APPENDIX H
SCIENTIFIC REVIEW: ACOUSTICS AND LOW ENERGY GEOPHYSICAL SURVEYS AND THEIR POTENTIAL FOR IMPACT

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LIST OF ACRONYMS AND ABBREVIATIONS

UNITS OF MEASUREMENT

µPa	microPascal(s)
μPa^2	microPascal(s) squared
µsec or µs	microsecond(s)
µV	microvolts
dB	decibel(s)
dB re 1 µPa	decibel referenced to one microPascal
kHz	kilohertz
hr	hour(s)
Hz	Hertz (cycles per second)
in	inch(es)
m	meter(s)
m^2	square meter(s)
mi	mile(s)
mi^2	square mile(s)
msec or ms	millisecond(s)
s or sec	second(s)

NUMBERS AND SYMBOLS

°	degrees
0-p	zero-to-peak

OTHER ACRONYMS AND ABBREVIATIONS

A	ABR	auditory brainstem response
	AEP	auditory evoked potential
	ATOC	Acoustic Thermometry of Ocean Climate
B	BOEM	Bureau of Ocean Energy Management
C	CDFG	California Department of Fish and Game
	CDFW	California Department of Fish and Wildlife
	CEQA	California Environmental Quality Act
	CESA	California Endangered Species Act
	cm	centimeter(s)
	CN	coastal and/or nearshore
	cSEL	cumulative sound exposure level
	CSLC	California State Lands Commission
D	D	depleted
	dB	decibel
	dBA or dB(A)	A weighting decibel scale
	DPS	distinct population segment
E	E	endangered
	EEZ	Exclusive Economic Zone
	EIS	Environmental impact statement
F	FESA	Federal Endangered Species Act
	FP	fully protected
G	GIS	geographic information system

H	HESS	High Energy Seismic Survey
	HF	high-frequency; M-weighting; also shown as M_{hf}
	hr	hour(s)
	Hz	Hertz
I	IMAPS	Integrated Marine Mammal Monitoring and Protection System
	in.	inch(es)
K	kHz	kilohertz
L	LF	low-frequency; M-weighting; also shown as M_{lf}
M	m	meter(s)
	MF	mid-frequency; M-weighting; also shown as M_{mf}
	min	minute(s)
	MMPA	Marine Mammal Protection Act
N	ND	not depleted
	NMFS	National Marine Fisheries Service
	NOAA	National Oceanic and Atmospheric Administration
	NS	Not strategic (stock)
	NSF	National Science Foundation
O	OEIS	Overseas environmental impact statement
	O	Offshore
	OCS	Outer Continental Shelf
	OPR	Office of Protected Resources
	oz	Ounce(s)
P	P	protected
	PAS	Periodic-acid Schiff
	p-p	peak-to-peak
	PTS	permanent threshold shift
	PW	pinnipeds (in water); M-weighting; also shown as M_{pw}
R	rms	root mean squared
S	S	strategic stock
	SEL	sound exposure level
	SPL	sound pressure level
	ST	State threatened
	SURTASS LFA	Surveillance Towed Array Sensor System, Low-Frequency Active
T	T	threatened
	TTS	temporary threshold shift
U	USGS	U.S. Geological Survey

1.0 OVERVIEW

The purpose of this review is to provide the California State Lands Commission (CSLC) with current information regarding hearing and noise impacts on marine resources, with an emphasis on the low energy geophysical seismic sources being used under permit within State waters. Specifically, the objectives of this summary are to:

- Synthesize pertinent research regarding the susceptibility of marine resources (i.e., marine mammals, sea turtles, fishes, invertebrates) to anthropogenic noise, with focus on low energy sound sources;
- Document what information is most applicable to California's species of concern and the types of surveys generally conducted off the California coast; and
- Identify other agencies' existing or proposed thresholds and bounds for energy, frequency, and pressure of surveying equipment.

While most of the noise-related research outlined in the following summary addresses effects to marine mammals, other marine fauna may be affected by sound exposure, including sea turtles, fishes, and, to a limited extent, invertebrates. Sound in water is composed of two physically linked components, propagating scalar pressure waves and directional particle motion, each of which differ in the pathways through which they reach marine fauna. Many fish and invertebrates are sensitive to particle motion (both otoliths in fishes and statocysts in invertebrates act as accelerometers). As appropriate, the results of particle motion studies are summarized in the following analysis.

