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Understanding the Scale and Impacts of Anthropogenic Noise upon Fish and Invertebrates in the Marine Environment

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Understanding the Scale and Impacts of Anthropogenic Noise upon Fish and Invertebrates in the Marine Environment

1 Effects of underwater noise on fish and invertebrates

1.1 Introduction

Sound is important to fish and other aquatic organisms. Many fish and invertebrates depend on sound to communicate with one another, detect prey and predators, navigate from one place to another, avoid hazards and respond to the world around them.

Seas, lakes, and rivers can be quite noisy, but many of the sounds are entirely natural. The sounds of falling rain, breaking waves, cracking ice, bubbles, spray, and turbulence provide a continuous but a varying background of noise. Ambient noise in the ocean is sound that is always present and cannot be attributed to an identifiable localised source (Urban, 1992). Less frequently, earthquakes, volcanic eruptions, and lightning strikes generate intense sounds, which travel over great distances. In addition, sounds from marine mammals, fish, and crustaceans add to the background noise. Snapping shrimps and chorusing fish can contribute continuous sounds at some times of day and may mask communication signals from other animals. Together with the noise from wind-driven waves, these biological sounds may dominate sounds in the sea.

Man-made sounds add to these natural sources of noise. In recent years, there has been a significant increase in the levels and incidence of human-generated underwater sound. Much of the technology contributing to ocean noise is new and in many cases the sounds generated are very different to natural sounds, both in their amplitudes and characteristics. Sound travels well in the sea and the influence of underwater noise can be pervasive. The ecological effects of particular sound sources may extend far beyond their immediate vicinity. In some cases, including ships and seismic surveys, the sources themselves are mobile.

There is concern over the effects of these extraneous sounds upon fish and other aquatic animals. It is known that very intense sounds may kill or injure animals. At lower levels, sound may impair their hearing, affect their ability to orientate, or make their vocalisations difficult to detect. Noise may evoke changes in behaviour that may affect spawning migrations or disrupt foraging and feeding. It may cause chronic stress and associated physiological responses. In some cases it may deny animals access to particular habitats, including preferred feeding grounds or spawning areas.

Marine animals make their own sounds and we know that birds and mammals may adjust their calls in a manner that suggests they are raising their “voices” or changing their calls to enable them to be heard. This is known as the Lombard effect (e.g. Miller *et al.* 2000; Foote *et al.* 2004; Holt *et al.*, 2008). There is also evidence that some species may simply stop calling, either because they are being disturbed or because they give up trying to communicate when it is noisy. There is evidence that the calls of whales change in response to increased noise even when the noise is natural (Dunlop *et al.* 2010).

Effects of noise on animals can therefore range from mild and insignificant to severe and lasting. Noise can exert effects upon individuals and in some cases it can affect large numbers of animals, affecting their survival or reproduction and potentially damaging whole populations. This review sets out to answer a number of key questions about the impact of man-made sounds upon fish and invertebrates:

> Does the noise we make in the sea harm marine life? Do man-made sounds have a significant and detrimental effect upon the fitness of aquatic organisms, affecting their welfare and their survival?
>
> If this is the case, what can and should we do about it? How might we reduce the levels of man-made sound or mitigate their impact?

In this review we will consider some of these man-made sources of sounds in greater detail. We will pay particular attention to defining the types of noise man is introducing into the ocean and their amplitudes and characteristics. We will then compare these man-made sounds with sounds from natural sources and, evaluate how the effects may affect marine fish and invertebrate population. Finally we will review ways the harmful effect of man-made noise can be eliminated or mitigated.

There is now interest in forms of regulation which set overall environmental objectives. The Marine Strategy Framework Directive sets out to define good environmental status for a variety of environmental descriptors including noise. However, how do we define good environmental status for noise? Is it likely that there will be a future expansion of noise-making activities in our seas? Certainly there are plans to expand conventional and alternative energy technologies into coastal and offshore waters with their accompanying sources of sound. Can we estimate the anticipated changes in noise level? What will be the consequences for aquatic animals? Should we be planning to monitor changes in noise in the sea and the possible effects? What we do know is that in some parts of the ocean man-made noise has been increasing across much of the frequency spectrum (Andrew et al., 2002; McDonald et al., 2006) and especially at lower frequencies (<500 Hz) (Frisk, 2007). Indeed, at lower frequencies, the level of noise above the natural noise background may serve as an indicator of the degree of industrialisation of the ocean.

Use of the oceans is likely to increase still further over the next few decades, particularly in coastal areas. A large proportion of the manufactured goods and raw materials needed by a growing global economy are shipped by sea. Demand for oil and gas is pushing exploration and production further offshore into deep waters at the edge of the continental shelf and into the Arctic regions. Extraction of renewable energy from the ocean, although small at present, is expected to increase over the next few decades. In coastal ocean areas, recreation is also increasing, bringing with it increasing noise levels from pleasure boats. Perhaps the only human activity likely to decline over the next few decades is fishing, where fish and shellfish resources have been over exploited. There are real concerns that increasing use of the sea has led us in small steps towards a position where the 'soundscape' of the sea has become altered on a global scale.

2 Underwater sound

2.1 Nature of underwater sound

Sound is the common term for an acoustic pressure disturbance, and is characterised by molecules moving back and forth in the direction of propagation of the wave, resulting in alternate regions of rarefaction and compression in the propagation fluid. The disturbance travels away from the source at a speed that depends on the density and elasticity of the medium. The standard way of detecting the passage of a sound in water is by monitoring the oscillatory change in pressure above and below the prevailing hydrostatic pressure; the sound pressure. It is important to recognise, though that the stimulus marine animals are responding to is not necessarily the sound pressure. Passage of the sound wave involves both compression and motion of the medium. There is back and forth motion of the medium that can be described by the particle displacement or its time derivatives particle velocity and acceleration. Particle motion is aligned along a particular direction; and is a vector quantity, whereas pressure acts in all directions (it is a scalar quantity). In a free or ideal sound field, the particle velocity can be calculated from the sound pressure. However, in most circumstances these conditions do not apply.

The speed of propagation of an acoustic wave can be expressed in terms of the bulk modulus of the medium, which is a measure of its compressibility, as follows:

$$c = \sqrt{\frac{\gamma\beta}{\rho_0}} \tag{1}$$

Here, c is the speed of propagation of an acoustic wave, γ is the ratio of specific heats, β is the (isothermal) bulk modulus and ρ_0 is the ambient medium density. One of the major differences between air and water is the sound speed, which in water is approximately 1500 m/s compared to 343 m/s in air. The higher sound speed in water is due to the relative incompressibility (large bulk modulus) of water compared to air, in other terms, water is stiffer than air. This has another implication; for a sound of given intensity sound pressure levels are higher in water than in air.

2.2 Background levels of underwater sound

2.2.1 Historical perspectives

We do not have historical records of how noise in the sea has changed. Systematic measurement of noise in the sea has often been at local sites and the records are often incomplete. One current estimate is that an expansion in shipping has been accompanied by an increase in anthropogenic sound in the frequency range below 500 Hz. Several studies have indicated that over the past few decades the contribution to ambient noise from ships in busy shipping lanes has increased by as much as 12 dB (Andrew *et al.*, 2002; Hildebrand, 2009).

A significant body of ambient noise measurements were taken in deep water during the first half of the 20th century. These measurements came as a result of the fact that a limiting factor in the performance of military SONAR (SOund Navigation And Ranging - a system used to locate objects in water) is the level of ambient noise present at the receiver location, which created a significant incentive to gain further understanding of the ambient noise process. Since this time the levels of background sound at many locations have been quantified and its effects on SONAR have been assessed so the level of interest in recording background sound levels has not been sustained.

2.2.2 Spectral characteristics of background sound

Knudsen and his colleagues made an important contribution to the field of knowledge (Knudsen et al. 1948) identifying that between 200 Hz and 50 kHz the level of ambient noise is dependent on the sea-state. The underlying physical processes that cause this variation are still unclear, but flow noise from surface wind, breaking waves and bubble formation (typically in the frequency range 15-300 kHz depending on size of bubble. Also bubble clouds tend to oscillate collectively to produce lower frequency noise) are all thought to contribute. Wenz (1962) built on the region defined by Knudsen, extending to the low and high frequency ranges. Below 10 Hz measured noise is thought to be due to oceanic turbulence and seismic disturbances. In the region around 100 Hz distant shipping makes a significant contribution in almost all of the world's oceans.

Mellen (1952) showed that at very high frequencies, from 50 kHz upwards, molecular motion of water (thermal noise) contributes to the noise level at an increasing rate. Figure 2-1 gives a summary of the range of ambient noise in the ocean as given in a paper compiled by Wenz (1962).

Low frequency ambient noise from 1 to 10 Hz is mainly comprised of motion of water at its boundaries and turbulent pressure fluctuations from surface waves. It exhibits a dependence on both wind strength and water currents. This is especially the case in shallow water. Turbulent pressure changes are not generally acoustic in nature: they do not propagate as alternate regions of high and low pressure. Hydrophones are equally as sensitive to turbulent pressure changes as propagating sound waves, and measurements will be a combination of both. However, low frequency propagating sound does exist, and can be measured where turbulent noise does not dominate. Low frequency acoustic noise in this region includes distant earthquakes and explosions. Between 10 and 100 Hz distant anthropogenic noise begins to dominate, with its greatest contribution between 20 Hz and 80 Hz. The noise in this region is not attributable to one specific source, but a collection of sources at distance from the receiver. However, distant shipping traffic is the greatest contributor to man-made ambient noise, with received levels up to 55 dB re 1 µPa for usual and 65 dB re 1 µPa for heavy shipping traffic.

In the mid-frequency range (around 10 kHz) sediment transport noise may be a significant noise source. This is particularly noticeable where strong currents and turbulence exist due to wave action or tidal flow. As the increased sediment movement around the hydrophone may increase self-noise due to more sediment hitting the device whether this level is accurate is unclear.

In the region above 100 Hz, the ambient noise level depends on weather conditions, with wind and wave related effects creating sound. The peak level of this band has been shown to be related to the wind speed, measured using the Beaufort scale, with levels ranging from 20 dB re 1 µPa to 55 dB re 1 µPa. The level of wind related noise decreases with increasing frequency above approximately 500 Hz, falling with a slope of between 5 and 6 dB per octave (doubling of frequency).

The data from Wenz (1962) and Knudsen et al. (1948) are generally accepted as providing an indication of the range of sea noise levels and the source of the dominant noise in each frequency range (Figure 2-1). However, when considering the spectral levels of ambient sea noise presented by Wenz and Knudsen, it is important to note that these measurements were undertaken over 40 years ago and in very deep water environments. The recent review of underwater noise by Hildebrand (2004) cites the data of Mazzuca (2001) in deriving an overall increase of 16 dB in low frequency noise during the period from 1950 to 2000, corresponding to a doubling of noise pressure level (6 dB increase) every two decades over the past fifty years.

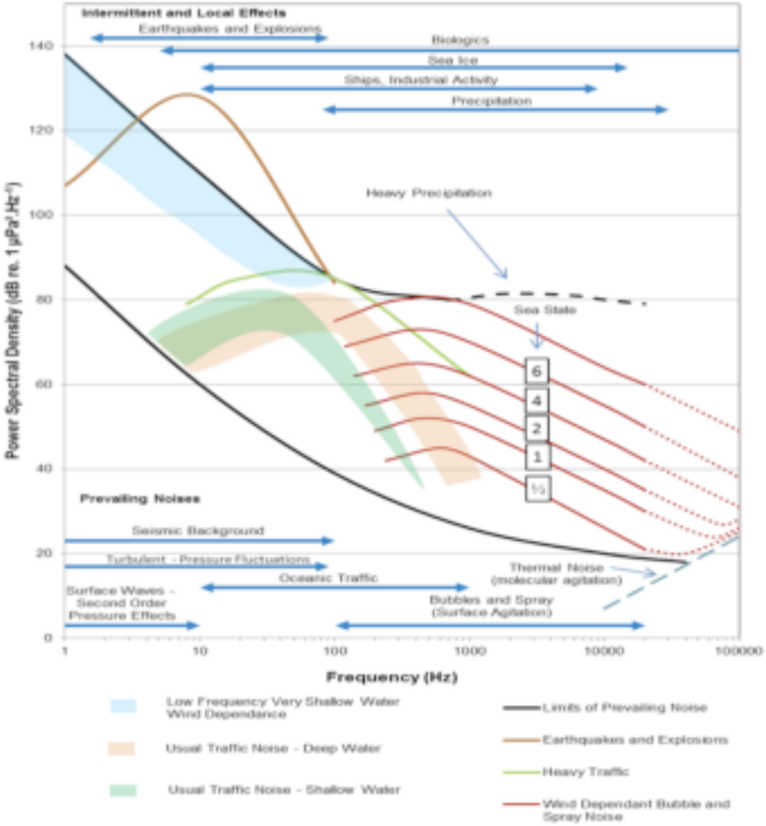


Figure 2-1: Ambient noise levels in the ocean. Adapted from Wenz (1962)

At frequencies above 20 kHz, measured sound levels may be influenced by thermal noise. This increases from a level of -10 dB re 1 µPa at 35 kHz by a rate of 6 dB per octave. During high winds, thermal noise may not dominate below frequencies of several 100 kHz. Other natural contributions to ambient noise in this frequency range include sea-ice and biological sources.

There are many sources of biological noise in the ocean, caused by animals such as such as shrimp, shellfish, some species of fish and many cetaceans. For example, snapping shrimp produce a loud sound by snapping their claws causing cavitation. When the bubble collapses, broadband sounds with components from 500 Hz to 80 kHz are produced. There are many varieties of sound-producing fish that vocalise in a number of ways all of which cause sound at typically less than 1000 Hz.

A detailed breakdown of anthropogenic noise is given in the following sections, however, since shipping and industrial activities noise is so ubiquitous when measuring underwater noise they have been included in Figure 2-1. Current evidence indicates that background sound levels in areas of low shipping are much lower than areas such as shipping lanes. Shipping traffic is believed to be one of the main contributors to noise levels at around 100 Hz, especially in the deep ocean. Other sources of anthropogenic noise, while sometimes higher in level, tend to be of much more local concern. This is because events that produce high levels of noise, for instance those associated with construction, do not cover the same area as shipping noise and occur only infrequently.

2.3 Coastal water ambient noise

A common definition in the underwater acoustics field is that shallow water is that which is less than 200 m deep; however, this definition covers the significantly different conditions of continental shelf edge areas and inshore harbours and bays. A more useful definition, which, for the purposes of this report will be called coastal waters, includes frequency dependence, with the water being of a depth of the same order of magnitude as the acoustic wavelength. For frequencies below 50 Hz water can be considered shallow for water depths of approximately 30 m. This definition is based on sound propagation considerations and, though not related to the generation of ambient noise, it has a bearing on its distribution.

Construction activity normally occurs in coastal waters but ambient noise in these regions is less well understood, and extremely variable; it can be both significantly quieter and louder than deep-water ambient noise. The shallow water noise spectrum is typically dominated by shipping, wind and wave and biological sources. Wenz (1962) states that ambient noise is 5 dB higher in shallow waters than in deep waters but this is an over simplification. In addition to ambient noise (which includes distant shipping traffic), in coastal waters, local shipping traffic, pleasure craft, oil and gas platforms, other mechanical installations and local wildlife all add to the level of noise received at a hydrophone.

Over the past 20 years, Subacoustech Ltd has made several thousand measurements of ambient noise during offshore construction projects in United Kingdom (UK) territorial waters. These measurements have been conducted in a large range of different geographical locations and sea states around UK waters, and may be regarded as giving a realistic representation of background sound in UK territorial waters. Some of these time histories have been analysed to yield typical spectra for underwater coastal background sound. Data gathered by Subacoustech will hereafter be referred to as having been gathered by ‘the authors’.

Analyses have been made of recordings of underwater noise taken at 10 different sites, all of which are between 1 and 20 km from the UK coast (Figure 2-2).

Figure 2-2: Map of the UK showing sites where background sound measurements have been collected and analysed. 1 - Orkney Islands, near Eday Island. 2 – North Moray Firth. 3 – South Moray Firth. 4 - Broadhaven Bay, Ireland. 5 – Mull of Galloway. 6 – Solway Firth. 7 – West of Morecambe Bay. 8 – North Thames estuary. 9 – South Thames estuary. 10 – Southern North Sea.

All of these underwater noise measurements were made using a Bruel & Kjaer Type 8106 hydrophone, connected to a proprietary hydrophone power supply / amplifier. This amplifier provided power to, as well as conditioning and amplifying the acoustic signal from, the hydrophone, and also could pre-emphasise recordings where this was required in order to achieve an adequate dynamic range. The measurements presented in this study are based on analysis over the frequency range from 1 Hz to 120 kHz. All of the measurements presented were taken in the absence of precipitation, with no other noticeable sources of underwater noise such as nearby shipping, and at sea state 1 (Figure 2-3) and 3 (Figure 2-4), with the hydrophone at half water depth (typically 10 m to 15 m from the surface).

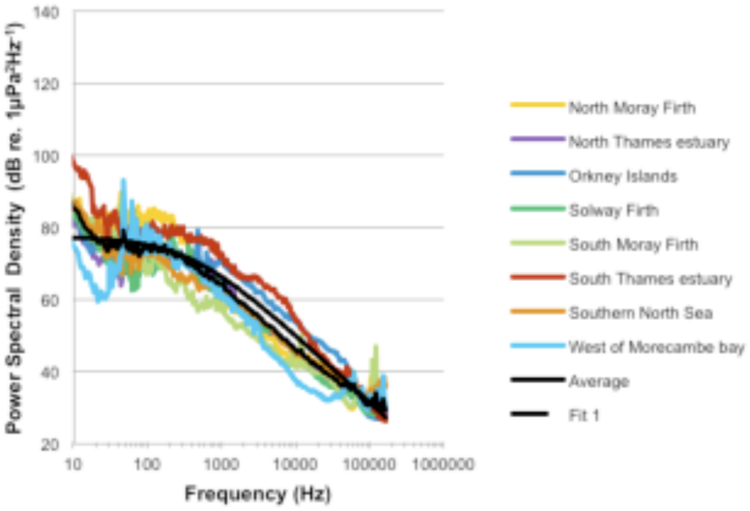


Figure 2-3: Background sound levels at sea state 1 in UK territorial waters

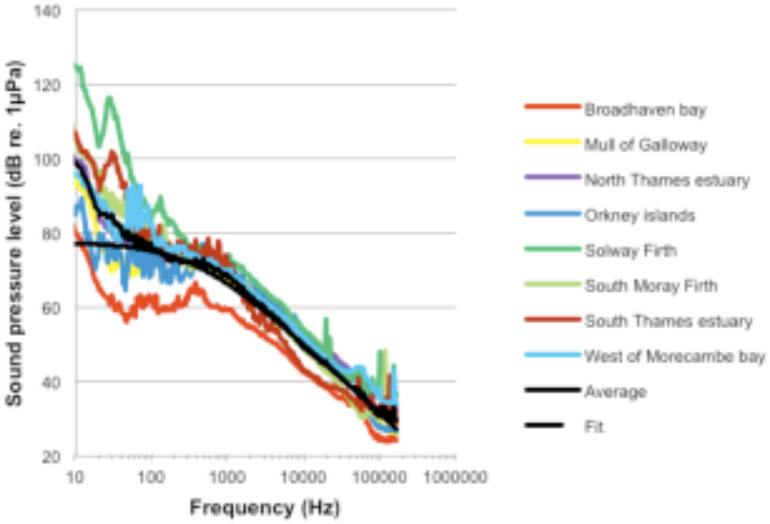


Figure 2-4: Background sound levels at sea state 3 in UK territorial waters

For coastal background sound the noise falls into three frequency regimes. At the lowest frequencies, of up to 50 or 60 Hz, noise is largely associated with local mechanisms such as wave passage and splash. Between 50 Hz and 300 Hz, the noise has a tonal or "swathe" structure typical of the noise from distant shipping (Nedwell *et al*, 2008). This is, to be expected due to the preponderance of shipping in coastal areas. Finally, at higher frequencies, there is a relatively featureless broadband component of noise, falling with increasing frequency at about 6 dB per octave. In some of the recordings sharp peaks in the frequency spectrum may be seen, for instance, at frequencies of about 22 kHz, and also at higher frequencies in the hundred kilohertz region. It is likely that these are due to the use of acoustic systems such as depth gauges, fish finders, and sonar. It may be commented that in terms of the energy at high frequencies in these coastal regions, noise from these systems dominates over the background sound.

It is interesting to note that in this higher frequency region the noise level is relatively constant, the difference between the highest and lowest level being generally no more than 15 dB In the case of deep ocean background sound, the level in this region depends on the sea state, since the noise is generated by natural processes at the water surface. However, in the case of coastal background sound, the much higher level of noise from shipping dominates at a much higher level than would be the case in the deep ocean.

A reasonable approximation of the spectral level may be provided by an equation of the form

$$SPL = 20\,log_{10}\left(\frac{7600}{1 + 1.667\times10^{-3} f^{0.94}}\right)$$

The two average spectra, the approximation given by the above equation, and the noise curves published by Wenz in are illustrated in Figure 2-5.

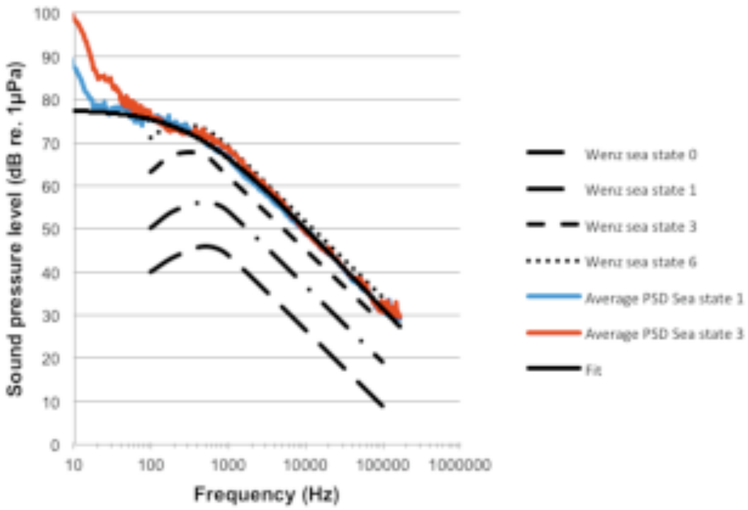


Figure 2-5: Comparison of average background data and background sound from Wenz (1962)

It can be seen that the deviation between the two average coastal noise PSDs (Power Spectral Density) and the approximation to them is only as the order of 2-3 dB over the interval of 500 Hz-10 kHz. There is a larger deviation at frequencies below 100 Hz, due to the dominance of wave noise in this region. It is interesting to note that this is in sharp comparison to the data from Wenz (1962) for deep ocean noise, which shows a difference of around 10 dB between the same two sea states, as well as much lower overall levels. The fit for coastal noise is used in subsequent analysis in this review and is referred to as “standard coastal noise”.

These data indicate that coastal noise is significantly higher in level than in the deep ocean, as can be seen by comparison of figures 2-3, 2-4 and 2-5. It should be added that previous measurements in the Morecambe Bay area indicated a very high source level of noise created by oil and gas platforms in the area; it is possible that noise from these large industrial facilities contribute to the particularly high noise spectral level noted in the West of Morecambe Bay measurements.

2.4 Deficiencies in our knowledge

Currently we do not know the precise distribution of background levels of sound in the sea. Offshore waters appear to be quieter than coastal areas. Natural background noise increases with sea state in all waters. This effect is often compounded by greater input of shipping and other sources of anthropogenic noise at inshore locations. The way frequency rich sound signals propagate has been extensively studied for piling and seismic and it has been found that the effect of water depth on sound propagation is much more significant than bottom hardness or roughness. However, the precise importance of bottom type and its interaction with bathymetry for other sources of sound is still not known.

3 Quantities for the measurement of sound

3.1 Introduction

The science of measuring noise and relating it to its effects on humans, and the use of metrics (scales) such as the dB (A), is well established. Aquatic organisms may perceive the *pressure* component caused by the sound wave and/or the *particle velocity* ("vibration") of the water. It is important to understand this effect because the appropriate quantity describing the noise must be related to its effects. For instance, if an animal perceives particle velocity, and encounters a sound field having a high level of this quantity, it may react to the sound, even where a measurement of sound pressure would indicate the level was too low to create a response. Measurements have therefore to be relevant to the hearing mechanisms and abilities of the biota under consideration, which may be fundamentally different to what humans may sense as sounds.

Sound pressure is in principle easily measured underwater by the use of a hydrophone. However, it should be noted that there are several effects that can severely compromise the quality of a measurement. First, the frequency range over which marine animals hear is much wider than that conventionally measured in air, and spans from, approximately, 10 Hz to at least 100 kHz. Any measurements made of waterborne sound pressure waves that do not cover this range are hence of little value for general analysis in terms of their environmental effects on marine species. Second, a major limiting factor that is generally ignored is the range between the highest and lowest pressure levels that can be measured by the hydrophone, otherwise known as the dynamic range.

3.2 Sound Pressure Level (SPL)

There is a very wide range of sound pressures measured underwater, from around 0.0000001 Pa (Pascal or Newton per square metre is the S.I. unit of sound pressure) in quiet sea conditions to 10,000,000 Pascal for an explosive blast. For convenience, sound pressure is expressed through the use of a logarithmic (dB = decibel) scale. The use of a logarithmic scale compresses the range so that it can be easily described (in this example, from 0 dB to 260 dB re 1 µPa). An additional advantage of working with the dB scale is that many of the physical mechanisms responsible of sound attenuation operate at a constant rate when there are expressed on the dB scale. Sound pressure differences expressed in this manner is termed the Sound Pressure Level or SPL.

The SPL is defined as:

$$SPL = 20\log_{10}\left(\frac{p^2}{p_{ref}^2}\right)$$

where pP is the sound pressure to be expressed 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.

This relationship is illustrated in Figure 3-1, which shows how the sound level increases by 6 dB with each doubling of pressure.

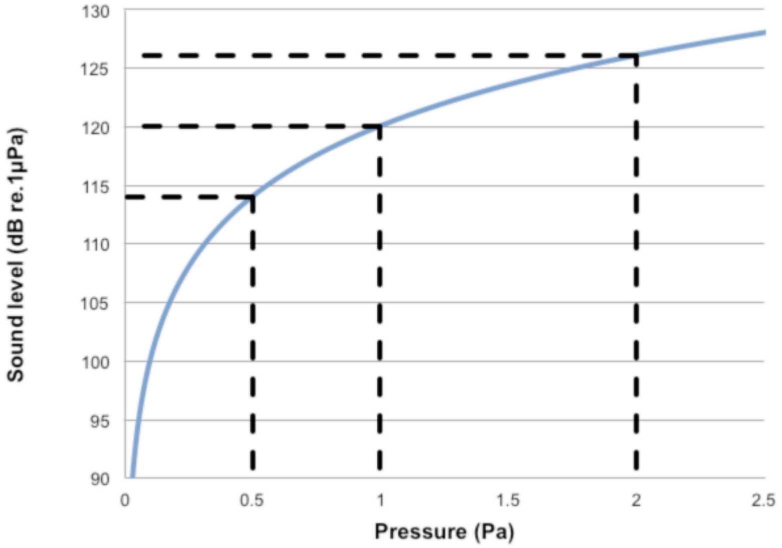


Figure 3-1: Illustration of the relationship between pressure and sound level

It should be noted that the convention for in air acoustics is to use a pressure reference of 20 μPa when calculating SPL, as this is, for humans, approximately the minimum audible pressure for a 1 kHz tone. It is possible to convert between reference pressures by adding a constant value, and in this instance 20 μPa is 26 dB greater than 1 μPa. Levels referred to 1 μPa will be 26 dB higher than levels referred to 20 μPa.

The SPL can be presented in many different forms, several of which are described below.

Peak Level. The peak level is the maximum level of the acoustic pressure, usually a positive pressure. This form of measurement is often used to characterise underwater blast, where there is a clear positive peak following the detonation of explosives. Examples of this type of measurement used to define underwater blast waves can be found in Bebb and Wright (1953 and 1955), Richmond *et al.* (1973), Yelverton *et al.* (1973) and Yelverton (1981). The data from these studies have been widely interpreted in a number of reviews of the impact of high level underwater noise causing fatality and injury in human divers, marine mammals and fish (see for example Rawlins (1974), Hill (1978), Goertner (1982), Richardson *et al.* (1995), Cudahy and Parvin (2001), Hastings and Popper (2005)). The peak sound level of a freely suspended charge of TNT in water can be estimated from Arons (1954), as summarised by Urick (1983). For offshore operations such as well head severance, typical charge weights of 40 kg may be used, giving a source peak pressure of 195 MPa, or 285 dB re 1μPa @ 1 m (Parvin *et al.*, 2007).

Peak-to-peak level. The peak-to-peak level is usually calculated using the maximum variation of the pressure from positive to negative within the wave. This represents the maximum change in pressure (differential pressure from positive to negative) as a transient pressure wave propagates. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak level will be twice the peak level, and hence 6 dB higher.

Peak-to-peak levels of noise are often used to characterise sound transients from impulsive sources such as percussive impact piling and seismic airguns. Measurements during offshore impact piling operations to secure tubular steel piles into the seabed have indicated peak-to-peak source level noise from 244 to 252 dB re 1 μPa @ 1 m for piles from 4.0 to 4.7 m diameter (Parvin *et al.* 2006a, Nedwell *et al.* 2007a).

RMS (Root mean squared) Level. The RMS level is normally used to characterise noise and vibration of a continuous nature, such as drilling, boring, continuous wave sonar, or background sea and river noise levels. To calculate the RMS level the variation in sound pressure is measured over a specific time period to determine the RMS level of the time varying sound. The RMS level can therefore be considered to be a measure of the average unweighted level of the sound over the measurement period. For a time series of n pressure values it can be expressed as

$$SPL_{RMS} = 20\log_{10}\left(\frac{\sqrt{\frac{\sum_{i=1}^{n} p_i^2}{n}}}{p_{ref}}\right)$$

Where p_i is the ith pressure value and p_{ref} is the reference pressure.

As an example, small sea going vessels typically produce broadband noise at source SPLs from 170 to 180 dB re. 1 μPa @ 1 m (Richardson *et al*, 1995), whereas a supertanker generates source SPLs of typically 198 dB re. 1 μPa @ 1 m (Hildebrand, 2004).

Where an RMS level is used to characterise transient pressure waves, such as that from seismic airguns, underwater blasting or piling, it is critical that the time period over which the RMS level is calculated is quoted. For instance, in the case of a pile strike lasting, say, a tenth of a second, the level calculated over that tenth of a second will be 10 dB higher (i.e. the apparent energy per second ten times higher) than that taken over one second. For this reason, although they are not directly comparable, the peak to peak level is usually used to characterise transient noise sources, and the RMS level is generally used to characterise continuous sources. The importance of the time-scale is introduced below under the heading SEL in section 4.1.

3.3 Particle velocity Level (PVL)

The particle velocity refers to the actual displacement of water under the influence of a sound field. The Particle Velocity Level (PVL) is defined for the purposes of this study as

$$PVL = 20\log\left(\frac{V}{P_{ref} / \rho c}\right)$$

where *V* 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 1 μPa plane wave, and has the advantage that for many sound waves that may be approximated as near to plane the PVL and the SPL will numerically be the same. However, in turbulent areas, such as in the presence of pressure-release materials and at the water surface, the SPL and the PVL may be very different.

3.4 Sound propagation

It is conventional, where possible, to evaluate measurements of sound in terms of the effective level of the source (the Source Level, or SL) and the rate at which this energy decays with distance (the Transmission Loss, or TL). The use of the SL/TL formulation has the advantage that it decouples the losses during propagation from the strength of the sound source.

Source Level. Where there is a single and well-defined source of noise, underwater sound pressure measurements are usually expressed as dB re 1 μPa @ 1 m. The SL is a versatile quantity that can be used, for instance, in estimating the level of sound that that source would generate in a different acoustic environment.

However, there is often confusion concerning the concept inherent in Source Level of “apparent level at a distance of one metre from the source”. In fact, since the measurements are usually made at some distance from the source (in the acoustic far field), and extrapolated back to the source, the true level at one metre may be very different from the Source Level. Indeed, a Source Level may be quoted for sources having dimensions greater than one metre, such that an actual level at one metre cannot be measured.

The SL may itself be quoted in any of the measures above; for instance, a piling source may be expressed as having a “peak-to-peak Source Level of 200 dB re 1 μPa @ 1 m”.

Transmission Loss. As underwater sound propagates away from the source it reduces in level. This reduction of sound with range is defined as:

$$TL = 20\log\left(\frac{P_0}{P_R}\right)$$

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 reflects between the surface and seabed. Sound may also travel through the rocks of the seabed, re-emerging back into the water at a distance. Refraction and absorption further distort the sound. Predicting the level of sound at distance from a source is therefore extremely difficult, and use is generally made of simple models or empirical data based on measurements for its estimation.

Propagation modelling. In many cases where a set of measurements of underwater noise 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 equation

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

where *L(r)* is the Sound Pressure Level at distance *r* from a source (in metres), *SL* is the source level, and *TL* is the transmission loss (Kinsler *et al,* 1982).

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 $dB.m^{-1}$ (Urick, (1983), Kinsler *et al,* (1982)). By combining the previous two expressions, the level of sound at any point in the waterspace can be estimated from the expression

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

Over short distances absorption effects have little influence on the T L and are sometimes ignored.

Several mathematical models exist which estimate T L 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 (Waite, 2002).

Despite these models, predicting the level of sound from a source is a difficult task, and where possible use is made of simple models or empirical data based on measurements for its estimation. Measurements of sound levels must be taken 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. In the authors' experience, shallow water Transmission losses of between N=12 and N=25 are most commonly measured (Nedwell *et al*, 1999, and Turnpenny *et al*, 1994).

Whether it is measured or predicted, the TL used will affect the predicted sound level significantly. For example, over a 10 metre range a noise subject to N=15 TL will be 10 dB louder than the same noise subject to N=25 TL. Over a 10 km range, using the same example, the difference will be 40 dB. Where there is 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.

It should be noted that sound propagation may be described in this way 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, dB_{ht} level, (detailed in section 4.2) particle velocity, etc. It should be noted that all of the metrics that are used to describe the level will be different for these different physical quantities. In other words, 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 peak pressure. Thus, depending on hearing abilities marine animals will perceive not only a different level of sound, but also a different rate at which it attenuates with distance.

3.5 Measurement of sound pressure level

Frequency range. For digital analysis of signals, from the Nyquist Criterion data must be sampled at a minimum of twice the maximum frequency of interest. Thus, for marine mammals capable of hearing sound at, say, 120 kHz any waveform must be recorded at a minimum sample rate of 240 samples per second. Much of the information presented in the open literature is recorded to a maximum frequency of 10 or 20 kHz and is hence completely unsuitable for general analysis at frequencies above 5 kHz.

Spectral dynamic range. The issue of dynamic range is of critical importance but is also very commonly overlooked. To some extent, this is due to the requirement to measure sound over a much wider frequency range that has previously been the case. This arises because the levels of noise in the ocean are much lower at high frequencies than at low frequencies, that is, the spectrum is highly sloped. Aquatic animals have evolved to match this environment, and those that have evolved to make use of the high frequencies tend to be very sensitive to them. Consequently, relatively low levels of underwater noise at high frequencies have the capacity to create an adverse effect.

However, consider recording these high frequencies. The level may be 50 – 100 dB below the level of the low frequency noise. Since the dynamic range of typical recording systems is perhaps 60 – 70 dB at best, the high frequency noise may be obscured by the noise floor of the recording equipment. Any analysis of such information in terms of its effects on high frequency hearing animals will hence be meaningless. This effect is particularly difficult to avoid, and in the case of the authors' work has been minimised by the use of spectral pre-emphasis techniques that in effect flatten the background noise floor before carrying out digitisation.

Temporal dynamic range. The preceding situation is significantly worse for measurements of transient pressure waves, such as those associated with impact piling, as the dynamic range of the equipment has to be sufficient not only to deal with the spectral dynamic range, but also with temporal changes in level with time caused by a pile being struck, etc. A system that can only just record the high levels of low frequency noise without clipping may not have a greater dynamic range to allow the much lower levels of noise at high frequency to be recorded. Clipping occurs when either the instrument or its associated electronic amplification circuitry reaches its maximum available output level and is hence is overloaded. The signal that is recorded has a characteristic square top, with the measured level being substantially below the actual signal level. This can lead to a gross underestimate of the true magnitude of the signal. These are additive, such the dynamic range required by a recording system may easily exceed 100 dB when impulsive noise sources are being recorded. These effects can be ameliorated by the use of a system configured for low levels of noise and a separate system for the upper levels.

Slew-rate limiting. Another, often unrecognised, limitation of recording equipment is that of slew-rate limiting. Many preamplifiers perform well at low signal levels, but with high amplitude signals the active devices are unable to supply enough current to drive capacitive loads, such as long cables. Under these circumstances they can produce a distortion of the waveform.

Unfortunately, much of the public domain data relating to underwater sound and vibration, and particularly that from biological research tends to be of poor quality as a result of these limiting effects. Data must therefore be interpreted with care.

All of the underwater noise and vibration measurements presented as part of this review were sampled, digitised and stored on a laptop computer system as high frequency digital files (typically 350,000 samples per second). This means that the data can be assessed in any of the noise assessment formats. Subsequent analysis of the acoustic data was conducted over the frequency range from 1 Hz to 120 kHz.

3.6 Measurement of particle velocity

Attempts have been made to use accelerometers in “neutral buoyancy” waterproof cylinders to measure the particle velocity of water. This approach is not appealing, since there is no evidence that the cylinder follows the water vibration, the frequency response of the accelerometers is limited, and the flexural modes of the cylinder will be superimposed on the response.

An alternative approach is to measure the pressure gradient in the water. The gradient may be shown by consideration of Euler’s equation to be given by

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

where x is the direction in which the sound energy flows and V is the velocity of the water as the sound wave passes. Now consider an estimate of the 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

$$V = -\frac{1}{\rho}\int \frac{(P_1 - P_2)}{\Delta x} dt \; .$$

Thus, the pressure measured using two hydrophones may be interpreted to yield the particle velocity along the line connecting the hydrophones. It may be noted that the approach is based on an assumption of linearity between the points; however, it may be shown that this is adequate if the variation in frequency spectra between the two hydrophones is adequately low. This is generally satisfied for propagating waves when the hydrophones are separated by significantly less than a wavelength at the highest frequency recorded.

The approach is attractive in that, 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. Thus the measurement may, for instance, be readily related to International Standards for measurement of sound pressure.

It may be noted, however, that there are several practical considerations when implementing this approach. The differential pressure (P_1-P_2) is typically formed by 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.

