface). The bottom penetrating piles were roughly equivalent to one another in their shock attenuating capabilities. All piles consisted of a 0.762 m diameter steel pipe with a wall thickness of 0.0254 m. The well conductors were 0.508 m diameter pipes containing a 0.2794 m pipe with cement grout in the annuli between the two casings.

Results were compared with those from an earlier project in the Potomac River in Virginia which investigated free water explosions and severance of buried half scale well casings (TAP-025: Heathcote, n.d.). The resulting parameters are presented in Table A1.3.

Table A1.3. Parameters of the shock wave similitude curves for TAP-118 project including free water and below mudline severance detonations. Source: Connor (1990); *Goertner (1981).

Detonation type	Explosive type	Explosive shape	$p_0(r)$ (Pa)		$I/W^{\frac{1}{3}}$ (Pa s kg$^{-1/3}$)		$J/W^{\frac{1}{3}}$ (Pa m kg$^{-1/3}$)	
			$10^7 K_p$	α_p	$10^3 K_i$	α_i	$10^4 K_j$	α_j
Free water*	Pentolite	spherical (assumed)	6.059	1.22	5.56	0.919	9.38	2.13
Half scale well casings*	Comp C-4	cylindrical	2.12	1.21	2.74	1.06	1.67	2.2
Conductors (air terminated)	Comp B	cylindrical	6.390	1.807	58.47	1.89	51.44	3.40
Conductors (water terminated)	Comp B	cylindrical	8.696	1.910	2.14	0.682	4.61	2.48
Piles (main jacket)	Comp B	octagonal	8.700	1.930	26.32	1.79	15.01	3.13
Piles (skirt)	Comp B	octagonal	7.636	2.000	85.75	2.23	64.71	3.82

No significant difference was noted between pressure pulses observed near piles when confined charges were detonated at different depths (approximately 2.44 m, 4.88 m and 7.93 m BML) (Connor 1990).

It should be noted that environmental conditions will not have been the same at the two locations.

A1.3.2 Model assumptions

As in TAP-118, the effects of seabed sediments were ignored because the first 1 to 2 m of seabed sediments in many parts of the ocean has a porosity of 60 - 80% (Connor 1990).

The particle diameters of silty material and fine sand range from 1/16 to 1/256 mm, and 1/4 to 1/8 mm, respectively. Thus, the shock from a severance detonation propagates through a largely water-like material, and the effect of the small solid particles was assumed negligible.

The procedure for measuring the sound generated from the use of explosives in TAP-118 (Connor 1990) involved several unavoidable assumptions. These include:

Charge-to-gauge slant ranges are indefinite for the following reasons:

- Charge depths below the mud were uncertain (± 45 cm)
- Surface float line curvature was estimated
- Gauges were assumed to hang vertically, directly below their respective surface floats, which ignores the effects of subsurface currents
- Gauge line-to-platform attachment points were chosen arbitrarily; and their exact locations were unknown for all shots
- Tie line length to the first gauge line was uncertain (± 1 m).

As a result of these ambiguities, the magnitude of the uncertainty in the charge-to-gauge slant ranges was estimated to be a minimum of 1.5 m.

Similar issues affected all Gulf of Mexico (GOM) projects.

A1.3.3 ARA underwater calculator (UWC)

The US Bureau of Safety and Environmental Enforcement commissioned a tool based on a model to predict the effects of underwater explosions used for the removal of oil and gas structures. The ARA UnderWater Calculator (UWC) - Versions 1 (Dzwilewski & Fenton 2003) and 2 (Dzwilewski 2014) are spreadsheet-based tools that calculate peak pressure, impulse, and energy of underwater sound, caused using explosives to remove offshore structures.

The UWCv1 is based on near-field energy coupling from the physics of shock wave propagation and the dampening effects of structural properties. Those near-field predictions of UW sound propagation are also used in the far field. The numerical simulations undertaken showed that less energy (30% to 70% reduction) is coupled to the water for the pile cases than would be coupled for open water explosions. Field data has indicated higher attenuation of peak pressure with range and an energy reduction of 90% or more when compared to open-water data.