2.0 NATURAL AND ANTHROPOGENIC NOISE IN THE MARINE ENVIRONMENT

2.1 Overview

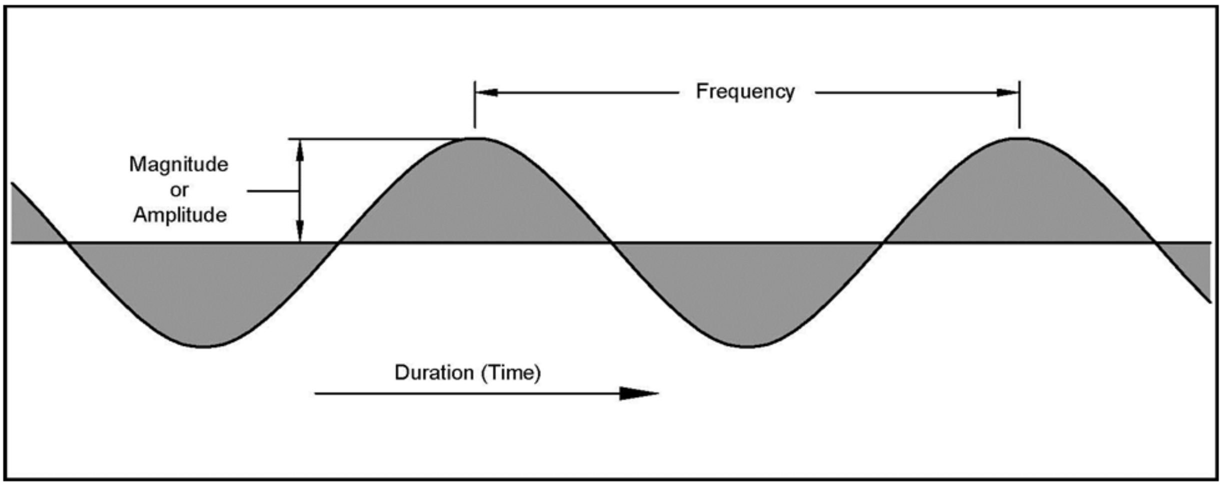
Sound is generated when an object vibrates and causes minute periodic fluctuations in atmospheric pressure, (i.e., sonic waves). Perception of sound is dependent on various factors, including the following:

- *Frequency*. Frequency is the number of pressure variations (vibrations) per second (Hertz [Hz]). Humans can typically hear sound waves with frequencies between 20 Hz and 20 kilohertz (kHz); the human ear does not perceive sound at the low- and high-frequencies as well as it does at the middle frequencies.
    - Tone vs. Pulse: A tone is a sound of a constant frequency that continues for a substantial time, whereas a pulse is a sound of short duration, and it may include a broad range of frequencies.
- *Frequency Range*. Because the range of frequencies of a sound source may vary, the sound's frequency bandwidth should be specified and included in the reference units. The units for a power spectrum are decibels (dB) referenced to (re) 1 square micropascal (μPa^2)/Hz.
- *Magnitude*. Sound magnitude, or degree of loudness, is measured on the decibel (dB) scale, which is a logarithmic scale of sound wave amplitude (i.e., the "height" of a sound wave; see **Figure H-1** below). A logarithmic scale is used because equal increments of dB values do not have an equal increase in effect. Any quantity expressed in this scale is termed a 'level'. These quantities are absolute values, however, and are not tied to how sound energy interacts with hearing organisms; therefore, sound is more commonly expressed as a sound pressure level (SPL),[1] which is a ratio of the dB level to a standard reference sound level related to sound levels at which humans can perceive noise. By convention, the reference quantity is smaller than the smallest value to be expressed on the scale, so that any level quoted is a positive value. For example:
    - A reference sound pressure of 20 microPascal (µPa) (expressed as "dB re 20 µPa") is used for sound in air, because this is the threshold of human hearing in air; and
    - For underwater sound, 1 µPa is used as the reference sound pressure (expressed as "dB re 1 µPa").[2]

[1] Recalling that sound moves as a wave, the higher the amplitude of the wave, the more pressure it exerts on the atmosphere or on a surface, such as an ear drum.