In general, the use of a purpose-built differencing amplifier in conjunction with high-quality phase matched hydrophones to measure particle velocity has been found to be satisfactory.

4 Derived sound metrics

There are several different sound metrics which have in the past been used to evaluate the level of underwater noise. They are reviewed herein.

4.1 Sound Exposure Level (SEL)

When assessing the noise from transient sources such as blast waves, impact piling or seismic airguns, the issue of the time duration of the pressure wave (highlighted above) is often addressed by measuring the total acoustic energy (energy flux density) of the wave. This form of analysis was used by Bebb and Wright (1951 to 1955) and later by Rawlins (1987) to explain the apparent discrepancies in the biological effect of short and long-range blast waves on human divers. More recently, this form of analysis has been used to develop an interim exposure criterion for assessing the injury range for fish from impact piling operations (Hastings and Popper, 2005 and Popper *et al*, 2006).

The Sound Exposure Level (SEL) sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound source and the duration the sound is present in the acoustic environment. 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 *t* is time in seconds.

The SE is a measure of the acoustic energy and, therefore, has units of Pascal squared seconds (Pa^2s).

To express the SE on a logarithmic scale by means of a dB, it is compared with a reference acoustic energy level of 1 μPa^2 (P^2_{ref}) and a reference time (T_{ref}).

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 noise, 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 broadband noise, and the SEL sums the cumulative broadband noise energy.

Therefore, for continuous sounds of duration less than one second, the SEL will be numerically lower than the SPL. However, the SEL is typically used for describing longer exposure times, for example the sound exposure over the duration of a pile being driven, which may be several hours. 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). For intermittent sounds such as piling the cumulative values are calculated for the time when the sound is present (in effect the length of a 'pulse' of noise multiplied by the number of pulses).

4.2 The dB_{ht}

The underwater sound metrics have so far focussed on unweighted SPL. However, the use of the dB_{ht} (*Species*) is a useful tool in quantifying the level of sound experienced by each species of marine life, and hence some discussion of the method is required here.

The dB_{ht} scale incorporates the concept of "loudness" for a species. The metric incorporates hearing ability by referencing the sound to the species' hearing threshold, and hence evaluates the level of sound a species can perceive. Experimental evidence indicates that the scale provides an objective rating of the effects of underwater noise on marine animals (Nedwell *et al*, 2007). It may be considered to be analogous to, or an extension of, the dB (A) scale that is used for human noise exposure in air.

Since any given sound will be perceived differently by different species (since 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 perceived noise levels of sources measured in dB_{ht}(*Species*) are usually much lower than the unweighted levels, both because the sound will contain frequency components that the species cannot detect, and also because most marine species have thresholds of perception above background sound levels. If the level of sound is sufficiently high on the dB_{ht}(*Species*) scale then an avoidance reaction or hearing impediment might occur. Unweighted SPL data do not allow the underwater sound to be assessed in this biologically significant manner. To determine the dB_{ht}(*Species*) sound level, high quality (1 Hz to 150 kHz) sound recordings are analysed by passing them through a filter that mimics the hearing ability of the animal in question (Nedwell *et al,* 2007). The output of the filter is therefore a sound level that represents the perceived level of underwater sound by the animal. It should be noted that this filtering is only used in the analysis of the noise.

The dB_{ht}(*Species*) metric is a frequency-dependent non-dimensional ratio of measured pressure to the pressure hearing threshold of an animal, and hence the units in which the noise is measured, and those in which the audiogram is presented, do not matter as long as they are the same.

The required filter response is the inverse of the pressure thresholds scaled by the reference pressure (if used) in subsequent decibel calculations.

$$\left|W_{ht}(f_k)\right| = \frac{P_{ref}}{\left|P_{ht}(f_k)\right|_{k=0,\ldots,N-1}}$$

Here, P_{ref} is the reference pressure to be used in subsequent decibel calculations. W_{ht} is the ideal frequency response.

To calculate FIR (Finite impulse response) filter coefficients, the inverse Fourier transform must be applied to the preceding equation.

$$P_{ht}(n) = \frac{1}{N}\sum_{k=0}^{N-1}\left|W_{ht}(f_k)\right|e^{j\frac{2\pi nk}{N}}$$

Although the frequency response of the filter will be accurate for all f_k, between these frequencies there may be significant divergence from the mean value of adjacent thresholds. The degree of this will be determined in part by the filter's length, and can be improved by windowing the filter coefficients.

The dB_{ht} level may be calculated as follows:

$$dB_{ht} = 20\log_{10}\left(\frac{P(n) * W_{ht}(n)}{P_{ref}}\right)$$

where *P(n)* is a measured pressure time history in Pascals, sampled at f_s samples per second. The symbols * and <> denote convolution and RMS averaging respectively. It should be noted that whatever reference pressure is used in the final decibel calculation, the final dB_{ht} value will remain unchanged as the P_{ref} in the various equations cancel. The actual reference is the frequency dependent variable P_{ht}.

Sometimes, when a species' avoidance reactions need to be analysed in respect of their reaction to a noise source, but its audiogram is not available, a surrogate with a known audiogram is chosen for its similarities in morphology and estimated auditory thresholds. This surrogate can then be used to allow the dB_{ht} levels and impact ranges to be obtained for the source. However, this method is still subject to errors, as the surrogate may turn out to be less sensitive than the animal of unknown sensitivity.

4.3 Design of a generic filter

Fish have a wide range of hearing capabilities, and most species' hearing abilities have not been examined and their audiograms have not been obtained. Therefore, when assessing the impact of a particular sound source, it is not always possible to determine the dB_{ht} level if a member of the species of fish native to the area have not undergone testing to determine their audiogram. Usually in this case, a surrogate would be used i.e. the audiogram of a fish of similar physical characteristics which is likely to have closely matching hearing capabilities. This allows estimation of the dB_{ht} level of the target species. When this is not possible, or if a more cautious approach is wanted, a general audiogram, covering all species of fish could be used. Such a general filter has been constructed which takes into account the average background level, and the knowledge that no species' audiograms are significantly more sensitive than the background level.

The filter designed to cover all species of fish is shown in Figure 4-1, combined with several audiograms of several fish species with the most sensitive hearing. The filter is designed, firstly, to take into account the highest and lowest frequencies for which these fish are sensitive to. Secondly, as it has been noted that no marine animal has thresholds significantly more sensitive than the background sound level, the filters take these frequency ranges and then apply the standard coastal noise as the lowest threshold throughout the filter. This filter can then serve as a surrogate for any fish species to be studied as if they will always provide a conservative estimate of the dB_{ht} level due to its low thresholds. The levels quoted when analysed using this filter can then be quoted as dB_{ht}(*fish*), and when applied in conjunction with a criterion level of 90 dB_{ht} may be used as a precautionary indication of the range of behavioural effect.

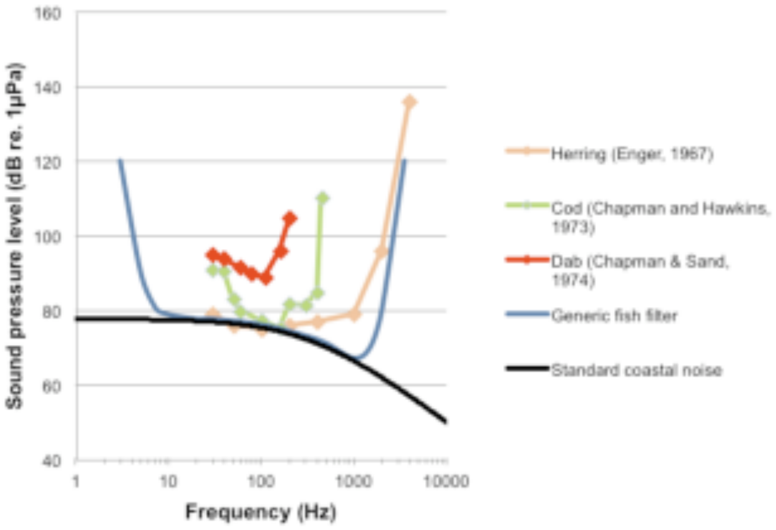


Figure 4-1: Generic fish filter based on the average background level and a collection of audiograms. All of the underwater noise and vibration measurements were sampled, digitised and stored on a laptop computer system as high frequency digital files (typically 350,000 samples per second). This means that the data can be assessed in any of the noise assessment formats. Subsequent analysis of the acoustic data was conducted over the frequency range from 1 Hz to 120 kHz.

5 Underwater sounds and their significance for fish and invertebrates

5.1 Introduction

Almost any object moving in water, or coming into contact with another object can generate sounds, and any animal capable of detecting those sounds may gain a number of advantages. Because sounds travel rapidly and effectively through water, a sound receptor provides the animal with early notification of the presence of a source even where there is no direct line of sight. Low frequency sounds, in particular, may diffract around solid objects without being absorbed, and may penetrate dense cover or travel around corners, providing almost instantaneous warning of an event or another animal that might otherwise go unnoticed or remain concealed. Moreover, as sounds may vary in their characteristics, the detector can potentially gain information about the object or action that generates them. An animal detecting a sound is potentially able to identify the nature of the source. It may be able to tell whether a source is alive or inert; whether it is a predator or prey. Perhaps more importantly, the sound receiver is potentially able to determine the direction and even the distance of the source and to determine whether it is coming closer or moving further away. It may then take appropriate action. The ability to detect sounds may be especially significant at depth in the sea where long distance vision is often impaired. Sensitivity to sounds may therefore be of great advantage to aquatic animals. It may enable them to evade predators or seek out prey. It may provide them with information on the space around them. The detection of sound – the sense of hearing – is an everyday sense, which can be of great importance in helping the animal to survive and increase its fitness.

The ability to produce sounds, as well as hear them, may bring additional advantages. Sounds offer unrivalled advantages for fast information transfer and long range transmission through an optically poor medium like water. Communication often appears to benefit both the receiver and the sender. A female fish may be able to identify a male fish because of the particular characteristics of the sound it makes. The sounds may bring the two fish together and enable them to mate successfully.

The production of sounds by an animal is not by itself evidence of communication. An animal may make sounds incidentally, as a by-product of some other activity like swimming or feeding. Moreover, the emission of sounds is not always of direct advantage to the sender. Predatory animals may detect both incidental sounds and communication calls and use these to locate and capture the sound producer.

Myrberg (1981) has laid down a definition of communication that provides us with an analytical framework for the analysis of signal exchange between individuals. He suggests that communication is the transfer of information between individuals where the functional aim rests solely in obtaining adaptive advantage for the sender. This definition does not exclude the possibility that the exchange of information is of mutual benefit to sender and receiver, and it does not exclude the possibility of deception by the sender. An insignificant male may imitate the signals sent out by a larger, fitter male to deceive a female. Krebs and Dawkins (1984) have emphasised the selective advantage of one animal manipulating another by emitting dishonest signals, intended to deceive. Myrberg's definition also includes the emission of warning signals – intended to scare away predators or competitors. However, this definition does exclude unintended interception – where the sender is disadvantaged by the emission of a signal. Myrberg's pragmatic definition of communication focuses on the basic functions of survival and reproduction and emphasises the benefits forthcoming to any animal that communicates with others by means of sounds or other signals.

5.2 Sound production

5.2.1 Aquatic invertebrates

Many invertebrates, especially those with hard body parts can generate sounds. Anyone who has placed a hydrophone close to the seabed will be aware of the many clicks, snaps and rustles that are generated mainly by aquatic invertebrates. Some of these sound producers have been identified, but many have not. Some of the sounds may be purely incidental, but others may be communication sounds which have significance for the animals emitting them and those predators who use these cues to localize their prey.

Amongst the crustacean sound producers are barnacles, Balanidae (Busnel and Dziedzic, 1962; Fish, 1964), decapods like the spiny lobsters, Palinuridae (*Palinurus*, Dijkgraaf, 1955; Buscaino et al., 2011: *Panulirus*, Moulton, 1957), prawns of the families Palaemonidae and Penaeidae (Dumortier, 1963), snapping shrimps of the family Alpheidae (Johnson *et al.*, 1947; Hazlett and Winn, 1962; Fish, 1964), the mantis shrimps *Gonodactylus* (Dumortier, 1963; Hazlett and Winn, 1962) and *Hemisquilla*, and brachyuran and anomuran crabs (Dumortier, 1963). Amongst the molluscans, populations of the common mussel *Mytilus* give rise to a pronounced crackling sound, while squid emit a popping sound. (Iversen *et al.*, 1963). Echinoderms like the sea urchins can produce a sustained ‘frying’ sound (Fish, 1964).

Some of the invertebrates that produce sounds have no clearly defined vocal organs, and the sounds they generate may well be incidental. However, some crustaceans make sounds which are species characteristic and which involve specific sound-producing mechanisms. The spiny lobsters have a pair of stridulating organs, each comprising a series of fine parallel ridges lining a surface on the base of the second antenna. By raising both antennae, the ridges are rubbed along the edge of the rostrum, producing a creaking sound. Moulton (1957) recorded two kinds of sound from *Panulirus argus*; a rasp or creak, and a slow rattle. The first was produced when prodding stimulated an animal and the second was recorded spontaneously from groups of lobsters. Californian spiny lobsters *Panulirus interruptus* produce pulsatile rasps when interacting with potential predators (Patek *et al.*, 2009). The rasp is produced by frictional vibrations - sticking and slipping - similar to rubber materials sliding against hard surfaces. The rasps from field recordings typically had a distinct narrow peak below 500 Hz and another broader peak around 1.5–2 kHz.

Male and female American lobsters (*Homarus americanus*) both produce a buzzing vibration of the carapace when grasped (Pye and Watson, 2004). Henninger and Watson (2005) concluded that the contraction of antagonistic muscles located at the base of the second antenna produces these sounds. The vibrations were reported to have a mean frequency of 183.1 Hz (range 87-261 Hz) and ranged in duration from 68 to 1720 ms (mean 277.1 ms). The lobsters most often produced these sounds using only one pair of muscles at a time and alternated between the muscles of the left and right antennae. Occasionally, they vibrated their carapaces by simultaneously contracting both sets of muscles. Larger lobsters were said to vibrate more consistently than smaller lobsters, suggesting that sound production may be implicated in mating behaviour.

King crabs (*Paralithodes camtschaticus*) produce impulsive sounds during feeding that appear to stimulate movement by other crabs, including approach behaviour (Tolstoganova, 2002). King crabs also produced ‘discomfort’ sounds when environmental conditions were manipulated. These ‘discomfort’ sounds differed from the feeding sounds in terms of frequency range and pulse duration. Other decapods like the ocypodid (ghost crabs) and pagurid (hermit) crabs stridulate – scrape hard parts of the body together - (Guinot-Dumortier and Dumortier, 1960; Field *et al.*, 1987), while astacid crayfish squeak with their abdomen (Sandeman and Wilkens, 1982).

The California mantis shrimp *Hemisquilla californiensis* produces a “rumble” (Patek and Caldwell, 2006). Sounds were recorded when animals were physically handled or approached by a stick. Only adult males produced rumbles. The rumbles are produced by vibrations of a pair of muscles that attach to the edge of the carapace. Rumbles last less than two seconds. The function of this sound is unknown. Recently, Staaterman *et al.*, (2011) demonstrated that the sounds produced by *H. californiensis* in the sea are very variable; different individuals produce rumbles that differ in dominant frequency and number of rumbles per bout. The rumble may play a role in establishing territories and/or attracting potential mates.

The sharp, explosive click or snap produced by the various species of snapping shrimp is generated by a plunger mechanism on the enlarged claw (Johnson *et al.*, 1947). The sound is caused by the collapse of a cavitation bubble, formed when the shrimp snaps its claw shut (Lohse *et al.*, 2001). The bubble emits not only a sound but also a flash of light—indicating extreme temperatures and pressures inside the bubbles before they burst. It is suggested that the shrimp uses its cavitation bubble to damage, stun or even to kill its prey. The high incidence of sound production by these shrimps suggests that the sounds may also serve other functions – perhaps facilitating social interactions. The combined snapping within a large population of snapping shrimps may generate a continuous crackle or frying sound which often interferes with sonar apparatus and with passive listening for ships and other sound sources. Reported source peak to peak sound pressure levels for snapping shrimp are 183–189 dB re 1 µPa at 1 m over a frequency range of 2–200 kHz (Au and Banks, 1998).

The prevalence of sounds from aquatic crustaceans suggests that sounds are important for communication between individuals; and that conspecifics are capable of detecting them. These sound producing crustaceans are not exotic tropical species. Many of them are found in UK coastal waters.

5.2.2 Deficiencies in our knowledge

There is very little information on the contribution made to ambient noise by aquatic invertebrates, especially for the waters around the British Isles. It is known that there is a substantial contribution from biological sources in some areas at some times of the year. But the individual sources have not all been identified. The significance of these sounds is poorly understood for many species and it is not known if the sounds serve a function in the lives of the animals or whether they are purely incidental. The role of these sounds in communication between individuals has hardly been explored.

5.2.3 Fish

Not only is sound important to fish, some fish are vocal, making sounds themselves. Over 800 species of fishes from 109 families are known to make sounds and this is likely to be an underestimate (Kaatz 2002). Of these, over 150 species are found in the northwest Atlantic (Fish and Mowbray 1970). Amongst the vocal fishes are some of the most abundant and important commercial fish species, including cod, haddock (Gadidae) and the drum fishes (Sciaenidae). Aristotle reported hearing sounds from fish (*Historia Animalium*, IV, 9). Fish *et al.* (1952) and Fish and Mowbray (1970) have summarised the earliest work in this field. Myrberg (1981) and Bass & Ladich (2008) have produced more recent reviews. Fishes produce sounds when they are feeding, mating, or fighting and they also make noises associated with swimming.

Fish produce species-specific sounds (Hawkins and Rasmussen 1978; Myrberg and Riggio 1985; Lobel 1998), and even individual-specific sounds (Wood *et al.* 2002). The sounds are often loud and may dominate sea noise. Fishes of the drum family Sciaenidae may interfere with military operations that involve passive listening (Fish and Mowbray 1970). Other fish, like the damselfishes, which live on coral reefs, or the gobies, produce weak sounds that are barely detectable (Mann and Lobel 1995).

Fish sounds vary in structure depending on the mechanism used to produce them, but they are generally composed of low frequencies, with most of their energy lying below 3 kHz. So far, no ultrasonic sounds have been recorded from fish, although marine mammals produce such sounds.

Stridulatory sounds are made by fish rubbing body parts together. Characteristically they are rasps and creaks, often made up of a series of rapidly produced and irregular transient pulses, containing a wide range of frequencies. Members of the grunt family Pomadasyidae produce a sharp vibrant call by grating a dorsal patch of pharyngeal denticles against smaller ventral patches. In the triggerfishes Balistidae the fused anterior spines of the dorsal fin produce a grating sound within their socket. Catfishes of the family Siluridae produce a squeak as the move their enlarged pectoral spines. Other fish clap parts of the body together. The grouper *Mycteroperca bonaci* bangs its gill covers against the body to produce a low-pitched thump. Fish that are actively swimming or rapidly turning, giving a booming or rushing sound. Very low frequency pressures and water movements are also set up by motion of the fish body.

The gas-filled swim bladder may be implicated in both stridulatory and hydrodynamic sounds, imparting a hollow resonant quality to the sound. In some fish, like the sprat and herring, sounds are produced by the release of gas from the anus, in this case giving a squeak. Perhaps the most characteristic and common method of sound production in fish utilizes a pair of striated muscles, which compress the swim bladder. The muscles contract sharply, producing a transient pulse of low frequency sound (a knock or thump). Repeated contractions of the muscle may result in a train of pulses, which can sound like a grunt. There may be major differences in the conformation of the sound-producing muscles even within the same family. It also appears that this mechanism may have evolved independently in different groups. In the haddock the muscles are attached dorsally to the swim bladder overlying strong lateral wings (parapophyses) extending out from the vertebrae. Ventrally the muscle inserts into the swim bladder wall (Figure 5-1).

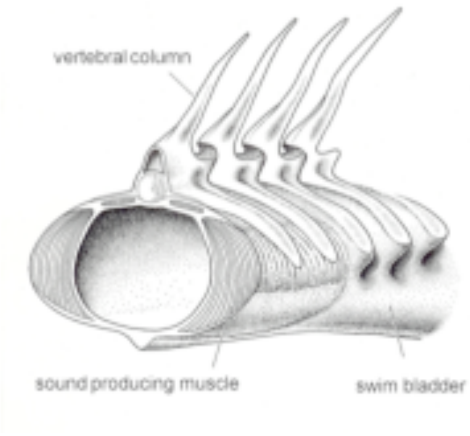


Figure 5-1: Section across the sound-producing muscles of the haddock, which are attached to the gas-filled swim bladder. Contraction of the muscles compresses the gas within the swim bladder resulting in a 'knock'.

The sound-producing muscle fibres themselves are highly specialized, with high myoglobin content and a rich blood supply. Their diameter is thin, they contain a well-developed sarcoplasmic reticulum and they are innervated by a large number of nerve fibres. They contract very rapidly, with a high degree of synchrony between the fibres, imparting a short sharp impulse to the swim bladder.

Fish make sounds in a wide variety of contexts. It has been possible to link sound production to the behaviour of fishes by means of a combination of *in situ* and tank studies. For example sounds produced by haddock during courtship and mating have been recorded and analysed in the aquarium and in the field (e.g., Hawkins 1986; Hawkins & Amorim, 2000). The repertoire of sounds produced by male haddock was related to the different patterns of behaviour shown by the fish (Figure 5-2). The sounds were classified by their duration and knock interval. They range varying from short sounds composed of slowly repeated knocks to long sounds of rapidly repeated knocks. Male fish also produced a continuous 'hum'. Long slow knocks were directed more commonly towards males or towards no other fish, while long fast knocks and humming were directed more often towards ripe females. Males in solitary display produced long sounds composed of knocks repeated at different rates. Humming was associated with a spawning 'dance' by the male fish. Once the association of sounds with a species and its behaviour has been established in this way, then it is possible to search for and locate the fish offshore, and even to decide what the fish are doing from the sounds that are detected.

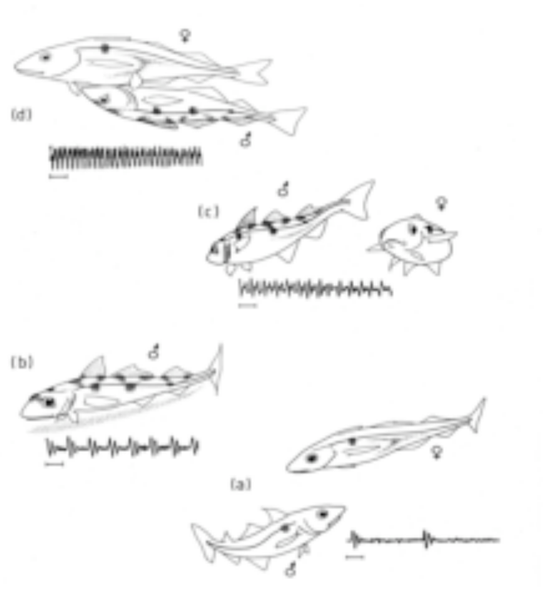


Figure 5-2: Courtship behaviour and associated calls in the haddock. The time base for the sounds is 50 ms (a) the male approaches a female uttering a call of slowly repeated knocks (b) the male sits on its own producing a very long call of rapidly repeated knocks (c) the male displays to a female, with speeded up knocks (d) the male mounts the female uttering a humming sound.

Working in an Arctic fjord in northern Norway, biologists have located a spawning ground of haddock by listening for the sounds. Passive listening revealed that this species, previously thought to spawn offshore in deep water, forms large spawning concentrations close to shore (Hawkins *et al.* 2002; Hawkins 2003). Similar mapping of spawning grounds and spawning activity has been reported for the sciaenid red drum (*Sciaenops ocellatus*) along the Texas coastline (Holt *et al* 2008)

The haddock belongs to the cod family (Gadidae). A number of codfishes are known to be vocal (Hawkins and Rasmussen 1978; Almada *et al.* 1996), and the trait seems widespread within the family. A strong correlation between vocal activity and the spawning cycle has been noted (Hawkins and Rasmussen 1978). The Atlantic cod appears to have a more limited vocabulary than the haddock described above. Both species have specialised sound-producing muscles that serve to set the gas within the swim bladder into motion (Hawkins, 1986). The muscle is sexually dimorphic in haddock being significantly larger in the mature males than in females (Templeman and Hodder, 1958; Hawkins *et al.,* 1967; Templeman *et al.,* 1978). In addition, the muscle undergoes a seasonal maturation cycle in concert with the gonad maturation cycle. The sound-producing muscle of Atlantic cod has only recently been studied in similar detail, and it also exhibits sexual dimorphism (Engen and Folstad, 1999) and a similar maturation cycle (Rowe and Hutchings, 2004). The importance of these muscles, and vocal behaviour, to the life cycle and spawning behaviour of Atlantic cod is underlined by findings that the state of the muscle appears to be related to the fertilization potential of the individual fish (Engen and Folstad, 1999; Nordeid and Folstad, 2000; Rowe and Hutchings, 2004).

Brawn (1961a, 1961b, 1961c) provided a detailed description of the role of sound in courtship and spawning behaviour in Atlantic cod. She found that vocal activity was most common during the spawning season, being rare at other times, except for an autumn "aggression period". She suggested that the autumn peak in vocal activity was related to increased aggressive interactions. Within the spawning season vocal behaviour was strongly associated with reproductive behaviour and both spawning activity and call frequency peaked during the early evening hours. Interestingly, vocal activity was most frequent at night during the spawning season, but most frequent during the day during the autumn "aggression period". Brawn (1961a, 1961b, 1961c) attributed this to nocturnal spawning in the winter, and diurnal feeding interactions during the autumn. Later studies showed that the cod produces sounds with frequencies lying in the range of 80-500 Hz (Fish and Mowbray, 1970; Hawkins and Rasmussen, 1978; Finstad and Nordeide, 2004). Nordeide and Kjellsby (1999) have recorded sounds of Atlantic cod from spawning grounds off the Lofoten Islands of Norway. They suggested that passive acoustics could be used to locate spawning grounds and to study spawning behaviour in the field. Haddock sounds have a similar frequency range to the sounds of cod, but can be distinguished from them by differences in their pulse characteristics (Hawkins and Rasmussen, 1978).

The sounds produced by fish are very diverse in their spectral and temporal characteristics. Most fish sounds consist of a train of transient low frequency pulses, produced at different rates and in different groupings. The train of pulses results from the repeated contraction of the sound-producing muscles. There are a number of fishes that produce longer continuous calls – the 'hum' of the spawning haddock being an example (Hawkins & Amorim, 2000). Such longer calls result when the muscles contract very quickly, so that the individual sound pulses overlap.

Fish sounds differ in their dominant frequencies. An inverse relationship between dominant frequency and fish size is widespread for many species that produce sounds composed of short repeated pulses (Myrberg *et al.*, 1965; Connaughton *et al.*, 2000; Amorim, 2006). The frequency is determined by the characteristics of the swim bladder - larger swim bladders are associated with lower frequencies - and by the characteristics of the sound-producing muscles - larger muscles produce longer twitches (Connaughton *et al.*, 2000). The repetition of the pulses generates a spectrum composed of a series of related harmonics, within the spectral envelope of the pulse itself. Analysis of such sounds may be based on descriptions of the temporal patterns, spectral patterns or both. In the temporal domain, the sound may be described by the waveform, the parameters measured typically include the separation into discrete pulses, the duration of individual pulses, the rise and fall characteristics of the pulses, and the repetition rate of the pulses. In the spectral domain, peaks in the spectrum may be associated with the characteristic of the sound-producing organ, or may reflect the repetition of similar pulses.

Behavioural studies have indicated that fish discriminate between calls uttered by different species by means of the pulse interval and pulse number, rather than the frequency (Winn, 1964, 1972; Myrberg and Spires, 1972). Within a family of fishes, the sounds of different species often differ in their temporal characteristics. Thus, The agonistic sounds of the cod, the haddock, the pollack (*Pollachius pollachius),* the tadpole-fish *(Raniceps raninus)*, and the shore rockling, (*Gaidropsarus mediterraneus)* can be distinguished by differences in their temporal structure (Brawn, 1961; Midling *et al.*, 2002; Hawkins and Chapman, 1966; Hawkins and Rasmussen, 1978). Indeed it has been suggested that fish acoustical signals encode information through temporal patterning since, with few exceptions, they show weak frequency modulation and are made up of brief low frequency pulses. This is consistent with the belief that hearing in fish is specialised in extracting information in the time domain (Fay, 1980). However, it is important to remember that changes in the temporal structure are also accompanied by changes in frequency related to the sound pulse repetition rate. Recent studies (reviewed by Bass and Ladich, 2008) have examined the relevant features of the calls to conspecifics and have confirmed the importance of the temporal characteristics of fish calls.

The calls of fish may serve a number of functions. During the breeding season, males may aggregate at particular locations and utilize sounds to attract mates and to advertise their occupation of a territory. Males may space themselves within a group of conspecifics using particular behavioural rules. An advertisement call is one cue that can mediate inter-male spacing and determine the locations of particular individuals (Boatright-Horowitz *et al.*, 2000; Bee and Gerhardt, 2001). Sound production during social interactions may give fish an additional opportunity to assess the physical strength of opponents; but one fish can only assess the strength of another if there are differences in sound structure that correlate with size or fighting abilities. Such differences are present in the case of haddock (Wood *et al.*, 2002).

Sounds may also attract females, and the females may then be able to discriminate males with different characteristics through sound detection. In the midshipman, *Porichthys notatus*, tonal sounds, generated by contraction of swim bladder muscles, attract gravid females that are able to distinguish between duration, frequency, amplitude and fine temporal content. In particular gravid females are capable of discriminating two signals differing by 10 or 20 Hz (McKibben and Bass, 1998). In many of the fish families that contain sound-producing species it is usually only the males that vocalise. Frequently in such cases, there is a sexual dimorphism in the physiology and morphology of the sound-producing mechanism (Rosenthal and Lobel, 2006). In other fish (for example in batrachoids, carapids, triglids and some sciaenids) females may be capable of making sounds but do so much less often than males (Rosenthal and Lobel, 2006). In the croaking gourami, females produce sound before and during mating to signal to the male that they are ready to mate (Ladich, 2007).

It is evident that sound production is extremely important in the lives of many fishes. Interference with communication, through masking or through a similarity of anthropogenic sounds with natural calls, may disrupt spawning and other activities that are important for the survival of fish populations.

5.2.4 Deficiencies in our knowledge

It is still not clear how widespread sound production is amongst fishes as relatively few species have been investigated. The behaviour of fish is often suppressed under aquarium conditions unless very special measures are taken to provide a quiet and appropriate environment. Where particular sound-producing species have been examined – like the gurnards (Triglidae) – it is evident that sound is important to them but the full range of their behaviour has not yet been observed and the role of sound in spawning, in particular, has not yet been described.

Sounds produced by spawning fish, like cod, haddock and many sciaenids, are sufficiently loud and characteristic for them to be used to locate spawning concentrations. We are still remarkably ignorant about the location and characteristics of their spawning sites and we do not know whether these species return to the same sites each year, or whether site choice is more variable. We currently cannot assess whether the spawning sites need special protection from activities such as fishing or high anthropogenic noise levels.

We are poorly informed on the characteristics of the sounds made by fish, and the distances over which they travel. However, we do know that some of the more common commercial species, including cod and haddock, aggregate at spawning time and communicate by means of sound. There is a need to identify locations where there are significant choruses of spawning fish, before further deterioration takes place in noise levels in the sea.

5.3 Sound detection

5.3.1 Aquatic invertebrates

Marine invertebrates are extremely abundant and important to aquatic ecosystems but our knowledge of their hearing capabilities is relatively poor. We do not know how well many of them can detect sounds.

Although there is a paucity of experimental evidence, Pumphrey (1950), Frings and Frings (1967) and others have suggested that many aquatic invertebrates can detect sounds. The sound receptors may be many and varied but two classes of organ have been suggested as likely candidates: one includes the wide range of statocyst or otocyst organs found in aquatic animals; the second covers water flow detectors.

Statocysts are found in a wide range of aquatic invertebrates (Laverack, 1981; Janse, 1980). In these organs, sensory hairs are attached to a mass of sand or calcareous material. Statocysts are undoubtedly stimulated by gravity and by linear accelerations and in many cases serve an equilibrium function (Schöne, 1975). However, they are remarkably similar to the otolith organs in fish and may also serve to detect the particle motions associated with sound or vibration. Essentially, it is suggested that the tissues of the animal move back and forth as a sound passes through, but the dense statolith lags behind, stimulating the sensory cilia. Cohen (1955) has reported that the statocyst in the lobster is especially sensitive to vibrations of the substratum.

Lovell *et al.* (2005, 2006) reported that the prawn *Palaemon serratus* is capable of detecting low frequency sounds. Auditory evoked potentials were acquired from prawns using electrodes positioned in the carapace close to the supraesophageal ganglion and the statocyst. Electrical potentials were detected during stimulation at frequencies ranging from 100 Hz up to 3000 Hz. However, there is to date no behavioural evidence of these prawns responding to sounds. Offutt (1970) claimed to have conditioned the heartbeat of the lobster *Homarus americanus* to pure tones in the frequency range 10-150 Hz, the animal showing a clear conditioned bradycardia (slowing of the heart) when sounds were presented. The animal was especially sensitive to frequencies within the range 18-75 Hz. More recently, Pye and Watson (2004) reported that immature lobsters of both sexes detected sounds in the range 20–1000 Hz, while sexually mature lobsters were said to exhibit two distinct peaks in their acoustic sensitivity at 20–300 Hz and 1000–5000 Hz.

Squid, cuttlefish and the octopus have complex statocysts (Nixon and Young, 2003). Again, because they resemble the otolith organs of fish, it has been suggested that they may also detect sounds (Budelmann, 1992). It has also been suggested that the paired statocysts are functionally similar to the vertebrate vestibular system (Williamson, 2009). They may detect both linear and angular accelerations, giving the animal information on its spatial orientation and rotational movements. The statocysts may also be involved in hearing. Early reports suggested that squid were attracted to 600 Hz tones (Maniwa, 1976) and that cuttlefish (*Sepia officinalis*) gave startle responses to 180 Hz stimuli (Dijkgraaf 1963b). Behavioural conditioning experiments have confirmed that squid (*Loligo vulgaris*), octopus (*Octopus vulgaris*) and cuttlefish can detect particle acceleration stimuli within the range 1-100 Hz, perhaps by using the statocyst organ as an accelerometer (Packard *et al.* 1990; Kaifu *et al.* 2008). In their key experiments Packard *et al* (1990) employed classical conditioning to test the sensitivity of cephalopods to vibrations of between 1 and 100 Hz generated in a standing wave tube. The animals were trained to associate sound stimuli with a weak electric shock, and the recorded conditioned responses were changes in breathing and jetting activity. Five specimens of *Sepia officinalis* were tested, and all responded to low frequency sounds. The relevant stimulus parameter was particle motion rather than sound pressure. The threshold values (measured as particle acceleration) decreased towards lower frequencies in the tested range, reaching values below 4×10^{-3} m s^{-2}. The thresholds in the most sensitive range may have been masked by background noise at the experimental site.

More recently Kaifu et al (2008) have conducted experiments on *Octopus ocellatus* using respiratory activity as an indicator of sound perception. Intact animals responded to 141 Hz at particle accelerations below 1.3×10^{-3} m s^{-2}, and the mean threshold at this frequency was approximately 6.0×10^{-4} m s^{-2}. Specimens in which the statoliths had been surgically removed did not show any response to accelerations up to 3.9×10^{-3} m s^{-2} at 141 Hz, which was approximately 16 dB greater than the mean detection threshold at this frequency. Specimens that had undergone a control operation in which the statoliths remained intact showed positive responses at 2.8×10^{-3} m s^{-2} for the same frequency stimulus.

Hu *et al.* (2009) suggested that squid (*Sepiotheutis lessoniana*) could detect sound pressures using their statocyst organs, but their evidence was weak. More recently Mooney *et al* (2010) obtained electrical responses from the statocyst organs of the longfin squid (*Loligo pealeii*) at frequencies between 30 and 500 Hz with lowest evoked potential thresholds between 100 and 200 Hz. The range of responses suggested that the statocyst acted as an accelerometer. It was suggested that squid might detect acoustic particle motion stimuli from predators and prey as well as low-frequency environmental sound signatures that may aid navigation.

Norris and Møhl (1983) suggested that squid might be affected by the high amplitude echolocation clicks of foraging odontocetes (toothed whales and dolphins). However, it has recently been shown that squid do not exhibit anti-predator responses in the presence of odontocete echolocation clicks (Wilson *et al.* 2007) indicating that squid may not be able to detect the ultrasonic pressure component of a sound field. Twelve squid were exposed to clicks with received peak to peak sound pressure levels of 199–226 dB re 1 μPa, mimicking the sound exposure from an echolocating toothed whale as it approaches and captures prey.

These intense ultrasonic clicks did not elicit any detectable anti-predator behaviour in *L. pealeii* and clicks with received levels up to 226 dB re 1 µPa (pp) did not acoustically debilitate the animals.

There are some differences between fish otolith organs and invertebrate statocysts. The chitinous sensory hairs in crabs are very much larger than the sensory cilia within fish otolith organs (by at least one order of magnitude), and the attachment and anatomical positioning of the hairs is rather different. Moreover although decapod statocysts may contain a number of sand grains these do not resemble the massive calcified otoliths found in most fish ears. It is likely that statocysts are less sensitive than otoliths organs to the small particle motions associated with propagated sound waves.

Various flow detectors are found in invertebrates. They include sensory cilia, either naked or embedded within a gelatinous cupula, projecting into the water or situated in pits on the body surface, as well as a great variety of other hair-like and fan-like projections from the cuticle, articulated at the base and connected to the dendrites of sensory cells. Most of these are considered to be receivers of water-borne vibration because they are highly sensitive to mechanical deformation and in close contact with the surrounding water (Laverack, 1981). The mechanosensory hairs on the surface of the crayfish telson are dually innervated, one sensory cell responding to head-ward, the other to tail-ward deflection of the hair. The receptors are displacement sensitive and thresholds are of the same order of magnitude over the frequency range 1-70 Hz when the hair is moved by a vibrating wire loop (Wiese, 1976). Horridge (1966) showed that the ctenophore *Leucothea multicornis* had single non-motile cilia which were sensitive to water movements, allowing the animal to detect and catch small moving objects close by. In chaetognaths, ‘fences’ of closely packed cilia serve as vibration detectors (Horridge and Boulton, 1967; Bone and Pulsford, 1978). Feigenbaum and Reeve (1977) have examined the sensitivity of *Sagitta hispida* and *Spadella schizoptera* to vibrating probes and have related this to the distances at which these predators attack their prey. Amongst the sessile tunicates *Ciona* is sensitive to vibrating probes placed close to the atrial siphon, detecting the water movements with large numbers of cupular organs (Bone and Ryan, 1978).

