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Review:

Ocean Acoustics Modelling for Environmental Impact Assessments

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Ocean Acoustics Modelling for EIAs: a Review

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SUMMARY

This review is one of the objectives of the project carried out as an MRE Knowledge exchange NERC Fellowship (NE/L014335/1) *Developing and testing models of fish behaviour around tidal turbines*. The overarching aim of this project was to provide an evidence-based tool to forecast the effects of anthropogenic noise on marine fish for Environmental Impact Assessments (EIA). The project was run in collaboration with the tidal turbine developer Sustainable Marine Energy (SME), the marine modelling consultant HR Wallingford (HRW) and University of Exeter. The review was asked by Natural England with the specific aims of presenting the projects that used sound propagation modelling in Environmental Impact Assessments.

The review has found that there are a number of numerical models available for the calculation of the sound propagation in ocean. These include ray tracing, normal mode and parabolic equation models. Each model has its own strengths and weaknesses. Some are best suited to shallow water, others to deep water; some can deal with complex bathymetry profiles, others require a fixed water depth; some can deal with shear waves, others cannot. It follows that the choice of the propagation model depends on the circumstances found in the environment considered. The collection of accurate oceanographic data such as sound speed profiles, sea floor properties, and bathymetry as well as ambient noise data for computational modelling presents several constrains and this has consequences on the outcome of an ocean acoustics propagation model.

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1. Introduction

Over the past sixty years, changes in the ocean sound levels and distribution have resulted from increased anthropogenic activity in water (e.g., seismic-exploration activity, maritime shipping, oil and gas research and extraction and wind farm development). In light of the increasing concern that the disruption of the natural acoustic environment has the potential to affect marine animals (Richardson *et al*., 1995; Madsen *et al*., 2006; Wilhelmsson *et al*., 2006; Popper and Hastings, 2009a,b), new regulatory initiatives have asked for additional investigations on the use of sound (either intentional or incidental) in the ocean and its levels. The EU Marine Strategy Framework Directive (MSFD 2008/56/EC) framework, which aims at achieving Good Environmental Status (GES) in the marine environment by 2021 across Europe's marine environment, has set out eleven high level descriptors of Good Environmental Status. Descriptor 11 states that "*introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment*". In the United Kingdom it is a legal requirement that new developments in sea are supported by an Environmental Impact Assessment (EIA) (Harvey and Clarke, 2012). Within an application, developers have to undertake an assessment of the potential impacts from noise on the developing area. A primary requirement in assessments of potential impactsof noise upon marine animals is the estimation of received levels at different locations where the targeted species are of concern. These levels can then be compared against criteria used to assess impacts upon different species (Nedwell *et al*., 2007a; Popper, 2006; Southall *et al*., 2007). The EIA would identify, for example, any geographical or seasonal restrictions that would need to be observed and mitigation options for those levels that may be a concern for marine species (e.g. Erbe and King, 2009).

EIAs are increasingly making use of predictive modelling of underwater radiated noise and assessment of the potential impact on marine life for a range of different coastal and marine developments. Models are used to predict the propagation of the noise radiated from the source and the distance at which the sound attenuates to a local ambient noise level. Several companies have developed proprietary models of the radiated noise impulsive noise (Nedwell *et al*., 2011a; Rossigton *et al*., 2013) to support EIAs. The additional ability of some software programs to predict species response to the underwater noise enables regulators to define zones of impact on marine animals and apply protection measures to minimize or prevent potentially detrimental noise levels for local marine species. However, predicting the levels of underwater radiated sound in coastal waters, as in shallow waters, has some challenges because modelling is more complicated by the shallow waters' physical features, which can significantly affect the sound propagation underwater. Nevertheless, most of the human activities that generate underwater noise, for instance marine renewable developments but also shipping, oil and gas exploration and coastal constructions, will happen in these areas and modelling has evolved to accomplish the complex task to predict their levels.

There are several modelling techniques to predict the sound propagation in the ocean, all with their assumptions and best conditions of application. Some models can be best suited for deep waters, some others for more shallow waters; some can give a full representation of the sound propagation accounting for the environmental parameters encountered or the acoustic characteristic of the sea bed. Some models give a high frequency solution, whereas some others will be best used to predict low frequency sound propagation. This review aims:

1. to present projects that have been undertaken within the field of underwater propagation modelling and/or have identified impacts of anthropogenic noise on marine animals.
2. To define the acronyms, metrics and assumptions most used in the literature associated with the models.

This paper is divided into three main sections. Section 1 addresses the challenges in using sound propagation models in terms of variability upon 1) the physical features that affect the sounds propagation in coastal waters and 2) the lack of information on background noise levels in shallow water as well as 3) the variety of effects of underwater anthropogenic noise on marine fauna. Section 2 reviews the basic acoustcs concepts, the metrics used to establish the impacts upon marine animals and the criteria. Section 3 discusses the sound propagation models in use with the inclusion of criteria such as the kind of literature (report vs peer-reviewed), the kind of animals targeted, the model type, the metric, whether the models include an assessment of the anthropogenic noise or not and whether the assessment has been done on a specific species or a proxy.

1.1. Variability in sound propagation in coastal waters

The challenges in using propagation of underwater sound to assess the impacts of anthropogenic noise in coastal water include 1) the high variability in the acoustic features of the coastal environment, which make modelling the propagation of sound complex, 2) the lack or scarse measurements of baseline ambient noise in a particular area and time, all coupled with 3) the high variability in the effects upon marine biota. This section will introduce and discuss these topics, although for more detailed information we recommend specific readings (Jensen *et al*., 2011; Normandeau, 2012; NRC, 2003)

1.2. The coastal acoustic environment

In shallow waters (by definition water at depth <200m) the sound propagates to a receiver by repeated reflections from the seabed and surface (Urick, 1983). Changes in depth in coastal waters affect the sound speed within the water column (Figure 1) and temperature, salinity and the properties of the seabed contribute significantly to the acoustic spread, making coastal areas a complex acoustic environments (Marsh and Schulkin, 1962, Katsnelson *et al.*, 2012).

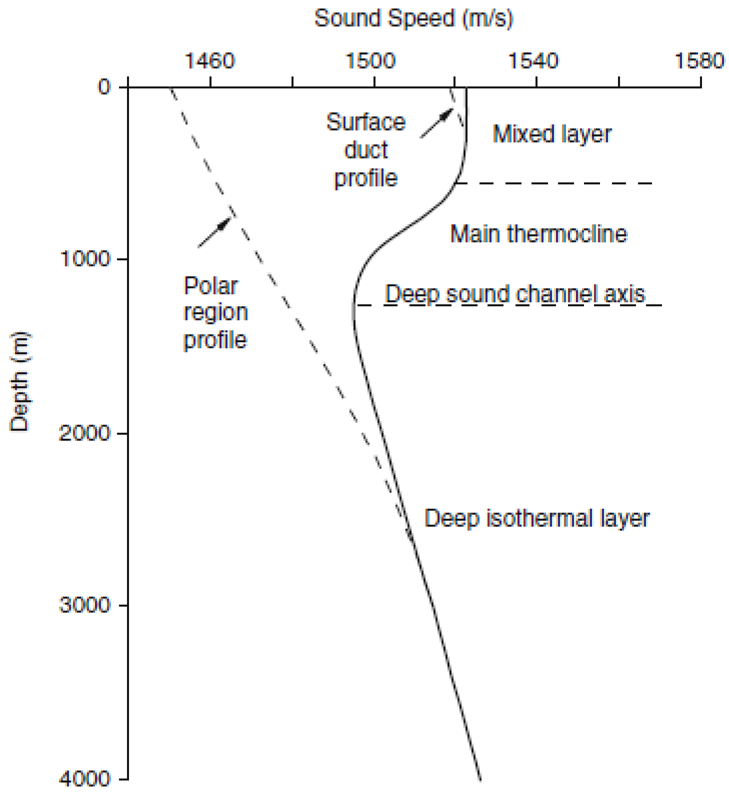

Figure 1 Generic sound speed profile. From Jensen et al., 2011.

With reference to Figure 1 and for temperate areas, the speed of sound profile varies depending on depth and range, altering the sound propagation. In the upper layer, the mixer layer, which is formed by the mixing forces of wind and wave activity, the sound speed profile depends on depth and the changing pressure gradient from near the surface to more deep waters. The result is that a portion of the acoustic energy emitted by a source placed in the mixed layer will be trapped in the surface duct. Underneath the mixed layer, the thermocline creates a region of constant temperature and the sound speed increases with depth as a result of increasing pressure. Just below the thermocline, the speed of sound decreases to its minimum forming a deep sound channel. In shallow water, diurnal and seasonal changes in temperature greatly affect the speed of sound in the upper layer, creating zones where the sound will be downward reflected by the surface. It follows that in shallow waters the sound profile in the water column is not linear with changes in depth and the sound propagation will depend on the interactions with the bottom.

Interactions of the acoustic fields with the sea bed is less influential in deep water, where the speed of sound depends on the water depths, whereas they become more important in coastal areas with varying bathymetry. A representation of the complexity of the sound's path may be depicted from Figure 2. In a shallow water region, such as a continental shelf, sound is channeled in a waveguide where the sound is trapped between the ocean surface and bottom. Because of the latter, the sound propagation path is reflected off by both the sea surface and the seafloor.To generate high-fidelity models of the sound propagation in shallow waters it is, thus, required a good understanding of the sea bed structure and bathymetry.

