The SoundWaves Consortium

Criteria and Metrics for Assessing the Effects of Underwater Sound on Fish and Invertebrates

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Introduction

The expansion of offshore industrial activities in recent years has led to concern about the impact of man-made or anthropogenic sounds upon marine animals and the marine environment. These activities include offshore oil and gas developments, wind farm construction, wave and tidal power resources, as well as attendant increases in shipping.

Many marine animals use sounds during their everyday lives; to track down prey, avoid predators, navigate and communicate with one another. A succession of reports and scientific papers have emphasised the risks to these animals from exposure to sounds (Richardson *et al.* 1995; Popper *et al*, 2004: NRC 2005; Madsen *et al.* 2006; Slabbekoorn *et al.* 2010; Southall *et al.* 2007; OSPAR, 2009; Normandeau 2012). Initiatives like the EU Marine Strategy Framework Directive and application of the OSPAR Convention (The OSPAR Convention is the current legal instrument guiding international cooperation on the protection of the marine environment of the North-East Atlantic) have also been aimed at protecting the marine environment from noise. Increasingly, environmental assessments of the impact of offshore developments have to consider the effects of underwater sounds on marine animals.

Such assessments involve evaluation of the effects of noise in causing physical injury, behavioural disturbance, and population level impacts in marine animals. The likelihood that an adverse effect upon biological receptors may occur as a result of sound exposure is evaluated. A conclusion is subsequently reached about the severity of the effects. Risk assessment can then be used to construct “what-if” scenarios to evaluate new and existing technologies for effective prevention, control, or mitigation of impacts, and to provide a scientific basis for action to reduce risks.

As part of the process of risk assessment it is necessary to know the levels of sounds that may cause potential harm to animals, as well as those levels that are likely to be of no consequence. Developing such criteria for harm resulting from sound exposure is currently of high priority. Criteria are usually provided as a threshold value of an acoustic metric, above which a particular level of damage or effect is likely to occur. The actual damage should be, but is often not, specified clearly. The metric should be, but is not always, specified clearly.

The first set of comprehensive underwater sound exposure criteria was defined for marine mammals (Southall, et al. 2007). There is much less information available for other aquatic animals including fish and invertebrates, although impacts are currently having to be assessed and interim procedures have been developed to achieve this. This paper reviews attempts to set sound exposure criteria for fish and invertebrates and considers the metrics associated with these.

Metrics are measures by which sounds can be defined and compared; values that quantify the effects of a sound. It is important to use accepted, well-defined, consistent and appropriate metrics. In this document we consider those metrics that best facilitate assessment of the effects of sound and vibration upon fish and marine invertebrates.

The effects of sounds on animals may vary in severity:

- At the highest sound level an animal may be killed or seriously injured by the forces associated with passage of the acoustic wave through its body.

- At lower levels the animal may receive injuries to its auditory system. This may not cause immediate effects but may have longer-term consequences in terms of communication, avoiding predators, or capturing prey.

- Lower levels still may cause no discernible physiological damage but may affect the behaviour of the animal: for instance driving it from, or perhaps attracting it towards, an area. Animals may be excluded from key habitats, and this may occur at a ‘bad’ time in terms of migration or breeding.

These distinctions between effects at different levels and distances from a source originated with Richardson et al (1995) and are summarised in Table 1.

Table 1. Proposed effects on animals (from Richardson et al., 1995).

Impact	Effects on animal
Mortality	Death from damage sustained during sound exposure
Injury to tissues; disruption of physiology	Damage to body tissue: e.g. internal haemorrhaging, disruption of gas-filled organs like the swim bladder, consequent damage to surrounding tissues
Damage to the auditory system	Rupture of accessory hearing organs, damage to hair cells, permanent threshold shift (PTS), temporary threshold shift (TTS)
Masking	Masking of biologically important sounds including sounds from conspecifics
Behavioural changes	Interruption of normal activities including feeding, schooling, spawning, migration, displacement from favoured areas

The users of sound exposure criteria need to be aware that the development and use of these criteria is at an early stage. Indications are that, certainly for behavioural responses, the detailed context of an animal’s behaviour, the environment and immediate ecological imperatives may well play an important role (Ellison et al., 2012). It is perhaps naïve and may even be inappropriate to seek single values of particular metrics to define a particular level of response by an animal. Nevertheless, single values are often required by current risk analysis procedures.

Scientists have developed their own specialised language for discussing underwater acoustics. This report is written for biologists, regulators, and those preparing environmental statements on the impact of underwater sound. Not everyone will be familiar with underwater acoustics and its terminology. The report therefore outlines in an appendix the terms used to describe, monitor, and measure underwater sounds and the operational procedures required to characterise sounds, especially in relation to their effects upon marine fishes and invertebrates.

Currently no formal consensus exists regarding measurement and evaluation of the effects of underwater sounds. Indeed, there is no internationally accepted terminology for the description of underwater sounds. Many measurements of sounds in the sea have been made in the course of specific studies for military purposes or for the preparation of environmental statements. There is no central repository for these data, nor are there standards or protocols for data collection. A report by the Netherlands Organisation for Applied Scientific Research (TNO) (Ainslie et al. 2011) puts forward proposals, but these have yet to be agreed upon internationally, and the text is difficult for the lay reader to follow. In 2011 the International Standards Organization (ISO) accepted an ASA proposal to create a sub-committee dedicated exclusively to underwater acoustics (ISO TC43 SC3). A Working Group was set up in 2012 dedicated to creation of a terminology standard. The publication of an International Standard for Underwater Acoustical Terminology is planned for March 2015. Currently, different terms and different metrics are used in different contexts. This is especially confusing to newcomers to the field.

The term ***noise*** is often used colloquially to describe unwanted sound, or sound that interferes with detection of any other sound that is of interest. However, noise is also used to describe background sounds in the sea, including the naturally occurring and spatially uniform sounds generated by distributed biological sources, weather events, or other physical phenomena, some of which cannot be assigned to individual sources. In this paper the term sound, rather than noise, is used both to refer to identifiable man-made sources, such as individual ships or oil and gas platforms, or to distant man-made sources, which cannot be located or identified. However, where others have used the term ***ambient noise*** or background noise to describe naturally occurring sounds from distributed sources, or where noise is used to describe interference with signal detection, then that usage will also be followed.

The role of this document is threefold:

1. To act as a relevant reference of acoustic theory at a level appropriate for use by biologists and regulators.

2. To act as an overview of present thinking in the role and application of acoustic metrics in assessing the effects of noise on fish and invertebrates.

3. To suggest important areas of research and gaps in present knowledge which could lead to a more consistent and considered set of metrics that would allow regulators to assess more reliably the effects of sound on fish and invertebrates.

The Nature of Underwater Sound

Sound is essentially a local mechanical disturbance generated within any material medium, whether it is a gas, liquid or solid. Sound does not travel through a vacuum.

In water, sound is generated by the movement or vibration of any immersed object and results from the inherent elasticity of the surrounding medium. As the source moves, kinetic energy is imparted to the medium and is passed on as a travelling acoustic wave, within which the component particles of the medium are alternately forced together and then apart. The particles of the medium oscillate back and forth along the line of transmission in waves of compression and rarefaction. The disturbance propagates away from the source at a speed that depends on the density and elasticity of the medium.

The passage of a sound involves a transfer of energy without any net transport of the medium itself. Close to a large sound source, however, it is not easy to draw a distinction between sound and bulk movements of the medium. Local hydrodynamic effects occur, including turbulence, which do involve net motion of the medium and that do not depend upon the medium being elastic. To a particular measuring instrument or an animal's sensory systems, these hydrodynamic (rather than strictly acoustic) phenomena, may be indistinguishable from sounds.

Sounds are most often described in terms of the changes in pressure that accompany passage of the disturbance: the deviation above and below the local hydrostatic pressure or sound pressure level. However some animals, including aquatic invertebrates and many fish, respond to the particle motion itself, even though the magnitude of the back and forth motion of the component particles of the medium may be very small.

Sounds inevitably diminish in level as they propagate away from a source, both as the wave fronts spread out over a larger area and as the sound is absorbed by the medium and its inclusions. Sounds also change close to a reflecting boundary. At a boundary with a 'soft' material, having low acoustic impedance, like air, the local amplitude of particle velocity will be much higher. The sound will also be reflected with inverted phase. Close to a 'hard' boundary, like the seabed, the amplitude of particle velocity will be reduced and the phase of the reflected sound will not be inverted. Sound is also refracted by temperature and salinity gradients that can affect water density and therefore impedance.

Thus, in considering propagation of a sound in the sea there are a number of effects to consider. There is a direct transmission path between the source and the receiver. There is reflection from interfaces, such as the water surface and the seabed. There is also refraction of sound and shielding effects from differences in the properties of the water itself. A significant difference between the propagation of sound underwater versus sound in air is that there are distinct and highly reflective boundaries (the water surface and the seabed), and changes within the medium itself, that can substantially affect sound propagation.

It is possible in the open sea, distant from the source, under conditions where the topography and any changes in temperature and salinity have been measured, to model the propagation of sound and to estimate the magnitudes of sound pressure and particle velocity at different distances, using the wave equations. It is also possible to take account of transmission loss (see appendix: which measures the dissipation in sound energy with distance), and geometric spreading (whether this is spherical as in open water, or cylindrical in shallow water). The effects of reflection, refraction and reverberation can be considered and any scattering at the seabed and sea surface and by any organisms or particles in the water can be taken into account. It is now commonplace to model and predict the propagation of sound from assumed simple point sources.

It is more difficult to model sound propagation from a large and complex source like a ship, a pile driver, or an array of seismic air guns. A ship is a distributed source, with many subsidiary sources of sound housed within the hull, flow noise from the passage and displacement of water, and additional sound from the propeller. A seismic array may be hundreds of metres across with many airguns firing in a particular sequence. Similarly, a driven pile is large in dimensions, generating sounds in a variety of ways, including the generation of compression and shear waves within the seabed. None of these sources are point sources. Pile driving is especially difficult to examine because transmission takes place through the different layers of substrate beneath the seabed, where most of the energy from the driven pile is dispersed. This energy can be re-radiated into the water, combining with the energy that has been transmitted directly into the water column and complicating the prediction of sound levels. The motion imparted to the seabed itself, as vibrations, may also affect marine animals. These effects are rarely considered in impact assessments.

It is often critically important to distinguish between the level of sound from a source – the ***source level*** – and the level received at a particular point in the sound field, for example at a hydrophone or at an animal's ear – ***the received level***. Defining the source level is complicated because of effects arising from reflection and refraction by the sea surface, seafloor, or other interacting boundary layers, and also by whether the source is impulsive or continuous. In pile driving, where the sound source is coupled to the seafloor, the water column, and in air, the conventional definition of source level is especially difficult to apply

In very shallow water, or in the extreme case of a water tank in the laboratory, any sound source is completely surrounded by reflecting surfaces and the acoustic conditions become extremely complex. It is no longer easy to predict or to model sound propagation. Many experiments on the hearing abilities of aquatic organisms have been carried out under these conditions, where measurements of the sounds received by the organisms under test have lacked precision. Such results must be treated with great scepticism (see under 'Determining the hearing abilities of marine mammals').

Monitoring and Measuring Underwater Sounds

Underwater sounds can be detected by means of a hydrophone, the underwater equivalent of a microphone. A hydrophone placed at a point in the sound field converts the fluctuating pressures experienced with passage of a sound into an electrical signal. Essentially, the sound pressure is converted into a fluctuating voltage that can then be amplified, filtered and measured. To express the measurement in terms of sound pressure it is necessary to calibrate the hydrophone by placing it in a known sound field. The calibration is given as the voltage that corresponds to a specified sound pressure; for example, 0.01 millivolt (mV) for a sound pressure of 1 microPascal (µPa).

It is important to recognise that many fish and invertebrates respond to particle motion rather than sound pressure. Measuring or estimating the sound fields to which these animals are exposed poses formidable difficulties (see below). It has become commonplace to estimate the particle velocity from measurements of the sound pressure, using either the plane wave equation or the spherical wave equation. Such estimates are only valid under well-specified circumstances, distant from reflecting boundaries. Such conditions do not prevail in small laboratory aquarium tanks, in shallow water, or close to the sea surface or seabed.

Underwater sounds may be divided into continuous and impulsive signals. Continuous sounds can be tonal or broadband, and some may be intermittent. Some continuous sounds may be ‘rougher’ than others, and are potentially more damaging than other continuous sounds. Exposure to rougher noise produces substantially greater hearing loss in mammals than exposure to Gaussian noise. Examples of sources producing continuous sounds include ships, aircraft, machinery operations such as drilling, operational wind turbines and tidal generators, dredging, and some active sonar systems.

In contrast, impulsive sounds are brief, broadband transients (e.g., explosions, seismic airgun pulses, and pile driving strikes). Near their source, such sounds have a rapid rise time, reach a maximum value, and are followed by decay. With increasing distance the time structure becomes drawn out and less “sharp” or less impulsive in character. Impulsive sounds have the potential to be much higher in amplitude at the source than continuous sounds.

A major issue in trying to describe and understand the effects of man-made sounds is how they are best described in terms that allow assessment of the energy that actually results in effects. The metrics applied to continuous sounds for estimating the likelihood of damage are the root-mean-square (rms) sound pressure, peak sound pressure, and, for many fishes, the corresponding particle motion in three dimensions. Transient sounds may be expressed in terms of their peak levels. However, rms and peak levels are not sufficient for characterizing the energy in sounds such as those generated by pile driving strikes or the discharge of seismic airguns. Hasting and Popper (2005) proposed the use of Sound Exposure level (SEL), the time integral of the pressure squared for a single event, as a metric for setting pile-driving criteria (as well as for other impulsive sounds). The sound exposure level (SEL) sums the acoustic energy over a measurement period, and effectively takes account of both the sound pressure level (SPL) of the sound source and the duration of the sound. It is a measure that can be summed across repeated emissions to give an overall measure of sound energy over a period of time. Subsequent papers (e.g., Popper et al., 2006; Carlson et al., 2007; Popper & Hastings, 2009) have advocated use of both SEL and peak levels and have emphasized the need to consider the effects of repetition of the impulse and/or the rise time of the signal.

Cumulative and Aggregate Effects

Assessment of sound-producing activities generally has to assess both cumulative and aggregate effects. ***Cumulative effects*** are those that arise from the temporal repetition and accumulation of effects from a particular source—for example the repeated strikes of a pile driver. By contrast, in-combination effects, sometimes described as synergistic or ***aggregate effects***, arise from the accumulation of effects from different types of source—for example, from sounds from a number of different pile drivers or from the combined effects of exposure to sounds from both pile driving and shipping. The challenge is to compare the effects of repeated exposure to single and multiple sounds and to examine interactions between sounds from different sources (both natural and man-made).

Currently there are difficulties in conducting appropriate cumulative impact assessments. More rigorous methods are required to assess the cumulative and aggregate impacts of exposure to sound. There has been increasing use of the $\mathrm{SEL_{cum}}$ as a metric (see Appendix), as a first step towards achieving that aim. The $\mathrm{SEL_{cum}}$ can be estimated from a representative single-strike SEL value and the number of strikes that would be required to place the pile at its final depth by using the following equation:

$$\mathrm{SEL_{cum}} = \mathrm{SEL_{ss}} + 10 \log (\text{number of pile strikes})$$

This assumes that all strikes have the same SEL value and that a fish would continuously be exposed to pulses with the same SEL, which is never actually the case.