Conversely, the UWCv2 is scenario dependent (Dzwilewski 2014), being based solely on curve-fits applied to data from each of the TAP-570 (Poe *et al.* 2009) and TAP-118 (Connor 1990) projects. These curve-fit data are used for both the near-field and far-field calculations. The outputs from UWCv2 will thus be driven specifically by the physical parameters of those individual project data sets and, therefore, may not be as universally applicable to all situations.

The inputs to UWCv2 have been simplified compared to the inputs required for UWCv1. Specifically, UWCv1 requires the user to input pile diameter and thickness, while the UWCv2 requires the user to select a scenario, such as “main pile Connor” or “well conductor TAP-570”. These scenarios represent the type of structure being removed as well as the source of the measurement data (Connor or TAP-570).

Both forward and backward calculation spreadsheets are provided for UWC Version 2.0. The forward calculation provides the peak pressure, impulse and energy flux for a given slant range, explosive weight, and open-water or pile scenario. Conversely, the backward calculation provides the slant range for the old US Level B harassment pressure and Energy Flux Density thresholds for the different open-water and pile scenarios. The pile scenarios include main piles, well conductors, open caissons, and skirt piles.

Field data from the US Bureau of Ocean Energy Management (BOEM) 2016 study (Barkaszi *et al.* 2016) were compared with UWC predictions Measured peak pressures were consistently lower than those predicted by UWCv1, but were variable compared to UWCv2; closer distances were overpredicted and farther distances were under predicted. UWCv1 provided a consistently more conservative and accurate prediction of measured values important in impact evaluation.

The BOEM 2016 study was conducted in deeper water and used larger charge sizes than either of the TAP projects which suggested that the effects of the differing parameter combinations are not fully incorporated into the UWCv2. Further, the sediment type and characteristics were different at the BOEM 2016 location compared to the TAP-118 and TAP-570 study sites. Propagation of acoustic waves through a porous seabed depends on the type, distribution, density, and stress state of the sediments.

The field measurements from the BOEM 2016 study and their predicted calculations using UWCv1 and UWCv2 show that UWCv1 provides a more accurate and conservative prediction of impact criteria.

The UWC was the subject of peer review in 2016 by NMFS (Ainslie 2016; Dahl 2016; Ketten 2016). At the time of writing (January 2025) the UWCv1 and UWCv2 spreadsheets were not available online.

A1.3.4 EDGAR confined severance model

Derivation of sound pressure and SPL are now in A1.3.1., and source level is in A1.3.2. and Brand (2021b). In its final form the EDGAR model for $L_{p,pk}$ is given by:

$$L_{p,pk} = \left(\frac{L_s + A_{ED} W^{b_{ED}}}{r^{m_x/10^3}} \right) \; m_x = 64, \;\; \text{for conductor or pile}$$

where L_s is the source level (zero-peak in dB re 1 µPa m), r is the impact radius (m) and m_x is a dimensionless gradient factor. Far-field adjustment is given by $A_{ED} W^{b_{ED}}$ for pile and conductor severance, where A_{ED}= 4.8256, b_{ED}= 0.1969 and W is the charge weight in kg.

SPL values were overestimated by the ARA model (Figure A1.3). Connor's model gave reasonable estimates over short distances but underestimated the SPL as distance increased (Figure A1.3).

