SOUND AND VIBRATION EFFECTS ON MIGRATING ADULT AND JUVENILE SALMON AT HYDROPOWER PROJECTS, CONSTRUCTION PROJECTS, AND IN THE NATURAL ENVIRONMENT
LOWER GRANITE DAM

Draft Literature Synthesis

Prepared for
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On behalf of
Anchor QEA, LLC

Prepared by
Anthony D. Hawkins
Loughine Ltd.

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<tr>
<td>µPa</td>
<td>micro Pascals</td>
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<tr>
<td>ABR</td>
<td>auditory brainstem response</td>
</tr>
<tr>
<td>AEP</td>
<td>auditory evoked potential</td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
</tr>
<tr>
<td>ASA</td>
<td>Acoustical Society of America</td>
</tr>
<tr>
<td>dB</td>
<td>decibel</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>Hz</td>
<td>hertz</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standards Organization</td>
</tr>
<tr>
<td>KE</td>
<td>kinetic energy</td>
</tr>
<tr>
<td>kHz</td>
<td>kilohertz</td>
</tr>
<tr>
<td>LFA</td>
<td>low frequency active sonar</td>
</tr>
<tr>
<td>m/s</td>
<td>meters per second</td>
</tr>
<tr>
<td>NEPA</td>
<td>National Environmental Policy Act</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>Pa</td>
<td>Pascals</td>
</tr>
<tr>
<td>PE</td>
<td>potential energy</td>
</tr>
<tr>
<td>PIT</td>
<td>Passive Integrated Transponder</td>
</tr>
<tr>
<td>PTS</td>
<td>permanent threshold shift</td>
</tr>
<tr>
<td>rms</td>
<td>root mean square</td>
</tr>
<tr>
<td>RSI</td>
<td>Response Severity Index</td>
</tr>
<tr>
<td>RWI</td>
<td>response-weighted index of injury</td>
</tr>
<tr>
<td>SEL</td>
<td>sound exposure level</td>
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<tr>
<td>SEL$_{\text{cum}}$</td>
<td>cumulative SEL</td>
</tr>
<tr>
<td>SEL$_{\text{ss}}$</td>
<td>single sound SEL</td>
</tr>
<tr>
<td>SPL</td>
<td>sound pressure level</td>
</tr>
<tr>
<td>STS</td>
<td>submersible traveling screen</td>
</tr>
<tr>
<td>TTS</td>
<td>temporary threshold shift</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
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<tr>
<td>USACE</td>
<td>U.S. Army Corps of Engineers</td>
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EXECUTIVE SUMMARY

This literature review and synthesis is intended to provide support for an evaluation of the effects of sound and vibration on passage of adult salmon through the adult ladder at Lower Granite Dam. The review describes the characteristics of underwater sounds, and considers those sounds produced in rivers, including those generated by human activities, and evaluates existing evidence of their effects on salmon behavior. Particular fish species considered are those native to the Snake River and listed under the Endangered Species Act, including Chinook salmon (*Oncorhynchus tshawytscha*; threatened), sockeye salmon (*O. nerka*; endangered) and steelhead trout (*O. mykiss*; threatened).

Rivers are often naturally noisy as a result of water flow and turbulence. Man-made sound sources associated with construction works on rivers and lakes will add to the background noise. Sources may include pile driving, dredging and trenching, concrete mining, the deposition of rock fill, and the operation of land- and water-based construction machinery. At hydroelectric dams and other installations, sound may also be generated through the running of the turbines and the opening and closing of sluices, lock gates, and screens, while an increase in recreational activities within the impounded area may result in noise from boats and jet skis.

Relatively little is known about the range of sounds associated with particular freshwater habitats and the contributions made to the soundscape by different natural and man-made sources. There have been few descriptions of the sounds generated in water by hydroelectric turbines or hydrokinetic devices, or by land-based machinery. Moreover, there have been very few experimental studies of the impact of noise from these sources upon fishes in rivers and lakes. Attempts to examine behavioral reactions of salmonids to underwater sounds have largely been unsuccessful, and the studies have often been carried out on captive fish and under inappropriate acoustical conditions. The one exception is that juvenile salmonids have been shown to display strong avoidance reactions to volume water displacements containing frequencies in the infrasound range (5 to 10 hertz [Hz]).

It became apparent during the preparation of the review that very little is known about the behavior of salmonids in response to underwater sounds in freshwater. Much of the relevant literature on the effects of sounds upon fishes included within the review is therefore
derived from studies of other freshwater and marine species. In addition, much of the experimental work that has been carried out has been conducted on fish held in tanks, cages, and enclosures rather than free-living fish. Such experiments can be valuable in allowing detailed observation of the responses of fish under controlled conditions. However, observations made on captive fish need to be supplemented by studies in the wild. Sound fields in small tanks and enclosures are dissimilar to those prevailing under more natural conditions in rivers and lakes, often with severe distortion of the sounds that are presented to the fish. In addition, captive fish may not show the same range and types of behavioral responses observed in the wild. Fish tend to behave differently when they are enclosed and their movements are restricted. Fish brought into captivity may also be damaged during capture, or their behavior affected by the circumstances under which they were reared. There is a real need for new observations on the behavior of wild salmonids exposed to sounds.

In water, sound is generated by the movement or vibration of any immersed object and results from the inherent elasticity of the water. As the source moves, kinetic energy is imparted to the water and is passed on as a travelling acoustic wave, within which the component particles of the water are alternately forced together and then apart. The particles of the water oscillate back-and-forth along the line of transmission in waves of compression (increase in pressure) and rarefaction (reduction in pressure). The disturbance propagates away from the source at a speed that depends on the density and elasticity of the medium. Sound travels almost 4.5 times faster in water than in air. Local hydrodynamic effects also occur in water. These may also result in local pressure waves and motion of the medium. To a fish, these hydrodynamic (rather than strictly acoustic) phenomena may be indistinguishable from sounds.

Propagation of sound in shallow water environments like rivers can be very complex as a result of the presence of many discontinuities and complex topography. It is often difficult to predict or model sound transmission. Propagation of low-frequency sounds may be especially constrained in shallow waters. However, low-frequency sounds generated within the substrate, including the riverbed, may travel considerable distances. The energy from substrate and interface waves can be reradiated into the water and may be detectable by salmon and other fishes.
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It is important to recognize that all fish, including salmon, respond to the particle motion accompanying passage of a sound rather than the fluctuations in pressure. Only a few species of fish can also detect sound pressure. Measuring or estimating the sound fields to which fish are exposed poses formidable difficulties. It has become commonplace to estimate the particle velocity and its directional components from measurements of the sound pressure. Such estimates are unlikely to be valid in the complex acoustic environment within a river, where it is necessary to measure the particle motion directly. The complexity of underwater sounds generated by different sources also requires a number of different metrics, depending on whether the sounds are continuous, impulsive, or repeated.

Sound is important to fishes. Many fishes use sound to communicate with one another, detect prey and predators, navigate from one place to another, and select appropriate habitats. Even though some fishes may not use sounds of their own to communicate, it is likely that all fishes use sound to learn about their environment by detecting and using the soundscape or “acoustic scene.” In effect, sound detection provides fishes with three-dimensional information from a larger space around them than is possible using vision, olfaction (the sense of smell), or electro-reception. Sound detection may be especially important for migratory fishes like salmon, which may navigate by using positional cues provided by natural geophysical sound sources.

Hearing abilities vary greatly between different species of fish. However, relatively few experiments on fish hearing have been carried out under appropriate acoustic conditions and many of the measurements made in tanks are unreliable, as they have been expressed solely in terms of sound pressure. Auditory thresholds for fish are determined using a variety of techniques. Those based on behavioral conditioning, and carried out under controlled acoustic conditions, are the most reliable. In general, fishes have a more restricted frequency range than mammals or birds. However, both frequency range and hearing sensitivity vary from one species to another. Recently, fishes have been classified as follows in terms of their hearing abilities:

- Fishes without a swim bladder with relatively poor hearing (particle motion detection): including sharks, skates, and rays; sturgeon; and many species of flatfish.
- Fishes with a swim bladder that is not involved in hearing and which have relatively poor hearing (particle motion detection): including salmon and steelhead trout.
Executive Summary

- Fishes with a swim bladder involved in hearing, which show more acute sensitivity and a wider frequency range (primarily sound pressure detection): including the cod, *Gadus morhua*, and its relatives, eels (Anguillidae), herrings (Clupeidae), and shad (Alosinae). Exceptionally, American shad (*Alosa sapidissima*) and blueback herring (*A. aestivalis*), are able to detect ultrasonic frequencies (above 20 kilohertz [kHz]).
- Fish eggs and larvae, for which little information is available.

It has been shown clearly that the salmon is sensitive to particle motion rather than sound pressure. Salmonids have a rather restricted frequency range, with a sharp cut-off at frequencies above 380 Hz. They are also much less sensitive to sounds than species like the shad and eel, and marine species like the cod and herring (*Clupea harengus*). At low frequencies the cod tends to be limited in its ability to detect sounds by the level of background noise. In contrast, masking of auditory thresholds for salmon by the level of ambient noise does not occur under very quiet sea conditions. It occurs only at the much higher noise levels that occur in fast flowing rivers. Nevertheless, salmon do detect sounds, and their lower sensitivity may simply reflect the fact that they spend much of their lives within noisy river systems, where the level of background noise is high. For salmon, frequencies in the infrasound range (1 to 10 Hz) have been shown to be especially effective for evoking both awareness reactions and avoidance responses. It has also been suggested that salmon may use the ambient infrasound in the ocean, produced by waves, tides, microseisms and other large-scale motions, for orientation during migration. However, the full importance of sound, including infrasound, to fishes like salmon remains to be evaluated.

Behavioral effects in fishes from exposure to sounds may operate over substantial distances from some sound sources. As well as simple startle reactions, which may have little importance in terms of effects upon vital functions, significant change in behavior may take place, with clear effects upon vital functions. These may include the break-up of fish aggregations, long-term changes in distribution, such as moving from preferred sites for feeding and reproduction, or alteration of migration patterns.

In addition to generating sound, moving bodies in water, and even stationary bodies in a flow field (e.g., boulders in a river) can generate hydrodynamic waves, surface waves, turbulence, and wakes. These local water movements may stimulate the lateral line system
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Fish essentially have the ability to make simultaneous particle motion measurements at multiple points along their body, giving them the potential to obtain information about turbulent eddies, local water currents, and the vortices generated by wakes. It is very likely that salmon make extensive use of their well-developed lateral line system for detecting and responding to local sources of turbulence and for orientating to the hydrodynamic stimuli that are prevalent in rivers. These responses to hydrodynamic stimuli have been used to manipulate fish movements in fish-avoidance schemes. It has been suggested that fish may create a hydrodynamic image of the world around them that allows them to navigate within topographically complex environments. Moreover, it is not only the lateral line that might serve to control the movements of fish in the presence of local water currents and turbulence. The inner ear in fishes is capable of detecting linear and angular accelerations and may play a key role in the orientation and navigation of fish.

This review considers whether any thresholds can be defined, in terms of the characteristics of sounds that are known to elicit responses in salmon, which might enable any impacts to be assessed. A report from an American National Standards Institute (ANSI)-Accredited Standards Committee has recently addressed this question and sets out broadly applicable sound exposure guidelines for all fishes. Guidelines were developed for broad groups of fishes, defined by the way they detect sound. Different sound sources were considered in terms of their acoustic characteristics and appropriate metrics were defined for measurement of the received levels. The resultant sound exposure guidelines for salmonid fishes are presented in Tables 1 through 3 in Section 5 of this review. However, clear numerical guidance can only be provided for responses to high-level impulsive sounds, in terms of levels that cause mortality, recoverable injury, or temporary threshold shift (a temporary change in hearing sensitivity). Guidelines cannot be given for continuous sounds because relevant data are simply not available.

There is a particular lack of data on the behavioral responses of fishes like the salmon to sound exposure. Monitoring behavioral responses is especially important, as these responses can occur at moderate sound levels and may therefore take place at some distance from a source. Behavior is also of particular importance in terms of assessing effects on salmon in and around hydroelectric installations. There are some data for several marine fishes on responses to impulsive sounds, like those generated by pile drivers and seismic air guns.
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However, there is a complete absence of data on responses of salmon to continuous sounds, apart from experiments done on the responses of salmon to short bursts of infrasound. No sound thresholds can currently be set to define those sound levels known to elicit behavioral responses in salmon.

Other than the knowledge that salmonids detect particle motion and respond to high levels of infrasound, few data are available to guide assessment of the effects of construction on the fish passage environment of fish ladders for adult salmonids. In most respects the proposed work on Lower Granite Dam, particularly the parts related to measurement of sound and vibration within the fishway, in the tailrace, and near fish ladder entrances, caused by construction activities, will be original work with few (if any) precedents. New scientific observations need to be made on the behavior of salmon in rivers if the impact of sound exposure upon them is to be fully understood.

River systems contain a wide variety of habitats including riffles, shoals, and waterfalls that may have their own distinctive soundscapes, which may greatly influence the movements and migrations of fishes. To take forward work on the Snake River and Lower Granite Dam, this review suggests that there is a need for more information on the ambient noise levels prevailing in the river and in and around the dam and its associated structures, as well as information on natural background sound in free-flowing large rivers. Measurements of the sound fields generated by any man-made sources in the vicinity of the dam are required, including the sounds generated in water and in the substrate by the hydroelectric turbines themselves, fishways, bypasses and their associated machinery, or by any land-based construction equipment to be deployed. Such studies must measure particle motion and its directional components, as these are especially important to salmon.

This review concludes that examining the detailed behavior of salmon and steelhead trout at different locations within the Snake River and fish passage systems may yield important insights into those physical features of the local environment that influence fish movements. While the detection of Passive Integrated Transponder (PIT)-tagged fish may assist in monitoring passage at different points within the river, it would be beneficial to supplement those measurements with direct observations of fish behavior made using television cameras (in air and in water), high-resolution scanning sonar, and active fish tracking, using either...
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acoustic or radio tags. Such techniques would allow the movements of fish to be observed in real time, and directional and other responses to topographical features, obstacles, and particular sources of both sound and hydrodynamic stimuli to be examined in greater detail.

Should salmon respond to particular acoustic features of the environment, including local man-made sound sources, it might be beneficial to carry out sound playback experiments at different locations within the Snake River to allow responses to sounds at different levels to be determined and dose/response relationships defined. Such experiments might allow behavioral sound exposure criteria to be put forward for salmon, defining those sound levels that might result in responses that put salmon populations at risk.

This review has identified a number of wider information gaps relating to:

- Natural noise levels in rivers
- Particle motion measurements
- Characterization of sound sources
- Hearing abilities of salmon
- Masking of sounds by noise
- Behavioral responses of salmon to sounds
- Habituation of responses
- Risk analysis

Finally, it is evident that the work that is to be carried out to evaluate the effects of sound and vibration on passage rates of adult salmon through the adult ladder at Lower Granite Dam will enable further progress to be made in understanding those key factors that influence the upstream movements of salmonid fishes.
1 INTRODUCTION

1.1 Context

The purpose of this literature review and synthesis is to provide support for an evaluation of the effects of sound and vibration on passage rates of adult salmon through the adult ladder at Lower Granite Dam. The effects of sound reviewed for this synthesis are related to the construction being undertaken to improve temperature regulation in the adult ladder and improvements to the Juvenile Bypass System at the dam. The review considers the effects of sounds on fishes, with a focus on those sounds produced by normal dam operations and construction activities affecting salmon behavior.

Lower Granite Dam is part of the Columbia River Basin system of dams. It was built and is operated by the U.S. Army Corps of Engineers (USACE). The dam is a concrete, gravity run-of-the-river dam on the lower Snake River in the State of Washington, USA. Lower Granite Lake, which extends 39 miles east to Lewiston, Idaho, is formed behind the dam. The project provides hydroelectric power, incidental irrigation and recreation, and barge navigation to central Idaho, allowing Lewiston to function as a shipping port.

Lower Granite Dam is the most upstream dam that allows for fish passage on the main stem of the Snake River. Anadromous adult salmonids depend on passage around Lower Granite Dam to complete their life cycles. Native Snake River salmonid populations have been severely impacted by barriers to passage and several are protected under the Endangered Species Act including Chinook salmon (Oncorhynchus tshawytscha; threatened), sockeye salmon (O. nerka; endangered) and steelhead trout (O. mykiss; threatened). Coho salmon (O. kisutch) were extirpated from the Snake River in the 1980s prior to the listing of other salmonids in the Endangered Species Act. However, efforts are being made to re-introduce coho salmon and several thousand have been passed around Lower Granite Dam in recent years.

A single fish ladder allows adult salmon and steelhead trout to migrate upstream around Lower Granite Dam. Salmon may enter the adult ladder by multiple entrances, and pass through collection channels along the face of the dam. The channels merge at the base of a
pool-and-weir fish ladder that gains approximately 30 m in elevation, allowing fish passage to the forebay of the dam.

A Juvenile Bypass System passes juveniles through the dam to collection facilities where fish can be passed back to the river, or loaded onto barges or trucks for transport through and around the Snake and Columbia River dams. USACE has also installed a removable spillway weir to improve the in-river passage of juvenile salmon via the spillway. Further improvements to the Juvenile Bypass System are planned.

There is a general lack of information on the effects of sounds on fishes, especially in large rivers and fishways at large hydropower dams. The complex acoustic environments to which salmon are exposed in rivers make both the sounds and their effects difficult to measure. The behavioral responses of salmon to sound in these environments have not previously been investigated in any detail.

1.2 Sounds and Fishes

Since the start of the Industrial Age, aquatic environments have been increasingly exploited. In particular, rivers have been used to provide a wide variety of services, including transport, water supplies, recreational activities, and the generation of power at hydroelectric stations. The latter may result in obstructions to the free movements of fish, including migratory salmon. Such human activities often involve the accidental or deliberate generation of underwater sounds. Today, in the early twenty-first century, those sources of sound have become more diverse and have the potential to add sound to large expanses of the aquatic environment. Some sources result in a chronic increase in low-level background noise over extended periods of time, effectively masking sounds of interest to fishes or having other behavioral effects. Other sources, while taking place over shorter periods, are more intense and have the potential to kill or injure fishes as well as alter their behavior (e.g., Slabbekoorn et al. 2010).

The various sources of man-made sound in water have been discussed extensively in the literature (e.g., Hawkins et al. 2008; Popper and Hastings 2009a, 2009b; Popper et al. 2014; Popper and Hawkins 2012; Hawkins and Popper 2014; Normandeau 2012). In brief, the...
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sources include (but are not limited to): pleasure boating, fishing activities, shipping, geophysical surveys for oil and gas, dredging, construction of bridges, hydroelectric dams and their turbines, harbors, oil and gas platforms, wind farms and other renewable energy devices, and the use of sonar by commercial and military vessels.

Fishes are especially sensitive to low-frequency sounds, below 1 to 5 kilohertz [kHz] depending on the species (Hawkins et al., 2015), although experiments with captive American shad (Alosa sapidissima) and blueback herring (A. aestivalis), of the family Alosinae, have shown that they can detect sounds at ultrasonic frequencies (reviewed by Mann et al. 2001, 2005). Particular sound sources associated with construction works on rivers and lakes might include pile driving, dredging and trenching, the deposition of rock fill, and the operation of land- and water-based construction machinery. At hydroelectric dams and other installations, sound may also be generated through the running of the turbines and the opening and closing of sluices, lock gates, and screens, while an increase in recreational activities within the impounded area may result in noise from boats and jet skis.

There is growing concern about the effects of man-made sounds on fishes. It has been pointed out that there are substantial gaps in our understanding of effects of these sounds (e.g., Popper and Hastings 2009a; Normandeau 2012; Hawkins and Popper 2014; Popper et al. 2014; Hawkins et al. 2015). Much of the information on effects currently comes from “gray literature” reports that have not been peer reviewed, are often anecdotal, and lack detail on experimental design and controls.