Frequency Weighting Functions

Animals do not hear equally well at all frequencies within their functional hearing range. They are more sensitive to some frequencies than others. Frequency weighting offers a method for quantitatively compensating for differences in the frequency response of sensory systems. It minimises the influence of extremely low- and high-frequency sounds sources that may be detected poorly, if at all, by the animal.

For humans, frequency-selective weighting is often employed to measure the sound pressure in a specific frequency band related to the relative sensitivity of humans to sound. The A-weighting curve is derived from the inverse of an idealised equal loudness hearing function across frequencies, standardised to 0 dB at 1 kHz. The measurements are often denoted as dB(A) levels. The practice of indicating weighting by attaching letters to dB, as in dB(A), has led to the mistaken belief that weighted levels are measured on a different scale, or by a frequency weighted decibel. Strictly the use of such attachments is incorrect, and is strongly deprecated by the standards authorities. We will continue to use dB attachments in this report to conform to its usage in other documents, but would emphasise that strictly the symbol dB indicates a non-dimensional ratio and is neither a quantity symbol nor an abbreviation for level.

For marine mammals generalized frequency-weighting functions have been derived for different functional hearing groups using principles from human frequency-weighting paradigms, with adjustments for the different hearing bandwidths of the various marine mammal groups (Southall et al. 2007). This ‘M-weighting’ has been used to investigate effects of man-made sounds upon marine mammals.

Equal-loudness contours are lacking for most marine animals and other frequency-weighting functions are used, based on ***hearing thresholds*** at different frequencies. It should be noted that these are not directly comparable to A-weighted levels.

The hearing threshold (or auditory threshold) is the average sound level that is just audible to an animal under quiet conditions. Plotted as a function of frequency it provides an ***audiogram***. Hearing thresholds are generally determined for pure tones (single frequency) against a natural level of background noise. Species can differ markedly with respect to the frequency range they can hear, and with respect to their absolute sensitivity. In addition, in noisy environments like the sea the threshold to a particular sound can be greatly affected by the level of background noise, which changes with time and weather conditions.

The use of weighting curves is especially important when effects in terms of behavioural responses of animals are being considered. When considering tissue injury or damage, however, frequencies falling outside the hearing range of the animals, that are inaudible, may also be important. In particular, the high frequencies associated with rapid rise-times may bring about or exacerbate injury. If injury is a concern, care must be taken when applying weighted measurements to avoid the exclusion of frequencies that may be damaging to tissues.

Nedwell et al. (2007) suggested the use of the dB_{ht} (*Species*) as a useful tool in quantifying the level of sound experienced by each marine species. The dB_{ht} takes account of hearing ability by referencing the sound to the species' hearing threshold. The dB_{ht} is similar to the A-weighting that is used for human sound exposure in air, but not strictly analogous to it as it is based on the audiogram rather than equal loudness contours. Since any given sound will be detected at different levels by different species (as they have differing hearing abilities) the species name must be appended when specifying a level. For instance, the same sound may have a level of 70 dB_{ht} (*Gadus morhua*) for a cod and 110 dB_{ht} (*Phoca vitulina*) for a common seal.

The sound level expressed as dB_{ht} (*Species*) is usually much lower than the un-weighted level, because the sound will contain frequency components that the species cannot detect. Where the energy within the received sound falls mainly within the hearing range of the animal, then the weighted level may be similar to the un-weighted level.

Not all fishes and invertebrates respond to sound pressure. Many are sensitive to particle motion. A dB_{ht} can be determined for particle velocity. However, particular care must be taken in applying a dB_{ht} expressed in terms of sound pressure to an animal that is sensitive to particle motion as the values will not be appropriate close to a sound source or near a reflecting boundary.

It is also very important that the hearing sensitivity curves or audiograms on which dB_{ht} values are based are expressed in appropriate metrics, and obtained under appropriate acoustic conditions. Of the 30,000 or more extant species of fish only a very small number have had their audiograms measured, and of these only a handful have been measured under appropriate acoustic conditions. Very few audiograms have been determined for marine invertebrates (Lovell et al., 2005).

There are methodological problems associated with the determination of hearing thresholds and the preparation of audiogram and these problems have a bearing on their use for determining the effects of man-made sounds. These problems are described in the Appendix.

Hearing Impairment

In addition to examining hearing thresholds in animals it is also important to examine those sound levels that may damage their auditory systems and impair the detection of sounds. It is here that physiological measurements become more valuable. There is a wide range of potential impacts from high-level sounds on the auditory system; some are temporary and others may be permanent. Permanent Threshold Shift (PTS) is a permanent loss of sensitivity, often detected by observing a decline in Auditory Evoked Potentials (AEPs, see Appendix). PTS may be a consequence of damage to the hearing organs including destruction of the sensory hair cells of the auditory epithelia of the ear. Fish are able to repair or replace sensory hair cells that have been lost or damaged (e.g., Lombarte et al. 1993; Smith et al. 2006) and it is possible that PTS may not occur in fish as a result of damage to hair cells, although it may occur if there is damage to accessory hearing organs or the nervous system.

Temporary Threshold Shift (TTS) is a short-term reduction in hearing sensitivity caused by exposure to intense sound. After termination of the sound causing TTS, normal hearing ability may return over a period that may range from minutes to days, depending on the intensity and duration of exposure and the type of sound causing the damage (e.g., Popper and Clarke 1976; Scholick and Yan 2001, 2002; Smith et al. 2004a, 2004b). During a period of TTS, the survival of animals may be at risk. The effects and significance of different levels of TTS on free-living fishes and invertebrates have not so far been examined. There is evidence that, given the same type and duration of sound exposure, a much louder sound will be required to produce TTS in fish that do not hear well compared to fish that are more sensitive to sounds (Smith et al. 2004a, 2004b). There is some controversy whether TTS can be regarded as a form of injury.

As there are very few valid audiograms and other information on the hearing of fish and invertebrates, including levels of sound that may invoke TTS or PTS, an important question is whether it possible to identify particular “types” of animal that may serve as models for other species and life history stages. There are major differences in auditory capabilities across fish and invertebrate species. Some broad generalisations can be made about the effects of sound on particular types of fish and it may be feasible to develop generalized weighting curves that describe the overall hearing sensitivities of these different groups. In some of the earlier literature, a distinction was made for fish between hearing generalists and hearing specialists, although it was always evident that this was a naïve approach and that some species like the Atlantic cod did not fit neatly into either category. A better approach may be to distinguish fish groups on the basis of their differing hearing mechanisms and audiograms. For example:

I. Fishes lacking swimbladders that are sensitive only to particle motion and show sensitivity to only a narrow band of frequencies. This group includes the dab *Limanda limanda*, and plaice *Pleuronectes platessa* (Chapman and Sand 1974), and elasmobranch species (Casper and Mann 2009).

II. Fishes with swimbladders, where the swimbladder does not appear to play a role in hearing. These fish are sensitive only to particle motion and show sensitivity to only a narrow band of frequencies. This group includes the Atlantic salmon *Salmo salar* (Hawkins and Johnstone 1967). However, because of the presence of a swimbladder these fish may be more susceptible than group I (above) to barotrauma injury when exposed to high sound pressures.

III. Fishes with swimbladders that are close to the ear, but not intimately connected to the ear. These fishes are sensitive to both particle motion and sound pressure, and show a more extended frequency range than group I or II, extending up to about 500 Hz. This group includes the Atlantic cod *Gadus morhua* (Chapman and Hawkins, 1973) and the European eel *Anguilla anguilla* (Jerko et al., 1989).

IV. Fishes that have special structures mechanically linking the swim bladder to the ear. These fishes are sensitive primarily to sound pressure, although they may also detect particle motion. They have a wider frequency range, extending to several kilohertz and generally show higher sensitivity to sounds than group I, II or III. The group includes some of the squirrelfishes (Holocentridae), drums and croakers (Sciaenidae), herrings (Clupeidae), and the large group of ostariophysan fishes (see Braun and Grande 2008 for a review).

V. Fishes that can detect high-level ultrasonic frequencies (above 20 kHz). These include the American shad *Alosa sapidissima* (Mann et al., 1997) and menhaden *Brevoortia* sp. (Mann et al. 2001).

There is some evidence that these divisions between fishes may apply not just to evaluating hearing abilities but also to evaluating effects in terms of injuries sustained from high-level sounds (Halvorsen, 2012c).

There are currently insufficient data to categorise marine invertebrates

Sound Exposure Criteria

Knowledge of those levels of sound that have particular effects upon marine animals is important for assessing the impact of man-made sounds. The term ***sound exposure*** is used in a general sense to describe the dose of sound received by an animal in terms of both its magnitude and its duration. It is critical for regulators to have knowledge of the levels of sounds that may be of potential harm to animals, as well as levels that have few or no consequences. However, the setting of recommended sound levels or sound exposure criteria for death, mortal injury, or behavioural responses has long been controversial, largely because of a shortage of data.

There are very few data on mortalities in fish or invertebrates as a result of sound exposure. There have been several reports documenting fish mortality very close to pile driving sources (Caltrans, 2001; Popper and Hastings 2009), and there is also evidence that explosions will kill nearby fish (e.g., Yelverton et al. 1975; Keevin and Hempen 1997; Govoni et al. 2003, 2008). However, death has not been documented for exposure to other sound sources; including seismic airguns, dredging, vessel noise, etc. Even exposure of fish to very high intensity Naval sonars below 1 kHz and from 2 to 4 kHz showed no mortality (Popper et al. 2007; Halvorsen et al. 2012a). Because direct mortality is relatively rare, in seeking criteria it may be more appropriate to consider effects in terms of injury, damage to hearing, or changes in behaviour.

Thus, one approach is to look at the effects of sound exposure on the physiology and anatomy of the animal. That is, to search for a defined sound level that results in the onset of a specified level of injury, or physiological response. with the potential to harm individual animals and populations. Another approach is to develop criteria for changes in behaviour that are potentially harmful to fish and fish populations in the longer term. The behaviour may involve animals moving from feeding sites, changing migration routes, not hearing potential predators, and other effects likely to be detrimental. The criteria for physiological injury and changes in behaviour are likely to be very different.

The search for sound exposure criteria began with marine mammals, and it is instructive to consider how these criteria developed. In the USA, the National Marine Fisheries Service guidelines (NOAA, 2005) originally defined two levels of harassment for marine mammals: Level A harassment had the potential to injure a marine mammal in the wild and the sound exposure criterion was set at 180 dB_{rms} re 1 µPa. Level B harassment had the potential to disturb a marine mammal in the wild by causing disruption to behavioural patterns such as migration, breeding, feeding, and sheltering and was set at 160 dB_{rms} re 1 µPa for impulsive noise such as pile driving and 120 dB_{rms} re 1 µPa for continuous noise such as vessel thrusters. The NOAA guidelines were based on research available for marine mammals, plus some data from terrestrial mammals and humans.

NOAA established similar criteria for the impact of pile driving upon fish. Here, injury was considered to occur when the peak sound pressure exceeded 180 dB re: 1 µPa. However, as with the marine mammal criteria, the criteria did not account for multiple strikes of impulsive sounds and did not resolve whether the peak sound pressure was the most appropriate metric.

Southall *et al*. (2007) reviewed and proposed criteria for sound exposure likely to cause injury to marine mammals. They also summarised data on impact levels that might cause behavioural changes. Their procedures for setting criteria are worthy of close examination. Although the criteria themselves cannot be applied directly to fish and invertebrates, the methods used to derive them have more general application.

The minimum exposure criterion for injury was defined by Southall et al (2007) as the level at which a single exposure is estimated to cause onset of permanent hearing loss (PTS). Data on

TTS in marine mammals, and on patterns of TTS growth and its relation to PTS in other mammals, were used to estimate thresholds for injury.

After considering a number of metrics for defining the effects of sounds, including rms or peak SPL and SEL, Southall et al. adopted a dual-criteria approach based on both peak sound pressure and energy. For an exposed individual, whichever criterion was exceeded first (i.e., the more precautionary of the two measures) was used as the operative injury criterion. The metric adopted for energy was the SEL, representing cumulative received energy, taking account of the sound pressure waveform and duration of either single or multiple sound events. Its use was based on the assumption that sounds of equivalent energy would have generally similar effects on the auditory systems of exposed subjects, even if they differ in SPL, duration, and/or temporal exposure pattern. Of the two measures of sound exposure, peak pressures were to be un-weighted (i.e., “flat-weighted”), whereas SEL metrics were to be M-weighted for the relevant marine mammal group.

Exposure criteria for injury were given for pulsed and non-pulsed (continuous sounds), and for single and multiple exposures (Table 2). For all marine mammal groups, the recommended criteria for exposure to multiple pulses, expressed in both SPL and SEL units, were numerically identical to the criteria for a single pulse.

Table 2. Proposed injury criteria for individual marine mammals exposed to “discrete” noise events (either single or multiple exposures within a 24-h period (from Southall et al. 2007).

Marine Mammal Group	Single pulses	Multiple pulses	Non-pulses
Low frequency cetaceans			
SPL SEL	230 dB re: 1 μPa (peak) (flat) 198 dB re: 1 μPa^{2}-s (Mlf)	230 dB re: 1 μPa (peak) (flat) 198 dB re: 1 μPa^{2}-s (Mlf)	230 dB re: 1 μPa (peak) (flat) 215 dB re: 1 μPa^{2}-s (Mlf)
Mid frequency cetaceans			
SPL SEL	230 dB re: 1 μPa (peak) (flat) 198 dB re: 1 μPa^{2}-s (Mmf)	230 dB re: 1 μPa (peak) (flat) 198 dB re: 1 μPa^{2}-s (Mmf)	230 dB re: 1 μPa (peak) (flat) 215 dB re: 1 μPa^{2}-s (Mmf)
High frequency cetaceans			
SPL SEL	230 dB re: 1 μPa (peak) (flat) 198 dB re: 1 μPa^{2}-s (Mhf)	230 dB re: 1 μPa (peak) (flat) 198 dB re: 1 μPa^{2}-s (Mhf)	230 dB re: 1 μPa (peak) (flat) 215 dB re: 1 μPa^{2}-s (Mhf)
Pinnipeds (in water)			
SPL SEL	218 dB re: 1 μPa (peak) (flat) 186 dB re: 1 μPa^{2}-s (Mpw)	218 dB re: 1 μPa (peak) (flat) 186 dB re: 1 μPa^{2}-s (Mpw)	218 dB re: 1 μPa (peak) (flat) 203 dB re: 1 μPa^{2}-s (Mpw)
Pinnipeds (in air)			
SPL SEL	149 dB re: 20 μPa (peak) (flat) 144 dB re: (20 μPa)^{2}-s (Mpa)	149 dB re: 20 μPa (peak) (flat) 144 dB re: (20 μPa)^{2}-s (Mpa)	149 dB re: 20 μPa (peak) (flat) 144.5 dB re: (20 μPa)^{2}-s (Mpa)

Southall et al (2007) went on to consider sound exposure criteria for changes in behaviour in marine mammals. They pointed out that the challenge in developing behavioural criteria is to distinguish a significant behavioural response from an insignificant, momentary alteration in behaviour. For example, the startle response to a brief, transient event is not likely to persist long enough to constitute significant disturbance. Even strong behavioural responses to single pulses, other than those that may secondarily result in injury or death (e.g., stampeding), are expected to dissipate rapidly enough as to have limited long-term consequence. Consequently, upon exposure to a single pulse, the onset of significant behavioural disturbance was proposed to occur at the lowest level of noise exposure that has a measurable transient effect on hearing (i.e., TTS-onset). Southall et al (2007) recognised that this was not a behavioural effect *per se*, but they suggested the use of this auditory effect as a *de facto* behavioural threshold until better measures were identified.