[2] A Pascal (Pa) is equal to the pressure exerted by one Newton over one square meter; 1 µPa equals one millionth of a Pascal.

Figure H-1. Diagram of Sound Wave Characteristics



Because sound energy is not constant, but occurs in waves, with positive peaks and negative dips, acousticians calculate the effective, average sound level by squaring the amplitudes of the wave to make all values positive, averaging those values over a period of time, and then taking the square root of that average. Sound pressures averaged in this way are measured in units of root mean square (rms) SPL. Sound pressure may also be expressed as peak-to-peak or zero-to-peak. Peak-to-peak (p-p) is the pressure difference between the maximum positive pressure and the maximum negative pressure in a sound wave. Zero-to-peak (0-p) is the pressure difference between zero and the maximum positive (or maximum negative) pressure in a sound wave.

Ambient underwater noise levels in the ocean can be complex, and vary spatially (i.e., from location to location; deep- versus shallow-water) and temporally (e.g., day to day, within a day, and/or from season to season). Both natural and anthropogenic (human-made) sources provide significant contributions to ambient noise levels in the ocean.

Sound in the marine environment may originate from several sources including environmental events (e.g., waves, rain, earthquakes), biological sources (e.g., vocalizations by marine mammals, fishes, and several invertebrates), and anthropogenic activities (e.g., vessel noise, oil and gas operations including drilling, seismic surveying, military operations; Hildebrand 2009). Detailed measurements of marine sound levels have been made for many of these sources, but their degree of overlap with and impacts on acoustically-oriented marine life remains generally poorly understood (Southall 2012).

Natural noise sources include wind, waves, rain, and biologics (e.g., whales, dolphins, fish). Naturally occurring noise levels in the ocean from wind and wave activity may range from 90 dB re 1 μPa under very calm, low wind conditions to 110 dB re 1 μPa under windy conditions. Wind is the major contributor to noise between 100 Hz and 30 kHz, while wave generated noise is a significant contribution in the infrasonic range (1 to 20 Hz). Surf noise, however, is specific to coastal locations (Simmonds et al. 2003).

Sound characteristics of anthropogenic noise sources, including shipping, industry (e.g., oil and gas drilling), and equipment, can be found in **Table H-1**.

Table H-1. Sound Characteristics of Major Ocean Sound Producers (From: MMC 2007; Hildebrand 2005)

Sound Source	Primary Frequency Range	Sound Pressure Levels	Distribution	Total Energy
Commercial Shipping	5–100 Hz	150–195 dB re 1 µPa^2/Hz at 1 m	Great circle routes, coastal and port areas	3.7 x 10^{12}
Seismic Airgun Arrays	5–300 Hz	up to 259 dB dB re 1 µPa	Variable, with emphasis on continental shelf and deep-water areas potentially containing oil and/or gas	3.9 x 10^{13}
Naval Sonars	100–500 Hz (SURTASS LFA)	235 dB re 1 µPa	Variable below 70º latitude	2.6 x 10^{13}
	2–10 kHz (Mid-frequency sonar)	235 dB re 1 µPa	Variable with emphasis in coastal areas	
Fisheries Sonars	10–200 kHz	150–210 dB re 1 µPa	Variable, primarily coastal and over the continental shelf	Unknown
Research Sonars	3–100 kHz	up to 235 dB dB re 1 µPa	Variable	Unknown
Acoustic Deterrents, Harassment Devices	5–16 kHz	130–195 dB re 1 µPa	Coastal	Unknown

Acronyms: SURTASS = Surveillance Towed Array Sensor System; LFA = Low-Frequency Active.

Increases in ambient underwater noise levels are a result of increased maritime activities including commercial shipping, seismic surveys associated with oil and gas exploration and academic research, military and commercial sonar use, maritime recreation, fishing activities, and coastal development. In many ocean areas, the dominant source of anthropogenic, low-frequency noise (i.e., 20 to 200 Hz) is from the propellers and engines of commercial shipping vessels (Rolland et al. 2012; McKenna et al. 2012), which can contribute to ambient underwater noise levels across large spatial scales (Curtis et al. 1999; Andrew et al. 2002; McDonald et al. 2006, 2008; Chapman and Price 2011).