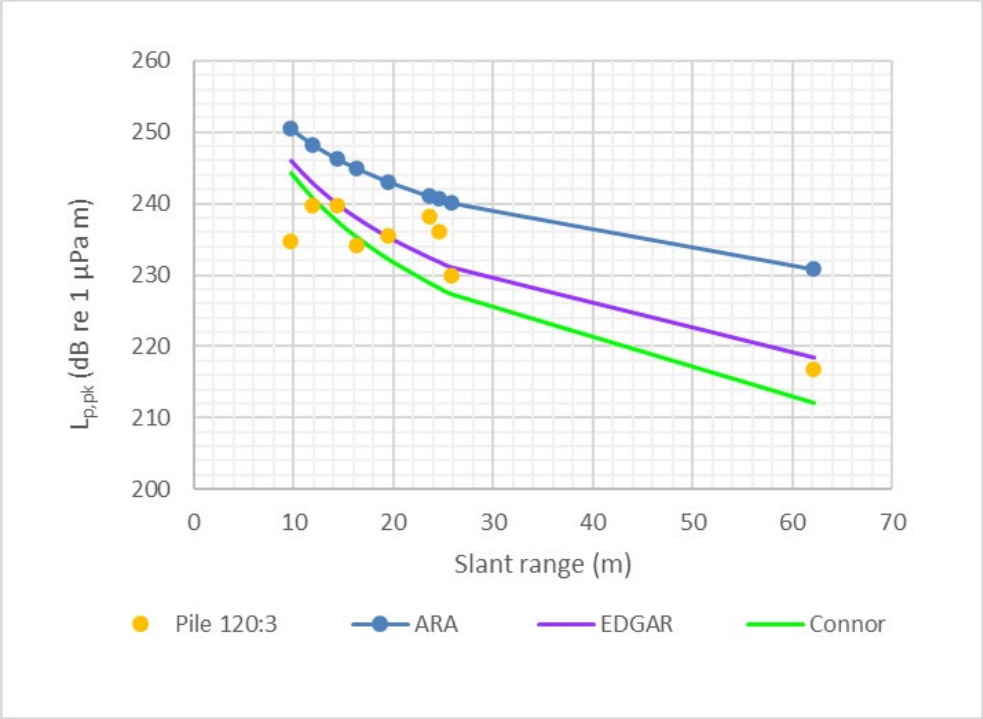


Figure A1.3. Comparison of simulated and measured sound pressure levels (peak) against slant range for explosive severance of Huber 120 pile 3 using a 4.6 lb RDX engineered charge (TAP-429: Saint-Arnaud *et al.* 2004). Models used include: ARAv1 (Dzwilewski & Fenton 2003), Connor (1990) and EDGAR (Brand 2021a, 2021b)

Appendix 2 'Simple' sound exposure models

Exposure to brief, high pressure, transient sounds (impulsive sounds, such as explosions, airgun shots or pile strikes) can be more damaging to marine life than exposure to continuous sound at lower pressures (Hastie *et al.* 2019). The hearing threshold rises faster when exposed to impulsive sound than to non-impulsive sound (such as from drilling and shipping). Consequently, the sound energy required to induce TTS or PTS is lower (Hastie *et al.* 2019).

SELs can be determined for single (shot) or multiple explosions (cumulative).

An "equal energy" approach is adopted where the cumulative SEL is used as a simplifying assumption to accommodate sounds of various SPLs, durations, and duty cycles (NMFS 2018). SEL is related to the energy of the sound, and this approach assumes exposures with equal SEL result in equal effects, regardless of the duration or duty cycle of the sound.

Two SEL models, EDGAR (Brand 2021b) and Soloway and Dahl (2014) with appropriate coefficients for both open water and BML/ confined scenarios are described.

A2.1 Determination of SEL

The SEL is defined as the level of continuous sound with 1 s duration and the same sound energy as the impulse. SEL is sometimes taken as a proxy for the energy level or EFD, $J(t)$, of a sound wave and is useful as a measure of the exposure of a receptor to a sound field (Robinson *et al.* 2014), EFD, $J(t)$ is given as

$$J(t) = {\rho_w}^{-1}{c_w}^{-1}\int_0^T p^2(t)\,dt$$

where ρ_w is the density of seawater (1,027kg m^{-3}), c_w is the speed of sound in seawater (1,500m s^{-1}), T is the time window of integration which represents the exposure duration (s) and $p(t)$ is the sound pressure (Pa).