Thus, for all cetaceans exposed to single pulses, the criteria were based on results for TTS-onset in a beluga, *Delphinapterus leucas*, exposed to a single pulse. The un-weighted peak sound pressure values of 224 dB re: 1 μPa (peak) and M-weighted SEL values of 183 dB re: 1 $\mu Pa^2.s$ were recommended as "behavioural" disturbance criteria for mid-frequency cetaceans. By extrapolation, the same values were also proposed for low- and high-frequency cetaceans. The only difference in the application of these criteria to the three cetacean groups was the influence of the respective frequency-weighting functions for SEL criteria. For pinnipeds exposed to single pulses in water, the proposed "behavioural" disturbance criteria were also the estimated TTS-onset values. However, for pinnipeds in air, the proposed behavioural criteria were based on strong responses (stampeding behaviour) of some species, especially harbour seals, to sonic booms from aircraft and missile launches, and the values selected were regarded as precautionary.

Similarly, for marine mammal responses to multiple pulses, like the sounds from airgun arrays, or responses to continuous sounds like ship noise, criteria were selected based on observations of behavior in the field and in the laboratory and were different for the various groupings.

For marine mammals, the UK Joint Nature Conservation Committee currently recommends the use of the Southall et al. (2007) criteria for impact assessment.

NOAA is now developing new acoustic guidelines for assessing the effects of anthropogenic sound on marine mammal species under their jurisdiction in the light of the Southall et al. (2007) paper. The US Navy is also considering new criteria applicable to its operations based on a more recent paper by Finneran and Jenkins (2012) and has published draft Environmental Impact Statements (EISs) for training and testing activities of its Atlantic [USN 2012a], and Hawaii-Southern California [USN 2012b] fleets, taking into account effects upon a wide range of animals.

In 2003 the German Federal Maritime and Hydrographic Agency introduced initial standard threshold values for piling noise (Werner, 2012). Since 2008 new recommended safety values are issued as part of any license for pile driving. The overall purpose is to prevent temporary threshold shift impairment (TTS) in harbour porpoises. It is recognised that sound duration is important as well as the sound level in estimating the damage to an organism, following Southall et al. (2007). Dual criteria are applied, combining information on the SEL and the Peak SPL. The criteria chosen are:

- An SEL of 160 dB re 1 µPa^2•s
- An SPL (peak-peak) of 190 dB re 1 µPa

Neither measure should be exceeded at a distance of 750 m from the piling site, after ensuring that no animals are left within the exclusion zone. These criteria follow the finding of Lucke et al. (2008) that a predefined TTS criterion was exceeded in the harbour porpoise, *Phocaena phoceana,* at a received sound pressure level of 199.7 dB_{pk-pk} re 1 µPa and a sound exposure level (SEL) of 164.3 dB re 1 µPa^2•sec.

It should be noted that the German criteria are more stringent than those being applied elsewhere in the North Sea. The criteria are difficult to comply with for pile driving operations with large monopole piles. As a result, in the German sector of the North Sea it is commonplace for wind turbines to be supported by several smaller piles, rather than a large monopole. Although the peak sound levels reached are lower, the duration of exposure will be longer, as the driving of several piles will require more strikes than the driving of a single pile. This inconsistency in adjacent parts of the North Sea illustrates the difficulties that can result from the choice of different criteria. It is possible that different criteria are entirely justified, on the grounds that an especially vulnerable marine mammal is present in one area and not in another. However, if the distribution of animals is uniform then the choice of different criteria may result in the imposition of different engineering procedures and higher costs simply as a result of the choice of particular sound exposure criteria.

Separate sound exposure criteria are required for fishes and invertebrates as their hearing mechanisms and their behaviour are very different. Tentative exposure criteria have been suggested for the onset of direct physical injury in fish exposed to the impact sound associated with pile driving. However, there are few criteria that apply to behavioural responses of fishes or other sub-injurious auditory effects, largely due to the absence of underlying information. No criteria exist for invertebrates.

High amplitude impulsive sounds are the subject of most concern in terms of their impact on fish and invertebrates. This type of sound can come from pile driving, seismic surveys and explosions. Fish are sometimes injured or killed by the impact sounds generated by explosions, percussive pile driving and by air guns. Their hearing may also be affected or their behaviour altered. The specific effects depend on a wide range of factors including the type of source, the environmental setting, and many other factors. The sound characteristics that are currently believed to be most important to assessing damage to fish, as for marine mammals, include the zero to peak sound pressure (whether positive or negative), the accumulation of energy over time within a single impulse, the “sharpness” of the sound (e.g., the ratio of peak to RMS pressure, or “crest factor”) and its rise time, the repetition of the sound and accumulation of energy over multiple exposures, and the particle motion associated with the sound (Normandeau, 2012).

Perhaps the first criterion to be put forward for assessing impact upon fish was that proposed by the National Marine Fisheries Service NMFS) in the U.S. NMFS has responsibilities under the Endangered Species Act, and the essential fish habitat provisions of the Magnuson-Stevens Fishery Conservation and Management Act (Stadler & Woodbury 2009). A value was initially set for managing pile driving by specifying a peak sound pressure of 180 dB re 1 μPa that if exceeded would result in injury to fish. The scientific basis for this value is obscure. Hastings and Popper (2005) reviewed all pertinent peer-reviewed and unpublished papers on noise exposure of fish and proposed the use of SEL to replace peak sound pressure level in setting pile-driving criteria. A subsequent paper (Popper et al. 2006) concluded that while SEL is an important criterion, it too has drawbacks and uncertainties when used exclusively. Instead, the paper advocated using both SEL and peak SPL together to set criteria for a single impulsive sound. The paper also pointed to the need to consider the effects of repetition of the impulse and/or the rise time of the signal. It suggested that interim criteria for pile driving be set at an SEL level of 187 dB re: 1 μPa^2•sec and a peak sound pressure level of 208 dB re: 1 μPa in any single strike. These suggestions were based on an analysis of studies of the effects of explosions upon fish.

A Fisheries Hydroacoustic Working Group (FHWG) was established in the U.S. by agencies wishing to improve and coordinate information on the impact on fishes from in-water pile driving (Buehler, 2010). The group revised the interim dual criteria recommended in Popper et al. (2006) and refined by Carlson et al. (2007), expressed in terms of peak and accumulated SEL. The new criteria set out to address three effects associated with pile driving on fishes:

- Non-auditory tissue damage,
- Auditory tissue damage (hair cell damage), and
- Temporary threshold shift (TTS).

The criteria agreed by this group identify sound pressure levels of 206 dB re: 1 μPa peak and 187 dB re 1 μPa^2•sec accumulated sound exposure level (SEL_{cum}) at 10 m for all listed fishes except those that are less than 2 grams. In that case the recommended SEL_{cum} is 183 dB re 1 μPa^2•sec. The period of accumulation for the SEL_{cum} value is the whole pile-driving sequence. First an estimate of the single-strike SEL is required and then an estimate of the number of pile strikes needed to place the pile in position. The assumption is that it is the number of strikes associated with driving a single pile that must be used. However, if multiple piles are being driven in the same location on the same day then it may of course be necessary to take account of all of these. The general rule that appears to have been adopted (although it is not stated in the criteria) is that a 12-hour break in the pile driving operation resets the SEL accumulation. The criteria are currently specific to the US Pacific Coast and relate only to pile driving

A further ambiguity is that no measurement bandwidth is provided. We must assume that the value is un-weighted (see below); that is, it does not include a frequency weighting to account for the sensitivity of different marine fishes to sound.

TNO (2011) have followed the lead set by the U.S. by defined the important 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 problem in setting actual values for sound exposure criteria using these metrics is that supporting data are scarce. Very few studies have been carried out to investigate the levels of sound at which injury occurs and those that have been carried out have not always utilised a clear definition of injury. Values are assumed in environmental impact assessments without stating their provenance, or significance. Thus, an SPL of 200 dB re 1 μPa peak has been taken as an impact criterion for a startle response, and 168-173 dB re 1 μPa peak as a criterion for possible avoidance of an area, although it is likely that a simple startle response is much less damaging to fish than avoidance of a preferred habitat. This adoption of unsubstantiated criteria underlines the need for agreed criteria based on experimental evidence.

Recent papers by Halvorsen et al., (2011, 2012b; 2012c) and Casper et al., (2013) set out to provide quantitative data to define the levels of impulsive sound that could result in the onset of injury to fish. A controlled impedance fluid filled wave tube was used to simulate in the laboratory exposure to high-energy impulsive sound pressures that were characteristic of aquatic far-field, plane-wave acoustic conditions. The sounds used were based upon the impulsive sounds generated by an impact hammer striking a steel shell pile. Neutrally buoyant juvenile Chinook salmon (*Oncorhynchus tshawytscha*) and other species were exposed to impulsive sounds and the injuries sustained subsequently evaluated for different sound exposure levels.

A defined level of injury (based on an index of observed injuries) was achieved for 1920 strikes at 177 dB re 1 μPa^2•sec SEL_{ss}, yielding a SEL_{cum} of 210 dB re 1 μPa^2•sec, and for 960 strikes at 180 dB re 1 μPa^2•sec SEL_{ss} also yielding a SEL_{cum} of 210 dB re 1 μPa^2•sec. It was suggested that these values be used define thresholds for onset of injury in juvenile Chinook salmon.

An important issue to consider when considering exposure to interrupted sounds is whether there is recovery from accumulation when there is some period of quiet between sound exposures. If a fish is accumulating an effect over time and there is then a period of quiet, does the accumulated effect restart at zero? This is the case in humans where the concept of ‘effective quiet’ has been long known and understood (Krytrer, 1985).

Experiments with marine mammals, where animals were exposed to sounds at the same SEL but for varying duration have confirmed that SEL alone is an insufficient metric for predicting Temporary Threshold Shift (Kastelein et al. 2011). It is clearly not possible to rely solely on cumulative SEL metrics or the three metrics listed by Ainslie et al. (2011). Information on the duration of exposure (including the total number and the repetition rate of impulsive sounds) must be provided when reporting the results of underwater sound monitoring. Other additional metrics may also be critically important. Rise time, kurtosis (the degree of ‘roughness of a signal, Southall et al 2007) and metrics for particle motion may also be important for invertebrates and fishes.

The criteria discussed so far all relate to impact pile driving or simulated impact pile driving. To date there has been no formal agreement on criteria that should be applied to vibratory pile driving, seismic air guns, ships, or other man-made sounds likely to affect fishes and invertebrates. In the absence of formal agreement the recent experiments of Halvorsen et al. (2012b) provide the most thoroughly researched measurements of the levels of injury that can result from the exposure of fish to impulsive sounds.

The current criteria from the FHWG (Buehler, 2010), mentioned earlier, specifically relate to the onset of injuries to fishes. There is no mention of effects upon behaviour. There have been very few studies of the behavior of wild free-swimming fishes in response to sound. Decreases in the catches of fish exposed to seismic surveys have been reported. Startle responses and changes in the movement patterns of fish have been observed. Direct observations of fish schools with sonar have shown fish diving and schools breaking up as a result of sound exposure (reviewed in Normandeau, 2012). The National Fisheries Service in the U.S. has used 150 dB re 1 μPa rms as a criterion for behavioral effects upon protected species, but without adducing data to support this choice, and without taking into considering differences in sound detection abilities and behavior of different species.

Nedwell et al. (2007) suggested that strong avoidance responses by fish start at about 90 dB above the dB_{ht} (*Species*) thresholds of fish. Mild reactions in a minority of individuals may occur at levels between 0 and 50 dB above the hearing threshold, and stronger reactions may occur in a majority of individuals at levels between 50 and 90 dB above the hearing threshold (see Table 3). These figures are largely derived from data available from the application of a fish avoidance system at a nuclear power station, supplemented by observations from the testing of a fish guidance system in shallow raceways (Maes et al. 2004; Nedwell et al. 2007). There are additional field data from wild fish under different conditions to support these assumptions, but few tests have been done at sufficiently high sound levels to determine how fish respond at 90 dB or more above their hearing threshold. Exposure was also for a short time and the effects of habituation were not addressed. Nedwell et al. (2007) suggested that the best available methodology for evaluating behavioural effects such as avoidance depended on future observations made under actual open water conditions, where the movement of individuals was not inhibited by the experimental conditions.

Table 3. Proposed behavioural response criteria for fishes exposed to sound (developed from Nedwell et al. 2007).

Level in dB_{ht}(Species)	Effect
50 and below	No discernible change to behaviour
75	Approximately 85% of individuals will react to the noise, although the effect will probably be limited in duration by habituation
90 and above	Strong avoidance reaction by virtually all individuals.

Above 110	Tolerance limit of sound; unbearably loud.
Above 130	Possibility of traumatic hearing damage from single event.

There are very few detailed studies on the behavior of fishes in the wild. Skalski et al. (1992) showed a 52% decrease in rockfish (*Sebastes* sp.) exposed to a single airgun emission at 186 to 191 dB re 1 µPa (zero to peak sound pressure level) (see also Pearson et al. 1987, 1992). They also demonstrated that fishes would show a startle response to sounds at a level as low as 160 dB. Wardle et al. (2001) used underwater video and an acoustic tracking system to examine the behavior of fishes on a reef in response to emissions from a single seismic airgun. They observed startle responses and some changes in the movement patterns of fish. Startle responses have been observed in several fish species exposed to airgun sounds (Hassel et al. 2004; Pearson et al. 1992; Santulli et al. 1999), although such responses may not be of great significance. However, several studies have demonstrated that man-made sounds may seriously affect the behavior of at least a few species of fish. Engås et al. (1996) and Engås and Løkkeborg (2002) examined movement of fishes during and after a seismic airgun study. Although they were not able to actually observe the behavior of fishes *per se,* they measured catch rate of haddock and Atlantic cod as an indicator of fish behavior. They found that there was a significant decline in catch rate of haddock and Atlantic cod exposed to the seismic survey. Later, Løkkeborg et al. (2012a, b) obtained data that could be interpreted to suggest that some sounds actually resulted in an increase in fish catch. Slotte et al. (2004) used sonar to observe the behaviour of fish schools including blue whiting (*Micromesistius poutassou*) and Norwegian spring-spawning herring. They reported that fishes appeared to swim to greater depths after airgun exposure.