Different noise sources are dominant in each of three frequency bands:

- Low: 10 to 500 Hz;
- Mid: 500 Hz to 25 kHz; and
- High: >25 kHz.

The low-frequency band is dominated by anthropogenic sources: primarily, commercial shipping and, secondarily, seismic exploration. Shipping and seismic sources contribute to ambient noise across ocean basins, since low-frequency sound experiences little attenuation (loss in sound energy level that occurs as sound travels away from its source), allowing for long range propagation. Over the past few decades, the contribution of shipping noise to ambient noise levels has increased, coincident with a significant increase in the number and size of vessels comprising the world's commercial shipping fleet (Hildebrand 2009).

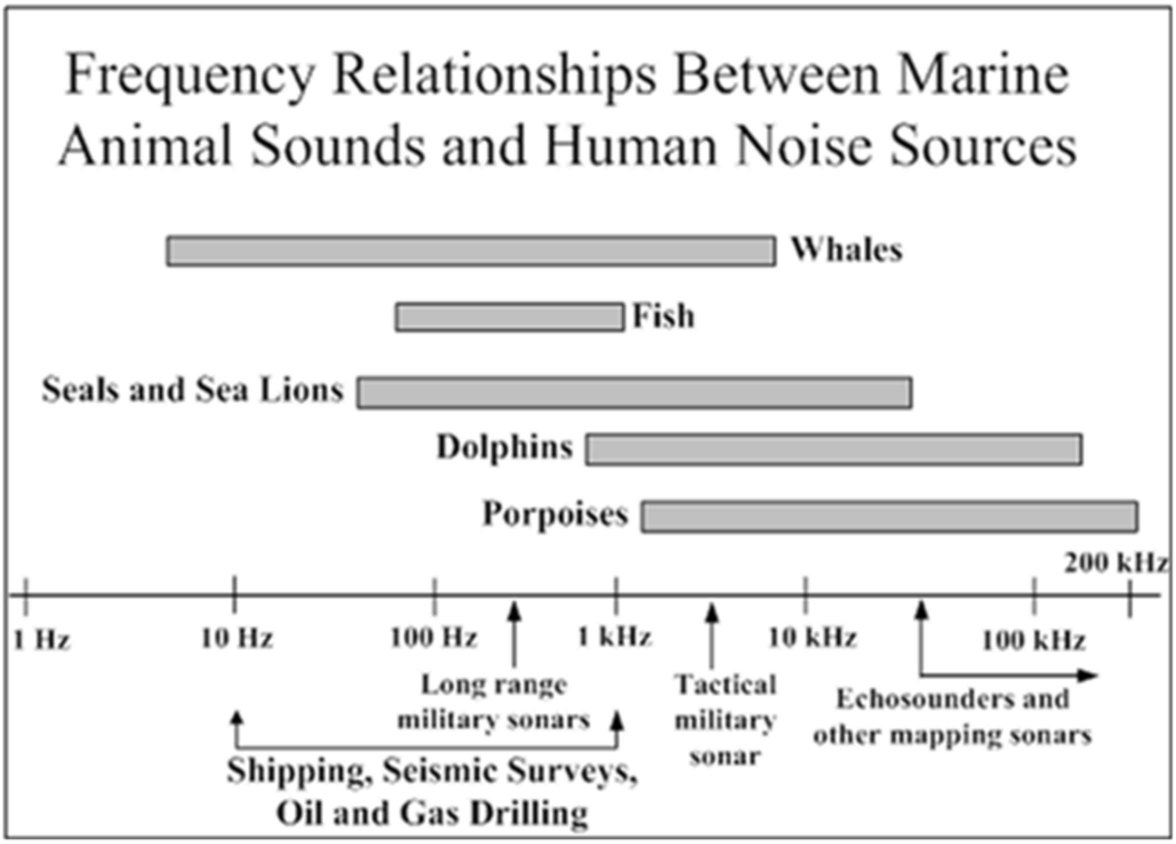
The mid-frequency band is comprised of natural (e.g., sea surface agitation) and anthropogenic (e.g., military and mapping sonars, small vessels) noise sources that cannot propagate over long ranges, owing to greater attenuation, with only local or regional sources contributing to the ambient noise field (Hildebrand 2009).