There are currently so many information gaps that it is almost impossible to come to clear conclusions on the nature and levels of man-made sound that have potential to cause changes in fish behavior or even physical harm. A recent paper by Hawkins et al. (2015) has set out priorities for future research. The origin of the analysis was a public workshop supported by the U.S. Bureau of Ocean Energy Management Environmental Studies Program, held in March 2012 “to identify the most critical information needs and data gaps” on the effects of various man-made sound on fishes, fisheries, and invertebrates resulting from the use of sound-generating devices by the energy industry (Normandeau 2012).
There is currently strong interest in developing appropriate sound exposure criteria, specifying those sound levels that might have adverse effects. Scientists, regulators, and industry have proposed criteria (e.g., Woodbury and Stadler 2008; Stadler and Woodbury 2009) but, to date, they have not been based on substantive data. An American National Standards Institute (ANSI)-Accredited Standards Committee recently published *Sound Exposure Guidelines for Fishes and Sea Turtles* (Popper et al. 2014). The guidelines were based on the work of an International Working Group that considered different sound sources in terms of their acoustic characteristics and effects upon a range of fishes. Appropriate metrics were defined for measurement of the received levels and definition of sound exposure criteria. Guidelines were developed for broad groups of fishes, based on their hearing abilities, defined by the way they detect sound. Fishes were classified as follows:

- **Fishes without a swim bladder with relatively poor hearing (particle motion detection):** including sharks, skates, and rays; sturgeon; and many species of flatfish.
- **Fishes with a swim bladder that is not involved in hearing and which have relatively poor hearing (particle motion detection):** including salmon and steelhead trout.
- **Fishes with a swim bladder involved in hearing, which show more acute sensitivity and a wider frequency range (primarily sound pressure detection):** including the cod and its relatives, eels, herrings, and shad. Exceptionally, shad are able to detect ultrasonic frequencies (above 20 kHz).
- **Fish eggs and larvae, for which little information is available.**

Depending on the fish concerned, its distance from the source, and the nature of the source, exposure to high levels of sound may result in the following effects:

- **Mortality and mortal injury –** immediate or delayed death due to injury
- **Recoverable injury –** injuries including damage to the ear, minor internal or external bleeding, etc.
- **Short- or long-term changes in hearing sensitivity (temporary or permanent threshold shift),** that may, or may not, reduce fitness and survival
- **Masking – where it is difficult for the fish to detect biologically meaningful sounds against the noise background**
• Behavioral effects – substantial changes in behavior for a large proportion of the animals exposed

The ANSI-accredited report (Popper et al. 2014) details the sound levels for different sound sources that are likely to result in these effects for the different categories of fish.

Relatively little is known about the range of sounds associated with particular freshwater habitats and the contributions made to the soundscape by different natural and man-made sources. In particular, there have been few descriptions of the sounds generated in the freshwater environment by hydroelectric turbines, construction machinery, or other activities. Moreover, there have been very few experimental studies of the impact of noise from these sources upon fishes in the wild, including salmonids.

1.3 Definitions

It is important to ensure that the right terminology is used in relation to discussions of the effects of underwater sound and vibration upon fishes. Currently no formal consensus exists regarding measurement and evaluation of the effects of underwater sounds. Different terms and metrics are often used in different contexts. There is no internationally accepted terminology, even for the description of underwater sounds.

Many measurements of underwater sounds have been made for specific purposes or for the preparation of environmental statements. There is no central repository for these data, nor are there standards or protocols for data collection. A report by the Netherlands Organization for Applied Scientific Research (Ainslie 2011) proposed some definitions and metrics, but these have yet to be agreed upon internationally. In 2011, the International Standards Organization (ISO) accepted an Acoustical Society of America (ASA) proposal to create a sub-committee dedicated exclusively to underwater sound. A working group was set up in 2012 dedicated to creation of a terminology standard. The publication of an International Standard for Underwater Acoustical Terminology is now planned for 2015. The draft paper, ISO/DIS 18405:2014 – “Underwater Acoustical Terminology” is available for purchase from: https://www.iso.org/obp/ui/#iso:std:iso:18405:dis:ed-1:v1:en.
The term *noise* is often used colloquially to describe unwanted sound, or sound that interferes with detection by humans and animals of any other sound that is of interest to them. However, noise is also used to describe background sounds in the environment, including the naturally occurring and spatially uniform sounds generated by distributed biological sources, weather events, or other physical phenomena, some of which cannot be assigned to individual sources (often referred to as *background noise* or *ambient noise*). In this review, the term *sound*, rather than noise, is used both to refer to identifiable man-made sources and distant man-made sources that cannot be located or identified. Where others used the terms ambient noise or background noise to describe naturally occurring sounds from distributed sources, or the term noise to describe interference with signal detection by fish, then that usage will also be followed.

In this review, a distinction is made between environmental *effects* and environmental *impacts*. Environmental effects are the broad range of potential measurable interactions between man-made sounds and biological receptors, including fish. Environmental impacts are effects that, with some certainty, rise to the level of deleterious ecological significance (Boehlert and Gill 2010). Thus the effect does not indicate the significance, whereas impact deals with the severity, intensity, or duration of the effect upon fish populations and the wider ecosystem.

The term *soundscape* is used in this review to describe the physical sound field in terms of the spatial, temporal, and spectral distribution of sound at a particular time and place. The term does not consider the sound field as experienced or perceived by any organism living there (which is better described by the term *acoustic scene*).

In considering effects of sound (or any stimulus) on organisms, reference is often made to *acute* or *chronic* exposure or effects. *Acute* exposure occurs when a fish is suddenly exposed to a short very intense sound. Acute effects may result in mortal or potentially mortal injury to fish as well as sudden changes in behavior. Effects may occur immediately upon exposure to a stimulus, or at some time afterwards due to the actual damage imposed or reduced fitness that leads to predation on the affected fish. Some acute responses are very short-term (the so-called “startle” responses). In many instances, short sounds may be repeated. With repeated exposure, there may be multiple short-term disturbances, in some cases leading to
**habituation** or **de-sensitization**, where the response by the fish diminishes with time and experience.

**Chronic** exposure involves exposure to both continuous sound and intermittent sounds over long time periods, not necessarily at high levels, and may result from increased levels of human activity. Chronic effects refer to long-term changes in the physiology and/or behavior of a fish. Such changes may include the masking of natural sounds by man-made sounds. These changes generally do not lead to mortality, but they may result in reduced fitness leading to increased predation, decreased reproductive potential, or other effects. The continuous sounds resulting in chronic effects may propagate over large areas, raising the overall level of sound above the natural background level.

**Cumulative** effects arise from the temporal repetition and accumulation of effects from a single type of source—for example, the repeated strikes of a pile driver. **In-combination** effects, also described as synergistic effects or aggregate effects, arise from the accumulation of effects from a number of different types of stressors—for example, from sounds from different sources or from the combined effects of sound exposure, water contamination, and fishing (e.g., Johnson 2012). The U.S. National Environmental Policy Act (NEPA) considers both cumulative and in-combination effects, as defined here, as cumulative impacts.

The plural of fish is usually fish, but fishes may also be used. In this review, **fishes** is used to refer to multiple species of fish.

A **fishway** is a device or contrivance for enabling fish to pass around a fall or dam in a stream. There are many different types of fishways or fish passes, including the **fish ladder**, a series of small dams and pools within a long, sloping channel, enabling fish to pass around the obstruction in a series of steps; the **baffled fish pass**, which uses a series of closely-spaced baffles within a narrow channel to enable the fish to swim upstream; and the **fish lift**, where the fish may be raised vertically to a position above the obstruction.

Finally, **man-made** is to be seen as synonymous with human-made and anthropogenic as used by other writers and is intended as a gender-neutral term.
2 THE PHYSICS OF UNDERWATER SOUND

2.1 The Nature of Underwater Sound

Sound is a local mechanical disturbance generated within any compressible medium, whether it is a gas, liquid, or solid. Sound does not travel through a vacuum. In water, sound is generated by the movement or vibration of any immersed object and results from the inherent elasticity of the water. As the source moves, kinetic energy (KE) is imparted to the water and is passed on as a travelling acoustic wave, within which the component particles of the water are alternately forced together and then apart. The particles of the water oscillate back-and-forth along the line of transmission in waves of compression (increase in pressure) and rarefaction (reduction in pressure). The disturbance propagates away from the source at a speed that depends on the density and elasticity of the medium. Sound travels almost 4.5 times faster in water than in air.

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

Thus, any acoustic field consists of pressure fluctuations (a scalar field, acting in all directions) and particle motion (a vector field, aligned in a particular direction). The total energy contained in a sound wave consists of the sum of its potential energy (PE) and its KE. The PE arises from the compression and expansion of the fluid and hence is related to the sound pressure, while the KE arises from fluid motion quantified by the sound particle motion. Sounds are most often described in terms of the changes in pressure that accompany passage of the disturbance: the deviation above and below the local hydrostatic pressure or sound pressure. However, some fishes and especially salmon (Hawkins and Johnstone 1978) respond to particle motion, even though the magnitude of the back-and-forth motion of the component particles of the medium may be very small.
In a free sound field, where there are no physical obstructions to passage of the sound, and where the advancing wave front is an almost planar surface, the oscillatory particle velocity (the first time derivative of the particle displacement, expressed as m/s) and the sound pressure (expressed as Pascals, 1 Pa is equal to 1 N/m²; or micro Pascals, 1 µPa = 1.0 x 10⁻⁶ Pa) are directly proportional to one another. They are described by the plane wave equation:

\[ u = \frac{p}{\rho c} \]

Where:
- \( u \) = the particle velocity (m/s)
- \( p \) = the sound pressure (Pa)
- \( c \) = the propagation velocity of sound in the medium (m/s)
- \( \rho \) = the density of the medium (kg/m³)

The quantity \( \rho c \) is known as the acoustic impedance (Z), a quantity analogous to the electrical resistance of an electrical circuit. Together the sound pressure and particle velocity determine sound intensity. The local instantaneous intensity is the product of the sound pressure and the acoustic particle velocity divided by the acoustic impedance of the medium. More formally, the sound intensity is the acoustic energy flowing through a unit area (A), perpendicular to the direction of propagation, per unit time (T). The sound intensity \( I = \frac{p^2}{Z} \) is expressed in units of watt per meter squared (W/m²).

### 2.2 Sound Propagation

The speed of propagation of a sound in a particular medium can be expressed in terms of the bulk modulus of the medium, which in simple terms is a measure of its compressibility. The speed of propagation in water varies with salinity, temperature, and other factors. There is a major difference in the speed of propagation of sound between water and air: in water, \( c \) is approximately 1,500 m/s, compared to 343 m/s in air. The higher sound speed in water arises from the relative incompressibility (large bulk modulus) of water compared to air. Water is much more resistant to being compressed. For a given sound pressure, the particle velocity is much smaller in water.
Sounds are reflected at any interface with a medium of different acoustic impedance; for example, an air/water interface. When the sound wave reaches a boundary between one medium and another, a portion of the wave is reflected and a portion of the wave is transmitted across the boundary. The reflection of the sound wave can lead to both an echo (a discrete inverted version of the sound wave) and reverberation (multiple reflections prolonging the duration of the sound wave). Because the acoustic properties of air and water are very different, most of the sound energy at an air/water interface is reflected; very little passes through in either direction.

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

Propagation of sound in shallow-water environments like rivers can be very complex and difficult to predict or model. In considering propagation of a sound in a river or lake, there are a number of effects to consider. There may be a direct transmission path between the source and the receiver. There is also reflection from the water surface and the riverbed. There is also refraction (a change in direction at an interface), diffraction (where the sound wave encounters an obstacle or passes through an aperture), and sound absorption effects arising from differences in the properties of the water itself, which often contains sound-absorbing air bubbles. A significant difference between the propagation of sound underwater versus sound in air is that there are distinct and highly reflective boundaries (the water surface and the riverbed), and changes within the medium itself, that can substantially affect the propagation of sound. The coherency of the original signal is also degraded by reverberation within the environment; that is, by the aggregation and merging of reflected sounds from different surfaces and objects.
The propagation of low-frequency sounds with long wavelengths may be constrained in shallow waters (Urlick 1983; Rogers and Cox 1988). Low-frequency sounds generated in the water may propagate less well through shallow rivers and lakes. For example, the freshwater goby *Padogobius martensii* emits sounds predominantly in the 80 to 200 hertz [Hz] band, but frequencies below 750 Hz do not propagate in water with a depth less than 50 cm (Lugli et al. 2003). Lugli and Fine (2003), working in shallow stony streams, found that the courtship sounds of the goby were attenuated by 15 to 20 decibels (dB) over distances of 20 cm. It is important to note, however, that this constraint does not apply to sounds generated within the substrate or to waves propagated along the interface between the water and the substrate. Some low-frequency sounds (including those generated by pile drivers or by natural sources including microseisms) may propagate over considerable distances.

Thus, although it may be possible in a deep lake, under conditions where the topography is simple and any temperature gradients have been measured, to model the propagation of sound and to estimate sound pressures and particle velocities at different distances from the source using the wave equations; modeling is not so easy in a shallow river.

It is especially difficult to model sound propagation from large and complex sources like pile drivers or construction machinery. These are often large and distributed sources, with several subsidiary sources of sound. They are rarely point sources. Moreover, much of the sound is being generated within the riverbed and other solid structures. Transmission of sound or vibration takes place through the different layers of substrate beneath the riverbed, where most of the energy may be dispersed. Compression waves and shear waves within the substrate may combine, and interface waves may propagate along the interface between the riverbed and the water. These waves may show both longitudinal (movement parallel to the direction of travel, like sound waves) and transverse motion. They may also travel at much lower speeds than sound in water.

The energy from substrate and interface waves can be reradiated into the water, combining with the energy that has been transmitted directly through the water and greatly complicating the prediction of sound amplitude and direction. The motion imparted to the riverbed itself may be detectable by fishes like the salmon, although these effects are rarely considered in environmental impact assessments.
It is critically important to distinguish between the level of sound measured at a specified
distance close to a source—*the source level*—and the level received at a more distant point in
the sound field, for example at a hydrophone or at a fish’s ear—*the received level*. The
source level is the sound pressure measured at 1 m from a hypothetical point monopole
source. Ainslie et al. (2009) have pointed out that useful information on source
characteristics is very scarce due to the lack of standardization and clarity on the definition
and measurement of source level. In practice, few real sources are either monopole or point
sources, and source level measurements are rarely made at a distance of 1 m. Source levels
are more often measured at a greater distance from the source, with a sound propagation
model applied to determine what the sound pressure might have been at 1 m range had the
source been a point source. For very large sources like pile drivers or air gun arrays, there is
no single point from which the sound radiates. The actual sound levels in the vicinity of a
distributed source will be much lower than the estimated source level (i.e., the predicted
source level will never actually be reached in the field). These estimated source levels are
perhaps better called *radiated sound levels*. Such levels are valuable for the prediction of far
field sound pressures. However, they cannot be used to predict sound pressures or particle
velocities in the close vicinity of the source. Sound sources may be coupled to the riverbed
or adjacent land, and may also generate sound in water and in air, so that the conventional
definition of source level is difficult to apply.

In very shallow water, or in the extreme case of a water tank in the laboratory, any sound
source is completely surrounded by reflecting surfaces and the acoustic conditions become
extremely complex. Many experiments on the hearing abilities of fish have been carried out
under these conditions, where measurements of the sounds received by the organisms under
test have lacked precision. In particular, the directional components of the particle motion,
the parameter that is often detected by fish, are often not measured. The results from such
experiments must be treated with skepticism.

### 2.3 Monitoring and Measuring Underwater Sounds

#### 2.3.1 Sound Pressure

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

It should be noted that there are several effects that can severely compromise the quality of a sound pressure measurement. First, the frequency range over which fishes hear is concentrated at low frequencies, and for fishes like the salmon and cod, may extend into the infrasonic range (frequencies below 20 Hz). Also, one particular family of fishes, the shads (Alosinae), can hear sounds extending into the ultrasonic range, above 20 kHz (Nestler et al. 1992; Mann et al. 2001). Any measurements made of waterborne sound pressure waves that do not cover the appropriate frequency range will be of little value for analysis in terms of their effects on fish. Another 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. Hydrophone signals can be “clipped” or saturated at high sound levels. At very low sound levels, the signals may be drowned by internal electrical noise.

2.3.2 Particle Motion

It is important to recognize that all fish, including the salmon, respond to particle motion rather than sound pressure. Only a few species can also detect sound pressure. Measuring or estimating the sound fields to which fish are exposed poses formidable difficulties. It has become commonplace to estimate the particle velocity from measurements of the sound pressure, using either the plane wave equation (distant from the source) or the spherical wave equation (close to the source). Close to the source, the particle velocity is much higher for a given sound pressure—the near-field effect. For a simple monopole source, radiating sound equally in all directions (a pulsating sphere), the outer limit of the near field is usually considered to be at $r = \lambda/2$, where $r$ is the distance and $\lambda$ is the wavelength of the sound. The volume of water outside that range is termed the far field. Such estimates of particle velocity are only valid under well-specified circumstances, distant from reflecting boundaries. Such
conditions do not prevail in shallow water lakes and rivers, close to the river surface, close to the riverbed, or in aquarium tanks. There, it is necessary to measure the particle motion directly.

The back-and-forth particle motion of the medium can be described by the particle displacement or its time derivatives, particle velocity and acceleration. As we have described, particle motion is aligned along a particular direction and is a vector quantity, whereas pressure acts in all directions (it is a scalar quantity). Particle motion hydrophones are not readily available, and they often have to be made for a specific purpose. They can be assembled from three moving coil geophones (arranged orthogonally) contained within a neutrally buoyant container, giving sensitivity to particle velocity. Or they can be assembled from three seismic accelerometers, giving sensitivity to particle acceleration. An alternative approach is to measure the sound pressure gradient in the water and derive the particle motion from that. An estimate of the sound pressure gradient can be made using two hydrophones separated by a known spacing to measure the two different sound pressures p1 and p2. It should be noted, however, that there are several practical considerations to be satisfied when implementing this approach. The differential pressure p1 minus p2 is typically created using a differencing amplifier to subtract one estimate of pressure from another; the result will generally be much smaller than each of the individual pressures. If there is an error in the measurement of either pressure, it may easily dominate the result. Thus, it is critically important that the hydrophones are well matched in both the magnitude and phase of their sensitivity. Note, also, that this implies that this calculation cannot be performed digitally after acquisition of the signal, due to the limitations of dynamic range caused by the convertor.

In addition, because particle velocity is a vector quantity, it is necessary to monitor its direction. Measurement of the pressure gradient using a single pair of hydrophones will only provide the particle velocity along the axis joining the two hydrophones. At least four sound pressure hydrophones are necessary to measure the amplitude and direction of particle velocity in three dimensions.

Particle velocity hydrophones are not commercially available. However, it is very important that particle motion should be considered in assessing effects upon fishes, including salmon,
and this requires vector rather than scalar measurements. The measurement, modeling, and correct prediction of the influence of particle motion on fishes are crucial considerations.

2.4 Underwater Sound Metrics

2.4.1 The Decibel Scale

A very wide range of sound pressures may be measured underwater, ranging from around 0.000001 Pa in a quiet lake up to 10,000,000 Pa for an explosive blast. For convenience, sound pressure is often expressed through the use of a logarithmic (dB) scale. The use of a logarithmic scale compresses the range so that levels can be described with a smaller range of numbers (in the example above, from 0 dB to 260 dB re 1 μPa). The sound pressure expressed in this way is termed the *sound pressure level* (SPL).

Values of sound pressure lower than the reference level result in negative dB values. The SPL is sometimes abbreviated to “dB,” which can give the erroneous impression that a dB is an absolute unit, rather than a level relative to a reference level. In expressing the level of sound pressure, it is always necessary to provide the reference level (normally 1 dB re 1 μPa in water, see below).