In an evaluation of the behavior of free-swimming fishes to noise from seismic airguns, fish movement (e.g., swimming direction or speed) was observed in the Mackenzie River (Northwest Territories, Canada) using sonar. Fishes did not exhibit a noticeable response even when sound exposure levels (single discharge) were on the order of 175 dB re 1 µPa^2·s, and zero to peak sound pressure levels were over 200 dB re 1 µPa (Jorgenson and Gyselman 2009; Cott et al. 2012).

There are also no substantive data on whether high sound levels from pile driving and other sources of impulsive sound would have physiological effects on invertebrates. The only potentially relevant data are from a study on the effects of seismic exploration on snow crabs on the east coast of Canada (Boudreau et al. 2009).

This absence of data on the responses to sounds by fishes prompted the experiments that have been carried out by the SoundWaves consortium. Studies of wild unrestrained fishes using underwater TV and sonar systems have examined the levels of simulated pile driving sound at which strong behavioural responses occur. These experiments are detailed in a separate report.

Acute and Chronic Exposure to Sound

Different types of sound have different effects upon animals. Impulsive sounds at high amplitudes may cause injury or death after very few presentations. Where there is mortal or potentially mortal injury to animals then the responses can be described as acute. In contrast, low amplitude sounds that last for long periods may have longer-term chronic effects. Chronic effects are long-term changes in the physiology and/or behaviour of an animal. These generally do not lead to mortality themselves, but they may result in reduced fitness that leads to increased predation, decreased reproductive potential, or other effects. They may for example cause a rise in the level of stress hormones, with long-term effects upon the fitness and ability of the animal to survive.

At present, much attention is being paid to assessing acute effects and developing sound exposure criteria for impulsive sounds like those resulting from pile-driving, seismic surveys and explosions. Chronic effects result from exposure to both continuous sound and intermittent sound over long time periods, not necessarily at high levels, and may result from increased shipping or other human activities. The sounds resulting in chronic effects may be generated continuously over large areas (e.g., a harbour, in the vicinity of a shipping lane, around an oil rig, or within an offshore wind farm, where the overall background level of sound in the area is higher than the natural background level).

The sea is full of natural sounds, some of which are produced by physical processes such as wind on the surface, rain, water moving over reefs, and tidal flow while others are sounds of biological origin produced by marine mammals (Richardson et al. 1995; Tyack 2000; Southall et al. 2007; Erbe 2012), fish (Tavolga 1971; Myrberg 1978, 1980; Hawkins and Myrberg 1983; Bass and Ladich 2008), and invertebrates (Popper et al. 2001). Such sounds are of great biological significance to the species that make them since they are often used for communication of reproductive state, location, presence of predators or competitors, or for finding other members of the same species. These sounds are also often intercepted where one species hears the sounds of another and may use such information as a warning of the presence of predators or to track down prey (Myrberg 1981).

Sounds of natural origin may be important to the fishes and invertebrates. The detection of sounds of interested to the animal can be influenced, however, by the presence of other sounds or “noise”. The phenomenon of masking may result in deterioration in the ability to detect a biologically important sound in the presence of unwanted sound or noise. The abilities of fishes and invertebrates to use sound to navigate, detect predators and prey, select habitat types and communicate with one another may be strongly affected by chronic exposure to sound. Any increase in the level of sound in the sea, whether natural or man-made, will have an impact upon the lowest sound levels that an animal can hear and may have adverse effects upon important life functions.

Masking occurs when the noise is strong enough to impair the detection of biologically relevant sound signals such as communication signals, echolocation clicks and passive detection cues that are used for navigation and finding prey. The zone of masking falls within the range at which sound levels from a noise source mask the detection of important sounds. Masking may start when the received level of the masking sound, for example noise from a nearby ship, is similar to the sound level of the signal. Masking can shorten the range over which sounds can be detected and conspecifics are able to communicate. Marine mammals use a range of frequencies to communicate, and it is unlikely that the full range of frequencies would be masked over long time periods. However, the sounds of fishes and invertebrates are much more restricted in frequency content and important information can readily be lost through masking. In some areas, the background noise level may be permanently raised as a result of man-made sounds, e.g. near shipping routes, and the ability of fish and invertebrates to hear one another may be almost continually impaired.

There are several levels of interference by noise with biological sounds. The noise may interfere with the ***detection*** of biological sounds. It may also impair the ability of an animal to ***discriminate*** or separate one sound from another. It may impair ***recognition*** of specific sounds and may make communication between animals more difficult (Normandeau, 2012).

Background levels of noise in the sea are changing as a result of the imposition of man-made sounds, with unknown effects upon the ability of animals to detect sounds and communicate with one another. Continuous sounds are more likely to promote masking than interrupted impulsive sounds (which have periods of silence between the pulses). However, where many impulsive sounds are being generated there may be overlap between sounds from different sources, compounded by the effects of reverberation and transmission along multiple pathways.

For most fishes the greatest amount of masking occurs when the masker is of a similar frequency range to the signal (Hawkins and Chapman, 1975). Thus, a 100-Hz signal is most heavily masked by a 100-Hz sound or by a signal that is on either side of 100 Hz. Much less masking of the 100-Hz signal will occur if the masker is at 200 Hz and even less if the masker is at 300 Hz. The frequency content of the masker, and the proportion of energy that falls within a critical frequency band around the frequency range of interest to the animal, is critical in determining the degree of masking that will occur. The bandwidth over which white noise may impair detection of a pure tone signal (known as the critical band) has been determined for a number of fishes at different frequencies (Hawkins and Chapman, 1975). However, there is very little information of the effects of different man-made sounds in terms of the degree of masking of biologically important sounds. Clark et al (2009) have provided a recent discussion of masking by underwater sound.

Thus, a fundamental concern with respect to man-made sound is whether it interferes with the ability of fishes and other animals to detect sounds of significance to them. It may affect the ability of animals to analyse the soundscape (the term ***soundscape*** describes the physical sound field at a particular time and place). Such interference can lead to an inability to find mates, food, or detect the presence of predators. Survival of individuals and/or populations is therefore at stake. Changes in the soundscape could be construed as a change in habitat value for some of these species, as it may reduce their ability to perform normal life functions.

There are growing concerns over increasing ambient noise levels and the associated impacts of chronic and cumulative noise exposure to marine fauna. It is likely that future management goals and actions will have to address the conservation of acoustic habitat quality in addition to the more traditional focus on minimisation of direct physical and behavioural impacts upon particular species.

Environmental Impact Assessment – Information Needs

Environmental impact assessments of offshore development activities are required as part of the process for approving such developments. These assessments inevitably involve evaluation of the effects of sound sources in causing physical injury, behavioural disturbance, and population level impacts upon marine animals.

Two types of information are required to assess any adverse effects from man-made sound at a particular location. First, knowledge is required on the species of fish and invertebrates present and the nature and importance of the fisheries upon them. The identified species may then be screened and evaluated for particular vulnerabilities or for any protection they may receive under the prevailing legislation. Combined with knowledge of their sensitivity and vulnerability to sound that knowledge in turn leads to evaluation of any effects upon them from their exposure to sound from the proposed development.

Knowledge is also required on proposed sound-generating activities, the associated sound sources, their characteristics, and the circumstances of their deployment, including time of year. Together with knowledge of the propagation conditions, the degree of exposure of animals to the sounds can then be estimated and expressed in appropriate metrics (magnitude, duration, and timing).

These two strands of information are then brought together, along with known population statistics of the animals of interest, in an assessment of any adverse effects. Given the inherent uncertainty of attempting to evaluate the impact of man-made sounds on fishes and invertebrates, one useful approach is to conduct a risk assessment. Risk analysis systematically evaluates and organizes data, information, assumptions, and uncertainties to help understand and predict the relationships between environmental stressors and their ecological effects. The likelihood that an adverse effect upon biological receptors may occur as a result of exposure to potentially harmful sounds is evaluated, and a conclusion is reached about the severity of the effects (Defra 2011).

As we have seen, a mass of information is required to assess the risk to fish and invertebrates from man-made sound in the marine environment so that management decisions can be made. Much of that information is not yet available or is incomplete. In the next section we highlight the present perceived shortcomings in the knowledge base.

Recommended future research to overcome present shortfalls in present knowledge

There are currently no standards for the description and measurement of underwater sounds and no protocols for the detection of sounds and their analysis, or on the storage and distribution of data on underwater sound levels. Provisional standards for measurement and monitoring of underwater sound (see TNO, 2011) need to be reviewed, explained in simple terms, and agreed for application in a wide context.

Full quantitative descriptions are required of the different sources of sound that exist, expressed in appropriate metrics. A variety of metrics exist for the physical description of underwater sounds (e.g., Ellison et al. 2012). Some sounds are more damaging than others, and for determining biological effects it is important to describe the sounds in terms of those features that relate to the damage caused. These include not just sound levels but other characteristics including the bandwidth, kurtosis (Henderson and Hamernik 2012), particle motion and sound exposure level. It is also necessary to determine how the characteristics of these sounds change with propagation over larger distances from the source. It is evident that the current range of metrics is limited, especially for repeated sounds, and that several metrics are needed to properly describe the effects of man-made sounds and their relative significance in terms of injury, hearing impairment, masking and behavioural effects.

Our knowledge of the way in which marine organisms detect sound and then respond to different sound stimuli is rudimentary for many invertebrates and fishes. One of the fundamental problems in most studies of effects of sound on fishes and invertebrates have been carried out in a laboratory environment in which the sound field is poorly defined and subject to major distortion. The sound field is often very complex and quite unlike the sound field that an animal would encounter in a normal aquatic environment. The problems arise from the numerous perturbations in the sound field that result from wall and air interfaces surrounding test tanks, no matter how large the tanks might be (see Parvulescu 1964 for a classic discussion of this issue).

Many fishes and invertebrates are sensitive to particle motion and perhaps also to vibration of the substrate. One major issue is the extent to which particular sources generate particle motion that may be detected or affect fishes and invertebrates and at what distances from the source. More observations are required under conditions where properly measured sound signals can be presented to fish and invertebrates. It is important in modelling sound fields to consider the particle motions generated as well as the sound pressures. There is a clear need for inexpensive instrumentation and methodologies to characterise the particle motion from various sound sources, concurrent with measurements of sound pressure at the same location. Information is also required on the particle motions associated with interface waves and ground roll that may affect fish and invertebrates, especially from pile driving and seismic sources.

It is evident that detailed knowledge of their hearing abilities and responses to sounds of most fishes and invertebrates is simply not available. The hearing abilities of many of the extant species (and entire taxa) of fishes remain completely unexplored. This results in a serious deficiency when metrics like the dB_{ht} (*Species*) are being applied. Priority species for examination include the herring (to be repeated), the mackerel, the sturgeon, skates and rays, and jawless fishes like the lamprey. Knowledge of the hearing abilities of aquatic invertebrates hardly exists. Auditory thresholds and audiograms are required for these species under natural and varied noise conditions. Information is especially lacking on the hearing abilities of larval fishes and on the changes that may take place with growth and age.

Many of the most valuable studies of the hearing abilities of aquatic animals have been carried out in the free field or at specialised facilities designed to provide appropriate acoustic conditions. Thus, studies have been carried out in specially designed tanks (Hawkins and MacLennan 1976; Popper et al. 2007; Halvorsen et al. 2011, 2012b) or in mid-water in the sea (e.g., Hawkins and Chapman 1973; Schuijf et al., 1972) where sound fields can be predicted and measurements made with confidence. Such facilities are currently not readily available to researchers. Their provision would undoubtedly stimulate further work.

Weighting functions need to be defined and refined for a number of fishes or fish categories, as has been done for marine mammals (Southall et al. 2007; Southall 2012). Currently, many weighting functions are based on fish and invertebrate audiograms obtained under far from satisfactory acoustic conditions, often using auditory evoked potential (AEP) techniques. Most measures to date do not distinguish between sensitivity to sound pressure and particle motion. There may be some advantages in developing generic weighting curves for the different categories of fish species, and applying these where knowledge of the hearing abilities of particular species is lacking.

Studies are also needed to document and quantify the levels of sound that have a specified impact upon fishes and invertebrates. The importance of the timing of exposure, in terms of both duration and intermittency is particularly poorly understood. How does long-term exposure to low levels compare to relatively brief exposure to high levels? For environmental assessment this is one of the most pressing unknowns for the whole range of marine fauna –from invertebrates to marine mammals. There is also a need to determine those characteristics of impulsive sound that make some sources more damaging than others. Is it the peak amplitude, the total energy, the rise-time, the duty-cycle, or all of these features that determines whether tissues are damaged? There is also a need to determine how the cumulative effects from multiple pulses from the same sources should be dealt with and whether there are recovery effects between pulses. Is there a better descriptor than sound exposure level (SEL) that is now expressed in two forms: the single strike SEL or the cumulative SEL?

A study by Normandeau (2012), prepared with the participation of one of the members of the SoundWaves consortium (Dr A. D. Hawkins), considers the shortcomings of current information on fishes and invertebrates in greater detail.

References

Ainslie, M. A., (2011). Standards for measurement and monitoring of underwater noise, Part I: physical quantities and their units, edited by M. A. Ainslie, TNO-DV 2011 C235 September 2011.
http://www.noordzeeloket.nl/ihm/themas/Shortlist_Ecologische_Monitoring_Wind_op_Zee/Geluidsonderzoek/.

Ainslie, M.A., de Jong, C.A.F., Dol, H.S., Blacquière, G. and Marasini, C. (2009). Assessment of natural and anthropogenic sound sources and acoustic propagation in the North Sea, TNO-report C085, available from:
http://www.noordzeeloket.nl/overig/bibliotheek.asp

Ainslie M.A. (2010) Principles of Sonar Performance Modelling. Springer.

Bass, A.H. and Ladich, F. (2008). Vocal-acoustic communication: From neurons to brain. In: Webb, J.F., A.N. Popper, and R.R. Fay, eds. Fish bioacoustics. New York: Springer Science + Business Media, LLC. Pp. 253-278.

Boudreau, M., S.C. Courtenay, and K. Lee, eds. (2009). Proceedings of a workshop held 23 January at the Gulf Fisheries Center – Potential impacts of seismic energy on snow crab: An update to the September review. Canadian Technical Report of Fisheries and Aquatic Sciences. 2836. http://www.dfo-mpo.gc.ca/Library/337176.pdf

Braun, C.B. and Grande. T. (2008). Evolution of peripheral mechanisms for the enhancement of sound reception. In: Webb, J.F., A.N. Popper, and R.R. Fay, eds. Fish Bioacoustics. New York: Springer Science + Business Media, LLC. pp. 99-144.

Buehler, D. (2010). Overview of Pile Driving Impacts on Fish, Current Interim Impact Criteria, and The Caltrans Guidance Manual. www.itre.ncsu.edu/ADC30/10_TRB_Winter_Conference/Presentations/Buehler_Overview_of_Pile-Driving_Impacts_on_Fish.pdf

California Department of Transportation (Caltrans). (2001). Pile installation demonstration project, fisheries impact assessment. San Francisco-Oakland Bay Bridge east span seismic safety project. PIDP EA 012081 Caltrans Contract 04A0148 Task Order 205.10.90. http://biomitigation.org/reports/files/PIDP_Fisheries_Impact_Assessment_0_1240.pdf

Carlson, T.J., Hastings, M.C. and Popper, A.N. (2007). Update on recommendations for revised interim sound exposure criteria for fish during pile driving activities. Memo to CALTRANS. http://www.dot.ca.gov/hq/env/bio/files/ct-arlington_memo_12-21-07.pdf

Casper, B.M. and Mann, D.A. (2009). Field hearing measurements of the Atlantic sharpnose shark (*Rhizoprionodon terraenovae*). Journal of Fish Biology 75: 2768-2776.