Experiments with decapod crustaceans and other invertebrates have shown a wide range of cuticular hair organs that are sensitive to oscillatory motion of the water (Laverack, 1981; Mellon, 1963; Tazaki and Ohnishi, 1974; Vedel and Clarac, 1976; Wiese, 1976; Tautz and Sandeman, 1980, Budelmann 1988; Breithaupt and Tautz 1990; Goodall *et al.* 1990; Budelmann 1992; Popper *et al.* 2001).

Many cephalopods have lines of ciliated cells on their head and arms. In the cuttlefish *Sepia* and the squid *Lolliguncula*, electrophysiological recordings by Budelmann and Bleckmann (1988) have identified these epidermal lines as an invertebrate analogue to the mechanoreceptive lateral lines of fish and aquatic amphibians and thus as another example of convergent evolution between a sophisticated cephalopod and vertebrate sensory system. Stimulation of the epidermal lines with local water displacements generated by a vibrating sphere causes receptor potentials that are similar to those from lateral line receptors.

In some semi-terrestrial crabs, each walking leg possesses a myochordotonal organ, a structure known to detect acoustic stimuli (Horch 1971, Salmon *et al.* 1977). In ghost crabs, this receptor is equally sensitive to both substratum-borne and airborne sound (Horch, 1971) while in fiddler crabs it responds primarily to substratum-borne vibration (Salmon *et al.* 1977).

5.3.2 Deficiencies in our knowledge

Although there is evidence that a range of invertebrates are sensitive to low frequency sounds it is not yet clear whether any of them are sensitive to sound pressure, or whether they show the same level of sensitivity to sound as other aquatic organisms like fish. Moreover, there has been very little work on the significance of hearing; whether these animals communicate with one another by means of sound, or whether they use sound detection to avoid predators or capture prey.

It is evident that there are many organs in invertebrates, both superficial and embedded within the tissues, which might detect back and forth motion of the animal and the surrounding water induced by passage of a sound wave. It is likely that these receptors will be most sensitive to low frequencies (below 100 Hz) and that they are especially stimulated in the close vicinity of a sound source (within the so-called near field, see section 2). Whether they respond to low amplitude sounds, at higher frequencies, from distant sources, must remain in doubt in the absence of clear experimental evidence. The thresholds that have been detected for these detectors are much lower than those observed from the otolith organs of fish and seem to fall short of the sensitivity necessary in a true auditory receptor. No physical structures have yet been discovered in aquatic invertebrates that are stimulated by sound pressure. We must conclude that many invertebrates are sensitive to local water movements and to low frequency particle accelerations generated by sources in their close vicinity. Some invertebrates, including crustaceans, may be especially sensitive to substratum vibrations. As we have seen, a number of aquatic decapod crustaceans produce sounds, and Popper *et al.* (2001) have concluded that many are able to detect substratum vibration at sensitivities sufficient to tell of the proximity of mates, competitors, or predators. However, whether these invertebrates respond to propagated sound waves at a distance from the source remains uncertain.

There is a particular lack of knowledge on the response of plankton and the smaller nekton (free-swimming organisms showing movements that are largely independent of currents and waves) to sounds. Such organisms are present in large numbers in the sea and form important components of marine food chains. Shipping routes and oil and gas developments are moving into waters of high biological production, where their impact upon plankton and nekton should be examined of sound is at present not known.

5.3.3 Fish

It was known by the end of the 19th century that fish could hear, and the morphology of the fish ear had already been well described by anatomists like Retzius (1881). However, critical experimental studies of fish hearing were not initiated until the early part of the 20th century (see Tavolga & Wodinsky, 1963, Kleerekoper & Chagnon, 1954; and Moulton, 1963 for historical accounts, and Fay, 1988; Hawkins, 1996; Fay and Popper, 2000; Popper *et al.*, 2003; Ladich and Popper, 2004 for more recent reviews).

Fish are generally most sensitive to low sound frequencies where the wavelength often exceeds the dimensions of the body of water that contains the experiment. In studies in tanks, the sounds are presented in a variety of ways, sometimes with immersed sound projectors, at other times with the projectors in air above the water. With an immersed projector in a small, open, thin-walled container very large particle motions are associated with quite low sound pressures, and those motions are usually normal to any air/water interface. With an air loudspeaker above the water the sound field consists almost entirely of sound pressure. In general, the relationship between pressure and particle velocity in an experimental tank is extremely complex, and there is no reliable way of calculating the relative levels of the two quantities. Ideally they should both be measured, but calibrated particle motion detectors are not widely available and this is rarely done.

Relatively few experiments on the hearing of fish have been carried out under appropriate acoustical conditions and the results from many of the measurements made in tanks, and expressed solely in terms of sound pressure, are unreliable and may be misleading. Results presented by different workers and in different studies must be treated with scepticism unless the sound field has been carefully specified.

Training and conditioning techniques are used to ensure that fish will repeatedly respond to those sounds that they can detect. Once a fish is trained to respond in a characteristic way the sound level can be reduced progressively until the animal no longer responds. The threshold for detection may then be determined.

Alternatively, electrical responses may be recorded from the nervous system as a sound is presented. Thresholds at different frequencies are determined by reducing the sound level until the evoked electrical potentials can no longer be observed; or frequency response curves may be prepared by comparing the sound levels that yield a given level of electrical response. Typically, the frequency response curves show less dynamic range (are flatter) than those determined by behavioural techniques. Responses may also be obtained to frequencies to which the fish do not respond behaviourally. The thresholds are usually higher than those determined as behavioural thresholds, as they are influenced by the inability of the experimenter to distinguish the very small electrical potentials against background electrical noise. Such techniques are easy to apply and are widely used for determining thresholds. However, their particular value is in assaying changes in sensitivity and bandwidth and any damage to the hearing characteristics of fish induced by high levels of sound. They do not provide an accurate measure of the sensitivity of the fish to sound and audiograms derived from them should only be used with caution.

The audiogram is a graphic representation of the threshold as a function of frequency. Different species of fish can be compared in terms of the range of frequencies, or bandwidth, they respond to, and also the lowest sound levels (thresholds) they are able to detect. For most fishes there are no empirical data to describe their hearing characteristics. However, several general conclusions can be drawn from the few audiograms that can be considered reliable. In this account we will consider mainly the larger and commercially important marine species.

Fish are sensitive to a rather restricted range of frequencies compared with amphibians, birds and mammals. Even the most sensitive fish have relatively poor hearing above 2-3 kHz. There are one or two exceptions; a few fishes do appear to be sensitive to very high amplitude high frequency sounds, including the ultrasonic frequencies generated by some sonar systems. However, fish are generally most sensitive to relatively low frequencies (Figure 5-3). Examples of audiograms obtained under a variety of acoustic conditions using both behavioural and evoked potential techniques are shown in Figure 5-3. It can be seen that some fish are not very sensitive to underwater sound. Most thresholds are above 70 dB.

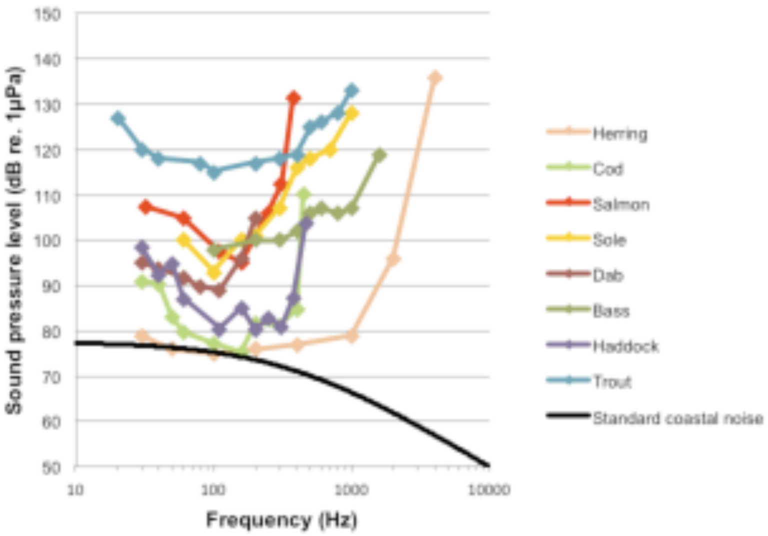


Figure 5-3: A selection of fish audiograms compared to the standard coastal noise

By varying the ratio of sound pressure to particle motion in sounds presented to fish, either by means of a special tank, or by varying the distance of the fish from a source in a free sound field (making use of the near-field effect), it has been possible to demonstrate that some fishes, like the plaice *Pleuronectes platessa* and dab *Limanda limanda* (Chapman and Sand, 1974; Hawkins and MacLennan, 1976) and the salmon *Salmo salar* (Hawkins and Johnstone, 1978), are sensitive to particle motion. Other fishes, like the cod *Gadus morhua* (Chapman and Hawkins, 1973), herring *Clupea harengus* (Enger, 1967) and catfish *Ictalurus (Amiurus) nebulosus* (Poggendorf, 1952), are sensitive to sound pressure. The latter species may be more sensitive than the former to sounds propagating in a free sound field, where particle motions are relatively small.

Species sensitive to sound pressure also respond to sounds over a wider frequency range. The hearing of fishes within the cod family has been especially well studied by means of experiments in midwater in the sea. In addition to the cod, examined by Chapman and Hawkins (1973), Chapman (1973) has also examined hearing in three close relatives: haddock *Melanogrammus aeglefinus*; ling *Molva molva* and pollack *Pollachius pollachius* (Figure 5-4).

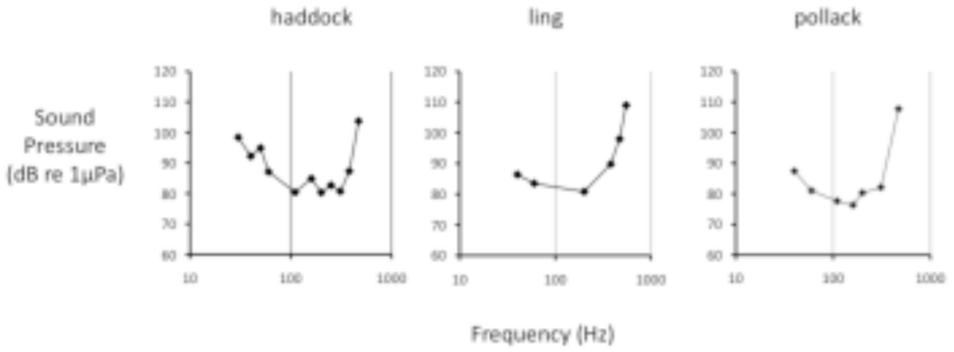


Figure 5-4: Audiograms for three species closely related to the cod; haddock *Melanogrammus aeglefinus*, ling *Molva molva*, and pollack *Pollachius pollachius*. All three show substantial overlap with each other and with the audiogram for cod. It is likely that at their most sensitive frequencies (up to 250 Hz) all three are limited by the level of ambient sea noise under most circumstances, as the thresholds change as sea noise varies. Audiograms are from Chapman (1973).

The family Clupeidae includes the herrings, shads, sardines, anchovies and menhaden. It includes many of the most important food fishes. Because these fish are especially susceptible to damage during capture, do not thrive in small tanks, and are resistant to conditioning techniques it is quite difficult to obtain behavioural audiograms. Enger (1967) detected auditory evoked potentials (AEPs) from herring *Clupea harengus* in a small tank containing an immersed sound projector. AEP studies on the spotlined sardine *Sardinops melanostictus* in a shallow tank with a loudspeaker in air above the tank showed a rather narrower and much less sensitive audiogram (Akamatsu *et al*, 2003). Other studies have shown that some clupeid fishes, including shads and menhaden, can detect ultrasound (sound with frequencies higher than 20 kHz) (Dunning *et al.* 1992; Nestler *et al.*, 1992). Thresholds obtained by cardiac conditioning of the American shad *Alosa sapidissima* by Mann *et al* (1997) show relatively poor sensitivity to frequencies below 1 kHz (although the authors acknowledged that the thresholds may have been masked by noise) but found sensitivity to high level sounds at ultrasonic frequencies (Figure 5-5). Similarly, it has been shown that the menhaden *Brevoortia* is capable of detecting sound frequencies from 40 kHz to at least 80 kHz (Mann *et al.* 2001). In contrast, Pacific herring *Clupea pallasii* in a shallow tank with immersed sound projectors showed AEP responses up to 5 kHz, but never to ultrasonic frequencies (Mann *et al*, 2005). Similarly negative results were obtained from other species of Clupeinae; the bay anchovy *Anchoa mitchilli*, scaled sardine *Harengula jaguana*, and the Spanish sardine *Sardinella aurita* only detected sounds at frequencies up to about 4 kHz (Mann *et al*, 2001). It seems that within the Clupeidae, only members of the subfamily Alosinae, which include the shads and menhaden, detect ultrasound.

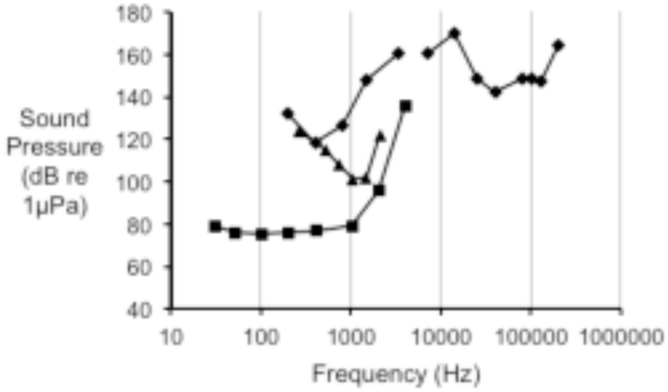


Figure 5-5: Audiograms for clupeid fishes. The audiogram for the herring *Clupea harengus* (Enger, 1967) was based on microphonic potentials (square symbols). That for the spotlined sardine *Sardinops melanostictus* (Akamatsu *et al.*, 2003) was based on AEPs (triangles). That for the American shad *Alosa sapidissima* (Mann *et al.*, 1997) was based on cardiac conditioning (diamonds).

Sharks are often the top predators in the seas and they are increasingly becoming species of concern from a conservation standpoint. Very little is known about hearing in this group, or how they react to anthropogenic sound. Another group about which we know little are the jawless fishes: the lampreys and hagfishes. These too lack a swim bladder and again very little is known of their hearing abilities or responses to high-level sounds.

Audiograms for particle motion have been obtained in five species of shark using classical conditioning or auditory evoked potential methods (see Casper and Mann, 2009 for a review). Since elasmobranchs do not have a swim bladder or any other air filled cavity it is usually assumed that they are incapable of detecting sound pressure and are reliant upon particle motion. The hearing bandwidth for elasmobranchs is from around 20 Hz up to 1 kHz, with similar thresholds in all species above 100 Hz (Casper and Man, 2009; Figure 5-6). Below 100 Hz, however, the two more active swimming piscivorous species, *Rhizoprionodon terraenovae*, the Atlantic sharpnose shark, and *Negaprion brevirostris,* the lemon shark, have more sensitive hearing, suggesting that in these species hearing could be more important for the detection of prey. The other three species, the nurse shark, *Ginglymostoma cirratum*, horn shark, *Heterodontus francisci*, and yellow stingray, *Urobatis jamaicensis*, are demersal species, and may rely on other senses, including the lateral line and electroreception to find their prey. In general elasmobranchs do not appear to be as sensitive as teleosts measured in comparable ways. However, knowledge of the hearing of elasmobranch fishes is based on data from only a few species.

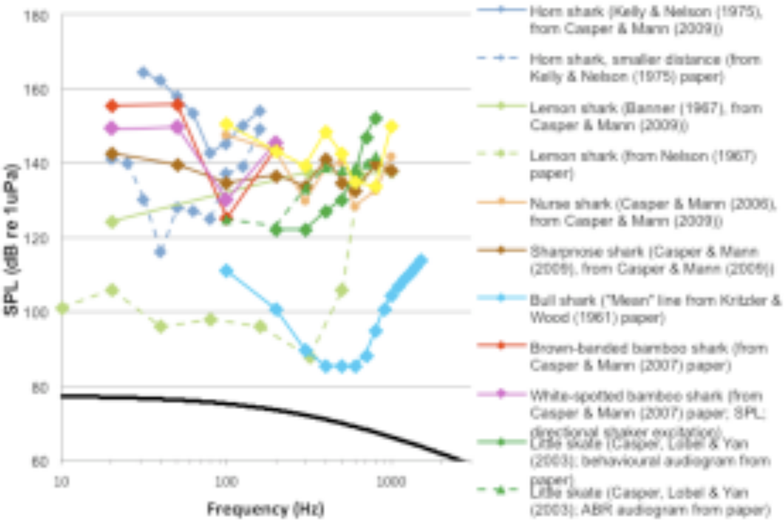


Figure 5-6: A selection of elasmobranch audiograms compared to the standard coastal noise (from Casper and Man, 2009)

Fish have been divided into two groups – hearing specialists and hearing generalists (or “non-specialists”) (Popper *et al.* 2003 and Ladich and Popper 2004), mainly on the basis of whether they have adaptations to their auditory apparatus that enhance their sensitivity and broaden their frequency range. Both hearing specialists and generalists are distributed through many fish taxonomic groups. The so-called specialists have adaptations (involving acoustic coupling between a gas-filled structure and the ear) that enhance their hearing bandwidth and sensitivity (i.e. lower their hearing threshold) under open sea conditions. They may also have an ability to detect airborne sounds if they are close to the water surface. Some fish like the cod do not fit neatly within either category and many of those fishes that are sensitive to particle motion may be specialists of a different kind. Comparisons of the sensitivity of different fishes simply in terms of sound pressure may not always be appropriate. Fish sensitive to particle motion may show increased sensitivity to sounds close to air/water interfaces, and in the near-field of a source, where the particle motion is amplified, and they may also be sensitive to substrate vibrations.

Most audiograms do not provide results for frequencies below 20-30 Hz because of the difficulty in obtaining sound projectors that produce undistorted sounds at very low frequencies. Sand and Karlsen (1986), working with a specially designed tank, have shown that cod have an acute sensitivity to extremely low frequency linear accelerations, or infrasound, extending below 1 Hz. The threshold values measured as particle acceleration decline (i.e., sensitivity increases) at frequencies below 10 Hz, reaching the lowest value at 0.1 Hz. The authors put forward the hypothesis that fish may utilize information about the infrasound pattern in the sea for orientation during migration. Knudsen *et al* (1992, 1994, 1997) later examined juvenile Atlantic salmon *Salmo salar* and species of Pacific salmon and concluded that frequencies in the infrasound range (5-10 Hz) were the most efficient for evoking both awareness reactions and avoidance responses. Similar avoidance responses to infrasound were also shown by downstream migrating European eels *Anguilla anguilla* (Sand *et al.*, 2000, 2001). More recently, Sand *et al.* (2008) have suggested that near-field particle motions generated by the moving hull of a ship are mainly in the infrasonic range, and infrasound is particularly potent in evoking directional avoidance responses. Large vessels, in particular, may generate especially extensive particle motion fields.

Within their relatively restricted frequency range some fish are acutely sensitive to sounds. Indeed, in the sea the cod is often not limited by its absolute sensitivity but by its inability to detect sounds against the background of natural ambient sea noise. Only under the quietest sea conditions do cod show absolute thresholds (Chapman and Hawkins, 1973). Any increase in the level of ambient sea noise, either naturally as a result of an increase in wind and waves or precipitation, or from the passage of a ship, results in an increase in the auditory threshold (a decline in sensitivity). The ability of these very sensitive fish to detect important signals (e.g. sounds from a predator, or the sounds made by conspecifics) will be affected not just by variations in natural ambient noise but will be masked by any extraneous sounds which raise the level of background noise. It should be noted that many of the difference in sensitivity seen in the audiograms of different species may result from variable noise levels prevailing under experimental conditions. Aquarium tanks are notoriously noisy, as is the sea itself.

It cannot be concluded that the thresholds of all fish are always masked. At their least sensitive frequencies the thresholds of a fish like the cod are well above the background noise level. Less sensitive species, like the dab and the salmon only show masked thresholds when the background noise is raised significantly (Hawkins and Johnstone, 1978).

Behavioural and physiological investigations have shown that fishes are able to discriminate between sounds of different amplitudes (Jacobs and Tavolga, 1967); different frequencies (reviewed by Enger, 1981); detect some sounds even in the presence of background noise; and distinguish between sounds from different directions. These higher level capabilities are important to a fish as they enable fish to discriminate between the sounds of predators and the sounds of prey, determine the location of potential predators or prey, and lift sounds out of a noisy background.

Especially important is the ability of fish to separate sounds from background noise by means of a filtering mechanism that selects particular frequencies. Not all frequency components of the background noise contribute to masking. Hawkins and Chapman (1975) showed that in the cod a pure tone signal is only masked by those frequencies within a narrow band on either side of the tone. Effectively the cod is able to employ a narrow band filter, which can be tuned to the frequency of a stimulus and which eliminates the masking effects of remote frequencies. This “critical bandwidth” varies with frequency but is of the order of one third of an octave.

Filtering is the only kind of sound discrimination mechanism that is present in fish. Many of the sounds made by fish themselves have a pulsed structure. Differences between closely related species, or between calls made in different contexts by the same species, often vary in their pulse patterning (Myrberg and Spires, 1972, 1980). It is likely that fish are able to discriminate between sounds and separate sounds from the noise background on the basis of their temporal as well as their frequency characteristics.

Experiments with cod have also shown that with increased special separation between two sound projectors, one emitting a pure tone and the other white noise, the degree of masking of the tone and the noise decreased (Chapman and Johnstone, 1974; Hawkins and Sand, 1977). The ability of fish to discriminate sounds from different directions has been established in a series of experiments carried out on cod in deep water under far-field conditions (Chapman and Johnstone, 1974; Hawkins and Sand, 1977; Schuijf, 1975; Schuijf *et al.*, 1972). Cod are able to discriminate between spatially separated sound projectors both in the horizontal and vertical planes (reviewed by Schuijf and Buwalda, 1980). It has also been shown that sharks orientate towards particular sources (Myrberg *et al.*, 1976).

It has already been emphasised that there are no empirical data to describe the hearing characteristics of a most fishes and even where there are data they are often of doubtful quality. It is evident, however, that the anatomy of the auditory system often provides a guide to the hearing abilities of particular species. For example, one of the most important indicators of auditory diversity is the presence or absence of a gas bubble or gas-filled bladder, which is important for the detection of sound pressure. Below, we consider the auditory system in fish, and the mechanisms by which fish detect sounds.

5.3.4 The fish ear

The basic mechanism for transduction of sound is the sensory hair cell, which is ubiquitous in the ears of all vertebrates. These cells are typically elongate cylinders, surrounded by supporting cells on a firm connective tissue base. Afferent and efferent neurones, running to and from the brain, synapse with the hair cells.

Mechanical stimulation of the ciliary bundle triggers a chain of events that culminate in the release of chemicals, called neurotransmitters, from the cell body that in turn stimulates the afferent neurones that send electrical signals to the brain. An important feature of the hair cell is that it is directional in its response to mechanical stimulation. The hair cells are directionally sensitive displacement detectors (Flock, 1965; Hudspeth and Corey, 1977). Depolarisation of the cell and excitation of the primary afferent nerve fibres is most pronounced when the stereocilia are deflected in the direction of the kinocilium, and hyperpolarisation and inhibition of the afferent fibres results when the stereocilia are deflected by shearing forces acting along the same axis in the opposite direction. The hair cells are often arranged in distinctive patterns within the different maculae of the ear.

Three sacs within each ear are linked with each other and with the semicircular canals (Figure 5-7). One of these sacs, the utriculus, communicates directly with the lumen of the semicircular canals and with them forms the pars superior. The other two sacs, the sacculus and lagena, form the pars inferior. In teleost fishes each of these sacs contains an otolith, a dense mass of calcium carbonate and other inorganic salts (Figure 5-8), sitting upon a bed or macula of sensory hair cells. The various sacs and their otoliths can vary greatly in size and shape between different species.

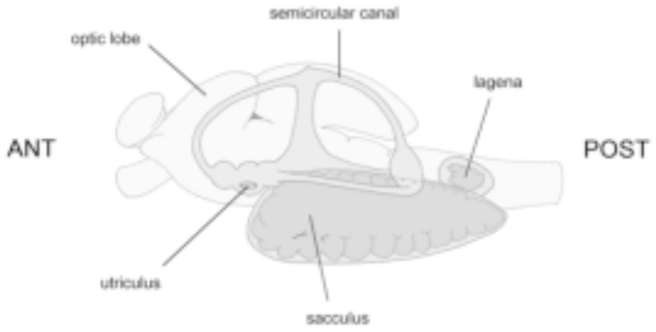


Figure 5-7: Drawing of the left ear of a cod *Gadus morhua* showing the three orthogonally arranged semicircular canals and the three otolith organs, the sacculus, utriculus and lagena.

In sharks, skates and rays the maculae of the sacculus, utriculus, and lagena are covered by otoconia, a gelatinous matrix of calcium carbonate granules, rather than otoliths (as in terrestrial vertebrates).

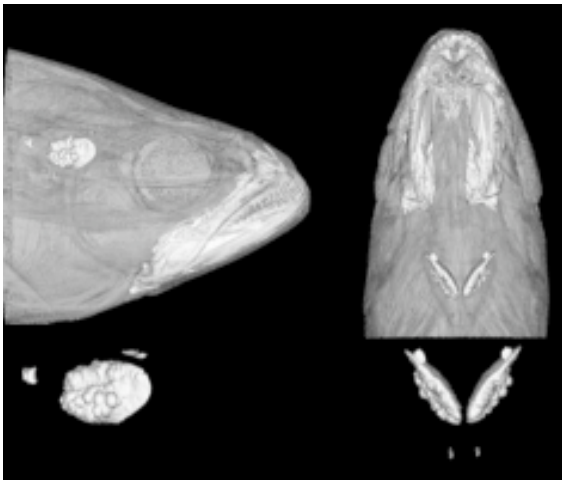


Figure 5-8: Reconstruction of the head of a white sea bass *Atractoscion nobilis* from micro-CT scan images (60 micron cubic voxels), with three pairs of otoliths in lateral view and in dorsal view. Otoliths are white and are magnified below. The cranial bones and soft tissues are semi-transparent gray; the premaxilla and dentary are white. Illustration provided through the kindness of Ted Cranford and Carl Schilt.

The macula of each otolith organ is divided into regions, each containing hair cells with their ciliary bundles organised in a particular direction (Dale, 1976). In most fishes, for example, the sacculus has at least four distinct hair cell regions, each organised in a different direction (see review by Popper and Coombs, 1982). Other species have different orientation patterns. The hair cell orientation pattern for the cod is shown in Figure 5-9.

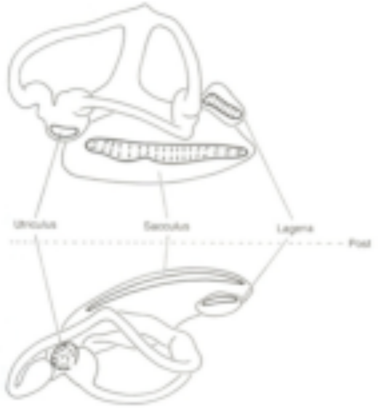


Figure 5-9: Hair cell orientation patterns in the left ear of the cod (after Dale, 1976).

Each otolith organ may have many thousands of sensory hair cells within the maculae. Fishes, unlike most tetrapods other than amphibians, continue to produce sensory hair cells throughout much of their lives (Lombarte and Popper, 1994). In addition, there is evidence that fishes, unlike mammals, can replace sensory cells that have been damaged as a result of exposure to certain drugs (Lombarte *et al.,* 1993).

It appears that the organisation of the auditory part of the brain in fish is consistent with that understood for most other vertebrates, and the flow of auditory information from the periphery to the mid-brain appears to be similar (reviewed by Fay and Edds-Walton, 2008).

The anatomy of the ear in sharks, skates and rays differs in several respects from that in teleost fishes. It appears that elasmobranchs detect sound using the same inner ear end organs as other fishes (see Myrberg, 2001 for review). However, elasmobranchs do not have the solid dense otoliths found in teleosts. Instead, the sensory epithelia of the sacculus, utriculus, and lagena are covered by otoconia, a gelatinous matrix of calcium carbonate granules (found also in lampreys and all terrestrial vertebrates). There is in addition a fourth end organ, the macula neglecta, covered by a gelatinous cupula.

5.3.5 Hearing mechanisms in fish

The otolith organs act through the movement of the otoliths relative to the sensory maculae and they undertake several functions. First, they serve as gravity receptors, enabling the fish to determine its orientation with respect to the Earth's gravitational field (Lowenstein, 1971). As the orientation of the head changes the otoliths move, deflecting the hair cells. Such a system is also sensitive to linear acceleration, the otolith tending to lag behind as the fish accelerates or overshooting when the body comes to rest. It is also evident that the otoliths play an important role in sound reception.

Pumphrey (1950) suggested that a sound passing through the head of the fish (which has similar acoustic properties to the surrounding water) will move the tissues back and forth but the dense otolith will lag behind, generating an oscillatory shearing force which will stimulate the hair cells. De Vries (1950, 1956) put forward a simple mathematical model of the otolith and its suspension. He suggested that the movement of the otolith is critically damped, with a rather low natural frequency of vibration. A critically damped oscillator has a nearly constant response to a broad range of frequencies. However, the amplitude of motion will decline steeply above the natural frequency, causing a reduction in sensitivity to higher frequency vibrations. Sand and Karlsen (2000, 2008) have pointed out that such a system is essentially an accelerometer. The otolith organs are inherently sensitive to the kinetic sound component, particle motion, and not to sound pressure, as confirmed by Chapman and Sand (1974) and Hawkins and MacLennan (1976) for two species of flatfish lacking swimbladders (gas bladders).

In elasmobranchs there is some evidence that the macula neglecta serves a role in acoustic detection. The macula neglecta is located in the dorsal portion of the ear in the posterior canal duct. It has been suggested (Corwin, 1981) that sounds travel through an area of tissue located above the ear called the parietal fossa. In the ventral end of this fossa is a small membrane, the fenestra ovalis, which leads to the posterior canal duct. Depression of this membrane by sounds may produce a fluid flow through the posterior canal duct, shifting the position of the cupula of the macula neglecta and stimulating the sensory hair cells.

In many fishes the ear is connected mechanically to accessory gas-filled organs. Thus, in the Ostariophysi (the second-largest super-order of fish, containing almost 8,000 species), an anterior chamber of the swimbladder is connected to the sacculus of each ear by a chain of small bones - the Weberian ossicles. The functioning of this apparatus was described by Alexander (1959, 1966). An association of diverticulae or ducts from the swimbladder with the ear has also been reported for the families Anabantidae, Balistidae, Chaetodontidae, Cichlidae, Clupeidae, Engraulidae, Holocentridae, Hiodontidae, Megalopidae, Moridae, Mormyridae, Notopteridae, Ophiocephalidae, Sciaenidae and Sparidae (Jones & Marshall, 1953; Alexander, 1966; van Bergeijk, 1967; Braun and Grande, 2008).

Gas-filled accessory structures like the swimbladder can assist in hearing because the contained gas is more compressible than the surrounding tissues and water. The pressure changes accompanying the passage of a sound will cause changes in the volume of the organ, which in turn may be translated into an amplified movement of the otolith. The system responds to sound pressure, though the end organ itself is still sensitive to particle motion. Poggendorf (1952), de Vries (1956) examined the displacement amplification provided by a swimbladder. They concluded that if an appropriate mechanism existed for coupling the movements of the swimbladder to the ear, then substantial amplification could occur over a wide range of frequencies. This mechanism of signal amplification is responsible for the increased hearing sensitivity and wider bandwidth of many fishes.

Poggendorf (1952), van Bergeijk (1967) and Alexander (1966) went further and suggested that the swimbladder might be capable of stimulating the ear even in the absence of a mechanical linkage. Pulsations of the swimbladder, induced by a sound, might be communicated to the ear directly through the intervening body tissues. Evidence that this occurs in the cod, a species which lacks any direct connection between the swimbladder and ear (Figure 5-10) was presented by Enger & Andersen (1967) and Chapman & Hawkins (1973).

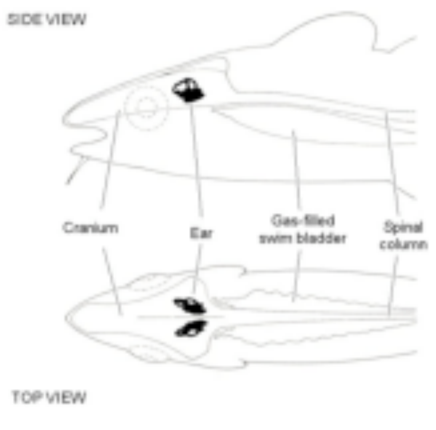


Figure 5-10: In the cod *Gadus morhua* the gas-filled swimbladder extends close to the ear, but does not have any specialised mechanical link with it. Nevertheless the cod responds to sound pressure.

Sand and Hawkins (1973) measured the resonance frequency and damping of the swimbladder in intact living cod at different depths and showed that the swimbladder served as a transformer, translating sound pressure into re-radiated particle motion with little phase distortion over an extended range of frequencies. Deflation of the swimbladder resulted in a decline in sensitivity to sounds (Sand and Enger, 1973). Remarkably, placing a small inflated gas-filled rubber bladder close to the head of a dab (which lacks a swimbladder) gave increased sensitivity and extended the frequency range (Chapman and Sand, 1974). However, the swimbladder does not appear to be involved in hearing in all species. Hawkins and Johnstone (1978) showed that the salmon (which does have a swimbladder) was sensitive to particle motion over its whole bandwidth. Moreover, deflation of the swimbladder does not change hearing sensitivity in the oyster toadfish *Opsanus tau* (Yan *et al*, 2000).

Fish have evolved a number of different mechanisms to acoustically couple the swim bladder (or other gas-filled structure) to the ear, thereby allowing the auditory system to detect the pressure component of the sound field (see Popper *et al.* 2003 for review). Best known are the Ostariophysans, where the anterior end of the swimbladder is coupled to the ear by a chain of moveable bones, the Weberian ossicles. Expansion or contraction of the anterior chamber of the bi-lobed swimbladder results in motion of the ossicles. This motion subsequently causes fluid motion in a small sinus filled with perilymph, which is then communicated to an endolymphatic transverse canal connecting with the lumen of both saccular chambers. Motion of the anterior end of the swimbladder causes displacement of the saccular otolith, stimulating the hair cells. Alexander (1959) described adaptations to the swimbladder that allowed the fish to accommodate changes in hydrostatic pressure while still enabling the coupling between the swimbladder and the ear to detect the much smaller sound pressure.

In the Clupeiformes or herring-like fish there is a very different coupling with the ear, described by Allen *et al.* (1976). The central feature is a pair of bullae, each divided into gas-filled and liquid-filled parts by a membrane under tension. The gas-filled part of each bullae is connected to the inner ear by a long gas-filled duct to the swimbladder, which acts as a reservoir of gas. Rapid motion of the membrane in the bulla by an incident sound generates motion in the perilymph which is transmitted to the maculae of the utriculus, sacculus, and perhaps also the lagena, stimulating the hair cells (Denton *et al.*, 1979; Denton and Gray, 1993, 1998) showed that the membranes in the auditory bullae had flat responses over a wide frequency range from less than 1 Hz to 1,000 Hz, which agrees with the audiogram derived for herring by Enger (1967).

Although the means by which fish detect sounds are relatively well understood, analysis of sound quality by the fish ear is still poorly elucidated. It is necessary to account for the ability of fish to discriminate sounds of differing frequency (reviewed by Enger, 1981) and the relatively narrow critical bands shown by species like the cod (Hawkins and Chapman, 1975). Furukawa and Ishii (1967) distinguished between nerve fibres responding to high and low frequencies in the goldfish ear. However, the frequency response of afferent fibres in most of the fish examined is quite broad (Horner *et al.*, 1981). Moreover, behavioural studies of sound communication have indicated that fish discriminate between calls on the basis of differences in repetition rate and duration, rather than frequency or bandwidth (Fine, 1978, Myrberg, 1981; Myrberg and Spires, 1972). However, the extent to which fish distinguish sound quality through differences in frequency spectra or fluctuations in amplitude with time is not well understood. Analysis may take place within both the frequency and time domains. What is known, however, is that many of the afferent neurones from the otoliths respond with a high degree of phase locking to the waveform of the sound (Horner *et al.*, 1981; Fay, 1982). Essentially, the waveform of the received signal is coded by the discharge rate of the neurones. Sand (1974) has suggested that the movement patterns of the otoliths may be frequency dependent, and that the parts of the macula that are stimulated may depend upon frequency although further studies are necessary before this suggestion can be confirmed.

5.3.6 Directional discrimination

The mechanisms used by fish to discriminate sounds from different directions are controversial (see review by Sand and Bleckmann, 2008). Van Bergeijk (1967) originally proposed that the single pressure detector present in many fish (the swimbladder) could not be used to localise a sound source, and that fish therefore could not detect sound direction in the far-field. However, field observations of freely ranging sharks showed that they orientated toward sound sources, often from large distances (reviewed by Myrberg *et al.* 1976). Moreover, it was subsequently established that teleost fish are able to discriminate between spatially separated sources under far-field conditions, both in the horizontal (Schuijf *et al.*, 1972; Chapman and Johnstone, 1974; Schuijf and Buwalda, 1975) and vertical (Hawkins and Sand, 1977) planes. Indeed, they are able to distinguish between sources at different distances (Schuijf and Hawkins, 1983). This ability not only enables fish to locate the sources of sound but may also assist them in discriminating sounds from a particular source against the general non-directional noise background.

There is strong evidence that the otolith organs themselves can provide a basis for the detection of the axis of particle motion. Experiments by Enger *et al* (1973) and Sand (1974) provided the first electrophysiological data supporting the notion that fish may detect the axis of particle motion by showing that each sacculus responded in a directional manner to vibrations presented along different angles of azimuth, suggesting that fish might determine the azimuth of a sound source by comparing the output from the two ears. The hair cells of the inner ear have a definite axis of sensitivity and there are orderly patterns of hair cell orientation within each macula, suggesting that the axis of sound propagation may be determined by a process of vector weighing. There is also evidence that this pattern of hair cell orientation is preserved at the level of the primary afferent neurones (Fay and Olsho, 1979). Polar diagrams of the directional sensitivity of primary auditory afferents in fish were first presented by Hawkins and Horner (1981), who recorded from the saccular and utricular branches of the auditory nerve in Atlantic cod during whole-body vibrations in the horizontal plane.

