A CUMULATIVE EXPOSURE MODEL FOR ASSESSING THE IMPACT OF UNDERWATER SOUND ON MARINE FAUNA – IMPLICATIONS OF NEW AUDIOGRAMS

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1 INTRODUCTION

Sound is introduced into the marine environment by man as a by-product of many activities, including transport, construction, offshore oil and gas, marine renewable energy, cable laying, dredging and recreation. Underwater acoustic transmissions are made for research, mapping, prospecting, fishing, defence and communication. Noise in the ocean may affect biological receptors by inducing adverse behavioural reactions or causing temporary or permanent physiological damage, including hearing impairment. However, the ocean is a naturally noisy place and marine fauna may be adapted to live with natural ambient noise levels [1] and may even become habituated to high levels of anthropogenic noise; for example, in the vicinity of busy seaports. Increasingly, there are legislative and/or policy requirements for the completion of environmental impact assessments (EIA) to gain formal planning consent for actions that may involve the deliberate or incidental introduction of sound into the environment. Two crucial elements of an EIA are to quantify potential noise impacts and to eliminate, reduce or mitigate these impacts.

The potential for adverse environmental impacts caused by exposure to noise may be assessed by source-pathway-receptor modelling that considers: the acoustic source characteristics and *modus operandi*; the propagated acoustic energy likely to be experienced by a receptor; and the potential behavioural response and physiological impacts of the acoustic energy on the receptors that are likely to be present. One of the principal challenges in conducting an EIA for acoustic impacts in the marine environment is the availability of data for source-pathway-receptor modelling. There is likely to be detailed technical information concerning an acoustic source. Environmental databases together with acoustic models will enable the spatial distribution of the acoustic field around the source to be predicted with some degree of confidence. Some data on the spatial and temporal distributions of marine fauna are available, although coverage is incomplete for many species. However, there is a lack of information on the potential behavioural and physiological effects of acoustic energy on marine fauna, including marine mammals. This paper introduces a cumulative exposure model and a new general threshold of hearing curve, and then demonstrates how they may be applied to support an EIA for the deployment of acoustic sources in the marine environment.

2 THE IMPACT OF SOUND ON MARINE LIFE

The effects of underwater sound on fish and marine mammals may be categorized as behavioural or physiological [2] and an EIA would normally consider both behavioural effects and physiological impacts. This paper focuses on physiological damage risk criteria (DRC), specifically the conditions likely to lead to temporary or permanent impairment of the hearing of marine mammals.

Exposure to prolonged, repeated or intense sound may lead to temporary loss in efficiency of the mechanical-chemical-electrical transfer of the inner ear. The consequence is a temporary increase in the animal's threshold of hearing around the acoustic exposure frequencies. This temporary threshold shift (TTS) may last for minutes, hours or days depending on its severity and on the species concerned. If the sound pressure level (SPL) or duration of sound is increased, there may be damage to the inner ear, resulting in permanent loss of hearing sensitivity. The consequence of this is an irreversible increase in the threshold of hearing or permanent threshold shift (PTS).

There is very little experimental evidence on the detrimental impact of sound on marine mammals. However, it has been demonstrated that DRC for impacts on human hearing may be developed for species exposed to underwater sound by utilizing the threshold of hearing for each species in the appropriate medium (water), at the relevant frequency [3]. An important conclusion of these investigations is that acoustic frequency, SPL and cumulative duration need to be considered during the assessment of acoustic impacts. These three aspects can be brought together as a concept of 'dosage', which forms the basis for the development of the DRC in this paper.

3 SENSITIVITY OF HEARING

The potential for underwater sound to impact on marine life and human beings may be assessed by inspection of threshold of hearing curves or audiograms. A comparison may be made of the frequency of a sound source with the frequencies at which aquatic animals and humans underwater have the most sensitive hearing (Figures 1 and 2). The following general deductions are possible. First, the potential for impacts is possible across a wide range of frequencies, and therefore species. Second, there are some parallels in that those frequencies that are likely to be optimum for use by man are also likely to be optimum for marine animals (e.g. they can be exploited to propagate sound over long ranges or used to achieve high spatial resolution).

