A primer on underwater sound and noise: Backgrounder for WWF's 2013 workshop on finding management solutions for underwater noise in Canada's Pacific.

This background document is intended for those who know relatively little about sound, the differences between sound in water relative to sound in air, and some of the more common sources of underwater man-made sounds (anthropogenic noise). It is not an exhaustive overview, but I hope that it will provide sufficient information to will give the reader some familiarity with the topic, and direct the reader to more detailed references that will be useful in the course of their own work.

Many marine animals use sound in much the way that terrestrial animals use light- to detect predators and/or prey, to communicate, and to navigate- it is their primary underwater sensory modality. This shouldn't be surprising to us, since in water sound travels much further than light does. Yet as the visual creatures we are, it is only within the last 10 years or so that concerns around the introduction of man-made sound (anthropogenic noise) into the oceans has moved well beyond the domain of a specialized group of researchers into the broader public domain. With this increased awareness has come motivation to understand and mitigate the impact of underwater noise on marine life.

The ears of all terrestrial vertebrates, including humans, are functionally similar to those of marine vertebrates (Fay and Popper 2000). In humans, hair cells in the inner ear that are sensitive to sounds that we hear can be damaged or destroyed by a number of causes, including aging processes, prolonged or intense exposure to noise, and chemical contaminants etc. Similar results have been found in other species ranging from fish to reptiles to birds (Rubel et al. 2013). Human noise exposure standards in the workplace have been developed in many countries around the world and significant progress has been made within the last decade to develop similar criteria for marine mammals (Southall et al. 2007).

What is sound?

A sound is produced by the mechanical vibration of particles in the medium (such as the ocean) through which the sound travels. As the particles of the medium vibrate (particle motion), their density increases and decreases (compression and rarefaction). These local oscillations result in disturbances that propagate, generating sound pressure waves. These waves can travel through air, water and rock, as well as other substrates, the speed of which depends on the medium (Table 1). While the ears of mammals primarily sense the very small pressure changes due to sound waves, the lateral lines and ears of fish are also sensitive to particle motion which occurs close to the source of the sound. For the purpose of this workshop, we will not be addressing particle motion in significant detail, and will focus on pressure waves.

Table 1. The speed of sound (m/s) in various media, from JASCO Applied Sciences (2009).

Medium	Speed of sound in m/s
Air at 20°C	343
Salt water at 25°C	1532
Sand	800-2,200
Clay	1,000-2,500
Sandstone	1,400-4,300
Granite	5,500-5,900
Limestone	5,900-6,100

How do we describe sound?

Laypeople typically describe a sound by its loudness, and sometimes its pitch. The criteria that determine these characteristics are basically the sound wave's amplitude (loudness), frequency (pitch), and duration. Waveforms are used to show time vs amplitude (Figures 1-2), and spectrograms show time vs frequency, much like a musical score (Figure 3). Continuous sounds such as boat noise are described as chronic or non-pulsed whereas sounds that are of short duration, such as an explosion, or of repeated short durations, such as pile driving or airgun firing, are pulsed (or acute, intermittent or transient) sources of noise. In the Atlantic Ocean, airgun firing is such a predominant sound that it is often described as chronic because it is ever-present, but the original signal is a pulsed sound. Sounds such as killer whale whistles or military sonars are generally described as narrowband, whereas sounds that encompass a range of frequencies, such as shipping noise or pile driving, are broadband (Figure 3).