An additional advantage of working with the dB scale is that many of the physical mechanisms responsible for sound attenuation operate at a constant rate when they are expressed on a dB scale.

There is sometimes scope for confusion, as two different forms of expression may be used for calculating SPLs in dB. The two types of level in widespread use in underwater acoustics are: 1) the level of a field quantity; and 2) the level of a power quantity. For a sound of a given SPL, the actual dB values are the same. Most underwater sound measurements are made in terms of field quantities. Power quantities are often described in acoustic textbooks, however, and their use seems to be favored by some specialists in theoretical acoustics.
When expressed in dB, the level (LF) of the field quantity (F) is:

$$LF = 20 \log_{10} \left( \frac{F}{F_0} \right) \text{ dB}$$

Where:

- $F_0$ - a reference value for the field quantity, the sound pressure, normally taken as 1 μPa

The level (LP) of a power quantity (P) is:

$$LP = 10 \log_{10} \left( \frac{P}{P_0} \right) \text{ dB}$$

Where:

- $P_0$ - the reference value of the power quantity, the sound pressure squared, normally taken as 1 μPa$^2$

Similarly, the reference values for field quantities of particle motion are:

- Particle displacement level, 1 picometer; 1 pm
- Particle velocity level, 1 nanometer per second; 1 nm/s
- Particle acceleration level, 1 micrometer per second squared; 1 μm/s$^2$

The reference values for power quantities of particle motion are:

- Particle displacement level, 1 picometer squared; 1 pm$^2$
- Particle velocity level, 1 nanometer squared per second; 1 (nm/s)$^2$
- Particle acceleration level, 1 micrometer squared per second to the fourth power; 1 μm$^2$/s$^4$

### 2.4.2 Different Types of Sound

The type of sound being monitored will affect the way the sound is to be measured and the metrics to be applied. Steady continuous sounds are conventionally expressed as root mean square (rms) values, equal to the square root of the mean-square sound pressure averaged...
over a time interval. Where an rms level is used to characterize transient pressure waves, the time period over which the rms level is calculated must be given.

However, many sounds are short and sharp, with the instantaneous sound pressure showing a clear maximum value. Such impulsive or pulsed sounds are sounds of short duration (generally less than 1 second) that start and then stop. They are characterized by a relatively rapid rise-time to maximum pressure followed by a decay that may include a period of diminishing and oscillating maximal and minimal pressures. Examples of pulses are sounds from explosions, sonic booms, seismic air guns, and pile driving strikes.

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

Impulsive sounds are better described by their peak values. The peak sound pressure is the maximum excursion in sound pressure whether it is a positive (compression) or negative (rarefaction) pressure. It is perhaps better described as the zero-to-peak sound pressure. This form of measurement is often used to characterize the underwater blast from an explosive charge, where there is a clear positive peak following the detonation of explosives. The highest pressure may also be described as the half peak-to-peak sound pressure, as it measures the excursion from the baseline hydrostatic pressure. The actual peak-to-peak sound pressure is the maximum variation of the pressure from positive to negative within the wave. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak sound pressure will be twice the zero-to-peak pressure, and hence 6 dB higher in level. Similarly, particle motion can be expressed as rms, peak-to-peak or zero-to-peak values.
2.4.3 Sound Exposure Level

When assessing the noise from transient sources such as blast waves, impact pile driving, or seismic air guns, the sound may vary greatly in amplitude throughout its duration. This variation with time of the pressure wave is often addressed by measuring the total acoustic energy (energy flux density) of the wave. The sound exposure level (SEL) sums the acoustic energy over a measurement period, and effectively accounts for both the SPL of the sound source and the duration of the sound. The SEL is a measure of the acoustic energy and, therefore, has units of Pascal squared seconds (Pa² s). Formally, the SEL is the integrated value of the squared sound pressure over time, where the reference value is 1 μPa² s.

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

\[ SEL = SPL + 10\log_{10}T \]

Where the SPL is a measure of the average level of the sound, and the SEL sums the cumulative sound energy. For single sounds lasting less than 1 second, the SEL will be numerically lower than the SPL. For periods of greater than 1 second the SEL will be numerically greater than the SPL (i.e., for a sound of 10 seconds duration, the SEL will be 10 dB higher than the SPL; for a sound of 100 seconds duration the SEL will be 20 dB higher than the SPL; and so on).

It should be noted that the SEL is often used not just for single sounds (SELss) but also for describing repetitive sounds. For example, the SEL can be used to describe the level over the duration of a pile being repeatedly hammered into the substrate, which may last for several hours and involve a large number of individual strikes, each generating a sound. For intermittent sounds, such as pile driving, the cumulative SEL (SELcum) values are usually calculated for the time when the sound is present (in effect, for pulses of identical amplitude, the length of a ‘pulse’ of noise multiplied by the number of pulses). In these circumstances it is better to refer to the SELcum value to distinguish it from the SELss value for a single impulse or strike. The term SEL is often used indiscriminately, without stating whether it is the SEL for a single impulse of sound or the SELcum for a series of impulses, and, if it is the latter,
without specifying the time period, the number of impulses, or whether it is for the whole
duration of driving a single pile. This is poor practice.

2.5 The Spectral Characteristics of Sounds

The waveform of a sound shows the variation in instantaneous sound pressure with time.
Displayed on an oscilloscope or a computer screen, it offers a useful way of illustrating the
overall temporal characteristics of the sound (Figure 1). 

![Waveform of Vibratory Pile Driving Sound](image)

Note: The maximum SPL was 164 dB re 1μPa rms at a distance of 94 meters from
the source, reducing to a steady level of about 156 dB rms. The background level
was 134 dB re 1μPa, measured over the bandwidth 10 Hz to 10 kHz.

**Figure 1**

Waveform of Vibratory Pile Driving Sound Measured in a River Estuary During the Driving of a
Sheet Pile, together with the Changes with Time of the SPL

Any waveform can also be decomposed mathematically into a series of sine waves of
differing frequency. All sound waves can be described as a linear superposition of a series of
such sine waves, each sine wave characterized by its frequency, its amplitude, and its phase
in relation to a zero-time mark.
The frequency spectrum is a plot of sound pressure or sound intensity against frequency showing the relative magnitudes of the components of a complex sound as a function of frequency. The spectrum is important because the frequency content of the sound may affect the way a fish responds to or is affected by the sound (in terms of physical injury as well as hearing loss). The spectrum is also important because it affects the expected sound propagation, as this is frequency-dependent.

Sound pressure or intensity levels are usually measured in dB and the frequency is measured in vibrations per second (or Hz) or thousands of vibrations per second (kHz). Many software packages can now take a sample of a sound recording, perform the calculation to obtain a spectrum (a Fast Fourier Transform [FFT]), and display it in “real time.” With Fourier transform analysis it is necessary to sample the input signal with a sampling frequency that is at least twice the bandwidth of the signal, due to the Nyquist limit. (The Nyquist limit sets a theoretical limit to the rate a signal has to be sampled to include data at a certain maximum frequency. Sampling below that limit does not sufficiently sample the signal, and the data obtained have corrupting artifacts.)

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

When preparing a sound pressure spectrum for a waveform, the unit of amplitude is normally the rms sound pressure, which is measured over a defined frequency band. The bandwidth can be as narrow as 1 Hz or as wide as 1/3 octave (an octave is a doubling of frequency); therefore, the measurement bandwidth must be specified. Spectra may be presented as spectrum levels: the SPLs in a band 1 Hz wide, expressed as dB re 1 μPa /Hz (e.g., Figure 2). Where a description of the power of a sound is to be related to the frequency, the power spectral density level may also be used, expressed in dB re 1 μPa²/Hz and representing the average sound pressure squared for a series of bands of width 1 Hz.
Note: A was measured in an estuary with shipping present, while B and C were measured in the river itself.

**Figure 2**

**Frequency Spectra of 5-second Samples of Background Noise in a River Measured as Sound Spectrum Levels (i.e., in a band 1 Hz wide) over the Range 10 Hz to 2 kHz**

The sound spectrogram is another form of display that provides an overview of the frequency content of a sound as it changes with time. It can be used to identify strong elements of the sound in both the time and frequency domain and is often used to characterize animal sounds or to define particular features of sounds from man-made sources (Figure 3). Figure 3 shows typical background noise recorded in a river estuary, with slow changes in level with the passage of a ship and noise spikes caused by tank cleaning operations on board a vessel moored nearby.
There is an uncertainty principle relating time to frequency and in preparing a sound spectrogram. One of the problems in using the FFT is that it has a fixed resolution. A choice must be made between high frequency resolution (long FFT length, or narrow bandwidth) and high time resolution (short FFT length, or wide bandwidth). This principle is often not understood by those preparing sound spectrograms. If rapidly repeated impulses are analyzed with a narrow bandwidth, then repeated pulses merge and give the impression of a continuous sound composed of related harmonic frequencies.

Sound spectrograms can be especially valuable for examining the structure of sounds that might be of interest in terms of effects upon fishes. In particular, they can reveal rapid changes in the amplitude and frequency of the sound, and may allow particular sources of sound to be identified within a complex sound field from their component frequencies and time-course.
3 THE DETECTION OF SOUNDS BY FISHES

3.1 The Sensitivity of Fishes to Sound

3.1.1 Fish Audiograms

Sound is important to fishes. Many fishes use sound to communicate with one another (Myrberg 1981; Ladich 2013), detect prey and predators (Remage-Healey et al. 2006), navigate from one place to another (Tolimieri et al. 2000; Cotter 2008; Stanley et al. 2012), and locate appropriate habitats (Simpson et al. 2004; Vermeij et al. 2010). Even though some fishes may not use sounds of their own to communicate, it is likely that all fishes use sound to learn about their environment by detecting and using the soundscape or “acoustic scene” (Cotter 2008; Montgomery et al. 2006; Slabbekoorn and Bouton 2008; Fay 2009). In effect, sound detection provides fishes with three-dimensional information from a larger space around them than is possible using vision, olfaction (the sense of smell), or electro-reception. Cotter (2008) suggested that sound detection is especially important for migratory fishes like salmon, which may navigate using natural geophysical sound sources to provide positional cues. He suggested that the underwater soundscape could be as familiar to aquatic animals as the visual landscape is to humans.

Seas, lakes, and rivers are often naturally noisy, with many of the sounds being geophysical in origin (Knudsen et al. 1948; Wenz 1962; Amoser and Friedrich 2010). Since the start of the industrial revolution, man-made sounds have added to the volume of background noise (Andrew et al. 2002; Hildebrand 2009). Sound travels faster in water than in air, and may propagate substantial distances (Urick 1983); as a consequence, the influence of underwater noise from construction work, ships, seismic exploration, energy developments, machinery, and other sources can be pervasive over large areas (e.g., Popper et al. 2014; Hawkins et al. 2015), especially in the sea. However, propagation of sound in rivers and estuaries may be less extensive because of the shallower water, complex topography, and presence of interfaces with media other than water.

Fishes do not hear equally well at all frequencies within their functional hearing range. Their hearing thresholds for the detection of sound vary with frequency. The hearing threshold (or auditory threshold) is the sound level that is just audible to an animal 50% of the time either under quiet conditions, or in the presence of a specified background noise.
level, or natural ambient noise. Plotted as a function of frequency these threshold data provide an audiogram (Figure 4). Hearing thresholds are generally determined for pure tones (a single frequency), ideally against a low level of background noise.

Very little is known about how most fish species detect and respond to sound. One of the fundamental problems in most studies of effects of noise on fishes, and indeed on basic studies of hearing and general bioacoustics, is that the sound fields in which experiments are done are often very complex and quite unlike the sound field that an animal would encounter in a normal aquatic environment. The presentation of measured sound stimuli to aquatic animals under experimental conditions presents severe difficulties, especially when done in tanks of any size (Parvulescu 1964; Rogers et al. 2015). As a result, much of the data on responses, behavior, and physiology from otherwise well-designed studies leave open questions as to the actual nature of the sound field to which the animals were exposed, and the stimuli to which they responded.

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


Notes: Each audiogram plots the auditory thresholds (the minimum sound levels that can be detected) determined by behavioral conditioning methods.

It has been shown experimentally that the dab and salmon are sensitive to particle motion, whereas the cod and catfish are sensitive to sound pressure. All the threshold studies were carried out under controlled acoustic conditions.

**Figure 4**

**Audiograms for Four Species of Fish**

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

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

Most audiograms for marine organisms have been derived from experiments in small laboratory tanks, where the presentation of measured sound stimuli presents enormous difficulties. Fish are generally most sensitive to low-frequency sounds, where the wavelength often exceeds the body of water containing the animals. The sounds are presented in a variety of ways, sometimes with immersed sound projectors and at other times with the projectors in air above the water, and only the SPLs are usually measured. With an immersed projector in a small, open, thin-walled container, very large particle motions are associated with quite low sound pressures. Conversely, with an air loudspeaker above the water the sound field consists almost entirely of sound pressure. It has been evident for some time that the ears in all fishes are essentially sensitive to particle motion (Pumphrey 1950; de Vries 1956). Only in some species are the ears coupled to gas-filled bodies that can act as acoustic transformers, converting incident sound pressures into particle motion at the ear (Poggendorf 1952; de Vries 1956; van Bergeijk 1967; Sand and Hawkins 1973).

The particle motion generated in these laboratory experiments to investigate the hearing abilities of fishes is rarely measured directly, although it is sometimes estimated by means of the plane or spherical wave equations. Sound pressure thresholds and audiograms
The Detection of Sounds by Fishes
determined in aquarium tanks must be treated with great skepticism, unless the sounds have been carefully presented and measured, for example, by the employment of controlled impedance wave tubes (Hawkins and MacLennan 1976) or by experiments in mid-water in the sea (Chapman and Hawkins 1973; Schuijf et al. 1972).

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

As detailed in subsequent sections, the hearing of salmon is not especially acute. Salmon are less sensitive to sounds than species like the cod, herring, and shad, and the span of frequencies that they can detect is narrow. They are essentially sensitive to particle motion rather than sound pressure. However, many man-made sources of disturbance in rivers may generate high particle velocities, and salmon will detect these.

3.1.2 The Ears of Fishes

The main sound receptors in fish are the otolith organs of the inner ear (Figures 5 and 6). The ears are paired structures embedded in the cranium on either side of the head, close to the mid-brain. There are no obvious external structures to indicate their presence, although in the clupeid fish there is indirect connection to the exterior via the lateral line system. Coombs and Popper (1982) described the morphology and evolution of the ear in fishes.

Three sacs within each ear are linked with each other and with the semi-circular canals (Figure 6). One of these sacs, the utriculus, communicates directly with the lumen of the semi-circular 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 or stone of calcium carbonate and other inorganic salts, sitting upon a bed or macula of hair cells. The body of the otolith is separated from the macula but coupled mechanically to it by a thin but layered otolithic “membrane,” into which the ciliary bundles of the hair cells project (Figure 7).

Notes: Otoliths are white and are magnified above. The cranial bones and soft tissues are semi-transparent gray; the premaxilla and dentary bones are white. Illustration provided through the kindness of Ted Cranford and Carl Schilt.

Figure 5
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 and Dorsal Views
Figure 6
The Left Ear of a Cod (*Gadus morhua*) Showing the Three Orthogonally Arranged Semi-circular Canals and the Three Otolith Organs, the Sacculus, Utriculus, and Lagena

Figure 7
The Heavy Calcareous Otolith, Separated from the Sensory Hair Cells of the Macula by the Otolithic Membrane, which has a Complex Structure
The various sacs and their otoliths can vary greatly in size and shape between different species. The sacculus and the saccular otolith are generally the largest in fishes like the salmon and cod, but in herrings (Clupeidae) the utriculus may exceed the sacculus in size, while in many carp (Cyprinidae) the lagenae may be especially large. Both the utricular macula and the otolith that sits upon it lie predominantly in the horizontal plane, and the saccular and lagenar maculae lie in different vertical planes. Most otoliths have a complex, sculptured shape and appear to have flanges, keels, and projections. These differences in shape, together with the enclosing shape of the membranous wall of the sac containing the otoliths, may constrain their freedom of movement. De Vries (1956) pointed out that the saccular otolith is curved, and that it may rotate rather than move along a linear axis. Krysl et al. (2012) examined the motion of the otolith organs of the white sea bass (Atractoscion nobilis) using a finite element model and suggested that the otoliths may show a rocking motion.

### 3.1.3 The Sensory Hair Cells

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 neurons, running to and from the brain, respectively, synapse with the hair cells. Each hair cell is strengthened at its apical end by a cuticular plate surmounted by a group of projections, the ciliary bundle, which extends above the surface of the epithelium in which the cell lies (the sensory epithelium, or macula). Many stereocilia, packed with microfilaments, are grouped together, with steadily increasing length towards a longer, eccentrically placed kinocilium containing nine double microtubules and two central single tubules. The positioning of the kinocilium towards one side of the cell gives the apical end of the cell a pronounced structural asymmetry (Figure 8).
The Detection of Sounds by Fishes

Figure 8

The Hair Cells of the Otolith Organs are Directional in their Physiological Response to Displacement, Having a Distinct Axis Defined by the Position of the Kinocilium; Adjacent Hair Cells often have a Common Axis of Orientation

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 neurons, which then 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). Depolarization of the cell and excitation of the primary afferent nerve fibers are most pronounced when the stereocilia are deflected in the direction of the kinocilium, and hyperpolarization and inhibition of the afferent fibers 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 (Figure 9).
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 organization 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).

3.1.4 Hearing Mechanisms in Fishes

The ears in fishes detect sounds through the movement of the otoliths relative to the sensory maculae. However, the otolith organs serve several functions. First, they serve as gravity receptors, enabling the fish to determine its orientation with respect to the Earth’s gravitational field (Lowenstein 1957, 1971). As the orientation of the head changes the
otoliths shift under the action of gravity, 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.

To explain the role that the otoliths play 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 (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 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) and Sand et al. (2008) have suggested that such a system is essentially behaving like 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, and by Hawkins and Johnstone (1978) working with Atlantic salmon (Salmo salar).

In many fishes the ear is connected mechanically to accessory gas-filled organs. Thus, in the Ostariophysans (the second-largest super-order of fish, containing almost 8,000 species), an anterior chamber of the swimbladder is connected to the saccus of each ear by a chain of small bones, the Weberian ossicles. Alexander (1959, 1966) described the functioning of this apparatus. An association of diverticulae or ducts from the swimbladder with the ear has also been reported for the fish families Anabantidae, Balistidae, Chaetodontidae, Cichlidae, Clupeidae, Engraulidae, Holocentridae, Hiodontidae, Megalopidae, Moridae, Mormyridae, Notopteridae, Ophiocephalidae, Sciaenidae and Sparidae (Jones and 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) and 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. 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 direct mechanical linkage. Pulsations of the swimbladder, induced by a sound, might be communicated to the ear through the intervening body tissues. Enger and Andersen (1967) and Chapman and Hawkins (1973) subsequently provided evidence that this occurs in the cod, a species that lacks any direct connection between the swimbladder and ear (Figure 10).

![Diagram](image)

**Figure 10**
Lack of Direct Connection between Swimbladder and Ear in the Cod

Notes: In the cod the gas-filled swimbladder extends close to the ear, but does not have any specialized 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 an acoustic 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, gas-inflated condom 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 Atlantic salmon (which does have a swimbladder) was sensitive to particle motion over its whole bandwidth. The salmon does not use the swimbladder to detect sound pressure.