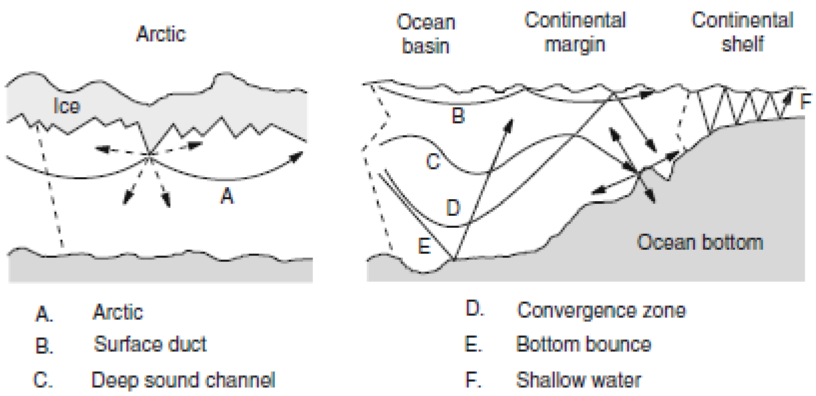

Figure 2 Schematic representation of types of sound propagation paths in oceans. From Jensen et al., 2011.

Hovem (2013) reviewed the effect of bathymetry and seasonality on the sound propagation of seismic noise from an airgun array. Results from the model revealed that the down sloping bottom caused a fast decay of the sound level, whereas the upslope propagation of sound created increasing density of rays with range up to a critical grazing angle of rays, which identifies the cut-off in propagation. In addition, reflection losses due to the bottom proximity occurring during different seasons (winter versus summer) were found to be relevant, with summer conditions showing more important bottom reflections, reducing the critical distance and sound levels compared to winter (see also Tronstad and Hovem, 2011; Hovem and Korakas, 2014). It follows that, in its path from the source to a receiver, a sound will not propagate monotonically as function of range but because of the interaction with the bottom and depending on the seasonal acoustic properties of the water it might create hot spots were the energy is concentrated (Hovem *et al.*, 2012) or where some frequencies contain more energy than other (DeRuiter *et al.*, 2006), The frequency of the sound source is also an important parameter. Minimum propagation frequency, known as the cut-off frequency, exists and rules whether the sound waves propagate forward or not. Frequency below the cut-off frequency cannot propagate in the horizontal direction and the sound energy will be trapped in the sea bed. This will change the amount of acoustic energy that propagates depending also on the kind of sea bed encountered. Typical optimum frequency for a water depth of 100 m is in the range 200–800Hz (Jensen *et al*., 2011) but for shallow waters it may be strongly dependent on water depth and sound-speed profile and only weakly dependent on the bottom type (Jensen and Kuperman, 1983).

In propagating sound waves interactions of the acoustic fields with the sea bed explains much of the absorption in the water and in the sediment of the energy of low frequency sounds (<1 KHz), therefore, a complicating feature of shallow-water propagation is the great variety of bottom types encountered, with mud, sand, rock and gravel all commonly found and overlapping (Urick, 1983; Ainslie, 2000). The amount of energy lost due to scattering varies with the roughness of the bottom and the frequency of the incident sound. Hard bottoms such as rocky or sandy shores may be associated with low bottom loss, whereas soft bottoms, like mud, would produce lower losses (Urick 1983).

1.3. Ambient noise

Ambient noise originates from a range of noise sources both natural (e.g. rain, wind and current) and biological (animals' sounds) and spans a large frequency range from below 1 Hz up to over 100 kHz (see Wenz, 1962 for relatively deep water). Because of variations in water depth and in ocean bottom properties as well as variations in the sources of noise themselves, ambient noise in shallow water can be highly variable from one location to another. Underwater ambient noise levels between 100 to 130 dB re 1 µPa are typically reported for UK waters (Nedwell *et al.* 2007b; Bailey *et al*. 2010; Theobald *et al.* 2010; Robinson *et al.* 2011).

For the purposes of evaluating the potential effects of underwater sound on the marine environment, both ambient noise and noise from identifiable sources must be considered (Erbe, 2002; Popper and Hastings, 2009a). Animals will only respond to sounds they can detect above the background noise and this can vary in time, location and depth. In particular, the relative signal-to-noise ratio will influence perception capability (Fay *et al*., 2000) and therefore the magnitude of the impacts (Ellison *et al*., 2012). The noise radiated during anthropogenic activities in waters is likely to be strongly correlated with the ambient noise level, since both depend on environmental conditions.The distinction between ambient noise and that from additional anthropogenic sources has a direct impact on modeling and the interpretation of the results.

Ambient noise in shallow water is highly variable also because of the presence of anthropogenic noise sources. Examples are the recreational boats that cruise the coasts, the costruction activities that pile or drilling foundations or the acoustic seismic research of the sea bottom. Quantifying the contribution of these additional noise sources to ambient noise level is not always possible especially in certain areas where the human activity in water is high and there is a great temporal overlap. Recent studies have indicated that the contribution to ambient noise in the frequency band 30-50 Hz due to distant shipping noise has increased the level of ambient noise by 2.5-3 dB per decades (McDonald *et al.* 2008). In the North Sea for example, the contribution of shipping noise to ambient levels is significant (Ainslie *et al.* 2009) and can affect some areas in different ways that depend on distance. However, there is a paucity of data on ambient noise for several locations.

1.4. Assessing the impact of anthropogenic noise on marine fauna

Underwater sound radiated from anthropogenic activities in water can potentially have a detrimental impact on marine animals, ranging from degradation of their acoustic habitat, inducing escape or changes in activities and, as extreme scenario, causing physical injury. The likely impact will depend on a number of factors including the type of source, the noise propagation conditions in the area and the sensitivity to sound of marine species present in the area and their activities.

The potential effects of anthropogenic noise are summarised in Table I along with some of the key references that reported effects.

Table I Potential effects of anthropogenic noise on marine animals

SOURCE	EFFECTS ON ANIMALS	Refererence
High noise level	Death or lethal injuries from sound exposure; Damage to tissue, internal organs, inner ear and lateral lines;	Madsen *et al*., 2006; Thomsen *et al*., 2006; Casper *et al*., 2012; Halvorsen *et al*., 2012a; Casper *et al*., 2013; Yelverton *et al*.,1975
High to moderate noise level	Increased stress; reduced feeding; increased oxygen consumption	Wright *et al*., 2007; Smith, 2004; Voellmy *et al*., 2014, Buscaino *et al*., 2010; Wale *et al*., 2013a,b
Moderate noise level	Masking of biological important acoustic cues: other animals' sounds; habitat sounds; PTS and TTS	Brumm & Slabbekoorn, 2005; Erbe, 2002; Vasconcelos *et al*. 2007; Southall *et al*., 2007; Codarin *et al*. 2009;
Moderate to low noise level	Interruption of normal activities including feeding, schooling, spawning, migration, displacement, attention shift; disruption of anti-predator behaviour; changing in acoustic behaviour	Chan *et al*. 2010; Wale *et al*. 2013b; Miksis-Olds & Wagner, 2011; Bracciali *et al*., 2012; Richardson *et al*., 1995; Slabbekoorn *et al*., 2010; Engås *et al*., 1995; Andersson *et al*., 2007; Sarà et al., 2007; Mueller-Blenkle *et al*., 2010; Tyack, 2008; Watkins, 1986; Simpson *et al*., 2014;

As it is evidenced from the above Table I marine animals may be negatively affected by anthropogenic noise in several different ways. The magnitude of the impact will depend on species, individual sensitivity, physiological and behavioural state, age, nature of the sound source (impulsive vs continuous), prior experience, resource availability and individual and group activity. Very high noise levels, for instance, originating from pile driving or seismic measurements, can cause tissue damage, damage of the inner ear and lateral lines of fish (Halvorsen *et al*., 2012a; Casper *et al*., 2013), although not all marine species have shown such effects and the levels at which injuries occur appeared to vary (Popper *et al*., 2007; Popper and Hastings, 2009a,b; Casper *et al*., 2012, 2013; Bolle *et al*., 2012; Halvorsen *et al*., 2012b).

Exposure to more moderate noise levels, such as boat noise, can trigger increased stress levels (Smith, 2004), temporary (TTS) or permanent shift hearing thresholds (PTS) (Southall *et al*., 2007; Codarin *et al*., 2009), impair detection of acoustic cues (Erbe, 2002; Vasconcelos *et al*., 2007), and change behaviour (reviewed in Slabbekoorn *et al*., 2010). Some marine mammals have been reported to avoid noisy areas (Francis *et al*., 2009) and fish have been shown to dive after exposure to airguns noise (Slotte *et al*., 2004) and boat noise (Bracciali *et al*., 2012). However, not all species have responded to noise exposure manifesting behavioural responses (Popper *et al*., 2005; Peña *et* *al*., 2013). Some species did not leave the area during playback of boat noise (Picciulin *et al*., 2010), but significantly modified their behaviour, others appeared to benefit from anthropogenic noise and increased their settlement where noise was at the highest level (Stanley *et al*., 2014; McDonald *et al*., 2014).

The magnitude of the impacts is dependent on species hearing sensitivity and in fish also on their hearing specialisations (Popper & Hastings 2009a). Species can differ significantly with respect to the frequency range they can hear and their absolute sensitivity. Many studies have been carried out in the free field or specialised acoustic chambers (Hawkins and Chapman, 1973; Hawkins and MacLennan, 1976; Richardson *et al*., 1995; Lovell *et al*., 2005, Popper *et al*., 2007) to obtain audiograms, which represent the average sound level that an animal can hear under quiet conditions (reviewed in Ladich and Fay, 2013). However, only for few species, audiograms are available. In the context of an impact assessment, having audiograms of the target species is a fundamental requirement as it will be used as baseline of the hearing capability of the species at certain frequencies and then compared to the levels of additional noise introduced in the water by human activities.