The high-frequency band is dominated by thermal noise, with anthropogenic noise sources such as sonars (for shallow-water echosounding and locating small objects, such as fish), contributing to the ambient noise field. At high-frequencies, acoustic attenuation becomes extreme so that all noise sources are confined to an area within a few kilometers of the source (Hildebrand 2009).

For most marine vertebrates, the production and reception of sound serve one or more critical functions, including communication (e.g., with conspecifics), foraging (i.e., identification and location of prey), orientation and navigation, and predator-avoidance (e.g., Schusterman 1981; Watkins and Wartzok 1985; Richardson et al. 1995; Tyack 1998; Wartzok and Ketten 1999; National Research Council [NRC] 2003; 2005; Clark and Ellison 2004; Southall et al. 2007).

The relative importance of sound production and reception among marine animals becomes a greater concern depending upon several factors, including the degree of overlap with anthropogenic sources of noise. As shown in **Figure H-2**, the frequency ranges for many groups of marine organisms overlap with the frequencies of many anthropogenic noise sources. At low-frequencies, commercial shipping and seismic surveys are the dominant sources of anthropogenic noise. At mid- and high-frequencies, naval, commercial, fishery, and recreational sonars are dominant (Marine Mammal Commission 2007).

Figure H-2. Measured or Estimated Functional Hearing Ranges for Different Marine Vertebrate Groups Relative to Various Anthropogenic Noise Sources



Studies conducted to assess the reactions of marine fauna to noise have shown widely varied responses depending on the individual, age, gender, and the activity in which the animals were engaged (Simmonds et al. 2003). An animal must be able to perceive a sound in order for an impact to occur. However, direct measurements of sound reception across all marine organisms is not feasible; in lieu of direct measurements, marine biologists and acousticians have estimated that animal hearing is most acute within those frequency ranges where their vocalizations occur. Most marine taxa have measured or estimated functional hearing capabilities across similar frequencies to those where their vocalizations occur, although perception may be slightly broader than the frequency range of vocalizations (Luther and Wiley 2009) (**Figure H-1**).

2.2 Sound Type Categories

Southall et al. (2007), in their analysis of marine mammal noise exposure criteria, categorized anthropogenic sound sources into functional categories based on their acoustic and repetitive properties (**Table H-2**). For the purposes of this analysis, these three different sound type categories (single, multiple and non-pulse) are considered to be applicable to all marine fauna potentially affected by low energy sound sources within the area of interest (i.e., State waters), although it is expected that single and multiple pulse sources are predominant.

Table H-2. Sound Source Categories, Acoustic Characteristics, and Examples (From: Southall et al. 2007)

Sound Type	Acoustic Characteristics (at source)	Examples
Single Pulse	Single acoustic event; >3 dB difference between received level using impulse versus equivalent continuous time constant	Single explosion; sonic boom; single airgun, watergun, pile strike, or sparker pulse; single ping of certain sonars, depth sounders, and pingers
Multiple Pulse	Multiple discrete acoustic events within 24 hr; >3 dB difference between received level using impulse versus equivalent continuous time constant	Serial explosions; sequential airgun, watergun, pile strikes, or sparker pulses; certain active sonar (IMAPS); some depth sounder signals
Non-pulse	Single or multiple discrete acoustic events within 24 hr; <3 dB difference between received level using impulse versus equivalent continuous time constant	Vessel/aircraft passes, drilling; many construction or other industrial operations; certain sonar systems (LFA; tactical mid-frequency); acoustic harassment/deterrent devises; acoustic tomography sources (ATOC); some depth sounder signals

Acronyms and Abbreviations: dB = decibel; hr = hour; ATOC = Acoustic Thermometry of Ocean Climate; IMAPS = Integrated Marine Mammal Monitoring and Protection System; LFA = Low-Frequency Active.

3.0 MARINE MAMMALS

Based on a recent review of the effects of anthropogenic noise on marine mammals prepared by Southall (2012), there has been significant progress in the last decade regarding the characterization of noise sources and impacts of noise upon marine mammals, particularly in regards to determining hearing impacts and behavioral responses to various types of noise. Research to date has focused on several aspects of noise impacts, including potential injury (e.g., hearing and tissue damage), behavioral responses (e.g., mass strandings of marine mammals exposed to military sonar), and the mechanisms by which biologically significant behaviors can be determined.