The EFD is often expressed in decibels (dB) referenced to 1 μPa^2 s, ${p_{ref}}^2(t)$, which equates to SEL, L_E,

$$L_E = 10\ \log_{10}\left(\frac{\rho_w c_w E_f(t)}{{p_{ref}}^2(t)}\right) = 10\ \log_{10}\left(\int_0^T \frac{p^2(t)}{{p_{ref}}^2(t)}dt\right)$$

There is no accepted standard for the definition of the integration time window, ($T = \tau\theta$ in s), despite it being a critical entity in these calculations: different SPL (and SEL) results may be obtained from the same time domain pressure signal according to the size of the time window (Sertlek *et al.* 2012; Madsen 2005). To ensure that all the energy was accounted for Blackstock *et al*. (2018) used a time window of 50 ms. Integration techniques varied across all GOM projects. The BOEM 2016 project energy values were calculated by summing the area under the pressure-time curve for 5 time constants (Barkaszi *et al.* 2016). TAP-570 used an integration factor, τ, of 6.7 (Poe *et al.* 2009), the window was extended to the time at which surface cut-off occurred for TAP-118 (Connor 1990) and energy time integrals for TAP-025 were taken to 1ms (Heathcote, n.d.)

The SEL for a single shot, L_E, ss (dB re 1 µPa^2 s), indicative for sound (SPL) received at one location, over a specific time duration, T (s), is defined as:

$$L_E, ss = SPL + 10log_{10}(T) = 10log_{10}\left(\frac{p_{\mathrm{pk}}}{p_{ref}}\right) + 10log_{10}\left(\frac{T}{t_{ref}}\right)$$

where p_{pk} is the peak sound pressure (Pa), p_{ref} is the reference pressure in water of 1µPa and $t_{ref}$is the reference time of 1s.

For other impulsive sound sources, the time window metric is often normalised to a single sound exposure of 1s. However, the NOAA guidelines (NMFS 2018) intend that the weighted cumulative SEL, $L_{E,24h}$ metric (in dB re 1 µPa^2 s) should account for the accumulated exposure, that is, the weighted SEL cumulative exposure over the duration of the operation within a 24h period.

$L_{E,24h}$ considers both the received level and the duration of exposure, as both factors contribute to noise induced hearing loss, and

$$L_{E,24h} = L_{p,pk} + 10log_{10}(N\tau\theta)$$

or

$$L_{E,24h} = L_E, ss + 10log_{10}(N)$$

where N is the number of events in a 24h period, τ is the time integration factor and θ is the decay constant (s).

NOAA recommend that the weighted $L_{E,24h}$ metric should only be applied to predict impacts for a single source/ operation in a discrete spatiotemporal scale (NMFS 2018).

A2.2 Marine mammal auditory weighting functions

Auditory weighting functions quantify the ability of animals to receive sounds by emphasizing noise at the frequencies in which species are more sensitive based on the spectral characteristics of the sound. For each defined marine mammal hearing group, different auditory weighted functions have been generated (NMFS 2018). The weighting functions are used to predict when the onset of PTS may occur for marine mammals by comparing the weighted exposure level to the weighted thresholds for PTS.

A2.3 EDGAR SEL model

The cumulative weighted SEL, $L_{E,24h,wt}$, including the auditory weighting function amplitude $W_{aud}(f)$ is given as follows:

$$L_{E,24h,wt} = L_{p,pk} + 10log_{10}(N\tau\theta) = \frac{L_s + W_{aud}(f) + A_{ED}W^{b_{ED}}}{r^{m_x/10^3}} + 10log_{10}(N\tau\theta)$$

where $L_{p,pk}$ is the peak SPL as determined using EDGAR, N is the number of events in a 24 h period, τ is an integration factor, θ is the time constant (s), L_s is the source level (zero-peak in dB re 1 µPa m), r is the impact radius (m) and m_x is a dimensionless gradient factor equal to 64 for confined/ severance BML blasts. Far-field adjustment is given by $A_{ED}W^{b_{ED}}$ for pile and conductor severance, where A_{ED} = 4.8256, b_{ED} = 0.1969 and W is the charge weight in kg.

