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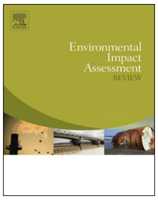

# Underwater noise modelling for environmental impact assessment

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ABSTRACT

Assessment of underwater noise is increasingly required by regulators of development projects in marine and freshwater habitats, and noise pollution can be a constraining factor in the consenting process. Noise levels arising from the proposed activity are modelled and the potential impact on species of interest within the affected area is then evaluated. Although there is considerable uncertainty in the relationship between noise levels and impacts on aquatic species, the science underlying noise modelling is well understood. Nevertheless, many environmental impact assessments (EIAs) do not reflect best practice, and stakeholders and decision makers in the EIA process are often unfamiliar with the concepts and terminology that are integral to interpreting noise exposure predictions. In this paper, we review the process of underwater noise modelling and explore the factors affecting predictions of noise exposure. Finally, we illustrate the consequences of errors and uncertainties in noise modelling, and discuss future research needs to reduce uncertainty in noise assessments.

## 1. Introduction

Underwater noise from human activities is known to have a number of adverse effects on aquatic life (Nowacek et al., 2007; Slabbekoorn et al., 2010; Williams et al., 2015). These can range from acute effects such as permanent or temporary hearing impairment (McCauley et al., 2003; Southall et al., 2007), to chronic effects such as developmental deficiencies (de Soto et al., 2013; Nedelec et al., 2014) and physiological stress (Wysocki et al., 2006; Wright et al., 2007; Rolland et al., 2012). While some anthropogenic noise is produced intentionally (e.g. naval sonar, echosounders), most noise sources are an incidental by-product of human activity (e.g. shipping, construction). Noise-generating activities are necessary for many proposed developments that are subject to a regulatory consenting process: construction may entail noise sources such as pile driving, dredging, or drilling, while geophysical surveys using seismic airguns are often needed prior to coastal construction and offshore energy developments. Many jurisdictions now require a noise impact assessment for proposed developments that have the potential to cause significant adverse impacts on key species. In some cases, effects on the wider ecosystem must also be considered.

The EIA process for underwater noise typically involves the application of quantitative noise exposure thresholds for particular species to a model of predicted noise levels at the site, resulting in effect zones — predicted areas for different categories of effect. Noise exposure thresholds are indicative noise levels at which certain effects (e.g. mortality, temporary hearing impairment, behavioural responses) are predicted, and may be defined for single noise exposures or for cumulative exposure to successive events. A number of different threshold criteria have been developed in recent years for marine mammals (e.g. Southall et al., 2007; NOAA, 2013, 2015) and fish (e.g. Popper et al., 2014), and it is expected that these will continue to evolve in light of new research into the effects of noise on aquatic species. Acknowledging that these thresholds form a necessary counterpart to modelling in noise impact assessments, the present work focuses on the acoustic modelling which underpins predictions of effect zones, independently of the (evolving) thresholds used to predict animal responses.

Modelling of underwater sound propagation has been an established discipline for decades, and has its origins in military applications of sonar technology. Several modelling approaches have been developed, each with differing suitability according to acoustic frequency range, water depth, computational requirements and ability to account for spatial variability in the environment (Jensen et al., 2011). The accuracy of model predictions depends both on employing an appropriate model and on the quality of the input data. Confidence in model predictions further requires validation with field measurements of sound propagation, and these measurements can also be used to optimise model parameters.

In practice, noise modelling for EIAs is often carried out using simplistic models, with limited environmental data, and without field measurements to ground-truth model predictions. In some cases, practitioners have developed proprietary models whose inner workings are not disclosed to regulators. This presents regulatory decision makers and their advisors with considerable uncertainty in the predictions of possible impacts (though this uncertainty may not be apparent). To better inform regulators, stakeholders, and developers of the factors which lead to uncertainty in noise assessments, this paper provides concrete

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examples of how different modelling procedures can affect predictions. By raising awareness of these issues, we aim to help promote best practice in noise impact assessments, and to enable more informed EIA processes for noise-generating developments.

## 2. Anatomy of a model

The basic objective of noise modelling for EIAs is to predict how much noise a particular activity will generate in the surrounding area. More formally, the aim is to model the received noise level (RL) at a given point (or points), based on the sound source level (SL) of the noise source, and the amount of sound energy which is lost as the sound wave propagates from the source to the receiver (propagation loss; PL). The relationship between these quantities is encapsulated in the classic sonar equation (Urick, 1983):

$$RL = \mathrm{SL}–PL \quad (1)$$

This straightforward expression is fundamental to the many approaches to modelling underwater noise, and its simplicity belies considerable complexity in the task of modelling the source level and propagation loss in order to predict received levels. In the following sections, we elaborate on the ways in which SL and PL can be predicted, and the various factors which affect the resulting estimates of RL.