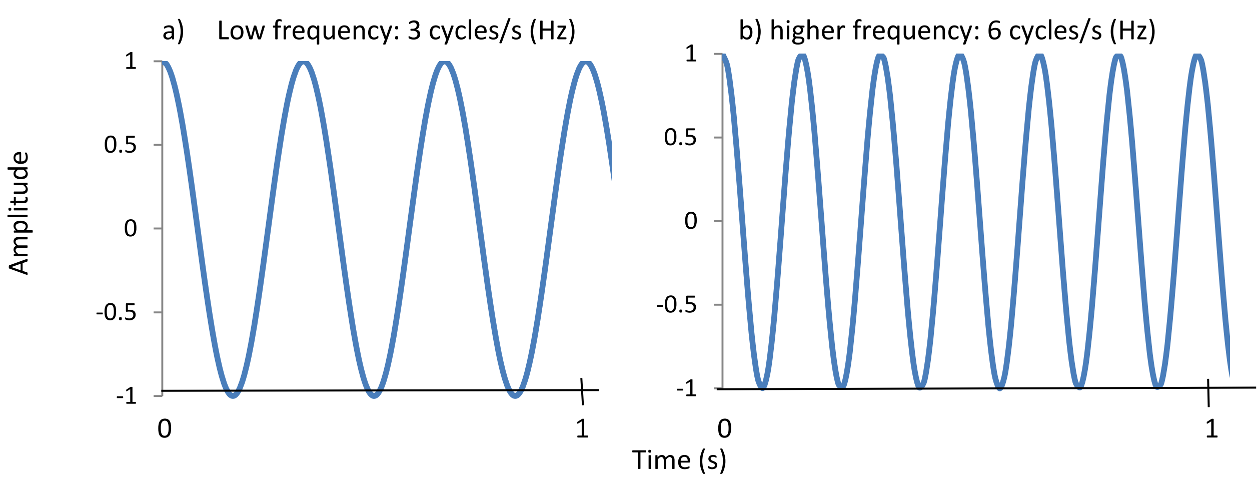

Figure 1. Waveforms of a low (a) and higher (b) frequency continuous sound wave.

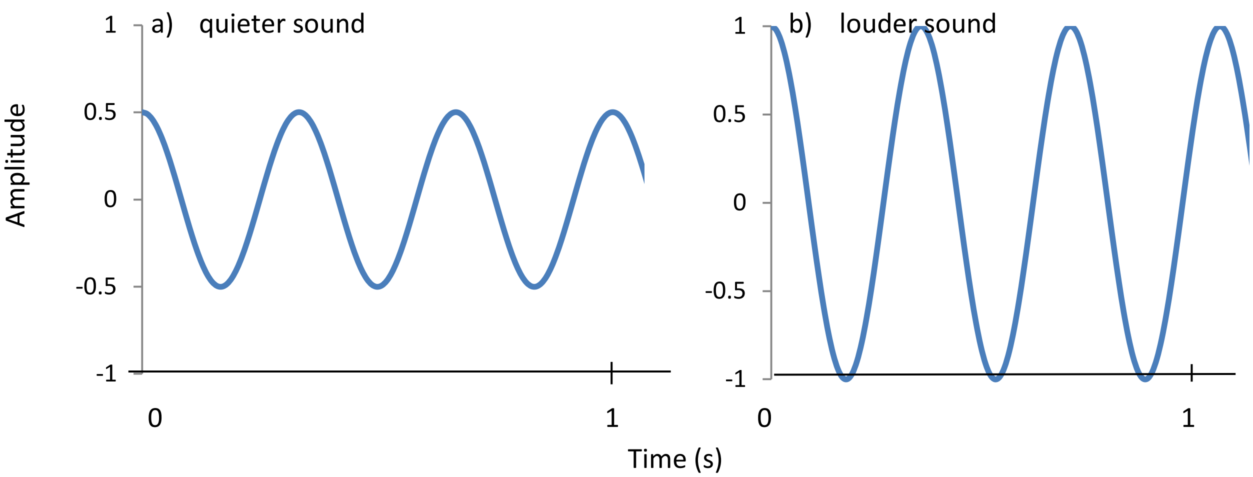

Figure 2. Waveforms of a quiet (a) and a louder (b) continuous sound wave of the same frequency.

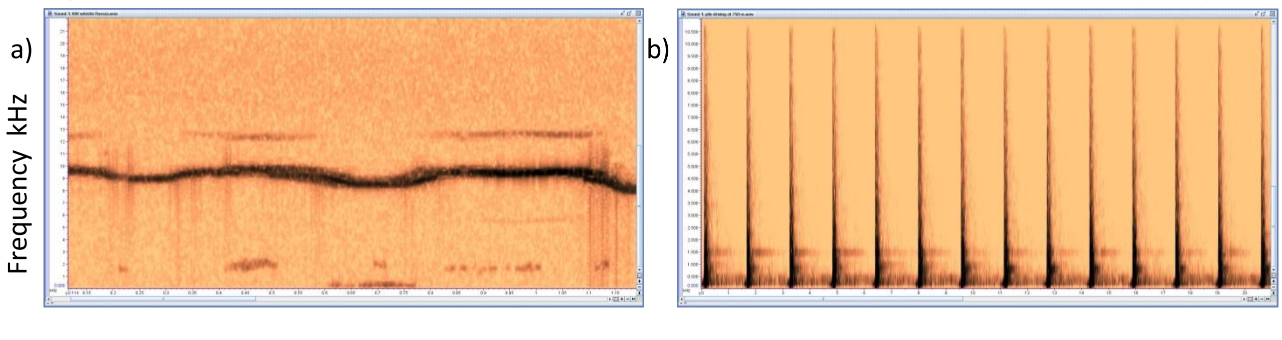

Figure 3. Spectograms of a) the continuous and narrowband sound of a killer whale whistle, and b) the pulsed and broadband sound of pile driving.