The EDGAR simulations for the open water blasts indicated a consistent overestimate (bias) of 12.31 dB re 1 μPa^2 (Brand, 2021b) and hence a correction was made to the cumulative weighted SEL, $L_{E,24h,wt}$, open water model to account for this:

$$L_{E,24h,wt} = \frac{L_s + W_{aud}(f) + A_{ED}W^{b_{ED}/3}}{r^{m_x/10^3}} + 10log_{10}(N\tau\theta) - 12.31$$

where L_s is the source level (zero-peak in dB re 1 μPa m), N is the number of events in a 24 h period, τ is an integration factor, θ is the time constant (s), r is the impact radius (m) and m_x is a dimensionless gradient factor equal to 44 for open water blasts. The far-field adjustment is given by $A_{ED}W^{b_{ED}/3}$ for pile and conductor severance, where A_{ED} = 4.8256, b_{ED} = 0.1969 and W is the charge weight in kg.

A2.4 Soloway and Dhal SEL model

Soloway and Dahl (2014) presented an equation for SEL, L_E (dB re 1μPa^{2}s) based on measurements from detonations in shallow water (< 15 m) and ranges out to 950 m for charge sizes up to 4.5 kg:

$$L_E = 219 + 6.14log\left[W^{1/3}\left(\frac{W^{1/3}}{r}\right)^{2.12}\right]$$

where W is the explosive weight in kg, and r is the measurement range in m. The coefficient 6.14 reflects the influence of a bounded underwater waveguide (i.e. where there is a degree of confinement in the water column due to proximity of the charge to the seabed).

For an unbounded medium (Open Water detonation) the suggested value of the coefficient was 10.

$$L_E = 219 + 10log\left[W^{1/3}\left(\frac{W^{1/3}}{r}\right)^{2.12}\right]$$

where *W* is the explosive weight in kg, and *r* is the measurement distance in m.

Appendix 3 Parameters used in models

Table A3.1. Parameters and variables used in underwater noise models.

Symbol	Term	Unit
p_{pk} or $p_0(r)$	Peak pressure	Pa
$t_0(r)$ or θ	Time constant for exponential decay	s
I	Impulse	Pa s
J	Energy Flux Density (EFD)	Pa m or dB re 1 μPa^2 s
W	Mass of explosive charge	kg
r	Measurement distance “slant range”	m
$r/W^{\frac{1}{3}}$	Reduced range	m kg$^{-⅓}$
$t_0(r)/W^{\frac{1}{3}}$	Reduced time constant	s kg$^{-⅓}$
$I/W^{\frac{1}{3}}$	Reduced impulse	Pa s kg$^{-⅓}$
$J/W^{\frac{1}{3}}$	Reduced energy	Pa m kg$^{-⅓}$
K_p	Empirical coefficient for pressure	Pa (m kg$^{-⅓}$)$^{\alpha p}$
K_t	Empirical coefficient for time constant	s kg$^{-⅓}$ (m kg$^{-⅓}$)$^{\alpha\theta}$
K_i	Empirical coefficient for impulse	Pa s kg$^{-⅓}$ (m kg$^{-⅓}$)$^{\alpha I}$
K_j	Empirical coefficient for energy flux density	Pa m kg$^{-⅓}$ (m kg$^{-⅓}$)$^{\alpha E}$
α_p	Empirical exponent for pressure	-
α_t	Empirical exponent for time constant	-
α_i	Empirical exponent for impulse	-
α_j	Empirical exponent for energy flux density	-
ρ	Density of the medium	kg m^{-3}
c	Speed of sound in the medium	m s^{-1}
β	Attenuation coefficient (a dimensionless acoustic nonlinearity parameter for water)	dB λ^{-1}
L_s	zero-to-peak (peak) source level of the explosive charge	dB re 1 μPa m
$L_{p,pk}$	zero-to-peak (peak) sound pressure level	dB re 1 μPa m
r_0	charge radius	m
L_0	characteristic distance	m
ρ_w	Density of seawater	kg m^{-3}
c_w	speed of sound in seawater	m s^{-1}