Subsequent studies have now confirmed these findings for toadfish (*Opsanus tau*; Fay and Edds-Walton 1997, 2000;), sleeper goby (*Dormitator latifrons*; Lu *et al.*, 1998; Lu and Popper, 1998, 2001), and plainfin midshipman (*Porichthys notatus*; Weeg *et al.* 2002). Thus, the primary auditory afferents in several species from different groups of fishes show directional response patterns similar to the response functions of single hair cells, indicating that each afferent neurone contacts a population of hair cells with the same directional orientation. The afferents from all otolith organs are sufficiently sensitive to respond to particle motions associated with sounds of normal intensity, indicating that the brain may use information from all otolith organs in its analysis of sound. Information about stimulus phase is also conveyed to the central nervous system through phase locking of the afferent neurones. Information from only one ear might suffice for computation of sound source elevation, while information from both ears might be required for computation of azimuth. The peripheral auditory apparatus of a fish certainly appears capable of three-dimensional detection of the axis of sound propagation through vector weighing (see review by Sand and Bleckmann, 2008).

It is still not understood how the directional information in the incident particle acceleration is protected against masking by the amplified secondary particle motions radiating from the swimbladder in those fish that detect sound pressure. Moreover, detection of the axis of particle motion is in itself not sufficient to determine the direction of the sound source, since the particle motion in the far-field is alternately either away from or toward the source. There is an inherent bi-directionality or 180° ambiguity in the vector weighing process, making it impossible to discriminate between opposing sound sources (180° apart). In practice, experiments have shown that the ide *Leuciscus idus* (a cyprinid) can discriminate between opposed sound sources (Schuijf *et al.*, 1977) as can the cod (Buwalda *et al,.* 1983).

This ambiguity is resolved in the phase model for directional hearing in fish (Schuif 1976, 1981). The model assumes that the fish is able to compare the incident particle movements with the sound pressure, and that by decoding the phase difference between these components the fish is able to discriminate between opposing sound sources. The re-radiated signal from the swimbladder acts as a phase reference to resolve the ambiguity. Certainly, the phase relationship between particle motion and sound pressure is crucial for the fish to be able to perform the discrimination (Buwalda *et al.,* 1983). A number of authors have found this model difficult to accept (see for example Rogers and Zeddies, 2008). Kalmijn (1997) has proposed that such a complex model is unnecessary and has suggested instead that fish can make their way to a sound source by maintaining a constant angle with respect to the axis of vibration.

5.3.7 The lateral line

The lateral line system is essentially a system for detecting water flow and mechanical disturbances close to the fish (Denton and Gray, 1988). It is found in all bony and cartilaginous fish, the lampreys and hagfish and even the earliest fossil fishes. It appears as an organized pattern of mechanoreceptors buried in canals, or as superficial organs over the head and body, although there is great structural diversity between fishes (Coombs and Montgomery, 1998). The receptor cells of the lateral line, like those of the ear, are sensory hair cells that respond to shearing forces. The superficial neuromasts are deflected by local water movements, while the neuromasts placed in canals may respond to pressure gradients along the body. In both cases they enable fish to detect and respond to sources of hydrodynamic disturbance in their close proximity.

The lateral line has been shown to play an important role in predator avoidance, prey capture, courtship and spawning, orientation to water currents and station holding in flowing water. It may also be used for spatial imaging and exploration in the absence of vision (Bleckmann, 1994). Dijkgraaf (1963) referred to the lateral line as a ‘distance-touch’ system and pointed to the importance of damming phenomena in front of moving objects in water as well as local water displacements. Recent studies have shown that some fish use their lateral line system to track the hydrodynamic wakes left by their prey.

Local turbulent and hydrodynamic effects involve the bulk transport of the medium at relatively low speeds, often over short distances. In contrast, sound propagation involves a transfer of energy through an elastic medium, at very high speed, over large distances, without any net transport of the medium itself. Although both the ear and the lateral line may respond to the large particle motions in the near-field of a large low frequency sound source the critical difference is that the lateral line responds to movements of water external to the fish’s body, while the inner ear responds to the back and forth motion of the whole body of the fish and in some cases to re-radiated motions from a gas-filled structure. In addition, although the sensitivity to particle motion of the lateral line can overlap with that of the auditory system, the hair cells of the lateral line system essentially encode frequencies below about 100 Hz (Denton and Gray, 1988).

Ships and other moving bodies in water, and even stationary bodies in a flow field (e.g. piles in an ocean current) can generate hydrodynamic waves, surface waves, turbulence and wakes that move away from the source. These local water movements may stimulate the lateral line system.

5.3.8 Deficiencies in our knowledge

Only a few species, like the cod, dab, plaice, salmon and goldfish, have had their hearing abilities examined under appropriate acoustic conditions and we are still largely ignorant of the abilities of most species to detect sound. Priority species for examination include the herring, the mackerel, skates and rays and jawless fishes like the lamprey. Behavioural audiograms are required for these species under natural and varied noise conditions. We are especially lacking information on the hearing abilities of larval fishes, and of the changes that may take place with growth and age.

The presentation of measured sound stimuli to fish under experimental conditions presents great difficulties. The relationship between sound pressure and particle velocity in an experimental tank is extremely complex, and there is no reliable way of calculating the relative levels of the two quantities. Both parameters should be measured, but calibrated particle motion detectors are not widely available and this is rarely done. Audiograms and sound pressure thresholds presented in the literature must be treated with great scepticism unless the sound field has been carefully specified. Relatively few experiments on the hearing of fish have been carried out under appropriate acoustical conditions and the results from many of the measurements made in tanks, and expressed solely in terms of sound pressure, are unreliable.

6 Anthropogenic sound sources

6.1 Introduction

There are many sources of anthropogenic noise, of varying sound levels and disturbance to marine life. This chapter summarises the most prolific ones present in the ocean today and attempts to explain some of the more damaging sources of nosie to the environment by grouping them according to their affects and possibilities for mitigation.

Table 6-1 summarises some of the largest sources of anthropogenic sources of noise. They are grouped into two sections; accidental, for noise which is the by product of another process, and intentional, where the sound itself serves a purpose. Accidental noise sources at least contain the possibility for mitigation as the noise produced is not integral to the process. With intentional sources the sound created is the purpose of the source in question and so any mitigation is difficult without hampering the effectiveness of the source.

	Type of Waveform		
Sound source	Low and mid-frequency, impulsive	High frequency, impulsive sound	Low frequency, continuous
Accidental	Blasting Impact piling	Sonar	Vibropiling Dredging Shipping noise Drilling
Intentional	Acoustic deterrent devices Communications Seismic airguns	Acoustic deterrent devices	Acoustic deterrent devices Communications

6.2 Blasting

Explosives provide an indispensable tool for underwater marine civil engineering, where they are used to create a blast, which is the mechanical disturbance that propagates away from an explosive when it is fired. In the immediate vicinity of the explosion the blast is immensely strong, and is used to cut or shatter material, but it reduces rapidly with distance. By far the biggest non-military use of explosives underwater is in borehole blasting where the blast from explosives confined in boreholes in rock are used to shatter the surrounding rock so that it can be removed by dredging.

In borehole blasting, explosive charges are placed in deep, small diameter holes that have been drilled into the rock or structure. A grid of holes is drilled in the area to be blasted. Holes are drilled to the required depth, which is deeper than the eventual depth required, and the charging takes place.

Subacoustech has taken a large number of measurements of marine borehole blasting. A typical recording is shown in Figure 6-1. In one case measurements were taken when a drilling barge was used as the position from which the boreholes were drilled and charged. In addition, it also served as the platform from which the blasts were fired. Charge weights were typically 15 to 30 kg. Land blasting was also undertaken on a spit of land, by drilling down through the blasted rock into the underlying bedrock.

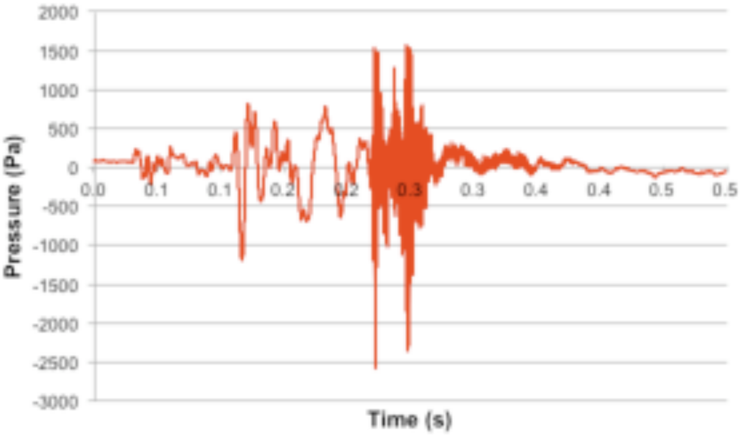


Figure 6-1: Time history of an underwater blast for a charge of 15kg with measurements made at a distance of 265 metres.

Even at a distance of 265 m the pressure varies from over -3000 Pa to 2000 Pa. The blast itself only lasts for less than half a second but at this distance is characterised by a period of low frequency noise, followed by more broadband noise including much higher frequencies. This is shown in Figure 6-2.

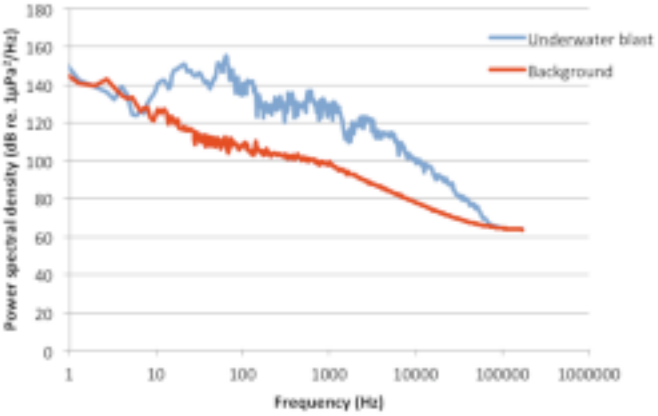


Figure 6-2: Power spectral density of the underwater blast

6.3 Impact piling

Impact piling involves a large weight or "ram" being dropped or driven onto the top of the pile, driving it into the ground. Usually, double-acting hammers are used in which compressed air not only lifts the ram, but also imparts a downward force on the ram, exerting a larger force than would be the case if it were only dropped under the action of gravity. Percussive impact piling has been established as a high level source of underwater impulsive noise (Wursig (2000); Caltrans (2001); Nedwell *et al* (2003b); Parvin *et al* (2006a); Thomsen *et al* (2006); Nedwell *et al* (2007a)).

Noise is created in air by the hammer, partly as a direct result of the impact of the hammer with the pile. Some of this airborne noise is transmitted into the water. Of more significance to the underwater noise, however, is the direct radiation of noise from the surface of the pile into the water as a consequence of the compressional, flexural or other complex structural waves that travel down the pile following the impact of the hammer on its head. The transmission of sound from one medium to another is related to the acoustic impedance of each medium (specific acoustic impedance is calculated by multiplying the density of the medium by the speed of sound travelling through it). The larger the difference is in acoustic impedances (the impedance mismatch), the larger the transmission loss. Steel has acoustic impedance approximately

100,000 times larger than that of air, while it is only about 26 times larger than that of water. Waves in the submerged section of the pile therefore couple sound efficiently into the surrounding water. These waterborne waves will radiate outwards, usually providing the greatest contribution to the underwater noise.

At the lower end of the pile force is exerted on the substratum not only by the mean force transmitted from the hammer by the pile, but also by the structural waves travelling down the pile inducing lateral waves in the seabed. These may travel as both compressional waves, in a similar manner to the sound in the water, or as a seismic wave, where the displacement travels as Rayleigh waves (Brekhovskikh (1960)). The waves can travel outwards through the seabed, or by reflection from deeper sediments. As they propagate sound will tend to "leak" upwards into the water, contributing to the waterborne wave. Since the speed of sound is generally greater in consolidated sediments than in water, some of these waves arrive first as a precursor to the waterborne wave. Other waves, those that travel through the interface between the seabed and water, travel at a lower speed and arrive later.

Generally, the level of the seismic wave is 10 – 20 dB below the waterborne wave, and hence it is the latter that dominates the noise, although where mitigation measures such as bubble curtains are used to attenuate the waterborne noise the seismic wave may dominate.

The majority of the analysis of the pile driving noise addresses the level of the noise as a function of the range from the pile driving, as this is critical in determining the range at which the pile driving may have an effect on the environment. The data are thus presented largely in the form of graphs which present level versus distance from the pile driving. However, it is instructive to first look at the detail of typical recorded waveforms.

Figure 6-3 illustrates a typical pressure time history (i.e. sound pressure *versus* time) for a five second period of pile driving. The time history was recorded during piling of a 4.7 m pile, at a distance of 100 m with the hydrophones located at approximately half the water depth.

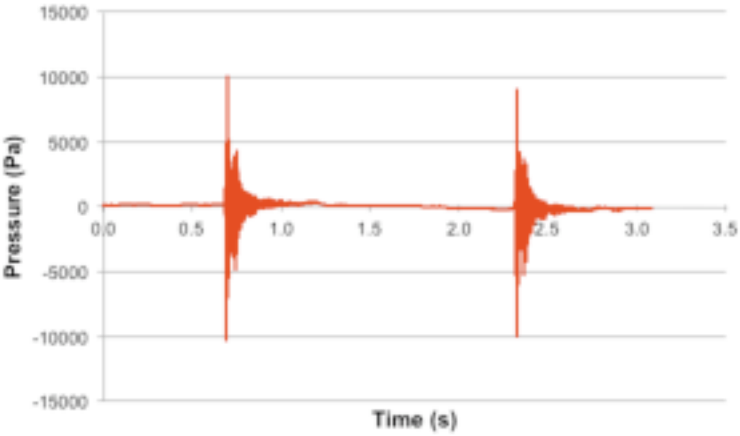


Figure 6-3: Example of a pressure~time history – taken during pile driving operations of a 4.7 m diameter pile, at a distance of 100 m

The individual pile strikes may be clearly seen in the time history; there are two clear individual strikes in this period, in which the pressure rises very rapidly to a maximum; there follows a period of decaying oscillatory pressure, the duration of each strike being about 0.5 second. The majority of the arrival is due to waterborne sound, but it may be seen that at the tail of each wave is a small low frequency arrival which it is thought is probably due to substratum-borne vibration. The pressure reaches a maximum positive pressure of about 10^4 Pa, or 0.1 bar, and a negative value of just over the same value. The peak-to-peak pressure level of this wave is therefore approximately 206 dB re 1 μPa.

Figure 6-4 presents the same information, but this time at a distance of 10 km. It may be seen that the pile strikes are much more spread in time due to dispersion in the water and also due to a significant component of the sound propagating through the seabed, or in seabed-coupled water waves. The level of the wave has dropped significantly, to approximately 20 Pa peak-to-peak, or 146 dB re 1 µPa. This is approaching typical background sound levels of 130 – 140 dB re 1 µPa and the noise may clearly be seen superimposed on the measurement, leading to its “ragged” appearance. These levels are typical of those that have been measured previously in the shallow coastal water of windfarm sites around the UK (Nedwell *et al.* (2003)).

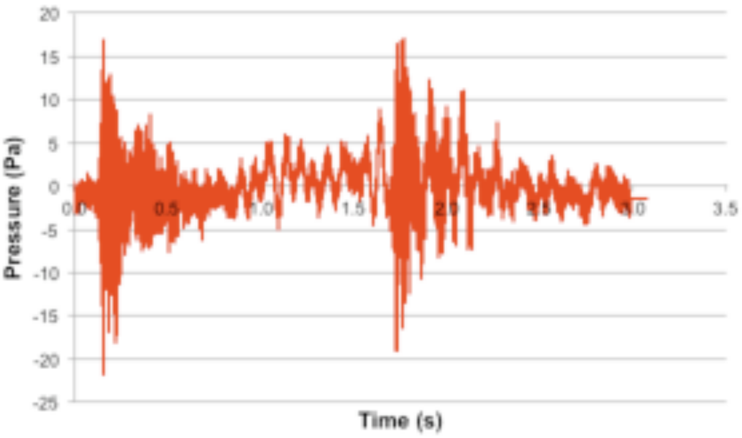


Figure 6-4 Example of a pressure~time history – taken during pile driving operations of a 4.7 m diameter pile at a distance of 10 km

Figure 6-5 illustrates the spectra of the time histories illustrated in Figure 6-3 and Figure 6-4. In addition, the background level of noise (recorded in periods where there was no pile driving) is illustrated. The figure presents the power spectral density of the pile driving noise as a function of frequency, for the two measurements at 100 m and 10 km. In all cases the level of noise from the measurements at 100 m of the pile driving is greatly above the background. It may be seen that the spectral level is generally of the order of 40-60 dB above that in the absence of pile driving over a wide frequency range from 100 Hz up to the highest frequencies presented of 100 kHz. It is important to note here that at short range there is substantial high frequency sound energy at frequencies from 100 Hz to above 100 kHz, but that at ranges of 10 km the spectra highlight that much of the high frequency energy has been attenuated during transmission. There is, in general, no tonal content to the pile driving, although there are some low level broad peaks or swathes at about 35 and 70 Hz.

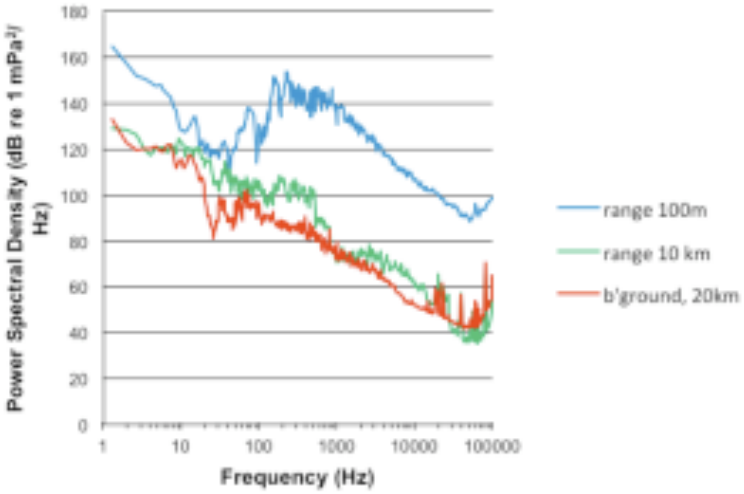


Figure 6-5: Spectra of the preceding two time histories, and a background recording taken at 20 km when no pile driving was occurring.

The measurements at 10 km are also above background, over a frequency range from about 10 Hz up to 10 kHz or so. Again, the spectrum is fairly flat without significant tonal components with most of the sound energy from the piling being concentrated between 50 Hz and 2000 Hz.

Figure 6-6 shows the recorded sound level versus the range along two different transects.

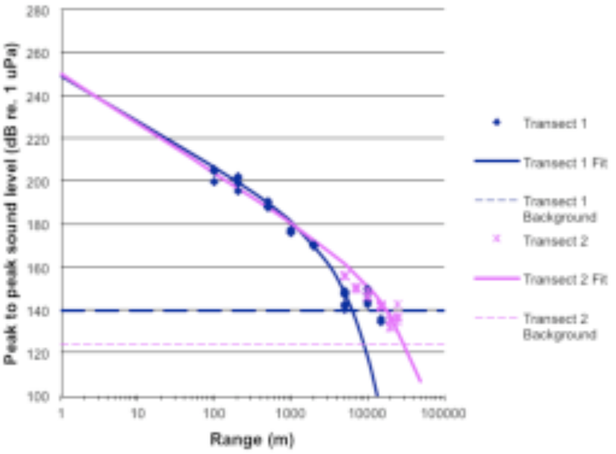


Figure 6-6: Sound level versus range from piling taken along two different transects. Along transect 1, which headed due west of the piling, the water depth was 7 m in the immediate vicinity of the pile, varying to a depth of 24 m at 15 km. Along transect 2, which was taken to the North West of the piling, water depths remained around 29 m.

For both sets of measurements a similar source level was obtained, 249 dB re. 1µPa for transect 1 and 250 dB re. 1µPa for transect 2. Similar transmission loss coefficients were observed for both transects also although the absorption loss coefficient was significantly lower for transect 2.

6.4 Seismic airguns

Seismic surveys are carried out as part of the investigation of subsea geological formations during marine oil and gas prospecting. During seismic surveys high level, low frequency sounds are directed towards the seabed from near-surface sound sources that are towed by a survey vessel. The reflected sound signals are then recorded and analysed to provide information about subsea geological formations.

Sources used in marine seismic exploration to rapidly vent high pressure air from a pressure vessel into the underwater environment. These pneumatic devices are commonly referred to as 'airguns'. The airguns are submerged in the water, typically at a depth of 5 to 10 m. When the airgun is 'fired' a gas bubble expands rapidly, before contracting and re-expanding. Underwater sound is generated by the initial gas bubble pulse and by the subsequent oscillations. The magnitude of the acoustic signal is proportional to the rate of change of the volume of the bubble.

A seismic survey is conducted by towing an array of multiple airgun sources behind the survey vessel at a distance of 50 to 100 m. The airgun array is typically fired once every few seconds, with individual airguns being triggered in a controlled, rapid sequence. Listening hydrophones towed behind the array receive the reflected signals from the seabed, allowing the seabed substratum to be imaged. Typically it is the low frequency components of the airgun noise that penetrate effectively into the seabed strata and allow an acoustic image to be formed.

Signals reflected from geological discontinuities below the sea floor are recorded by hydrophones made from piezoelectric material encased in a rubber or plastic hose. This hose containing the hydrophones is called a streamer. The length of streamers can range from 2,000 m to 8,000 m.

A 2D survey involves a single or just a few airguns and one length of streamer towed behind the vessel. In this simplified form of the technique the seabed reflections are assumed to originate from directly below the sail line, hence the term '2D'. These surveys are used to provide an initial survey of an area, and to indicate the presence of oil and gas.

3D surveys are a more complex and accurate means of seismic surveying. 3D surveys typically involve the use of several strings of airguns, fired with precise timing to produce a coherent pulse of sound. The airguns typically cover an area of tens of square metres, towed a distance of several hundred metres behind the survey vessel. Behind these are the arrays of streamers that receive the reflected acoustic signal. These signals are processed to produce a three dimensional image of the seabed subsurface, hence the term 3D.

A single airgun typically produces peak-to-peaks sound levels in the order of 222 – 238 dB re 1 µPa @ 1 m (Richardson *et al* (1995)), while arrays produce peak-to-peak sound levels in the region of 240 to 265 dB re 1 µPa @ 1 m. Most of the energy produced is in the 10 to 120 Hz bandwidth (Richardson *et al* (1995)), although energy at much higher frequencies is also generated (Goold and Fish (1998)). High resolution surveys and shallow penetration surveys require relatively high frequencies of 100 – 1000 Hz, while the optimum wavelength for deep seismic work is in the 10 – 80 Hz range.

Figure 6-7 shows a set of measurements taken of the sound from two sets of six airguns, measured whilst being towed behind a boat in blocks 14 and 14a of the North Sea. The volumes of the airguns in each array were 70, 90, 105, 110, 125, 145, 160, 185, 196, 250, 2 of 290, and 2 of 370 cubic inches. The variation in airgun size allowed the level of noise to be compared to the sound level (Nedwell *et al* 1999).

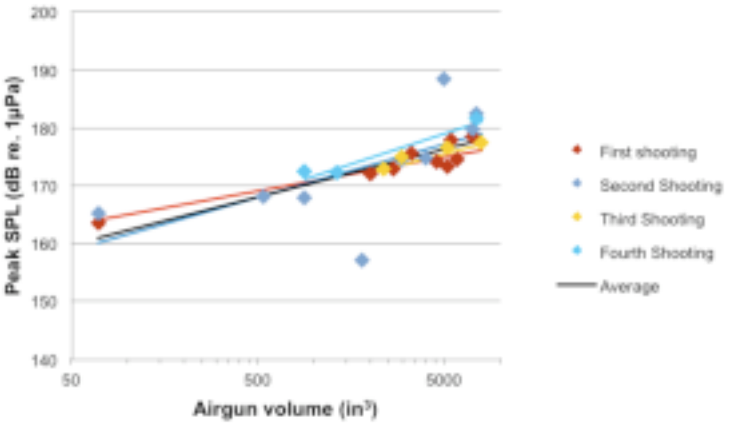


Figure 6-7: Sound level produced by varying sizes of airguns.

It may be seen that there is a fairly consistent relationship between the total volume V discharged by the array and the resulting level of sound. Several sets of measurements on subsequent days were completed and each was fitted to a law of the form:

$$\mathrm{SPL} = M \log_{10} V + V_0$$

Where *M* and V_0 are constants, *V* is the total volume of compressed air discharged and *SPL* is the resulting sound pressure level. It may be seen that the constant *M* has a value of approximately 8.4, indicating that the sound pressure *P* is proportional to the volume of the airgun array to the power 2.4, that is,

$$P = kV^{2.4}$$

where *k* is a constant. By implication, in terms of the unweighted levels the soft start procedure achieves its objective of gradually raising the sound pressure level during the start of the firing of the array.

The underwater noise generated during a seismic pulse is characterised by a transient pressure wave, rising to its maximum peak-to-peak level in approximately 1 ms, and then decaying over several bubble pulses during a period of approximately 100 ms. Measurements were taken of a single Bolt Model 1900LL-X seismic airgun in the Moray Firth, which was charged to a pressure of 60 bar each time. A typical noise time history taken from the survey at a distance of 100m from the airgun is shown in Figure 6-8.

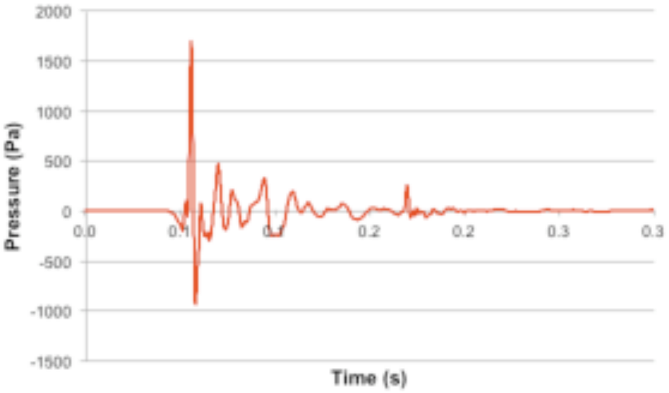


Figure 6-8: A typical unweighted pressure time history of underwater noise from a single seismic airgun, measured at 10 metres depth and 100 metres range

The spectra for the above firing compared to background sound is presented in Figure 6-9.

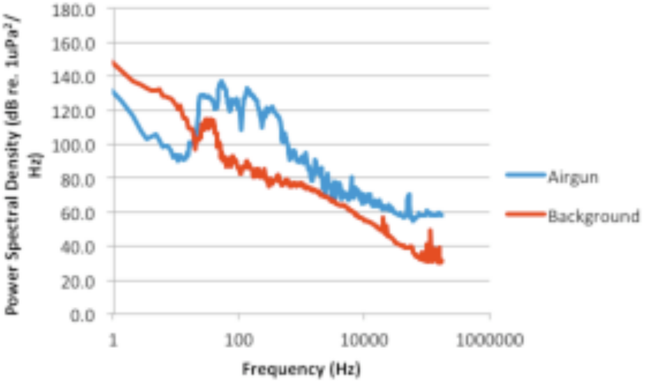


Figure 6-9: Typical spectra obtained from an airgun compared to background levels

The figure indicates that the majority of the emitted noise is at very low frequency from 10 Hz to around 300 Hz. Close to the source there are some high frequency components of the noise that extend up to a frequency of approximately 10 kHz, but these are at very much lower levels than the main low frequency components of the noise.

6.5 Vibropiling

The principle of operation of a vibropiling system is that counter-rotating, out-of-balance masses that are geared together rotate in an enclosure attached to the top of the pile. The rotating masses generate a resultant vertical vibratory force that slowly forces the pile into the ground. This is sometimes used as the sole method of piling, and sometimes used before impact piling, in order to partially secure piles to the bottom until movement is no longer possible.

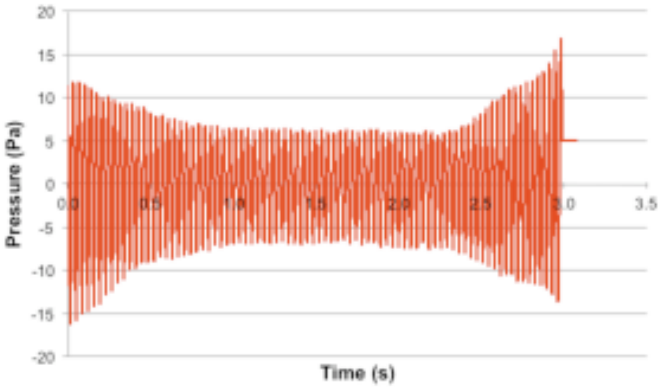


Figure 6-10 shows a typical 30 second, underwater noise time history, recorded in a river at a range of 22 m from vibropiling operations. The vibropiler was an OVR S-50 with a maximum power of 75 kW operating at 2500 rpm. The noise level in the river slowly varies over the measurement period, until the end of the recording, at which point the vibropiling stops, and the noise in the river returns to background river noise levels. As this is a continuous noise it is more appropriate to specify it in terms of the RMS Sound Pressure. During vibropiling operations the RMS pressure reached a maximum level of approximately 60 Pa (156 dB re 1 μPa). The one second, RMS Sound Pressure Levels during this recording varied from 129 to 146 dB re 1 μPa (equivalent to one second SELs from 129 to 146 dB re. 1 μPa^2-s).

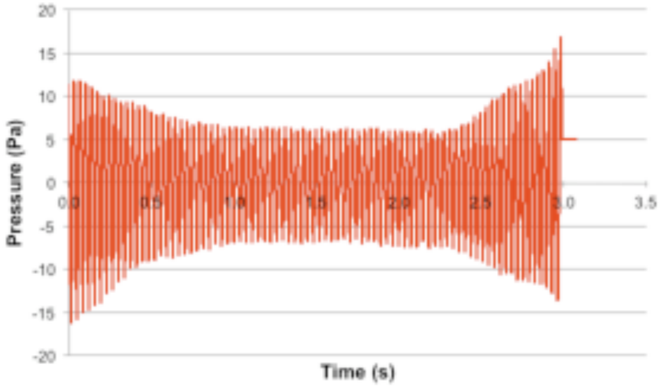


Figure 6-10: Thirty second Time history of measurements taken of vibropiling

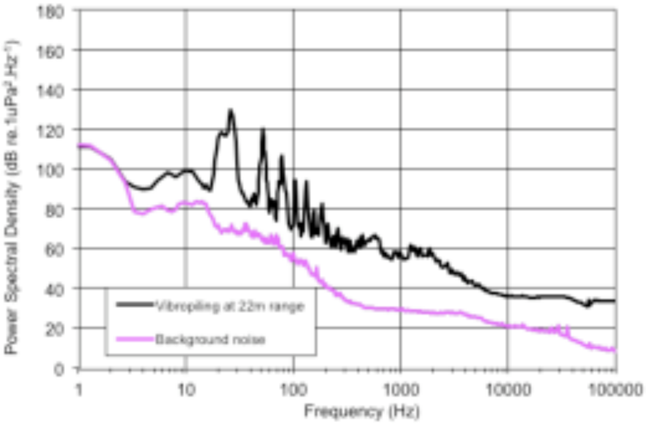


Figure 6-11 shows the spectra of a typical vibropiling operation along with data taken at the same location when no vibropiling was taking place.

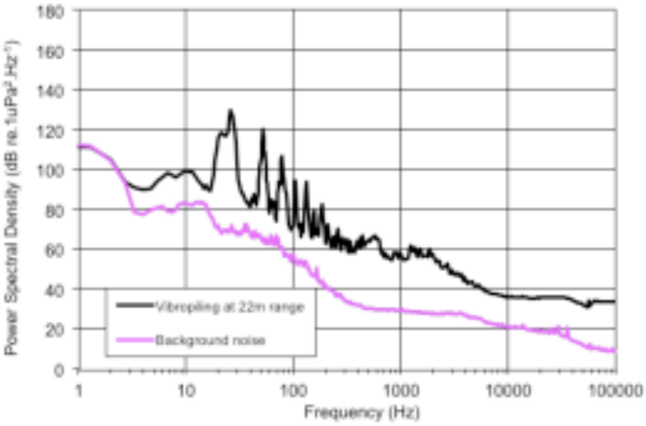
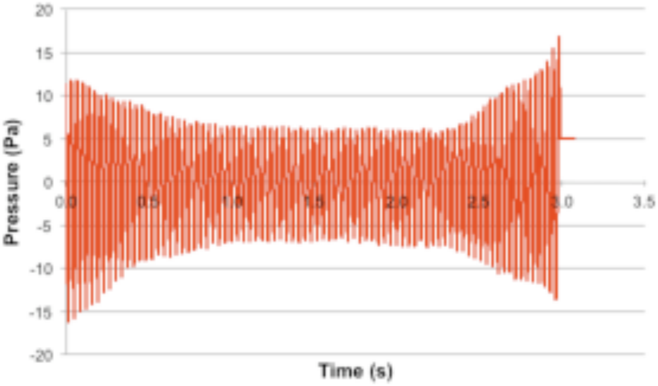


Figure 6-11: Power spectral density of the time history shown in Figure 6-10.



The frequency of the vibropiler is clearly visible at 26 Hz along with several harmonics extending to over 100 Hz. The maximum rotational speed of the piling hammer is 2500 rpm which would indicate that this frequency may vary up to 42 Hz. The spectral levels of noise indicate that the vibropiling increases the noise in the river over the frequency range from approximately 5 Hz to frequencies greater than 10 kHz. The greatest contribution to the increase in noise in the river is over the frequency range from 18 Hz to 200 Hz.

6.6 Wind turbine noise

Although there are a large number of offshore windfarms in UK waters with a total power production of over 1.5 TW, with plans double that capacity, the amount of research on the effect of operational windfarm noise on fish of any sort is slim, the focus so far being directed toward marine mammals. Some post construction studies have been completed, for example the Horn's Rev windfarm, which has completed numerous installation and operational studies (Hvidt *et al* 2006) which did not find any significant change in fish distribution after completing Hydroacoustic monitoring of fish communities.

Noise is produced from wind turbines in a similar fashion to most mechanical devices such as ships at sea, that is vibration of the turbine's generator and gearbox travelling to the section in contact with the water and radiated as sound. This produces low frequency noise with most energy at frequencies of 200 Hz and below (Thomsen *et al* 2006, Betke *et al* 2004).

Measurements of underwater noise have been taken from a 3.6 MW turbine, on the edge of a round 1 windfarm located in UK waters. At the time of the measurements the windspeed was approximately 7 m/s. One recording, taken at a range of 22 m from the turbine is shown in Figure 6-12.

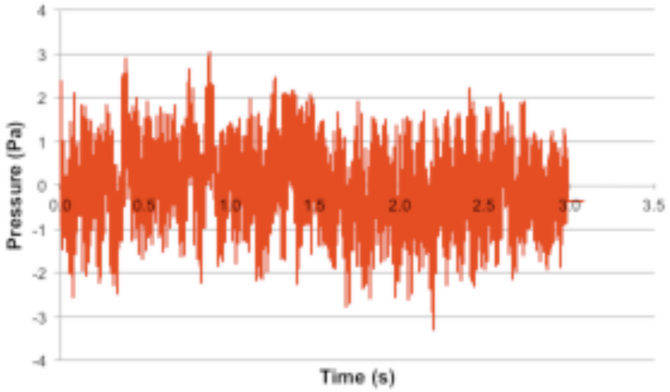


Figure 6-12: Time history of a recording taken 22 m away from an operational 3.6 MW wind turbine

The sound produced by the turbine is fairly typical mechanical noise, with little variation over the time spent recording. Varying between 3 and -3 Pa, the sound level of the turbine did not exceed 120 dB re. 1μPa RMS at 22 m indicating it was of low level compared to other sources of underwater noise examined in this section.

The frequency content of the noise is also fairly typical for offshore machinery with the majority of the noise occurring at frequencies less than 300 Hz with various peaks compared to the more uniform background spectra (Figure 6-13).

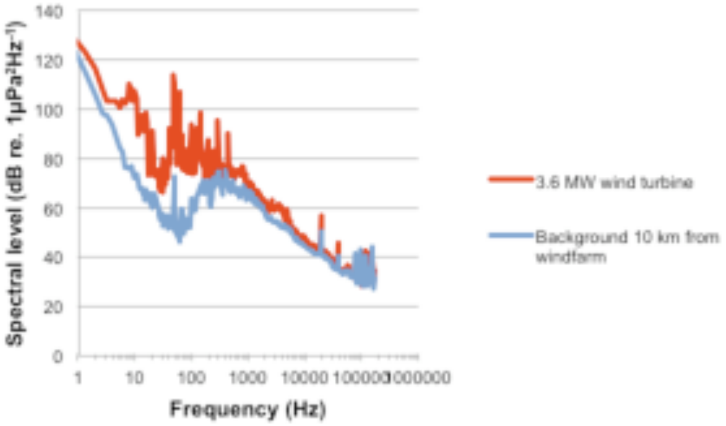


Figure 6-13: Spectral levels of the recording shown in the previous figure compared to a background recording taken 10 km away from the windfarm.

6.7 Dredging and aggregate abstraction

There are broadly two forms of dredging operation, depending upon the method used to transport the loosened material from the seabed to the water surface and into the supporting vessel or cargo hold. They can be described as hydraulic (suction) dredgers and mechanical dredgers.

Mechanical dredging operations involve the use of some form of grab or bucket to loosen the seabed material, and then to raise and transport the material to the sea surface. There are several techniques. A Bucket dredger has a continual chain of buckets that fill by scraping over the seabed and then empty by turning upside down by passing over a tumbler at the top. A Grab dredger has a large mechanical grab consisting of two half shells that are used to pick up material from the seabed, and then to lift and place the excavated material into a support barge. A Backhoe dredger is a mechanical excavator equipped with a half-open bucket. The excavator is filled by moving the bucket toward the machine, scraping it along the seabed. The dredged material is then lifted to the surface in the bucket, where it is normally loaded into a support barge.

Suction dredging involves raising the loosened material to the sea surface in suspension via a pipe system and centrifugal pump. Where the seabed material is loose the suction of seawater close to the seabed is sufficient to raise material to the sea surface. Firmer material may require mechanical loosening or the use of water jets, and hence suction dredging is most efficient when working with fine substratum materials.

A trailing suction hopper dredger is a self-propelled ship that is equipped with trailing pipes that suck up seawater and seabed sediment into a large hopper contained within the hull of the vessel. The suction pipe terminates in a drag head that moves over / through the surface of the seabed. At the sea surface the seawater is allowed to run off, leaving the extracted material in the hopper. Trailing suction dredgers remove layers of material in long runs, and are typically used for channel dredging and harbour maintenance.