It is important to note that most fish, especially those without hearing adaptations, and invertebrates are sensitive to particle motion (Fay *et al*., 2008; Popper and Fay, 2011). Sensitivity to particle motion is likely to be important for behavioural responses and near the source where particle motion is predominant (for a review, Hawkins and Popper, 2014). Impact assessments have so far disregarded the particle motion component of the sound, measuring only sound pressure (see exception in Mueller-Blenkle *et al*., 2010). No audiograms based on this component are available and this greatly limits the knowledge on the effects of noise on particle motion sensitive animals and the development of conclusive criteria for these species.

1.4.1. Frequency Weighting Functions

Development of frequency weighting functions was introduced because animals are more sensitive to some frequencies than others. With this approach the signal is first filtered relative to the hearing ability of the target species and the sound exposure level (SEL; see section 2.2.1) is then computed. It follows that energy contribution from frequencies that are not detected by the animal will be reduced or disregarded from the exposure. It must be noted that the use of frequency weighting is important for behavioural studies. However, frequencies falling outside the hearing range of the animals may also be important as they may result in damage to tissues or injuries.

A series of frequency weighting functions were developed by Southall *et al.* (2007) based on the existing knowledge and interpolation of marine mammal hearing data. These are the M-Weighting.

Similarly, Nedwell *et al*. (2007a) proposed the dB_{ht} (*species*) for fish (but see Thompson *et al*., 2010 and 2013 for the use of the dB_{ht} for marine mammals).

1.4.2. Criteria to define noise impact

Knowledge of levels of sound that have particular effects or no consequences upon marine animals is important for assessing the impact of sounds. There are well established and agreed setting of criteria for marine mammals and this are based on the SEL (Southall *et al*., 2007). However, there are not agreed settings of recommended sound levels or sound exposure criteria for fish or invertebrates, largely because of a shortage of data (Normandeau, 2012).

Criteria for marine mammals

The M-Weighting model proposed by Southall *et al.* (2007) has recently been adopted by the UK Joint Nature Conservation Committee (JNCC) for the assessment of marine operations that may cause injury or disturbance effects on marine mammals. This is based on criteria using two metrics, the peak sound pressure level and M-weighted SEL for various groups of marine mammals (low, mid and high frequency cetaceans and pinnipeds). Clearly defined criteria are proposed for auditory injury for impulsive signals. Quantitative criteria are also presented for behavioural response to single pulses, based on the level at which Temporary Threshold Shift (TTS) occurs. These criteria are presented in Table II and Table III.

Table II Proposed injury criteria for marine mammals exposed to impulsive noise within a 24-h period (from Southall et al. 2007).

Marine Mammal Groups	Pulse	Estimated Auditory Bandwidth
low-frequency cetaceans		7 Hz to 22 KHz
SPL peak	230 dB re 1 µPa	
SEL	198 dB re 1 µPa^2 s	
mid-frequency cetaceans		150 Hz to 160 KHz
SPL peak	230 dB re 1 µPa	
SEL	198 dB re 1 µPa^2 s	
Hig-frequency cetaceans		220 Hz to 180 KHz
SPL peak	230 dB re 1 µPa	
SEL	198 dB re 1 µPa^2 s	
Pinnipeds in water		75 Hz to 75 KHz
SPL peak	218 dB re 1 µPa	
SEL	186 dB re 1 µPa^2 s	
Pinnipeds in air		75 Hz to 30 KHz
SPL peak	149 dB re 20 µPa	
SEL	144 dB re (20 µPa)^2	

More recent work by Lucke *et al.* (2009) suggested for harbour porpoise (high-frequency cetacean) a peak pressure level of 199.7dB re 1 µPa and a SEL of 179dB re 1 µPa^{2}s.

Table III Propose behavioural criteria for marine mammals exposed to impulsive noise within a 24-h period (Southall et al., 2007).

Marine Mammal Groups	Pulse
low-, mid-, high- frequency cetaceans	
SPL peak	224 dB re 1 µPa
SEL	183 dB re 1 µPa^2 s
Pinnipeds in water	
SPL peak	212 dB re 1 µPa
SEL	171 dB re 1 µPa^2 s

The recent work by Lucke *et al.* (2009) suggested a peak level of 168dB re 1 µPa and a SEL of 145dB re 1 µPa^{2}s for harbour porpoise.

Criteria for fish

Sound exposure criteria for fish as those proposed for marine mammals do not exist and this is mainly due to the fact that there are significant gaps in the knowledge of the effects of anthropogenic sound on fish species to develop definitive noise exposure criteria (Popper *et al*., 2014).

Tentative exposure criteria have been suggested for the onset of direct physical injury in fish exposed to the impact sound associated with pile driving (Popper *et al.*, 2006; Carlson *et al.,* 2007; Halvorsen *et al*., 2012a; 2012c; Casper *et al*., 2013). However, there are few criteria that apply to behavioural responses of fishes (McCauley *et al.*, 2000; Pearson *et al.,* 1992), largely due to the absence of underlying information.

Based on the interim dual criteria recommended in Popper *et al*. (2006) and refined by Carlson *et al*. (2007), the criteria proposed identify sound pressure levels for injury of:

206 dB re: 1 µPa peak
187 dB re 1 µPa^{2}s SEL

at 10 m for all fish species except those that are less than 2 grams. In that case the recommended SEL is 183 dB re 1 µPa^{2}s (Bolle *et al.* 2011; 2012). Carlson *et al.* (2007) also recommended that the SEL for larger fish should be 197dB re 1 µPa^{2}s for fish over 8 grams and 213dB re 1 µPa^{2}s for fish over 200 grams. The period of accumulation for the SEL value is the whole pile driving sequence.

These criteria are currently in use in the USA and relate only to pile driving. TNO (Netherlands Organisation for Applied Scientific Research, 2011) have defined the metrics for measuring underwater sound in relation to the impact on marine life as:

1. Un-weighted sound pressure level (SPL) for continuous sound.
2. Un-weighted sound exposure level (SEL) for transient sounds.
3. Un-weighted zero to peak sound pressure level for transient sounds.

The recent papers by Halvorsen *et al*. (2012a; 2012c) and Casper *et al*. (2013) provided the levels of impulsive sound that result in the onset of injury to juvenile Chinook salmon (*Oncorhynchus tshawytscha*; mean weight 11.8g) and other species based on a 1 to 10 response weighted index (RWI). A level of injury was achieved for 1920 strikes at 177 dB re 1 µPa^{2}sec SELss (SEL for a single strike), yielding a SELcum of 210 dB re 1 µPa^{2}sec, and for 960 strikes at 180 dB re 1 µ Pa^{2}sec SELss also yielding a SELcum of 210 dB re 1 µ Pa^{2}sec.

There is insufficient evidence to determine behaviour criteria for fish species. Consideration has been given to works by Mueller-Blenkle *et al.* (2010) that reported behavioural response in Atlantic cod at 161dB re 1 µPa, Pearson *et al*. (1992) that observed a startle response at 200dB re 1 µPa and McCauley *et al.* (2000) for changes in swimming and schooling behaviour (level between 168 to 173dB re 1 µPa).

Nedwell *et al*. (2007a) suggested using the frequency weighted dBht (*species*) as criteria for behavioural impact in fish. Based on this, strong avoidance responses by fish would start at 90 dB above the dBht (*Species*) thresholds of fish (Table IV).

Table IV Proposed behavioural response criteria for fishes exposed to sound (Nedwell et al. 2007)

Level in dBht (species)	**EFFECT**
Above 130	Hearing damage
Above 110	Tolerance limit to sound
90 and above	Strong avoidance
75	85% of the animals react to noise
50 and below	no change in behaviour

As underlined in this section, assessing the impact of radiated noise on marine animals is challenged by the high variability in responses by marine species to noise exposure as well as the lack of information on effects, including injury and behaviour, in wild unrestrained animals. More information is available for marine mammals than for fish and it resulted in more reliable criteria. For fish, an additional complexity is found in that the behavioural responses to noise has been quantified in enclosed environments (tanks or cages) where sounds may propagate differently from open water conditions (Parvalescu, 1964) and do not reflect the levels found in the ocean. Finally, most measures to date do not distinguish between sensitivity to sound pressure and particle motion (see exception in Mueller-Blenkle *et al.,* 2010), to which fish are primary sensitive (see Section 1.4).

2. Introduction to underwater acoustics and propagation modelling

2.1. Metrics and Units

This section introduces some basic underwater acoustic concepts to consider when assessing and interpreting the potential for impact on marine life from underwater noise generated by human activities in waters.

2.1.1. Sound Pressure Level

When measuring sound amplitude in water, what it is obtained is a measure of the sound pressure, which is the difference between the pressure produced by a sound wave (P) and a reference pressure at the same point in space (P_0). Sound Pressure is measured in Pascals (Pa) units or in Newton per square metre (N/m^2). Because measurements of the sound pressure span over a wide range, sound pressure is more conveniently expressed using a logarithmic scale (dB = decibel). Sound pressure differences expressed in this way is called Sound Pressure Level or SPL and it is defined as:

$$\mathrm{SPL} = 10\ \log_{10}\left(\frac{P}{P_0}\right)$$

where P is the measured sound pressure and P_0 is the reference pressure, which for underwater applications is 1 µPa. The SPL can be presented in several metrics described below.