Symbol	Term	Unit
m	dimensionless gradient factor	-
A_{ED}	Constant (4.8256 in EDGAR)	-
b_{ED}	Constant (0.1969 in EDGAR)	-
W_{TNTeq}	TNT equivalent charge weight	kg

Appendix 4 Key literature sources for marine mammal and fish populations

Table A4.1. Key literature sources for marine mammal distribution at the time of writing.

Abundance

Source	Summary
Scientific Advice on Matters Related to the Management of Seal Populations (SCOS)	The Special Committee on Seals (SCOS) produce annual reports, which outline abundance estimates and Potential Biological Removal for seals (both grey and harbour seals) across the UK.
Updated abundance estimates for cetacean Management Units in UK waters (Inter- Agency Marine Mammal Working Group (IAMMWG 2023)	The IAMMWG defined management units for the seven most common cetacean species found in UK waters. Abundance estimates were calculated for each species within their respective management units.
Small Cetaceans in the European Atlantic and North Sea (SCANS-IV): Estimates of cetacean abundance in European Atlantic waters in summer 2022 from the SCANS-IV aerial and shipboard surveys (Gilles *et al.* 2023)	Abundance estimates for cetacean species in the European Atlantic and North Seas.
Regional Baselines for Marine Mammal Knowledge Across the North Sea and Atlantic Areas of Scottish Waters (Hague *et al.* 2020)	A review of data sources which presents all known abundance and distribution estimates for each species within Scottish waters.
Integration of multiple data sources to assess the distribution and abundance of bottlenose dolphins in Scottish waters (Cheney *et al.* 2024)	NatureScot report on the condition of bottlenose dolphin within the Moray Firth SAC in six-year intervals. In addition, a yearly report on the assessments of trends in abundance and patterns of distribution (and other biological parameters). Further information is reported on the wider east coast of Scotland population inclusive of the Firth of Forth and Firth of Tay.

Density

Source	Summary
Site-specific density estimates	Utilising project-specific surveys prior to development (if available) assists in establishing a marine mammal baseline by identifying presence in the area. Thus, aiding to inform density estimates within the site-specific area.
ObSERVE Programme; Aerial Surveys of Cetaceans and Seabirds in Irish Waters: Occurrence, distribution and abundance in 2015-2017 (Rogan *et al.* 2018) and 2021-2023 (Giralt Paradell *et al.* 2024)	The ObSERVE Programme, initiated in 2014, was designed to conduct aerial and acoustic surveys to study protected offshore species and habitats within Ireland's exclusive economic zone. The reports provide both density and abundance estimates across different regions around the Irish coast. ObSERVE phase 1 surveys took place between 2015 and 2017. ObSERVE Phase 2 surveys were conducted between 2021 and 2022. Both phases cover both summer and winter seasons.
Revised Phase III Data Analysis of Joint Cetacean Protocol Data Resources (Paxton *et al.* 2016)	Effort-linked sightings data contained within the Joint Cetacean Protocol data resource were used to estimate spatio-temporal patterns of abundance for seven species of cetacean over a 17-year period. The report provides maps of densities, numerical estimates of abundance and rates of change between reporting period for the seven regularly occurring cetacean species. The density surface models are used over a fine-scale grid of 25 km^2.
SCANS III density surfaces (Lacey *et al.* 2022)	Modelled density surfaces of cetaceans in European Atlantic waters in summer 2016 using the SCANS III data.
Seal habitat preference maps (Carter *et al.* 2020, 2022, 2025)	Habitat modelling was used, matching seal telemetry data to habitat variables, to understand the species-environment relationships that drive seal distribution. Haul-out count data were then used to generate predictions of seal distribution at sea from all known haul-out sites. This resulted in predicted distribution maps on a 5x5 km grid. The estimated density surface gives the percentage of the British Isles at sea population (excluding hauled-out animals) estimated to be present in each grid cell at any one time during the main foraging season.