Audiograms draw attention to the importance of SPL and frequency, but do not emphasize the importance of the temporal domain in evaluating impacts, i.e. the length of time that an animal may be exposed to a sound. While it is true that a sufficiently intense sound may cause instantaneous hearing loss, as with humans it is the measure of exposure to persistent noise that is needed in assessing the true extent of acoustic impacts on hearing. This does not diminish the importance of the audiogram in understanding the effects of noise pollution and it should be noted that even this rudimentary information is lacking for a significant number of animals.

There are comprehensive reviews of hearing in fish, marine mammals and human beings [2,4,5,6]. Historically, however, the published information on the hearing sensitivity of marine mammals has been very limited. In 1995, just nine audiograms of eight species were available [2]. In the last ten years there has been a marked increase in the number of audiograms; investigations into marine mammal hearing being motivated by increasing awareness and concern about the effects of anthropogenic noise on marine mammals. Enabling factors include the availability of suitably trained subjects and the development of evoked potential measurement techniques. The number of odontocete (toothed whale) species for which audiograms are available is now thirteen. There is increased confidence in current knowledge of the threshold of hearing for small cetaceans, but no audiograms are yet available for mysticetes.

The author has reviewed and collated the currently published audiogram data for odontocetes to provide precautionary but representative hearing thresholds for each species or species group (Figure 1). These hearing thresholds have been formed by collapsing the available measurements down to the region of the most sensitive audiogram data available at each frequency.

In Figure 1, harbour porpoise (*Phocoena phocoena*) is the most sensitive odontocete species between 500 Hz and 2 kHz, with killer whale (*Orcinus orca*) being more sensitive between 4 kHz and 32 kHz. Above 32 kHz, harbor porpoise is again the most sensitive species. Note that data are available for beluga [7] with the acoustic source stimulus below (dashed curve in Figure 1) as well as in front (solid curve) of the subject. The lower bound of the precautionary hearing thresholds delineates a general odontocete threshold of hearing curve representing the most sensitive odontocete species at any frequency. A more precautionary odontocete curve lies below the general odontocete curve for frequencies below 8 kHz, where measurements on beluga, made with the source stimulus below the subject, indicate greater sensitivity.

The method described later in this paper exploits a general threshold of hearing (GTH) curve (Figure 2) in an approach that would be regarded as precautionary for a majority of species. The GTH curve has been compiled using the precautionary threshold of hearing curve for odontocetes (see Figure 1 and above), together with precautionary hearing curves that have been compiled for pinnipeds, fish and humans (divers and swimmers). There have been no direct investigations reported on the auditory sensitivity of mysticetes (baleen whales).