3.1.5 The Hearing Abilities of Fishes

Relatively few experiments on the hearing of fishes have been carried out under appropriate acoustic conditions and many of the measurements made in tanks, and expressed solely in terms of sound pressure, are unreliable. A few species of fishes, including the Atlantic cod (*Gadus morhua*; Chapman and Hawkins 1973), common dab and European plaice (*Pleuronectes platessa*; Chapman and Sand 1974), Atlantic salmon (Hawkins and Johnstone 1978), and several elasmobranch species (Casper and Mann 2009), have had their hearing abilities examined under appropriate acoustic conditions. However, the abilities of most fish species to detect sound remain to be explored.

From those audiograms that are available for fishes an important question that arises is whether it possible to identify particular “types” that may serve as models for other species and life history stages. There are major differences in auditory capabilities from one fish species to another. Some broad generalizations can be made about the effects of sound on particular types of fish and it may be feasible to develop generalized weighting curves that describe the overall hearing sensitivities of these different groups. In some of the earlier literature, a distinction was made between hearing generalists and hearing specialists, although it was always evident that this was a naïve approach and that some species like the Atlantic cod did not fit neatly into either category. A better approach may be to distinguish
fish groups on the basis of their audiograms and differences in their anatomy. For example, Popper et al. (2014) suggested the following categories:

1. Fishes lacking swimbladders that are sensitive only to particle motion and show sensitivity to only a narrow band of frequencies – This group includes the dab and plaice (Chapman and Sand 1974), and elasmobranch species (Casper and Mann 2007, 2009).

2. Fishes with swimbladders, where the swimbladder does not appear to play a role in hearing – These fish are sensitive only to particle motion and show sensitivity to only a narrow band of frequencies. This group includes salmon (Hawkins and Johnstone 1978). However, because of the presence of a swimbladder, these fish may be more susceptible than group 1 (above) to injury when exposed to high sound pressures or to sudden changes in the hydrostatic pressure (barotrauma; Brown et al. 2012).

3. Fishes with swimbladders that are close to the ear, but not intimately connected to the ear – These fishes are sensitive to both particle motion and sound pressure, and show a more extended frequency range than groups 1 or 2, extending up to about 500 Hz. This group includes the Atlantic cod (Chapman and Hawkins 1973) and the European eel (Anguilla anguilla; Jerko et al. 1989).

4. Fishes that have special structures mechanically linking the swim bladder to the ear – These fishes are sensitive primarily to sound pressure, although they may also detect particle motion. They have a wider frequency range, extending to several kHz and generally show higher sensitivity to sounds than groups 1, 2, or 3. The group includes some of the squirrelfishes (Holocentridae), drums and croakers (Sciaenidae), herrings (Clupeidae), and the large group of Ostariophysan fishes (see Braun and Grande 2008 for a review).

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

There is some evidence that these divisions between fishes may apply not just to their hearing abilities but also to the effects in terms of injuries sustained from exposure to high-level sounds (Popper et al. 2014).
The hearing abilities of many of the extant species (and entire taxa) of fishes remain completely unexplored. Priority species for examination include the herring (to be repeated), mackerel, tuna, skates and rays, and jawless fishes like the lamprey. Behavioral audiograms are required for these species under natural and varied noise conditions. Information is especially lacking on the hearing abilities of larval fishes and on the changes that may take place with growth and age.

It is clear that sound provides an important source of environmental information for most fishes (e.g., Fay and Popper 2000). Whereas low light levels and the scattering of light restrict vision underwater, the sense of hearing provides a three-dimensional, long-distance sense that works under most environmental conditions. It is likely that hearing evolved for detection of the acoustic scene (Fay and Popper 2000), and that fishes use sound to learn about their general environment, their location, the presence of predators and prey, as well as for acoustic communication in many species. Sound is important for fish survival.

3.1.6 Sensitivity of Fishes to Infrasound

Most audiograms for fishes do not provide results for frequencies below 20 to 30 Hz because of the difficulty in obtaining sound projectors that produce undistorted sounds at very low frequencies. However, Sand and Karlsen (1986), working with a specially designed tank, showed that cod had an acute sensitivity to extremely low-frequency linear accelerations, or infrasound, extending below 1 Hz. The threshold values, measured in terms of particle acceleration, declined (i.e., sensitivity increased) 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 and several species of Pacific salmon and concluded that frequencies in the infrasound range (5 to 10 Hz) were the most efficient for evoking both awareness reactions and avoidance responses. Downstream migrating European eels showed similar avoidance responses to infrasound (Sand et al. 2000). More recently, Sand et al. (2008) have suggested that near-field particle motions generated by the moving hulls of ships are mainly in the infrasonic range, and infrasound is particularly potent in evoking directional avoidance responses to ships. Large vessels, in particular, may generate especially extensive particle motion fields.
The full importance of infrasonic frequencies to fish remains to be evaluated. We are largely ignorant of the natural levels of infrasound in the sea, lakes, and rivers, although it is apparent that there are many potential sources, both natural and man-made. The few experiments that have been carried out on fishes with infrasound suggest that they may be especially sensitive to such sounds. It is particularly important to examine the different stimuli provided by volume displacements of water in rivers and streams, created by water currents, and supplemented by reflections from obstacles within the river. Water displacements may affect the lateral line system of fishes directly; they may generate sounds at very low frequency; and they may stimulate the ear as the fish is subjected to linear and angular accelerations.

3.1.7 **Masking of Sounds by Noise**

Although the frequency ranges over which the majority of fish are sensitive is much more restricted than for most mammals and birds, it is evident that some fish are acutely sensitive to sounds. Indeed, in the sea the Atlantic cod is often not limited by its absolute sensitivity but by its inability to detect sounds against the background of ambient sea noise. Only under the quietest sea conditions do cod show absolute thresholds (Chapman and Hawkins 1973; Hawkins and Chapman 1975). 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 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 that raise the level of background noise. It should be noted that many of the differences in sensitivity seen in the audiograms presented for different species might result from variable noise levels prevailing under experimental conditions. Aquarium tanks, like the sea itself, are noisy.

However, 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 Atlantic salmon only show masked thresholds when the background noise is raised significantly above the lowest levels found in
the sea (Hawkins and Johnstone 1978). Such conditions may occur, however, in especially noisy rivers.

Masking indicates an inability to separate the signal and noise. However, not all the frequency components of the noise may cause masking. For human subjects it has long been known that a pure tone signal is masked most effectively by noise components at the same and similar frequencies. Fletcher (1940) applied the term *critical band* to the frequency span of noise that is effective. He introduced the analogy of an auditory filter, which can be tuned to the frequency of the stimulus and effectively eliminates noise at remote frequencies.

An analogue of the critical band exists in the cod (Hawkins and Chapman 1975). Two different techniques were used to examine the effects of noise. First, bands of noise of different width were transmitted, and the threshold for detection of a pure tone stimulus determined as the band was progressively narrowed. The signal-to-noise ratio remained constant until a point was reached where the signal-to-noise ratio declined. This showed that only frequencies close to that of the pure tone were responsible for the masking.

In another experiment, pure tone thresholds were determined in the presence of a succession of narrow bands of noise (10 Hz wide), centered at different frequencies. Masking was most pronounced when the center frequency of the noise band coincided with the frequency of the signal. A small shift in the center frequency of the noise band above or below the frequency of the pure tone resulted in a sharp decline in masking. Again, the experiment confirmed the existence of a critical band for masking. Figure 11 illustrates the filter bandwidths determined for the cod by Hawkins and Chapman (1975) using narrow bands of noise to mask pure tone stimuli.

Similar experiments were later carried out with Atlantic salmon (Hawkins and Johnstone 1978). Critical bands in the salmon were wider than those for the cod at any given frequency, suggesting that the ability of salmon to lift signals from a noise background is less well developed.
Masking is a complex phenomenon. Little is known of those sounds that are likely to be most important to fishes like salmon and consideration of the effects of different noise backgrounds in masking those sounds requires new research.

![Critical Bands: Atlantic Cod](image)

*Figure 11*
Comparison of the Relative Masking Effect of 10-Hz-wide Noise Bands upon Pure Tone Stimuli at Different Frequencies across the Audiogram of the Cod

3.1.8 *Discrimination of Different Sounds by Fish*

Behavioral and physiological investigations have also shown that fishes are able to discriminate between sounds of different amplitudes (Jacobs and Tavolga 1967) and different frequencies (reviewed by Enger 1981). 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, as well as lift sounds out of a noisy background. In mammals and birds, frequency discrimination and the existence of the critical band have been interpreted in terms of the mechanical response of the cochlea of the inner ear (von Békésy 1960), different parts of
which respond to different frequencies. There is no obvious form of mechanical frequency analyzer within the fish ear comparable to the cochlea. It seems likely that frequency selectivity in the fish auditory system is mediated within the brain.

### 3.1.9 Frequency Weighting

We have seen that fish are more sensitive to some frequencies than others (Figure 4). Applying frequency weighting to measurements of man-made sounds offers a method for quantitatively compensating for differences in the frequency response of sensory systems. It minimizes the influence of extremely low- and high-frequency sound sources that may be detected poorly, if at all, by the animal (Hawkins and Popper 2014).

For marine mammals, generalized frequency-weighting functions have been derived for different functional hearing groups, distinguishing species that only detect lower frequencies from those that detect ultrasound. Thus, Southall et al. (2007) developed “M-weighting” curves to compare the effects of man-made sounds upon different marine mammals.

The use of weighting curves is especially relevant when considering effects in terms of behavioral responses of animals. With tissue injury, or damage to the auditory system, frequencies falling outside the hearing range of the animals may still be important and cannot be eliminated. In this case weighting is not always appropriate. For example, although they may be inaudible, the high frequencies associated with rapid rise-times in impulsive signals may bring about or exacerbate injury. If an animal is subject to seismic air guns or pile driving, the higher frequency components may result in injury even if the animal cannot hear those frequencies. For this reason, the latest draft National Oceanic and Atmospheric Administration (NOAA) guidelines for marine mammals do not recommend the use of weighting for measuring peak sound levels (NOAA 2013).

In evaluating the impact of sounds upon humans, use is made of weighting curves based on equal loudness contours (Suzuki et al. 2004). Observers are asked to match sounds against one another to compare their subjective loudness. Such curves are applied in the evaluation of effects from environmental and industrial noise, and for assessing potential hearing damage and other noise health effects. Thus, the A-weighting curve is derived from the
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inverse of an idealized equal loudness hearing function across frequencies, standardized to 0 dB at 1 kHz (ANSI 1994, 2006).

Equal-loudness contours are lacking for most marine animals and frequency-weighting functions are instead often based on hearing thresholds at different frequencies. Such weighting is not directly comparable to A-weighting. The hearing threshold (or auditory threshold) is the sound level that is just audible to an animal 50% of the time either under quiet conditions, or in the presence of a specified background noise level. Plotted as a function of frequency these threshold data provide an audiogram (Figure 4). Hearing thresholds are generally determined for pure tones (a single frequency), ideally against a low level of background noise.

Although measuring equal loudness levels in human listeners is relatively straightforward, it is much more difficult to examine loudness matching or perform loudness comparisons with aquatic animals like fish. Nevertheless, some workers have aspired to determine such weighting curves for marine mammals. Finneran and Schlundt (2011) have relied upon objective measurements, such as response latency, to estimate equal loudness contours for the bottlenose dolphin (*Tursiops truncatus*). From their experiments they derived auditory weighting functions, which they have suggested could be used to predict the frequency-dependent effects of noise on odontocetes (toothed whales, including dolphins). Such measurements might also be possible with fishes.

In the latest provisional NOAA guidance on sound exposure criteria (NOAA 2013) marine mammals are divided into functional hearing groups (low-, mid-, and high-frequency cetaceans, and otariid and phocid pinnipeds). Marine mammal auditory weighting functions are incorporated into the setting of threshold criteria in the SELcum metric. Use is made of “representative” or surrogate individuals/species for establishing auditory threshold levels for species where little or no data exist. This is done as a matter of practicality, as there are insufficient adequate data for all marine mammal species found worldwide.

With fishes, it is necessary to use audiograms to provide weighting curves, as equal loudness data are not yet available. It is of course important that the audiograms on which weighting curves are based are obtained under acoustic conditions that give reliable and repeatable
measures that truly reflect the performance of the animal’s hearing system. Of the many extant species of fishes, few have had their audiograms measured (Ladich and Fay 2013), and of these only a few have been measured under acoustic conditions that provided a calibrated acoustic field with valid measurement techniques. Hawkins (2014) recently reviewed experiments aimed at providing those conditions.

The techniques that have been used to obtain actual auditory thresholds from fishes also vary by investigator and laboratory (i.e., there is no standard protocol). Some thresholds have been determined using behavioral conditioning techniques. Others have used physiological measures such as AEPs to determine audiograms in fishes (reviewed by Ladich and Fay 2013). AEP measures of the audiogram can differ significantly from those derived using behavioral conditioning techniques and they are less reliable than behavioral conditioning methods (Hawkins and Popper 2014). Physiological measures are very useful for comparing hearing mechanisms, or for determining differences before and after some intervention, such as exposure to loud sounds. But they are much less useful for determining the hearing capabilities of a particular species, or comparing the behavioral responses of different species.

3.1.10 The Use of Weighted Sound Measurements

Nedwell et al. (2007) put forward a systematic weighting approach for application to aquatic animals, including fishes, using a metric known as the dBht (Species) as a tool for quantifying the level of sound experienced by individual species. The dBht metric takes into account each species’ hearing ability by referencing the sound to the hearing thresholds for that species. Since any given sound will be detected at different levels by different species (as they have differing hearing abilities) the species name is appended when specifying a level. For instance, the same sound may have a level of 70 dBht for the Atlantic cod and 110 dBht for a common seal (Phoca vitulina), because the latter has more acute hearing. The dBht is said by the originators to be similar to the A-weighting that is used for human sound exposure in air. Actually, it is not strictly analogous to A-weighting as the dBht is based on the audiogram, whereas the A-weighting is based on subjective equal loudness contours.

The level of a man-made sound expressed as dBht (Species) is usually much lower than the un-weighted sound level, because the latter contains energy at frequencies that the species
cannot detect. The weighting eliminates this energy. Where the energy within the received sound falls mainly within the hearing range of the animal, then the weighted level may be similar to the un-weighted level.

Essentially, the dBht (Species) metric is a frequency-dependent, non-dimensional ratio of measured sound level to the hearing threshold of an animal. The weighting is not just applying a frequency filter; it is providing a level that is weighted by the actual sensitivity of the animal to sound, as indicated by the audiogram. The level of a sound expressed in dBht will be higher for an animal with greater hearing sensitivity.

However, as detailed in earlier sections, not all fishes respond to sound pressure. Many, including the salmon, are sensitive to particle motion. In theory a dBht value can be determined for particle motion. However, the value is more commonly expressed in terms of sound pressure, even for fishes that are known to be sensitive to particle motion. Particular care must be taken in doing this, as the values will not be appropriate under all acoustical conditions, especially for low-frequency sounds. Indeed, there are many circumstances where it will be inappropriate; for example close to a sound source, close to the sea surface, and in shallow water.

Despite the lack of high-quality audiograms for the majority of marine animals, the dBht (Species) has often been utilized within the United Kingdom (UK) for assessing the effects of man-made sounds upon fishes, and it appears to have the tacit approval of some regulatory agencies. In particular, the dBht (Species) has been used to evaluate the likelihood of fishes responding behaviorally to sound exposure. Nedwell et al. (2007) suggested that strong avoidance responses by fishes start at a level about 90 dB above the dBht (Species) thresholds, while different proportions of fishes respond at lower weighted levels. Mild reactions in a minority of individuals may occur at levels between 0 and 50 dB above the hearing threshold, and stronger reactions may occur in a majority of individuals at levels between 50 and 90 dB above the hearing threshold.

It must be noted, however, that these recommended levels are largely derived from the proportion of fishes reacting to sounds in only a very few studies on a few species of fish in very particular environments (Maes et al. 2004; Nedwell et al. 2007). There are very few
other field data derived from wild fishes under different conditions to support the assumptions about the sound levels at which fishes will react. Moreover, the initial observations by Nedwell and his colleagues were based on fishes exposed to swept tonal sounds; sounds that are rather different from the sounds generated by, for example, machinery or percussive pile drivers. Clearly, substantial caution must be exercised in applying the dBHt measure. Indeed, defining response criteria applicable to all species may be too simplistic an approach to evaluating behavior. An additional problem in assessing magnitude of effect is how to interpret expressions used in the dBHt approach such as “strong avoidance reaction by virtually all individuals” in terms of the effects on the behavior of particular fishes engaged in different activities.

### 3.1.11 Directional Hearing in Fishes

Whether fish can discriminate sounds from different directions, that is, whether they can locate sound sources, has long been controversial. Van Bergeijk (1967) originally proposed that the single pressure detector (the swimbladder) present in those fish detecting sound pressure could not be used to localize a sound source, and that fish therefore could not detect sound direction in the far field. However, field observations of freely ranging sharks (which lack a swimbladder) showed that they orientated toward sound sources, often from great distances (Myrberg et al. 1969; Nelson and Gruber 1963). It is now evident that some fish can discriminate sounds from different directions (reviewed by Sand and Bleckmann 2008). Teleost fishes are able to discriminate between spatially separated sources under far-field conditions, both in the horizontal plane (Schuijf et al. 1972; Chapman and Johnstone 1974; Schuijf and Buwalda 1975) and vertical plane (Hawkins and Sand 1977). Indeed, they are able to distinguish between sources at different distances (Schuijf and Hawkins 1983), an ability that is poorly developed in humans. This ability not only enables fish to locate the sources of sound in three-dimensional space but may also assist them in discriminating sounds from a particular source against the general non-directional noise background.

### 3.1.12 Mechanisms of Directional Hearing in Fishes

In terrestrial mammals, including humans, sound direction is determined by the brain comparing time of arrival and phase differences between the two ears, and also comparing differing amplitudes at the two ears caused by the presence of the head. In fishes, the ears
are close together and the speed of propagation of sound is much faster. Time of arrival and phase differences are much smaller. Moreover the fish head is effectively acoustically transparent in water, minimizing amplitude differences between the two ears. However, there is strong evidence that the otolith organs themselves can provide a basis for the detection of the axis of particle motion. In effect they function as vector detectors. 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. We have seen that 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 vector weighing is used to determine the axis of sound propagation. 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 (Figure 12).
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 cosine response functions of single hair cells, indicating that each afferent neuron 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 the 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 neurons. 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 motion 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 actual 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 cod can discriminate between opposed sound sources (Buwalda et al. 1983).

This ambiguity is resolved in the phase model for directional hearing in fish (Schuijf 1976). 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 cod to be able to perform the discrimination (Buwalda et al. 1983). A number of authors have found this model difficult to accept (e.g., Rogers and Zeddies 2008), and have suggested alternative mechanisms that will also work for those fishes that do not possess a swimbladder (or where the swimbladder is not involved in hearing). Kalmijn (1988) proposed that such a complex model was unnecessary and suggested instead that fish can make their way to a sound source by maintaining a constant angle with respect to the axis of vibration.

Experiments on directional hearing have not yet been carried out on salmon, and the precision with which salmonids can locate particular sound sources has not yet been established.
3.1.13 **The Lateral Line in Fishes**

The lateral line system is essentially a system for detecting water flow and mechanical disturbances close to the fish (Denton and Gray 1993). It is found in all bony and cartilaginous fish, including salmonids, sharks and rays, 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. Local water movements deflect the hair cells of superficial neuromast organs, while 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 1993). 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 volume water displacements. Recent studies have suggested that some fish use their lateral line system to track hydrodynamic wakes behind immersed objects, and that the lateral line is involved in habitat selection by the rainbow trout (Liao 2006).