Zero-to-peak Level. The peak pressure level is the maximum level of the acoustic pressure, usually a positive pressure (Figure 3) and it is expressed in units of $\mathrm{dB}_{\text{zero-to-peak}}$ reference pressure of 1 µPa. This measurement is often used to characterise underwater blast (Yelverton *et al.*, 1976) and it has been used in impacts assessment of underwater noise causing injuries or death (see for example Popper *et al*., 2006 and Carlson *et al*., 2007).

Peak-to-peak level. The peak-to-peak pressure level is the amplitude difference between the most positive and most negative value in a time waveform (Figure 3) and it is expressed in units of $\mathrm{dB}_{\text{peak-to-peak}}$ reference pressure of 1 µPa. This represents the maximum change in pressure as a transient pressure wave propagates. Where the wave is symmetrically distributed in positive and negative pressure (e.g. sine wave), the peak-to-peak level will be twice the peak level. Peak-to-peak pressure levels are often used to characterise sound transients from impulsive sources. The use of peak-to-peak pressure has been adopted for UK marine piling and seismic airguns measurements (Parvin *et al.* 2006, Nedwell *et al.* 2007a).

It should be noted the EU MSFD (2008) has adopted the peak sound pressure level (in addition to the sound exposure level) defined as the zero-to-peak amplitude for impulsive sounds.

RMS (Root mean squared) Level. The RMS level is used to characterise noise of a continuous nature, such as drilling, vessel, turbine operational noise and background sea noise levels and, by convention, it describes the root mean square (RMS) level over a one second interval referenced to an RMS pressure of 1 µPa. The RMS sound pressure is usually calculated over the period of the pulse that contains 90 percent of the acoustical energy. The description of SPL in terms of RMS values is only valid over a particular period of time, the duration of the signal of interest, measured in seconds. If the source is moving relative to the hydrophone, or is changing in source level then the SPL must be measured repeatedly. In addition, certain classes of signals, for example impulsive signals, may fluctuate in level over time and the averaging process will yield to measurements unrepresentative of their instantaneous level.

It is important to know that if the waveform is a pure sine wave, the relationships between peak, peak-to-peak and RMS amplitudes are fixed and known, as they are for any continuous periodic wave (Figure 3). However, this is not true for other waveform (e.g. noise) where they relationship is not arithmetically computable.

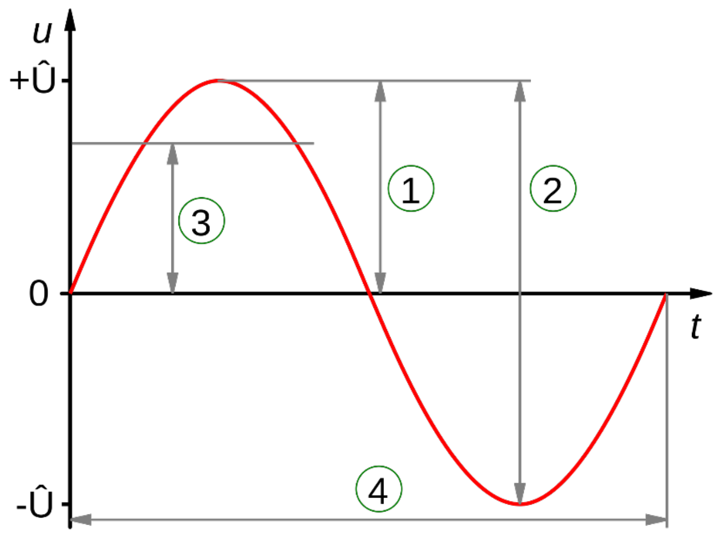

Figure 3 A sinusoidal curve 1 = Peak amplitude (+U), 2 = Peak-to-peak amplitude (2U), 3 = Root mean square amplitude ($U\sqrt{2}$), 4 = Wave period

2.2. Derived metrics

2.2.1. Sound Exposure Level (SEL) and cumulative SEL (SEL_{dose})

When assessing the noise from transient sources such as impact piling or seismic airguns, the time duration of the pressure wave for a single event (e.g. pile strike) is taken into account by integrating the square of the pressure waveform over the duration of the pulse and the amplitude level is then expressed in dB re 1 μPa^2 s (Urick, 1983; Southall *et al.*, 2007). The duration of the pulse is defined as the region of the waveform containing the central 90% of the energy of the pulse.

By defining the Sound Exposure (SE) for a plane wave with the equation:

$$SE_{90} = \int_{t_5}^{t_{95}} p^2(t)dt$$

where p is the acoustic pressure in Pascals, t_{95} and t_0 is the time at which the pulse has 95% and 5% of the energy and t is time in seconds, the SEL is then define by:

$$\text{SEL} = 10\ \text{LOG}\ \frac{SE}{SE_0}$$

where E_0 is the reference value of 1 μPa_2 s.

The SEL for each impulsive noise event can also be summed across emissions (e.g entire piling sequence) to give an overall measure of sound energy over a certain period of time (Southall *et al.,* 2007).

2.3. Sound propagation

2.3.1. Source level (SL)

Where there is a single and well-defined source of noise (a monopole sound source in an infinite lossless uniform medium and in the far-field of the source), underwater sound pressure measurements can be expressed as Source Level (SL) in units of dB re 1 µPa at 1 m (dB re 1 µPa @ 1 m). The SL is the amount of sound radiated by a sound source and it may be quoted in any of the measures above. For example, a piling source may be expressed as having a peak-to-peak SL of 224 -236 dB 1 µPa at 1 m or a SEL SL of 204.5 and 213.5 dB re $\mu Pa^2\ m^2$ s (pile diameter= 2 m, depth= 21 m, sea bed= chalk; Robinson *et al*., 2007; Lepper *et al*., 2012). Similarly, a zodiac with twin 175 HP outboard motors travelling at 55 km/h may have a RMS SL of 169 dB 1 µPa at 1 m (Erbe, 2002).

The use of the SL has the advantage that can be used, for instance, to compare the levels that a sound source would generate in different acoustic environments. However, since the measurements are usually made at some distance from the source (in the acoustic far-field) and calculated back to the reference distance of 1 metre from the acoustic source, the sound pressure level at one metre may be very different from the SL. The relationship between SL and the sound propagation is described by the passive sonar equation (Urick, 1983) shown in the formula below:

$$\text{SL} = \text{RL} + \text{TL} \qquad (1)$$

where RL is the SPL at distance r from a source (in metres) and TL is the transmission loss (Kinsler *et al.,* 1982).

The above method assumes a point source (monople) in the far-field. However, sound sources in the ocean are rarely monopoles (e.g. ships, pile drivers or air gun arrays) and for these sources the predicted levels may be lower. The SL can be computed by backcalculating the levels at 1 m from empirical measurements or the SL can be computed using propagation models. Both these methods are used, however, the lack of standardization in the measurement seems to preclude comparisons between different sources (Ainslie *et al*., 2009). For pile driving, measurements a fixed distance of 500 or 750 m from the pile are commonly used for wind farms noise levels in the North Sea and Baltic Sea (De Jong *et al*., 2012).

2.3.2. Transmission Loss

As underwater sound propagates away from the source it reduces in level. The reduction of sound with range may be defined as:

$$\mathrm{TL} = 20\log\frac{\mathrm{P_0}}{\mathrm{P_r}}$$

where P_0 is the acoustic pressure at a point at 1 m from the source, and P_r is the acoustic pressure at range r away from it.

As sound propagates through the ocean, the effects of spreading and attenuation diminish its intensity. In a free acoustic field (far-field) without any reflecting boundaries, the sound will decrease by 20 log (r) (spherical spreading) as the energy is dispersed over a large area. In shallow water the bottom and water surface will reflect the sound, causing interferences and the transmission loss will be better described by 10 log (r) (cylindrical spreading). Attenuation loss due to absorption, scattering and diffraction increases with increasing frequencies and it is dependent on temperature, salinity, depth and the pH value of the water.

TL may be estimated from the measured received level data as a function of range using the formula 1. Ideally, the TL should be estimated by fitting an appropriate transmission loss model including all parameters (bathymetry and sea bed acoustic properties) that have effect on the propagation of the signal of interest.

2.3.3. Received Level

The received Level (RL) is the acoustic pressure measured at a particular point away from a sound source and provides information of the sound pressure that arrives at any acoustic receptor after transmission. The RL may be expressed as a sound pressure level (dB re 1 µPa) or a sound exposure level (dB re 1 $\mu Pa^2 \cdot s$) and may be computed from the formula 1 when SL and TL are known. The RL can be described by:

$$\mathrm{RL} = 20\log_{10}\left(\frac{P}{\mathrm{P_0}}\right)$$

Where P is the pressure measured at a particular point and P_0 is the reference pressure.

3. Sound Propagation Modelling of anthropogenic noise

3.1. Introduction

As introduced earlier in this review, models can be used to estimate the range over which anthropogenic noise impacts marine animals for EIAs. In order to do that, it is important to understand the propagation of the noise away from the source and understand the relationship between received noise levels and impact thresholds.

Modelling techniques include empirical fits to measured data, such as the Wenz and Knudsen curves (Wenz, 1962; Knudsen *et al*., 1948) and numerical models (Etter, 2003, 2013; Jensen *et al*., 2011), which can be based on observed data (requiring computation of the SL) or on physics-based approaches (incorporating the actual source mechanisms).