Casper BM, Smith ME, Halvorsen MB, Sun H, Carlson TJ, Popper AN (2013) Effects of exposure to pile driving sounds on fish inner ear tissues. Comp Biochem Physiol A, in press.

Chapman, C.J. and Hawkins, A.D. (1973). A field study of hearing in the cod, *Gadus morhua* L. J. Comp. Physiol., 85: 147—167.

Chapman, C.J. and O. Sand. (1974). Field studies of hearing in two species of flatfish (*Pleuronectes platessa* L. and *Limanda limanda* L.) (family Pleuronectidae). Comparative Biochemistry and Physiology, 47: 371-385.

Clark, C.W., Ellison, W.T., Southall, B.L., Hatch L., van Parijs, S.M., Frankel, A. and Ponirakis, D. (2009). Acoustic masking in marine ecosystems: intuitions, analyses, and implication. Marine Ecology Progress Series, 395: 201 – 222

Cott, P.A., A.N. Popper, D.A. Mann, J.K. Jorgenson, and B.W. Hanna. (2012). Impacts of river-based air-gun seismic activity on northern fishes. In: Popper, A.N. and A.D. Hawkins, eds. The effects of noise on aquatic life. New York: Springer Science + Business Media, LLC. Pp. 367-370.

Department for Environment, Food and Rural Affairs (Defra). (2011). Green leaves III. Guidelines for environmental risk assessment and management. Defra Publication PB13670. http://www.defra.gov.uk/publications/files/pb13670-green-leaves-iii-1111071.pdf

De Vries, H. (1956). Physical aspects of the sense organs. Prog. Biophys. biophys. Chem. 6, 207-64

Ellison, W.E., Southall, B.L., Clark, C.W. and Frankel, A.S. (2012). A New Context-Based Approach to Assess Marine Mammal Behavioral Responses to Anthropogenic Sounds. Conservation Biology, 26: 21-28.

Engås, A. and S. Løkkeborg. (2002). Effects of seismic shooting and vessel-generated noise on fish behaviour and catch rates. Bioacoustics 17: 313-316.

Engås, A., S. Løkkeborg, E. Ona, and A.V. Soldal. (1996). Effects of seismic shooting on local abundance and catch rates of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*). Canadian Journal of Fisheries and Aquatic Sciences 53:2238-2249.

Erbe, C. (2012). Effects of underwater noise on marine mammals. In: Popper, A.N. and A.D. Hawkins, eds. The effects of noise on aquatic life. New York: Springer Science + Business Media, LLC. pp. 17-22.

Finneran, J.J. and Jenkins, A. K. (2012). Criteria and thresholds for U.S. Navy acoustic and explosive effects analysis, April 2012, available from:
http://aftteis.com/Portals/4/aftteis/Supporting%20Technical%20Documents/Criteria and_Thresholds_for_US_Navy_Acoustic_and_Explosive_Effects_Analysis-Apr_2012.pdf,

Govoni, J.J., Settle, L.R. and West. M.A. (2003). Trauma to juvenile pinfish and spot inflicted by submarine detonations. Journal of Aquatic Animal Health, 15:111-119.

Govoni, J.J., West, M.A., Settle, L., Lynch, R.T. and Greene, M.D. (2008). Effects of underwater explosions on larval fish: implications for a coastal engineering project. Journal of Coastal Research, 24: 228-233.

Halvorsen, M.B., B.M. Casper, C.M. Woodley, T.J. Carlson, and A.N. Popper. 2011. Predicting and mitigating hydroacoustic impacts on fish from pile installations. National Cooperative Highway Research Program Research Results Digest 363 October.
http://www.trb.org/Publications/Blurbs/166159.aspx

Halvorsen, M.B., D.G. Zeddies, W.T. Ellison, D.R. Chicoine, and A.N. Popper. (2012a). Effects of mid-frequency active sonar on fish hearing. Journal of the Acoustical Society of America 131:599-607.

Halvorsen, M. B., Casper, B. M, Woodley, C. M., Carlson, T. J., and Popper, A. N. (2012b). Threshold for onset of injury in Chinook salmon from exposure to impulsive pile driving sounds. PLoS ONE, 7(6) e38968. doi:10.1371/journal.pone.0038968

Halvorsen, M.B., B.M. Casper, C.M. Woodley, T.J. Carlson, and A.N. Popper. (2012c). Proc Biol Sci. 7; 279(1748):4705-14. doi: 10.1098/rspb.2012.1544. Epub 2012 Oct 10.

Hassel, A., T. Knutsen, J. Dalen, K. Skaar, S. Løkkeborg, O. Misund, Ø. Østensen, M. Fonn, and E.K. Haugland. (2004). Influence of seismic shooting on the lesser sandeel (*Ammodytes marinus*). Journal of Marine Science 61:1165-1173.

Hastings, M.C. and A.N. Popper. (2005). Effects of sound on fish. California Department of Transportation (Caltrans). Contract 43A0139 Task Order 1. http://www.dot.ca.gov/hq/env/bio/files/Effects_of_Sound_on_Fish23Aug05.pdf

Hawkins, A.D. 1992. Underwater sound and fish behaviour. In Behaviour of Teleost Fishes (ed. T.J. Pitcher), Chapman & Hall, London, 129-166.

Hawkins, A.D. and Chapman, C.J. (1975). Masked auditory thresholds in the cod, *Gadus morhua* L. *J. comp. Physiol*., Ser. A, 103, 209—226.

Hawkins, A.D. and A.D.F. Johnstone. (1978). The hearing of the Atlantic salmon (*Salmo salar).* Journal of Fish Biology 13:655-673.

Hawkins, A.D. and MacLennan, D.N. (1976). An acoustic tank for hearing studies on fish. Schuijf, A., and Hawkins, A.D. (eds.). Sound reception in fish. Netherlands, Elsevier, 149—169.

Hawkins, A.D. and A.A. Myrberg, Jr. (1983). Hearing and sound communication underwater. In: Lewis, B., ed. Bioacoustics, a comparative approach. London: Academic Press. pp. 347- 405.

Henderson, D. and R.P. Hamernik. (2012). The use of kurtosis measurement in the assessment of potential noise trauma. In: Le Prell, C.G., D. Henderson, R.R. Fay, and A.N. Popper, eds. Noise-induced hearing loss scientific advances. New York: Springer Science + Business Media, LLC. Pp. 41-55.

Jensen F.B., Kuperman W.A. Porter M.B. and Schmidt H. (2011, 2nd edition). Computational ocean acoustics. Springer.

Jerko H., Turunenrise I., Enger P.S., Sand O. Hearing in the Eel (*Anguilla anguilla*) *J. Comp. Physiol. A.* 1989;**165**:455–459.

Jorgensen, J.K. and E.C. Gyselman. (2009). Hydroacoustic measurements of the behavioral response of arctic riverine fishes to seismic airguns. Journal of the Acoustical Society of America 126:1598-1606.

Kastelein, R.A. et al. 2011. Harderwijk: SEAMARCO (DRAFT) report 2011/01 'Temporary hearing threshold shifts and recovery in a harbor porpoise and two harbor seals after exposure to continuous noise and pile driving sounds' (version 1 April 2011).

Keevin, T.M. and G.L. Hempen. (1997). The environmental effects of underwater explosions with methods to mitigate impacts. U.S. Army Corps of Engineers, St. Louis District. http://www.denix.osd.mil/nr/upload/underwaterexplosions.pdf

Kryter K.D. (1985). The effects of noise on man. Academic Press.

Ladich, F. and Fay, R. R. (2013). Auditory evoked potential audiometry in fish. Rev. Fish Biol. Fisheries, DOI 10.1007/s11160-012-9297-z

Løkkeborg, S., E. Ona, A. Vold, and A. Salthaug. (2012a). Effects of sounds from seismic air guns on fish behavior and catch rates. In: Popper, A.N. and A.D. Hawkins, eds. The effects of noise on aquatic life. New York: Springer Science + Business Media, LLC. Pp. 415-419.

Løkkeborg, S., E. Ona, A. Vold, and A. Salthaug. (2012b). Sounds from seismic air guns: gear- and species-specific effects on catch rates and fish. Canadian Journal of Fisheries and Aquatic Sciences 69:1278-1291.

Lombarte, A., H.Y. Yan, A.N. Popper, J.S. Chang, and C. Platt. (1993). Damage and regeneration of hair cell ciliary bundles in a fish ear following treatment with gentamicin. Hearing Research 64:166-174.

Lovell J.M., Findlay M.M., Moate R.M. and Yan R.H. (2005) The hearing abilities of the prawn Palaemon serratus. Comparative Biochemistry and Physiology, Part A 140 (2005) 89 – 100.

Lucke, K, Siebert, U, Lepper, PA, Blanchet, M-A. (2009). Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli, J. Acoust. Soc. Am., 125(6), 4060-4070.

Madsen, P. T. (2005). Marine mammals and noise: Problems with root mean square sound pressure levels for transients. J. Acoust. Soc. Am., Vol. 117 (6),. 3952-3957.

Madsen, P.T., Wahlberg, M., Tougaard, J., Lucke, K., and Tyack, P. (2006). Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. Mar. Ecol. Prog. Ser., Vol. 309: 279—295.

Maes, J., Turnpenny, A.W.H., Lambert, D., Nedwell, J.R., Permentier, A and Ollevier, F. (2004). *Field evaluation of a sound system to reduce estuarine fish intake rates at a power station cooling water inlet.* J. Fish Biology, V64, pp. 938-946.

Mann, D.A., Z. Lu, and A.N. Popper. (1997). Ultrasound detection by a teleost fish. Nature 389:381.

Mann, D.A., D.M. Higgs, W.N. Tavolga, M.J. Souza, and A.N. Popper. (2001). Ultrasound detection by clupeiform fishes. Journal of the Acoustical Society of America 109:3048-3054.

Myrberg, A.A., Jr. (1978). Ocean noise and the behavior of marine animals: Relationships and implications. In: Fletcher, J.L. and R.G. Busnel, eds. Effects of noise on wildlife. New York: Academic Press. Pp. 169-208.

Myrberg, A.A., Jr. (1980). Fish bio-acoustics: Its relevance to the 'not so silent world.' Environmental Biology of Fishes 5:297-304.

Myrberg, A.A., Jr. (1981). Sound communication and interception in fishes. In: Tavolga, W.N., A.N. Popper, and R.R. Fay, eds. Hearing and sound communication in fishes. New York: Springer-Verlag. Pp. 395-426.

Nedwell, J.R., Needham, K, Turnpenny, A.W.H. & Thompson, D. (1999). Measurement of sound during a 3D seismic survey in blocks 14/14a of the North Sea. Subacoustech report to Texaco, Ref: 356R0108, 26th February 1999.

Nedwell J R, Turnpenny A W H, Lovell J, Parvin S J, Workman R, Spinks J A L, Howell D (2007). A validation of the dB_{ht} as a measure of the behavioural and auditory effects of underwater noise. Subacoustech Report Reference: 534R1231, Published by Department for Business, Enterprise and Regulatory Reform.

NOAA (2005) Endangered Fish and Wildlife; Notice of Intent to Prepare an Environmental Impact Statement for National Acoustic Guidelines on Marine Mammals. Federal Register. 70(7).
www.nmfs.noaa.gov/pr/pdfs/acoustics/scoping_report_eis.pdf

NOAA (2012) Status of NOAA's Guidelines for Assessing Impacts of Anthropogenic Sound on Marine Mammals.
www.nmfs.noaa.gov/pr/acoustics/guidelines.htm

Normandeau Associates, Inc. (2012). Effects of Noise on Fish, Fisheries, and Invertebrates in the U.S. Atlantic and Arctic from Energy Industry Sound-Generating Activities. A Literature Synthesis for the U.S. Dept. of the Interior, Bureau of Ocean Energy Management. Contract # M11PC00031. 135 pp.

NRC/National Research Council (2003). *Ocean Noise and Marine Mammals*. The National Academies Press. 192 pp.

Oestman, R., D. Buehler, J.A. Reyff and R. Rodkin (2009)
http://www.dot.ca.gov/hq/env/bio/files/Guidance_Manual_2_09.pdf: Sacramento: California Department of Transportation. 'CALTRANS Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish'

OSPAR (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. OSPAR Commission.

Parvulescu, A. (1964). Problems of propagation and processing. In: Tavolga, W.N., ed. Marine bio-acoustics. Oxford: Pergamon Press. Pp. 87-100.

Pearson, W.H., J.R. Skalski, and C.I. Malme. (1987). Effects of sounds from a geophysical survey device on fishing success. U.S. Department of the Interior, Minerals Management Service. Contract number 14-12-0001-30273.

Pearson, W.H., J.R. Skalski, and C.I. Malme. (1992). Effects of sounds from a geophysical survey device on behavior of captive rockfish (*Sebastes ssp*). Canadian Journal of Fisheries and Aquatic Sciences 49:1343-1356.

Poggendorf, D. (1952). The absolute auditory threshold of the dwarf catfish *{Ameiurus nebulosus)* and notes on the physics of the Weberian apparatus in the Ostariophysi. Z. vergl. Physiol. 34, 222-57.

Popper, A.N., Fewtrell, J., Smith, M.E. and McCauley, R.D. (2004). Anthropogenic sound: Effects on the behavior and physiology of fishes. Marine Technology Soc. J. 37(4). 35-40.

Popper, A.N. and N.L. Clarke. 1976. The auditory system of the goldfish (*Carassius auratus*): Effects of intense acoustic stimulation. Comparative Biochemistry and Physiology 53:11-18.

Popper, A.N., Carlson, T.J. Hawkins, A.D. Southall, B.L. and Gentry. R.L. (2006). Interim criteria for injury of fish exposed to pile driving operations: A white paper. http://www.wsdot.wa.gov/NR/rdonlyres/84A6313A-9297-42C9-BFA6-750A691E1DB3/0/BA_PileDrivingInterimCriteria.pdf

Popper, A.N., M.B. Halvorsen, A.S. Kane, D.L. Miller, M.E. Smith, J. Song, P. Stein, and L.E. Wysocki. (2007). The effects of high-intensity, low-frequency active sonar on rainbow trout. Journal of the Acoustical Society of America 122:623-635.

Popper, A.N. and M.C. Hastings. (2009). The effects of anthropogenic sources of sound on fishes. Journal of Fish Biology 75:455-489.

Popper, A.N., M. Salmon, and K.W. Horch. (2001). Acoustic detection and communication by decapod crustaceans. Journal of Comparative Physiology 187:83-89.

Pumphrey, R. J. (1950). Hearing. Symp. Soc. exp. Biol. 4, 3-18.

Richardson, W.J., Malme, C.I., Green, C.R.jr. and Thomson, D.H. (1995). Marine Mammals and Noise. Academic Press, San Diego, CA. 576 pp.