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 1993).
Moving bodies in water, and even stationary bodies in a flow field (e.g., boulders in a river) can generate hydrodynamic waves, surface waves, turbulence, and wakes. These local water movements may stimulate the lateral line system (Liao 2006). Fish essentially have the ability to make simultaneous particle motion measurements at multiple points along their body, giving them the potential to obtain information about turbulent eddies, local water currents, and the vortices generated by wakes. Chagnaud et al. (2006) showed that fish are sensitive to vortex-ring motions. Some surface-feeding fish are able to move towards prey by detecting the surface waves generated by movements of the prey (Bleckmann 1985, 1993). It is very likely that salmon make extensive use of their well-developed lateral line system for detecting and responding to local sources of turbulence, and for orientating to the hydrodynamic stimuli that are prevalent in rivers. Fish respond to hydrodynamic stimuli, and this has been used to manipulate fish movements in fish-avoidance schemes (Haro et al. 1998; Kemp et al. 2006; Kemp and Williams 2009). It has even been suggested that fish may create a hydrodynamic image of the world around them that allows them to navigate within topographically complex environments (Nestler et al. 2012). It may be possible to make use of these abilities of fish, based on the lateral line system, to guide their movements through fishways and around obstacles. The direction of water flows to direct or attract fish is commonly used to draw upstream migrants to the entrances of fishways (Popper and Schilt 2008).

It is not only the lateral line that might serve to control the movements of fish in the presence of local water currents and turbulence. The otolith organs of the inner ear are capable of detecting linear accelerations and they may also play a key role in the orientation and movements of fish in complex hydrodynamic environments.

### 3.2 Detection of Sounds by Juvenile and Adult Salmon

Many of the fishes that are most sensitive to sounds, and especially those that respond to sound pressure, have swimbladders. In the most sensitive of fishes, like the Ostariophysans, there are physical connections between the swimbladder and the ear. Salmonid fish have a swim bladder. However, unlike the cod and many marine species, where the swim bladder is closed, there is a connection (the pneumatic duct) between the bladder and the digestive tract. The organ is also placed farther back in the abdomen than in many other species, and
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there is no physical connection to the ear. On this basis it has been considered that salmon are unlikely to be highly sensitive to sound pressures.

The hearing abilities of Atlantic salmon were first studied on a specially designed acoustic range in the sea, located in a Scottish fjord (Hawkins and Johnstone 1978). The range was originally designed for experiments on marine fishes like the cod. A sheltered fjord was chosen, where relatively deep water could be reached within a short distance of the shore. A tower was built on the seabed, with loudspeakers moored at different distances (Figure 13). The individual salmon were placed in the sea in a cage on top of the tower, and left for 24 hours to equilibrate. They were then conditioned to respond to sounds, and auditory thresholds were determined for different sound frequencies.

![Diagram of the acoustic range](image_url)

Note: Pure tone signals were transmitted to the fish from loudspeakers placed at different distances to vary the ratio of sound pressure to particle motion, using the near-field effect.

**Figure 13**

**Acoustic Range Used to Examine the Hearing Abilities of Atlantic Salmon in a Scottish Fjord**
A cardiac conditioning technique (Otis et al. 1957) was employed to train the salmon to respond to sounds and allow auditory thresholds to be determined. The electrocardiogram of the salmon was monitored with a small metal electrode. The fish was confined in a narrow open mesh cage on top of the underwater tower and the electrode plugged into a cable running 200 m to the shore. A pure tone stimulus was presented for the duration of four normal heartbeats, followed by a mild electric shock. The conditioned response consisted of a delay in one or more heartbeats following the onset of the sound. Once a clear positive response had been established the sound level was progressively lowered with each positive response and raised with each negative response to determine the threshold to a pure tone of a particular frequency. Hearing thresholds were then determined at a number of frequencies to provide an audiogram for the salmon.

Salmon responded only to low-frequency tones, below 380 Hz (Figure 14). The salmon were relatively insensitive compared to cod, their audiograms more closely resembling those obtained from the plaice and dab (marine flatfish lacking swimbladders).

Note: The audiogram on the left plots thresholds in terms of the SPL. The audiogram on the right plots thresholds in terms of sound particle displacement. Thresholds obtained with the sound source at different distances come together when plotted as particle displacement rather than sound pressure. The different symbols represent different sound source distances.

**Figure 14**
Audiograms for the Atlantic Salmon
The Detection of Sounds by Fishes

Use was made of the near-field effect to expose the fish to different ratios of sound pressure to particle motion (the ratio of particle motion to sound pressure increases closer to the source). As with the dab and plaice, lower sound pressure thresholds were obtained closer to the source, but the estimated particle motion thresholds remained constant with distance, confirming that the salmon was sensitive to particle motion rather than sound pressure. The swimbladder is not involved in hearing in the salmon. It should be noted that a recent review (Ladich and Fay 2013) cites Hawkins and Johnstone (1978) as showing that the salmon is pressure sensitive at the higher frequencies but sensitive to particle acceleration at the lower frequencies. This is a serious misquotation. Salmon were shown to be sensitive to particle motion at all frequencies.

Parallel experiments on salmon in a laboratory tank were especially revealing. Use was made of Parvulescu’s suggestion (Parvulescu 1964) that a sound field characterized by especially small particle motions could be obtained by imposing changes in the air pressure surrounding a tank containing a fish. Conversely, very large particle motions could be obtained with a submerged loudspeaker close to the fish. Sound pressure thresholds determined for salmon in a tank differed greatly under these two different conditions. The thresholds were much higher (the fish were less sensitive by more than 30 dB) with the sounds presented from a loudspeaker in air. Again, it was evident that the salmon was responding only to particle motion. The experiment underlined the extreme care that has to be taken in interpreting the results of hearing experiments on fish in a small tank in the laboratory. The use of a loudspeaker in air to determine sound pressure thresholds would greatly underestimate the hearing abilities of any fish sensitive to particle motion, including the salmon. These experiments also confirmed that the salmon is relatively insensitive to any sounds generated in air.

Masking of the thresholds for salmon by noise did not take place under natural conditions of sea noise, as occurred with cod, but could be imposed by transmitting high levels of noise (Figure 15).

Thus, masking of auditory thresholds for salmon by the level of ambient noise does not occur under very quiet sea conditions, although it may occur at the much higher noise levels that occur in a fast-flowing river.
Hawkins and Johnstone (1978) demonstrated that critical bands existed for salmon. That is, there is a fine-tuning mechanism that exists in the salmon, enabling the fish to improve the detection of pure tones against a noisy background. However, the critical bands in salmon were much wider than those in the cod, suggesting that the ability of salmon to discriminate sounds in the presence of noise is inferior to that of the cod.

Note that the thresholds for salmon are not affected by the increase in noise level until much higher levels are reached than for the cod.

**Figure 15**

Changes in Auditory Thresholds to a Pure Tone at a Frequency of 160 Hz at Different Background Noise Levels for Cod and Atlantic Salmon

There are very few natural ambient noise data available for rivers. There are some difficulties in making such measurements as hydrophones tend to be sensitive to buffeting and to flow noise over the surface of the transducer, which tend to generate false or pseudo-noise (much like that caused by the effects of wind on a microphone in air). Hawkins and Johnstone’s measurements indicated that noise levels at low frequencies (below 100 Hz) were much higher in a river than in the sea under comparable conditions. They also showed that airborne sounds (a human voice) would be rather difficult for salmon to detect within the
river. However, salmon would readily detect human footfalls on the riverbank, transmitted through the substrate into the water.

From the salmon audiogram prepared by Hawkins and Johnstone (1978), it would seem that sound does not have the importance for salmon that it does for a fish like the cod. The frequency range of the salmon is narrow, its sensitivity is low, and its power to discriminate signals from noise is poor compared with some other species. Nevertheless, salmon do detect sounds, and their lower sensitivity may simply reflect the fact that they spend much of their lives within noisy river systems, where the natural level of background noise is high.

However, the response of salmon to very low-frequency sounds also needs to be taken into account. Enger et al. (1993) showed that the frequency response of a number of species of fish extended well below the lower limit of 20 to 30 Hz usually examined in hearing studies. Cod, salmon, and a few other species were found to respond to sound frequencies extending down to below 1 Hz (infrasound). Tests on the behavior of juvenile salmon performed in a large tank showed that the fish produced spontaneous avoidance responses to sounds at 10 Hz, but not to sounds at 150 Hz. Tests on down-river migrating salmon smolts were also performed. Over a stimulation period of 170 minutes, only 6 smolts passed an operating 10-Hz sound source, whereas 338 smolts passed during a silent period of the same duration. Stimulation at 150 Hz had no evident effect on the migration of salmon smolts. There have, however, been relatively few recent studies on the detection of infrasound by salmon, despite the interesting results from these early experiments.

Few data are available on the hearing abilities of Pacific salmon species, or on the hearing abilities of juvenile salmon.
4 EFFECTS OF SOUND ON FISHES

4.1 Assessing Effects

Many reports and scientific papers have emphasized the potential risks to fishes from exposure to man-made sounds or noise (most recently, Popper and Hawkins 2012; Popper et al. 2014; Hawkins and Popper 2014; Hawkins et al. 2015). Increasingly, environmental assessments of the impact of developments and other activities in the sea or close to rivers and lakes have been required to consider the effects of underwater noise on fishes. There has been particular concern over the impact of pile driving and seismic surveys on the movements of salmon in the sea. Sources of renewable energy, including wind farms and tidal devices, are currently being considered for a number of inshore locations and these may pose risks to migrating salmon, especially if salmon are using acoustical cues to enable them to navigate and orient.

An environmental assessment essentially evaluates the effects of underwater sound in terms of mortality or any physical injury, impairment to hearing, or behavioral disturbance it might cause to fish. The assessment end points are typically aimed at determining whether there is a significant impact on fish populations and on the wider ecosystem. Often a threshold for an adverse effect is sought, and this can lead to conclusions about the likely severity of any impact. This process, referred to as risk assessment, can subsequently be used to construct “what-if” scenarios to evaluate methods for effective prevention, control, or mitigation of impacts, and to provide a reasoned basis for action to reduce risks.

As part of the risk assessment process, it is necessary to predict the levels of different types of sounds that may have potential impacts on fish like the salmon, as well as those that are likely to be of no consequence. A criterion is usually provided as a threshold value, expressed in a particular acoustic metric, above which a particular level of damage may take place or behavioral change may occur. The precise nature of any effects and the actual metrics that describe the sounds must be specified clearly, although there are many difficulties in achieving this. For example, not only the level of the sound but its frequency range, rise time, duration, repetition rate, and a number of other parameters can also be important in assessing its impact. Understanding the risk to animals therefore becomes more
complex than just setting a single threshold value. But in all cases, the fundamental issue involves understanding how animals respond to sounds of different kinds, at different levels.

4.2 Setting Sound Exposure Criteria

Recent guidelines, developed under the auspices of the Standards Group of the ASA, provided some directions and recommendations for ultimately setting criteria for fishes (Popper et al. 2014).

Depending on the fish concerned, its distance from the source, and the nature of the source, exposure to high levels of sound may result in the following:

- Mortality and mortal injury – immediate or delayed death due to injury
- Recoverable injury – injuries including damage to the ear, minor internal or external bleeding, etc.
- Short- or long-term changes in hearing sensitivity (temporary or permanent threshold shift) that may, or may not, reduce fitness and survival
- Masking – where it is difficult for the fish to detect biologically meaningful sounds against the noise background
- Behavioral effects – substantial changes in behavior for a large proportion of the animals exposed

The ANSI-accredited report providing guidelines for fishes (Popper et al. 2014) sets out the sound levels for different sound sources that are likely to result in each of these effects.

Thus, in setting sound exposure criteria there are a number of scientific options. It has been commonplace in the past to specify those sound levels that result in injury to animals, especially if these are likely to result in death. However, this level of damage occurs only very close to very intense sound sources like percussive pile drivers.

For marine mammals it has been considered more relevant to estimate the received levels, or thresholds, above which individual marine mammals are predicted to experience changes in their hearing sensitivity (either temporary or permanent) from underwater sound sources. In its most recent guidelines for marine mammals, NOAA (2013) designated acoustic
threshold levels for the onset of both temporary (TTS) and permanent hearing threshold shifts (PTS) for different marine mammal groups, and for both continuous and impulsive sources. However, NOAA has stressed that these acoustic threshold levels do not represent the entirety of an impact assessment. Rather, they provide one of several tools (in addition to behavioral impact thresholds, auditory masking assessments, and other evaluations) to help understand the ultimate effects of any particular type of impact.

With fishes, effects on behavior are considered most relevant in terms of effects upon populations (Popper et al. 2014). These effects can occur at much greater distances from the source than sound levels that can do physical harm, and they almost always involve a lower onset threshold than tissue injury or damage to the auditory system.

Because of a general lack of information on the effects of sounds on fishes and other marine animals, the sound exposure criteria that have been applied in practice do not always reflect the complexity of the sounds to which animals are being exposed or the hearing capabilities and behavioral responses of the animals themselves. For example, as a conservative measure, NOAA Fisheries and the U.S. Fish and Wildlife Service have suggested 150 dB re 1 μPa rms as the threshold for behavioral effects to fish species that are listed as being threatened or endangered. This criterion has been applied in many biological opinions evaluating percussive pile driving activities. The criterion was selected on the basis that SPLs in excess of 150 dB re 1 μPa rms could cause temporary behavioral changes (startle and stress) that might decrease a fish’s ability to avoid predators (Woodbury and Stadler 2008; Stadler and Woodbury 2009). The scientific origin of this value is not known (Hastings 2008). In addition, species differences have not been taken into consideration in applying this exposure criterion.

Sound levels expressed as rms values may be appropriate for some continuous sounds but they do not adequately describe more complex sounds, as the rms measurement simply averages out varying sound levels. Sounds that are transient or impulsive (of short duration and high amplitude) can cause particular damage to tissues, and may also evoke strong behavioral responses. For impulsive sounds the instantaneous peak level has been used in a number of sound exposure criteria, although this metric does not account for the total energy within the sound and requires a fast sampling rate for effective measurement. The SEL,
which is related to the total acoustic energy, is used as a complementary metric. The SEL takes into account both level and duration of exposure (ANSI 1994). This metric can be used to normalize a single sound exposure to 1 second, enabling sounds of differing duration to be compared. As we have seen, the SEL can also be used to account for accumulated exposure to repeated sound energy over the duration of a repetitive activity such as pile driving, or for continuous activity over a specified period of time. The exposure is then expressed as the SELcum (Popper and Hastings 2009a; Halvorsen et al. 2012a).

The criteria agreed upon by the U.S. Fisheries Hydroacoustic Working Group (FHWG 2009) for the onset of effects of percussive pile driving activities in terms of injuries to fishes identified the dual criteria of a peak SPL of 206 dB re 1 μPa and an SELcum of 187 dB re 1 μPa²s. The additional specification of a peak level recognizes that a SELcum on its own may not be sufficient to account for all potential impacts. However, it is clear that even the use of these dual metrics cannot distinguish fully between a series of sounds that are damaging and those that are not. If the SELcum is to be used as a metric for a series of impulses, it is also important to specify the time period over which the SEL is accumulated, the number of impulses, the repetition rate (as there may be recovery between repeated pulses), and the rise time of individual pulses.

Recently, Halvorsen et al. (2011, 2012a, 2012c) described an extensive investigation into the effects of simulated pile driving impulsive sounds upon juvenile Chinook salmon and other species. An important advance with this work was the development of an injury response variable, the Response Severity Index (RSI), based on the physiological impact of different injuries on the health of the fish. Halvorsen and her collaborators were able to determine peak SPLs associated with different levels of the RSI for different species. They also derived a function that related both the SELcum and the number of pile strikes to the RSI. An important finding from these studies was that tissue damage increased both as energy accumulated over multiple strikes (SELcum) and/or as the energy in single strikes increased. However, the relationship was not linear, and it is clear that application of an “equal energy hypothesis,” in which effects are related to total energy no matter how that total energy is achieved, is not appropriate.
Another issue is that in some cases, sound exposure criteria specify the level received by the animal. In others, they specify a level at a particular distance from the source (often neglecting the distributed nature of many real sources, whether they are large ships or extensive seismic air gun arrays). For simplicity, it is often assumed that animals remain at a constant distance from the source, but this may seldom be the case. Where animals are moving, perhaps to avoid the sounds, these movements may later take them outside the range of any effects. Some sources, like seismic air gun arrays and ships, are also moving. It can therefore be difficult to model the actual sound levels received by the animals over time and space, or to define precisely the SEL_{cum} that they experience. There is also often insufficient information about the complexity of actual animal responses to understand when they will avoid sounds and when they will not.

As we have already seen, although sound levels are commonly expressed in terms of sound pressure, not all fishes can detect sound pressure. Fishes, including salmon, are essentially sensitive to the kinetic elements of sounds (particle motion). Relatively few species of fish detect sound pressure (Popper and Fay 2011). But it is still relatively rare to specify and measure sounds in terms of their particle motion levels.

Mortality from sound exposure is relatively rare in fishes and occurs only for fishes close to explosions and to pile drivers (which is used for the construction of foundations for a large number of structures in water including bridges, buildings, retaining walls, harbor facilities, barrages, offshore wind turbines, and offshore structures for the oil and gas industry). Injuries, and changes in hearing sensitivity, are also most likely to be encountered with high-level impulsive sounds, including sounds from pile drivers. It is conceivable that such effects might occur during the construction of dams, tidal barrages, and lagoons, or in the emplacement of hydrokinetic devices in estuaries or open waters. Some observations have shown that fish within a few meters of driving a large pile may be killed (Caltrans 2004), but the sound levels to which the fish were exposed were not documented. At greater distances, data from caged fish showed no mortality and no damage that could be clearly associated with pile driving activities (Abbott et al. 2005; Nedwell et al. 2006; Houghton et al. 2010).

In a series of experiments where Chinook salmon smolts were exposed to noise from tidal turbines over a 24-hour period (Halvorsen et al. 2011) it was noted from electrophysiological...
testing of the auditory system that there were no effects on hearing sensitivity. This suggests that as Chinook salmon pass very near to a turbine they would not experience changes in their hearing sensitivity, although they might show changes in behavior as a result of exposure to the noise. Analysis of fish indicated a low level of tissue damage, but the injury responses from the juvenile Chinook were minor and had a low physiological cost to the fish.

Masking, the impairment of hearing in the presence of noise, is most prevalent in the presence of continuous noise, including that from ships and operating turbines. In the presence of such noise there may be deterioration in the ability of the fish to detect the sounds of prey, or predators, or to detect underwater sound cues that may guide its movements. Hawkins and Chapman (1975) were able to show that masking occurs in a sensitive species like the cod even as a result of raised levels of natural sea noise (caused by wind and waves). Rather higher levels of ambient noise were required to mask hearing in the salmon (Hawkins and Johnstone 1978). However, it has been suggested that low-frequency auditory cues may be important in guiding the offshore migrations of salmonid fishes (Cotter 2008). More recently, Guerin et al. (2014) suggested that natural sounds generated close to shore especially at infrasonic frequencies may offer consistent cues for orientation by coastal migrants. There is potential for masking of these cues by man-made sounds.

Behavioral effects from exposure to sounds may operate over substantial distances from some sound sources. As well as simple startle reactions, which may have little importance, significant change in behavior may take place. These may include long-term changes in behavior and distribution, such as moving from preferred sites for feeding and reproduction, or alteration of migration patterns.

In the case of shad, which are able to detect ultrasonic frequencies, it is possible that behavioral responses may occur to echo sounder and sonar systems. Indeed, ultrasound sources have been used to deflect shad away from water intakes in rivers. At an installation on the River Wye in the UK, using sonar systems to count fish, it was noted that migrating shad would not pass the monitoring site and showed avoidance behavior when the sonar was operating at 200 kHz, but were unaffected when the sonar was operating at the much higher frequency of 420 kHz (Gregory and Clabburn 2003). There have also been reports of the use
of ultrasound to keep shad and blueback herring from entering cooling water intakes and large power plants (reviewed by Popper and Schilt 2008). It has not always been clear, however, whether the responses observed from these fish have been the result of the incidental generation of sound at lower frequencies (within the hearing range of fishes) rather than the sonar operating frequencies. It has been suggested that frequency leakage from the center frequency of sonars may affect marine mammals (Deng et al. 2014). In addition, the rapid onset of sonar pulses may also generate audible “clicks” at much lower frequencies in some instances.