Ocean acoustics propagation models can be divided in fundamental classes based upon the frequency of the source (low or high frequency), the dependency of the sound propagation to the local environment (range –dependent or –indipendent) and the water depth (shallow or deep water) (Table V). All these models solve the Helmholtz equation (wave equation) that describes the underwater sound field in a particular frequency band and environment:

$$\nabla^2 \emptyset + k^2 \emptyset = 0$$

where k = (w/c) = (2p/ λ) is the wavenumber and λ is the wavelength (Etter, 2013).

Table V Frequency band and depth conditions to which different propagation models apply.

	SHALLOW WATER	DEEP WATER
LOW FREQUENCY	normal modes; wave number integration; parabolic equation; energy flux	wave number integration; parabolic equation
HIGH FREQUENCY	ray tracing; wave number integration; energy flux	ray tracing

The available propagation models are commonly categorised into the following groups [Jensen *et al*., 2011; Etter, 2013):

1. Ray tracing
2. Normal mode
3. Parabolic equation
4. Wavenumber integration
5. Finite difference and finite element

A description of the available models for the sound propagation in water is outlined in the following sections along with the projects that used them to assess the impacts on marine biota. More detailed information regarding the physics and implementation of the wave equation solutions are provided by Jensen *et al*. (2011), whereas a list of the available models until 2013 is provided in books by Etter (2003, 2013) and summarised in Table VI.

Table VI Organization of propagation models into five distinct techniques. Taken from Etter, 2013

▪ Frequency-domain solutions	$\nabla^2\phi + k^2\phi = 0$
▪ Ray theory	$\phi = F(x,y,z)\, e^{iG(x,y,z)}$
▪ Normal mode	$\phi = F(z) \cdot G(r)$
▪ Multipath expansion	$\phi = F(z) \cdot G(r)$
▪ Fast field/wavenumber integration	$\phi = F(z) \cdot G(r)$
▪ Parabolic equation	$\phi = F(r,\theta,z) \cdot G(r)$
▪ Environmental range dependence	x, y, z, θ, (r,θ,z)
▪ Range independent (1D)	$f(z)$
▪ Range dependent (2D, 3D)	$f(z,r), f(z,r,\theta)$

3.2. Type of models

3.2.1. Spreading loss

As seen in section 2.3.2 the propagation of sound in water can be compute using geometrical spreading models. These models are simple to compute and have the advantage that they do not require a large amount of input data (e.g. N and α values; see below). The transmission loss from equation (n) maybe expressed as (Urick, 1983):

$$TL = N\log_{10}(r) + \alpha r$$

where r is the distance from the source in metres, N is a factor for geometric spreading loss and α is the absorption coefficient in water and at boundaries (dB m^{-1}). The absorption coefficient is frequency-dependent and can be calculated by:

$$\alpha = 0.036\ f^{1.5}\ (\text{dB/km})$$

with f = frequency in kHz (Richardson *et al*., 1995). A factor of N=20 corresponds to a reduction in level observed with spherical spreading and is often assumed near to a source in deep water. A factor of N=10 corresponds to a reduction in received level when cylindrical spreading of the sound occurs and this is often the case of sound propagation in deep channels and shallow waters. In real conditions, the spreading may be described by an N value between 10 and 20. Often a value of N=15 is used as a working compromise (Madsen *et al*., 2006), with N=12 and N=25 being the most measured for shallow water transmission loss (Nedwell *et al.*, 1999; Turnpenny *et al.*, 1994). However, the choice of N depends on local conditions. For instance, measurements made of the noise from piling using piles of 4.3 m diameter during the construction of offshore windfarms in the UK indicated a peak-to-peak Source Level of 260 dB re 1 µPa at 1 m for 5 m depth and 262 dB re 1 µPa at 1 m at 10 m depth, associated with a transmission Loss given by 22 log (r) (Nedwell *et al*., 2003). The simple model applied to an impact assessment study employing caged Atlantic salmon predicted that sound levels generated by pile driving were not a concern for this species (Nedwell *et al*., 2006).

Bailey *et al*. (2010) employed a geometrical spreading model with a N=20 (based on sound measurements) to predict the transmission loss of pile driving sound emitted during the construction of two wind turbine in Scottish waters. The use of this N value was supported by the fact that measurements were taken in relatively mid water depths (14.5 to 51.4 m). A coefficient of absorption α= 0.0004 was also included in the model. Propagation measurements of pile driving source levels and sound propagation indicated that behavioural disturbance could occur at distances of 43 and 70 km for bottlenose dolphins and harbour porpoises, respectively, while strong avoidance reactions would occur within 20 km from the piling site. Noise emission from the pile installation reached a peak-to-peak source level of 205 dB re 1 µPa at 100 m from the pile-driving and only become indistinguishable from background noise at 80 km away. It was estimated that TTS or PTS could only occur within 100 m from the piling site (piles of 1.8 m diameter, blow energy 510 kJ).

Thomsen *et al*. (2006), using a spreading loss model with a factor N=15, predicted the ranges at which offshore wind farm related noise (pile driving and operational noise) has an effect on selected marine mammal (harbour porpoises and harbour seals) and fish species (cod, herring, dab and salmon). It was estimated that a broadband pile driving noise with a zero-to-peak sound pressure level of 238 dB re 1 µPa might be audible to herring (*Clupea harengus*) and cod (*Gadus morhua*) at distances of at least

80 km from the source. The Atlantic salmon (*Salmon salar*) and the dab (*Limanda limanda*) might detect pile driving over considerable distances, yet, as both species are thought to be only sensitive to particle motion, the exact detection range could not be assessed. Thomsen *et al*. (2006) also found that ranges of audibility of operational windfarms to cod and herring were in the range of 4.6 Km whereas for dab and salmon detection of the operational noise might occur at ranges below than 1 Km. Pile driving noise was estimated to be audible to cetaceans over hundreds of kilometres. Behavioural responses of harbor porpoises and harbour seals may extend to distances of 20 km. Operational noise was estimated to be audible to harbour porpoises at around 100 m and to harbour seals at over 1 km. Hearing loss may occur at 1.8 km in harbour porpoises and 400 m in seals during pile driving.

INSPIRE (Impulse Noise Sound Propagation and Impact Range Estimator) is a custom-written acoustic analysis programme developed by Subacoustech Ltd. This uses a combined shallow-water geometric and hysteris loss model to conservatively predict the propagation and levels of noise. The model has been tested against measurements from offshore wind farm piling operations (Nedwell *et al*., 2011a) and seismic survey operations (Thompson *et al*., 2010). The model imports electronic bathymetry data as a primary input to calculate the transmission losses along transects away from the source of the noise. Other physical data may also be provided; for instance, in the case of piling, the blow energy, pile diameter, strike rate and water depth would be used (Nedwell *et al*. 2011b). An important feature reported in Thompson *et al*. (2010) was that INSPIRE computed conservative received levels compared to measured values at great distances, whereas close to the source, the model under predicted noise levels.

INSPIRE is one of those proprietary models that has the additional advantage to predict the effect of the radiated noise on targeted species. The model incorporates a "fleeing animal receptor" extension that calculates the exposure dose an animal receives as it is moves away from a sound source. The disturbance to marine life is quantified using available audiogram of the relevant species. The criteria against which INSPIRE predicts impacts are based on the dB_{ht} (*species*) (Nedwell *et al*., 2007a). In Thompson *et al.* (2013) for example the predicted propagation of noise resulting from the piling operations required to install the wind turbine foundations within the Moray Firth, NE Scotland, was modelled using INSPIRE and predictions were given in terms of dB_{ht} (harbour porpoise) (as a proxy for harbour seals). The study aimed to propose a framework to assess the extent to which effects from construction noise may overlap with areas used by harbour seals population. The population of modelled harbour porpoise resulted largely driven by the baseline dynamics of the population and only a short term reduction in numbers was predicted, even in a worst-case scenario of impacts. The proportional decreased in the number of individuals was higher in close proximity with the construction site.

A potential limitation in the use of INSPIRE is that the model makes predictions based on the dB_{ht} (*species*) metric (see section 1.4.1), which requires measurements that have a good signal-to-noise ratio through the whole hearing range of the species, and this requirement is not always possible to achieve (Thompson *et al.*, 2010). In addition, the use of the dBht metric as output somewhat limits the use of this model in that it become difficult to compare its output with others. However, the sound propagation model is able to provide a wide range of outputs, including the un-weighted peak pressure, impulse and SEL of the noise, and this allows users to test the predicted levels against the assessment criteria in use.

The limitations of spreading loss models should be considered. Simple spreading loss models depend only on range from the source, do not account for the interaction between sound and boundaries (bottom and surface) nor the frequency-dependent attenuation in the water and in the sediment. Nevertheless, these models represent the most used tools for predicting sound exposure level for EIAs in the UK and the reason lies in that they are simple and fast to compute and do not require high amount of data to be run. As we have seen, these models can incorporate additional data that can increased the model fidelity, such the blow energy for pilling noise prediction in INSPIRE, but, more sophisticated models, which incorporate the interactions of sound with the physical environment exist and they are often necessary (Handegard *et al*., 2013). These models are described in the following sections.