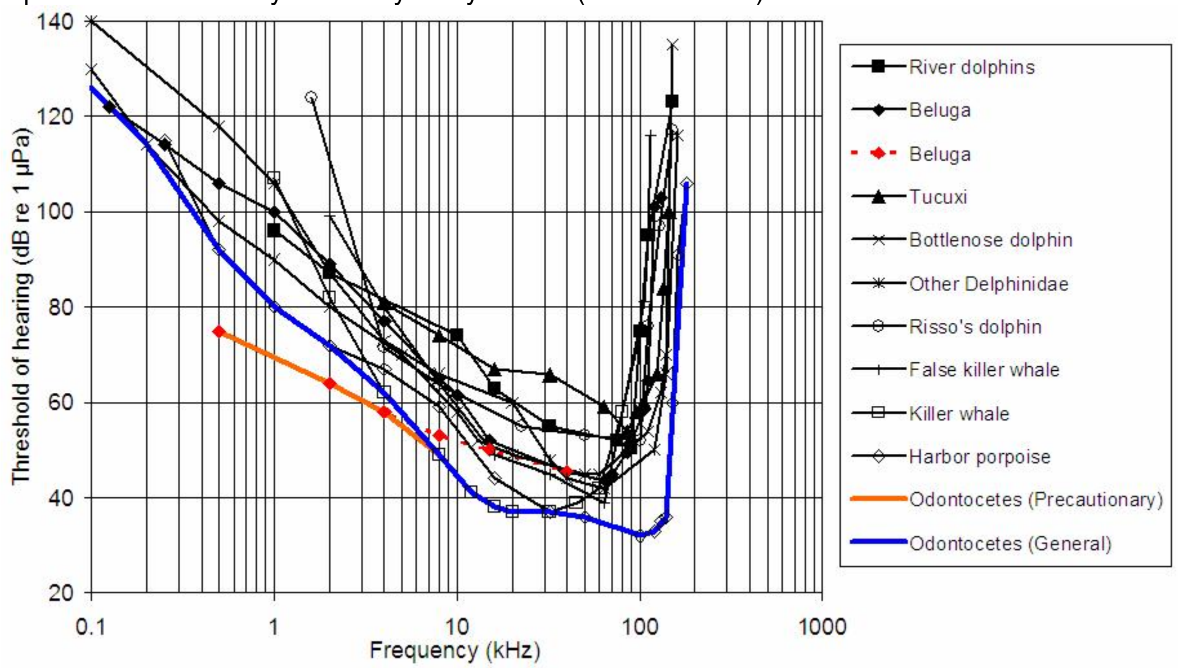

Figure 1. Precautionary hearing thresholds for odontocete species

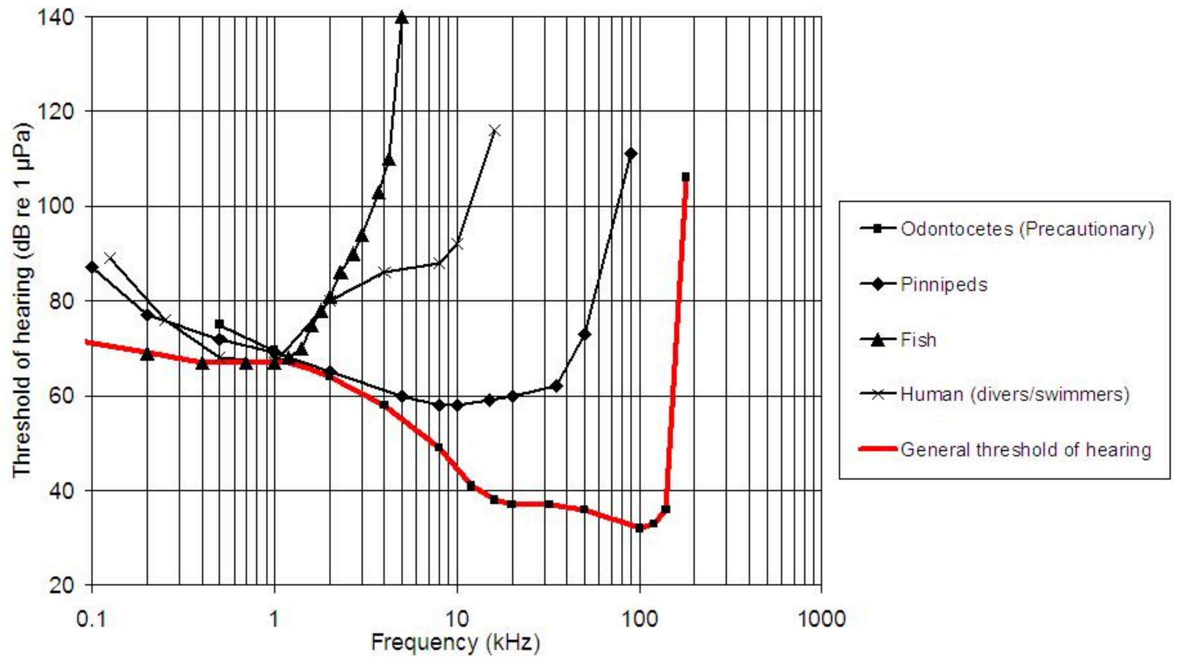

Figure 2. General threshold of hearing (GTH), with thresholds for Odontocetes (from Figure 1), pinnipeds, fish and human divers/swimmers