Most research indicates that the *impact footprint* (*sensu* Southall 2012) that produces direct harm (e.g., physical injury) to a marine mammal is relatively small, while the total area within which a marine mammal may be disturbed can be quite large. The extent of the area ensonified and the degree of behavioral modification realized by marine mammals exposed to a particular sound are tempered, to a certain degree, by the nature of the sound (e.g., source level, frequency composition) and the receptor (e.g., hearing sensitivity of the marine mammals exposed).

3.1 Effects of Noise Exposure

Potential effects of noise exposure to marine mammals represents a continuum and includes, in order of increasing severity: (1) behavioral response; (2) masking; (3) hearing threshold shift; (4) physiological effects; and (5) mortality. Definitions of these effect levels include:

- Behavioral Response – a wide range of behavioral responses to noise exposure is possible. Southall (2012) identifies at least seven levels of response, including (in increasing severity and decreasing likelihood): no observable response, increased alertness, minor behavioral responses (e.g., vocal modifications associated with masking), cessation of feeding or social interaction, temporary avoidance behavior, modification of group structure or activity state, and habitat abandonment. The context in which the noise exposure occurs is a critical factor in determining auditory impacts (Wartzok et al. 2004; Southall et al. 2007). Key references include Ljungblad et al. (1988); Richardson et al. (1995); McCauley et al. (1998; 2003); Ridgway and Carder (2001); Miller et al. (2005); NRC (2005); Southall et al. (2007); Wirsing et al. (2008); Bejder et al. (2009); Barber et al. (2010). General observations regarding behavioral response include: (1) many of the responses observed across taxa were temporary avoidance behavior; (2) certain species (e.g., harbor porpoises, beaked whales) appear to be categorically more sensitive to noise than other species observed; and (3) certain behavioral states (e.g., migrating) can make species such as bowhead whales more sensitive to noise exposure (Richardson et al. 1999). Recent results are available from both controlled exposure experiments and opportunistic observations of anthropogenic noise source operations on the behavioral responses of particularly sensitive marine mammals, including harbor porpoises (Kastelein et al. 2008a,b; Gilles et al. 2009) and beaked whales (Caretta et al. 2008; McCarthy et al. 2011; Southall et al. 2011; Tyack et al. 2011).

- Auditory Masking – results from the spectral, temporal, and/or spatial overlap between a noise source and an organism, whether a sender or receiver, and causes a reduction in the ability of the organism to effectively communicate, detect predator, prey, and/or conspecific signals, and/or properly determine its spatial orientation. Masking has received only limited scientific study; see Clark et al. (2009) for a review. Clark et al. (2009) provided a quantitative means of determining the relative loss of acoustic communication range for marine mammals using specific calls in conditions where the mammals are exposed to specific anthropogenic noise sources (i.e., continuous, but moving, vessel noise). A recent summary by Reichmuth (2011) addresses psychophysical studies of masking in marine mammals; key references include work done with odontocetes (Branstetter and Finneran 2008; Branstetter et al. 2011; Erbe 2000; Erbe and Farmer 1998; Kastelein and Wensween 2008; Kastelein et al. 2009; Lemonds 2009) and pinnipeds (Holt and Schusterman 2007; Southall et al. 2000, 2003; Turnbull 1994).

- Hearing Threshold Shift – noise-induced increases in hearing thresholds within a specific frequency range; threshold shifts can be temporary (temporary threshold shift [TTS]) or permanent (permanent threshold shift [PTS]). Sound impulse duration, peak amplitude, rise time, number of pulses, and inter-pulse interval are the main factors thought to determine the onset and extent of PTS (NMFS 2012). Both TTS and PTS can result from either physical damage (e.g., cell structure fatigue) or metabolic change (e.g., inner ear hair cell metabolism). Key references include Kryter (1994), Ward (1997), Kastak et al. (1999), Yost (2000), Schlundt et al. (2000); Finneran et al. (2002, 2005, 2010a,b); Lucke et al. (2009); Mooney et al. (2009a,b); Finneran and Schlundt (2010); Gedamke et al. (2011). Per Southall (2012), intense sound exposure more often results in mechanical processes, whereas prolonged exposure more typically results in metabolic changes (e.g., Saunders et al. 1985). Two important factors were noted by Southall (2012) regarding threshold shift: (1) the exposure level relative to the subject's absolute hearing sensitivity (i.e., the sensation level) is particularly important in determining TTS onset; and (2) exposure levels in the region of best hearing sensitivity should be used as generic TTS-onset values against which frequency weighting functions could be applied to correct for frequency-specific hearing.