3.2.2. Ray tracing

Ray tracing models are most used for high-frequency, range-dependent sound propagation conditions when the sound originated from a point source changes little over distances. Ray tracing method divides the water column into a finite number of layers with similar density and different sound speed and applies the Snell's law to calculate the wave's path through the water in the form:

$$\frac{\cos\theta_1}{c_1} = \frac{\cos\theta_2}{c_2}$$

where θ_1 and θ_2 are the angles of the incident wave and the reflected wave, respectively, and c_1 and c_2 are the sound speeds. The assumption of the ray theory is that the sound wave propagates along trays that are perpendicular to the wave front (creating concentric circles) and the sound field is computed from the source at specific increments in range. Where changes in the sound speed occur along the sound' path, the ray tracing technique allows calculation of the trajectories of the ray paths at each range incorporating the local sound speed changes with depth. In deep waters where this assumption holds, the ray tracing model will be the best suited to describe the propagation of the sound from the source to a receiver, although it appears to be an acceptable choice even at low frequencies and shallow water environments (Hovem and Korakas, 2014).

Examples of projects that used the ray tracing technique in assessing the impacts of anthropogenic noise on marine animals include works from Erbe and Farmer (2000b) on boat noise marine mammals and Hovem *et al*. (2012) on airguns noise and fish. Considering the high dependence of the ray tracing technique to environment, the models have been modified or implemented to fit the environmental conditions found in the study areas. In Erbe and Farmer (2000a) the model for the sound propagation employing the ray tracing technique included absorption loss by the sediment and frequency dependent absorption by ocean water as well as changes in sound speed profiles with depth. Given a source spectrum of the underwater noise, the output of the sound propagation model is a matrix of received sound pressure levels and sound spectra as a function of range and depth. In a companion paper by Erbe and Farmer (2000b) the model was employed to estimate the ranges over which icebreakers may affect beluga whales in the Beaufort Sea. It was found that the ships were audible to beluga whales up to 78 Km with the mid-frequencies of the noise (3-10 KHz) retaining most of the energy over long ranges. The icebreaker noise was audible to belugas and capable of causing communication masking at ranges to 62 km. A temporary hearing shift was modelled to occur if a beluga stayed within 1–4 km of the icebreaker for at least 20 min. Coupling this sound propagation model with acoustic impact assessment models, Erbe (2002) predicted ranges over which boat noise 1) was audible to killer whales, 2) interfered with killer whale communication, 3) could cause a behavioural response and 4) could cause a temporary or permanent hearing loss.

PLANERAY, a Matlab based program developed by Hovem (2008) uses ray tracing to map the trajectories and travel times of a large number of eigenrays connecting the source to the receivers positioned on a horizontal line. This model assumes sound propagation in conditions where bathymetry varies moderately and the bottom is made of a solid layer overlapped by a fluid-like sediment layer. The time response for each receiver along the sound's path from the noise source to the receiver is calculated for every position and the sound fields are computed. No rays are traced into the bottom since bottom interaction is modelled by plane-wave reflection coefficients. The program needs a sound speed profile and bathymetry specified by the user as well as the source depth and receiver depth and range. Hovem *et al*. (2012) used PLANERAY supplemented with a wave number integration model (see section 3.2.5) to calculate the critical distance above which the sound levels from an array of seismic airgun elicit startle responses in Atlantic cod. The results from the model indicated a required distance in the range of 5-10 km for a seismic noise to elicit startle response, but dependent on the depth and the season (Hovem and Korakas, 2014). As per DeRuiter *et al*., (2006), it was found that the different propagation paths converged in zones to give highly elevated levels at larger distances.

RAY (Bowlin *et al*., 1992) has been employed in DeRuiter *et al*. (2006) to explain the propagation of airguns array noise in the Gulf of Mexico and compute the relative path and time of arrivals of the sound to tagged sperm whales. RAY shoots a fan of rays from the source and propagates all rays out to a desired range and depth by repeatedly applying Snell's law. The authors identified areas of high frequency content (>500 Hz) near the surface when a surface duct occurred. The results of the model were compared with those obtained during the period in which the surface duct was absent and found that the high frequency content was also absent. In the context of impact assessment this result has an exceptional impact as it shows that investigators using modelling techniques may learn about the behaviour of a particular signal in advance and therefore, include in the impact assessment also those species that were excluded. In the case of DeRuiter *et al*. (2006), for example, animals sensitive to high frequency sound may avoid the surface and this can be of particular concern for high frequency cetaceans (e.g. dolphins) that need to spend time at the surface to breathe and may be affected by the high energy released at high frequency by a commonly known low-frequency source (airgun).

Erbe and King (2009) used RAY to described the airguns array source and predict the ranges of cumulative impact of marine seismic survey over a tropical coral reef. In this case the ray tracing technique was used in the near-field (with sea floor modelled as a fluid-to-solid boundary) and the parabolic equation method (see section 3.2.4) in the far-field. RAY was run from each airgun in the array to a receiver grid in space. The transmission loss was modelled for each bathymetry profile clustered with a neural network and the energy was integrated over time and area at all receivers over all shots providing maps of cumulative SELs to identify regions of high risk.

A variant of ray tracing is the beam tracing (Porter and Bucker, 1987) that applies a beam width associated with each ray to determine the amplitude of the sound pressure at each range and depth. This technique has the advantage to predict sound fields at shadow zones and at caustics where the ray tracing method cannot.

Modelling of the acoustic output of operational offshore wind turbines using the beam trace model was presented in a study by Marmo *et al*. (2013) and found that the relative levels of underwater noise emitted depended on different types of foundations. Finite element (FE; see section 3.2.6) methods were used to determine the near-field (<40 m) noise level produced by operational turbines on monopile, gravity base and jacket foundations and results were then modelled with the beam trace method to compute cumulative far-field noise levels generated by 16 wind turbines. The modelled noise levels were predicted to be audible to marine mammals particularly at high wind speed when the monopole produced the highest SPL (<200 Hz), but perception of the operational noise was dependent to the hearing sensitivity of the species; low frequency marine mammals (minke whales) would detect the operational noise at ranges up to 18 Km and similar distance range was predicted for the fish species (Atlantic salmon, European eel, allis shad, sea trout). Jacket foundations (maximum SPL generated at frequencies >500 Hz) predicted the lowest marine mammal impact ranges compared to monopile and gravity foundations (audible SPL modelled at high wind speed for frequencies <100 Hz). High frequency marine mammals (seals, harbour porpoise and bottlenose dolphin) would not be displaced by the modelled operational wind farm noise.

The BELLHOP model (Porter, 2011) is an example of beam tracing method. It is a very fast computational program suitable for high frequency signals propagating in deep water areas. Given its relatively high speed and low memory demand and in conditions where the horizontal sectors are narrow enough to proper sample the environment, BELLHOP may be also used to produce a 3-D sound field display based on a set of 2-D sound fields from different bearings merged into a 3-D sound field.

BELLHOP has been employed by Miller *et al*. (2015) in an assessment of the changes in acoustic behaviour of tagged northern bottlenose whales (*Hyperoodon ampullatus*) to playback sonar pulses (90–100 m depth). The propagation model was fed with data of bathymetry, sound speed profile measured before the control exposure experiments, and sound source level. Although the results should be taken with caution because only one whale was examined, strong changes in swimming and diving behaviour were found to start at received modelled level of 107 dB re 1 μPa (SPL) but substantial movements were recorded at 30-46 Km away until at least seven hours after the playback experiments.

The beam tracing method offers an additional advantage to the investigators as it allows users to estimate the acoustic field at points taking in consideration the directivity pattern of certain frequencies of the sound (Ward and Needham, 2012). For the noise measured during the drilling of a foundation socket for a wave energy device at EMEC, Billia Croo, Orkney, the use of a frequency dependent beam pattern revealed that compared to simple models the beam pattern predictions were closer to the measured levels, whereas the SPL estimated by simple models significantly over estimated the levels. Computation of the received levels for propagating high frequency range (1 kHz to 160 kHz) using BELLHOP coupled with RAM model (see section 3.2.4) for low frequencies (0 Hz to 1 kHz), identified zones of behavioural response for marine mammals most likely to occur within 97 m from drilling noise and 65 m from operational device (derived from drilling noise by subtracting an arbitrary 3dB) (Ward, 2014).

3.2.3. Normal Mode

Normal mode solutions are derived from an integral representation of the wave equation. This method find its best application in cases where the sound speed is constant along the horizontal sound's path but changes vertically with depth. When a plane wave travels trhough a channel formed by a close proximity of two layers (e.g. between the surface and the bottom), the propagating wave is reflected at two opposite grazing angles, forming the propagating mode. If the grazing angle of the modes is smaller than the critical angle, then the modes will travel a long distance from the source. The normal mode technique is used to compute only those modes that propagates and the complete acoustic field is then constructed by summing up contributions of each of the modes weighted in accordance to the source depth.The propagating modes are characteriased by low attenuation and their propagation will depend on the frequency, depth and the sea water and sea bed composition and acoustic properties. The propagation model is complicated by the presence of those modes that do not propagate (evanescent or leaky modes; Jensen *et al*., 2011), so mode solutions is less accurate in predictions of the near-field where energy that is only partially reflected from the seabed is significant.

The normal mode is used in both shallow (in conditions where the number of modes is small) and deep waters and it is best suit for range-independent environments but it can be extended to range-dependent environments when range dependence is low. In the latter case, the mode may be computed for several vertical sections at defined distance from the source, where the enviromental parameters are costant and approximate the field as range-independent within each section (Evans, 1983).