Relatively little is known about the range of sounds associated with particular freshwater habitats and the contributions made to the soundscape by different natural and man-made sources. In particular, there have been few descriptions of the sounds generated in water by hydroelectric turbines or hydrokinetic devices, or by land-based machinery. There have also been few experimental studies of the impact of noise from these sources upon fishes in rivers and lakes.

### 4.3 Effects on Fish Behavior

Sounds may have a number of different effects on fish behavior, depending on the level of the sound, the level of ambient noise, what the fish is doing at the time, and previous experience of the same and other sounds. Whether a fish responds or not may also depend on its condition, motivational state, and the presence of other animals including predators (De Robertis and Handegard 2013). Significant changes in behavior might include abandonment of spawning sites; movement away from preferred habitats; disruption of feeding; increased energy consumption; greater exposure to predators; and diversion or delay of migrations.

Sound exposure experiments have often previously been conducted on fish held in tanks, cages, and enclosures (Hassel et al. 2004; Boeger et al. 2006; Kastelein et al. 2008; Doksæter et al. 2012; Thomsen et al. 2012; Voellmy et al. 2014). Such experiments can be valuable in allowing detailed observation of the responses of fish under controlled conditions. However, observations made on captive fish need to be supplemented by studies in the wild. Sound fields in small tanks and enclosures are dissimilar to those prevailing under more natural
conditions in rivers and lakes, often with severe distortion of the presented sound stimuli, as Parvulescu (1964) pointed out. In addition, captive fish may not show the same range and types of behavioral responses observed in the wild. Voellmy et al. (2014) recently showed that the three-spined stickleback (*Gasterosteus aculeatus*) and the European minnow (*Phoxinus phoxinus*) consumed significantly fewer live prey, and showed startle responses significantly more often during playback of additional noise than during control conditions. However, the experiments were carried out in small (10 liter) plastic tanks in the laboratory, and it remains to be tested whether these observations translate into similar impacts on the same species in the wild. Fish tend to behave differently when enclosed than when their movements are unrestricted (Benhaïma et al. 2012; Oldfield 2011). Fish brought into captivity may also be damaged during capture, or their behavior affected by the circumstances under which they were reared (Balaa and Blouin-Demers 2011).

In one of the few studies of the responses of wild, pelagic fish to sound playback (Hawkins et al. 2014), the behavior of fish was observed with a sonar/echo sounder. Schools of sprat (*Sprattus sprattus*) and mackerel (*Scomber scombrus*) were examined at a quiet coastal location. The fish were exposed to a short sequence of repeated impulsive sounds, simulating the strikes from a pile driver, at different SPLs. The incidence of behavioral responses increased with increasing sound level. Sprat schools were more likely to disperse and mackerel schools more likely to change depth. The SPLs to which the fish schools responded on 50% of presentations were 163.2 and 163.3 dB re 1 μPa peak-to-peak, and the single strike SELs were 135.0 and 142.0 dB re 1 μPa^2 s, for sprat and mackerel, respectively, estimated from dose response curves. For sounds leading to mackerel responses, particle velocity levels were also estimated. The method of observation by means of a sonar/echo sounder proved successful in examining the behavior of unrestrained fish exposed to different sound levels. Such techniques may allow further testing of the relationship between responsiveness, sound level, and sound characteristics for different types of man-made sound, for a variety of marine and freshwater fish species under varied conditions.

Recently, fish protection at cooling and hydroelectric water intakes has become a topic of major interest. Mechanical screens are inherently hampered by clogging, causing reduction of the available water flow and high maintenance costs. Among the non-mechanical behavioral barriers that have been developed in order to induce an avoidance response away
from a water intake, or a guiding response towards a fish pass, are electrical screens, bubble
curtains, artificial light arrays, and underwater acoustic fences. In the UK, the Environment
Agency has prepared a Best Practice Guide for intake and outfall fish screening (Turnpenny
and O’Keeffe 2005). The guide contains a great deal of information on environmental
mitigation techniques for intakes, as well as background data.

Early attempts to construct efficient acoustic barriers based on sound frequencies were often
unsuccessful (reviewed by Carlson 1994; Popper and Carlson 1998; Popper and Schilt 2008).
The latter authors also point out that failures to achieve responses are often less likely to be
reported than successes. Goetz et al. (2001) found no effect in an attempt to use a 200 to
300 Hz signal to change juvenile salmonid distributions in a large navigation lock, and
concluded that “low frequency sound is not an effective means of guiding salmon smolts.”
However, effective reductions of fish entrainment at power-generating sites have been
reported for air guns, electronic sound sources, and a “mechanical hammer” (Popper and
Schilt 2008). In the River Schelde estuary in Belgium, an acoustic shield system employing
frequencies between 20 and 600 Hz is said to have dramatically reduced the impingement of
clupeids (i.e., c. 94.7% for herring [Clupea harengus] and 87.9% for sprat; Maes et al. 2004).
Smaller, but still significant, reductions were also observed for seven other species, including
one cyprinid species.

Mueller et al. (2001) carried out laboratory tests on caged juvenile Chinook salmon, brook
tROUT (Salvelinus fontinalis), and rainbow trout (Oncorhynchus mykiss) to determine
responses to infrasound (frequencies less than 20 Hz) and flashing strobe lights and examine
whether juvenile salmonids could be deterred from entrainment at water diversion
structures. Wild Chinook salmon and hatchery reared Chinook salmon exhibited avoidance
responses when initially exposed to a 10-Hz volume displacement source of infrasound.
Rainbow trout did not respond with avoidance or other behaviors to infrasound. Wild and
hatchery Chinook salmon displayed a higher proportion of movement during initial exposure
to infrasound, but habituation to the infrasound source was evident for Chinook salmon
during repeated exposures.

Sonny et al. (2006) tested the behavioral effects of infrasound on cyprinids at a lake in
Norway. Acute avoidance responses were observed at a distance up to 10 m from a 16 Hz
infrasound projector using echo sounding to monitor behavior. At 10 m distance, a coarse estimate of the stimulus level (measured as the acceleration component of the particle motion) was circa $10^{-3}$ m/s$^2$. Habituation was not evident during the tests. Two synchronized infrasound units were also installed 6 m apart in front of a cooling water intake of a nuclear power plant on a river in Belgium. Echo sounding was used to compare the number of fishes entering the intake canal during on–off infrasound sequences. Relative to off-periods, the reduction of the number of fishes entering during on-periods was greater than 80% at a distance of 0 to 12 m from the units. A significant reduction of 48% was observed considering the whole width (54 m) that was monitored. Fish impingement on the mechanical screens during the study revealed that greater than 90% of the fishes entering the intake were cyprinids.

Acoustic barriers based on intense infrasound are said to be good candidates for development of multi-specific repulsion systems (Sand et al. 2001). Fishes appear to be sensitive to infrasound (less than 20 Hz), even down to less than 1 Hz (Sand and Karlsen 1986, 2000), and the relevant stimulus parameter is thought to be particle acceleration (Popper et al. 2003).

Considerable success has been obtained in the use of ultrasound to keep Alosine fishes from entering cooling-water intakes and large power plants (Popper and Schilt 2008). Alosine herrings not only hear ultrasound, they also show avoidance reactions to pulsed ultrasound (Nestler et al. 1992; Plachta and Popper 2003). Gregory and Claburn (2003) reported that the 200 KHz side-scan sonar, which they used to detect upstream migrating Atlantic salmon, had to be turned off at intervals because it had the unforeseen consequence of stopping the concurrent upstream migration of the Alosine twaite shad (*A. fallax*). However, such responses to ultrasound appear to be confined to fishes of the family Alosinae. There is also a question whether the fish are responding to “frequency leakage” from these pulsed sources of ultrasound.

It is evident that many different things may influence whether sounds have an impact upon fish. The characteristics of the sounds themselves are very important: whether they are continuous or intermittent, their amplitude, rise time, duration, and repetition rate. The circumstances under which sounds are presented are also critical: whether the fish have previously experienced such sounds, and whether they resemble natural sounds of interest to
the fish. In many sound playback experiments, the stimulus and the noise fields are very poorly described, if they are described at all (Popper and Schilt 2008).

4.4 **Effects of Sound on Salmon Behavior**

In general, experimental attempts to examine behavioral reactions of salmonids to underwater sounds have been unsuccessful. Nedwell et al. (2006) investigated the impact of underwater pile driving on fish in Southampton Water on the South Coast of England. Monitoring was simultaneously undertaken of the waterborne sound from impact and vibratory pile driving and its effects on brown trout (*Salmo trutta*) in cages at increasing distances from the pile driving. No obvious signs of trauma that could be attributed to sound exposure were found in any fish examined, from any of the cages. No increase in activity or startle response was seen to vibratory pile driving. Analysis using the dBht metric indicated that the sound levels at the nearest cages during impact pile driving reached levels to which fish were expected to react strongly. However, the brown trout showed little reaction. An audiogram of the brown trout was measured by the ABR (more correctly the AEP) method, which indicated that the hearing of the brown trout was less sensitive than that of the salmon. However, it is often the case that AEP thresholds are higher than those obtained by behavioral methods (that is, the fish appear less sensitive to sounds).

It has been suggested that fishes, including salmonids, may use infrasound to detect moving objects in their surroundings. The major acceleration component of the noise generated by a swimming fish is in the infrasound range less than 10 to 20 Hz (Enger et al. 1989; Bleckmann et al. 1991). Infrasound sensitivity in fishes may be important in prey/predator interactions. Juvenile salmonids display strong avoidance reactions to infrasound (Knudsen et al. 1992, 1997), and it is reasonable to suggest that such behavior has evolved as a protection against predators. Infrasound has been used as an effective acoustic barrier for descending Atlantic salmon smolts (Knudsen et al. 1994), and also descending European silver eels are deflected by intense infrasound (Sand et al. 2000).

In the experiments by Knudsen et al. (1994), the reactions of Atlantic salmon smolts were examined in a small Norwegian river. Intense 150 Hz sounds had no impact upon descending salmon smolts, even at sound levels well above the hearing thresholds for
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Salmon. However, sounds transmitted at 10 Hz effectively deterred the smolts from moving downstream. No habituation was observed to the 10 Hz sounds. The authors concluded that low frequencies in the infrasound range (5 to 10 Hz) were the most efficient for evoking both awareness reactions and avoidance responses in juvenile salmon.

Subsequently, Knudsen et al. (1997) carried out similar experiments in the United States on juvenile spring Chinook salmon and rainbow trout. Groups of fish were placed in 3-m-diameter circular tanks and exposed to sounds from a piston-driven source generating a frequency of 10 Hz. The tests resulted in a strong flight response, with fish swimming as far away from the source as possible. The results of this study, although performed in a relatively small tank, suggested that salmon might avoid very intense sources of infrasound. It was therefore suggested that infrasound might be used in acoustic screens to divert Pacific salmon away from water inlets. More recently, Sand and Karlsen (2000) proposed the hypothesis that salmon may use the ambient infrasound in the ocean, produced by things like waves, tides, and other large-scale motions, for orientation during migration. Fish like salmon might possess an inertial guidance system, where they detect infrasound as part of their system for detecting linear acceleration. Infrasound may provide cues for salmon migrations.

Thus, experiments with infrasound have yielded important findings, which need to be followed up. Larger-scale field studies are needed to test the real effectiveness of infrasound in changing the behavior of salmon under more natural conditions.

Some observations have been made on the responses of salmon to construction work. Jepson et al. (2004) investigated the passage behavior of adult fall Chinook salmon and steelhead at Lower Monumental Dam, when construction associated with a new spill basin bottom was taking place. The movements of adult fall Chinook salmon and steelhead fitted with radio transmitters were monitored and measurements made of the time they used to make their first approach and first entrance at a monitored fish ladder opening, and their total time to pass the dam. Values from 2002, when construction occurred, were compared with those from the preceding 2 years, prior to construction. In addition, the proportionate use by salmon and steelhead of three available openings were compared, together with the proportionate use of the two fish ladders to pass the dam. All of these comparisons were
made across 3 years to evaluate any changes in adult fish behavior that may have been associated with construction activity.

No significant difference was found among years in the median times fall Chinook salmon required to first approach, first enter, or pass Lower Monumental Dam. However, significant differences among years did occur in the proportionate use of the three openings to first approach the fish ladders at the dam and in proportionate use of the two ladders to pass the dam. While there were no significant differences among years in the median times to first approach, first enter, or pass the dam, the highest proportionate use of the north shore entrance to first approach, and the north shore ladder to pass the dam, occurred in 2002. This may have been associated with salmon avoiding the construction area, which was closer to the south powerhouse entrance and south spillway entrance.

For steelhead, significant differences occurred among years in the median times the fish used to first approach, first enter, and pass Lower Monumental Dam, but the highest median times to first approach and first enter a fish ladder did not occur during 2002. The median time for steelhead to pass Lower Monumental Dam was highest in the year with construction (2002) but it was not significantly different from the median time observed in 2000. Significant differences were found among years in the proportionate use of the three fish ladder openings by steelhead to first approach and first enter the ladders, and in use of the two ladders to pass the dam. As with fall Chinook salmon, this may have been associated with the steelhead avoiding the construction area.

It was concluded that construction activity at Lower Monumental Dam in 2002 did not significantly retard fall Chinook salmon passage, but it may have mildly impeded steelhead passage, and may have caused an increased proportion of fish to use the opening and ladder on the north shore to preferentially approach, enter, and pass the dam. These are interesting findings. They may indicate the kinds of effects that may occur when construction work is undertaken at Lower Granite Dam.
4.5 Damage and Injury to Salmonids from Sound Exposure

There have been relatively few studies of any injuries caused to salmonids from exposure to high-level sounds. Davidson et al. (2009) investigated the effects of aquaculture production noise on the growth, condition factor, feed conversion, and survival of rainbow trout. They were concerned that sound levels and frequencies measured within intensive aquaculture systems were within the range of fish hearing, and that fish behavior and physiology might be negatively impacted by intense sound. Chronic exposure to aquaculture production noise might cause increased stress, reduced growth rates and feed-conversion efficiency, and decreased survival. In their experiments, rainbow trout were cultured in replicated tanks using two sound treatments: 117 dB re 1 μPa rms, which represented sound levels lower than those recorded in an intensive recycle system, and 149 dB re 1 μPa rms, representing sound levels near the upper limits known to occur in recycle systems. After five months of exposure no significant differences were identified between treatments for mean weight, length, specific growth rates, condition factor, feed conversion, or survival. Mean final weights for the 117 and 149 dB treatments were 641±3 and 631±10 g, respectively. Overall specific growth rates were equal, i.e., 1.84±0.00 and 1.84±0.01%/day. Analysis of growth rates of individually tagged rainbow trout indicated that fish from the 149 dB tanks grew slower during the first month of noise exposure; however, fish acclimated to the noise thereafter. This study further suggests that rainbow trout growth and survival are unlikely to be affected over the long term by noise levels common to intensive aquaculture systems.

Terhune et al. (1990) had previously observed decreased growth and smolting rates of Atlantic salmon in fiberglass tanks that had underwater sound levels 2 to 10 dB re 1 μPa higher at 100 to 500 Hz than concrete tanks. This is an interesting finding as particle motion levels were likely to have been higher in the fiberglass tanks because of pressure-release effects.

Wysocki et al. (2007) found that the hearing, growth, survival, and disease resistance of rainbow trout were not negatively impacted by long-term exposure to intensive aquaculture production noise (at SPLs of 115, 130, and 150 dB re 1 μPa rms). However, anecdotal evidence from Wysocki et al. (2007) showed decreased feeding and slightly slower growth rates, particularly at the onset of noise exposure, suggesting that there might be some effects on rainbow trout growth.
Particle motion levels were not recorded in any of the above experiments. Moreover, the fish were exposed to steady continuous sounds rather than the irregular sound patterns, including loud bursts of sound, which often occur in real aquaculture facilities due to construction, use of power tools, and the operation of equipment related to harvesting and cleaning.

The observation by Davidson et al. (2009) that fish adjusted or acclimated to high sound levels might suggest a progressive loss of hearing sensitivity by the rainbow trout following exposure to high noise levels. However, this possibility was not investigated.

Popper et al. (2007) and Halvorsen et al. (2012b) investigated the effects on rainbow trout of exposure to high-intensity, low-frequency sonar using an element of the standard U.S. Navy Surveillance Towed Array Sensor System Low Frequency Active (LFA) sonar source array. Effects of the LFA sonar on hearing were tested using ABRs (more correctly, AEP responses). Effects were also examined on inner ear morphology using scanning electron microscopy and on non-auditory tissues using general pathology and histopathology. Animals were exposed to a maximum received rms SPL of 193 dB re 1 $\mu$Pa$^2$ for 324 or 648 s, an exposure that is far in excess of any exposure a fish would normally encounter in the wild. The most significant effect was a 20-dB auditory threshold shift at 400 Hz. However, the results varied with different groups of rainbow trout, suggesting developmental and/or genetic impacts on how sound exposure affects hearing. There was no fish mortality during or after exposure. Sensory tissue of the inner ears did not show morphological damage even several days after sound exposure. Similarly, gross- and histopathology observations demonstrated no effects on non-auditory tissues.

Halvorsen et al. (2011) examined auditory and tissue effects upon juvenile Chinook salmon from simulated tidal turbine noise that was presented for 24 hours at an SPL of 159 dB re 1 $\mu$Pa. This was believed to represent a worst-case exposure scenario for juvenile salmon. After exposure, the fish were assessed for tissue damage and for changes in hearing sensitivity. Some of the treated fish appeared to show significant levels of injury compared with controls.
In other experiments (Halvorsen et al. 2012a), juvenile Chinook salmon were exposed to pile driving signals that had been recorded in the field during actual pile driving installations. One objective of the project was to prove a correlation between the $SEL_{cum}$ and the response level of barotrauma injury. A further objective was to test the validity of the “equal energy” hypothesis that has been implicitly accepted by regulators for management of activities that generate impulsive sounds. The equal energy hypothesis states that the relevant metric for risk of injury to fish is the $SEL_{cum}$ while other metrics are not relevant (e.g., single-strike $SEL_{ss}$ and/or the number of strikes). In other words, the equal energy hypothesis predicts that no matter how a damaging of an $SEL_{cum}$ is reached (e.g., a few strikes or many strikes), the effects on fishes would be the same. To test this hypothesis, experiments paired sound exposures such that there were two treatments with the same $SEL_{cum}$, while the $SEL_{ss}$ and number of strikes changed.

The distributions of results from experimental treatments of 1,920 and 960 pile driving strikes showed a statistically significant correlation between a response-weighted index of injury (the RWI) and $SEL_{cum}$. Additional statistical analysis showed that as $SEL_{cum}$ increased, there was an increase in RWI values. The increase in RWI was the result of the number of injuries each exposed fish experienced as well as the physiological significance of those injuries. Results also showed that fish exposed to 960 strikes had a significantly higher RWI value than fish exposed to 1,920 strikes at the same value of $SEL_{cum}$. Thus, for the same values of $SEL_{cum}$, higher levels of $SEL_{ss}$ resulted in increases in the number and severity of injuries observed. This finding demonstrates that the equal energy hypothesis does not apply to effects of pile driving, thereby confirming that a single metric of total energy, $SEL_{cum}$, is not sufficient to provide a clear criterion for damage to the fish. Other metrics are necessary and should be taken into consideration. Those metrics include, but are not necessarily limited to, $SEL_{cum}$, $SEL_{ss}$, and total number of strikes.