At age 10, the typical human hearing range is between 20 Hz and 20,000 Hz (20 kHz). However, we do not hear equally well at all of the frequencies in between. Hearing tests, or audiograms, have shown that human peak hearing frequencies range between 2-4 kHz, and fall off at frequencies above and below this range. You can make your own audiogram at www.myhearingtest.net Audiograms have been undertaken for a number of marine animals, and have been used as a tool to determine noise exposure criteria. In the US, for the purposes of developing noise exposure criteria, marine mammals have been divided into functional groups depending on their best hearing sensitivity (Southall et al. 2007).

Table 2. The five functional hearing groups for noise exposure criteria based on Southall et al. (2007).

Group	Examples
Low-frequency cetaceans	baleen whales- eg. gray, fin, and blue whales
Mid-frequency cetaceans	toothed whales and dolphins – eg. sperm, killer and beluga whales, Pacific white-sided dolphins
High- frequency cetaceans	porpoises – eg. Dall's and harbour porpoises
Pinnipeds in air	all seals, sea lions and fur seals eg. Harbour seals, Steller sea lions
Pinnipeds in water	all seals, sea lions and fur seals eg. Harbour seals, Steller sea lions

It is critically important to appreciate that the lower the frequency of the sound, the further the sound will travel. In water, a 100 Hz signal can travel over 1000 km with relatively little loss of sound energy. Most of the energy in shipping noise, and in baleen whale communication signals, lies in frequencies below 1000 Hz. In many approaches to analysing sounds, the energy is measured within different frequency bands. The bandwidth used most often in bioacoustics is 1/3 of an octave, where an octave represents a doubling of frequency (Table 3). The European Union has chosen the 63 Hz and 125 Hz 1/3 octave bands as the focus of their long term underwater noise monitoring program.

How do we describe sounds quantitatively?

There are a number of units that are used to describe sound, but unlike volume or length measurements that have absolute values, measures of sounds are relative. The decibel (dB) is now the most commonly used unit when considering the biological impacts of sound, and it is simply a unit in a logarithmic scale that describes sound intensity level or pressure level relative to a fixed reference intensity or pressure. For every 3 dB increase, the sound energy doubles. In air, the reference intensity is 20 micropascals (µPa) or .0002 microbars, which is considered to be the general lower limit of audibility to the human ear. However, the reference intensity for sound in water is 1 micropascal (µPa). Therefore sound pressure levels in air are not the same as sound pressure levels in water. When evaluating sound measurements, the reference intensity should always be clearly stated. In water, the reference intensity is typically expressed as dB re 1 µPa @ 1 m.

Table 3. Octave and 1/3 octave band centre frequencies and band limits. The lower the frequency, the further the sound will travel, in both air and water.

Frequency (Hz))					
Octave Band			1/3 Octave Band		
Lower Band Limit (Hz)	Centre Frequency (Hz)	Upper Band (Hz)	Lower Band Limit (Hz)	Centre Frequency (Hz)	Upper Band (Hz)
11	16	22	14.1	16	17.8
			17.8	20	22.4
			22.4	25	28.2
22	31.5	44	28.2	31.5	35.5
			35.5	40	44.7
			44.7	50	56.2
44	63	88	56.2	63*	70.8
			70.8	80	89.1
			89.1	100	112
88	125	177	112	125*	141
			141	160	178
			178	200	224
177	250	355	224	250	282
			282	315	355
			355	400	447
710	1000	1420	891	1000	1122
			1122	1250	1413
			1413	1600	1778
1420	2000	2840	1778	2000	2239
			2239	2500	2818
			2818	3150	3548
1420	2000	2840	1778	2000	2239
			2239	2500	2818
			2818	3150	3548
2840	4000	5680	3548	4000	4467
			4467	5000	5623
			5623	6300	7079
5680	8000	11360	7079	8000	8913
			8913	10000	11220
			11220	12500	14130
11360	16000	22720	14130	16000	17780
			17780	20000	22390

* The EU Marine Strategy Framework Directive on Noise[1] has selected the 63 and 125 Hz 1/3 octave bands as the focus of their long term underwater noise monitoring program.