Source	Summary
Small Cetaceans in the European Atlantic and North Sea (SCANS-IV): Estimates of cetacean abundance in European Atlantic waters in summer 2022 from the SCANS-IV aerial and shipboard surveys (Gilles *et al.* 2023)	Density estimates for cetacean species in the European Atlantic and North Sea.
Modelled distributions and abundance of cetaceans and seabirds of Wales and surrounding waters (Evans & Waggitt 2023)	This dataset provides the maximum and monthly (mean) modelled densities of certain cetacean and seabird species in the Irish and Celtic seas around Wales. These modelled densities are informed via both predictive modelling of sightings and environmental variables. Both the maximum and monthly densities are expressed per 2.5 km^2 cells.
Distribution maps of cetacean and seabird populations in the North-East Atlantic (Waggitt *et al.* 2019)	Density mapping for the most common cetacean species in European and North-East Atlantic waters for each month. These density layers are spatially explicit in that they consider environment variables.

Table A4.2 Key literature sources for fish populations at the time of writing.

Publicly available datasets

Source	Summary
ICES Trawl Survey Data	Long-term time series dataset of species distribution from trawl surveys conducted across the North Sea and wider ICES regions.
UK sea fisheries annual statistics reports	Information on landings of the UK fishing fleet, and the status of commercial fish stocks.
EMODnet broad scale seabed habitat map for Europe (EUSeaMap) (EMODnet 2021)	EUSeaMap is a predictive habitat map covering the North Sea. Habitats are described in the EUNIS 2019 classification system.
Fisheries datasets available from the National Marine Plan Interactive (NMPi), including ScotMap data	An interactive map providing a data overview of the Scottish marine environment.
IFISH (Integrated Fisheries System Holding) Database	Fisheries data, including landings and fishing effort data.
BGS Marine Sediment Particle Size dataset sourced from the BGS GeoIndex Offshore portal	National Particle Size Analysis (PSA) dataset to help inform habitat suitability for demersal spawning species.

Source	Summary
International Herring Larval Survey (IHLS) data	Herring larvae surveys conducted across the North Sea and adjacent areas to provide quantitative estimates of herring larval abundance used as a relative index of changes of herring spawning stock biomass.

Literature

Source	Summary
Fisheries Sensitivity Maps in British Water (Coull *et al.* 1998)	Coull *et al.* (1998) and Ellis *et al.* (2010, 2012) are widely regarded as key references for understanding the spatial extent, relative intensity, and duration of fish spawning grounds. These studies are based on comprehensive compilations of various data sources.
UK fisheries for skates (Rajidae): History and development of the fishery, recent management actions and survivorship of discards (Ellis *et al.* 2010)	
Spawning and Nursery Grounds of Selected Fish Species in UK (Ellis *et al.* 2012)	
Updating Fisheries Sensitivity Maps in British Waters (Aires *et al.* 2014)	Aggregations of 0-group fish and/or larvae of key commercial species.
Kyle-Henney *et al.* (2024) Identifying and Mapping Atlantic Herring Potential Spawning Habitat: An Updated Method Statement	Methods for defining potential spawning habitat for Atlantic herring.
Reach *et al.* (2024) Identifying and Mapping Sandeel Potential Supporting Habitat: An Updated Method Statement	Methods for defining potential spawning habitat for sandeel.

For Welsh waters, Natural Resources Wales have published a list of key marine ecology datasets for marine developments (Natural Resources Wales 2025). This webpage should be checked for relevant datasets, for projects in Welsh waters and adjacent waters.