Table 6-2 presents the unweighted data measurements of two vessels at various ranges. It may be noted that although vessel Q has a higher source level than vessel C there was greater transmission loss in the environment around the vessel, thus the sound was attenuated more rapidly. It may also be noted that the larger vessel, vessel Q, is rather noisier than vessel C.

	Vessel C	**Vessel Q**
Source Level / Transmission Loss	$L_r = 186 - 16 \log(r) - 0.0006\ r$	$L_r = 192 – 20 \log(r)$
dB re. 1 µPa level at 100m	154	152
dB re. 1 µPa level at 1000m	137	132
dB re. 1 µPa level at 10km	116	112
Approximate Range to Background (m)	8000	7000

Table 6-2: Source level and transmission loss for noise from TSHD

Figure 6-14 gives an indication of typical measurements of a TSHD, along with the least sum of squares fit line from which the transmission equation is derived. This gives an indication of the spread of results (correlation) at each range. It can be seen that there is a spread of approximately ±5 dB re 1 µPa, with the exception of the most distant data. The poorer fit to this distant data may have been due to external factors such as vessel orientation.

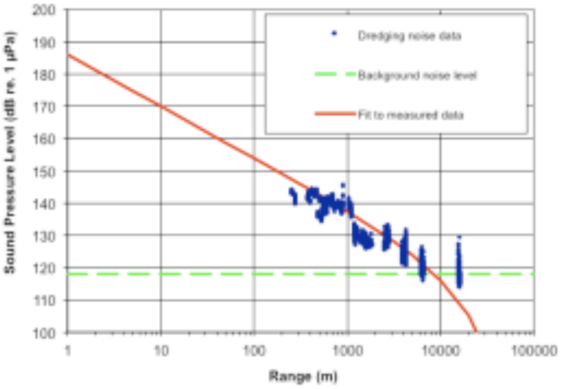


Figure 6-14: A typical plot of dredging noise measurements against range

The underwater noise time history illustrated in Figure 6-15 indicates that at a range of 250 m, the noise has a peak to peak level that varies from a minimum of approximately 112 to a maximum of 158 Pa, (161 to 164 dB re. 1 µ Pa). In this case, the analysis of the noise recording indicated that the one second RMS Sound Pressure varied from 14 to a maximum of 16 Pa over the measurement period, giving a Sound Pressure Level from a minimum of 143 to a maximum of 144 dB re. 1 µPa.

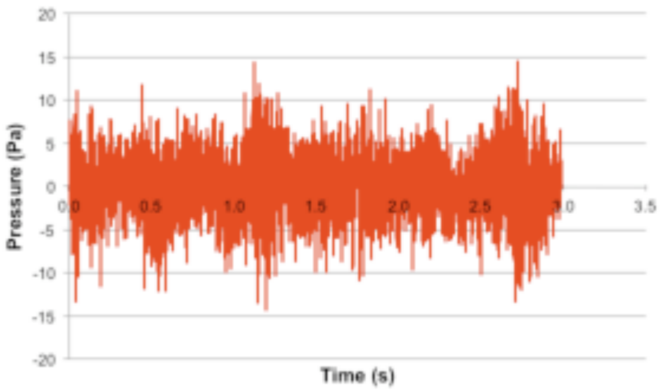


Figure 6-15: Time history of dredging

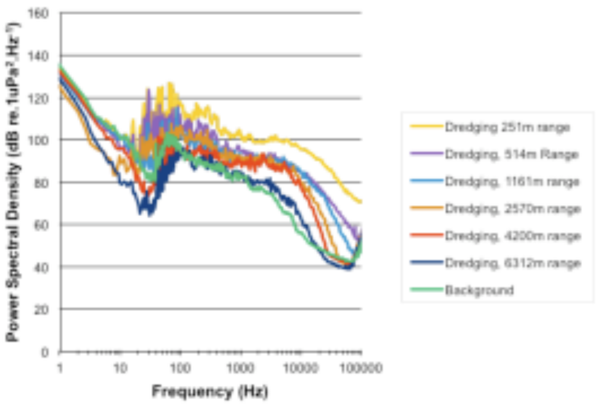


Figure 6-16 illustrates the Power Spectral Density of actual noise from vessel C at distances from about 250 m to 6.3 km. In addition, the background sound, taken when no dredger was in the area, is also illustrated. Generally, the background sound determines the lowest level of noise that can be recorded. However, it should be noted that as these recordings were not contemporaneous, the level of the noise from the dredging may on occasion be below the level of the background sound. This is because the background sound in a particular area is rarely constant, and may have been lower at the time the dredging noise measurement was being taken. The Source Level (i.e. the estimated Sound Pressure Level at an effective 1 m from the source of the noise) is about 190 dB re. 1 µPa @ 1 m.

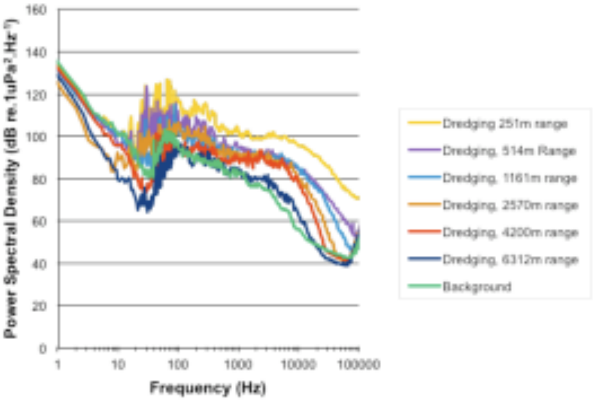


Figure 6-16: Power Spectral Densities of Dredger C at various ranges

It may be seen that the spectrum is characterised by three regimes. Below about 10 Hz there is no noise created by the dredging. Between about 10 Hz and 100 Hz there are tonal components, which are typical of rotating machinery such as pumps, propellers and thrusters. For frequencies above 100 Hz, and up to frequencies of at least 100 kHz, there is a high level of broadband noise or "hissing", probably caused primarily by sand and other debris rubbing against the side of the suction pipe as it is sucked upwards from the seabed. For convenience these regimes may be termed "machinery noise" and "flow noise". In this case, for frequencies of below 100 Hz, the background is actually of a higher level than some of the dredging recordings. The backgrounds were most likely due to the measurements being taken at a time of increasing sea state and turbulence.

6.8 Shipping

All forms of motorised vessels generate underwater noise. The noise from large shipping is one of the dominant underwater noise sources in the sea (Section 2 highlighting that shipping contributes to ambient ocean noise at frequencies from 20 to 80 Hz).

Individual vessels may generate very different sound levels and have different frequency characteristics depending upon factors such as the propulsion system, and whether there is propeller cavitation or singing. Richardson *et al* (1995) provides a review of the underwater noise from various classes of ship. For example, small ships are quoted as producing a broadband noise with source level of typically 170 to 180 dB re 1µ Pa @ 1 m, with larger ships, such as supertankers, producing underwater broadband noise at source levels of up to 190 dB re 1 µPa @ 1 m (Table 6-3).

Vessel Type	Source Broadband Sound Pressure Level (dB re. 1µPa @ 1 m)
Tug / barge	170
Trawler	168
34 m Diesel	163
Supertanker	189

Table 6-3: summary of the vessel noise from Richardson *et al* (1995). The broadband Sound Pressure Levels are calculated from the Third Octave Levels.

The measurements of underwater noise discussed above, however, refer to ships that are fully underway in open waters. In harbour large vessels may travel at much slower speeds, of typically a few knots, and hence the underwater noise characteristics are likely to be very different from the levels published in the literature.

Figure 6-17 shows the time history of a recording taken of a 130 m, 8300 ton tanker taken at a distance of 225 m from the ship (Nedwell *et al* 2008). The ship generates very featureless noise, at this distance varying mostly between -100 Pa and 100 Pa.

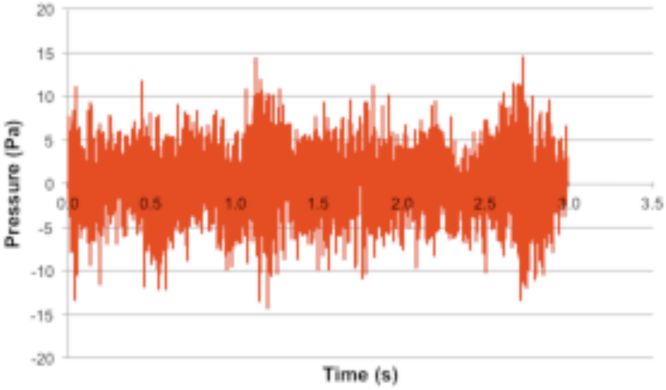


Figure 6-17: Time history of a recording tanker (data from Nedwell *et al* 2008).

The spectra from this recording is shown in Figure 6-18. The data are presented as estimated spectra at a distance of 1 m from the source, based on the extrapolation of shipping noise data measured at various far field distances. These data only present the underwater noise spectrum at low frequency, but highlight that there is considerable underwater noise energy at frequencies from 10 Hz to 1000 Hz, coinciding with the peak frequencies at which fish can perceive underwater noise.

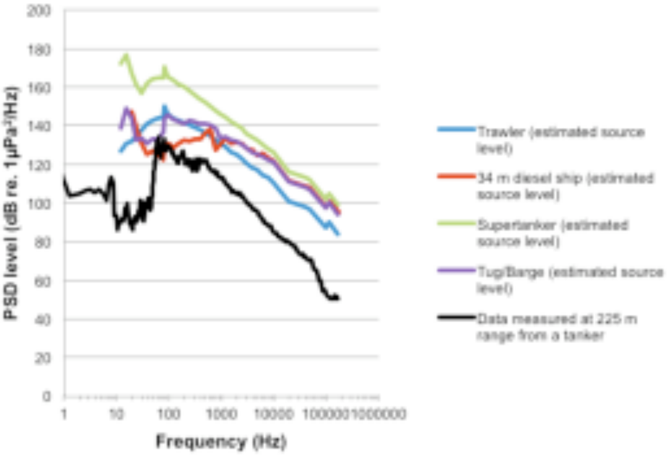


Figure 6-18: Spectra of the recording shown in Figure 6-14 (black line) compared to estimated source levels (at 1 m) for typical examples of shipping. Data from Richardson *et al* (1995), based on data from Cybulski (1977), Malme *et al* (1989) and Richardson and Malme (1993).

It can be seen that this tanker has generated fairly featureless broadband noise of approximately 30 dB above the background level. This frequency range of the noise reaches from as low at 80 Hz up to over 100 kHz and is such is fairly consistent with the data shown in Richardson (1999) excepting slightly higher minimum frequencies generated.

6.9 Drilling

Drilling is another source of underwater noise which is produced by many water-borne construction sites. There are many method of drilling in the sea or river bed, one of which is Reverse Circulation Drilling (RCD). In this case the device needs to be attached to the river/sea bed and will sit on a separate casing, with the drill string passed through the centre of the casing to the drill bit underneath. The drill slowly bores into the substratum material to the desired penetration depth using its own weight to exert a downward force. The reason why this technique is called RCD is that, in order to remove the waste material, water or air is pumped down the drill pipe, causing the waste material to rise up the drill string and be ejected via a hose on the side of the rig. When the drill has been removed from the hole the pile will be inserted and grouted in.

Underwater noise is probably generated primarily by interactions of the drill teeth with the substratum material, causing vibrations that are transmitted through the drill string and surrounding structures. The primary route for noise to be transmitted into the surrounding body of water is through any of these structures that are directly in contact with the water. Although little research has been performed into drilling noise, it is likely that transmission of sound into the water would be through either via a ground-borne or structure-borne path. Ground-borne vibration will be created at the drill/rock interface by the movement of the drill head. This will radiate out as both compressional and shear waves to the ground/water interface, where it will "leak" into the water. The mechanical vibrations that are generated in the drill may also be transmitted to the water via the drill shaft and the surrounding pile. Underwater noise may also be generated by the discharge of substratum material from the top of the drill into the water below.

The study of Nedwell and Howell (2004) presents a detailed review of offshore wind farm-related underwater noise, and includes information on offshore drilling techniques related to oil and gas exploration and production drilling. It is noted that the type of platform used for the drilling may affect the levels of underwater noise produced and that, be it man-made or natural island, jack-up, floating or semi-submersible barge, it is likely that the size of a platform used for offshore wind farm operations would be considerably smaller than those reviewed.

Results from measurements of drilling noise at the North Hoyle Offshore Wind Farm are presented in Nedwell *et al.* (2003a). During the installation of steel monopiles at North Hoyle harder rock was encountered underneath the initial sediment phase. Rock socket drilling was required during installation of all of the piles, and measurements of underwater noise during drilling activity were carried out at ranges of between 100 m and 9 km. Analysis of the data indicated a series of strong tonal peaks in frequency spectra associated with the drilling activity at 125, 250 and 375 Hz that were between 5 – 15 dB above background sound spectral levels.

Figure 6-19 presents a typical time history of underwater noise at a range of 54 m from drilling operations conducted in a lough. The drill used was a Seacore / Wirth B5 pile top drilling at 80 kW. The underwater noise is characterised by regular peaks in the noise levels above that of the drill alone. These peaks may correspond to the drill head periodically grating against harder substratum material. At this range from the drilling operation the one second RMS sound pressure varied from 2.3 to 4.2 Pa (127 to 133 dB re. 1 µPa RMS). The analysis of the data file indicated that the mean RMS level of the sound during this period was at a level of 3 Pa, or a Sound Pressure Level of 130 dB re. 1 µPa. This is equivalent to a one second Sound Exposure Level of 130 dB re. 1 µPa^2-s.

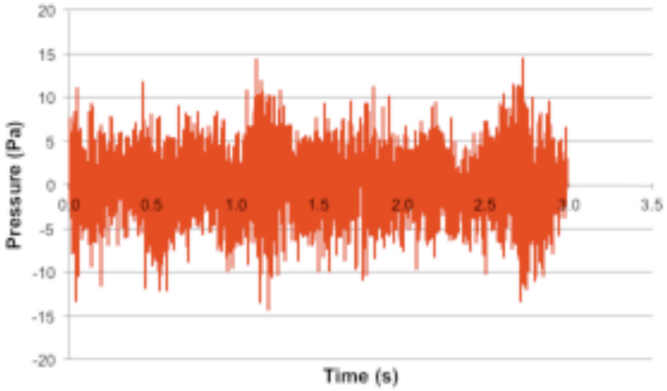


Figure 6-19: An underwater noise time history at a range of 54 m from the drilling operations

Figure 6-20 presents the spectral levels of noise for the underwater noise time history discussed above, in comparison with several files taken at various ranges from the drilling operation and the spectral levels of background underwater noise in lough. Comparison of the data indicates a trend whereby the spectral levels of noise decrease with increasing range. This trend is more apparent for the low frequency components of the noise. The data indicates that the drilling operation produces underwater noise with frequency components from 20 Hz to 100 Hz. At higher frequencies the noise shows little variation indicating that these components of noise do not contribute very much to the overall noise levels. Figure 6-19 also indicates the influence of flow noise on the spectral levels of noise. The period of down time for the drilling operation during which background sound levels were recorded was during a period of high tidal flow, whereas the other data presented in the figure were obtained close to slack water at high tide. There is a considerable increase in levels of underwater noise in the frequency range from 3 kHz to 100 kHz during the period of high tidal flow due to noise possibly created by interaction of turbulent water with the seabed and at the surface.

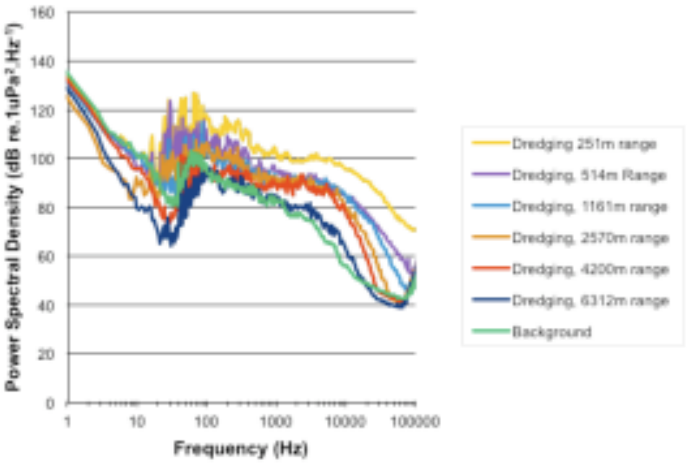


Figure 6-20: Comparison of the spectral levels of underwater noise at increasing range from a drilling operation.

6.10 Acoustic deterrent devices

Acoustic deterrent devices (ADDs) are also used to either block fish from entering a certain area, or deflect their path to a different route. ADD, are systems intended to create a high level of noise in an area, sufficient to cause annoyance, unbearable loudness or physical discomfort to fish, thereby causing them to flee the ADD, excluding them from the area of the noise. This area may be termed the “exclusion area”.

In general, ADD systems comprise a signal generating circuit and an amplifier, which together generate a powerful electrical signal. This is fed to a transducer that converts the signal into sound. The transducers produce sound via a flexible neoprene membrane, with depth compensation provided by an air reservoir. Higher frequencies can also be produced with the use of piezoelectric materials, which deform when an electrical signal is applied across their active faces, vibrating the adjacent water and hence causing radiation of sound, typically used to deter marine mammals.

There are many commercially available ADDs, with varying source levels and frequency ranges. Fish ADDs will typically operate with frequencies under 1 kHz, as this is the hearing range of fish they are designed to deter. To minimise habituation to the sound, its signal pattern is changed regularly, although this is less of a problem if fish are not to be exposed to the sound for extended periods.

7 The effects of noise on fish and invertebrates

7.1 Introduction

There is a variety of ways of registering the impacts of noise. Death rates can be evaluated and pathologists can define criteria for injury. Similarly, changes in hearing sensitivity can be demonstrated following exposure to sounds, either by showing a change in threshold to a particular sound (temporary threshold shift or TTS), or by demonstrating injury to the sensory hair cells of the inner ear. It is also possible to ascertain whether sound exposure has caused a physiological response, in terms of elevating the levels of stress hormones in the tissues, or evoking a change to the heart rate or breathing rhythm. Such responses have been observed under both laboratory and field conditions and have been especially useful in helping to define the levels, frequencies and other characteristics of sound which are capable of affecting individuals adversely. Often, however, our concern is not whether a sound causes physical or physiological damage to individuals but whether exposure results in changes to the behaviour or distribution of marine animals. Under these circumstances damage may not be apparent on the individual but effects may be relevant at the population or community levels. Population effects will be only briefly mentioned here but explained in more detail in Section 8 of this review.

We can list the criteria for assessing effects under the following headings:

Death and Injury

Hearing impairment

Stress and arousal responses

Behavioural responses

Masking of signals important to the lives of animals

Evidence for all these impacts need to be considered for both invertebrates and fish. However, perhaps the strongest current interest is in sublethal effects, such as behavioural responses and masking effects, as these could influence the fitness of individuals over relatively large distances from a sound source.

7.2 Criteria for assessing behavioural response

In considering behavioural responses by invertebrates or fish we must avoid the adoption of a deterministic approach. We must not assume that the same stimulus will always evoke the same response. Animals do not invariably respond in the same way to a particular stimulus. Each animal has an array of sense organs that can provide an integrated overview of the surrounding world. And they are capable of a wide range of motor responses that can be adjusted to different conditions. They may show some stereotypical reactions to stimuli of particular significance but they are also capable of learning from experience, remembering, and adjusting their behaviour. Moreover, different animals are adapted to different circumstances, and stimuli that may evoke a pronounced response from some species may not evoke any reaction at all from other species. Gender, age and life cycle stage also modify response threshold and behaviour, for example spawning fish do not behave the same as non-mature fish (Albaret & Gerlotto, 1976). Similarly, hungry fish have different reaction thresholds from satiated ones (Josse *et al*., 2000; Doray *et al*., 2008). A well-fed cod is at the limit of its metabolic scope, and is already consuming oxygen at a high rate. Its ability to move may be compromised. Likewise with a fatigued fish, this has been exercising heavily. Engås et al. (1998) reported a large variation in response to approaching vessels between and within individual cod that might reflect different metabolic states.

Nor do animals always respond in an equal way to different types of sound. Some low amplitude sounds may evoke a strong response; whilst other louder sounds do not. The metabolic status of animals may determine how they respond to a noxious stimulus.

Ultimately we are concerned with behavioural responses by animals that affect 'fitness'. If a response does not affect fitness it is not important. Increases in the energy diverted by animal as a result of a response to anthropogenic sound will ultimately affect its fitness and the amount of energy devoted to vital activities like growth and reproduction. Behaviour that conserves energy may be critical in subsequently defining fitness on the spawning grounds. Claireaux et al (2000) suggest that, when faced with heterogeneous or unstable hydrological conditions, marine organisms tend to behaviourally maximise their metabolic scope. Through this adaptive response, they reduce energy budgeting conflicts and presumably increase the probability of routinely operating away from lethal boundaries In terms of energy, the double challenge facing an animal trying to survive is to achieve the power output necessary to live in its selected niche while operating as low as possible from its maximum metabolic work or active aerobic metabolic rate (Priede, 1977 and 1985). The magnitude of the scope for growth is negatively related to mortality risk (Priede, 1977).

Fry (1947, 1971) classified the effect of the environment on fish physiology using five master factors; lethal, controlling, limiting, masking and directive. Considering underwater sounds and their effects on the animal's physiology and energy budget, sounds may be regarded as having all these effects. A lethal effect is when an environmental factor interdicts with animals physiology in a way that it cannot sustain life processes (e.g. injury-causing noise) while masking imposes additional physiological load that reduces the scope of active metabolism resulting in an energetic burden (e.g. noise levels inducing escape responses or stress). Sounds may be considered to have a directive role (e.g. use of noise as clue to direct metabolic scope towards a specific energy demanding task such as fleeing from a noisy environment). The advantage of the Fry's approach is the direct association between physiological or behavioural work and fitness in a bioenergetic framework that could be used to model expected responses at population or community levels.

Thus, in looking at behavioural responses the key questions that need to be addressed relate to effects upon fitness:

- Is access impaired to essential habitat for feeding, reproduction, concealment, territoriality, communication, or other life processes?
- Are migratory patterns, pathways and schedules altered?
- Is reproduction, sheltering and feeding behaviour disrupted?
- Is there inhibition of vocal behaviour?
- Is there masking of sounds involved in courtship, predator avoidance, prey capture, navigation etc.?

All these changes can have major effects upon animal populations, reducing the feeding rate and growth rate of animals, preventing their reaching spawning areas at the appropriate time, or interfering with reproductive success.

An important question is whether there is a dose/response relationship between the levels of sound presented to fish, and the magnitude of the response observed – a graded response with sound level. One of the areas where this search has been followed through is the avoidance by pelagic fishes of research vessels conduction acoustic surveys to determine stock biomass. Here it is clearly important to ascertain the extent to which fish move away from the vessel, compromising the results of the survey. Measurements of avoidance of clupeids in several areas using research vessels have confirmed that fish reaction to vessel noise is not a simple linear process between stimulus and reaction. The degree of response in one place and time seems very difficult to predict based on results collected from elsewhere (Soria *et al*., 1996; Gerlotto *et al*., 2004). The level of response appears to be species specific and to depend on environmental and seasonal factors rather than a linear function of the received sound level. The same species in the same place can display different avoidance behaviour depending on its environment, e.g. the time of day or meteorological events (Gerlotto et al, 1997).

In relation to masking effects, animals are unaware of the acoustic signals inducing animals' normal behaviour. In this case inhibition of the response may be mixed with a reaction to the masking sound making simple dose/response reaction models impractical.

7.3 Invertebrates

In general, there has been less research into the impact of sounds upon aquatic invertebrates. Interest has largely been confined to the effects of noise from seismic surveys, upon fisheries for commercially valuable crustaceans (crabs and lobsters). Christian *et al.* (2003) carried out a detailed study of the effects of seismic air gun noise upon the valuable snow crab (*Chionoecetes opilio*) fishery. Catches in an experimental commercial fishery were examined before and after commencement of seismic shooting to determine whether there was a change in the catch rate. Snow crabs were also observed during initial exposure to sound to examine any behavioural responses. In addition, snow crab activity was monitored using telemetric techniques to determine whether post- seismic activity patterns were different from pre-seismic activity patterns. Finally, snow crabs and fertilized eggs were exposed to various seismic noise exposure levels to determine whether seismic energy had any acute or chronic physiological or pathological effects on the haemolymph (invertebrate 'blood'), various organs and associated tissues, adult crab and egg mortality, and embryo development. Christian *et al* (2003) concluded that there were no obvious effects from seismic signals on crab behaviour and no significant effects on the health of adult crabs. They recommended that future studies should concentrate on egg and larval stages, which might be more vulnerable.

In the laboratory, snow crabs slightly reacted to sharp sounds from nearby sources. However, in the field, while being observed with a video camera, caged crab sitting on the bottom showed no visible reactions to an air gun array being fired 50m above them. Acoustically tagged crabs did not show any large-scale movements out of the area.

Crab catch data were examined using a variety of statistical techniques. Post-seismic catches were higher than pre- seismic catches but it was concluded that this was probably the result of physical, biological, or behavioural factors unrelated to the seismic source. There was no significant relationship between catch and distance from the seismic source. It was also concluded that there were no effects on the health of the snow crabs, as measured by a suite of variables, as a result of seismic shooting.

A preliminary experiment conducted with 4,000 eggs from one female crab suggested that exposure to high levels of received sound (221 dB re 1 µPa at 2 m depth) may retard the development of eggs (Christian *et al* (2003). Other studies have indicated that the young stages are often the most sensitive part of a species life history. Kostyuchenko (1973) and Booman *et al.* (1996) found indications of seismic effect on fish eggs when exposed to an air gun shot at close distance. Saetre and Ona (1996) observed effects of seismic signals on fish larvae.

In earlier experiments, Pearson *et al* (1994) found no effects of seismic signals upon crab larvae. In blind, controlled field experiments, early zoeae of Dungeness crab (*Cancer magister*) were exposed to sounds from single discharges of an array of air guns. Their survival and development were followed during subsequent laboratory culture. Immediate mortality was low (0 to 2%) and showed no significant difference between control and exposed larvae. For immediate and long-term survival and time to moult, the field experiment revealed no statistically significant effects on zoeae neither for exposures as close as 1 m from the array, nor for mean sound pressure as high as 231 dB re 1 µPa and cumulative energy density up to 251 J/m^2. Post hoc calculations showed that any reduction in zoeal survival as a result of sound exposure was low. Yet sound exposures in the study were at the maximum levels likely to be experienced by a zoea during an actual survey.

Payne *et al* (2007) examined the effects of seismic signals upon lobsters *Homarus americanus*. Exposure of lobster to very high as well as low sound levels had no effects in terms of immediate or delayed mortality or damage to mechano sensory systems associated with animal equilibrium and posture. There was also no loss of legs or other appendages (which may be observed from crustaceans under stress). However sub-lethal effects were observed with respect to feeding and serum biochemistry with effects sometimes being observed weeks to months after exposure. A histochemical change was also noted in the hepatopancreata of animals exposed four months previously, which may have been linked to organ ‘stress’. These initial studies were meant to be exploratory in nature. However, they do point to the need for more comprehensive studies of the potential for seismic surveys to affect lobsters. Studies on moulting and effects on egg development and animal behaviour were recommended, which might be carried out in a cost effective manner through laboratory and small-scale field experiments.

Chan *et al* (2010) designed a playback experiment to test the effect of noise on predation risk assessment. They found that in response to playback of boat noise Caribbean hermit crabs (*Coenobita clypeatus*) allowed a simulated predator to approach closer to the crabs before they hid. They concluded that anthropogenic sounds distracted prey and made them more vulnerable to predation. This is an important finding, as it suggests that quite subtle responses to sound by an animal may affect its survival. These experiments also point to the importance of examining particular and significant behaviour patterns, rather than simply describing changes in movements or simple startle reactions.

Andriguetto-Filho *et al.* (2005) measured bottom trawl catches from a non-selective commercial shrimp fishery comprising the Southern white shrimp, *Litopenaeus schmitti*, the Southern brown shrimp, *Farfantepenaeus subtilis*, and the Atlantic seabob, *Xyphopenaeus kroyeri* (Decapoda: Penaeidae), before and after the use of an array of four synchronized air-guns, with a peak pressure of 196 dB re 1 µPa at 1 m. They did not detect any significant deleterious impact of seismic prospecting on the studied species. In a related study, Ostrensky *et al.* (2002) placed individuals of *L. schmitti, F. subtilis,* and *X. kroyeri* in cages that were placed at varying distances from a transect of air-gun passage. No mortality was observed even when the air guns were discharged at very close distances to the caged shrimp. A detailed study of the gonads, branchiae and hepatopancreas showed negligible histopathological damage that could be associated with exposure to the pressure wave from the air guns.

André *et al* (2011) have concluded that low frequency sounds induce acoustic trauma in cephalopods. Four cephalopod species were subjected to low frequency controlled-exposure experiments. Exposure to low-frequency sounds resulted in permanent and substantial alterations of the sensory hair cells of the statocysts, the structures responsible for the animals’ sense of balance and position. All exposed individuals from all four species presented the same lesions and the same incremental effects over time. Immediately after exposure, damage was observed in the macula statica princeps and on the crista sensory epithelia. Kinocilia within hair cells were missing, bent or flaccid. The authors concluded that if the relatively low levels and short exposure applied in their study can induce severe acoustic trauma in cephalopods, and that the effects of similar noise sources on these species in natural conditions over longer time periods may be considerable.

7.4 Deficiencies in our knowledge

We can perhaps conclude that although some adult crustaceans are affected by exposure to high-level seismic sources the effect is often minimal. In some cases no detectable response has been observed. Nor is there evidence of impact of seismic surveys upon catches in crustacean fisheries. However, there is evidence that the statocysts of cephalopods may be affected by exposure to noise. There is also some evidence that the development and survival of larvae may be affected by exposure to high-level seismic sources. Bearing in mind the wide diversity of aquatic invertebrates and sources, and the importance of many species to marine fisheries, there is clearly a need for further studies.

7.5 Fish

There are more than 30,000 species of fish, occupying a very wide range of habitats. Fish vary greatly with respect to their abilities to detect and communicate by sounds, and also in their potential susceptibility to damage by sounds. Ecological and morphological factors are important in determining the effects of sound exposure and the longer-term consequences of exposure for fitness and survival. For example, work with explosive sources has shown that the presence of a gas cavity in the body of a fish may make the animal more liable to damage from abrupt changes in hydrostatic pressure. The most common gas-filled organ is the swim bladder, found in many but not all fish. This organ conveys neutral buoyancy to the fish but it may also serve other functions. The compressible gas contained in such a gas body renders the organ and the surrounding tissues vulnerable to trauma from pressure change. The affected tissues include the kidney, gonads and blood vascular system. Additional effects may result from the motion of small bubbles that may occur in the circulatory system. Gas organs within a fish may also be involved in hearing (Section 6), and their presence may increase the ability of fish to detect sounds. Damage to these organs and surrounding tissues from pressure changes may therefore affect the hearing abilities of fish.

However, a distinction must be made between barotrauma, the exposure of fish to changes in the hydrostatic pressure, and trauma as a result of exposure to high levels of sound pressure. The former occurs when a fish is suddenly taken from one depth to another, or exposed to fluctuating pressures in passing through a hydroelectric installation. The latter involves exposure to the much faster oscillatory pressure changes resulting from passage of a sound, although the changes in pressure may be equivalent in magnitude in each case.

Those fish lacking a gas-filled chamber are likely to be less vulnerable to trauma from pressure changes compared with fish with a gas-filled space. Some flatfishes, all elasmobranchs (sharks, skates and rays), jawless fish (lampreys and hagfishes), some gobies, some bottom-living and inter-tidal fishes, and some mackerel, tuna and other pelagic fishes lack swim bladders. Experimental work on the hearing of some of these species shows that they do not detect sound pressure, but their auditory system responds to particle motion (e.g., Chapman and Sand, 1974; Hawkins and MacLennan, 1976; Casper and Mann, 2007a, b, 2009). In investigating hearing and behaviour in these species it is important to measure the particle motion as well as the sound pressure. It is also important to bear in mind that damage to the otolith organs may result from exposure to very high levels of particle motion – although this is a neglected area.

Eggs and larvae require special consideration; primarily because of their small size and physical fragility. However, there are very few data on the effects of noise on fish eggs and larvae (Jorgensen *et al.* 2005; Banner and Hyatt, 1973; Kostyuchenko, 1973; Govoni *et al.*, 2003, 2008). As we have seen for the larvae of aquatic invertebrates, there is some evidence that eggs and larvae may be susceptible to damage from very high-level sounds. There is some evidence that vibrations from explosive and other sources may affect incubating eggs of salmonid fishes and regulatory measures are in place in Canada where peak particle velocity greater than 13 mm.s^{-1} in a salmon spawning bed during the period of egg incubation is not allowed. Concern for eggs and especially for larvae containing gas bubbles may be more related to barotrauma than hearing. Zeddies and Fay (2005) have determined startle thresholds for fish larvae, and Higgs *et al.* (2002) have examined developmental changes in fish hearing.

Concern for eggs and especially for larvae containing gas bubbles may be more related to barotrauma (see below) than hearing. Eggs do not contain gas cavities, but swim bladders may develop at the larval stage and may render larvae vulnerable to barotrauma.

In considering the impact of anthropogenic sounds upon fish it is useful to place fish into different functional categories, depending on their structure and degree of hearing specialisation. Fish may tentatively be separated into:

- Fish with no swim bladder or other gas volume (particle motion detectors)
- Fish with a swim bladder or other gas volume, and therefore susceptible to barotrauma, but where the organ is not involved in hearing (particle motion detectors)
- Fish with a swim bladder or other gas volume, and therefore susceptible to barotrauma, where the organ is also involved in hearing (sound pressure and particle motion detectors).

7.5.1 Death and Injury

Lethal and direct physical injury from an underwater transient pressure wave are related to the peak pressure level, rise time and duration that the peak pressure acts on the body (usually measured by the impulse of the blast wave). The criteria that have been developed for assessing gross injury of this type are based on data from blast injury at close range to explosives. Injury has been related both to the incident peak positive pressure of the wave and to the impulse. To obtain an effective measure of the impulse of the wave, an estimate of the effective duration must be made by integrating over the waveform. A number of different techniques for assessing the duration of an impulsive waveform are described by Hamernik and Hsueh (1991) based on the studies by Coles *et al* (1968), Pfander *et al* (1980) and Smoorenburg (1982). The measure of impulse will therefore depend upon which technique is applied.

There is currently very limited data relating to fish kill from piling (Hastings *et al*, 2005), although the study by Caltrans (2001) during impact piling operations on the San Francisco– Oakland Bay Bridge indicated fish kill to a range of approximately 50 m. By fitting Abbot’s results to a spreading model, it is possible to estimate the Source Level of the piling to be about 242 dB re 1 µPa @ 1 metre. This equates to fish being killed when the peak pressure level exceeds about 208 dB re. 1 µPa, which corresponds to an interim criterion that was proposed by Popper et al (2006).

High levels of underwater sound have been demonstrated to be lethal to fish. Fish mortality has often been observed at close range during exposure to explosions (e.g. Aplin, 1947; Yelverton *et al.*, 1975; Nedwell *et al.*, 2004; Govoni *et al.*, 2008) and to pile driving (Caltrans, 2004). Studies carried out on the effects of blast on various species of fish by Yelverton *et al.* (1975) (also reproduced in Richardson *et al.,* 1995) demonstrated that mortality rates were related to body mass and magnitude of the impulsive wave. The results show that a 50% mortality rate would occur in fish weighing 1kg when exposed to an impulse of about 340 Pa.s. According to this model, to cause the same mortality rate in fish weighing 10 kg they would have to be exposed to an impulse of approximately 800 Pa.s. The work indicates that there are levels below which a sound would cease to be lethal to a fish of a certain weight. While this sound level may not cause the swim bladder rupture or kidney and liver damage that may be seen after lethal doses of sound, there may still be considerable tissue damage to susceptible organs such as the lungs, gastro-intestinal tract or eyes and hence possible long term survival implications.

7.5.2 Hearing impairment

Exposure to high-level sounds has been shown to induce hearing loss in a number of fishes (Amoser and Ladich, 2003; McCauley *et al.*, 2003; Popper *et al.*, 2005; Scholik and Yan 2001; Smith *et al.* 2004, Popper and Hastings, 2009) (Table 7-1).

Permanent threshold shift (PTS) is a permanent loss of hearing, demonstrated either by a lasting rise in threshold determined by a behavioural technique, or as a lasting reduction in the auditory evoked potential in response to a given sound. PTS is often a consequence of the death of the sensory hair cells of the auditory epithelia of the ear, but it can also result from damage to other auditory tissues. Temporary threshold shift (TTS), by contrast, is a temporary hearing impairment of variable duration and magnitude. Normal hearing ability may return over a period of minutes to days, or even months, depending on many factors, including the intensity and duration of exposure (e.g., Scholick and Yan, 2001, 2002; Smith *et al.* 2004a, b, 206; Popper & Clarke, 1976; Smith *et al.*, 2004; Smith *et al.*, 2006; Scholik and Yan, 2001). It has been suggested that TTS itself is not evidence of injury (Richardson *et al.*, 1995; Smith *et al.* 2006), although it may result from injury. During a period of TTS the survival of the animal may be at risk. Its ability to communicate may be impaired, it may be unable to respond to predators, and its ability to seek out prey may be compromised.

TTS in fish is usually detected by the auditory evoked potential (AEP) method. Scholik and Yan (2000) tested the effect of white noise at 142 dB filtered to 0.3 - 4 kHz on goldfish and minnows. This produced a threshold shift of approximately 10 dB up to 2 kHz after two hours of exposure, and half the threshold shift at 1 hour. At their most sensitive thresholds this equates to a level of 77 dB_{ht}(*Carassius auratus auratus)* for goldfish and 66 dB_{ht} for minnows.

In the US, The current criteria in use for onset of physiological effects on fish are interim criteria developed on the U.S. west coast by the Fisheries Hydroacoustics Working Group (see http://www.dot.ca.gov/hq/env/bio/files/fhwgcriteria_agree.pdf). Those interim criteria are:

Peak SPL	206 decibels dB re 1 μPa
SEL_{cum}	187 dB re $1\mu Pa^2 \cdot s$ for fishes above 2 grams (0.07 ounces).
SEL_{cum}	183 dB re $1\mu Pa^2 \cdot s$ for fishes below 2 grams (0.07 ounces).

Guidance in the use of these criteria is described in Caltrans (2009).