## 3. Model selection

The first step in carrying out a noise assessment is to identify an appropriate sound propagation loss model. A large number of propagation models have been developed, based on several underlying mathematical methods, such as ray theory, normal modes, multipath expansion, wavenumber integration or parabolic equation (Porter, 1992; Collins, 1993; Porter and Liu, 1994; Etter, 2009, 2013; Jensen et al., 2011). No single model is applicable to all acoustic frequencies and environments (see Table 1). For a given scenario, a particular model may be limited by the validity of the model assumptions, by the number of computations required, or by instabilities in the model algorithm. Important factors to consider are the frequencies of sound to be modelled, the water depth, and whether spatial variation in the environment is significant (known as range dependence or range independence). Each of these factors should influence model selection. For example, models based on ray theory (e.g. BELLHOP; Porter and Liu, 1994) poorly describe the way that sound propagates at low frequencies in shallow water (Table 1), which is a common EIA modelling scenario.

For convenience, propagation loss is often estimated using simple spreading laws of the form.

$$PL = \mathrm{N}\log_{10}(R) \quad (2)$$

where $R$ is the distance from the noise source in metres, and $N$ is a scaling factor. Since this simplistic approach does not account for complexities in the environment, it can only produce reasonable predictions for uncomplicated propagation scenarios, for example range-independent environments where extensive measurements from the study site are available to derive the value of $N$. Though widely used, spreading law models can lead to substantial errors if applied to the more complex environments typical of many coastal and inland waters.

To illustrate this, we compared predictions from a spreading law model to a parabolic equation model. For the spreading law model, sound levels were predicted using $15\log_{10}(R)$ (sometimes called ‘intermediate spreading’ or ‘practical spreading’), which is derived from a theoretical treatment of sound propagation in shallow water obtained by Brekhovskikh (1965) and extended by Weston (1971). The parabolic equation model was based on RAM (developed by Collins, 1993, 1999), and utilised local data on bathymetry, sediment structure, and sound speed. Measurements of impact pile driving noise were made simultaneously at two locations in the Cromarty Firth, Scotland, and each model was then used to calculate the source level of piling (the sound level at a nominal distance of 1 m from the source). This source level was then used as the input to each model to predict levels of noise within the line-of-sight of the piling, yielding noise maps for each model (Figs. 1a and b).

**Table 1**
Applicability of the most common propagation models according to water depth, acoustic frequency, and range dependence (RI = range independent; RD = range dependent). Black cells indicate modelling approach is applicable and computationally efficient; grey cells indicate limitations in accuracy or computational efficiency; white cells indicate that the modelling approach is neither applicable nor practicable. Adapted from Etter (2009).

| Model approach | Example algorithm | Applications | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Shallow water | | | | Deep water | | | |
| | | Low frequency | | High frequency | | Low frequency | | High frequency | |
| | | RI | RD | RI | RD | RI | RD | RI | RD |
| Ray | BELLHOP (Porter and Liu, 1994) | | | ▨ | ■ | ▨ | ▨ | ■ | ■ |
| Normal mode | KRAKEN (Porter, 1992) | ■ | ▨ | ■ | ▨ | ■ | ▨ | ▨ | |
| Parabolic equation | RAM (Collins, 1993) | ▨ | ■ | | | ▨ | ■ | ▨ | ▨ |

Spreading laws assume that sound levels decrease monotonically with increasing distance from the source, and that the pattern of sound levels has circular symmetry, both of which are evident in Fig. 1a. In practice, however, sound propagation is much more complex. The RAM predictions show both strong variability with angle from the source, as well as some local increases in sound levels with increasing distance (e.g. directly to the south of the source; this was confirmed by the measurements). The difference between the two models is shown in Fig. 1c. Compared with RAM, the spreading law underestimates noise levels close to the source and substantially overestimates noise levels further from the source (the regions where there was no difference between the models include the sites where the field measurements were made). In this example, predictions for an EIA made on the basis of the spreading law model would underestimate noise exposure close to the source, which is the region where noise levels are highest (and risk of injury and disturbance is greatest). Furthermore, noise levels are overestimated further from the source (Fig. 1c), giving the misleading impression that a larger area would be affected. This clearly demonstrates why selection of an appropriate model is critical to making reliable assessments of potential noise exposure.

## 4. Input data

While it is critical to select an appropriate propagation model for the site, even a suitable model will not yield valid results if based on insufficient input data. The quality and resolution of the bathymetry, sediment, and water column data each affect the accuracy of propagation modelling, and any errors in the predicted sound level of the noise source will produce corresponding errors in the model output. In this section, we consider each of these factors in turn, and provide some illustrations of how inadequate input data can affect predictions of noise exposure.

### 4.1. Bathymetry

To set up a noise propagation model it is first necessary to choose the spatial extent and spatial resolution of the modelled area (the model domain). Most developments requiring a noise assessment occur in shallow water environments (e.g. <100 m), where the topography of the seafloor has a strong influence on sound propagation. This is because in shallow water, the main mechanism for sound propagation is