There are a number of ways to describe sound pressure levels (SPL), but there is still disagreement amongst acousticians on what the best metrics are, and there are no internationally agreed upon standards to report SPLs. Depending on how the pressure or sound energy is calculated or measured, the numerical value associated with a sound can vary significantly (by 20 dB or more). Figure 4 shows a waveform and 3 different ways of describing the energy of the sound pressure wave of a continuous sound (root mean square [rms], peak amplitude (or 0-peak), and peak to peak amplitude). Rms measures are almost always lower than peak to peak or peak amplitude measures, because they are typically (but not always) averaged over one second. The length of time that passes before a sound

[1] http://ec.europa.eu/environment/marine/pdf/MSFD_reportTSG_Noise.pdf

reaches its peak amplitude is the rise time. The shorter the rise time, particularly for high amplitude sounds, the greater the concern for potential biological impacts. Table 5 shows how rms pressures can be calculated for Figure 4. Sound pressures reported for short duration pulsed sounds will have the same zero-peak and peak-peak amplitude as a continuous sound, but the rms value will be lower than for a continuous sound (Figure 5). Thus rms values are not ideal for describing high energy pulsed sounds, since they don't appropriately characterize the sound (Madsen 2005).

Table 4. Some examples of underwater sound pressure levels in different units, modified from JASCO Applied Sciences (2009).

Sound source	dB re 1 μPa	Bar	Pascal (Pa)
Peak pressure of one GI 45 in^3 airgun @ 1 m	228	2.5	2.5×10^5
Peak pressure of a sperm whale click	223	1.4	1.4×10^5
Peak pressure of pile driving (75 cm diameter, 13 mm wall thickness, 180 kJ hammer @14 m)	207	0.2	20,000
Source level (rms) of a zodiac with twin 175 hp outboards travelling at 55 km/hr	169	2.8m	280
Source level (rms) of a zodiac with twin 175 hp outboards travelling at 10 km/hr	147	0.2m	20
Source level of a killer whale whistle	140	0.1m	10
Snapping shrimp power spectrum density level at 4 kHz	72	40n	4m

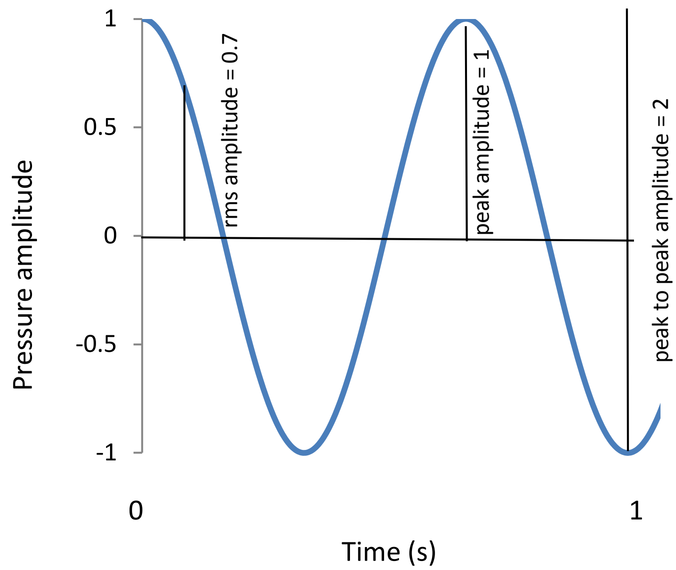

Figure 4. A waveform showing several ways of expressing the amplitude of a continuous sound. The root mean square (rms) amplitude is 0.8, the peak amplitude is 1 and the peak to peak amplitude is 2.
Table 5. Sample calculation for the rms pressure of the sound wave in Figure 4.

