Chapter 51
Developing Sound Exposure Criteria for Fishes

Anthony D. Hawkins and Arthur N. Popper

Abstract In assessing the impact of aquatic developments, it is important to evaluate whether accompanying underwater sounds might have adverse effects on fishes. Risk assessment can then be used to evaluate new and existing technologies for effective prevention, control, or mitigation of impacts. It is necessary to know the levels of sound that may cause potential harm to different species from different sources as well as those levels that are likely to be of no consequence. The development and use of impact criteria are still at an early stage for fishes.

Keywords Sound • Behavior • Impact • Injury • Pile driving

1 Introduction

In many countries, legislation now requires the assessment of potential impacts on aquatic life of in-water sound-producing activities. However, few scientific data are available regarding the effects of sounds on fishes. Moreover, there are few guidelines on appropriate assessment procedures and potential mitigation measures. This paper provides an overview of issues that require understanding if criteria are to be developed for the effects of man-made sounds on fishes. Only limited references are provided. Much of the literature on the effects of sound on fishes was reviewed by Popper and Hastings (2009) and in a more recent review prepared by Normandeau Associates (2012).

Prerequisites for evaluating the effects include (1) a description of the sound-producing activities and the characteristics of the sounds produced; (2) knowledge of prevailing background noise levels in the environment; (3) prediction of the

A.D. Hawkins (✉)
Loughine Ltd., Kincraig, Blairs, Aberdeen AB12 5YT, UK
e-mail: a.hawkins@btconnect.com

A.N. Popper
Department of Biology, University of Maryland, College Park, MD 20742, USA
e-mail: apopper@umd.edu

A.N. Popper, A. Hawkins (eds.), *The Effects of Noise on Aquatic Life II*, Advances in Experimental Medicine and Biology 875,
DOI 10.1007/978-1-4939-2981-8_51

Table 51.1 Potential effects resulting from sound exposure

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

The actual sound levels and distances from the sources at which each of the effects may be found will vary depending on the actual sound level and distance

transmission of sound from various man-made sources; and (4) consideration of any effects on fishes at different locations relative to the source.

In looking for impacts, it is especially important to distinguish between minor effects that elicit only transient changes in behavior and those that materially affect the well-being of individual fishes and of fish populations. The potential effects resulting from sound exposure are summarized in Table 51.1

As part of the process of risk assessment, it is necessary to determine the levels of sound that have particular effects from different types of sources. The goal is to provide criteria to serve as threshold values, expressed in an appropriate acoustic metric, above which the onset of effects might occur or a particular level of damage be incurred. Both the effects and the metric itself must be specified clearly. The development and use of these criteria are at an early stage, however, and neither the degree of damage nor the metrics to be used have been clearly defined in the past. Moreover, no formal consensus currently exists on the measurement and evaluation of the effects of underwater sounds. Different terms and metrics are used in different contexts. The purpose of this paper is to not provide criteria or guidelines for sound exposure for fishes but to provide an outline of the issues that need to be considered in developing such criteria. A fuller treatment of guidelines and information gaps can be found in Popper et al. (2014) and Hawkins et al. (2015).

2 Sound Sources

Underwater sounds may be divided into continuous and impulsive signals. Continuous sounds can be tonal or broadband and some may be intermittent. Some continuous sounds may be "'rougher" than others and are potentially more damaging than other continuous sounds. Examples of sources producing continuous sounds include ships; aircraft; machinery operations such as drilling, operational wind turbines and tidal generators; dredging; and some active sonar systems.

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

3 Metrics

A major issue in trying to describe and understand the effects of man-made sounds is how they are best described in terms that allow assessment of the energy that actually results in effects (see Chapter 3 by Ainslie and de Jong). The metrics applied to continuous sounds for estimating the likelihood of damage are the root-mean-square (rms) sound pressure, peak sound pressure, and, for many fishes, the corresponding particle motion in three dimensions. Transient sounds may be expressed in terms of their peak levels. However, rms and peak levels are not sufficient for characterizing the energy in sounds such as those generated by pile-driving strikes or the discharge of seismic airguns. Hastings and Popper (2005) proposed the use of sound exposure level (SEL), the time integral of the pressure squared for a single event, as a metric for setting pile-driving criteria (as well as for other impulsive sounds). Subsequent papers (e.g., Popper et al. 2006; Carlson et al. 2007; Popper and Hastings 2009) advocated the use of both SELs and peak levels and emphasized the need to consider the effects of repetition of the impulse and/or the rise time of the signal.