4 DAMAGE RISK CRITERIA FOR THE EVALUATION OF IMPACTS

In order to assess the severity of an acoustic impact on an animal's hearing, it is necessary to consider not only the acoustic frequency and SPL but also the length of time to which an environmental receptor has been exposed [2,8]. The following sections describe how the frequency and time domain aspects of the problem can be brought together with SPL and propagation characteristics to arrive at scientifically supportable criteria for assessing the effects of a sound source on fish, marine mammals and human beings.

The approach adopted in this paper adapts the principles of human in-air DRC to marine mammals in water. A number of authorities including the UK Health and Safety Executive [9] and the US National Institute for Occupational Safety and Health [10] have established DRC for human hearing in air. The human in-air DRC form a good basis for assessing the effects of noise on humans and other species in the marine environment. The application of human DRC to hearing in fish and sea mammals is contentious but it has some scientific justification given the basic similarities in audiological response and inner ear transduction mechanisms in the various species [2]. Furthermore, with the immediate needs of assessing acoustic impacts in mind, it is probably the best that can be done given the limited scientific evidence that is available on the effects of noise on marine mammals [1,11].

HSE guidance on the UK Noise at Work Regulations (NAWR) [9] uses the concept of sound exposure dosage to legislate against the risk of people at work being exposed to potentially harmful levels of acoustic energy. Calculation of the sound dosage involves integration of the acoustic energy received by an individual over a 24 hour period with the dosage being dependent on the time-averaged SPL. The concept of sound dosage thus considers the SPL, its frequency content and the total duration of exposure. This gives the daily personal noise exposure of an individual ($L_{\mathrm{EP,d}}$) as:

$$L_{\mathrm{EP,d}} = 10\log_{10}\left[\frac{1}{T_0}\int_0^{T_e}\left(\frac{p_{\mathrm{A}}(t)}{p_0}\right)^2 \mathrm{d}t\right], \tag{1}$$

where exposure T_e is the duration of the person's personal exposure to sound, T_0 = 8 hours, p_0 = 20 μPa and p_A is the time-varying A-weighted instantaneous sound pressure. Considering noise exposure of marine mammals and other species in water, and replacing the integral by a summation of the individual acoustic exposure events, Equation (1) becomes:

$$L_{\mathrm{EP,d}} = 10\log_{10}\left[\frac{1}{T_0}\sum_{t=0}^{t=24\,\mathrm{h}}\left(10^{\frac{SPL-GTH}{10}}\Delta t\right)\right], \tag{2}$$

where SPL is the instantaneous sound pressure level (dB re 1 μPa), and GTH is the sensitivity of hearing of the most sensitive species at the frequency of interest (Figure 2). This has the same reference pressure as SPL. The duration of each acoustic transmission in seconds is Δt.

The duration of an individual animal's exposure to sound is integrated over 24 hour periods; it is the 24 hour period for which exposure is potentially the greatest that will determine the range at which the DRC will be exceeded. In many cases, the application of these ideas will be complicated by the fact that the sound source is moving and that fish and sea mammals are at various times passing in and out of the insonified region of water.

Because of the logarithmic nature of Equation (2), a brief exposure at high SPL contributes to a receptor's daily dosage significantly more than continual exposure at much lower SPL. A daily dosage of 75 dB above threshold could, for example, be made up of 8 hours of exposure at 75 dB above threshold of hearing or by a single 8 s pulse at 110 dB above threshold. Equally, ten 8 s pulses at 100 dB above threshold would give the same total exposure.