Steps for calculating the rms pressure in Figure 4	Sample calculation
Measured pressure along the wave	1,0,-1,0,1,0,-1
Square the measured pressures	1,0,1,0,1,0,1
Average the squared pressures	(1+0+1+0+1+0+1)/7= 0.57
Take the square root of the averaged sound pressures to calculate the rms. This is the sound pressure averaged over one second.	=0.76

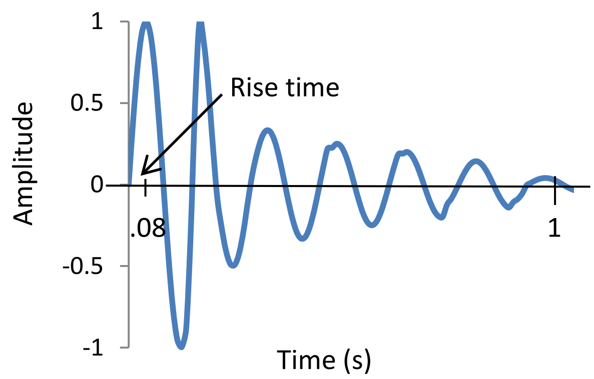

Figure 5. A waveform of a hypothetical pulsed sound. The rms is ~0.35, the peak amplitude is 1 and the peak to peak amplitude is 2. The rise time for the pulse to reach peak amplitude is ~0.08 s.

For simplicity, in the previous figures I have ignored the very basic rule that should be followed when evaluating sounds: the units and their reference pressure should be clearly stated. The units for underwater sound pressure levels (SPL) are dB re 1 μPa^2 although they are often presented as dB re 1 μPa (Ainslie 2010). Sound pressure levels are commonly expressed as peak or zero to peak sound pressures (SPL_{pk}), root mean square (rms) sound pressures (SPL_{rms}), or peak to peak sound pressures (SPL_{p-p} or SPL_{pk-pk}) depending on the source and duration of the sound. If SPL_{rms} is used to describe a pulsed sound, the duration of the pulse is the time between 5 and 95% of the total sound energy of the signal.

Unlike sound pressure levels, sound exposure levels (SEL) measure the total energy of a signal over time. In water, the sound exposure units are dB re 1 μPa^2 ·s and can be used to compare sounds that are continuous, single, or multiple pulses, and can also be used to describe the cumulative exposure of a sound over the duration of a specified time period. SELs are often used to compare transient sound events that have different durations and pressures. They are also reported as energy flux densities. It is also very important to <u>note whether the sound energy is reported at the source, or is a received level</u>. Source levels are most commonly described as occurring at 1 m from the source, yet for sources over a few cm in size, this is technically impossible to measure, because the sound is actually produced over a distance greater than 1 m. The noise produced by a 200 m ship occurs over the length of the ship, and similarly in a multi-airgun array used in a seismic survey, there are multiple individual sources of noise (each airgun). Source levels are therefore mathematically back-calculated from measures of received sound levels at a distance from the source, which are then modeled to compute the pressure at 1 m range, as if the real source was collapsed into a point-source.

What is a sound and what is noise?

The answer is qualified- it depends on the perspective of the listener. Noise is unwanted sound. It can include ambient background noise, and local interfering sounds. There are many naturally occurring sounds in the ocean, and they can be quite loud. These range from abiotic sources (eg. rainfall, wind and wave noise, thunder and earthquakes etc.) to the sounds of marine animals (made by fish, invertebrates and marine mammals). The reader should appreciate that the marine environment is not a naturally quiet place. However, for the purpose of this backgrounder, we will consider 'noise' to be anthropogenic (man-made) 'sounds' that may potentially impact marine animals.

What are some of the sources of anthropogenic noise in the marine environment?

On the BC coast, the most common source of anthropogenic underwater noise is vessel traffic, and finding solutions to manage it is the main focus of this workshop. Source levels of a selection of anthropogenic noise sources are listed in Table 6. In the open Pacific, ambient noise levels have increased ~2.5- 3 dB per decade during the last 40 years, particularly at frequencies below 300 Hz, and much of this is attributed to increased commercial shipping (McDonald et al. 2006, Spence et al. 2007, Chapman and Price 2011 amongst others). Recall that each 3 dB increase is effectively a doubling of the amount of sound energy produced, because dB measurements are based on a logarithmic scale. In inshore waters, characterizing the contribution of vessels to the ambient noise environment is more variable, as some areas have relatively few boats, whereas others, such as the vessel traffic approaches to major harbours, can be incredibly noisy (see Erbe et al. 2012a, b). As shipping traffic grows in BC, we can expect the overall ambient noise levels to increase, unless there is a mandate to reduce underwater noise levels.