It is also now clear that assessment of sound-producing activities and the potential for impacting fish generally has to consider both cumulative and aggregate effects, that is, cumulative effects arising from repetition of a particular source, such as the repeated strikes of a pile driver, and the aggregate effects from different types of sources, such as from different pile drivers or from the combined effects of pile driving and shipping.

It is now accepted that it is necessary to take into account the potential effects not in terms of exposure to a single sound but to the accumulated energy over exposure to multiple sounds over some period of time. The metric generally used is the cumulative SEL (SEL_{cum}). This metric can be estimated from a representative single-strike SEL (SEL_{ss}) value and the number of strikes that would be required to place the pile at its final depth. However, this accumulation assumes that all strikes have the same SEL value and that a fish would continuously be exposed to pulses with the same SEL, which is never actually the case.

4 Frequency Weighting

Because animals do not hear equally well at all frequencies within their functional hearing range, weighting may be applied to measurements of sounds to quantitatively compensate for differences in their frequency response. For marine mammals, generalized frequency-weighting functions have been derived for different functional hearing groups (Southall et al. 2007). In fishes, Nedwell et al. (2007) have proposed the frequency-weighting technique for determining the level of sound relative to hearing threshold [dB_{ht}(*Species*)] as a useful metric for quantifying the level of sound experienced by different species. The dB_{ht} references the sound to the species' hearing threshold in terms of sound pressure.

However, not all or even most fishes respond to sound pressure. Many are sensitive to particle motion. Particular care must be taken in applying a dB_{ht} expressed in terms of sound pressure to species, such as the Atlantic salmon *Salmo salar*, plaice *Pleuronectes platessa*, or lemon shark *Negaprion brevirostris*, that are sensitive to particle motion because the values will not be appropriate when a fish is close to a sound source or near a reflecting boundary. It is also very important that the hearing sensitivity curves or audiograms on which dB_{ht} values are obtained under appropriate acoustic conditions are based on behavioral measurements of what a fish really hears rather than measurements of potentials generated within the central nervous system (Ladich and Fay 2013). Of the 32,000 or more extant species of fish, only a handful of audiograms have been measured under appropriate acoustic conditions using suitable threshold assessment methods. Note that frequency weighting may only be appropriate in considering detection and behavioral responses to sounds; it may not be relevant where injury from sound exposure is being assessed.

5 Sound-Propagation Modeling

To determine the sound levels to which fish will actually be exposed, it is necessary to model the propagation of sound from the source into the wider environment and also to consider any movements by the fish. The geometry of noise exposure is important. However, most models and most studies have focused on modeling acoustic pressure. Although this is suitable for marine mammals and some fishes as well as for other types of injury (e.g., barotrauma) in all fishes (see Chapter 14 by Casper et al.), hearing in most fishes involves the detection of particle motion. Thus, for fishes, models that focus on pressure alone are of limited value, at least with regard to the potential effects on sound detection. Instead, it is important to have data and models that provide insight into the particle motion emanating from a source. Modeling of the levels of particle motion to which fishes are exposed is complex and is seldom done. There is a particular lack of data on the transmission of particle motion through the seabed from sources such as impact pile driving (see Chapter 53 by Hazelwood and Macey).

Background noise in the area of interest is also important because it has the potential to mask detection by fish of biologically important signals. Some areas are already noisy as a result of shipping and other activities. Others may have characteristic soundscapes, perhaps dominated by biological sources, where it may be important to try to retain predevelopment noise levels.