It would seem that salmonids only show significant levels of damage and injury when they are exposed to impulsive sounds at very high SPLs. However, there is a lack of data on the effects of exposure to very high levels of vibration, where particle motion levels are high. Shaking the fish may be more damaging, especially to the auditory system, than exposing it to pressure fluctuations.
4.6 Sound and Vibration Levels Associated with Hydropower Projects Within or Outside the Columbia River Basin

There are remarkably few data on the levels of sound and vibration that prevail in rivers close to hydropower stations and their associated structures. Anderson et al. (1989) examined low-frequency sound generated by four Columbia River hydropower projects, including Lower Granite Dam. The measurements were prompted by concerns that a portion of downstream migrating salmonids avoided the submersible traveling screen (STS) and passed through the power-generating turbines. It had been suggested that an STS might generate low-frequency sounds that fish might perceive at a distance.

The SPLs in turbine entrances differed between powerhouses. Each project had a distinctive acoustic signature. Far field measurements indicated that fish approaching the Bonneville project perceived sounds of the dam twice as far from the Bonneville First Powerhouse as from the Second Powerhouse. In addition, the same SPLs occurred farther out in the forebay at McNary Dam than they did at the Bonneville First Powerhouse.

SPLs in front of the dams, described as the near field, were about 10 dB lower than in fish bypass slots. In addition, bypass slot spectra had a number of acoustic peaks that were absent in the near field. SPLs increased by about 10 dB from just below the surface to the level of the turbine entrance. Note that it is very common for SPLs to be lower close to the water surface. This is because of pressure release at the surface interface with air, which converts sound pressure to particle motion. The particle motion levels are therefore often higher near the surface.

The acoustic signatures in the bypass slots of the Bonneville Second Powerhouse were a function of the configurations of the bypass slots. In addition, distinct low-frequency peaks appeared to increase in intensity closer to the STS and it appeared that water flow through the gap between this screen and the turbine intake ceiling may produce these peaks.

Coherence and phase data indicated that the acoustic environment at the Bonneville Second Powerhouse was complex and many of the observed acoustic phenomena could not be explained. However, sound at frequencies at 18 Hz and 30 Hz was coherent at almost all locations suggesting that the turbines were the primary source for these frequencies.
Multiple sound sources and reflectors within the dam could conceivably startle juvenile salmonids.

Fish moving with the flow would experience higher rates of SPL increase in front of the trash rack at the Bonneville Second Powerhouse compared to the Bonneville First Powerhouse and McNary Dam. In addition Bonneville had a peak of sound energy localized to the bypass slot and STS frame ranging from 120 to 160 Hz. Water rushing through the gap at the STS may be the cause of this peak. The peak was absent at the trash rack.

These measurements provided useful indication of what can be expected in terms of SPLs at different locations. They also indicated that fish might alter their behavior as a result of the sounds they experienced as they passed through the trash rack. However, no measurements of particle motion level and direction were made, although these are the stimuli to which salmon respond. An attempt was made to estimate particle velocity levels by comparing the outputs of two spaced sound pressure hydrophones, but the technique was not adequate even to provide an indication of actual particle velocity levels. As particle velocity is a vector, it is necessary to use at least four sound pressure hydrophones to properly monitor sound pressure gradients in three orthogonal directions, and hence to examine the level and direction of the particle motion. Two hydrophones can only be used to monitor particle motion along one axis.

Anderson et al. (1989) concluded that there was insufficient information on fish responses to sound to infer how such changes would affect the movements of fish and fish guidance efficiency. Further studies were required.

Hall (1989) measured noise levels downstream of the two outlet draught tubes at Pitlochry Hydro-Electric station in Scotland, when one turbine was operating. The noise levels were said to be very high compared to typical river noise, but it was observed that salmon were present within the outlet pool, suggesting that the noise offered no barrier to fish entry into the pool.

Recently, an MSc study has been carried out to estimate acoustic particle motion levels and determine source bearing using a drifting hydrophone array near a river current turbine to
assess disturbances to fish (Murphy 2015). Sounds with strong tonal peaks and a harmonic structure at frequencies less than 500 Hz were measured near an operating river hydrokinetic turbine. The frequency and level of the fundamental tone (approximately 100 Hz) were found to vary with the rotation rate of the turbine, suggesting that generator "cogging" was the source of the tones.

Sounds originating from the turbine were within the frequency range to which salmon are most sensitive. However, it was not possible to distinguish acoustic particle acceleration from background noise at the measurement depth. It was therefore unclear whether salmon would be capable of detecting the turbine sound. It was noted that the sound pressure levels associated with recreational fishing traffic occurs at similar frequencies to turbine operation, and a thorough accounting of contextual sources of sound during the fish migration up and down river would be required as part of any behavioral study. Source bearing estimations were conducted using the same array used for particle motion estimation, but the results were inconclusive.

It is clear from this literature review that there is little information on the response of salmonids in rivers to various sound sources. We know that salmon detect particle motion and respond to high levels of infrasound, but few data are available to guide assessment of the effects of construction on the fish passage environment of fish ladders for adult salmonids. The proposed work at Lower Granite Dam, particularly the parts related to measurement of sound and vibration in the fish ladder caused by construction activities, will be original work. There are few (if any) precedents.

### 4.7 Sound and Vibration Levels Associated with Non-hydropower Larger River Passage Corridor Habitats Within or Outside the Columbia River Basin

There are a number of natural sources of sound, contributing to the natural background of sounds (or ambient noise) in rivers and lakes. Fishes and other animals may seek out and select suitable habitats by analyzing the environmental information they obtain via their various sensory pathways, including the acoustical information obtained using the ears. It is important to understand those natural environmental features that aquatic animals like salmon can sense, including those cues provided by the soundscape.
Thermal noise arises from molecular motion within water. This is important at high frequencies, greater than about 30 kHz (Wenz 1962). It is unlikely that this high frequency noise is detected or utilized by fishes, or that it interferes with signal detection, except perhaps in the Alosine fishes, which can detect ultrasonic frequencies (Mann et al. 2001).

Sediment transport by water currents is known to generate sound. Harden Jones and Mitson (1982) detected sounds at 30 and 300 kHz originating from tidal currents moving over sand waves in the sea. This source of sound needs further examination. It is likely that any movement of rocks and boulders on riverbeds under high flow conditions will generate sounds, perhaps down to quite low frequencies (below 1 kHz).

Surface waves produce low-frequency pressure oscillations in water (at frequencies of 20 Hz or less) associated with the changes of water level as each wave passes (Ross 1993). The low-frequency pressure fluctuations from large waves may be supplemented by the sounds created by waves breaking on rocks and riverbanks.

Wind noise may dominate ambient underwater noise at frequencies between about 100 Hz and 25 kHz, with maximum levels between 100 and 1,000 Hz, depending on weather conditions (Wenz 1962). Much of the higher frequency noise comes from oscillating and bursting bubbles, and splashes created by breaking wave crests (Ross 1993).

Rain and snow can raise ambient underwater noise greatly at frequencies between approximately 1 and 30 kHz. Thunder and lightning may also generate lower frequency sounds that can contribute significantly to background sound levels even at considerable distances from the locality of the storm.

Turbulence and other hydraulic effects from currents and eddies generate sound over a broad range of frequencies. Flow and turbulence induces spurious ‘self noise’ or pseudo-noise around a moored hydrophone (Zakarauskas 1986). Wenz (1962) considered that although pressure fluctuations and water movements occur close to a zone of turbulence, very little sound is radiated outside. There have been few reported measurements of turbulent sounds in rivers but it is likely that at many locations they may dominate the ambient noise over a broad frequency range.
Small movements of the Earth’s crust (microseisms), together with breaking ice and other mechanical movements, generate underwater sounds (Lynch et al. 1993). It has been argued by Urick (1983) that microseisms could be a significant source of ambient oceanic noise below 1 Hz. It is also apparent that microseisms are detectable on land (as so-called earth hum) at infrasonic frequencies and it is very likely that they will be detectable in freshwater rivers and lakes. Ardhuin et al. (2015) recently reported that this micro seismic activity, recorded everywhere on Earth, is largely due to ocean waves. The pressure of the waves on the seafloor generates seismic waves that cause the Earth to oscillate. Recent work has clearly identified sources of microseisms in the most energetic band, with periods from 3 to 10 s. In contrast, the generation of longer-period microseisms has been strongly debated. Two mechanisms have been proposed to explain seismic wave generation: a primary mechanism, by which ocean waves propagating over bottom slopes generate seismic waves, and a secondary mechanism that relies on the nonlinear interaction of ocean waves. Ardhuin et al. (2015) showed that the primary mechanism explains the average power, frequency distribution, and most of the variability in signals recorded by vertical seismometers, for seismic periods ranging from 13 to 300 s. Since some, and perhaps all, fishes are sensitive to infrasound (Sand and Karlsen 1986) it is possible that microseisms provide them with an important source of information about their location.

Rivers can be very noisy environments (sound levels often exceeding 100 dB re 1 µPa (rms) with a potential for masking the detection of important acoustic signals by animals (Wysocki and Ladich 2005; Scholz and Ladich 2006; Ladich 2013). A series of measurements by Wysocki et al. (2007) described a broad range of aquatic habitats in central Europe, including running waters such as creeks and rivers and stagnant waters such as lakes and backwaters. They found considerable differences in noise levels and spectral profiles between the 12 habitats investigated. Stagnant habitats were quiet, with overall noise levels below 100 dB re 1 µPa (rms) under low wind conditions. Noise levels in fast-flowing waters were typically above 110 dB re 1 µPa (rms) and peaked at 135 dB in a free-flowing section of the Danube River. Noise levels differed by more than 50 dB between habitats. Most environmental noise in stagnant habitats was concentrated in the lower frequency range below 500 Hz. In fast-flowing waters, high amounts of sound energy were present in the frequency range above 1 kHz, leaving a low energy “noise window” below 1 kHz.
Additional high-amplitude sounds in rivers and lakes come from human activities, including boat traffic, nearby traffic on land and over bridges, manufacturing industry, mineral extraction and drilling, construction works, and other noisy activities. Acoustic processes engaged in by fishes including sound detection, sound transmission, and communication would be limited by this noise. Fishes using sounds to communicate, orient, or navigate through rivers have to cope with this situation (Ladich 2013). Sound sources that result in substrate transmission of sound and vibration may pose particular problems to fishes. We have seen that fishes like the salmon are most sensitive to low and infrasonic frequencies. High amplitude, low-frequency sounds and vibrations are generated by sources like impact and vibratory pile drivers, jackhammers, dredging, and digging activities, with much of the energy entering the substrate. Conventional sound propagation models do not deal adequately with substrate transmission and few, if any, direct measurements have been made of the levels of particle motion generated at different distances from such sources.

We have seen that the auditory system of fish may help them to form a three-dimensional image of the local environment. The changes in soundscape from place to place may help fish to navigate their way through rivers and seas (Sand and Karlsen 1986; Cotter 2008). It has been shown that fish have flexible mental abilities to form, memorize, and use spatial maps (Braithwaite 2006; Braithwaite and Burt de Perera 2006). Experimental work has shown that fish can use landmarks, can integrate different types of spatial information to find their way and orientate, can associate events with times and places, and can learn locations (e.g., of food sources) from experienced individuals of the same species. It is not beyond the bounds of possibility that fish may use some form of inertial navigation, relying on their otolith organs to monitor changes in their movement or displacement in different directions. As Braithwaite (2006) states: “It is surprising that it has taken until now for us to appreciate just how cognitively competent many fish are.” On the other hand, as Cotter (2008) has pointed out, these abilities have proved extraordinarily hard to demonstrate scientifically.

Several studies have investigated the potential effects of high levels of white noise on sound detection by fishes. The fish were usually exposed to white (Gaussian) noise for several hours (or days) at different noise levels in order to study any decline, as well as subsequent recovery, in hearing sensitivity. Typically, exposure to high noise levels resulted in TTS for a particular time period depending on the absolute auditory sensitivity of the species, the
exposure time, and the exposure level. Ladich (2013) suggests that fish lose their hearing abilities at least partly when exposed to SPLs of more than 100 dB above hearing thresholds. However, those hearing thresholds have usually been described in sound pressure units. Fish have rarely been exposed to high, measured levels of particle motion.

Johnson and Rice (2014) recently investigated potential transport mechanisms and the sensory information used by animals in gravel-bed rivers. They considered how the physical nature of sensory signals was affected by river hydromorphology. Some authors have suggested that there is a “noise window,” a quiet area of the spectrum, between high- and low-frequency noises, which may be of potential significance to some fishes (Wysocki et al. 2007; Tonolla et al. 2009). The noise window usually falls in the 100 to 300 Hz range, and is dependent on environmental conditions, although the exact characteristics responsible for the position of this quiet window are not fully understood. The quiet window in the spectrum was more defined in the main channel of the Danube in comparison to a shallow, cobble-bedded alpine stream (water depth less than 0.5 m) where fluctuations in energy content were greater (Wysocki et al. 2007). It has been suggested that the noise window corresponds to the frequency range used by many fish for communication (Lugli and Fine 2003). However, it must be remembered that sounds generated in shallow water at these low frequencies are constrained by the poor propagation conditions (Rogers and Cox 1988).

Sound levels in rivers vary from place to place and from time to time in ways that reflect local conditions and changes in the world around them. This heterogeneity may offer a scope for fishes to gain physical knowledge about their environment and any changes that are taking place that might require them to change their behavior. Better understanding of the environmental phenomena that fish directly perceive would substantially improve our knowledge of what controls the distribution and behavior of fishes. Any change in background noise levels caused by human agencies may interfere with the ability of fish to use local natural soundscapes through masking, and through the imposition of higher-level signals that may evoke behavioral reactions from the fish.

River systems contain a wide variety of habitats including riffles, shoals, and waterfalls that may have their own distinctive soundscapes. Indeed, the soundscapes may greatly influence the movements and migrations of fishes. Playback of the underwater sounds generated at...
the foot of a waterfall provokes jumping behavior by juvenile Atlantic salmon (Hawkins, personal observation). Holt and Johnston (2015) point out that the increasing prevalence of road and train crossings over small streams and increased boat traffic in navigable rivers present the fish with new man-made noise sources. They investigated the relationship between vocalizations and the natural soundscape of a common fish of the Southeastern United States, the blacktail shiner (*Cyprinella venusta*). Results revealed a particularly close association of a quiet window in the natural soundscape of this fish and dominant frequencies of the sounds made by the fish during courtship. Results also indicated that the fish sounds propagated only short distances, and that they were masked by noise generated at bridge crossings. The authors suggested that road traffic noise propagates to an extent that virtually entire watersheds are impacted by this noise pollution, especially in urban areas.

In the sea, there is often a heavy background of noise generated by living organisms, including many invertebrates (e.g., snapping shrimp, sea urchins), fishes, and marine mammals. Choruses of sound from these animals may dominate the soundscape in some parts of the sea. However, there is little evidence that sound from living organisms may dominate ambient noise levels in any lakes and rivers. The burbot (*Lota lota*) is a northern freshwater gadoid fish that spawn under ice-cover. Burbot show a wide repertoire of loud calls, from slow knocks to fast buzzing (Cott et al. 2014), similar to the closely related haddock (*Melanogrammus aeglefinus*). Choruses from burbot calling under ice-cover are likely to constitute an important part of the soundscape in the northern lakes and rivers where these fish are found. McMichael et al. (2005) used underwater sound recordings to identify spawning activity in fall Chinook salmon. They found that collisions between substrate particles during female digging activity associated with spawning produced sound primarily in the 2,000 to 4,000 Hz range, but as low as 100 Hz. However, so far there has been no other evidence presented to show that biological sounds may dominate freshwater soundscapes.

### 4.8 Other Factors Affecting the Movements of Salmon within River Channels

In examining the effects of sound in influencing the behavior of salmon in river channels and fishways, it is important to take account of other factors that might affect their movements. It is often assumed that water flow is an important factor influencing the in-
Effects of Sound on Fishes

Early papers by Banks (1968) and Peters et al. (1973) suggested that the rate of flow of a river is the most important if not the dominant stimulus controlling the up-stream return migration of salmon, and it has been proposed that salmon life cycles may have adapted to match local hydrological regimes (Beechie et al. 2006). However there are many factors associated with increases in water flows such as water and air temperature, turbidity, noise level, atmospheric pressure, and light level. Banks (1968) suggested that although flow is an important determinant of migration, behavioral responses to flow may be modified by many other factors and responses might differ between rivers, seasons, and species.

A wide range of physical obstructions and other features, both natural and man-made, may affect fish passage through rivers; much attention has been paid to easing the passage of salmon past obstructions. Fishways may be constructed to allow fish to pass upstream or downstream under controlled conditions, without exhausting them or exposing them to predation. However, even where access has been provided, water flows, temperatures, and other conditions must be at levels that facilitate the passage of fish. Salmon may fall back downstream even where access is open to them. On average, 15% to 22% of the fishes from studied runs of Chinook salmon and steelhead fell back over at least one in-river dam during migration (Boggs et al. 2004). Most fishes that fell back at a dam did so apparently in response to dam operations, changes in the river environment, or to return to spawning site locations. Keefer et al. (2006) suggested that fallback at Columbia and Snake River dams reduced adult escapement to spawning areas for several Chinook salmon and steelhead runs, and that multiple fallbacks may incur additional energetic and reproductive costs.

The efficiency of any means for promoting upstream passage through a fishway depends on a number of factors, outlined by Castro-Santos et al. (2009), Roscoe and Hinch (2010), and other authors. Salmon must:

- Be guided or attracted to the fishway entrance – An important element of attraction of salmon moving upstream to passes is the provision of adequate water flow in relation to other competing flows, especially from the turbines.
- Be able to gain easy entrance into the fishway – Although high flows may attract salmon to the entrance, too high a flow rate may prevent their entry. The entrance should also be sited at a depth and location suitable for the fishes passing through.
Ascend and pass through the fishway with a minimum of effort.
Leave the fishway at a point that will take it on its next stage of migration without exposure to predation or other risks.

Larinier (1998), Roscoe and Hinch (2010), and Williams et al. (2012) have reviewed the effectiveness of different fishways. These authors are critical of many designs and have highlighted the need for monitoring their effectiveness. Recent efforts have been directed toward quantifying the rather complex fishway hydraulics and developing configurations with lower velocities, slopes, head drops, and power dissipation; breaking up eddies; or using roughness in the bottom of the passes. Research has also focused on the development of fishways with greater degrees of hydraulic heterogeneity to provide conditions that allow more species and much greater range in sizes of fish that can pass through them. For upstream migrants, a fishway must not only attract fish, it must also have hydraulics that allow a fish to physically ascend it. In designing fishways for upstream migrating salmon, it has been suggested that there is a critical velocity requirement for these actively swimming fish; if the velocity drops beyond a certain point, salmonids will exit from a fishway instead of being attracted to continue upstream (Castro-Santos and Haro 2010).

It is clear that full consideration must be given to the swimming behavior and energetics of fish as they ascend a fishway. High levels of electromyogram activity have been recorded during ascent of a pool and weir fish ladder, indicating that high energy demanding burst swimming may be required from the fish (Gowans et al. 2003). Thus, hydrodynamic factors may be especially important for upstream fish passage. Salmon that do not rapidly pass dams may spend many additional hours in the tailrace from the turbines (Bjornn et al. 1995, 1998). Passage within the tailrace appears to be energetically costly compared to passage of other segments (Brown et al. 2006). For instance, Brown et al. (2002) found that 81% of the energy used by spring Chinook salmon during upstream passage of Bonneville Dam was expended in the tailraces while only 18% and 1.5% were used in the fishways and forebays, respectively. The design of fishways must take into account the behavioral preferences of salmon in terms of preferred patterns of water flow.