Table 6. A selective list of source levels of anthropogenic noise sources in the marine environment, modified from Hildebrand (2009).

Sound source	**Source level (dB re 1UPa @ 1m)**	**Duration (s)**
Short duration sounds		

Ship shock trial (4536kg explosive)	304	2
Torpedo MK-48 (44 Kg explosive)	289	0.1
Air-gun array	260	0.03*
Pile driving 1000 kJ hammer	237	0.05*
US Navy 53C ASW sonar	235	2*
Multi-beam shallow water sonar	232	0.002*
Seal bomb (2.3 g explosive)	205	0.03
Continuous sounds		
Cargo vessel 173 m @ 16 knots	192	Continuous
Acoustic telemetry	190	Continuous
Outboard powered small boat @20 knots	160	Continuous
Operating wind turbine	151	Continuous

*Short duration but repetitive pulses

Noise comes from a variety of sources on a vessel, but the largest contributor is cavitation of the ship's propeller. Generally speaking, the faster a vessel travels, the greater the cavitation noise, especially at speeds in excess of 8 to 12 knots (Spence et al. 2007, McKenna et al. 2013). However, some vessels have variable pitched or controllable pitched propellers, and shafts that are rotating continuously (eg. the new BC Ferries), and these vessels can generate more noise at slower speeds than when operating at full speed (Renilson Marine Consulting 2009). Other sources of noise on a vessel include bow thrusters, machinery noise (esp. the propulsion system), pumps, and propeller singing[2]. Manoeuvring, loading, hull design and operator's behaviour also affect the amount of noise each vessel generates. Poor vessel maintenance can increase the noise of a vessel: McKenna et al. (2013) found that 10 % of all container ships transiting Santa Barbara Channel produced additional narrowband high frequency tones: these are likely associated with propeller damage and/or onboard machinery requiring maintenance. Shipping noise is broadband and can extend to greater than 100 kHz, but it is usually the lower frequencies that are of concern because they travel furthest. Although often not considered in describing large scale changes to the ambient noise environment in an area, small to medium size vessels, including coastal freighters, tugs, fishing vessels, pleasure craft, and whale-watching vessels, also contribute to the underwater soundscape.

Table 7. Source spectral densities for different types of commercial vessels underway, for several frequencies (from NRC 2003).

			Source spectral density (dB re 1 µPa^2/Hz @ 1 m)				
Ship Type	Length (m)	Speed (m/s)	10 Hz	25 Hz	50 Hz	100 Hz	300 Hz
Supertanker	244-355	7.7-11.3	185	189	185	175	157
Large tanker	155-214	7.7-9.3	175	179	176	166	149
Tanker	122-153	6.2-8.2	167	171	169	159	143
Merchant	84-122	5.1-7.7	161	165	163	154	137
Fishing	15-46	3.6-5.1	143	143	141	132	117

[2] Propeller singing is audible to the human ear and typically ranges from 10-1,200 Hz but up to 12 kHz, and is due to the vortices associated with the trailing edge of the propeller as it turns. It is often mediated by notching the trailing edge of the propeller.

Noise associated with construction and industrial activities is also a significant concern. Harbours can be particularly noisy, not just due to vessel traffic, but because of pile driving, dredging, and shipyard activities, amongst other sources. An additional and possibly significant but poorly documented source of noise in harbours is nearshore land based machinery noise that propagates through the substrate into the marine environment (NRC 2003).

Pile driving noise is of concern both in air and in water because the sound energy of each pulse has a very fast rise time and high peak pressure, and the strikes are repeated for up to thousands of times per day. Driven piles are used to support structures such as docks, bridges, wind turbines and navigational aids. The piles are driven into the substrate using impact hammers, or alternatively, vibratory hammers or press-in piles. The amount of noise produced by driving piles depends on the diameter of the pile, the hammer size, the material the pile is constructed of, the characteristics of the substrate, etc. In addition, the pulse that propagates down the pile can couple with the substrate and cause pressure waves to propagate through the sediment (recalling that sound travels through rock even more readily than through water, Table 1). Thus it is possible that a distance from the pile, there can be localized areas of very high or very low sound pressure and acoustic particle motion than at distances closer to the pile. See Popper and Hastings (2009) for a more detailed discussion of this topic. Table 8 shows sound pressure levels reported for different types of piles and hammers, and illustrates how the range of reported values varies depending on which metrics are used.