6 Assessment of Effects

6.1 Injury

Exposure to high-amplitude impulsive sounds is of most concern in terms of death and injury, although there are very few instances of death shown in the literature unless the fish are within a few meters of a very intense source. Fish may be harmed by the sharp high-level sounds generated by explosions, impact pile driving, and seismic air guns. In response to concerns about such sounds, and particularly sounds from impulsive pile driving, the Fisheries Hydroacoustic Working Group (FHWG) in the United States developed interim criteria for pile driving to sound pressure levels of 206 dB re 1 μPa peak and 187 dB re 1 $\mu Pa^2 \cdot s$ SEL_{cum} at 10 m for all listed fishes except those that were <2 g. In that case, the recommended SEL_{cum} is 183 dB re 1 $\mu Pa^2 \cdot s$. The period of accumulation for the SEL_{cum} value is the whole pile-driving sequence. It has been suggested that a 12-h break in the pile-driving operation resets the SEL accumulation (Stadler and Woodbury 2009).

However, recent papers have provided quantitative data to define the levels of impulsive sound that could result in the onset of injury to fish (e.g., Halvorsen et al. 2012a, b; Casper et al. 2012, 2013; see also Chapter 14 by Casper et al.). A controlled-impedance fluid-filled wave tube simulated exposure to high-energy impulsive sound pressures characteristic of far-field, plane-wave acoustic conditions. Juvenile Chinook salmon (*Oncorhynchus tshawytscha*) and five other species were exposed to impulsive sounds and the injuries sustained were subsequently evaluated for different sound exposure levels (see Chapter 14 by Casper et al.). A defined level of injury (based on an index of observed injuries) was achieved for an SEL_{cum} of 210 dB re 1 $\mu Pa^2 \cdot s$, suggesting that FHWG interim criteria are well below those that would result in the onset of any physiological effect.

Halvorsen et al. (2012a) were able to reject the hypothesis that the same type and severity of injury would occur for the same total energy level of exposure (SEL_{cum}) regardless of how that was reached (e.g., through many low-energy impulsive sounds or fewer high-energy impulsive sounds). Although the SEL_{cum} is the most important variable to consider, the SEL_{ss} and the number of impulses are also important. In a further paper, Halvorsen et al. (2012b) exposed three other species to simulated pile-driving sounds. Their results suggested that the type of swim bladder present in the fish was correlated with injury at higher sound levels. Casper et al. (2012; see Chapter 14 by Casper et al.) subsequently evaluated the ability of Chinook salmon to recover from injury after exposure to impulsive sounds. Their data supported the hypothesis that one or two mild injuries resulting from pile-driving exposure were unlikely to affect the survival of the exposed animals, at least in a laboratory environment. The authors also confirmed that the six very different species studied could be exposed to pile-driving sounds substantially louder than the current industry guidelines of 187 dB re 1 $\mu Pa^2 \cdot s$ SEL_{cum} without sustaining injury. Casper et al. (2013) have also shown that the onset of injury to the ear (and presumably hearing loss) starts at higher SEL_{cum} levels than other injuries.

6.2 Impairment of Hearing

We have recently reviewed the effects of sound on the hearing of fishes (Normandeau Associates 2012). Because fish can regenerate lost or damaged sensory cells of the ear, it is unlikely that any species would show permanent hearing loss (often referred to as permanent threshold shift [PTS]). In contrast, temporary threshold shift (TTS), a short-term reduction in hearing sensitivity caused by exposure to intense sound, has been found in a number of species. After termination of the sound causing TTS, normal hearing ability may return over a period that may range from minutes to days depending on the intensity and duration of exposure. During a period of TTS, survival of the animals may be at risk. The effects and significance of different levels of TTS on free-living fishes have not been examined so far. There is evidence that, given the same type and duration of sound exposure, a much louder sound will be required to produce TTS in fish that do not hear well compared with fish that are more sensitive to sounds (see Chapter 132 by Smith for a discussion of TTS in fish). Physical effects such as TTS are likely to be governed largely by the transient characteristics of sounds (e.g., rise time, peak pressure, and signal duration) and influenced also by the duration of exposure.