Recent controlled studies on the effects of simulated pile driving on Chinook salmon (Halvorsen et al. 2011) and other species have suggested that onset of physiological response occurs at least 16 dB above the levels being used in the current interim criteria, and are probably over 23 dB higher (SEL_{cum}).

Paper	**Experiment**	**Source level**	**Outcome**	**Estimated level**	**Range (m)**	**Method of Calculation**	**Remarks**
Scholik and Yan 2000	White noise filtered to 0.3 to 4kHz on minnows for 24h. Thresholds measured using ABR method.	142 dB	Fish showed a threshold shift of approx 10 dB up to 2 kHz. This shift was achieved after only 2 hours of exposure. 1 hour's exposure gave approx half the threshold shift.	65 dB_{ht}	1	Measured level, subtracted threshold at most sensitive frequency.	1m range assumed, no mention of size of tank in paper.
Smith *et al* 2004	White noise on goldfish and tilapia for up to 28 days. Threshold measured using ABR method.	110 to 160 dB	Tilapia had almost no threshold shift. Goldfish exhibited varying degrees of threshold shift; the maximum was approx 20 dB for frequencies 100 Hz to 2 kHz.	35-85dB_{ht}	1	Measured level, subtracted threshold at most sensitive frequency.	1m range assumed, no mention of size of tank in paper.
Popper *et al* 2005	Seismics on various types of fish. Thresholds tested after exposure via ABR. Airguns first at 17m from fish tanks, then 13m.	234 dB (measured level at 13m + 20logR)	Broad whitefish: thresholds increased by approx 20 dB post exposure. Northern Pike - thresholds increased by approx 10 dB, biggest change at 400 Hz. Lake chub - Experienced large threshold shifts up to 35 dB at 200 Hz.	Broad W:95 dB_{ht}, Nthern Pike: 110 dB_{ht}, Lake Chubb : 112 dB_{ht}	13-17	Measured level minus threshold at most sensitive frequency	
Enger *et al* 1993	tones on salmon	15 dB // 1 m/s2					Insufficient data for analysis

Table 7-1: Summary of the available data on TTS onset in fish

7.5.3 Stress

Animals may show no overt sign of responding to an environmental stimulus like a chemical contaminant or an increase in noise, but may nonetheless show physiological changes. They may for example show changes in heart rate or breathing rhythm, or levels of particular hormones in the bloodstream and tissues may change. This response is often termed stress. This word is used in a casual way, however. There is a need for consistency and clarity in describing stress. Some research is taking place on this topic, including examination of the relationship between behavioural change and its physiological manifestations. However, stress is often a normal part of life, integral to stimulating and maintaining healthy neuro-endocrine responses and immune system activity. Predicting when stress becomes excessive or damaging to the animal remains difficult. Moreover the very acts of capture, handling and the taking of samples from the fish may induce the actual response that is being monitored.

Stress can be energetically costly either through the relocation of energy or through changes in whole organism metabolic rates (Wendelaar Bonga, 1997). Stressed fish have higher demands for available dietary energy, which is accompanied by an increase in metabolic rate (Barton and Iwama, 1991).

The response of a fish stressed by noise may be manifested as reduced appetite, feeding activity, and food intake (Wendelaar Bonga, 1981). It has been suggested that growth rates, feed conversion efficiency, and survival can be negatively affected by chronic exposure to noise (Wysocki *et al.*, 2007; Davidson *et al.*, 2009). Wysocki *et al.* (2007) showed that rainbow trout growth, survival, and disease responsiveness were not adversely affected by long-term exposure to noise levels at levels of 115, 130, or 150 dB re 1 µPa. However, decreased feeding and slightly slower growth rates were recorded at the onset of noise exposure. Davidson *et al.* (2009) showed that rainbow trout growth and survival were not affected over the long term by noise (117-149 dB re 1 µPa). However, analysis of growth rates, feed conversion, weight and length of individual fish indicated that rainbow trout exposed to 149 dB re 1 µPa tanks grew slower during the first month of noise exposure.

Cortisol is one of the primary stress hormones secreted by fish in response to a stressor (Wendelaar Bonga, 1997) and is the most commonly reported hormonal indicator of stress (Barton and Iwama, 1991; Wendelaar Bonga, 1997). A rise of cortisol in response to stressors such as crowding, netting, or handling is well documented. Recently, an elevation of cortisol has been attributed to noise-induced stress (Smith *et al.*, 2004 Wysocki *et al.*, 2006). It is evident that anthropogenic noise can elicit significant elevation of plasma cortisol levels (Smith *et al.*, 2004 Wysocki *et al.*, 2006). These studies suggest that the reaction occurs very quickly and depends on the type of noise. In Wysocki *et al.,* 2006, three freshwater fishes exposed to ship noise (153 dB re 1 uPa) for 30 min showed increased secretion of cortisol in the holding water regardless of their hearing capabilities. However, none of the three species responded with an increase in water cortisol level when exposed to 30 min of Gaussian noise (mean 150 dB re 1 uPa). It was speculated that the secretion of cortisol was more likely to occur in response to noise that was variable in level, time, and frequency composition (such as boat noise) compared with continuous noise. Smith *et al.* (2004) found that plasma cortisol levels in goldfish increased significantly (three-fold) after only 10 min of exposure to white noise (160-170 dB re 1 uPa) and then decreased to control levels after 60 min. No trend in cortisol was evident in a long-term experiment. It appears that noise exposure has a short-lived effect on the primary physiological response in fish and then cortisol levels returns to pre-noise exposure levels over time. Physiological adaptation to a continuous stressor is commonly found in fishes (Schreck, 2000).

It is clear that fish may experience acute effects to noise but it is much less certain that it results in long-term chronic effects. It is the chronic effects, though, that may be more significant. The term allostatic load is applied to the physiological consequences of chronic exposure to fluctuating or heightened neural or neuroendocrine response that results from repeated or chronic stress. Normally, the body's stress response, essential for managing acute threats, is essential for adaptation, maintenance of homeostasis, and survival.

However, repeated responses may damage the body in the long term (creating the allostatic load). The effects can be measured as chemical imbalances in the autonomic nervous system, central nervous system, neuroendocrine, and immune systems as well as changes in growth rate, perturbations in diurnal rhythms, and changes in behaviour. These changes may introduce risks to individual fitness including loss in reproductive capacity. We must therefore distinguish between normal or tolerable variations in response to environmental stress from those changes that will have consequences for survival and reproduction. At present, critical examination of these long-term changes in fish as a result of noise exposure has been lacking.

7.5.4 Behavioural responses

There have been relatively few detailed studies of the behaviour of fish in response to sounds, perhaps because experiments are difficult to perform under representative conditions in the field. Studies of fish behaviour in response to sounds are difficult to perform, especially in the field. Many factors may influence the results, and a careful approach must be adopted, based on well-designed experiments. There are many advantages to carrying out experiments on fish under carefully controlled conditions; i.e. in tanks in the laboratory or in cages in the wild. A fixed installation at a carefully chosen location with measuring instruments precisely positioned can yield precise information on responses to sound. Detailed observations can also be made of the behaviour of the captive animals by means of underwater cameras or other observation systems including acoustic tracking.

It has become increasingly evident, however, that the behaviour of many fish in tanks and enclosures is distorted. It may be nothing like the behaviour they show in the wild and often, their repertoire is severely restricted in captivity. They will not feed, or they will not spawn. Fish unaccustomed to being enclosed may damage themselves against the sides of tanks or through abrasion with netting. They become habituated to the repeated presentation of sounds and cease responding. Background noise levels may be high from pumps and other machinery and detection of some of the sounds presented to them, including the sounds they make themselves, may be impaired or masked. Therefore, current laboratory evidence must be regarded with extreme caution.

Where it has been possible to observe the behaviour of wild fish in the presence of human-generated sounds a range of responses have been observed. Some fish have shown changes in swimming behaviour and orientation, including startle reactions (Wardle *et al.* 2001). In some cases those startle reactions are brief and transient, and the response may habituate with repeated presentation of the same sound. Sound can also result in more pronounced responses including changes in swimming behaviour, schooling and distribution (Pearson *et al.* 1992). The horizontal and vertical distributions of both pelagic and ground fish have changed during and after airgun operations (Dalen & Knutsen, 1987; Engås *et al.* 1996; Slotte *et al.* 2004). In some circumstances, fish may react to approaching ships, leading to concern amongst fisheries scientists that vessel avoidance will bias stock-assessment surveys (Mitson and Knudsen, 2003). Fish can respond to approaching vessels by diving towards the seafloor or by moving horizontally out of the vessel's path, with reactions often initiated well before the vessel reaches the fish (Vabø *et al.* 2004; Ona *et al.*, 2007). Engås *et al* (1993) detailed an experiment using an array of seismic airguns with a source level of 250 dB to test the avoidance reactions of cod and haddock. Acoustic mapping of the density of fish in the surrounding area was performed before and after the seismic shooting. The backscatter from the fish was found to significantly reduce up to a distance of 5 nautical miles around the ship. This 5 nautical mile limit was found to correspond to a level of 101 dB_{ht}(*Gadus morhua)* calculated using an estimation of level with range from the authors' data. Engas (1996) also details a similar experiment but does not detail the distance to which the fish were affected and so is of limited value.

Reductions in catches of fish have been observed in commercial line and trawl fisheries both during and after seismic surveys (Løkkeborg and Soldal 1993; Engås *et al.* 1996; Skalski *et al.* 1992). Paradoxically, increased catch rates have been observed for gillnets fished in seismic survey areas (Løkkeborg *et al.* 2010). This result has been explained by postulating that the fish increase their swimming activity in response to the air-gun sounds, thus making the fish more vulnerable to capture by gillnets. There are, however, very few of these studies to draw definitive conclusions at this moment. Future studies should be designed in a way that makes it possible to differentiate between effects of seismic shooting, the mere presence of survey vessels, and other more natural factors (Slotte *et al.*, 2004).

For fish, it has not so far been possible to draw up dose response curves – to scale the magnitude of the response to the level and characteristics of the sound. Pearson *et al.* (1992) have drawn a distinction between involuntary startle reactions; small changes in behaviour; and outright avoidance, in an attempt to separate inconsequential behaviour from significant responses.

Data on fish avoidance to underwater sound is also available from the use of acoustic deterrent devices, developed to reduce fish kill at power station water inlets. Measurements undertaken at the Doel power station in Belgium (Maes *et al.,* 2004) and at the Wolff Hatchery, Illinois, USA (Nedwell *et al.,* 2005a), have shown that the efficiency (ability of the underwater sound system to repel fish) is related to the level of the sound above the hearing threshold of the respective species. The acoustic fish deflection system was made up of a number of sound projectors producing continuous wave sound at frequencies from 20 to 600 Hz, and at a nominal Source Level of 174 dB re 1 µPa @ 1 m, per projector. For fish species that are comparatively sensitive to underwater sound, such as the herring (*Clupea harengus)* and the sprat (*Sprattus sprattus)*, average intake rates decreased by 94.7% and 87.9% respectively (Maes *et al.,* 2004), indicating that fish were avoiding the high sound field (at a level of 83dB$_{ht}$) surrounding the power station water inlet. The data indicated that for the fish species that were considered less sensitive to underwater sound (based on hearing threshold data) only a moderate response to the sound was demonstrated. For the flatfish species the efficiency for the flounder (*Platichthys flesus)* was at 37% and for the sole (*Solea solea)* was at 47%.

In assessing the behavioural responses of fish we must also take into account the range of sounds that they can actually hear.

If the level of sound is sufficiently high on the dB$_{ht}$(*Species*) scale it is likely that an avoidance reaction will occur. Without knowing species-specific and age-specific behavioural thresholds this appears to be a reasonable assumption. The response from a species will be probabilistic in nature (e.g. at 75 dB$_{ht}$(*Species*) one individual from a species may react whereas another individual may not and may also vary depending upon the type of signal. A level of 0 dB$_{ht}$(*Species*) represents a sound that is at the hearing threshold for that species and is therefore at a level at which sound will start to be 'heard'. At this and lower perceived sound levels no response occurs as the receptor cannot hear the sound.

Currently, on the basis of available measurements of fish avoidance of noise (Nedwell *et al.* 2005a, Maes *et al.* 2004), the following assessment criteria have been suggested for assessing the potential impact of the underwater noise and vibration on marine species:

- 90 dB$_{ht}$(*Species*) – Strong avoidance reaction by the majority of individuals;
- 0–50 dB$_{ht}$(*Species*) – Low likelihood of disturbance.

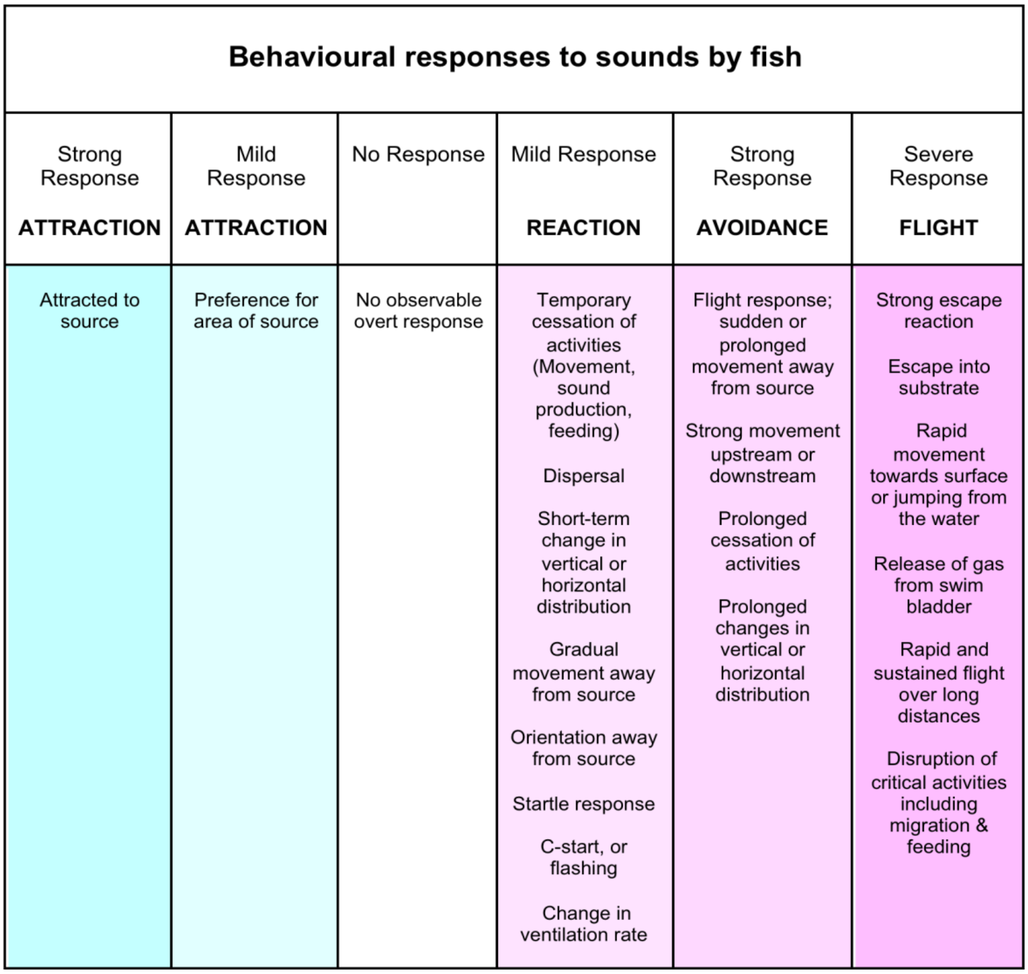
It should be noted that in some cases a level of 50 dB$_{ht}$(*Species*) is preferred by the Environment Agency as a criterion for a level at which an avoidance effect may occur (Nedwell, 2004). The use of this measure has typically been for endangered species in quiet riverine environments, where it represents a highly precautionary criterion. It was chosen as a result of the work of Nedwell (2004) as a level at which less than 50% of individuals would react at all to noise.

Others have suggested that sound pressure levels of 150 or 160 dB re 1 µPa @ 1 m should be regarded as those at which avoidance behaviour is triggered. Although it is more cautious, the assumption has also been made that fish will react significantly to ship noise that is 30 dB above the fish's hearing threshold (Mitson, 1995).

In general, it is appropriate to search for clear-cut responses with definable consequences, which can readily be described and measured. Examples of different behavioural responses are shown in Table 7-2 below. There is an argument, however, for not simply describing the movements or overt behaviour shown by the fish but also investigating the consequences. Does the reaction affect the time allocated by the fish to different activities; perhaps driving the fish to seek shelter rather than feeding or defending a territory? What is the impact upon the time devoted to different activities – upon the time budget? Does the reaction have a significant effect upon the animal's energy budget, impairing its ability to undertake other activities?

We must also consider the relevance of particular behavioural reactions. An action or activity becomes biologically significant to an individual animal when it affects the ability of the animal to grow, survive, and reproduce. Such effects may have consequences at the population-level and may affect the viability of the species (NRC, 2005).

Thus, an important question to ask when behavioural responses have been observed is whether that response is likely to be costly to the fish in terms of preventing other biologically important activities, causing energy loss or risk to fitness. Is it only a transient and unimportant change in behaviour? Or will it result in longer-term impairment of survival? Has the behaviour resulted in the permanent displacement of the fish? Has the fish been denied access to a key habitat? Will feeding and growth be impaired? Will migration be disrupted? Will the change in behaviour result in reduced growth or impaired reproduction? Does it result in death in the longer term? Many of these questions may be difficult to answer, especially because population effects may be separated in time and space from exposure to sound.



Behavioural responses to sounds by fish

Strong Response **ATTRACTION**	Mild Response **ATTRACTION**	No Response	Mild Response **REACTION**	Strong Response **AVOIDANCE**	Severe Response **FLIGHT**
Attracted to source	Preference for area of source	No observable overt response	Temporary cessation of activities (Movement, sound production, feeding) Dispersal Short-term change in vertical or horizontal distribution Gradual movement away from source Orientation away from source Startle response C-start, or flashing Change in ventilation rate	Flight response; sudden or prolonged movement away from source Strong movement upstream or downstream Prolonged cessation of activities Prolonged changes in vertical or horizontal distribution	Strong escape reaction Escape into substrate Rapid movement towards surface or jumping from the water Release of gas from swim bladder Rapid and sustained flight over long distances Disruption of critical activities including migration & feeding

Table 7-2: Behavioural responses to sounds in fish.

7.5.5 Masking

Masking is a particular form of hearing impairment. In essence, during masking the presence of sounds above the hearing threshold of the species interfere with the detection of sounds that are especially important to the survival and fitness of the animal (see Section 6). Where high levels of noise are present, whether natural or generated by human sources, sounds are more difficult to detect than they are under quiet background conditions. Masking generally occurs where the background noise reaches a level where it can be detected by the animal. For the more sensitive fishes, masking occurs at relatively low background levels in the presence of natural ambient noise alone. Chapman and Hawkins (1973) showed that the hearing thresholds for cod *Gadus morhua* to pure tones varied from hour to hour as the level of ambient noise in a sea loch changed with weather conditions.

Masking depends on several factors, including signal duration, the spectral features of the sound to be detected, the location of the sound source relative to any masking sources, and the level and spectral features of the masking sounds.

There are a number of consequences arising from masking. There may be a loss of ability by the fish to detect sounds that it can hear in the absence of the interfering background. In addition the range over which the fish can detect sounds may diminish. The ability of the fish to identify or discriminate particular sounds may deteriorate. Moreover, the ability of the fish to determine the direction of a sound may be impaired. In general, continuous noise is more effective at masking sounds than interrupted or intermittent noise. However, at a distance intermittent noise may become more continuous in its characteristics as a result of propagation effects.

Although masking has been demonstrated for a number of fish species it has usually been examined in experiments where the ability to detect pure tones has been measured in the presence of white noise. Fishes examined have been the goldfish (Fay 1974), marine catfish (Tavolga 1982), African mouthbreeder (Tavolga 1974), pinfish (Tavolga 1974), and the cod (Buerkle, 1968). Of most interest are experiments carried out in the sea with both controlled noise bands and actual sea noise with cod (Chapman and Hawkins 1973; Hawkins and Chapman, 1975; Chapman and Johnstone, 1974; Hawkins and Sand, 1977); and salmon (Hawkins and Johnstone, 1978).

In general, signal to noise ratios for pure tones (measured against the spectrum level of ambient noise) range from about 13 dB at low frequencies, to over 25 dB at higher frequencies. For the goldfish (Fay 1974), the function is approximately linear with log frequency from 100 to 1200 Hz. The data for the other species are more variable, but generally increase with frequency at about 3 dB per octave (Fay, 2011).

The effective bandwidths and shapes of the detection filters for pure tones have been measured for several species using different masking techniques. In general, the filter shapes are approximately Gaussian-shaped; only the noise frequency components immediately on either side of the signal frequency are effective in causing masking (Hawkins and Chapman, 1975).

It is likely that filtering within the fish auditory system can take place in the time domain as well as the frequency domain. Many of the sounds made by fish are repeated pulses of sound, and it is likely that the auditory system will be capable of discriminating such sounds against natural noise backgrounds. The masking effects of man-made noise such as ship noise, pile driving, seismic shooting, sonars, etc. has not been studied and remains a topic for future research.

An interesting question is whether fish can compensate for man-made noise through the Lombard effect. Many animals raise their voices, or change the characteristics of their calls, in the presence of high levels of ambient noise. There is so far no evidence of this occurring in fish, which may be more limited in their abilities to adapt the characteristics of their calls. The use of sounds by fish during courtship and spawning, and the prevalence of choruses of spawning fish, may be especially vulnerable to human-generated noise.

7.5.6 Effects of blasting

The total blast signature covers a wide range of frequencies from as low as 80 Hz, to in excess of 100 kHz. A number of studies have been carried out on the effects of explosions, especially looking at death as a result of exposure. Explosives produce very high level pressure impulses and very steep rise times compared to air guns and pile drivers. Fish mortality has often been observed at close range (e.g. Aplin, 1947; Yelverton *et al.*, 1975; Nedwell *et al.*, 2004; Govoni *et al.*, 2008). Yelverton *et al.* (1975) exposed fish of different sizes, from several different species, all with swim bladders, to explosions. Many of the fish died. The results from exposure, expressed in terms of peak explosive pressure, showed a logarithmic relationship between the LD50 (the level at which half the fish died) and fish weight. If these peak pressures are converted to SEL, on the assumption of a particular impulse shape, values range from 183 to 213 dB re 1 µPa^2-s, with the increase occurring for fishes of greater weight (Yelverton *et al.* 1975; Carlson *et al.*, 2007; Hastings and Popper, 2005). These values should be treated with caution since they were derived using a particular explosive, Pentolite, with a rise time that may differ from that of other explosives. Keevin *et al.* (2002) have pointed out that depth and position of the fish relative to the source is also an important factor in producing an effect from explosions. The evidence from these limited experiments suggests that exposure to a single explosion may damage and kill fish, with smaller fish (and presumably fish larvae) affected at lower source levels and hence at longer distances (Table 7-3).

Filter	**Source Level (dB/dB$_{ht}$ Peak to peak)**	**N**	**α**	**Range to 90 dB$_{ht}$ (meters)**
Unweighted	265	27	0.003	N/A
Herring	190	29	0.004	2000
Cod	182	27	0.007	2000
Dab	165	25	0.008	700
Generic fish	190	25	0.008	3000

Table 7-3: Impact ranges produced during blasting in a harbour

The transmission of compression waves, shear waves and interface waves from land into water is well established and it is especially important to monitor both sound pressure and particle motion levels transmitted into water from explosions in this way. Unfortunately there is a complete lack of information on the effects of very high particle motion levels upon fish.

The blasting produces extremely high levels of underwater noise, and the broadband noise gives a large source level for every species of fish. Although the source levels produced by the blasting are significantly higher than any other source of underwater noise analysed in this review, the impact ranges are smaller than those produced by piling for example. This may be because of the shallow water in the harbor and surrounding area. Blasting is frequency used to clear harbours but has little use in construction at sea, and is therefore not thought to be as large a disturbance to fish as other forms of anthropogenic underwater noise such as piling.

7.5.7 Effects of piling noise

There are some data on the effects of pile driving on fish but few are found within peer-reviewed literature. The potential effects of pile driving sounds are complicated by the type of pile (steel vs. concrete vs. wood), distance of animals from the source, duration of exposure, number of “strikes” to which fish were exposed, cumulative effects from multiple strikes, and whether the piles were driven by hammers or by vibropiling systems. Hastings and Popper (2005) and by Popper and Hastings (2009a, b) have discussed critically the effects of pile driving upon fish. Although there are few data, there has been considerable discussion by regulators on noise exposure criteria for preventing harm to fishes (Popper *et al.*, 2005; Carlson *et al.*, 2007; Stadler and Woodbury, 2009; Woodbury and Stadler, 2007).

Carlson *et al.* (2007) proposed a set of hypothetical maximum SEL's for salmonids correlated with fish mass and based upon the data from explosions in Yelverton (1975) (see also Hastings and Popper, 2005). Subsequently, a cSEL of 187 dB re 1 uPa^2-s was proposed for the US west coast. More recent studies upon salmonids, have demonstrated that there is no mortality or physiological effects at 194 dB re 1 uPa^2-s cSEL (Caltrans, 2010a, b) up to perhaps 203 dB re 1 uPa^2-s cSEL (Ruggerone *et al.*, 200x). Current quantitative studies of simulated pile driving on Chinook salmon show that there is no mortality or tissue damage at 207 dB re 1 uPa^2-s cSEL, although tissue damage is evident at higher levels (Halvorsen *et al.*, 2011). Additional data suggest tissue damage onset occurs at rather lower levels for striped bass (Casper *et al.*, 2011).

There are data to show that fish within a few meters of a driving of a large pile may be killed (Caltrans, 2004). At greater distances, data from caged fish show no mortality and no damage (Abbott *et al.*, 2005; Nedwell *et al.*, 2006; Caltrans 2010a, b; Ruggerone *et al* 200X). In the one carefully controlled study of injury to fish, no pathology was shown by fish after exposure to pile driving (Abbott *et al.* 2005).

Feist *et al.* (1992) and Anderson (1991) reported that fish might move away from a pile-driving source. However, there is almost a total lack of information on the behaviour shown by fish exposed to pile driving

Eggs and larvae that are buried in the substratum or drifting with the current may be exposed to pile driving. However, no data are available on the effects of exposure.

Results from measurements of impact piling noise at the North Hoyle Offshore Wind Farm are presented in Nedwell *et al.* (2003a). During the installation of steel monopiles at North Hoyle harder rock was encountered underneath the initial sediment phase. Rock socket drilling was required during installation of all of the piles, and measurements of underwater noise during drilling activity were carried out at ranges of between 100 m and 9 km. Analysis of the data indicated a series of strong tonal peaks in frequency spectra associated with the drilling activity at 125, 250 and 375 Hz that were between 5 – 15 dB above background sound spectral levels.

Table 7-4 shows the impact ranges produced by the piling at Burbo Bank for a variety of filters. N and α refer to the transmission and absorption losses respectively. The filters used include the audiogram of herring, a hearing specialist, the cod, another hearing specialist and the dab, a hearing generalist, as well as the generic fish filter.

Filter	**Source Level (dB/dB$_{ht}$ peak to peak)**	**N**	**α**	**Range to 90 dB$_{ht}$ (meters)**
Unweighted	250	23	0.005	N/A
Herring	170	22	0.006	3000
Cod	155	17	0.003	500
Dab	135	17	0.003	400
Generic fish	182	22	0.006	6000

Table 7-4: Impact ranges of piling the 4.7 m pile at Burbo Bank for a variety of filters

Based on the data analysed here, piling at this location would be predicted to cause a strong behavior avoidance reaction in herring to a distance of 3 km. As a consequence of the wider, more generalized filters, impact ranges for the generic fish filter is larger than the impact range for herring. Piling operations undertaken in differing conditions such as when using a different pile size, more powerful hammer or in different water depths are likely to produce significantly differing sound levels (Nedwell *et al*, 2011) and so the impact ranges shown in table 7-4 should not be taken as representative of piling noise as a whole.

7.5.8 Effects of seismic airguns

Particular attention has been paid to the effects of seismic air guns and seismic surveys upon fish. Fish with swim bladders have not shown mortality (Popper *et al.*, 2007; Hastings *et al.*, 2008; McCauley *et al.*, 2011), and since any damage would be greatest in fish with a swim bladder (as with explosives), mortality of fish without a swim bladder seems unlikely.

Examination of the sensory cells of the inner ears after exposure to seismic air guns have shown loss of cells in one species that has a swim bladder distant from the ear (pink snapper – McCauley *et al.* 2003) but paradoxically not in several other species that have swim bladders closer to the ear (Song *et al.* 2008; McCauley *et al.*, 2011). Pink snapper showed no evidence for recovery 58 days after exposure (McCauley *et al.*, 2003). Evidently the effects of air guns on the ear differ for different species, and a number of reasons for these differences have been proposed (Popper *et al.* 2005; Popper and Hastings 2009a, b) including use of different sources, different water depths, and different species. More data are badly needed.

There are few data on damage to other tissues. Popper *et al.* (2005) examined the body cavity of several freshwater fishes with swim bladders after exposure to an air gun in a river and found no evidence of bleeding or swim bladder damage. Data are needed for more species, for controlled exposure to seismic sources.

The effects of seismic air guns on hearing were examined by Popper *et al.* (2005) who showed TTS in a fish that had a connection between the swim bladder and inner ear and in one of two other species that did not have connections. There was recovery within 18 hours of exposure in all cases. Hastings *et al.* (2008) examined hearing using AEP in reef fishes exposed to a seismic survey with a full air-gun array in the Indian Ocean. They found no hearing loss following sound exposures up to 190 dB re 1 µPa2-s cumulative SEL in one species where the swim bladder connected to the ear and in three species where it did not. There are no data on masking by seismic sources. Indeed there is an acute paucity of data on masking by repetitive sounds.

A number of studies have demonstrated that exposure to seismic surveys has an impact on fish catch, presumably as a result of changes in fish behaviour and distribution (Engås *et al.* 1996; Engås and Løkkeborg 2002; Slotte *et al.* 2004, Skalski *et al.* 1992; Pearson *et al.* 1992; Løkkeborg *et al.* 2010). Handegard (2010) has summarized the results of two sets of experiments of the effects of seismic shooting on fish catch in Norway (Engas *et al.*, 1996, and Løkkeborg *et al.*, 2009). In the earlier observations, trawl and long-line catches of cod and haddock declined by about 40%-50% following 5 days of shooting. In a more recent experiment, long-line catches declined, but gill net catches increased. The calculated exposure levels for a 1-day daily dose ranged between 156 dB for the Engas *et al.* (1996) experiment and 164 dB SEL for the Løkkeborg (2009) experiment (Handegard, 2010). The effect of seismic shooting on fish catch may depend on the fishing method employed. Thus trawl net and long line catches may decline as a result of fish removing themselves from the area, while gill net catches may increase as a result of the increased activity of fish.

Studies on caged sandeels (*Ammodytes marinus*), a species without a swim bladder, revealed distinct but minor reactions to seismic shooting (Hassel *et al.* 2004; Skaar 2004). No increased mortality was observed in comparison with controls. Dalen & Knutsen (1987) observed that the distribution of fish at 100 – 300 meters depth changed along the course lines of a seismic vessel towing an airgun array. The average measured echo abundance, which represented the quantity of fish, was reduced by 36 % after the shooting, compared with the measured values prior to shooting. Slotte *et al.* (2004) also observed that fish (herring and blue whiting moved out of an area where seismic shooting occurred or went into deeper water (10-50 m deeper). Wardle *et al.* (2001) observed small changes in the position of pollack in response to the firing of an air gun. Startle responses observed from saithe were elicited by the visual stimulus associated with the air gun shots.

Studies on the eggs and larvae of several fish species suggest that they are likely to suffer mortality and tissue damage close to air guns (Kostyvchenko (1973; Booman *et al.*, 1996). However, Saetre and Ona (1996) concluded that mortality rates caused by exposure to air gun sounds were so low compared to natural mortality that the impact from seismic surveys must be regarded as insignificant.

Table 7-5 shows the impact ranges of a single seismic airgun described in section 6-4.

Filter	**Source Level (dB/dB$_{ht}$ Peak to peak)**	**N**	**α**	**Range to 90 dB$_{ht}$ (meters)**
Unweighted	223	17	0.001	N/A
Herring	135	11	0.003	3000
Cod	132	11	0.003	2000
Dab	115	11	0.003	200
Generic fish	136	11	0.003	3000

Table 7-5: Impact ranges of Bolt Model 1900LL-X seismic airgun firings

The single seismic airgun produces a large impact range for most fish extending up to 3 km in the general case. In comparison, the impact range of dab is small, but would still exclude fish from an area of over 100,000 m^2.

7.5.9 Effects of wind turbine noise

The sound levels produced my most of the turbines are of such a level that they are unlikely to even be audible to some species of fish such as dab and salmon (Thomsen et al., 2006).

During investigations by Westerberg (1994,2000) results were obtained at the Svante wind farm in Sweden, in this case with eels. The eels did not change their swimming patter when passing a 220 kW turbine at a distance of 500 m. In fact due to the reef effect, inoperational turbines seemed to attract cod at roach as the catch rates of these fish were significantly higher less than 100 m from the turbine compared to catch rates at 200 m and at 800 m. However, when the turbines were activated catch rates decreased by a factor of 2 within 100 m from the turbines. This is contrary to findings by Wilhelmsson *et* al (2005), who found that fish abundance was greated in the vicinity of the turbines than in surrounding areas.

Wahlberg and Westerberg (2005) found that although detection distances of wind turbines by fish may be up to 25 km, it was estimated that fish will only be scared away from turbines at distance of less than 4 m, and even then only at windspeeds of over 13 m/s.

Transect measurements have been taken from a 3.6 MW turbine at the edge of a round 1 windfarm and used to determine its source level. The turbine was turning at roughly 1 revolution every 3 seconds caused by the wind blowing at a steady 7 m/s. The results of these measurements are shown in Table 7-6.

Filter	Source Level (dB/dB$_{ht}$ RMS)	Range to 90 dB$_{ht}$ (meters)
Unweighted	147 dB	N/A
Herring	80 dB$_{ht}$	0
Cod	85 dB$_{ht}$	0
Dab	54 dB$_{ht}$	0
Generic fish	86 dB$_{ht}$	0

Table 7-6: Impact from an operational wind turbine

Compared to other sources of underwater noise discussed in this report, operational turbine noise is one of the quietest, as it did not produce level of over 90 dB$_{ht}$ for any species studied. Higher windspeeds may produce higher levels of noise underwater but it is unlikely that they would become high enough to produce siginificant levels of disturbance to fish.

7.5.10 Effects of dredger noise

Marine aggregate extraction is now commonplace, and with pressures to reduce extraction on land there may be increased extraction from the sea. In 2009, the total dredged area in the seas around the UK alone was 123.6 km^2 with more than 20 million tonnes of sand and gravel extracted. A key finding of a recent study of aggregate dredging (Robinson *et al.* (2011) is that the noise output of dredging vessels at frequencies below 500 Hz is similar to a ‘noisy merchant vessel’ at moderate speed and is substantially quieter in terms of acoustic energy output than some other anthropogenic noise sources such as seismic air guns and marine pile driving. However, while extracting aggregate, the vessels generate higher levels of noise at frequencies above 1 kHz than a typical merchant ship. The major source of this higher frequency noise is the impact/abrasion of the aggregate material passing through the drag head, suction pipe and pump. Extracting gravel is noisier than extracting sand.

Thus, dredging by suction does not appear to generate high noise levels at low frequencies compared with a merchant vessel, but when full dredging is underway, an unusually high level of broadband noise is radiated in the frequency range from 1 kHz to high tens of kilohertz. Robinson *et al.* (2011) suggest that dredgers may still be regarded as just noisy ships. However, one issue that has to be considered when evaluating the impact is the length of time the dredger spends in an area, which is considerably longer than the time for a similarly noisy merchant ship to transit through the area. This means that the cumulative exposure from the dredging activity would be greater than for a single transiting vessel.

Measurements of ground vibration have been made with tri-axial geophones for one dredger and indicated a correlation between seabed vibration and the onset of dredging. As fish are sensitive to particle motion bottom living species may be especially sensitive to this vibration. However there are few data on typical ambient seabed vibration levels, or those levels that cause damage of disturbance to fish.

The effects of noise from suction dredgers are likely to be similar to those from ships, as above. The noise will be at a higher level than ambient noise levels and it is likely that the most serious effects will relate to masking. Contact of the drag head with the seabed may result in substratum borne vibrations that will affect fish and invertebrates. Other forms of dredging, with buckets and grabs may be worse in this respect.

Table 7-7 shows impact ranges produced by dredger C, described in section 6.7.

Filter	Source Level (dB/dB_{ht} RMS)	N	α	Range to 90 dB_{ht} (metres)
Unweighted	186	16	0.0006	N/A
Herring	101	14	0.0035	7
Cod	96	14	0.0035	3
Dab	81	14	0.0025	0
Generic fish	103	14	0.0003	9

Table 7-7: Impact ranges produced by dredger C

The high frequency noise produced by the dredger means that impact zones for fish are not as large as many other sources of underwater noise. There would be little, avoidance reactions from fish in the vicinity of the dredger as the avoidance reaction as 90 dB_{ht} is reached at a maximum of 9 m using the generic fish filter.

7.5.11 Effects of shipping noise

Ships generate continuous noise, although levels can vary greatly with the speed of the vessels and as a vessel manoeuvres. It is not easy to compare continuous sources such as ships with impulsive sources such as air gun arrays or marine piling.

Mitson and Knudsen (2003) point out that many vessels radiate significant levels of sound into water. There is concern that research vessels, in particular, must not cause fish avoidance behaviour when they are deploying survey trawls or applying acoustic assessment methods, where unbiased and fishery-independent estimates of the fish stocks are required. This problem was recognised by ICES with the publication of Cooperative Research Report No. 209 (CRR 209, Mitson, 1995).

CRR 209 provided a graph representing the level above which fish were likely to show avoidance behaviour. Experimental evidence was taken from a number of sources relating to two particular species, the cod and the herring, as these two appeared to be especially sensitive to sound as well as being commercially important species. Reaction distances were noted for fish in response to ships with known noise signatures and ranged from 200 m to 400 m. It was suggested that these distances were too great for research vessels and would affect the validity of the surveys. Attempts should be made to reduce response distances by reducing the radiated noise levels. It was proposed that fisheries research vessels should be able to approach within 20m of the fish before provoking a reaction. A low frequency sound level was therefore set for such vessels about 30 and 40 dB above the most sensitive hearing thresholds determined for herring and cod (based on rather provisional AEP thresholds from Enger, 1967, for the herring and the classically conditioned thresholds obtained by Chapman and Hawkins, 1973, for the cod). Projected to 1 m range this gave a maximum allowable level of radiated noise from a vessel (a mean level of 132 dB re 1μPa, measured over a band 1 Hz wide, over the frequency range 20 Hz to 1 kHz, at one metre). Fish were not expected to encounter radiated noise 30 dB above their hearing threshold from vessels that met this standard at distances greater than 20 metres.