Table 8. Sound pressures from marine pile driving expressed in different metrics, from Rodkin and Reyff (2007).

Pile type (diameter)/ Hammer type	Distance from pile (m)	Peak sound pressure (dB re 1 µPa)	RMS sound pressure (db re 1 µPa)	Sound exposure level (dB re 1 $\mu Pa^2 \cdot s$)
Timber (0.3 m)/drop	10	177	165	157
Steel shell (0.3m)/drop	10	177	165	152
Concrete (0.6 m)/impact	10	183	171	160
CISS (0.3m)/impact	10	190	180	165
CISS (2.5m)/impact	25	212	197	188

(CISS = Cast in steel shell piles = concrete piles within a steel shell)

In the Atlantic Ocean, industrial activity related to offshore oil and gas production is a very significant source of underwater noise. Airguns used for seismic surveys generate high-amplitude broadband pulsed sounds that have been a source of concern for decades, because of their potential impacts on marine life. Much of the sound energy they generate is at low frequencies, which can be detected 4,000 km away (Nieukirk et al. 2012). At greater distances, the duration of the pulse increases (due to multi-path propagation), increasing the background noise level. However, airguns are rarely used in British Columbia, except for research purposes. Other sources of underwater noise include vessel sonars, and military activities (including low, mid and high frequency sonars, torpedos, ship-shock trials etc.). New and emerging technologies (autonomous underwater vehicles, modems etc.) also add noise to the underwater environment.

Why is underwater noise a concern for marine life?

Anthropogenic noise has the potential to interfere with the ability of marine animals to carry out vital life processes, such as foraging, reproduction, predator avoidance, communication and navigation. Noise can impact animals by causing behavioural changes, although these are often subject to interpretation and can depend on the age, sex, health, context and prior experience of the animal. Noise can mask important biologically important sounds such as communication and echolocation signals and the ability of animals to passively listen for predators, prey or environmental cues (eg. beaches, high surf areas). High energy sound can cause physiological responses, including changes in stress hormone levels, tissue resonance, and acoustic trauma, as well as temporary and/or permanent threshold shifts in hearing ability. Marine animals that lose their ability to hear the sound of approaching predators or the ability to detect their prey acoustically are at greater risk of mortality. Ultimately, in certain conditions high-energy noise can result in direct mortality.

It is not within the scope of this backgrounder to provide a full review of the potential impacts of underwater noise on marine life, and there are many references that address this topic in significant detail. A number have been published within the last 10 years, almost all of which call for further research (Table 9). This list is not comprehensive, but rather a sampling of the literature. The complete reference is provided in the Relevant Literature section of this backgrounder.

Table 9. A selection of recent literature on the effects of underwater noise on marine life. Complete details of each reference are provided in the Relevant Literature section below. This list is not comprehensive.

Author (date)	**Focus of paper**
NRC (2003)	A synthesis of what is known about marine mammals and noise
IACMST (2006)	A summary report on the effects of underwater noise on marine life from

	a UK perspective
Nowacek et al. (2007)	A review of behavioural response of marine mammals to noise
Southall et al. (2007)	A review of the impacts of noise on marine mammals with criteria for noise exposure standards for the US
Weilgart (2007)	A synthesis of the impacts of noise on cetaceans
Wright and Highfill (2007)	A collection of papers on the effects of noise on marine life
Wright (2008)	A review of the impacts of shipping noise on marine mammals
Boyd et al. (2008)	A draft research strategy to assess the effects of noise on marine mammals
Hawkins et al. (2008)	A collection of papers presented at the 2007 'Effects of noise on aquatic life' conference in Nyborg, Denmark
OSPAR (2009)	A synthesis of the impacts of underwater noise on marine life
Popper and Hastings (2009)	A synthesis of the effects of anthropogenic noise on fish
Slabbekoorn et al. (2010)	A synthesis of the consequences of increasing ambient noise levels for fish
Normandeau and associates (2012)	A synthesis of the effects of noise on fish and invertebrates
Popper and Hawkins (2012)	A collection of papers presented at the 2010 'Effects of noise on aquatic life' conference in Cork, Ireland

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Relevant Literature

A selection of reviews or papers, some of which are cited in this backgrounder, which may be helpful in dealing with underwater noise management issues. All have been published within the last 10 years, and this list is not comprehensive.

Ainslie, M. 2010. Principles of Sonar Performance Modeling. Spinger Praxis Publ. Chichester, UK.

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