Currently, no criteria have been set for damage to the auditory system of fishes, although recent data show that the onset of damage to sensory cells of the ear, a likely harbinger of hearing loss, occurs at SELs substantially higher than those that produce the onset of other physiological effects (Casper et al. 2013). There are substantial reasons for thinking that fish can be grouped into “types” that share hearing characteristics based on the presence or absence of a swim bladder. Many lacking swim bladders and some with swim bladders unconnected to the ear are sensitive only to particle motion and respond to only a narrow band of frequencies. Fishes with swim bladders that are close to the ear or intimately connected to the ear are sensitive to both particle motion and sound pressure and show a more extended frequency range.

6.3 Changes in Behavior

There have been very few studies of the behavior of wild free-swimming fishes in response to sound. Decreases in the catches of fish exposed to seismic surveys have been reported. Startle responses and changes in the movement patterns of fish have been observed. Direct observations of fish schools with sonar have shown fish diving and schools breaking up as a result of sound exposure (reviewed by Normandeau Associates 2012).

The National Marine Fisheries Service in the United States has used 150 dB re 1 μPa rms as a criterion for behavioral effects on protected species but without adducing data to support this choice and without taking into consideration differences in sound detection abilities and behavior of different species. More recently, Nedwell et al. (2007) suggested that strong avoidance responses by fish start at ~90 dB above the dB_{ht}(*Species*) thresholds of fish. Although this concept takes into consideration the hearing characteristics of individual species, the allocation of the dB_{ht} metric is often open to doubt for reasons discussed earlier. Moreover, the assumption that strong avoidance occurs at a particular level above the dB_{ht}(*Species*) requires experimental confirmation. A number of factors are likely to affect behavioral responses, including any prior experience and the similarity of the sound to biologically important signals. Indeed, making a general assumption that all (or even many) of the 32,000 species of fish respond to sound stimuli in a similar manner at a particular relative level is not, in our view, at all realistic.

Indications are that, certainly for behavioral responses, the detailed context of an animal's behavior, the environment, and immediate ecological imperatives may play important roles (Ellison et al. 2012). It is perhaps naive to seek single values of particular metrics to define a particular level of response.

Regulatory agencies have tended to address only the acute effects of sound on hearing and behavior. Chronic exposure to low- and moderate-amplitude sounds that last for long periods may not lead to mortality or injury, but any reduction in fitness may lead to increased predation, decreased reproductive potential, or other effects. Chronic exposure may, for example, cause a rise in the level of stress hormones, with long-term effects on the fitness and ability of the animal to survive.

6.4 Masking

Sounds of biological significance are produced by fishes and are often used for communication of reproductive state, location, presence of predators or competitors, or finding other members of the same species. Many other sounds of natural origin may also be important to fishes, including sounds made by prey, predators, and natural features in the soundscape. Sounds from both biological and physical sources may be important for fish orientation, navigation, and habitat selection. In the presence of man-made sound and other noise, there may be impairment of the ability of fishes to detect biologically relevant sound signals (see Chapter 28 by Dooling and Blumenrath). Background levels of noise in the sea are changing as a result of the imposition of man-made sounds, with unknown effects on the ability of animals to detect sounds and communicate with one another.

Currently, little is known about the masking effects of man-made sounds, and criteria for masking have yet to be developed. However, masking by man-made sounds may have important short- and long-term effect on the behavior and well-being of fishes.

7 Conclusions

It is critical for regulators to have knowledge of the levels of sounds that may harm fishes as well as levels that have few or no consequences. However, the setting of recommended sound levels or sound exposure criteria for injury, damage to the auditory system, or behavioral responses has long been controversial, largely because of a shortage of data. In this paper, we have set out some of the levels that have been suggested and have emphasized their strengths and weaknesses.

In 2004, the National Oceanic and Atmospheric Administration (NOAA) convened a panel to prepare sound exposure criteria for fishes and turtles. That working group has gathered and reviewed papers from both the peer-reviewed and gray literature on the exposure of fish and sea turtles to various sound sources. It is setting out broadly applicable sound exposure criteria to serve as guidelines for fishes and sea turtles across the complete range of taxa and sound types, considering a range of impacts. The working group expects to publish its report in 2014.