In retrospect these proposals were naive. There was little recognition of the great variability shown in fish behaviour which prevents definition of a precise ‘reaction distance’. Ships are large. They are extended sound sources, consisting of a complex series of sources within and outside the vessel, each of which has its own vibration amplitude and frequency. These individual sources include the engine, transmission, and the propeller. Moreover the noise signatures of ships are complex, often containing strong spectral lines or bands, and with a ‘rough’ temporal texture. They are just the kind of sounds which fish are able to separate out from ambient sea noise. It is now recognised that there is great variability in the response of fish to nearby vessels with changes in the condition and physiological state of the fish at different times of the year, or under different local environmental conditions. Fish are potentially able to react to any sound that is a few decibels above their hearing thresholds.

For fish that are susceptible to predation the sense of hearing may provide their only means for detecting and locating predators at a distance, enabling avoidance. The response of fish to what must appear to be a large distributed sound source will depend largely on the assessment by the fish of the risk posed to its wellbeing. Does the sound resemble the sounds made by a predator? Is it moving towards the fish? Is it so unusual and spatially extensive that it might be assessed as a risk?

For cod, at its most sensitive frequencies, an increase above the ambient noise of 3 to 6 dB, measured over one third of an octave, is sufficient to be detected. Such sensitivity will allow most ships to be detected at distances of hundreds of metres and in some cases thousands of metres. It must be recognised that conventional surface vessels will always produce sounds at distances of hundreds of metres which will be capable of being detected by sensitive fish like the cod and herring. The aspiration of building large ocean-going research vessels which are inaudible to fish even at close distances may not be able to be achieved unless extraordinary measures are taken. It may be sensible to accept that fish *will* react to survey vessels and to plan surveys with this in mind.

There is no evidence to suggest that the continuous sounds produced by ships cause mortality or permanent tissue damage. There are very few data on TTS and other forms of physiological effects. Lasting exposure to continuous noise can result in recoverable damage to sensory hair cells in the ears of goldfish in which the swim bladder is connected to the ear (Smith *et al.* 2006). There have also been demonstrations of small changes in hormone levels in goldfish after long-term exposure to continuous increased ambient noise (Smith *et al* 2004a, b, 2006) but not in rainbow trout (Wysocki *et al.*, 2007).

Exposure to long-term noise, including boat noise, can impair hearing sensitivity and may result in TTS in fishes with connections between the swim bladder and ear. Several AEP studies have shown that thresholds are raised during exposure to boat noise (e.g., Amoser *et al.*, 2004; Smith *et al.*, 2004a). Fish without such connections have not shown TTS (Smith *et al.* 2004a, b, 2006; Scholik and Yan, 2001, 2002; Wysocki *et al.*, 2007; Scholik and Yan, 2001, 2002; Ladich, 2003). At least one such study (Smith *et al.*, 2006) correlated TTS and damage to sensory hair cells in goldfish, and demonstrated that normal hearing returned prior to recovery of the sensory cells. Rainbow trout exposed to increased noise for nine months in an aquaculture facility showed no hearing loss, as determined by AEP, or upon health of the fish (Wysocki *et al.* 2007).

Continuous ship noise is likely to result in masking, and may have a pervasive effect on fish behaviour. As with TTS, masking results in a reduction in the distance over which fishes detect all sound sources, and a corresponding reduction of fitness.

Ships, including fishing vessels and their trawling gear, may affect the behaviour of fish (Chapman and Hawkins, 1969). Fish can respond to approaching vessels by diving towards the seafloor or by moving horizontally out of the vessel's path, with reactions often initiated well before the vessel reaches the fish (Vabø *et al.* 2004; Ona *et al.*, 2007). Sand *et al.*, (2008) have pointed out that passing ships produce high levels of infrasonic and low frequency noise (>10 to 1000 Hz), and those infrasonic frequencies may be responsible for the avoidance reactions.

There are no data on the impact of ship noise upon eggs and larvae.

Table 7-8 shows the avoidance zones based on dB_{ht} analysis generated by the tanker noise shown in Section 6.8.

Filter	Source Level (dB/dB$_{ht}$ RMS)	N	α	Range to 90 dB$_{ht}$ (metres)
Unweighted	186	15	0.0075	N/A
Herring	115	17	0.0075	30
Cod	112	17	0.0075	20
Dab	95	18	0.005	10
Generic fish	120	17	0.0075	60

Table 7-8: Impact ranges produces by the 130 m, 8300 ton tanker.

Due to its broadband noise this tanker has an effect on fish despite much of its acoustic output being at high frequencies and creates a small strong avoidance zone of up to 60 m.

7.5.12 Effects of drilling noise

The comparatively low level of noise produced by drilling indicates that there would be no impact zone for fish (Table 7-9). The source level for the generic fish filter is lower than 90 dB$_{ht}$ and because the sound does remain above background noise for a long range, the absorption coefficient cannot be determined. Therefore drilling is thought to be of minimal impact on fish compared to other forms of underwater noise.

Filter	Source Level (dB/dB$_{ht}$ RMS)	N	α	Range to 90 dB$_{ht}$ (metres)
Unweighted	155	12	N/A	N/A
Herring	75	12	N/A	0
Cod	70	12	N/A	0
Dab	60	14	N/A	0
Generic fish	80	12	N/A	0

Table 7-9: Impact ranges produced by a Seacore / Wirth B5 pile top drilling machine at 80 kW

7.5.13 Effects of acoustic deterrent devices

Maes *et al* (2004) and Nedwell *et al* (2005a), have shown that the efficiency (ability of the underwater sound system to repel fish) is related to the level of the sound above the hearing threshold of the respective species. The acoustic fish deflection system was made up of a number of 600 W sound projectors, each producing continuous wave sound at frequencies from 20 to 600 Hz, and at a nominal Source Level of 174 dB re 1 µPa @ 1 m, per projector. For fish species that are comparatively sensitive to underwater sound, such as the herring (*Clupea harengus)* and the sprat (*Sprattus sprattus)*, average intake rates decreased by 94.7% and 87.9% respectively (Maes *et al.,* 2004), indicating that fish were avoiding the high sound field (at a level of 83dB$_{ht}$) surrounding the power station water inlet. The data indicated that for the fish species that were considered less sensitive to underwater sound (based on hearing threshold data) only a moderate response to the sound was demonstrated. For the flatfish species the efficiency for the flounder (*Platichthys flesus)* was at 37% and for the sole (*Solea solea)* was at 47%.

It may be noted that, since an ADD operates by inducing a behavioural effect (avoidance), it may be considered to be causing an environmental effect. Ideally, therefore, an exclusion zone will be created that is just sufficient to deter the target species from the effect zone, thereby preventing injury. It is not true that an exclusion zone should be as big as possible, or an ADD as powerful as possible, but rather that the power and behaviour of a given ADD should be closely matched to its application and the particular requirements of the application.

In general, the optimum position for an ADD will be co-location with the noise source in order to achieve a roughly equal exclusion zone in all directions. Where the ADD has to be mounted away from the noise source it may need to be more powerful in order that its exclusion zone covers the potential zone of effect of the noise source in all directions.

7.5.14 Effects of Naval Sonars

There have been several studies of the impact of both low frequency and mid-frequency sonar on fish (Popper *et al.* 2007; Doksæter *et al.* 2009, in press; Halvorsen *et al.* in prep); and on eggs and larvae (Jørgensen *et al.* 2005). None of these studies indicate mortality, although exposure levels and durations have far exceeded exposure during normal sonar operations (e.g., Popper *et al.* 2007; Kvadsheim and Sevaldsen, 2005). Close examination of several species exposed to both low and mid frequency sonars showed no damage to tissues (Popper *et al.* 2007; Kane *et al.* 2010). While studies have not been conducted with fish lacking swim bladders, it is unlikely that fish in this category would be damaged by sonar.

There is some evidence of TTS in fish that have been exposed to both low and mid frequency sonar, though the duration of such TTS is not yet clear (Popper *et al.* 2007; Halvorsen *et al.* in prep.). Since sonars are generally mounted on or towed by moving vessels, exposure of fish to these sounds at the highest sound levels is for short durations.

Behavioural responses to mid-frequency naval sonar have been examined in caged herring. No escape reactions (vertically or horizontally) were observed from herring exposed to sonar transmissions of 1-2 kHz and 6-7 kHz (received RMS sound pressure level tested at 127-197 and 139-209 dB re 1 µPa, respectively) (Doksaeter *et al.* 2009).

Studies of the impact of low and mid-frequency sonars (Popper *et al.*, 2007; Kane *et al.*, 2010; Halvorsen *et al.*, in prep.) found no mortality or damage to tissues, including the inner ear, in rainbow trout (which does not use the swim bladder for hearing) and channel catfish (*Ictalurus punctatus*) (which does). The low frequency sonar was operated at 193 dB re 1 µPa (rms) (maximum exposure level for the sonar used) for up to 618 seconds of exposure. The mid frequency sonar was operated at levels up to 207 dB re 1 µPa for up to 15 second of exposure. TTS was found at these levels with both rainbow trout and channel catfish for low frequency sonar, but only for channel catfish with mid frequency sonar.

Jørgensen *et al.* (2005) observed increased swimming activity and startle responses in juvenile herring exposed to sonar signals (1.6 and 4 kHz), but no responses were observed from cod, saithe, and wolf fish (*Anarhichas minor*). The behavioural reactions were observed from the herring larvae at levels of 170 dB re 1 µPa (rms).

There was some mortality to clupeid eggs at the highest sound levels. Statistical analysis showed that the likelihood of mortality to eggs and larvae from this kind of source is lower than the level of natural mortality (Kvadsheim and Sevaldsen, 2005).

7.5.15 Overall effects upon fish

It is evident that a single universal sound exposure criterion cannot be applied to all animals for all sources under all circumstances. The impact caused by underwater noise will depend on the nature of the animal being considered and often its location relative to the source. Standards set for one species will be different from those for another and effects may differ depending on the sound exposure time in the life cycle of the animal.

Noise may have no effect on fishes, or may result in effects ranging from minor behavioural or physiological changes to substantial changes that threaten the survival of the exposed animals (Richardson et al, 1995). It is especially difficult to assess the consequences of noise-induced changes in behaviour. Such changes, together with masking, temporary hearing loss, and tissue injury, may or may not lead to decreased abilities to find food or mates, or to avoid predators (reduced fitness). Anthropogenic sounds perceived as threats by one species may elicit escape or avoidance reactions by one species, and be seen as opportunities by another.

Most concern about adverse impacts has been expressed for activities such as pile driving, or seismic surveys by means of air guns, where fish are exposed to impulsive sounds at very high levels. In some circumstances there have been attempts to regulate the use of such sources. For example, regulatory authorities have set standards for the use of pile drivers. One such standard stipulates that sound pressure levels must be maintained below 150 decibels (dB) rms (root mean square) with reference to 1 micro-Pascal (µPa) for a minimum of half the impacts or strikes; and peak sound pressure levels must be maintained below 180 dB re 1 µPa for all strikes in areas of potential fish presence. The setting of these standards has often been done in an arbitrary way. In particular, a peak value of 180 dB re 1 µPa seems to have gained wide acceptance as an upper limit, above which fish may be injured or impaired, without clear justification or critical appraisal. Some researchers have emphasized that several factors, including the rise time, the total energy, the duration and the repetition rate are as important as the peak pressure in causing damage to fish. Interim criteria for the onset of injury in fish have been set in the US (FHWG, 2008) at a peak sound pressure level of 206 dB re: 1 µPa, and accumulated sound exposure levels (SEL) of 187 dB re 1 µPa2-sec (for fish >2 grams body weight) and 183 dB SEL (for fish <2 grams body weight). The accumulated SEL is a measure of the cumulative energy to which a fish is exposed to over the course of a pile-driving event (less than one day).

The setting of a cumulative level raises the question - what are the accumulative effects from repeated sounds? It is important to distinguish between effects that occur over time (true cumulative effects), from those that co-occur or overlap in time (aggregate effects). Interactions between stressors are potentially linear (additive) or nonlinear (multiplicative, synergistic, exacerbating, logarithmic). In describing the effects of multiple recurrences of the same stressor or effects of combinations of stressors, development of an interaction factor will be needed to account for both cumulative and aggregate effects. Examples of chemical and biological effects that illustrate these interactions are well documented. Interactive effects between multiple acoustic stressors or between acoustic stressors and other stressors are not well documented.

Data of noise levels produced by many forms of anthropogenic underwater noise is summarised in Table 7-10.

Source	Source level (dB_{ht}(*fish*))	Peak to peak or RMS	Range to 90 dB_{ht} (*fish*) (metres)
Piling	187	Peak to Peak	6000
Seismic	140	Peak to peak	3000
Blasting	200	Peak to peak	3000
Dredging	136	RMS	9
Shipping	122	RMS	60

Table 7-10: Impact ranges calculated using the generic fish filter. Data was gathered along a transect which enabled estimated of the variation of noise level against distance from the source. This allows the impact ranges of strong avoidance to be calculated using the 90 dB_{ht} criterion.

It is clear from the table that the source of underwater noise with the largest impact area is impact piling. With impact ranges extending past 10 km for the generic fish filter, and the other forms of underwater construction noise such as vibropiling, dredging and drilling are almost insignificant in comparison.

7.6 Deficiencies in our knowledge

Our current knowledge of the impact of human generated sound on fish is fragmentary. In particular, knowledge of the response of fish is limited and relies, with a few notable exceptions, on experiments carried out in the laboratory. The presentation of measured sound stimuli to fish under experimental conditions in the sea presents formidable difficulties.

Further studies are required on the actual consequences of tissue damage and of temporary threshold shift (TTS) upon fish. There is a need to compare the survival and behaviour of hearing impaired animals with that of controls in the natural environment in order to gain information on the effects of hearing loss upon populations in the wild.

There are few or no data on the masking effects of anthropogenic sounds on the signals of greatest interest to fish, including sounds used for communication, detection of prey, avoidance of predators and navigation. The effects of anthropogenic noise upon the ability of fish to detect the sounds of conspecifics, or their predators or prey remain to be determined.

8 Population-level and ecological effects

8.1 Introduction

In previous chapters we have shown that there is a substantial overlap between man-made noises and hearing ability of marine fish and invertebrates. It is often speculated that there is a natural threshold that must be exceeded before a noise-producing activity starts to influence an individual's normal activity (here activity is used in its broadest sense and includes behaviour, metabolic work and reproduction). Yet exceedance of such a threshold may not have further consequences and instead be absorbed within the variability and range of routine activity levels. Partly substantiated is the consideration that certain noise levels exceed those that healthy individuals can accommodate, resulting in direct or indirect noxious effects (Kaatz 2002, Slabbekoorn *et al.* 2010). The threshold where vibration and sound pollution becomes a burden to the individual, affecting its fitness, is of utmost importance since from this moment onwards population- and community-level effects are expected (Apitz *et al.* 2006). It is at this point that the effect on the individual becomes biologically significant, affecting demographically important variables such as growth rate, life expectancy, or reproductive output, resulting in impaired population dynamics.

This conceptual linkage between effects on the individuals and population-level consequences is clear. However, effects operate at different temporal and spatial scales and are invariably mediated by multiple and complex biotic and abiotic interactions.This makes it difficult to associate viability of the population with any causative (behavioural or otherwise) event on the individual. Nevertheless, marine conservation initiatives and management plans operate at the level of the population and therefore changes in population structure, distribution and abundance (survival) are the metrics more often proposed to assess ecological quality (Niemi *et al.* 2004). How does one determine whether an acoustic disturbance results in a significant alteration of any one of these parameters? And when observed deviations reach the threshold of biological significance? Attempts to solve this puzzle have been initiated for marine mammal populations where more data is on hand (NRC 2005). One possible way is to create mechanistic models based on empirical responses to noise and fundamental knowledge of ecological functioning (Apitz *et al.* 2006). It is clear that to model complex ecological systems, the underlying controlling processes have to be understood, requiring precise knowledge of ecological functioning. For populations such key processes are mostly demographic (birth rates, recruitment, mortality, immigration, emigration and death). We will review and discuss in this section the approaches to transfer individual responses to higher levels of complexity in natural organization, and to devise ways to evaluate the environmental cost of man-made marine sounds to populations.

8.2 What are the ecological risks from noise exposure?

Any logical approach to ecosystem-level assessment of impacts and risks requires a proper conceptual model (Ducrotoy & Elliott 2008). It provides the framework to evaluate pressures and impacts as well as conveying the potential for change to all audiences. To properly assess risks, the model should consider, in this case, the potential impacts, including the severity, persistence and spatial extent of sound pollution and at the same time differentiate the important features driving population change from the less important or improbable ones. While general models can be formulated with relative ease, it is very hard to capture the functional linkages among the different parts and to forecast impacts relative to the pristine situation.

The extent to which noise pollution affects the structure and functioning of marine ecosystems as a whole has yet to be determined (Richards *et al.* 2007, Popper & Hastings 2009). There are numerous studies and reviews where a range of effects is assumed to be relevant at the level of marine populations, however little is known (see previous chapter for references to particular studies). Ultimately this lack of understanding is affecting our ability to properly evaluate and mitigate effects of manmade sound on marine ecosystems and therefore making it impossible to implement informed risk management initiatives. The shortcomings of current science start with the practical difficulties of describing individual responses in a meaningful dose-response way, but more worryingly, bridging the gap between the individual and population effects is just beyond the technical abilities of current environmental science (Apitz *et al.* 2006, Richards *et al.* 2007, Teck *et al.* 2010). Moreover, noise is expected to have similar impacts to other forms of human pressures upon marine systems and as such, effects will have to be considered in combination with them. Yet it is at least implicit in all regulatory initiatives that management of ecosystems should consider higher levels of biological integration such as in the ecosystem approach (CBD-UNESCO 2000), or the functional approach underlying the EC Marine Strategy Framework Directive (MSFD) (EU 2008, Van Hoey *et al.* 2010).

Currently, we are poorly equipped to do any more than use expert judgements for predicting population impacts and usually these decisions are based on the ecology of a single species (Gotz *et al.* 2009, Teck *et al.* 2010). Within this mostly subjective framework we have some empirical evidence of direct in situ reactions of fish to seismic airguns (Engas *et al.* 1996, Bain *et al.* 2000, Wardle *et al.* (2001), pile driving (Nedwell *et al.* 2003, Andrews 2009, Mueller-Blenkle *et al.* 2010), fish deterrent devices (Popper *et al.* 2002, Gordon *et al.* 2007, Andrews 2009), and vessel noise (Codarin *et al.* 2009, Picciulin *et al.* 2010). The reactions to these acute experimental exposures, loud but not intense enough to cause physical injury or death, did not result always in a marked and sustained altered behaviour although more subtle behaviour with ecological relevant endpoints may be occurring (Picciulin *et al.* 2010). In addition to direct behavioural effects, physiological reactions such as increases of stress hormone levels have been also documented (Smith *et al.* 2004, Wysocki *et al.* 2006) (Table 8-1).

Zone	Perception level and response	Effect on individuals	Expected effect on population parameters
1 zone of damage	non auditory, direct trauma to tissue, death or severe injury	injury, hearing loss, or severe discomfort and avoidance reactions, stress and physiological impairment	decreased abundance, reduction of growth and reproductive output, distribution changes, size and age structure alterations
2 zone of responsiveness	audible and intense, causes direct reactions or mimics behavioural triggers -habituation or conditioning possible under chronic exposure	acute response to sound (behaviour or physiological reactions), energy budgets, scope for activity and growth, stress in extreme cases	general reduction of growth and abundance, reproductive output and distribution changes, size and age structure alterations
3 zone of masking	audible above ambient sound but lower intensity and interfering with behavioural clues or triggers	no direct reactions, noise resulting in the delay or disruption of native behavioural responses, vulnerability to predators, access to food items, energy budgets	decreased abundance, reduction of growth and reproductive output, size and age structure alterations
4 zone of audibility	as above but non interfering with behavioural clues or triggers, ignored	no direct reactions, none expected	none expected
5 zone of no audibility	below auditory threshold, confounded with natural background sounds	no direct reactions, none expected	none expected

Table 8-1 Conceptual framework indicating expected effect of waterborne sounds on populations. The zoning of noise influence is based on Richardson *et al.* (1995). The model considers four different impact zones radiating from a hypothetical sound source, zone 1 will be closest to source and 5 the furthest (note: zones 3 and 4 overlap).

8.2.1 Zone of damage

Direct effects including death or physical injury have been reported during pile driving or blasting, although these effects are only apparent under intense noise dose levels only possible at relative close distances from the source (Forrest *et al.* 1993)

Direct injury data (field or laboratory) may be extrapolated to population effects (i.e. death rate) although studies including modelled death rates have not been conducted in the literature identified in this review. Effects such as PTS or even TTS (if the sensitivity shift is long-lasting) have the potential to affect the individual's ability to forage or detect predators, which in turn could lead to effects on population vital rates (Table 8-1). In any case, intense direct effects are likely to be present only under the most extreme scenarios and at relatively short distances from the source; therefore they might have limited relevance when considering entire population ranges. The effects, on the other hand, may be severe if harmful levels of noise affect key habitats, for example migratory corridors or nurseries and spawning grounds as these may intensify the relative effect on the population.

8.2.2 Zone of responsiveness

Below the threshold of physical damage down to the limit of individuals hearing (i.e. audible sounds above background level), noise induces the suite of behavioural effects outlined earlier in this section (Table 8-1) and section 7 of this review. Although there is a great deal of variability in sound propagation, acoustic models indicate that the intensity of the exposure effect attenuates with distance in a frequency-dependent manner (Forrest *et al.* 1993) (see also section 3.4 for further details). The potential zone of influence is then comparatively larger, with louder sounds inducing greater distress and reactions, and low frequency sound affecting larger areas. In principle any sound that is audible above the background level can trigger a response. However, given that there is a response, it is not clear how much of it actually has population or community-level consequences and how much is buffered within the normal resilience of the individual or the population. Furthermore, responses to repeated exposure may disappear (habituation) or get stronger (conditioning). For example a fish predator may benefit from fishing by catch only if it does not swim away after detecting the propeller noise of the fishing vessel. Equally important are innate behaviours such as startle responses, schooling and other anti-predator defences which if triggered too often may easily impair overall performance.

8.2.3 Zone of masking

In addition to direct responses, sounds may have an effect indirectly by masking biologically relevant signals, averting or altering normal response thresholds of normal behaviours (Forrest *et al.* 1993, Slabbekoorn & Bouton 2008, Popper & Hastings 2009, Belanger *et al.* 2010). These effects are always sublethal and linked to subtle alterations in behaviour (i.e. courtship, aggressive displays, schooling, swimming, etc.). Masking effects have similar implications to the animal as TTS and PTS, they impair the ability to hear over the natural background and this can lead in failure to detect predators, prey or to communicate between conspecifics (Anonymous 2004). This could have large effects on fitness and relatively small effects may translate into ecologically relevant outcomes (Gotz *et al.* 2009). Masking of low frequency sounds has the potential to operate over an increased area and affect a substantial portion of the population. The boundary of biological significance will greatly depend on the hearing abilities of the individuals and it is greatly species-dependent (see discussion of dBht (*species*) in section 4.2. Evidence of masking effects is still patchy and when suspected cannot be directly linked to demographic or population effects (NRC 2005).

8.3 Assessing the impacts of underwater sound

Understanding the impact of man-made noise in the context of normal spatial and temporal variation requires the definition of: 1- a biological reference baseline and 2- a target for conservation. To fulfil the first requirement we require information on responses to noise and threshold of biological significance, which in the present context are population-level consequences. The second requirement may not be obvious, but is necessary as it is unlikely that sound pollution will cease completely and therefore it would have to be managed along other pressures acting upon marine ecosystems. In the European marine policy action EC Marine Strategy Framework Directive (MSFD) (EU 2008, Mee *et al.* 2008), this conservation target is referred as Good Environmental Status (GES). It is of note that the MSFD explicitly includes noise among the quality descriptors defining GES in the marine environment (Mee *et al.* 2008, Leverett & Crane 2010, Lyons *et al.* 2010). It is also important to consider that assessing population effects in isolation will probably not be enough to define GES and community effects will have to be considered and placed within the wider context of the entire ecosystem (Mee *et al.* 2008).

The propagation of effects from the individual level further into population or community effects is difficult to predict with precision. Apart from direct physical damage, it is clear that only audible sounds are capable of triggering a cascade of effects. Therefore hearing ability (audiograms) for all sensitive receptors and sound background levels are the first necessary steps in any impact assessment methodology (Popper and Hastings 2009). Given the premise that underwater sound pollution has the potential to elicit a response in the individual, then the question is; what is the likelihood of it affecting fitness or being demographically significant? One way to answer this question is to model the consequences of such effects using ecological transfer functions linking individual level responses and population effects. Such conceptual framework is followed in the Population Consequences of Acoustic Disturbance (PCAD) model proposed for marine mammals (NRC 2005). Essentially the model links the different ecological steps starting with the sound exposure characteristics and effects on behaviour, assumptions on the life functions impacted, and finally the translation of these demographic effects to population consequences. The rationale behind the PCAD model is directly transferable from marine mammals to any other biological element of the ecosystem. It is also a valid approach to understand cumulative and in-combination effects. A criticism to the PCAD is the lack of integration beyond the population level. However, due to the multiple and often unknown mechanisms linking anthropogenic pressures and population or community responses, it is unrealistic to account for all linked factors and interactions leading to loss of ecological integrity (Fausch *et al.* 1990, Aubry & Elliott 2006). Nevertheless, models like this are useful simplifications of the 'real world' and as such provide a tool to look into relationships and interactions between different aspects, identify key processes, and in some cases forecast outcomes.

The PCAD predictive model relies on just four transfer functions based on calibrated behavioural responses and ecological demographic theory. Although a rational framework to derive higher order effects from cause-effects relationships, most of the variables necessary to implement the PCAD model are currently unavailable. For example the bottom-up approach of the PCAD requires precise knowledge of the response to sound ideally quantified by dose-response experiments. This is in practice difficult to assess due to difficulties of presenting a field-realistic exposure in controlled conditions (Hawkins 1993, Nedwell *et al.* 2003, Popper & Hastings 2009). Useful generalizations and model simplifications can be achieved by dividing marine organisms into functional categories on the basis of hearing, i.e., hearing specialist vs. generalist but once again our knowledge is limited and for example only a handful of fish audiograms are available (Nedwell *et al.* 2007).

TEXT BOX1: Summary of the transfer functions of the PCAD model by NRC (NRC 2005). A function example is given between brackets.

Function 1. Relates acoustic stimuli to behavioural responses (i.e. sound exposure effects on swimming)

Function 2. Expresses behavioural disruption in terms of effects on critical life functions (i.e. consequences of swimming alterations on feeding and metabolic rate)

Function 3. Integrates functional outcomes of responses over relevant temporal and spatial scales and link them to vital rates in life history (i.e. effects of altered feeding or metabolism on growth rate)

Function 4. Produces the final link between individual vital rates and population effects using demographic theory (i.e. effects of impaired growth rate on population size structure)

The PCAD approach critically bases the effects on populations in demographic models that are built using calibrated responses to noise at the individual level. Due to the lack of quantitative estimates of responses to noise, qualitative categorical models (QCM) are often the only approach available. The QCM approach characterizes the strength of links between stimulus and response, and these with function and demography using a low-medium-high scoring system similar to the sensitivity matrices commonly used in risk evaluation. This scoring represents a simplified version of the PCAD transfer functions and is based on qualitative evidence and expert judgment. The precision of this approach is often questioned due to potentially large subjectivity and it is a rather unrefined tool (NRC 2005).

A different method is the direct modelling of population effects where idealized population trajectories are computed by calculating the survival of individuals. This approach is generically known as individual based modelling (IBM) (NRC 2005). These models compute idealized growth trajectories and survival of a large number of individuals, a model population, in a computer simulation. This requires a certain degree of accuracy with the parameters values and assumptions making up the models. The IBM approach uses model parameters based on physiology (growth rate, size, feeding rates, metabolic rate, reproductive output, etc.) and behaviour (vulnerability to predators, prey encounter rates, escape response thresholds, etc.) of individuals along with a synthetic representation of the environment (prey density and type, predator field, temperature, salinity, noise level, etc.) (Rose *et al.* 2003, Fuiman *et al.* 2006, Murphy *et al.* 2008). The IBM approach has been used in ecotoxicological studies aiming to forecast population consequences from sublethal effects of pollutants on larval fishes (Rose *et al.* 2003, Alvarez *et al.* 2006). In principle, sound could be treated in the same way a chemical pollutant is, and therefore, the IBM approach may prove very useful to scale individual reactions to population effects. By and large the necessary evidence for the estimation of such as IBM is at the moment not available.

Complementary to these approaches, bioenergetic models may also be useful to integrate the costs of various activities (growth, reproduction, swimming, etc.) and their impact on overall fitness and performance.

8.3.1 Sound propagation modelling

Over the past few decades there has been an increased interest in modelling the way that broadband underwater sound propagates. One such model developed to describe the way that this occurs is The Impulse Noise Sound Propagation and Impact Range Estimator (INSPIRE) model which has been developed by the authors specifically to model the propagation of impulsive broadband underwater noise in shallow waters. It uses a combined geometric and energy flow/hysteresis loss model to conservatively predict propagation in relatively shallow coastal water environments and has been tested against measurements from a large number of other offshore wind farm piling operations (Nedwell *et al* (2011)), and is also being tested against seismic sources.

Transmission Losses are calculated by the model on a fully range and depth dependent basis. The model imports electronic bathymetry data as a primary input to allow it to calculate the transmission losses along transects extending from the source of the noise. Other simple physical data are also supplied as input to the model, in the case of piling, the bow energy, pile diameter, strike rate and water depth would be used. The model is able to provide a wide range of outputs, to estimate the likelihood of auditory injury to any marine life present, as well as the total area over which disturbance may occur.

As well as calculating the sound level with range, the model incorporates a "fleeing animal receptor” extension that enables the noise dose an animal receives as it is moves away from a piling operation to be calculated. This feature permits the calculation of the closest distance to the noise source under consideration from which an animal must start fleeing such that its noise dose just reaches a particular criterion value at the cessation of the piling operation. Thus the disturbance to marine life in a particular area can be quantified if a suitable audiogram is available to describe the hearing capabilities of the relevant species.

8.4 Current data sources

Most of the research found in the peer reviewed literature with direct application to models concentrates on audiograms and the direct effects of noise on the hearing apparatus, especially physical damage to hair cells. Field studies on behavioural effects are comparatively less frequently undertaken and there are very few studies focusing on indirect, masking, effects. The importance and need for further research on the effect of masking sounds is frequently highlighted in papers discussing the effects of noise on marine life in general, especially marine mammals. Despite the lack of comprehensive studies, in general, the outcomes of available research may be used (with more or less success) to derive approximate parameters and define the model structure. As introduced earlier in the chapter, the problem current science faces is the lack of empirical evidence about the effects, experiments are needed to link responses to precise sound signatures and mode of presentation. It is clear that to formulate any predictive model of population consequences, the current focus on correlations will have to be complemented by dose-response experiments gathered in controlled yet realistic trials such as Control Exposure Experiments (CEE) (Engas & Lokkeborg 2002, NRC 2005), and field manipulative studies or laboratory experimentation (Fuiman *et al.* 1999, Smith *et al.* 2004, Alvarez *et al.* 2006, Kastelein *et al.* 2008). Although this precision is essential to produce accurate parameters for the models, there is still a need for a better understanding of processes and functional links between components of whole marine ecosystems, for which large field datasets are essential.

Additional data may be available from surveys intended to inform ecological statements for marine developments and other activities such as marine renewable, oil and gas, shipping or dredging. These surveys are required by law for most large scale projects and often noise is included among the factors identified as having potential deleterious effect on the local ecology. Although potentially a steady stream of information on sound pollution under realistic conditions in the field, the scope and effort associated with these ecological studies is often too narrow and/or too low to provide any direct evidence of effects other than gross changes. Nevertheless, these projects provide a direct insight on the overall ecology and functioning of marine systems. This information may prove useful to define general tends in background ecological processes which can be of great relevance to refine current ecological knowledge. This knowledge is clearly essential to create models grounded on ecological theory able to predict the pace of ecological change at scales compatible with marine management. This will only be possible if there is greater harmonization of methodologies and also a centralized data compilation effort. In any case, monitoring work especially noise recordings over the lifetime of these projects, is by itself of great importance to define impacts and assist future project assessments.

From a conservation perspective, the immediate impact of anthropogenic sounds on individuals or on schools of fish is less important than the long term impact on populations and ecosystems, either alone or in combination with other stresses (which will often include fishing). Any reduction in the numbers of fish through exposure to sound may or may not have a major effect on the ability of fish populations to renew themselves. Some fish populations go through a period of density dependent mortality, and removing a small number may simply result in their replacement through the improved survival of others. Nevertheless, a reduction in the spatial distribution of fish, or a reduction in genetic diversity created for example by disrupting the migrations of a particular sub-population, may have serious consequences at a local level. There have been attempts to develop predictive models for marine mammals based on studies of the disruption to individuals and examining effects on key life functions like feeding, growth, reproduction and migration (NRC, 2005). But such models are still in their infancy.

8.5 Metrics to evaluate effects of Underwater Sound on ecological quality

The main potential threat of underwater sound pollution is the disruption of natural processes. Therefore, there must be a consideration of what components are affected and in what quantities, and thus the links to ecosystem structure and function. A priori, any physical, chemical and biological variables (i.e. metrics thereafter) can be used to produce the experimental evidence necessary to assess ecological integrity or damage (Niemi *et al.* 2004, Kaplan *et al.* 2010). Best assessment metrics would be those quality features with demonstrable sensitivity to sounds, direct or indirect linkage with population parameters and must be easy to estimate. The degree of response naturally varies depending on the species hearing abilities, susceptibility to injury and reliance on sound for ecological significant behaviours. In practice most direct assessments of noise disturbances are limited to investigations at the individual level. There is large list of these metrics, too extensive to be covered in detail here. In all practical cases they are based on the qualitative or quantitative appreciation of features deemed to represent a fundamental aspect of ecological structure and functioning of the system under evaluation (Bain *et al.* 2000).

TEXT BOX2: Quality features of natural ecosystems, structure and function.

The presence of a fish species may be one of such quality features other examples are the presence of viable spawn, the size frequency of the population or overall ecological diversity. These define the structure of ecosystems. In other cases these quality features may be rate processes such as growth or mortality rates or reproduction rates, all very important demographically hence with direct relevance to populations and ecosystems. These are known as functional features.

8.6 Deficiencies in our knowledge

The inadequate science available and lack of knowledge directly translates into a large uncertainty in the way risk can be measured and managed (Richards *et al.* 2007). More than this though, the different risk perspectives of marine users in contrast to regulators, conservation organizations and the scientific community causes additional problems. The different parties often seek explanation and gain support for their arguments from the lack of adequate science, that is, marine users use uncertainties to claim no significant effects, regulators and conservationist to justify an overly conservative approach and scientists to cast doubts on any risk assessment. The ecological risk imposed by noise will remain uncertain and impossible to manage until robust and cost-effective assessments methodologies are developed (EU 2000, Harwood 2000, Halpern *et al.* 2008). Scaling effects from individuals to populations or community effects is still in need of much refinement. Modelling appears to be a promising option but to be effective they will need laboratory and crucially field calibration. Developing such modelling methods will require a significant research effort (Harwood 2000) but are necessary for informing management decisions (i.e. licensing and monitoring) and guide policy actions.

9 Observation techniques and experimental designs

In examining the behaviour of fish and invertebrates to anthropogenic sound it is more meaningful to conduct studies in the wild, where fish behaviour is natural, and less influenced by artificial conditions. It is only in the wild that a full repertoire of behaviour is seen. Predators behave like hunters and may range widely in search of prey, or they may hide in order to ambush vulnerable food organisms. Prey can protect themselves by adopting cryptic habits or by joining together in large schools. Nomadic fish can range more widely in their movements, while territorial fish can defend a selected home range. Only when fish are showing their own distinct behaviour patterns in a natural habitat, under quiet ambient noise conditions, can we expect them to express their full range of responses to imposed sounds. Moreover, under these conditions fish can be exposed to man-made sounds under more appropriate acoustic conditions. Sounds are difficult to reproduce under laboratory conditions, where the fish may be close to reflecting boundaries and where sounds may propagate very differently from open water conditions.

There are therefore very good reasons for looking at the behavioural responses of fish to sounds in the wild, rather than in an aquarium or sea cage. It is usually preferable to examine free-swimming wild fish, unconfined by walls or netting and unaffected by the trauma of capture, and handling. However, the problems of examining fish in the wild are formidable.

Although it is relatively easy to look at the behaviour of fishes that live in shallow streams or pools, it is exceedingly difficult to observe animals in the ocean. Humans are essentially visual creatures. We use mainly our eyes to observe the world around us; but our eyes do not work well underwater or in the dark. We can look at aquatic animals in daytime, using SCUBA gear or by snorkelling, but we are visually impaired in the aquatic environment, especially at night. We are forced to use instruments and aids which can be deployed in water for long periods, under a range of light levels, at significant depths.

Such underwater observation instruments:

- Have to be robust, waterproof and capable of operating at depth
- Should not influence the behaviour of the fish being observed. Ideally they should not emit light at wavelengths which can be seen by fish or emit sounds which can be heard. They should not affect the movements of the fish.
- Must be capable of providing clear and unequivocal observations of behavioural change.

There are many methods for observing animal behaviour underwater. Visual observations, by eye or by camera, have been used frequently to observe and record fish behaviour. However, water is much less suited to making visual observations than air. It is less transparent and it behaves as a filter, taking out red light and leaving yellow and green. It is often full of dispersed particulate material, which scatters and absorbs light and results in fog-like conditions. Contrast is poor and light levels, especially at depth, are low. It is difficult to see any distance, and almost impossible to see animals at night or at extreme depths.

Nevertheless, in daytime, visual observations can provide detailed information on the behaviour of shallow water animals, and under these conditions, cannot be rivalled by any other technique. In tropical waters the behaviour of fish and invertebrates can be observed in detail, especially if their movements are restricted to a small area.

Sound travels well through water and forms the basis for many underwater observing systems. Although sound cannot provide the detailed images created by light-sensitive cameras it can be used to observe animals over much greater distances and areas. Through the use of sonar behaviour can also be observed and recorded at great depths. In particular the movements of schools of pelagic fish can be plotted in two and even three dimensions, often against background images of the seabed and other features.