Sand, O and Hawkins, A.D. (1973). Acoustic properties of the cod swimbladder. J. Exp. Biol., pp 797—820.

Santulli, A., A Modica, C. Messina, L. Ceffa, A. Curatolo, G. Rivas, G. Fabi, V. and D'Amelio. (1999). Biochemical responses of European sea bass (*Dicentrarchus labrax* L.) to the stress induced by offshore experimental seismic prospecting. Marine Pollution Bulletin 38:1105- 1114.

Scholik, A.R. and H.Y. Yan. (2001). Effects of underwater noise on auditory sensitivity of a cyprinid fish. Hearing Research 152:17-24.

Scholik, A.R. and H.Y. Yan. (2002). The effects of noise on the auditory sensitivity of the bluegill sunfish (*Lepomis macrochirus*). Comparative Biochemistry and Physiology A 133:43-52.

Schuijf, A., Baretta, J.W., Wildschut, J.T. (1972). A field investigation on the discrimination of sound direction in *Labrus bergylta* (Pisces: Perciformes). Neth. J. Zool. 22, 81-104.

Skalski, J.R., W.H. Pearson, and C.I. Malme. (1992). Effects of sounds from a geophysical survey device on catch-per-unit-effort in a hook-and-line fishery for rockfish (*Sebastes spp.*). Canadian Journal of Fisheries and Aquatic Sciences 49:1357-1365.

Slabbekoorn, H. N. Bouton, I. van.; A. Coers, A., ten Cate, C., and Popper, A.N. (2010). A noisy spring: The impact of globally rising underwater sound levels on fish. Trends in Ecology & Evolution 25:419-427.

Slotte, A., K. Kansen, J. Dalen, and E. Ona. (2004). Acoustic mapping of pelagic fish distribution and abundance in relation to a seismic shooting area off the Norwegian west coast. Fisheries Research 67:143-150.

Smith, M.E., A.S. Kane, and A.N. Popper. (2004a). Noise-induced stress response and hearing loss in goldfish (*Carassius auratus*). Journal of Experimental Biology 207:427-435.

Smith, M.E., A.S. Kane, and A.N. Popper. (2004b). Acoustical stress and hearing sensitivity in fishes: Does the linear threshold shift hypothesis hold water? Journal of Experimental Biology 207:3591-3602.

Smith, M.E., A.B. Coffin, D.L. Miller, and A.N. Popper. 2006. Anatomical and functional recovery of the goldfish (*Carassius auratus*) ear following noise exposure. Journal of Experimental Biology 209:4193-4202.

Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene, Jr., C.R., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A. and Tyack, P.L. (2007). Marine mammal noise exposure criteria: Initial scientific recommendations. Aquatic Mammals 33: 411- 521.

Southall, B.L. (2012). Noise and marine life: Progress from Nyborg to Cork in science and technologies to inform decision making. In: Popper, A.N. and A.D. Hawkins, eds. The effects of noise on aquatic life. New York: Springer Science + Business Media, LLC. 3- 10.

J. H. Stadler, J. H. and Woodbury, D. P. (2009). Assessing the effects to fishes from pile driving: Application of new hydroacoustic criteria. Inter-noise 2009, 23-26 August 2009, Ottawa, Canada.

Tavolga, W.N. (1971). Sound production and detection. In: Hoar, W.S. and D.J. Randall, eds. Fish physiology. New York: Academic Press.

Tyack, P.L. (2000). Functional aspects of cetacean communication. In: Mann, J., R.C. Connor, P.L. Tyack, and H. Whitehead, eds. Cetacean societies: Field studies of dolphins and whales. Chicago: University of Chicago Press.

Urick, R.J. (1983). Principles of underwater sound. New York: McGraw-Hill Book Company.

USN (2012a) USN Atlantic Fleet Training and Testing, draft Environmental Impact Statement/Overseas Environmental Impact Statement, 4 May 2012. Available from https://aftteis.com/Home.aspx

USN (2012b) Hawaii-Southern California Training and Testing Activities Draft Environmental Impact Statement/Overseas Environmental Impact Statement. Available from http://hstteis.com/

Van Bergeijk, W. A. (1967). The evolution of vertebrate hearing. In Contributions to Sensory Physiology, vol. 1 (ed. W . D. Neff), New York: Academic Press. pp. 1-50.

Wardle, C.S., T.J. Carter, G.G. Urquhart, A.D.F. Johnstone, A.M. Ziolkowski, G. Hampson, and D. Mackie. (2001). Effects of seismic air guns on marine fish. Continental Shelf Research 21:1005-1027.

Werner, S. (2012). Determination of noise exposure criteria – the German approach. www.bfn.de/fileadmin/MDB/documents/themen/erneuerbareenergien/Tgng_offshore2012/2_3_werner.pdf

Yelverton, J.T., D.R. Richmond, W. Hicks, K. Saunders, and E.R. Fletcher. (1975). The relationship between fish size and their response to underwater blast. Director, Defense Nuclear Agency. Report DNA 3677T.
http://www.dtic.mil/cgi- bin/GetTRDoc?AD=ADA015970

Appendix A: The description of sounds

Specifying sounds

An acoustic field consists of pressure fluctuations (a scalar field) and particle motion (a vector field). The total energy contained in a sound wave consists of the sum of its potential energy (PE) and its kinetic energy (KE). The PE arises from the compression and expansion of the fluid and hence is related to the acoustic pressure, while the KE arises from fluid motion quantified by the acoustic particle velocity.

In a free sound field, where there are no physical obstructions to passage of the sound, and where the advancing wave front is an almost planar surface, the oscillatory ***particle velocity*** (u, the first time derivative of the particle displacement, expressed as m s^{-1}) and the ***sound pressure*** (p, expressed as Pascals (Pa), equal to 1 N m^{-2} or 1 kg m^{-1} s^{-2}) are directly proportional to one another. They are described by the plane wave equation:

$$u = p/\rho c \; \mathrm{u = p/\rho c}$$

Where c is the propagation velocity of sound in that medium (m $s^{-1)}$ and ρ is the density of the medium (kg m^{-3}).

The quantity ρc is known as the acoustic impedance (Z), a quantity analogous to the electrical resistance of an electrical circuit. In water Z has the value and units 1.5 MRayl (a Rayl is 1 Pa·s m^{-1}).

Together the sound pressure and particle velocity determine ***sound intensity***. The local instantaneous intensity is the product of the sound pressure and the acoustic particle velocity divided by the acoustic impedance of the medium.

The speed of propagation of a sound in a particular medium can be expressed in terms of the bulk modulus of the medium, which in simple terms is a measure of its compressibility. The speed of propagation in water varies with salinity, temperature and other factors.

There is a major difference in the speed of propagation of sound between water and air. In water c is approximately 1500 m s^{-1} compared to 343 m s^{-1} in air. The higher sound speed in water arises from the relative incompressibility (large bulk modulus) of water compared to air. Water is much more resistant to being compressed. For a given sound pressure the particle velocity is much smaller in water (approximately 3,500 times less than in air).

Both p and u are expressed in SI Units. The SI unit for pressure is the Pascal. In the past a variety of other units have been used for sound pressure, including the bar and microbar (μbar) and the dyne cm^{-2}. The conversions are 1 Pa = 1 N m^{-2} = 1 $x10^{-5}$ bar = 10 μbar = 10 dyne cm^{-2}.

In SI Units the particle motion can be described in terms of the displacement (m), the velocity (m s^{-1}) and the acceleration (m s^{-2}). Here we shall consider only particle velocity since it appears naturally from detailed consideration of the wave equation.

Many simple sound sources, like a tuning fork or a bell, generate regular waves of motion and pressure, where the amplitudes of both particle velocity and sound pressure vary with time in a regular and even sinusoidal way. Other sources may generate more complex sounds, with irregular waveforms. However complex waveforms can be broken down into an assemblage of sine waves of differing frequency (f), amplitude, and phase to yield a spectrum. Various forms of spectral analysis can therefore be used to describe complex sounds (see section X below). It is also important to note that in making measurements of sounds it is important to include all the frequencies that make up the sounds of interest.

The spatial distance between two successive peaks in a propagating sinusoidal wave is described as the wavelength (λ, expressed in m), where $\lambda = c/f$ as shown in figure 1. Thus, the wavelength of a 100 Hz sinusoidal sound wave in water is approximately 15 m. In air the corresponding wavelength is about 3 m.

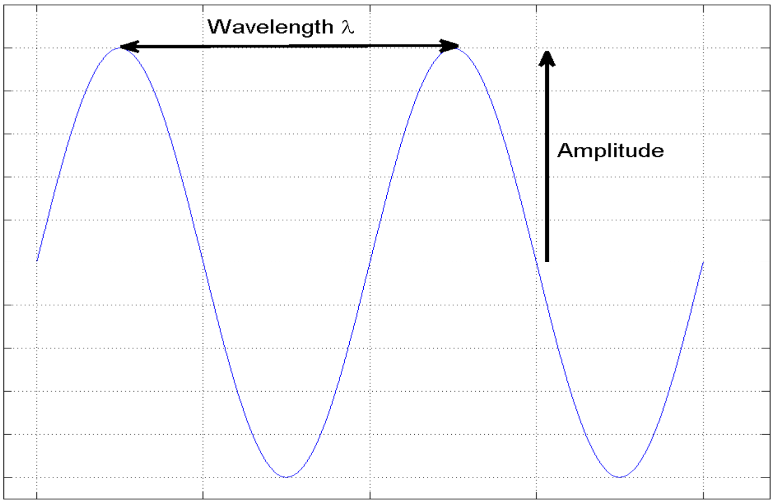

Figure 1 Wavelength and amplitude for a sinusoidal wave.

The ***power*** of a sound is the quantity of sound energy transferred within a specified time expressed in Watts (W); 1 W = 1 J s^{-1}

The ***energy*** of a sound wave is proportional to the sound pressure squared summed over the time it is present and is expressed in Joules.

The ***sound intensity*** is the acoustic energy flowing through a unit area (A), perpendicular to the direction of propagation, per unit time (T). The intensity can be shown to be $I = p^2/Z$ expressed in units of W m^{-2} s^{-1}.

The Propagation of Sounds

Sounds inevitably diminish in level as they propagate away from a source, both as the wave fronts spread out over a larger area and as the sound is absorbed by the medium and its inclusions. Distant from a source, in a free acoustic field, where the plane wave equation applies, both sound pressure and particle velocity decline with the inverse of the distance (i.e. by a factor of 2 for a doubling of distance). Both parameters remain in phase with one another.

Close to a source, where the radiating wave fronts are no longer plane but spherical, or even more complex, the simple plane wave equation relating particle velocity to sound pressure is no longer valid. A more complex relationship can be applied which for an outgoing spherical wave, from a monopole (see below) is

$$\frac{p}{u} = \rho c \left[\frac{4\pi^2 r^2}{\lambda^2 + 4\pi^2 r^2} + i \frac{2\pi r\, \lambda}{\lambda^2 + 4\pi^2 r^2} \right]$$

Where the inclusion of the i, the square-root of -1, indicates that the pressure and the particle velocity are not generally in phase.

Close to the source the particle velocity is much higher for a given sound pressure, the relationship being:

$$\frac{p}{u} = i2\pi\rho c r/\lambda$$

This equation characterises the ***near-field*** effect. The particle velocity declines with increasing distance for a given pressure, the phase of velocity lagging that of pressure (the lag being 90° close to the source).

For a simple monopole source, radiating sound equally in all directions (a pulsating sphere), the outer limit of the near field is usually considered to be at $r = \lambda/2$, where $r$is the distance and λ is the wavelength. The volume of water outside that range is termed the ***far-field***.

Not all sources are monopoles. Some sources are dipoles (approximated by a sphere that oscillates back and forth giving a figure of 8 directivity pattern). Others are quadrupoles (with a directivity pattern resembling a four-leaved clover). Indeed there are many different types of source, and for each of these the pattern of the ratio of particle velocity to pressure will differ close to the source.

Sounds also depart from the plane wave equation close to a reflecting boundary. At a boundary with a ‘soft’ material, having low acoustic impedance, like air, the local amplitude of particle velocity will be much higher. The sound will also be reflected with inverted phase. Close to a ‘hard’ boundary, like the seabed, the amplitude of particle velocity will be reduced and the phase of the reflected sound will not be inverted. Sound is also refracted by temperature and salinity gradients that can affect water density and therefore impedance.

The source level is the sound pressure measured at 1m from a hypothetical point monopole source. Ainslie *et al*. (2009) have pointed out that useful information on source characteristics is very scarce due to the lack of standardization and clarity on the definition and measurement of source level. In practice, few real sources are either monopole or point sources, and source level measurements are rarely made at one metre. Source levels are more often measured at some distance from the source and a sound propagation model (see under ‘Estimating Changes in Sound Level with Distance’) applied to determine what the sound pressure might have been at 1m range had the source been a point source. For very large sources like ships, pile drivers, or air gun arrays there is no single point from which the sound radiates. The actual sound levels in the vicinity of the distributed source will be much lower than the source level, i.e. the predicted source level will never actually be reached in the field. These estimated source levels are perhaps better called “***radiated sound levels***”. Such levels are valuable for the prediction of far-field sound pressures. However, they cannot be used to predict sound pressures or particle velocities in the close vicinity of the source.

The Decibel Scale

A very wide range of sound pressures is encountered underwater, ranging from around 0.0000001 Pascal in quiet sea conditions to 10,000,000 Pascal close to an explosive blast. Because of this, and because the human ear behaves in a logarithmic fashion, it has become customary to express measured sound pressures in terms of a logarithmic scale the decibel scale - that compresses the range of values.

Measurements expressed in terms of decibels are normally described as sound levels, the most common being the ***sound pressure level*** or SPL.

The SPL is defined as:

$$SPL = 20\log_{10}\left(\frac{p}{p_{ref}}\right)$$

Where p is the sound pressure that we are expressing on the scale and p_{ref} is the reference pressure, which for underwater applications is 1 µPa. For instance, a pressure of 1 Pa would be expressed as an SPL of 120 dB re 1 µPa. In the examples of sound pressures given above, the sound pressure level ranges from 0 dB re 1 µPa to 260 dB re 1 µPa. Values of sound pressure lower than the reference level result in negative decibel values.

The SPL is sometimes abbreviated to "dB", which can give the erroneous impression that a dB is an absolute unit. In expressing the level of sound pressure it is always necessary to provide the reference level, normally 1 dB re 1 µPa in water.

An additional advantage of working with the SPL is that many of the mechanisms affecting sound underwater cause loss of sound at a constant rate when it is expressed on the dB scale. Although in water, the sound pressure level is determined in relation to a reference pressure of 1 µPa (10^{-6} Pa), in air it is determined in relation to a different reference pressure of 20 µPa (0 dB re 20 µPa is 26 dB re 1 µPa).

Caution should be exercised however when any comparison is made between levels in air and in water. The comparison between the two is more complex than just the difference in the value taken for baseline comparison. The actual energy contained in a wave is related to the acoustic impedance of the medium. Usually it is best not to make a cross comparison between the two media.