Heathershaw [3] extrapolated human DRC to assess the potential impact of sound on other species, using published in-air hearing data to set equivalent 8 hour dosage limits. He showed that the onset of TTS and PTS occurred at an exceedance of 75 dB and 95 dB respectively above the threshold of hearing at the frequency of concern. An exchange rate of +3 dB per halving of exposure duration determines the onset levels for shorter exposures. The 24 and 8 hour periods used to formulate the in-water DRC may seem somewhat arbitrary, although they correspond to effects measured in air.

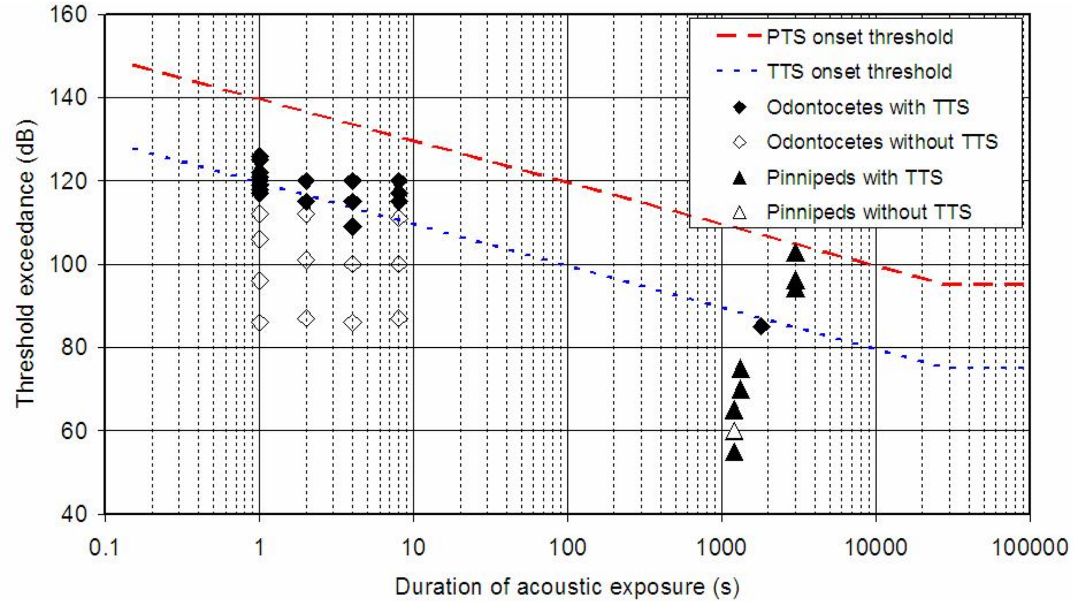

Figure 3 Temporary threshold shift (TTS) onset data for odontocetes and pinnipeds

This paper finds that the available in-water TTS datasets for marine mammals indicate that the approach described above is realistic for the species for which data are available. Measurements of TTS in bottlenose dolphins and beluga resulting from exposure to single 1 s, 2 s, 4 s and 8 s tones [12,13] suggest that the level for TTS onset is a sound exposure level of 195 dB re 1 μPa^{2}s [13]. This is equivalent to exceeding the threshold of hearing by 120 dB for a 1 s exposure (or 111 dB for 8 s exposure), based on a hearing threshold of 75 dB re 1 μPa. Some TTS data are available for longer exposures. TTS onset has been observed in bottlenose dolphins after exposure to a noise signal for 30 min at a SPL of 160 dB re 1 μPa [14] equivalent to 85 dB above the hearing threshold. Measurements on pinnipeds (harbor seal (*Phoca vitulina*), California sea lion (*Zalophus californianus*) and Northern elephant seal (*Mirounga angustirostris*)) [15,16] straddle the TTS threshold (Figure 3). The data for pinnipeds suggest that a precautionary approach based on smaller exceedance values (<75 dB) may be appropriate.