In addition, fish themselves make sounds and these sounds may be used to locate fish, make inferences about the behaviour being shown, and even to track fish.

Finally, small electronic devices can be attached to animals and used to follow their movements. In the sea, ultrasonic transmitters can be detected over distances of hundreds of metres. Some electronic recording tags can also store data on environmental parameters for months, and when retrieved can allow the movements and behaviour of the animal to be reconstructed.

The techniques used to observe fish will vary with the range of behaviour shown in the wild. A recent workshop in Halifax Nova Scotia on Fish Behavior in Response to Seismic Sound, was funded by the Environmental Studies Research Funds (ESRF, Canada), the Offshore Energy Environmental Research Association (OEER), and the Sound and Marine Life Joint Industry Program of the International Oil & Gas Producers Association (OGP). The workshop examined the different techniques applicable to fish behaviour studies in the presence of seismic survey activities. A report of that meeting is available at http://www.esrfunds.org/pdf/190.pdf

The workshop concluded that the following factors limit the applicability of observations obtained from captive or controlled studies to wild fish behaviour and populations:

- Captive fish are not free to exhibit the broad range of potential natural behaviour, including avoidance to reduce the level of exposure;
- A specific marine species of interest may not behave in a similar fashion to different species previously studied; and
- Sound propagation and exposure in captivity are rarely directly transferable to sound propagation in open water.

The report emphasizes the factors that limit the applicability of observations obtained from captive or controlled studies and stresses the importance of examining the behavior of wild free-living fish. The techniques applicable are discussed and recommendations made on the methods that can be used in different circumstances.

Table 9-1 summarises the views of the workshop on methods applicable to the study of particular groups.

Type of Study	Species	Methods Applicable
Aquarium Tank/Sea Pens (Support for larger scale field programmes by providing detailed descriptions of behaviour)	Gobies Wrasses Juvenile gadoids Inshore fish species Lobster Norway lobster Some crabs and other invertebrates	Description of behaviour from detailed visual observations, aided by TV and cameras. Must ensure ambient noise levels are low, that environmental conditions are appropriate Light levels etc.), and that the animals are healthy Sound playback may be problematical, especially for seismic signals and pile driving
Field Studies of Site-Attached Demersal Species showing limited movement	Gobies Wrasses Juvenile gadoids Inshore fish species Lobster Norway lobster Some crabs and other invertebrates	UWTV observations, with camera arrays Acoustic tags (pingers) attached to individuals, with hyperbolic tracking High resolution bottom mounted sonars (DIDSON, Blueview) Passive acoustics for sound-producing species Monitor ambient noise. Specify stimuli in terms of sound pressure and particle motion. Use sound projectors with ground roll components where appropriate Fishing studies with traps, gill nets and angling to provide ancillary information (stomach contents, size and weight)
Field Studies of Demersal Species showing extensive movement	Cod Haddock Some crabs Dogfish Skate Flatfish (Plaice and Sole) Squid Cuttlefish	Acoustic tags (pingers, archival, transponding) attached to individuals used in conjunction with dispersed receivers; vessel tracking by passive receivers and sonars (transponding tags) Passive acoustics for locating spawning grounds of sound producing species augmented by gliders (transects) and autonomous vehicles for location of aggregations Monitor ambient noise and specify stimulus in terms of sound pressure and particle motion. Use sound projectors with ground roll components where appropriate Fishing studies with traps, gill nets, long lines and trawls to provide ancillary information (stomach contents, size and weight)

Field Studies of Pelagic Species	Herring Sprat Mackerel Zooplankton	Behavioural observations on schools (and individuals) with echo-sounders and sonars. Combined studies of zooplankton (multi-frequency acoustics) Passive acoustics for herring and sprat voiding gas Acoustic biomass estimation before, during and after disturbance Monitor ambient noise and specify stimulus in terms of sound pressure in most circumstances (except near surface where particle motion is relevant). Some fishing for species identification (gill nets) Water sampling (zooplankton identification)
Coastal and Estuarine Species	Salmon smolts Salmon adults Sea trout Eels	Acoustic tags (pingers, archival, transponding) attached to individuals used in conjunction with dispersed receivers; vessel tracking by passive receivers and sonars (transponding tags) Combined acoustic/radio tag if entering rivers River-based monitoring with counters and traps Monitor in-river catches Monitor ambient noise and specify stimulus in terms of sound pressure and particle motion Use sound projectors with ground roll components where appropriate

Table 9-1: Methods applicable to the study of particular groups

9.1 The near field and far field

In many experiments, a recording of sound is replayed and reactions to it assessed. In principle, it would appear to be relatively simple to investigate the effects of noise on marine species by using a playback experiment based on the use of an underwater sound projector array. However, for a successful investigation, the sound projector array must produce a sound field which closely approximates that generated by, for example, piling in real life.

In general, it is intuitively obvious that the wave form that is generated by the underwater projector should be similar or identical to that of the original source that it is intending to mimic. However, it should be remembered that a sound field is not only characterised by its spectrum, but also by its spatial dependence. Both of these properties are of critical importance in assessing the behavioural effects of noise. In essence, the spectrum determines “what the animal hears”, and the spatial dependence determines “where it appears to come from”. Both of these are of importance in determining the effect of noise on a species. Primarily the noise spectrum determines whether an animal will react. The spatial field, however, provides a clue as to the direction of the source of the sound, and hence determines an animal’s intent or ability to react to the sound by fleeing from it.

A sound wave arriving from a source at distance in deep water will generally be characterised by being approximately plane, that is it will have surfaces of constant phase and amplitude that are plane and perpendicular to the direction of propagation. In shallow water the wave may be more complex as a result of reflections from surface and seabed. Near to the source the wavefield may be complex, and there may be significant variations in both the pressure and particle velocity of the field, but as the wave propagates away from the source it will become more constant in form. Generally, the area around a source where the wave field is complex is referred to as the “near field” and that far from the source where the sound field is more constant in form is referred to as the “far field”.

One definition of the geometric far field is when as the distance from a source where the difference between the lengths of the longest and shortest signal paths is equal to a half wavelength. From this point, all distances closer to the source are said to lie in the acoustic near field, while those further away are in the acoustic far field. It is be critically important during playback experiments to be aware of the extent of both the acoustic near and far fields, as measurements taken in both fields can be significantly different. The significant difference lies in the fact that the pressure distribution in each sound field will be dissimilar, in terms of its evenness. It will be vital to position the fishes in the acoustic far field, where the pressure distribution tends to be more uniform as the difference between signal paths does not result in significant interference. Obviously, when path differences approach a half wavelength pressure nulls begin to appear. When a receiver moves still closer to a source (less than the half wavelength mark), differences in phase will lead to additional pressure maxima and minima, resulting in an undesirable uneven coverage in the near field.

However, the geometry of a source alone does not dictate the point of the beginning of the far field; this distance is also dictated by the wavelength of the projected sound. The role of wavelength has already been expressed in the definition of the geometric far field, i.e. ‘the far field begins when the path difference is equal to a half wavelength’. This frequency dependency implies the far field is more difficult to realise for higher frequencies. The effect of frequency complicates matters, as the far field may only be achievable over a restricted practicable frequency range. In other words, if the receiver is not far enough away from the array, the far field will only be achievable for low frequencies. Additionally, with oblique receivers, the far field distance is greater still due to an emphasised path length difference between signals.

It is possible to estimate the point of the beginning of the far field for a reasonably directive array, when the wavelength of the projected sound is much smaller than the source’s largest radiating dimension (Kinsler and Frey, 2000):

$$r_{\min} \approx \frac{L^2}{4\lambda}$$

where *r* is the distance from the source, L is the length of the largest dimension of the source and λ is the wavelength of the projected sound.

9.2 Level of test signal

It is of importance to initially determine whether it is possible, at any range, to simulate the sound level of noise.

Figure 9-1 shows the spectrum of recorded piling noise at 1 km from an active piling operation, piling 4.7 m diameter steel monopiles recorded during the construction of Burbo bank windfarm (Nedwell *et al.*, 2007). Over this data has been plotted the measured output Source Level from an FGS Type 30-600 sound projector driven at 30 V. This may be considered to be the effective sound level at a range of 1m from the projector. It may be seen that the level of sound generated by the projector is sufficient to reproduce the piling noise level. This would mean that a single FGS 30-600 sound projector can produce a level of sound representative of piling operations at 1 km from the source.

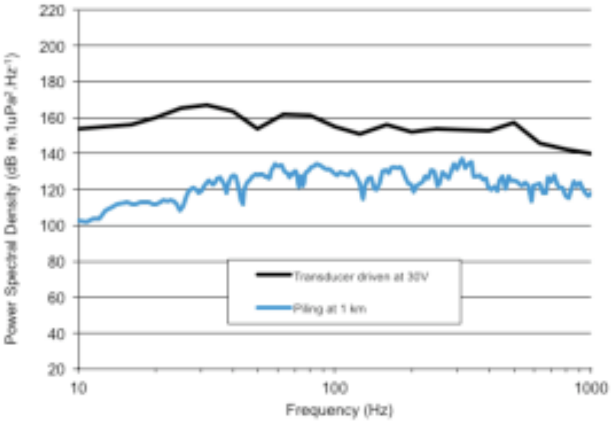


Figure 9-1: A piling spectrum and low-mid frequency sound projector response.

9.3 Characterisation of experimental sound field

When performing a critical experiment it is essential that the condition under which the animals are exposed is carefully designed prior to the experiment, and documented to demonstrate that the experiment is representative of typical exposure conditions. It is equally important to ensure that the conditions in which the animal is exposed during the experiment mimic those in which the animal will be exposed under typical field conditions. They must hence provide both an adequate level and a sound field that mimics that of the source at a relevant distance. It is unlikely that, for playback experiments, a single sound projector near to the experimental facility and hence in close proximity to the animal will provide an adequate model of a sound field from a distant source. Hence in order to design an experiment, a criterion must be developed to allow the spatial quality of the sound field to be assessed.

It is relatively simple to address the frequency content of the noise, by measuring it and presenting the results as a spectrum. However, the way in which the spatial behaviour is investigated is worthy of particular attention. Formally, the field may be decomposed as an equivalent set of plane wave components, generally known as wave vector analysis. This enables the experimental field to be compared with a true far field representation. The method is exact but difficult to implement, and so an alternative strategy has been adopted.

The concept of "field error" has been introduced. Conceptually, we might consider an area 20m by 20m, in which an experiment on fish avoidance of noise will be performed. If the experimental source is piling noise at distance, it would generate a given sound field in this area. The sound would decrease slightly across the area. If a projector array that attempts to mimic the noise is employed as source, the level will drop significantly across the area and will also vary considerably as a result of near-field effects (Kinsler and Frey, 1982). The *variation* of the noise field from that of a distant source may thus be considered to be a measure of its spatial accuracy in modelling it.

Also, some fish are sensitive to particle velocity rather than sound pressure. This is significant, since the particle velocity increases greatly in the vicinity of the source. Animals that are sensitive to particle velocity would hence be expected to react more strongly in the vicinity of a transducer than a measurement of pressure would indicate.

This has been initially evaluated using an acoustic program written by the authors, *PrISM*, which uses the image-source model to estimate the noise level and distribution of sound pressure and sound particle velocity from underwater sound projector arrays in shallow water. Initially, an assumption has been made of a 20 m x 20 m area in open water with a depth of 25m. This may be amended when detailed analysis of an optimised experiment is undertaken.

Table 9-2 illustrates the considerations that might apply when choosing the size of the array for the experimental sound and particle velocity field. As an example Table 9-2 and the rest of this chapter uses the audiogram of the herring (*Clupea harengus*). Although the herring primarily hears sound pressure rather than particle velocity, the two measurements are included here to compare the sound pressure and particle velocity levels in the near field and far field. As a hearing specialist, the herring appears to have one of the best hearing capabilities of any known fish and serves as an example of the necessary sound levels that need to be achieved for a successful experiment.

Source Distance from Test Area (m)	**Number of Sources (N)**	**Average Pressure Level dB_{ht} *(Clupea harengus)***	**Average Particle Velocity Level dB_{ht} *(Clupea harengus)***
1	1	117.1	127.6
7	1	101.7	100.9
38	4	100.2	100.7
73	9	100.2	100.4
100	16	100.9	100.6

Table 9-2: Estimated dB_{ht} (*Clupea harengus*) Level for pressure and particle velocity at selected distances for various numbers of transducers.

Only a square array (*i.e. n* transducers by *n* transducers where *n* is an integer) has been considered at this point. If, say, it is decided that a minimum average level of 100 dB_{ht} (*Clupea harengus*) is required, to ensure a reaction, it is seen that this may be achieved by 4 projectors at 38 m from the test area, 9 projectors at 73 m, or 16 projectors at 100 m. While on cost and simplicity grounds it may be tempting to use a small array close to the experimental facility, the field from projectors in close proximity to the experimental area will not be representative of sound from a distant source. A uniform field with a clear directional cue is important because, if not achieved, a fish exposed to the noise will not perceive it as a distant source and so may not respond in a consistent fashion, making testing for a reaction extremely difficult and the results ambiguous.

The results indicate a similarity between the two field types which changes little when the number of sound projectors is varied or the distance between the test area and sound projector array is increased. Average Levels for the two field types differ by approximately 0.3dB_{ht} on average (for the configurations tested) leading to the following conclusion; provided the sound projector array is positioned at least 7m from the test area, the difference between the resulting pressure and particle velocity fields is insignificant. Conversely, when the sound projector array is closer to the experimental area the resulting fields are likely to be significantly different (up to 10 dB_{ht} at 1 m).

An increase in level difference is to be expected in the reactive near-field of the source where the particle velocity is much more prominent.

Figure 9-2 illustrates how the test field error within the test area varies with the distance from the transducers. The figure presents the level of sound from a source, calculated using PrISM. However, the results are presented as the level for a source at various different distances, normalised by the level for a source at 250m.The results may therefore be regarded as the deviation in level from that which would result for a true far field noise source. Figure 9-3 demonstrates the same situation, but shows the particle velocity produced by the transducers, normalised by the level at 250 m.

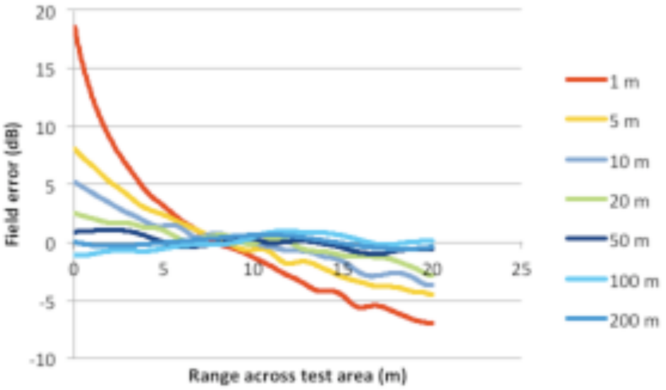


Figure 9-2: RMS Pressure Levels along a Single Plane of the Experimental area

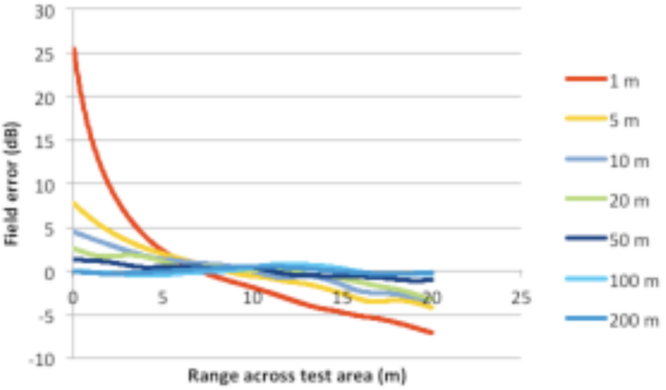


Figure 9-3: RMS Particle Velocity Levels along a Single Plane of the Experimental area

It may be seen that for projector arrays closer than 20m, the deviation from the average sound pressure level is greater than ±3dB$_{ht}$, and thus their field might be considered to be significantly different from a far field from a distant piling source.

This information can be combined with that above to provide an initial indication of the number of transducers needed to ensure both an adequate level of noise to ensure a reaction, and a field from a sufficient distance to ensure its behaviour is similar to a field from a noise source at range. It may be seen that if a maximum field error greater than ±3 dB$_{ht}$ is assumed, an array of 9 projectors at 73 m would be sufficient to both generate an adequate level, and a sufficient field representation for herring. If a less stringent criterion of ±5 dB$_{ht}$ is adopted, an array of 4 transducers at a distance of 38 m may be used.

Figure 9-2 and 9-3 present simple views of the pressure and particle velocity distributions across the test area as a function of source distance (for a single source). Y-axis values are given in terms of the deviation from an average level inside the experimental area. Again, the figures show similar distributions for both pressure and particle velocities, with the largest variation on the side of the experimental area closest to the source (see x-axis values close to 0m).

The above data indicate the importance of the array design and placement in achieving the appropriate sound field. It can clearly be seen that the array must be placed at a distance of at the very minimum 5 m from the test area in order to produce a sound field in which the pressure and particle velocity distributions have a relationship approximately of far-field conditions. But it will be desirable to keep a minimum of 20m distance to the transducer array to ensure a homogeneous field across a 20 m-wide test area.

Figure 9-4 displays PrISM plots for pressure and particle velocity distributions at a far shallower depth of 1m. The figure shows concisely how the two fields can differ much more significantly as the measurement plane moves upwards and indicates a level difference of approximately 5dB (ref. 1µPa) between fields when at this depth.

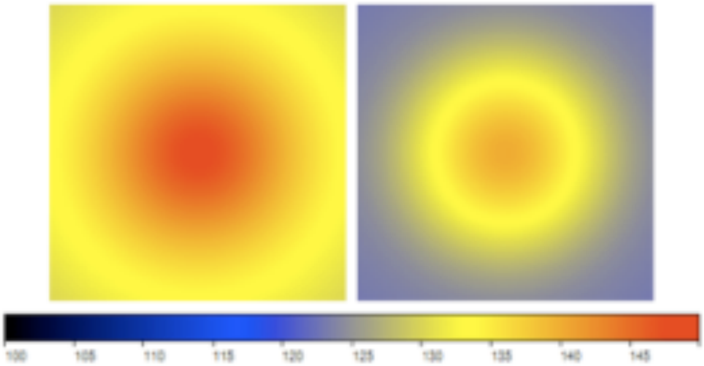


Figure 9-4: Particle Velocity Field (left) and Pressure Field (right) for the same Source Near-surface (1m depth). (Note difference of approximately 5dB due to boundary effects).

10 Mitigation

10.1 Introduction

Marine habitats along with resident fauna and flora are a source of considerable wealth to human society and are, or should be, considered a shared asset to mankind. In order to rationalize and ensure its long term use and conservation there are a number of guidance and regulatory schemes enforced by international and national legislation (Wood 1995, Firestone & Jarvis 2007, Ducrotoy & Elliott 2008, Gotz *et al.* 2009). A fundamental tool to identify potential impacts is the Environmental Impact Assessment (EIA) which is required for most offshore developments in Europe ((EU Directive 85/337/EEC 1985) as amended by (EU Directive 97/11/EC 1997) and (EU Directive 2003/35/EC 2003)). Further, in direct response to the mandate set forth by the European Marine Strategy Framework Directive (EU Directive 2008/56/EC 2008), the UK has enacted the Marine and Coastal and Access Act (2009), which integrates environmental decision-making procedures into a unified framework. In this regulatory context, the process by which impacts on ecosystems are minimized or avoided is known as mitigation (Harwood 2002). Mitigation is thus a management tool arising from the need to harmonize societal needs and public opinion with the conservation of natural ecosystem. Economic or technical arguments often make it difficult to completely eliminate the pressures and residual impacts may remain. These, when relevant, can be addressed though compensation (or restoration) schemes where the expected residual loss of ecosystem function is rebuilt elsewhere (Wood 1995). Both mitigation and compensation are generally considered together in management plans of those public and private projects, which are likely to have significant effects on the environment. The overarching intention of mitigation is thus to reduce or prevent unnecessary human pressure on natural systems while allowing for economic activities.

In clear contrast with most human pressures on marine systems, the introduction of sound energy in the ocean is short-lived and leaves no detectable physical alteration. For that reason stopping the source of noise or reducing its intensity is a priori the best form of sound mitigation. The real difficulties for mitigation are in the wide range of concurrent human activities producing underwater sounds (Table 10-1). Man-made sound is now an ubiquitous and ever increasing pressure worldwide causing a globally continuous background interference with natural sounds. Indeed for this reason, there has recently been a call for a 'quiet ocean' experiment, that is, a temporary cessation of human activities in the ocean (Boyd *et al.* 2011). Despite their global presence man-made sounds are not generally directly associated with any definitive impact of general concern apart from perhaps marine mammal strandings (Geraci & Lounsbury 2005). Sublethal effects such as masking of marine mammals communications are a much greater cause of concern, but the underlying science is still unclear and even prone to different interpretations and conflicts of interest (Wade *et al.* 2010).

Previous chapters have reviewed direct evidence of noise effects on fish and invertebrates that also suggest that direct, indirect or cumulative effects of noise harassment have the potential to exceed the level of biological relevance and have consequences on ecological processes. Therefore, mitigation measures have to be considered and its efficacy evaluated taking into consideration not only economic arguments but also conservation objectives and even moral considerations.

	Type of Waveform		
Sound source	Low and mid-frequency, impulsive	High frequency, impulsive sound	Low frequency, continuous
Accidental	Blasting Impact piling	Sonar	Vibropiling Dredging Shipping noise Drilling
Intentional	Acoustic deterrent devices Seismic airguns Communications	Acoustic deterrent devices	Acoustic deterrent devices Communications

Table 10-1: Type of activities causing sound pollution and characteristic waveform.

10.2 Need and scope of mitigation

Coastal areas are shallower, afford easier access and at the same time harbour the greatest diversity and productivity known to marine ecosystems. This coastal zone results in areas where there is a large spatial overlapping of noise and organism so impacts are more significant. Technological advancements have allowed access to an unprecedented range of marine resources, continuously extending the human footprint to almost every location in the sea (Lotze *et al.* 2006,Halpern *et al.* 2008). Sound pollution occurs as a result of marine development projects, dredging, energy extraction, shipping, fishing, leisure activities, defence, etc. Moreover, sound is also deliberately introduced by other activities such as seismic shooting, sonar, or underwater communications. Sound pollution is therefore a by-product of human activity and as such, it is governed by various factors which are mostly related to technological and economic factors, i.e., what it is possible to do, given the current technology and the need for economic development. But it is also liable to socio-cultural factors, i.e., what is socially and politically permissible by the majority of citizens. It is important to stress that mitigation is a management measure and, as such, is a mechanism intended to reconcile the exploitation of the sea with the preservation of marine ecosystems (Ducrotoy & Elliott 2008).

At first instance, mitigation should be proportional to the magnitude of the suspected noise damage (EU Directive 85/337/EEC 1985). Taking the view that any mitigation measures come at a cost, i.e. loss of profit or added investment on compensation schemes, any mitigation measure will have to be economically viable to be implemented or the activity causing the sound pollution will cease (Ducrotoy & Elliott 2008). Therefore, it will take some judgment to identify the necessary level of mitigation to reconcile economic development and societal expectations. In the case of sound which is in many cases a pressure incidental to many human activities, it is important to consider mitigation of cumulative[1] and in-combination[2] impacts. This ideally requires a comprehensive management plan where clear conservation targets and economic needs are identified. It is generally the case that a residual impact is tolerated if the expected socio-economic benefits outweigh the potential loss of ecological function. Much less discussed but nevertheless important are the potential added benefits of mitigation schemes. For example, the ecological value of a marine protected area (MPA) introduced to compensate for loss of ecological integrity may result in a net gain in ecological functioning for the overall area (Micheli *et al.* 2004). Mitigation is therefore a management option and requires the careful weighting of potential pros and cons not only with regards to ecosystem conservation but also to socio-economic and socio-politic considerations.

10.3 Mitigation options

The intention of mitigation is to avoid exposure or to reduce it to levels that are harmless to the animals that might be exposed. Traditionally most sound mitigation efforts have been concentrated on marine mammal programmes (Wood 1995, Gordon *et al.* 2007, Compton *et al.* 2008, Andrews *et al.* 2009) , but in general, any mitigation is likely to be also beneficial for other marine groups including fish and invertebrates. In most circumstances there is a range of mitigation options and these could be used in isolation of combined for greater effect (Table 10-2). All methods work on three basic premises that can be characterized by the concepts of reduction, technical refinement and replacement. The mitigation actions are chosen primarily in base of the type of activity producing the sound pollution. This is a very practical approach as the possible mitigation options are effectively limited by the technical specifications of the equipment generating the noise and the deployment method. Finally, while scoping a mitigation plan, it is necessary to know the expected vulnerability, i.e. threshold of biological significance, of the animals for which the mitigation is intended. Audiograms are necessary and should be carefully considered to define the level of required mitigation, although due to the cost and difficulty of producing these relatively few are available (Nedwell *et al.* 2007).

	Method	Mitigation Examples	Relevant Activity
1	Stop sound emission	stop activity, technological replacements	All
2	Minimising sound output	bubble curtains, shrouded devices, reduce vessel speed, silent vessels	All
3	Trading intensity for duration	Lower piling force and increase driving strikes	Pile driving, drilling
4	Safety exclusion zones or precautionary mitigation	Marine Protected Areas, compensation zones	Basting, pile driving, drilling, offshore renewable, sonar
5	Temporal and spatial restrictions	Close areas during breeding season	Pile driving, drilling, sonar
6	Built up noise intensity overtime	Soft-start or ramp-up	Pile driving, seismic shooting, sonar
7	Acoustic deterrent devices	Power plant intake screens	Pile driving, energy generation
8	Sighting-free period	Observers, passive acoustic monitoring	Pile driving, seismic shooting, sonar

Table 10-2: Mitigation methods

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[1] The term “cumulative effects” refers as the impact on the environment which results from the incremental sum of impacts when added to other past, present, and future actions.

[2] The term “in-combination effects” refers to the combined impact of different pressure types on one sensitive ecological receptor

10.3.1 Offshore construction and exploration

For marine developments and oil and gas exploration, great efforts have been placed in mitigating piling noise (Wursig *et al.* 2000, Nedwell *et al.* 2003, Carlson *et al.* 2007, Compton *et al.* 2008, Andrews *et al.* 2009) and seismic shooting (Deffenbaugh 2002, Compton *et al.* 2008). Piling, seismic shooting and also blasting, are loud impulsive sounds able to cause tissue damage. Most mitigating measures linked to this type of sounds aim to reduce the peak intensity and thus reduce the likelihood of exposure to the levels causing direct injury or damage (permanent or transitory) to the hearing apparatus. This approach, reducing the intensity or loudness of the sound at source, falls within the reduction approach. For seismic shooting keeping sound emission to lowest practicable levels is the mitigation measure of choice (Compton *et al.* 2008).

In the case of piling several engineering options have been used. For impact pile driving, mitigation options include the use of smaller piles, free or encased bubble curtains, shrouded ramming piles, soft-starts and duration of the ramming. In general these measures reduce the intensity of the sound by 5-25 dB re 1uPa, with greater effect for high frequencies (Richardson *et al.* 1995, Wursig, 2000). A more intense effect may be obtained by replacing the method of driving the pile from impact hammers to hydraulic rams or vibratory drivers (Gotz *et al.* 2009), these alternatives could be considered either a technical refinement or a replacement strategy.

Additional or complementary measures to lower the exposure to noise can be achieved by removing sensitive receptors from the immediate vicinity of the sound source. For example seismic shooting, piling or blasting may be mitigated by the use of acoustic deterrent devices or soft-starts if these could drive the organisms away before the work commences (Gotz *et al.* 2009, Andrews, 2009). Limiting these activities to the months where the animals are using alternative areas works on a similar fashion. These constitute operational refinements and their common objective is to reduce the overlapping between the presence of sensitive receptors and the activity producing the sound. A different way to achieve the same result is by limiting the duration of the sound-producing activity or by implementing temporal and spatial restrictions to prevent noise during the time when the animals are likely to be present and/or are especially sensitive to noise disruption. The designation of quiet zones on a permanent or temporal basis is a very effective mitigation option to prevent disturbance to breeding animals for example. All these measures reduce or eliminate the likelihood of noise effects and work on the basis of technical refinements.

10.3.2 Sonar and communications

Echosounders, hydrographic survey sonar and military ranging sonar use sound waves to find submerged objects. They are widely used in safe navigation to measure depth or to localize fishing or military targets. Acoustic modems or beacons are similarly used for navigation and direction finding or to relay or acquire data. Acoustic decoys and active sonobuoys are also used by the military to localize submerged targets. Different from most noise-producing activities, where sound is a by-product of human activities, the use of sonar or communication devices introduces sound deliberately and as such the level and direction of the noise is controlled both in intensity, frequency and direction. An immediate mitigation option is to regulate these parameters to levels that minimize the effects on sensitive targets. For example energy levels may be reduced to the practical minimum. Mitigation on military vessels often involves the displacement of practices and war exercises to areas where there is low probability to interfere with marine fauna, soft-starts, passive acoustic monitoring, etc. Most guidelines are drawn up to avoid disturbance to marine mammals (Gotz *et al.* 2009) since it has been shown that, for example, that whale songs lengthen in response to sonar (Miller *et al.* 2000) - these guidelines work on the principles of reduction and technical refinements.

Fish with swim bladders are very effective underwater targets. Some hearing specialist fish are known to hear at the frequencies used by mid-frequency sonars and direct disruptions are likely. Physical injury is unlikely unless the fish is within the immediate vicinity of the transducers therefore behavioural reactions, temporary threshold shifts and masking might be the most likely effects of sonar (Popper *et al.* 2007).

Finally, complete replacement may be also possible. This option does not always require the complete cessation of activities, for example a particular sonar frequency of operation may be changed to an alternate frequency where there is little or no overlapping with sensitive receptors. It is also possible to combine several mitigation options, and combine these with vessel noise reduction measures. Sonar and navigation devices used on merchant vessels are widely used for safe navigation and will be difficult to reduce its use on the grounds of marine safety regulations. Instead technological refinements of transducers and signal processing algorithms as well as restrictions on certain waveforms may introduce better devices with reduced effect on marine life in general. Comparatively, military operations have a smaller footprint and might be mitigated in a more effective way than merchant vessels using exclusion areas (Gotz *et al.* 2009, Richards, 2007).

10.3.3 Shipping

Mechanical propulsion creates a steady source of noise pollution. The vast majority of the underwater noise and widest frequency range is generated by the propeller and other motion-related hydrodynamic noise. In addition to these other general machinery noise is also radiated from the main engines, gearing system, thrusters, generators, etc. The frequencies of noise created by boats are directly related to their size (Richardson *et al.* 1995), but in general the noise is characterised by relative low frequencies similar to the sensitive are of fish hearing. This means it has a potentially large area of impact and is especially likely to mask natural sounds. This scenario rules out acute mitigation measures used to reduce the effect of point source impulsive sounds such as bubble curtains, acoustic deterrent devices or soft-starts methods to name a few. But, in turn, it is especially suitable for mitigation measures based on technological refinements such as better designs to reduce the overall acoustic signature, i.e., producing a quieter vessel or reduced operational speed as well as the diversion of shipping lanes away from sensitive areas.

A range of technical refinements have been introduced with success, for example technological developments in ship propulsion have been applied to research and military vessels. Some of these new developments are likely to result in improved performance and more fuel-efficient operation. If these factors are taken into account noise-reduction may be more widely introduced in new vessels, especially as there is some evidence that fish do not avoid such ‘quiet’ vessels (Fernandes *et al.* 2000a, b, De Robertis, 2010). Nevertheless, the evidence is still unclear as there have been also reports showing similar or stronger reaction to vessels purposely designed with a reduced noise signature (De Robertis *et al.* 2008, Ona, 2007). More drastic measures such as limits in vessel traffic may not be economically feasible or even possible. Re-routing some shipping lanes or the designation of Marine Protected Areas as quiet areas may be a more practical mitigation of vessel noise.

10.3.4 Blasting

To minimise the waterborne blast the minimum quantity of explosive that will achieve adequate shattering is used; this is a function of the structure and spacing between the holes. Use is also made of delay blasting. The radiating underwater blast wave may be of significance because water is an efficient conductor of blast waves. Therefore the explosives are also fired in limited individual charges (“delays”) successively, rather than in a single detonation. Using this technique the level of blast is reduced, as it tends to be associated with the individual charge sizes rather than the total charge weight.

10.4 Uncertainty

Mitigation actions are usually considered in base of the nature of the activity causing the acoustic disturbance. The aim is to maintain or improve the conservation of marine ecosystems while at the same time allowing for profitable commercial initiatives, leisure, research or education to take place. The effectiveness of any method is likely to vary between species and circumstances, with some options better suited to certain activities (Gotz *et al.* 2009). There are no general rules and the decision is often based on the relative facility to implement them. Mitigation could result from voluntary actions but it is more likely that the need for mitigating measures results from compulsory schemes of licenses and consents. In any case, to select appropriate mitigation measures, the possible routes of impacts and magnitude of the effects and risks of noise pollution will need to be assessed with enough level of precision (Harwood 2000). The repercussions are that developers and regulators first need robust methodologies to detect and quantify the effects of underwater sounds, an area that is still in a very early stage of development (Diederichs *et al.* 2008), this is where metrics such as the dBht(species) scale (Nedwell *et al.* 2007) become useful, as discussed in previous sections.

Likewise, once implemented, mitigation measures will need to be assessed to ensure these are effective. As discussed in the previous chapter, industry-funded and regulatory research, such as ecological and environmental impact assessments or surveillance monitoring could generate basic understanding and provide important benefits to future developments and regulatory actions in the field of noise mitigation. In this context it would be advantageous to base mitigation decisions on better models than simple risk tables based on qualitative assessment and expert knowledge. Models able to integrate different sources of uncertainty such as Bayesian decision networks or fuzzy logic (Marcot *et al.* 2001, Ocampo-Duque *et al.* 2006, Said 2006, Sylaios *et al.* 2010) may provide a more subjective way to inform management decision. In any case it is essential to identify and address information shortfalls through scientific research and use the knowledge gained to better understand the underlying natural systems and the effects of noise on them.

Human civilization has in the last century developed to a level that has started to influence global processes. There is much less general awareness of global effects occurring in the oceans but as direct result of an ever-increasing use of marine resources mankind’s pressures on marine habitats is now greater than ever (Lotze *et al.* 2006, Halpern *et al.* 2008). Generally we are most concerned about activities that have already caused change (i.e. impacts) with respect to the historical conditions. For example, commercial fishing has resulted in overfishing, gas and oil exploitation regularly results in oil spills or shipping needs safe port facilities which impact on coastal areas. Sounds of various intensities and frequencies are in great extent incidental by-products of anthropogenic activities. Some others are introduced deliberately to support exploration for new resources. We are becoming increasingly aware of the risks of sound pollution (Slabbekoorn *et al.* 2010) and, as such, ways to mitigate their impact are now starting to be included in management plans. However, there is still a need for scientific validation of the performance of mitigation measures, both technical feasibility and socio-economic viability.

10.5 Recommended sound monitoring methods

To minimise the effects of noise the Marine Strategy Framework Directive put together by Task group 11 (Tasker *et al*, 2010) lays out 3 indicators to help assess any increase in the level of underwater noise. These are not designed to show levels of environmental damage in a particular area, but are designed to show increases in underwater noise when measured in subsequent years.

These indicators are:

1. Low and mid-frequency impulsive sounds: The proportion of days within a calendar year, over areas of 15'N x 15'E/W in which anthropogenic sound sources exceed either of two levels, 183 dB re $1\mu Pa^2s$ (i.e. measured as Sound Exposure Level, SEL) or 224 dB re 1µPa peak (i.e. measured as peak sound pressure level) when extrapolated to one metre, measured over the frequency band 10 Hz to 10 kHz.
2. High frequency impulsive sound: The total number of vessels that are equipped with sonar systems generating sonar pulses below 200 kHz should decrease by at least x% per year starting in 2012.

3. Low frequency, continuous sound: The ambient noise level measured by a statistical representative sets of observation stations in Regional Seas where noise within the 1/3 octave bands 63 and 125 Hz (centre frequency) should not exceed the baseline values of year 2012 or 100 dB (re 1µPa RMS; average noise level in these octave bands over a year).

Indicator 1 is intended to deal with many types of noise, but primarily piling operations. The indicator is intended to serve as a measure of the frequency with which piling operations are disturbing the marine life in a particular map rectangle. It is noted, however, that the measure does not consider the behavioural effects of noise, which may dominate at considerable ranges.

Indicator 2 serves as a check on commercial and private shipping. Due to the low level of background sound at high frequencies and the corresponding sensitive thresholds of marine mammals, even low levels of noise can produce a significant effect. For this reason sonar systems are suggested to be one of the main dangers to marine animals, especially in areas of heavy shipping.

Indicator 3 is designed to measure noise produced by commercial shipping, which is the primary cause in the increase in low frequency, continuous sound in the ocean. McDonald *et al* (2006) shows that there has been an increase of 10-12 dB at frequencies of 30-50 Hz over the study conducted by Wenz (1962), at a time roughly corresponding to a doubling in shipping traffic over the last survey. With shipping traffic forecast to double again from the time from when the McDonald survey took place, until 2020, an even greater increase in background sound levels is expected to take place. However, the current 3rd indicator is not sufficient to sample the full range of shipping noise. Such noise is present in the 31.5 Hz band as well as the 63 and 125 Hz as proposed in the indicator.

The problem with these measures is that they represent quantities that are easily measured, rather than any quantity that is directly related to the significance or effects of noise. They may be criticized on two grounds.

1. Since the overall level of noise will be determined by level of noise in the part of the spectrum that dominates, the two measures proposed (SEL and peak pressure) will tend to measure sound at the peak spectral levels, say of a few Hz to a few tens of Hz. In this region, the noise is dominated by physical processes associated with wave passage rather than anthropogenic noise. Consequently, indicators 1 and 3 are considered unlikely to be associated with the level of man-made noise in an area.
2. Inspection of the hearing ability of most marine mammals demonstrates that they have evolved to make use of high frequencies of sound, where background noise levels are lowest. Thus noise pollution at high frequencies, that is, at their most sensitive hearing frequencies, may well be of most significance to marine mammals. The indicator 2 proposed is thus unduly simplistic, and is likely to fail to characterise the effect of man-made noise on marine life.

Baseline studies have been conducted by many authors as far back as Wenz (1962), but so far the only broadband study of noise in British waters is that presented in this report. Sources of data such as SOSUS, the US navy developed chain on underwater listening stations, cover far too limited a frequency range to be able to characterise noise in terms of its likely effects on marine mammals having hearing over an aggregate range of at least five decades of frequency. It is considered critical that measurements of noise should be made in a way that recognises the spectral significance of noise.

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