References

Carlson TJ, Hastings MC, Popper AN (2007) Update on recommendations for revised interim sound exposure criteria for fish during pile driving activities. Memo to the California Department of Transportation and Washington Department of Transportation. Available at http://www.dot.ca.gov/hq/env/bio/files/ct-arlington_memo_12-21-07.pdf

Casper BM, Popper AN, Matthews F, Carlson TJ, Halvorsen MB (2012) Recovery of barotrauma injuries in Chinook salmon, *Oncorhynchus tshawytscha* from exposure to pile driving sound. PLoS ONE 7, e39593. doi:10.1371/journal.pone.0039593

Casper BM, Smith ME, Halvorsen MB, Sun H, Carlson TJ, Popper AN (2013) Effects of exposure to pile driving sounds on fish inner ear tissues. Comp Biochem Physiol A 166:352–360

Ellison WE, Southall BL, Clark CW, Frankel AS (2012) A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds. Conserv Biol 26:21–28

Halvorsen MB, Casper BM, Matthews F, Carlson TJ, Popper AN (2012a) Effects of exposure to pile driving sounds on the lake sturgeon, Nile tilapia, and hogchoker. Proc R Soc B Biol Sci 279:4705–4714. doi:10.1098/rspb.2012.154

Halvorsen MB, Casper BM, Woodley CM, Carlson TJ, Popper AN (2012b) Threshold for onset of injury in Chinook salmon from exposure to impulsive pile driving sounds. PLoS ONE 7, e38968. doi:10.1371/journal.pone.0038968

Hastings MC, Popper AN (2005) Effects of sound on fish. Report prepared by Jones & Stokes under California Department of Transportation (Caltrans) Contract 43A0139, Task Order 1. Available at http://www.dot.ca.gov/hq/env/bio/files/Effects_of_Sound_on_Fish23Aug05.pdf. Accessed 29 July 2013

Hawkins AD, Pembroke A, Popper AN (2015) Information gaps in understanding the effects of noise on fishes and invertebrates. Rev Fish Biol Fisheries 25:39–64. doi: 10.1007/s11160-014-9369-3

Ladich F, Fay RR (2013) Auditory evoked potential audiometry in fish. Rev Fish Biol Fish 23:317–364. doi:10.1007/s11160-012-9297-z

Nedwell JR, Turnpenny AWH, Lovell J, Parvin SJ, Workman R, Spinks JAL, Howell D (2007) A validation of the dBht as a measure of the behavioural and auditory effects of underwater noise. Subacoustech Report No. 534R1231

Normandeau Associates, Inc. (2012) Effects of noise on fish, fisheries, and invertebrates in the U.S. Atlantic and Arctic from energy industry sound-generating activities. A workshop report prepared under Contract No. M11PC00031 for the Bureau of Ocean Energy Management, US Department of the Interior

Popper AN, Carlson TJ, Hawkins AD, Southall BL, Gentry RL (2006) Interim criteria for injury of fish exposed to pile driving operations: A white paper. Available at http://www.wsdot.wa.gov/NR/rdonlyres/84A6313A-9297-42C9-BFA6-750A691E1DB3/0/BA_PileDrivingInterimCriteria.pdf. Accessed 29 July 2013

Popper AN, Hastings MC (2009) The effects on fish of human-generated (anthropogenic) sound. Integr Zool 4:43–52

Popper AN, Hawkins AD, Fay RR, Mann D, Bartol S, Carlson T, Coombs S, Ellison WT, Gentry R, Halvorsen MB, Løkkeborg S, Rogers P, Southall BL, Zeddies D, Tavolga WN (2014) Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. ASA S3/SC1.4 TR-2014. Springer and ASA Press, Cham, Switzerland

Southall BL, Bowles AE, Ellison WT, Finneran JJ, Gentry RL, Greene CR Jr, Kastak D, Ketten DR, Miller JH, Nachtigall PE, Richardson WJ, Thomas JA, Tyack PL (2007) Marine mammal noise exposure criteria: Initial scientific recommendations. Aquat Mamm 33:411–521

Stadler JH, Woodbury DP (2009) Assessing the effects to fishes from pile driving: Application of new hydroacoustic criteria. In: Proceedings of Inter-Noise 2009: Innovations in Practical Noise Control, Ottawa, ON, Canada, 23-26 August 2009, pp 1-8. Available at Geo-environmental FTP site