There are differences in the way that SPL may be defined in the literature. Whereas the definition given above, in terms of reference to a pressure, is undeniably the more used, some authors prefer to define the SPL as a ratio of powers appropriately scaled (Ainslie, 2010) – remembering that the power is the square of the pressure. This alternative approach has no influence on the numerical values produced but results are given relative to μPa^2 rather than µPa as used here.

Relating Measurements to the Type of Sound

Sounds with different characteristics are measured in different ways to best capture their main features.

Many sounds are effectively continuous or last for a relatively long time. Such sounds can be tonal (dominated by a single frequency and its harmonics), broadband (containing a wide range of different frequencies), or both. They may be of short duration but without the essential properties of pulses (see later). Examples of man-made, oceanic sources producing such sounds include ships, aircraft, machinery operations such as drilling or wind turbines, and some Naval sonar systems.

With such continuous sounds, like the sound radiated by a moving ship or from an operational wind turbine, the instantaneous sound pressure varies continuously above and below a mean value (the ambient or hydrostatic pressure) with time. To allow for this variation and describe the sound by a single metric, the sound pressure p is first squared (to make all values positive) and then averaged (to smooth out the rapid fluctuations with time) to give the Root Mean Square

(RMS) value. In Equation 2 above, a bar drawn above the squared pressure represents the averaging process. In practice, the effective sound pressure level is calculated by taking the decibel value of the ratio of the RMS pressure, over a particular time period, to the reference pressure as follows:

$$SPL = 20\log_{10}\left(\frac{p_{RMS}}{p_{ref}}\right)$$

Note that the description of SPL in terms of RMS values is only valid over a particular period of time, the ***duration,*** measured in seconds. Duration is important because it affects other sound measures, specifically RMS sound pressure (Madsen, 2005). Because of background noise and reverberation, duration can be difficult to specify precisely.

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 do not lend themselves well to being averaged, for example impulsive signals vary significantly in amplitude over time and will have an average that is unrepresentative of their instantaneous level. The RMS sound pressure is usually calculated over the period of the pulse that contains 90 percent of the acoustical energy (the total energy minus the initial 5 percent and the final 5 percent). This is termed the ***effective sound pressure***.

Impulsive or pulsed sounds are sounds of short duration (generally less than one second) that start and then stop. They are characterised by a relatively rapid rise-time to maximum pressure followed by a decay that may include a period of diminishing and oscillating maximal and minimal pressures. Examples of pulses are sounds from explosions, sonic booms, seismic airgun pulses, and pile driving strikes.

Where sounds are single or pulsed, like the firing of a seismic air gun, a single RMS value does not adequately describe the sound or its potential impact. The RMS value is also inadequate for assessing effects upon animals, which are often governed largely by transient characteristics of sounds (e.g., rise time, peak pressure, and signal duration). The limitation of RMS as a metric for assessing the levels for impulsive type signal has been addressed in some detail in the literature (Madsen 2005).

The ***rise time*** is the time a sound takes to rise to its highest peak value. The slope of the pressure rise within a particular sound may be of particular importance in evaluating its effects.

The ***peak sound pressure*** is the maximum excursion in sound pressure whether it is a positive (compression) or negative (rarefaction) pressure. It is perhaps better described as the ***zero to peak sound pressure***. This form of measurement is often used to characterise the underwater blast from an explosive charge, where there is a clear positive peak following the detonation of explosives. The highest pressure may also be described as the half peak-to peak-pressure, as it measures the excursion from the baseline hydrostatic pressure. The actual ***peak-to-peak sound pressure*** is the maximum variation of the pressure from positive to negative within the wave. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak pressure will be twice the zero to peak pressure, and hence 6 dB higher in level.

Another measure is the ***sound exposure level*** (SEL), the integrated value of the squared signal over time, where the reference value is 1 µPa$^{2}\cdot$ s.

The sound exposure level sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound source and the duration of the sound. For a plane wave the sound exposure (SE) is defined by the equation:

$$SE = \int_{0}^{T} p^{2}(t)dt$$

Where p is the acoustic pressure in Pascals, T is the duration of the sound in seconds, and the integral is over t in seconds. The SE is a measure of the acoustic energy and, therefore, has units of Pascal squared seconds (Pa^{2}.s).

To express the SE on a logarithmic scale by means of a dB, it is compared with a reference sound energy level of 1 µPa^{2} (p^{2}_{ref}) and a reference time (T_{ref}), usually one second.
The SEL is then defined by:

$$SEL = 10\log_{10}\left(\frac{\int_{0}^{T} p^{2}(t)dt}{p_{ref}^{2}T_{ref}}\right)$$

By selecting a common reference pressure P_{ref} of 1 µPa for assessments of underwater sound, the SEL and SPL can be compared using the expression:

$$SEL = SPL + 10\log_{10}T$$

Where the SPL is a measure of the average level of the sound, and the SEL sums the cumulative sound energy.

For single sounds lasting less than one second, the SEL will be numerically lower than the SPL. For periods of greater than one second the SEL will be numerically greater than the SPL (i.e. for a sound of ten seconds duration the SEL will be 10 dB higher than the SPL, for a sound of 100 seconds duration the SEL will be 20 dB higher than the SPL, and so on).

It should be noted that the SEL is often used not just for single sounds but also for describing repetitive sounds, for example the level over the duration of a pile being repeatedly hammered into the substrate, which may last for several hours and involve a large number of individual strikes, each generating a sound.

For intermittent sounds, such as piling, the cumulative SEL values are usually calculated for the time when the sound is present (in effect, for pulses of identical amplitude, the length of a ‘pulse’ of noise multiplied by the number of pulses). In these circumstances it is better to refer to the $\mathrm{SEL}_{\mathrm{cum}}$ value to distinguish it from the $\mathrm{SEL}_{\mathrm{ss}}$ value for a single impulse or strike.

Note that the term SEL is often used indiscriminately, without stating whether it is the SEL for a single impulse of sound or the $\mathrm{SEL_{cum}}$ for a series of impulses, and, if it is the latter, without specifying the time period, the number of impulses or whether it is the duration for driving a single pile.

Measurement of Particle Motion

Most aquatic invertebrates and many fish are sensitive not to sound pressure but to the motion of small imaginary ‘packets’ of the conducting medium. These packets should be regarded as being much smaller than the scale of the boundaries of the medium but larger than the mean free path of the molecules that make up the medium.

The actual organs that respond to sound in fish are driven not by sound pressure but by the oscillatory particle motion; described by the particle displacement or its time derivatives: particle velocity and acceleration**.**

The ***particle velocity level*** (PVL) may be defined as

$$PVL = 20\log_{10}\left(\frac{u}{p_{ref}/\rho c}\right)$$

Where u is the particle velocity in metres per second, ρ is the density of water and c is its sound speed. The definition effectively expresses particle velocity relative to that of a plane wave with a sound pressure of 1 μPa, and has the advantage that for sound waves under free field conditions, distant from the source, the PVL and the SPL will numerically be the same. However, particle motion is aligned along a particular direction; it is a vector quantity, whereas pressure acts in all directions (it is a scalar quantity). In measuring or estimating the particle motion it may be important to specify the direction, or to measure the three orthogonal components.

In many circumstances, such as close to a source or in the presence of pressure-release materials, at the water surface, the relationship between the SPL and the PVL may be very different to that described by the plane wave equation. It is especially difficult to estimate the particle velocity in small water tanks in the laboratory, where reflecting (and often pressure release) surfaces surround the animal. However, it is crucially important in considering the effects of sound upon fish or invertebrates to distinguish between sound pressure and particle motion.

Attempts have been made to monitor and measure particle velocity by mounting seismic accelerometers in “neutrally buoyant” waterproof spheres or cylinders. The main difficulty with this approach is that it is difficult to suspend the system without constraining its motion. The neutrally buoyant body may not follow the back and forth water movements exactly. The frequency response of the accelerometers is also limited, and at higher frequencies the responses of the container will be superimposed on the response. Where such devices are employed it is important to ensure that they have been calibrated.

An alternative approach is to measure the sound pressure gradient in the water. The sound pressure gradient is given by

$$\frac{\partial p}{\partial x} = -\rho \frac{\partial u}{\partial t}$$

Where x is the direction in which the sound energy flows and u is the velocity of the water as the sound wave passes. Consider an estimate of the sound pressure gradient made using two hydrophones separated by a spacing of Δx to measure sound pressures p_1 and p_2. The particle velocity may be estimated as

$$u = -\frac{1}{\rho} \int \frac{(p_1 - p_2)}{\Delta\, x} dt$$

Thus, the sound pressure measured using two hydrophones may be processed to yield the particle velocity along the line connecting the hydrophones. The approach is based on an assumption of linearity between the points; however, it can be shown that this is adequate if the frequency of the wave is low; for example where the hydrophones are separated by significantly less than a wavelength at the highest frequency recorded. Provided the hydrophones are calibrated and offer an accurate measurement of sound, as will generally be the case, the estimate of particle velocity will also be accurate. The measurement may be readily related to International Standards for measurement of sound pressure.

It may be noted, however, that there are several practical considerations to be satisfied when implementing this approach. The differential pressure $(p_1 - p_2)$ is typically created using a differencing amplifier to subtract one estimate of pressure from another; the result will generally be much smaller than each of the individual pressures. If there is an error in the measurement of either pressure it may easily dominate the result. Thus, it is critically important that the hydrophones are well matched in both the magnitude and phase of their sensitivity. Note, also, that this implies that this calculation cannot be performed digitally after digital acquisition of the signal, due to the limitations of dynamic range caused by the convertor.

Particle motion, which is an important component of sound detection for fishes and invertebrates, is seldom measured. Particle velocity ‘hydrophones’ are not commercially available – although an alternative technology, measuring the pressure gradient, is expected to be available commercially in the near future. However, particle motion does need to be considered in assessing effects and it requires vector rather than scalar measurements. The measurement, modelling and correct prediction of the influence of particle motion on aquatic animals is one of the more important areas for research in this field today.

Estimating Changes in Sound Level with Distance

As underwater sound propagates away from the source it reduces in level. This reduction of sound with range, the ***transmission loss***, is defined as:

$$TL = 20\log_{10}\left(\frac{p_0}{p_r}\right)$$

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. The TL is therefore a measure of the rate at which the sound energy decreases.

The sound from a source can travel through the water both directly and by means of multiple reflections between the surface and seabed. Sound may also travel through the seabed, re-emerging back into the water at a distance. Refraction and absorption further affect the sound. Predicting the level of sound at distance from a source is therefore complex, and use may be made either of propagation models or empirical data based on measurements.

In many cases where a set of measurements of underwater sound from a source has been made, the data are fitted to a simple propagation model so that general conclusions about the level of the sound source and the rate at which the sound decays with distance can be made.
Sound propagation may be described by the passive sonar equation (Urick 1983). It relates a property of the received sound field, say the SPL at a given distance to the source level:

$$L(r) = SL - TL$$

Where *L(r)* is the SPL at distance *r* from a source (in metres), *SL* is the source level, and *TL* is the transmission loss.

A more accurate model of the transmission loss is described by the equation:

$$TL = N \log(r) + \alpha r$$

Where *r* is the distance from the source (in metres), *N* is a factor for attenuation due to geometric spreading, and α is a factor for the absorption of sound in water and boundaries in $dB.m^{-1}$. By combining the previous two expressions, the level of sound at any point in the water space can be estimated from the expression:

$$L(r) = SL - N \log(r) - \alpha r$$

Over short distances, and for low frequencies, absorption effects have little influence on the TL and are sometimes ignored.

Several mathematical models exist which estimate *TL* for given water column properties. A value of *N*=20 corresponds to spherical spreading of the sound and is often assumed near to a source in deep water. Further afield, *N*=10 represents cylindrical spreading that can occur in deep water channels and shallow water columns. Often a value of *N*=15 is used as a working compromise.

Despite these models, predicting the level of sound from a source at a particular point in the sound field is a difficult task. Measurements of sound levels must be made in the far field to give a reasonable estimate of sound attenuation within this region. Transmission loss is the gradient of a linear fit to this data. Shallow water transmission losses of between *N*=12 and *N*=25 are commonly found (Nedwell *et al*, 1999).

Whether it is measured or predicted, the *TL* used will affect the predicted sound level significantly. For example, over a 10 metre range a sound subject to *N*=15 TL will be 10 dB higher than the same sound subject to *N*=25 *TL*. Over a 10 km range, using the same example, the difference will be 40 dB. Where there are insufficient data for an accurate estimation of *TL* using a linear fit, for example when measurements are only reported for one range, a *TL* of *N*=20 is often assumed, which equates to spherical spreading.

Noise propagation is in fact far more complex than the simple model described above. There are multipath reflections from the surface and seafloor and interactions with water of differing characteristics and interactions with the bottom substrate leading to many propagation paths that may subsequently recombine.

It should be noted that sound propagation might be described for any physical quantity that expresses a level of sound. For instance, it is possible to describe the peak pressure of the source in terms of a formulation of this sort. However, equally well, it is possible to describe another physical quantity for the identical source in a similar way, such as the SEL, particle velocity, etc. It should be noted that all of the metrics that are used to describe the level would be different for these different physical quantities. The source level and transmission loss for the SEL of the source will not be the same as the source level and transmission loss for the zero to peak pressure. Thus, depending on their hearing abilities marine animals will perceive not only a different level of sound, but also a different rate at which it attenuates with distance.

In some cases, the animal could be responding not only to the absolute received level of the sound, but also to the sound level in relation to competing background noise This relation is defined as the signal-to-noise ratio where the measurements of both signal and noise are in the same frequency band, and the noise level is measured in the absence of the signal. In practice, the signal is not always detected at values of SNR > 0, but at some higher value.

Estimating the Received Level of a Sound

There is often a requirement to assess whether a particular sound, as received by an animal after transmission from a man-made source, is likely to cause death, injury, damage to the auditory system, or significant changes in behaviour. The first step in this procedure, as described above, is to take field measurements of the sound pressure level at different distances away from the source, and then estimate the source level at one metre (or more correctly, the radiated sound level, see above) either by means of the sonar equation, assuming a given transmission loss, or by application of an appropriate propagation model (Jensen, 2011). The level received by an animal exposed to sound at a particular point in the sound field can then be estimated by application of the reverse procedure, to ascertain whether received level exceeds a recommended threshold level. Alternatively, the distance at which the received level exceeds a recommended level is estimated, to define a zone of effect, within which an animal may be killed, injured, or show a strong behavioural response.

Such estimates require caution. Transmission losses and propagation models cannot be selected to yield a particular outcome. They must be based on the conditions that actually prevail in the area and for the source under consideration. It would not be appropriate to select a high transmission loss when a lower value might be more valid. It is not sensible to adopt a model that ignores transmission through the seabed, for example for a pile-driving source. Indeed best practice for assessing the effect of noise on fauna is to assume the worst possible or likely case. Hence efforts must be taken to ensure that the lowest transmission loss is used that is consistent with the known physical parameters.

The Spectral Characteristics of Sounds

The ***waveform*** of a sound shows the variation in instantaneous sound pressure with time, and displayed on an oscilloscope or a computer screen it offers a useful way of illustrating the overall temporal characteristics of the sound.