In Figure 3, onset data for odontocetes and pinnipeds are represented by diamonds and triangles, respectively, with closed and open symbols indicating whether or not a significant TTS was observed. Here, TTS onset data are plotted as threshold exceedance levels, not as absolute SPL. The dashed lines represent the onset levels for TTS and permanent threshold shift (PTS) used as damage risk criteria. These define hearing threshold exceedance levels of 75 dB (TTS) and 95 dB (PTS) for cumulative exposures of 8 hours or greater, with exceedance levels for shorter exposures increasing by 3 dB for each halving of exposure duration. No data on TTS are currently available for the cumulative effects of multiple exposures to short tones, corresponding to typical active sonar or echo sounder transmissions. There is no information on PTS onset in marine mammals. Extrapolation from studies on terrestrial animals to marine mammals underwater yields the 20 dB offset of PTS above the TTS onset (Figure 3) [3].

5 DEVELOPING MITIGATION MEASURES

To calculate safe stand-off distances for the purposes of mitigation, it is necessary to compute the TTS and PTS dosages given by Equation (2) and Figures 2 and 3, and then to estimate the distances at which these effects may occur from a sound source. Depending on the transmitted source level and in-water acoustic impact threshold levels, this may be accomplished using simple geometrical spreading laws or numerical acoustic propagation models. While there are plenty of models from which to choose [17], it is important that an appropriate modelling technique is used and that conditions are not over-simplified.

Table 1 illustrates the calculation of stand-off distances associated with underwater acoustic transmissions. The in-water impact threshold levels depend on frequency, impact criterion and cumulative exposure duration, with the stand-off distance also being dependent on the transmitted source level. The in-water acoustic threshold levels at which the PTS and TTS risk criteria would be exceeded have been calculated using the GTH value for the frequencies concerned, taking into account the exposure duration and the PTS and TTS threshold exceedance values (95 dB and 75 dB respectively). In each case the in-water SPL, predicted using an acoustic propagation model, is compared with the acoustic impact threshold levels to obtain the ranges at which PTS and TTS would occur. In the examples illustrated in Table 1, the in-water thresholds decrease with increasing frequency and duration. There is a corresponding increase in the values for stand-off distance, which also depend on the transmitted source level, although the effects of acoustic absorption cause this trend to break down at higher frequencies and longer ranges.

Transmitter frequency (kHz)	Transmitter source level (dB re 1 μPa at 1m)	Damage risk criterion	Exposure duration (s)	In-water threshold level (dB re 1 μPa)	Stand-off distance (m)
4	180	PTS	40	181.6	<1
		PTS	120	176.8	1
		TTS	1200	146.8	46
	200	PTS	40	181.6	8
		PTS	120	176.8	14
		TTS	1200	146.8	860
	220	PTS	40	181.6	83
		PTS	120	176.8	160
		TTS	1200	146.8	16750
16	180	PTS	40	161.6	8
		PTS	120	156.8	14
		TTS	1200	126.8	560
	200	PTS	40	161.6	82
		PTS	120	156.8	150
		TTS	1200	126.8	5375
	220	PTS	40	161.6	1615
		PTS	120	156.8	2000
		TTS	1200	126.8	11750

Table 1. Calculation of stand-off distances for underwater acoustic transmissions

Taking transmissions at a frequency of 16 kHz and source level of 180 dB re 1 μPa at 1 m, typical of an underwater acoustic communications device, the stand-off distance defining the PTS zone increases from 8 m to 14 m as the exposure duration increases from 40 s to 120 s. This corresponds to in-water threshold levels of 161.6 and 156.8 dB re 1 μPa respectively. Similarly, the stand-off distance for TTS is 560 m for a cumulative exposure duration of 1200 s. The in-water threshold level in this case is 126.8 dB re 1 μPa. If transmissions are made at a frequency of 4 kHz and a source level of 220 dB re 1 μPa at 1 m, the PTS stand-off distance lies in the range 83 m to 160 m, corresponding to in-water threshold levels of 181.6 and 176.8 dB re 1 μPa respectively. The TTS zone extends to 17 km from the source, where the in-water SPL would be 146.8 dB re 1 μPa.