KRAKEN (Porter, 1992) normal mode model uses a coupled-mode to find only the propagating modes in the water column. It is easy to compute and can be applied to range-indipendent and range-dependent conditions. DeRuiter *et al*. (2006) in a study to define zones of impact of playback airguns noise on tagged sperm whales used KRAKEN to find the cut-off frequency at five frequencies (from 50 to 1600 Hz) and determined whether or not the modes would propagate at each frequency tested.

3.2.4. Parabolic Equation

The Parabolic Equation (PE) solution (Tappert, 1977; Collins, 1993) is derived from the wave equation with the assumptions that only the outgoing wave is modelled and the back scattered energy is not considered. The PE is suitable for range-dependent environments over a range of water depths, irregular sound speed profiles and is commonly used in shallow and deep water. PE models are generally used at frequencies less than 1 kHz. The use of models based on the parabolic equation in the field of underwater acoustics has recently increased because they provide full solution to the wave equation compared to ray tracing models for example that do not.

The parabolic equation method was used to model the long range cumulative sound propagation of ship noise in Erbe *et al*. (2012). The model incorporates sound speed profiles, the acoustic properties of the sea bed and seawater absorption. When benchmarked against a simple geometric model (combining spherical and cylindrical spreading) the PE model showed good agreement and the deviation from the median PE and measured TL was 10dB at 80km (less at shorter ranges). Applying the same propagation model in a dose-response study to ship-noise exposed killer whales, Williams *et al*. (2014) found that subtle responses occurred around broadband received levels of 130 dB re 1 µPa (RMS). In both studies the source spectral density was derived by using RANDI model (Breeding *et al.*, 1994) and the source level was calculated as a function of ship length and speed corrected based on vessel size and propeller depth.

In condition where the sound speed was constant and reflection highly affected the sound propagation, Theobald *et al*. (2013) employed the parabolic equation method to predict the long-range propagation of pile driving and estimate zone of impacts for marine mammals and fish. For the sound source level the Energy Flux model (Weston, 1980) was employed and implemented to include the frequency-dependent absorption (Thorpe, 1967) to account for scattering effect that characterised the study area. It was estimated that instantaneous injury (PTS) of marine mammals would be likely to occur within 150m from the pile (700 m for pinnipeds) for a hammer of energy equal to 300KJ, whereas for fish injuries may occur at distance less than 250 m, depending on location. The zone of impact is reduced when hammer blow energy of 3,000 kJ was assumed.

RAM (Range-dependent Acoustic Modelling) is a software for sound propagation that uses the split-step Padé expansion approach developed by Collins (1993). RAMGEO is a version of RAM modified to handle sediment layers that are range-dependent and parallel to the bathymetry. The frequency at which RAM becomes too computationally difficult to use is dependent on the wavelength of the signal and the water depth in which the source is located. When the water depth is less than eight times the wavelength of sound, RAM is computationally efficient. Hastie *et al*., (2015) used RAM to compute the long range transmission loss of pile driving noise and predict long-term acoustic exposure based on movement and dive data in harbour seal. A median peak to-peak source level estimated by Nedwell *et al*. (2011b) was used and corrected to include the blow energy of the pile and the peak-to-peak field measurements.

HAMMER (Hydro-Acoustic Model for Mitigation and Ecological Response) is a proprietary modelling tool developed by HRWallingford that combines a three-dimensional, range-dependent, sound propagation model with data from a hydrodynamic model. The model takes into account local bathymetry and sound attenuation by sediments, as well as changes in sound speed with depth. Data can be incorporated in an ecological model that predicts movements of the fish driven by the combination of local hydrodynamics and noise fields. Several behavioural rules can be applied to simulated fish and include the individual response to noise, swimming behaviour (individual or school) and individual sensitivity to noise (bold or shy fish). In Rossington *et al*. (2013) the predicted sound levels compared with the measured levels in the Burbo Bank offshore wind farm showed a good agreement at 200 and 500 Hz (Nedwell *et al*., 2007b; Parvin and Nedwell, 2006). The model was used to assess the responses to pile driving (a source level of 120 dB re 1µPa was assumed) in Atlantic cod and it was predicted that, based on the behavioural input used in the simulation, the sensitive fish (hearing fish) would delay their arrival to the estuary. Clearly, the use of the definition of "hearing fish" and "non-hearing fish" is based on data on auditory sensitivity of the target species and as underlined before (section 1.4) these data are not always available. The use of this model is still at its infancy, although Bruintjes *et al*. (2014) presented a HAMMER simulation using behavioural data on European sea bass recorded in playback experiments in tanks. It was predicted that sea bass would reach the spawning area later due to an increased metabolic rate and simultaneous decrease in food intake when exposed to playback pile driving sound. In general, caution should be placed in using behavioural data collected in tanks (see section 1.4), but the authors anticipated that more data collected from field exposure of different fish species are currently being collected to implement the ecological response of the model (Bruintjes *et al*., 2015).

3.2.5. Wave number integration

The wave number integration method, also known as Fast Field Program (FFP; Di Napoli and Deavenport, 1980), has its best application in those conditions where the physical properties of the medium varies only with depth (range-independent), where it provides exact solution for the wave equation using the Green's function (Schmidt and Jensen, 1985) for the field in a horizontally stratified medium. This method has the advantage compared to the normal mode in that it can predict the sound field including not only the propagating modes, but also those that do not propagate (evenescent modes; Jensen, 2011). The inclusion of the leaky modes in the solution is most important for cases with few propagating modes, for instance, in low-frequency shallow-water acoustics and near the source. However, the method is restricted to horizontal stratified media.

SAFARI (Schmidt, 1987) and OASES (Schmidt, 2004) have been developed for solving the depth-separated wave equation in general fluid/solid horizontally stratified media. They are used to predict transmission loss in range-independent channels. A range-dependent application of the wave integration method is found in Goh and Schmidt (1996), where SAFARI was used to generate the Green's function in an ocean with arbitrary fluid-elastic stratifications.

The wavenumber integration method provides full solution of the wave equation solution, in contrast to the normal mode method, since it includes the contributions from the propagating modes and evanescent modes. This made the method particularly useful in Lippert *et al*. (2013) for predictions of the wave front in water and soil due to a pile driving strike, allowing computation of the full field, including the evanescent spectrum, at long ranges. This method was coupled with a finite element model (FE; see section 3.2.6) consisting of both the pile and its nearer surroundings (the soil was assumed to be an equivalent fluid).

In a simulation study using a wave integration modelling method, SCOOTER (included in AcTUP; Duncan and Maggi, 2006] was employed to predict transmission loss for selected frequencies of noise from a tidal turbines array, including also hydrodynamic interaction between turbines (inflow velocity and turbulence intensity), mechanical noise and gearbox as input to characterise the source level. Results showed that frequencies in the range 63 to 250 Hz attenuate the least (Lloyd *et al*., 2014).

3.2.6. Finite difference (FDM) and finite element (FE)

These solutions are not commonly found in the literature and generally apply to near source propagation. For example, FE has been used to model the interactions of the pile, soil and water near the pile driving and validation of this method is found in Zampolli *et al*. (2013) and further developed to characterise the acoustic source in the near field (Tsouvalas and Metrikine, 2013; Tsouvalas and Metrikine, 2014).

Breitzke and Bohlen (2010) based on a 2.5-D FDM determined sound exposure levels of single shots and cumulative sound exposure levels of multiple shots fired along a seismic line in the Southern Ocean.

3.3. Models comparison in the context of EIAs

This section discusses the sound propagation models used in projects that assessed the impact of anthropogenic noise on marine animals. These are presented in Table VII.

As already outline in section 3.2.1, simple models based on geometrical spreading of the sound away from the source exist. These models are still the most used in the UK for EIAs, but they have shown limitations especially in shallow waters because they do not consider variation in sound propagation due to bathymetry and acoustic properties of the sea bed. Good agreement with measured data could be achieved with the inclusion of parameters such as the blow energy for pile in pile driving activities, bathymetry and α (Thomsen *et al*., 2006; Bailey *et al*., 2010), or with a proper N factor, but this requires access to field measurements, which are not always available. INSPIRE for example, has been developed based on several measurements taken by Subacoustech Ltd around the coastal waters of UK and it is considered reliable by its developers (Mason *et al*., 2012). However, the choice of the input parameters and minimal representation of the sound changes while it moves from the source to the receiver could underestimate the computation of the received levels, as it is for example in the near field (Thompson *et al*., 2010), with consequences on the interpretation of the output (Handegard *et al*., 2013).

As we have seen in the previous sections, the calculation of propagated underwater sound fields using computational models is based on the solution of the wave equation with appropriate boundary conditions and environmental parameters. Each set of solutions are valid and computationally efficient over a limited frequency, depth and range regime. Ray theory is most suited to short range (range-independent) and high frequency scenarios in deep waters, whereas, normal mode and parabolic equation are applied to long range (range-dependent) and low frequency models. These features have allowed users like Erbe (2002) and Erbe and Farmer (200b) to employ the ray tracing method to calculate zones of impact in deep waters in marine mammals that might be impacted by high frequency sounds. The feature of being most suitable for short ranges made the ray tracing suitable to describe near-field acoustic field as shown in Erbe and King (2009), Hovem *et al*. (2012) and DeRuiter *et al*. (2006). Nevertheless, although being employed for predictions in deep waters and high frequency sounds, in range-dependent scenarios (e.g. up-sloping bottom profiles), assuming fluid and elastic bottom layers, the ray tracing seems a promising choice even for long range prediction of sounds that have energy concentrated at low frequencies such as airguns (Hovem and Korakas, 2014).