Any waveform can also be decomposed mathematically into a series of sine waves of differing frequency. The main elements of a ***frequency spectrum*** are a number of sine waves with differing frequencies. All sound waves can be described as a linear superposition of such sine waves. Each sine wave can be characterised by its frequency, its amplitude and its phase in relation to a zero-time mark.

The frequency spectrum is important because the frequency content of the sound may affect the way a fish responds to or is affected by the sound (in terms of physical injury as well as hearing loss). The frequency spectrum is also important because it affects the expected sound propagation, as this is frequency dependent.

The frequency spectrum is a plot of sound pressure or sound intensity against frequency showing the relative magnitudes of the components of a complex sound as a function of frequency. The sound pressure or intensity is usually measured in decibels and the frequency is measured in vibrations per second (or Hertz, Hz) or thousands of vibrations per second (kiloHertz, kHz). Many software packages can take a sample of a sound recording, perform the calculation to obtain a spectrum (a Fast Fourier Transform or FFT) and display it in 'real time'.

With Fourier transform analysis it is necessary to sample the input signal with a sampling frequency that is at least twice the bandwidth of the signal, due to the Nyquist limit.

The spectra of continuous sounds are usually made up of a number of sine waves of differing frequency. Those sounds with a tonal structure, made by resonant structures including musical instruments, yield a series of harmonics – frequencies that relate to one another through whole number ratios. Such series have some musical importance and the individual components are called harmonics. The lowest harmonic is often called the fundamental frequency. Many continuous sounds do not have a harmonic structure, and they often contain a wide range of unrelated frequencies.

When preparing a sound pressure spectrum for a waveform, the unit of amplitude is normally the rms sound pressure, which is measured over a defined frequency band. The bandwidth can be as narrow as 1 Hz or as wide as 1/3 octave (an octave is a doubling of frequency); therefore, the bandwidth must be specified.

Where a description of the power of a sound is to be related to the frequency, the power spectral density level is expressed in dB re 1 μPa^2/Hz and represents the average sound pressure squared for a series of bands of width 1 Hz.

The ***sound spectrogram*** is another form of display that provides an overview of the frequency content of a sound as it changes with time. It can be used to identify strong elements of the sound in both the time and frequency domain and is often used to characterize animal sounds. There is an uncertainty principle relating time to frequency and in preparing a sound spectrogram. One of the problems in using the FFT is that it has a fixed resolution. A choice must be made between high frequency resolution (long FFT length, or narrow bandwidth) and high time resolution (short FFT length, or wide bandwidth). This principle is often not understood by those preparing sound spectrograms. If rapidly repeated impulses are analysed with a narrow bandwidth then the pulses will merge and give the impression of a continuous sound composed of related harmonic frequencies.

Determining the hearing abilities of fish & invertebrates

Most audiograms for marine organisms have been derived from experiments in small laboratory tanks, where the presentation of measured sound stimuli presents enormous difficulties. Fish and invertebrates are generally most sensitive to low frequency sounds, where the wavelength often exceeds the dimensions of any water tank containing the animals. The sounds are presented in a variety of ways, sometimes with immersed sound projectors and at other times with the projectors in air above the water, and only the sound pressure levels are usually measured. With an immersed projector in a small, open, thin-walled container very large particle motions are associated with quite low sound pressures. Conversely, with an air loudspeaker above the water the sound field consists almost entirely of sound pressure. It has been evident for some time that the ears in all fishes are essentially sensitive to particle motion (Pumphrey, 1950; de Vries, 1956). Only in some species are the ears coupled to gas-filled bodies that can act as acoustic transformers, converting incident sound pressures into particle motion at the ear (Poggendorf, 1952; de Vries, 1956; van Bergeijk, 1967; Sand and Hawkins, 1973). The hearing of marine invertebrates has barely been investigated but here too it seems likely that they are sensitive to particle motion rather than sound pressure. Particle motion is rarely measured directly, although it is sometimes estimated by means of the plane or spherical wave equations. Sound pressure thresholds and audiograms determined in aquarium tanks must be treated with great scepticism, unless the sounds have been carefully presented and measured (for example by the employment of controlled impedance wave tubes (Hawkins and MacLennan, 1976) or by experiments in mid-water in the sea (Chapman and Hawkins, 1973; Schuijf et al. 1972).

A further acoustic problem encountered in aquarium tanks arises from the presence of high levels of background sound and vibration. It has been shown that in fishes like the cod, at their most sensitive frequencies background noise levels in the sea may interfere with hearing even under quiet conditions (Hawkins and Chapman, 1975). Interference with the detection of one sound by another sound is called ***masking***. Masking results in an increase in the threshold for detection or discrimination of one sound in the presence of another. Conditions in noisy aquarium tanks may result in greatly elevated hearing thresholds. Moreover, noise at particular frequencies may mask sensitivity to those frequencies, but not others, altering the shape of the audiogram.

There are several different ways of determining hearing thresholds for fishes. Fish may habituate to the repeated presentation of sounds, making it difficult to present a full range of sound stimuli and fully explore their responses. Various training and conditioning techniques have therefore been developed to ensure that fish will always respond to sounds that they can hear. Thus, fish have been trained to press a lever, or swim through an aperture when they hear a sound, in anticipation of a subsequent reward of food. Or the electrocardiograph of the fish is monitored and fish conditioned to show a delay in the heartbeat when presented with a sound, in anticipation of a mild electric shock. Once a fish is trained the sound level can be reduced progressively until the fish no longer responds. Raising the sound level if the fish does not respond and reducing it when the fish responds may then bracket the threshold for detection. Although application of these techniques is very labour intensive, the thresholds obtained are repeatable and reliably reflect the full hearing abilities of the fish. The thresholds are usually determined for pure tones and plotted against frequency to give the audiogram

Physiological techniques may also be applied to examine the hearing capabilities of fish. Here an electrical response is recorded from the nervous system of the animal as a sound is presented. For example, microphonic potentials may be detected from the auditory hair cells of the ear with an embedded electrode; or an auditory brainstem response (ABR) may be monitored by surface electrodes typically placed on the head of the fish, as done with mammals. It is probably more correct to call the latter auditory evoked potentials (AEPs) rather than ABRs, as they may not be strictly from the brainstem. Thresholds at different frequencies may be determined by reducing the sound level until the potentials can no longer be detected against the background of electrical noise; or frequency response curves may be prepared by comparing the sound levels that yield a given level of electrical response. Typically, the response curves show less dynamic range than those determined by behavioural techniques. Thresholds are usually higher, as they are usually determined by the inability of the experimenter to distinguish very small electrical potentials against background electrical noise.

Fay and Ladich (2013) have suggested that hearing is generally defined as the act of perceiving sound, a sensory function that involves the entire organism’s behaviour. This behavioural ‘‘act of perceiving’’ can only be measured using behavioural methods. They emphasise that behavioural studies of hearing have a degree of validity that AEP measures lack and that AEP audiograms, while popular and increasingly used, require comparison with behavioural audiograms wherever possible to help establish their usefulness as a possible description of a species characteristic. Physiological methods (i.e. AEPs) only measure detectable electrical responses from the ear or lower portions of the brain. They do not fully reflect the ability of the animal to process and extract information, or indicate whether there will be a behavioural response by the animal.

Glossary of Terms

Aggregate effects	Effects arising from the accumulation of effects from different sources or different stressors
Ambient Noise	Background sound in the sea. Normally restricted to naturally occurring sounds from distributed sources but sometimes applied to all background sounds. Examples of naturally occurring sound sources include waves, wind, rain, snapping shrimp, fish, marine mammals, earthquakes, and volcanoes.
Audiogram	The measurement of hearing sensitivity (or lowest sound level detectable – see ***Auditory Threshold***) at a number of different frequencies in the hearing bandwidth of an organism.
Auditory Evoked Potential (AEP)	A physiological method for determining the hearing characteristics of animals without training. Electrodes (wires) are placed on the head of the animal to record electrical signals (emitted by the ear and central nervous system) in response to sounds. These signals are low in level and are averaged to raise them above the background electrical noise. It is not possible to determine auditory thresholds for fishes that are comparable to behavioural thresholds using this method but it is possible to gain an idea of the frequency range and to compare the effects of various treatments, such as exposure to high levels of sound.
Auditory Threshold	The auditory threshold generally represents the lowest sound level an animal will detect in some statistically predetermined percent of presentations of a signal. Most often, the threshold is the level at which an animal will indicate detection 50% of the time.
Continuous sound	A sound that continues for a long period and in which the mean squared sound pressure is approximately independent of averaging time.
Cumulative effects	Effects arising from the repetition and accumulation of effects from a particular source like a pile driver
Critical Band	One of a number of adjacent frequency bands into which the audio- frequency range of an animal may be notionally divided, such that sounds in different frequency bands are heard independently of one another, without mutual interference. An auditory critical band can be defined for various measures of sound perception that involve

	frequency.
Cumulative sound exposure level (SEL_{cum})	The accumulated SEL for a specified sequence of repeated sounds. The sequence may be defined by a time period (e.g. 24 h) or by the operation producing the train of impulses (for example the number of strikes to insert a particular pile). See ***Sound exposure level (SEL).***
Decibel (dB)	A logarithmic scale most commonly for reporting levels of sound. The actual sound measurement is compared to a fixed reference level.. The decibel value for sound pressure level is $20\log_{10}$ (actual sound pressure/reference pressure). The standard reference for underwater sound pressure is 1 microPascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (i.e., dB re 1 µPa). In terms of energy, the decibel value is defined as $10 \log_{10}$ (actual/reference), where (actual/reference) is a power ratio.
dB_{ht}	A measure used for analysing noise that reflects the sensitivity of the species to different frequencies. It can be used for range of species, both marine mammals and fish. The approach combines the levels of noise at the receptor with the known hearing capabilities of a specific species and delivers results in levels that can then be related to behavioural changes. Sometimes written as dB_{ht} (*Species)* where *Species* refers to the species being considered.
Far-field	A region far enough away from a sound source that the sound pressure behaves in a predictable way, and the particle velocity is related to only the fluid properties and exists only because of the propagating sound wave (see ***Near Field***).
FFT	Fast Fourier Transform. A mathematical calculation for determining the spectrum of a sound wave.
Frequency	The rate of repetition of a regular event in a waveform. The number of cycles of a wave per second. Expressed in Hertz (Hz)
Frequency spectrum	A plot of sound pressure or sound intensity against frequency showing the relative magnitudes of the frequency components of a complex sound.
Fundamental frequency	The lowest frequency of a harmonic series. The fundamental frequency is also called the first harmonic frequency (f) of a harmonic series.
Impulsive sound	A transient sound, usually produced by a rapid release of energy. The sound is made up of one or more pulses, each of short duration (less than 10 s), and with gaps without significant sound emission between the repeated pulses. Such sounds include sounds from seismic air gun arrays,

	impact pile driving, some sonars and explosions.
Instantaneous sound pressure	A measurement of the sound pressure at a particular time and place
Kurtosis	A statistical measure of the roughness of a sound. In terms of an impulsive signal, kurtosis gives an indication of how the signal changes over the duration of the signal. Signals with a high kurtosis tend to have a single peak near the beginning and a long tail of lower energy, whereas signals with very low kurtosis would have a uniform distribution of energy.
M-weighted Sound Exposure Level	An approach which has been proposed by Southall *et al* (2007) and has recently been adopted by the UK Joint Nature Conservation Committee (JNCC) for the assessment of marine operations that may cause what could be defined as a deliberate injury or disturbance effect on marine mammals. This is based on criteria using two metrics; the peak sound pressure level and M-weighted Sound Exposure Levels (SELs) for various groups of marine mammals (low, mid and high frequency cetaceans and pinnipeds). Clearly defined criteria are proposed for auditory injury for single pulses, multiple pulses and non-pulses. Quantitative criteria are also presented for behavioural response to single pulses (based on the level at which Temporary Threshold Shift (TTS) occurs).
Near-field	A region close to the source, where the plane wave equation no longer applies. Characteristically there is exponentially increasing sound pressure towards the source, and a high level of particle velocity. The extent of the near field depends on the wavelength of the sound and/or the size of the source.
Noise	Unwanted sound that interferes with the detection of sounds of interest. Often applied to all man-made sounds. Also used to describe background sounds in the sea including naturally occurring sounds (see ***ambient noise***)
Particle acceleration	A time derivative of particle velocity. The units of acceleration are meters per second squared (m s^{-2}).
Particle displacement	The displacement of particles of a medium created by the forces exerted on the fluid in the presence of a sound wave. The units of velocity are meters (m).
Particle motion	The back and forth motion of the component particles of a medium accompanying the passage of a sound.
Particle velocity	The time rate of change of the displacement of fluid particles created by the forces exerted on the fluid in the presence of a sound wave. The units of velocity are meters

	per second (m s^{-1}).
Peak to peak sound pressure	The range in sound pressure between the most negative and the most positive instantaneous sound pressures
Peak sound pressure	The range in sound pressure between zero and the greatest instantaneous sound pressure. Also called the ***Zero to peak sound pressure***
PTS	Permanent Threshold Shift is a permanent shift in auditory threshold due to exposure to an acoustic signal
Propagation loss	The reduction in level of a sound with distance from the source
Received level	Measure of the sound energy arriving at a receptor. Measured on a logarithmic scale.
Rise time	The interval of time required for a signal to go from zero, or its lowest value, to its maximum value.
rms	Root mean square. For a time series $x(t)$ considering a time period T. RMS = $\sqrt{\frac{1}{T}\int_0^T \lvert x(t)\rvert^2 dt}$
Sound exposure	The integral over time of the square of the sound pressure of a transient waveform.
Sound exposure criterion	The level of sound that results in specified effects upon animals. The effects (which are specified) may include death, mortal injury, tissue injury, impairment of the auditory system and behavioural responses.
Sound exposure level (SEL)	A measure that takes the different duration of sounds into account. It is the accumulated energy over a defined period (usually 1 second). It allows comparison of sounds of different durations. Formally, the SEL is the integral of the squared acoustic pressure with respect to time, expressed as a level in decibels over defined period.
Sound intensity	The product of particle velocity and sound pressure divided by the acoustic impedance. More formally, the work done per unit area and per unit time by a sound wave on the medium as it propagates. The units are Joules per square meter per second (J/m^2-s^{-1}) or watts per square meter (W/m^2). The acoustic intensity is also called the acoustic energy flux.
Sound pressure	The fluctuations in pressure above and below the hydrostatic pressure accompanying the passage of a sound, measured in Pascals.
Sound pressure level	The effective sound pressure, averaged in time, relative to a standard reference pressure. More specifically it is the root mean square (RMS) sound pressure expressed as a level, in decibels. The reference pressure in use is as 1

	microPascal (symbol µPa), which is one millionth of a Pascal.
Source level	Characterises the sound power radiated by an underwater sound source expressed in decibels. It is often specified as the sound pressure level referred to a distance of 1 m from a hypothetical point monopole source.
TTS	Temporary threshold shift is a temporary shift in the auditory threshold due to exposure to an acoustic signal.
Zero to peak sound pressure	The range in sound pressure between zero and the greatest instantaneous sound pressure. For a sinusoidal waveform such as shown if figure ** it corresponds to the amplitude.