These results illustrate the importance of duration or cumulative sound exposure in controlling the overall spatial scale of any adverse acoustic effect, while clearly the choice of impact criteria (e.g. TTS or PTS) will determine the nature of any adverse effect. The calculated distances define the maximum ranges at which PTS and TTS may occur and they may therefore be used to define a mitigation strategy to minimize the risk of adverse impacts on marine fauna. The dimensions of the PTS zones are used for the purposes of developing a suitable monitoring strategy (e.g. visual observers plus passive acoustic monitoring techniques) to detect for the presence of cetaceans in advance of a moving acoustic source (e.g. a survey vessel). The dimensions of the TTS zone form the basis of mitigation using marine spatial planning to protect fixed areas of conservation.

As described earlier in this paper, the calculation of PTS and TTS onset uses a general threshold of hearing curve (Figure 2). The GTH curve takes into account those animals whose hearing is most acute at the frequency of interest, regardless of whether they are known to be present or not. If it is known which animals are present in an area, the mitigation may be designed around an individual animal's audiogram, leading, possibly, to some relaxation of the more stringent measures arising from the use of the general approach. The important point is that the method has the flexibility to take either approach.

Mitigation measures are designed to reduce environmental risk to manageable levels. For sound sources that are controllable such as ocean research sonars, it may be possible to limit exposure by reducing source levels or suspending transmission if monitoring activities indicate the presence of e.g. whales or dolphins. This paper has also demonstrated the importance of sound exposure duration in controlling the spatial extent of potentially adverse effects. Therefore, in situations where it is not possible to reduce the source level, acoustic emissions should be 'managed' by controlling cumulative transmission duration and using the exposure arguments described earlier. To be truly effective, however, mitigation should begin well in advance of any activity. Environmental protection planning should identify sensitive areas or habitats and ensure that potentially harmful sound emission activities are prevented from encroaching.

6 DISCUSSION

The principal aim of the work described in this paper has been the development of mitigation measures that are applicable to a range of environments and underwater sound sources, and which offer a reasonably precautionary approach to assessing the likely adverse effects of underwater sound on marine life and human beings. It is a basic methodology, which should be capable of extension and refinement as new research results become available. For the purposes of assessing the adverse environmental effects that may be associated with underwater sound transmissions, and based on the available scientific evidence, it is concluded that a reasonable approach might be based upon a source-pathway-receptor modelling methodology, together with the use of:

(a) a general threshold of hearing value (GTH) curve to alleviate species dependency and deal with frequency dependency;

(b) quantified damage risk criteria (DRC) to deal with SPL and duration aspects of underwater sound transmissions; and

(c) stand-off distances to delineate buffer zones around conservation areas, in which sound sources should not be used, along with cordons around the sound source where monitoring and mitigation strategies should be applied.

A great deal of progress has been made towards understanding the effects of noise on marine life, but substantial knowledge gaps remain. In response to these knowledge gaps, a precautionary approach to the mitigation of potential impacts has been adopted. There is currently no information on exposure levels for PTS onset in marine mammals and ethical considerations mean that it is unlikely that there ever will be. It is not possible to predict the occurrence of PTS by extrapolation from TTS data. The audiology of baleen whales has yet to be determined and inference of risk thresholds by extrapolation from other marine species is necessary but may be unsound. There are serious deficiencies in current knowledge of cumulative impacts: extending from repeated sonar transmissions from a single transmitter, multiple noise sources operating in an area, and repeated use of a sea area over a long period. The potential for long-term impacts is therefore difficult to quantify. The definition of behavioural impact criteria is controversial. It should be possible to determine whether an animal would be aware of a sound, but it is more difficult to define global SPL criteria for disturbance and potentially adverse behavioural reactions. A simple threshold exceedance criterion is likely to be inadequate, because the potential for adverse reactions is context dependant and may benefit from a statistical approach [2].

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