The application of the ray tracing methodology has limitation in that it does not compute acoustic prediction in shadow areas (up sloping and down sloping bottom) and at caustic areas, which are commonly created in shallow waters. In these situations, the WI models appear the most employed. This is the case for example in Hovem *et al*. (2012) where the assumption of being in shallow waters (between 100 to 200m) with a very variable depth within the study area has justified the use of OASES for long range transmission of low frequency sounds that would create shear waves. When the directionality of the source is a requirement (e.g. airguns) in range-dependent scenarios the beam tracing appeared the most used method. This is the case in Miller *et al*. (2015) where the signal was a playback sonar pulse and in Marmo *et al*. (2013) where the sound field were assumed to be strong related to wind direction and intensity.

When low-frequency sounds are to be modelled in shallow waters, the PE models appear to be the preferred choice. For example in Hastie *et al.* (2015) the study area included a radius up to 200 km and the transmission loss was calculated for each 1 km interval having changing depths (between 1 and 110 m). Similarly, the very shallow waters found in Williams *et al*. (2014) (source depth was 6 m and a receiver depth was 5 m) and the variable bathymetry made the use of the parabolic equation appropriate in describing the sound propagation. However, these models require a large amount of input data to describe the bathymetry, sound speed profiles and sediment properties in the local area. Such information may not always be available, and any model is only as accurate as its input data. HAMMER software for example incorporates a hydrological model in the software package and this has the value to increase the fidelity of the model prediction to some extent (Rossington *et al*., 2013).

A common drawback found during this review is related to the accurate representation of the sound source and thus computing the Source Level. Some of these studies used propagation models to derive the source level from empirical data (Bailey *et al*., 2010; Nedwell *et al*., 2006; Thomsen et al., 2006; Hastie *et al*., 2015), others developed more sophisticated propagation modelling of the source acoustic fields (e.g. Theobald *et al*., 2013; Williams *et al*., 2014), which have their relative assumptions based on the environment and the kind of source to model. Only few have measured the sound source level (Erbe and Farmer, 2000b; Erbe, 2002). It follows that the resulting received levels could differ from the empirical measurements and only ground truth validation of these models can improve the reliability of such models. The use of coupled models appear to be a good approach to derive the source level in cases where the sound propagation is to be computed over long ranges in conditions where the speed of sound varies with depth and not with range (Theobald *et al*., 2013) but also when the source to be model is not a monopole and affected by a large geographic scale and long duration (Hastie *et al*., 2015; Erbe *et al*., 2012).

All papers included in this review compared the received levels obtained by means of sound propagation modelling against the hearing sensitivity of the target species. When audiograms of the targeted species were not available, a proxy or a combination of audiograms found in literature has been used (e.g. Erbe, 2002; Nedwell *et al*., 2006). Clearly, in absence of similar empirical data for target species, authors must assume that both species respond in a similar way to sound pressure levels within the range of frequencies that they are able to hear. However, this approach could lead to problems in the interpretation of the output because, although grouping of animals under general criteria of impacts based on the threshold of marine animals exists (Southall *et al*., 2007), the assumption does not hold for all species, which have different thresholds and respond to noise in individual- and species-specific way. The high reliance of the impact assessments on audiograms of the target species found with this review has highlighted the need to obtain more data on hearing sensitivity of marine species in order to support EIAs. In addition, there is a need for more data on the behavioural and physiological response to anthropogenic noise, which add to the already existing criteria for impacts, as these will form the base against which modelled levels and ranges will be used. This is even more important for those proprietary software that include an impact assessment (INSPIRE and HAMMER), whose output is based on the available literature on the effects on marine animals. Finally, to be able to produce a reliable impact assessment, data of ambient noise levels of the study area should be known to define when levels of audible additional noise exceed critical levels, especially but not only when masking from the anthropogenic source is a concern. For some of the studies reviewed here, data of ambient noise were not available or where taken from close areas (e.g. DeRuiter *et al*., 2006) and this adds uncertainty to the modelling output.

Finally, it is important to note that most modelling is used to predict the transmission of sound energy or sound pressure and disregard modelling vector field quantities such as sound particle velocity and only Erbe and King (2009) mentioned it. The omission of the particle motion component from modelling can higly compromise the interpretation of the impacts on fish or invertebrates, which can detect the particle motion component of the sound, expecially in the near field or at reflecting boundaries.

Table VII Summary of the projects reviewed that used sound propagation modelling to assess the impacts of anthropogenic noise on marine biota.

ENTRY #	author	Year	Title	Literature Kind	Animals	Model Kind	SOUND LEVELS METRICS	ASSESS EFFECTS OF NOISE	DIRECT EFFECTS ON SPECIES OR PROXY
1	DeRuiter et al.	2006	Modeling acoustic propagation of airgun array pulses recorded on tagged sperm whales (*Physeter macrocephalus*)	peer-review article	marine mammals	RAY + parabolic equation; KRAKEN to find cut-off frequencies	SPL	YES	Sperm whales
2	BAILEY et al.	2010	Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals	peer-review article	marine mammals	spreading loss	SPLpeak to peak	YES	proxy
3	Rossington et al.	2013	Eco-hydro-acoustic modeling and its use as an EIA tool	peer-review article	fish	HAMMER	SPLpeak to peak	YES	Atlantic cod
4	Nedwell et al.	2006	An investigation into the effects of underwater piling noise on salmonids	peer-review article	fish	Linear Transmission Loss	dBht	YES	proxy
6	Erbe and Farmer	2000b	Zones of impact around icebreakers affecting beluga whales in the Beaufort Sea	peer-review article	marine mammals	ray tracing	12th octave band levels SPL	YES	beluga whale
8	Erbe	2002	Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca*), based on an acoustic impact model	peer-review article	marine mammals	ray tracing	12th octave band levels SPL	YES	proxy
10	Hovem	2012	Modeling Propagation of Seismic Airgun Sounds and the Effects on Fish Behavior	peer-review article	fish	PlaneRay + OASES	SPL; SEL	YES	Atlantic cod
11	Miller et al.	2015	First indications that northern bottlenose whales are sensitive to behavioural disturbance from anthropogenic noise	peer-review article	marine mammals	BELLHOP	SPL	YES	northern bottlenose whales (*Hyperoodon ampullatus*)
12	Thomsen et al.	2006	Effects of offshore wind farm noise on marine mammals and fish, biola, Hamburg, Germany on behalf of COWRIE Ltd.	Report	marine mammals; fish	spreading loss	SPL zero to peak; SEL	YES	Atlantic cod, Dab, Atlantic salmon, harbours porpoise; harbor seal
13	Thompson et al.	2013	Framework for assessing impacts of pile-driving noise from offshore wind farm construction on a harbour seal population	peer-review article	marine mammals	INSPIRE	dBht	YES	proxy
15	Marmo et al.	2013	Modelling of noise effects of operational offshore wind turbines including noise transmission through various foundation types	Report	marine mammals; fish	FE + Beam trace	SPL	YES	harbour porpoise; Atlantic salmon, European eel, shad, sea trout + proxy
16	Williams et al.	2014	Severity of killer whale behavioral responses to ship noise: A dose–response study	peer-review article	marine mammals	RANDI + parabolic equation	SPL	YES	proxy
17	Hastie et al.	2015	Sound exposure in harbour seals during the installation of an offshore wind farm: predictions of auditory damage	peer-review article	marine mammals	parabolic equation	SEL	YES	harbour seal
18	Theobald et al.	2013	Underwater Noise Modelling to Support the Dogger Bank Wind Farm Environmental Impact Assessment for Creyke Beck A and Creyke Beck B	report	fish; marine mammals	Energy flux + parabolic equation	SEL	YES	proxy

4. Conclusion

There are a number of numerical models available for the calculation of the sound propagation in ocean. These include ray tracing, normal mode and parabolic equation models. Each model has its own strengths and weaknesses. Some models are best suited to deep water, others to shallow water; some can deal with complex bathymetry profiles, others require a constant water depth. Some models can be computationally more efficient than others when dealing with specific frequencies. It follows that the choice of the propagation model depends on the circumstances found in the environment considered and the characteristic of the underwater signal.

There are challenges in using sound propagation modelling that include the high variability of the bottoms and environmental parameters encountered in shallow waters, the lack or scarse available data of ambient noise, and paucity of auditory data available for most of marine species, coupled with the lack of criteria of impacts for fish and invertebrates. For fish and invertebrates in particular, the particle motion component of the sound should be included in the criteria for impacts, but at today, this has not been done by many. Definite conclusions on the effects of anthropogenic noise also cannot be drawn yet, considering the high variability in responses shown by species and individuals. This has an impact on the knowledge of long term consequences on population and effect on fitness.

Finally, the collection of accurate oceanographic data such as sound speed profiles, sea floor properties, and bathymetry data for computational modelling, although being identified as a fundamental requirement for effectively represent the sound propagation in EIA contexts, presents several constrains and this has consequences on the outcome of an ocean acoustics propagation model. It would be beneficial to organise data collected by different users, including research institutions and developers, in a consistent database that could be shared by investigators and where data are easy to find. The latter could be applied to measurements of underwater noise as well. In fact, although the number of activities aimed to collect underwater noise data has increased greatly, this review has identified a shortage of measurements in several areas, which in turn could limit the application of sound modelling for EIAs. In the United Kingdom Cefas, The Crown Estate and The British Oceanographic Data Centre have collections of noise data. However, management of data in a standardised and sharable database would be significantly beneficial.

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