Temperature may be especially important in mediating upstream passage rates. Salinger and Anderson (2006) determined the migration times of Passive Integrated Transponder (PIT)—
Effects of Sound on Fishes

tagged adult Chinook salmon upstream between Bonneville and Lower Granite dams over the years 1998 to 2002, and found that a maximum swim speed of about 1 body length/s occurred at 16.3°C. Speed was less above and below this optimum temperature. For steelhead, migration speed uniformly decreased with increasing temperature, suggesting that the fish migrated at temperatures above the optimum. Salmon entering fish ladders may encounter relatively cool water in dam tailraces and lower ladder sections, and warmer water in the upstream portions of ladders.

The impoundment of water behind dams, creating large, slow moving reservoirs, may result in high water temperatures being generated, even reaching upper lethal limits for salmon, causing a barrier to migration during the hottest summer months. Caudill et al. (2013) showed that as the temperature gradient increased, migrants were consistently more likely to move down fish ladders and exit into dam tailraces, resulting in upstream passage times that ranged from hours to days. Fish body temperatures equilibrated to ladder temperatures and often exceeded 20°C, indicating potential negative physiological and fitness effects. Collectively, these results suggested that gradients in fishway water temperatures might present an obstacle to migrating fishes. In these circumstances, adult fish passage may be improved within such a fishway by providing cooler water from deeper within the reservoir.

Light levels may also be important in mediating fish passage. Downstream movement of juvenile salmonids can be inhibited by darkness, as the fish exhibit alternative types of behavior in the absence of visual cues (Kemp et al. 2006; Kemp and Williams 2009).

Thus, it is evident that there are a number of factors that may affect upstream fish passage, including the time of year, time of day, light levels, temperatures, and flow rates. When examining the effects of sound and vibration on fish passage it will be important to monitor these other factors, together with dam operation data. There is a need to establish a baseline for the normal behavior of salmon in any fish ladder before behavioral responses to additional stimuli, including construction noise, can be examined.
5 DISCUSSION

Although there is an extensive body of literature on the effects of sounds on fish we are still remarkably ignorant about the actual impacts on fish populations. An important question that arises following this review is whether any thresholds can be defined, in terms of the characteristics of sounds that are known to elicit responses in salmon, which might enable any impacts to be assessed. Can we establish sound thresholds for protecting salmon based on previous studies? Or must we carry out new scientific observations?

A Technical Report from an ANSI-Accredited Standards Committee recently addressed this question. That report (Popper et al. 2014) sets out broadly applicable sound exposure guidelines for all fishes (and also sea turtles). Guidelines were developed for broad groups of fishes, defined by the way they detect sound. Different sound sources were considered in terms of their acoustic characteristics and appropriate metrics were defined for measurement of the received levels. The resultant sound exposure guidelines are presented in Tables 1 through 3. In some cases, where there are data, numerical guidelines are provided, expressed in appropriate metrics. When there were insufficient data to support numerical values, the relative likelihood of effects occurring was evaluated. Indeed, because of the lack of data for many fishes, including salmon, the sound exposure guidelines, based on the best scientific information at the time of writing, should be treated as interim. During the current review, no data have been uncovered that would alter the conclusions arrived at in the Technical Report with respect to salmon. It is evident that new scientific observations on the responses of salmon to different sound sources are still required.

The report grouped fishes into a series of categories, based on the mechanisms they employ for detecting sounds. It should be emphasized, however, that such criteria might not be sufficient for analyzing the behavioral effects of sounds. Behavior in response to sounds does not just depend on the ability of the fish to detect the sound. Most sounds that result in behavioral responses are high in amplitude, well above hearing thresholds. Experiments described earlier on the responses of wild sprat and mackerel (Hawkins et al. 2014) have shown that on average these two species react to very similar sound levels, although the hearing abilities of sprat are superior to those of mackerel. Behavioral responses depend on a
Discussion

A wide range of factors, and although fishes will not respond to sounds that they cannot hear, their responses to sounds at levels that they can hear will depend on a wide range of factors.

That said, we should examine the criteria that were assigned to fish like the salmon. The salmon fits within the category of fishes with swim bladders in which hearing does not involve the swim bladder or other gas volume. Such species are susceptible to barotrauma although hearing only involves particle motion, not sound pressure. Guidelines are provided for such fishes in relation to different types of sound source, and also in terms of criteria for mortality, recoverable injury, temporary hearing loss, masking, and the likelihood of behavioral responses being shown.

For strong impulsive sounds, including pile driving and seismic air guns, the guidelines for fish like the salmon are shown in Table 1.

**Table 1**

<table>
<thead>
<tr>
<th>Mortality and Potential Mortal Injuries</th>
<th>Recoverable Injury</th>
<th>Temporary Threshold Shift (TTS)</th>
<th>Masking</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>210 dB SEL cum or &gt; 207 dB peak</td>
<td>203 dB SEL cum or &gt; 207 dB peak</td>
<td>&gt;186 dB SEL cum</td>
<td>(N) Low (I) Low (F) Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(N) High (I) Moderate (F) Low</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
Peak and rms SPLs are dB re 1 μPa; SEL dB re 1 μPa² s. All criteria are presented as sound pressure even for fish without swim bladders since no data for particle motion exist. Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).
Data on mortality and recoverable injury are from Halvorsen et al. (2011, 2012a, 2012c) based on 960 sound events at 1.2 s intervals. TTS based on Popper et al. (2005). Note that the same peak levels are used both for mortality and recoverable injury since the same SELcum was used throughout the pile driving studies. Thus, the same peak level was derived (Halvorsen et al. 2011).

Guidelines for low-frequency naval sonars, which generate signals about 10 s long at frequencies below 1 kHz, are based on experiments that showed no effect on the ear or non-auditory tissues of fishes when the maximum received SPLs were at 193 dB re 1 μPa rms. Those guidelines are shown in Table 2.
Table 2
Low-frequency Naval Sonar Sound Exposure Guidelines for Salmonid Fishes

<table>
<thead>
<tr>
<th>Mortality and Potential Mortal Injury</th>
<th>Recoverable Injury</th>
<th>Temporary Threshold Shift (TTS)</th>
<th>Masking</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 193 dB rms</td>
<td>&gt; 193 dB rms</td>
<td>&gt; 193 dB rms</td>
<td>(N) Low</td>
<td>(N) Low</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(I) Low</td>
<td>(I) Low</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(F) Low</td>
<td>(F) Low</td>
</tr>
</tbody>
</table>

Notes:
rms SPLs are dB re 1 μPa. All criteria are presented as sound pressure even for fish like the salmon since no data for particle motion exist. Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).
Data in table from Popper et al. (2007) and Kane et al. (2010).

Guidelines for continuous sound like shipping noise could not be given with any precision because data were not available. The guidelines in Table 3 are based on knowledge of hearing sensitivity, but hard figures could not be provided.

Table 3
Continuous Sound Source Sound Exposure Guidelines for Salmonid Fishes

<table>
<thead>
<tr>
<th>Mortality and Potential Mortal Injury</th>
<th>Recoverable Injury</th>
<th>Temporary Threshold Shift (TTS)</th>
<th>Masking</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N) Low</td>
<td>(N) Low</td>
<td>(N) Moderate</td>
<td>(N) High</td>
<td>(N) Moderate</td>
</tr>
<tr>
<td>(I) Low</td>
<td>(I) Low</td>
<td>(I) Low</td>
<td>(I) High</td>
<td>(I) Moderate</td>
</tr>
<tr>
<td>(F) Low</td>
<td>(F) Low</td>
<td>(F) Low</td>
<td>(F) Moderate</td>
<td>(F) Low</td>
</tr>
</tbody>
</table>

Notes:
rms SPLs are dB re 1 μPa. All criteria are presented as sound pressure even for fish without swim bladders since no data for particle motion exist. Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).
Data in this table are based on knowing that fish will respond to sounds and their hearing sensitivity, but there are no data on exposure or received levels that enable guideline numbers to be provided.

The gaps in these tables, and especially the lack of data expressed in terms of sensitivity to particle motion, point to the need to acquire more data on the effects of sounds on fishes.

We conclude that there is a particular lack of data on the behavioral responses of fishes like the salmon to sound exposure. Behavioral responses are especially important, as they can
occur at quite moderate sound levels and may therefore take place at some distance from a source. Behavior is also of particular importance in terms of assessing effects on salmon in and around hydroelectric installations.

There are relatively few data on behavioral responses from any species of fish. We described the experiments of Hawkins et al. (2014) on sprat and mackerel where the SPLs to which the fish schools responded on 50% of presentations were around 163 dB re 1 μPa peak-to-peak SPL for both species, estimated from dose response curves. The mackerel, like the salmon, is sensitive to particle motion, and the particle velocity levels to which 50% of the schools responded were estimated as -80.4 dB re 1 m/s peak-to-peak and the single strike particle velocity exposure level as -101.7 dB re 1 m²/s. The SPLs were quite close to the level set by NOAA Fisheries in the United States of 150 dB re 1 μPa rms as a criterion for behavioral effects upon protected species, although data have not been presented to support this choice of level.

Skalski et al. (1992) showed a 52% decrease in catch-per-unit-effort of rockfish (Sebastes sp.) after a single air gun emission at 186 to 191 dB re 1 μPa (zero-to-peak SPL) at the base of rockfish aggregations (see also Pearson et al. 1992). They also demonstrated that fishes would show a startle response to sounds at a level as low as 160 dB. Wardle et al. (2001) used underwater video and an acoustic tracking system to examine the behavior of fishes on a reef in response to emissions from a single seismic air gun. They observed startle responses and some changes in the movement patterns of fish at similar sound levels.

However, in an evaluation of the behavior of free-swimming fishes to noise from seismic air guns, fish movement (e.g., swimming direction or speed) was observed in the Mackenzie River (Northwest Territories, Canada) using sonar. Fishes did not exhibit a noticeable response even when SELs (single shot) were on the order of 175 dB re 1 μPa²-s, and zero-to-peak SPLs were over 200 dB re 1 μPa (Cott et al. 2012).

There is a complete absence of data on responses of salmon to continuous sounds apart from the work of Knudsen et al. (1992, 1994, 1997) on the responses of salmon to short bursts of infrasound. Flight and avoidance responses were observed from the fish to sound at a frequency of 10 Hz. Higher frequencies did not result in any behavioral changes (even at
150 Hz, the most sensitive frequency for salmon). Knudsen et al. (1992) reported that a particle acceleration of 0.01 ms$^{-2}$ at 3 m deterred downstream migrating Atlantic salmon smolts in a river.

Ultimately, we are concerned with finding out whether sound, including infrasound, affects fish passage through rivers and around dams. Do sounds provide valuable cues to fish during their movements through rivers and around obstacles? Do high levels of sound cause significant delays in passage through fish ladders and bypass systems? It is not yet clear whether major passage problems (delays) are associated with sound/vibration related to construction activities. New scientific studies are required to answer these questions.
6 CONCLUSIONS

6.1 Measurement of Sound Fields in the Snake River

To take forward work on Lower Granite Dam, and to examine the effects of sounds on salmon, there is a need for more information on the ambient noise levels prevailing in the river, and in and around the dam and its associated structures. Measurements of the sound fields generated by any man-made sources in the vicinity of the dam are also required, including the sounds generated in water and in the substrate by the hydroelectric turbines themselves, fishways, bypasses and their associated machinery, or by land-based construction equipment to be deployed. Such studies must measure particle motion and its directional components, as these are especially important to salmon. Self-noise of hydrophones, generated by water flow and waves, is likely to pose major difficulties and it will be important to distinguish between these pseudo sounds and the actual sounds of interest. Measuring particle motion, either by measuring the pressure gradient or using neutrally buoyant accelerometers, is likely to be especially difficult because of highly turbulent flows. It is suggested that it would be more practical to measure the low-frequency motion of substrates within the river, over a frequency range extending down to infrasonic frequencies if possible. Characterization of the substrate motion generated by sound sources at different locations would indicate which of those sources could be detected by salmon.

The various sources of man-made sound may include impulsive, semi-continuous, non-impulsive, and continuous non-impulsive sound. Different metrics will be needed for measuring these different types of sound. Repeated impulsive sounds (e.g., jack hammer, pile driver, active sonar) should be expressed in terms of $\text{SPL}_{\text{peak}}$, $\text{SEL}_{\text{ss}}$, and $\text{SEL}_{\text{cum}}$ metrics, with their equivalent particle motion levels. Continuous sounds should be expressed in terms $\text{SPL}_{\text{rms}}$ for both sound pressure and particle motion measurements, and consideration should be given to the “roughness” of the sound, or changes in level with time.

It will also be important in considering those factors that influence the movements of salmon to take note of hydrodynamic conditions at different locations within the river and in the vicinity of the dam and its associated structures because, to the fish, these hydrodynamic phenomena may be indistinguishable from sounds, especially at low and infrasonic frequencies.
6.2 Monitoring the Movements of Salmon

Examining the detailed behavior of salmon and steelhead trout at different locations within the Snake River and fish passage systems may yield important insights into those physical features of the local environment that influence their movements. While the tracking of PIT-tagged fish may assist in monitoring passage rates at different points within the river, it would be beneficial to supplement those measurements with direct observations of fish behavior made using television cameras (in air and in water), high-resolution scanning sonars, and active telemetry, either acoustic or radio, within the fishway (as well as in the tailrace near ladder entrances). Increased detail in documenting passage behavior would allow the movements of fish to be observed in real time, and responses to topographical features, obstacles, and particular sources of both sound and hydrodynamic stimuli to be examined. It might also be possible to determine threshold levels for different behavioral responses by the salmon.

Should salmon respond to particular sounds, it might be beneficial to carry out sound playback experiments at different locations within the Snake River to allow responses to sounds at different levels to be determined and dose/response relationships defined. Such experiments might then allow behavioral sound exposure criteria to be defined for salmon.

6.3 Information Gaps

This review has identified a number of wider information gaps, detailed in Sections 6.3.1 through 6.3.8.

6.3.1 Natural Noise Levels in Rivers

There have been few studies of natural noise levels in rivers, especially at the low and infrasonic frequencies that salmon can detect and respond to. Some natural sound sources may provide important cues for the orientation and navigation of salmon. Spatial changes in ambient noise levels may be especially important, and some natural sounds may provide directional cues to salmon, guiding their movements through rivers. Currently, few data are available on natural noise levels, their spatial distribution, and their directional components. Measurements of particle motion levels are especially important for estimating the effects of sounds upon salmon.
Methods for the measurement, description, and analysis of soundscapes may be critical in the future for identifying trends in level and characteristics of the acoustic environment. Monitoring of soundscapes in rivers before, during, and after new developments, including the construction and operation of roads, bridges, dams, and other structures, is needed, but has rarely been carried out in the past.

6.3.2 **Particle Motion Measurements**

Measurement of particle motion levels is currently difficult to perform as standard calibrated sensors and measurement protocols are not available and must be developed.

6.3.3 **Characterization of Sound Sources**

There is a need to describe the characteristics of the sounds generated by different sources in rivers, in terms of particle motion as well as sound pressure; measured to agreed standards using appropriate metrics and terminology. Information on the particle motion associated with interface waves and ground roll would be especially valuable, as such signals may travel significantly greater distances compared with water-borne sound.

There is also a need to identify those characteristics of particular sound sources most likely to have effects on salmon, although initially this may require sound playback experiments (see below). Models of sound propagation that are specifically tailored to estimate the exposure of salmon to sound in rivers, expressed in terms of sound pressure and particle motion, are required.

Breakdown of the overall contribution to sound levels in rivers from man-made sources is needed. Agreement needs to be reached on how measurements of the outputs from different sources should be compared. Knowledge of contribution of different sources to the overall river soundscape, in the form of inventories or sound budgets, would be very useful.

6.3.4 **Hearing Abilities of Salmon**

There is a need to extend our knowledge of the hearing abilities of salmon. In particular, there is a need to examine auditory thresholds for infrasonic frequencies (below 20 Hz) and to examine the abilities of salmon to determine sound source direction and distance. Such
experiments should be done using behavioral measures wherever possible. Equivalent experiments have already been performed on species like the cod (reviewed by Hawkins 2014). It will be especially important to measure particle motion levels.

6.3.5 **Masking of Sounds by Noise**

Masking of pure tones by high levels of white noise has been demonstrated for salmon. There is now a need to determine the ability of salmon to detect, discriminate, and identify sounds with differing temporal characteristics, including natural sounds, in the presence of actual man-made sound sources. Masking of biologically important sounds, and especially any acoustical cues to orientation and migration, may have far-reaching effects on the behavior of salmon. It will be important to determine the behavioral consequences of masking, estimate the range over which different sounds can be detected, and determine how masking affects the ability of salmon to localize sound sources.

6.3.6 **Behavioral Responses of Salmon to Sounds**

Detailed data on behavioral responses of free-swimming salmon in their natural habitats following exposure to relevant sounds are required. There is a need to determine dose/response curves for behavioral responses to sound exposure to allow behavioral sound exposure criteria to be defined. Data are also required to rank the significance of different behavioral responses for a given species. The ability to distinguish between inconsequential responses and responses that will affect vital functions is important for defining the impact of sound exposure. It may be important to examine the effects of chronic exposure over long periods to low-level man-made sounds.

Some aspects of sound stimuli are more important than others in evoking a response, depending on the type of sound. Parameters like the rise time and roughness may be as important as the sound level. Experiments are needed with different sounds to determine which features of the stimulus salmon are most attentive to. There is an indication that infrasonic frequencies may be especially important to salmon.

Behavior is often different in different contexts, including location, time of day, time of year, etc. Determining the effects of context is important.
Conclusions

Currently, we are almost totally lacking experiments and observations on responses to sound exposure obtained on salmon in the wild. It is important that acoustic field conditions are appropriate for such experiments, especially as the salmon responds to particle motion. Earlier experiments have often been carried out on captive animals, in a poor physiological state, conditioned by their upbringing, and exhausted by repeated sound presentation. It is exceedingly important to carry out sound playback experiments on salmon living under natural conditions in the river. It is evident that some fishes, including salmon, are sensitive to infrasound and some studies have indicated that they may respond strongly to volume displacements of the water (which result in sound at infrasonic frequencies, local water currents, and the application of linear accelerations to the fish). It is important to examine these responses more closely.

6.3.7  Habituation of Responses

It is important to examine the possible habituation or de-sensitization of salmon to sounds that are presented repeatedly, and to examine cumulative effects. There have been some reports of fishes adjusting to high sound levels, and becoming less sensitive to sounds after repeated presentation. Very few experiments have been done to assess the significance of this habituation in the field. Recovery time following exposure is also important. We also need to know whether effects may accumulate from repeated exposures to sound, and whether there is “recovery” between sound exposures.

6.3.8  Risk Analysis

Observations on the behavioral responses of salmon to sounds, and determination of those sound levels that result in particular effects, will not by themselves enable impacts upon salmon populations to be assessed. High sound levels can exert effects upon individuals and in some cases might affect large numbers of animals, influencing survival or reproduction and potentially damaging whole populations. Information on changes in population structure, distribution, and abundance is required if we are to fully assess the impacts on populations and ecological communities. At the moment, the necessary supporting data are inadequate or lacking. Decisions may have to be taken in the absence of adequate data.
Risk-assessment procedures are needed, utilizing such knowledge that may exist, to enable
the levels of risk to salmon populations from particular sources of disturbance be assessed and
to enable rational decisions to be made to mitigate any effects. In some cases it may be
possible to carry out construction and other work using different techniques that create less
noise. Or it may be possible to carry out work at a particular time of year, when effects upon
salmon might be minimal. The extent to which sound affects the structure and functioning
of salmon populations and ecosystems has yet to be established. Bridging the gap between
observed effects on individual animals and the impacts on salmon populations may be
beyond the capacity of current environmental science. Currently, we are poorly equipped to
do any more than use expert judgment for predicting population impacts. A risk assessment
framework is required to enable us to develop a qualitative or quantitative estimate of the
likelihood that any of the hazards associated with the sound source will be realized in
exposed salmon.
7 REFERENCES


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References