- Physiological Effects – results from damaging but non-lethal exposure to high levels of sound or shock waves, with similar short duration, high peak pressure sources; may include stress responses and direct physical injury (e.g., tissue damage). See Busch and Hayward (2009) and Wright et al. (2007a,b) for recent reviews. Direct measurements of physical stress responses in marine mammals from sound exposure are relatively limited; key data sources include Thomas et al. (1990), Miksis et al. (2001), and Romano et al. (2004).

- Mortality – results from direct physical injury as a consequence of exposure to high levels of sound or shock waves (e.g., from high intensity events, explosions), characterized by short duration, high peak pressures that damage air-filled body cavities (e.g., lungs) and other internal organs (e.g., see Yelverton et al. 1973; Goertner 1982; Young 1991); key data sources include Todd et al. (1996) and Cudahy and Ellison (2002). More recently, another form of physiological damage among marine mammals has been investigated – the formation of gas bubble lesions and fat emboli. This damage has been noted in several beaked whale species that have stranded in the vicinity of naval mid-frequency sonar training exercises (Jepson et al. 2003; Fernández et al. 2005; Tyack et al. 2011). Currently, these tissue impacts are thought to result from a behavioral response that changes diving patterns in some way and subsequently causes lesion/emboli formation, rather than as a direct physical effect of sound exposure (Cox et al. 2006; Zimmer and Tyack 2007).

Impact analysis of marine mammal exposure to sound has typically utilized SPL, or more recently, sound exposure level (SEL) as a metric for determining the significance of an impact. Recent environmental impact statements have focused on SPLs coupled with the cumulative effects of sound exposure over time (e.g., over a 24-hour period).

Several comprehensive reviews and syntheses have been published in recent years, including the treatise on sound exposure criteria (Southall et al. 2007) and the compendium on the effects of sound on marine life (Popper and Hawkins 2011), as well as an overview of the response of cetaceans to anthropogenic noise (Nowacek et al. 2007). Marine mammal hearing covers a very wide band, with baleen whales (mysticetes) likely hearing down into very low-frequencies, pinnipeds at low- to intermediate frequencies, and toothed whales (odontocetes) hearing over a very broad range extending well into the ultrasonic range. The following summaries are based on recent reviews and summaries of marine mammal hearing capabilities.

3.2 Mysticete Hearing

Direct measurements of mysticete hearing are unavailable due to the logistic constraints associated with experimenting with these large marine mammals. Consequently, hearing in mysticetes is estimated based on other forms of analysis, including vocalizations (Wartzok and Ketten 1999), anatomy (Houser et al. 2001; Parks et al. 2007), long range orientation (Payne and Webb 1971), behavioral responses to sound (Frankel 2005; Reichmuth 2007), and nominal natural background noise conditions in the likely frequency ranges of hearing (Clark and Ellison 2004).

Results suggest that mysticetes are most sensitive to low-frequency sounds ranging from tens of hertz to approximately 10 kHz. Southall et al. (2007) estimated the lower and upper frequencies for functional hearing in mysticetes, collectively, to be 7 Hz and 22 kHz; more recently, Southall (2012) suggests that this may be a slight underestimate of the high-frequency cutoff. For example, recent acoustic data suggest that humpback whales (*Megaptera novaeangliae*) produce sounds with harmonics extending above 24 kHz (Au et al. 2006), and anatomical data suggest that some mysticetes may hear frequencies up to 30 kHz (Ketten et al. 2007).

3.3 Odontocete Hearing

Odontocetes are thought to hear over a broad frequency range, due to the presence of high-frequency biosonar and lower frequency communication systems. Southall (2012) notes that the frequency range of some odontocetes span 12 octaves.

Wartzok and Ketten (1999) and Southall et al. (2007) reviewed the available literature on hearing in odontocetes and identified two functional hearing groups – mid-frequency cetaceans with functional hearing between 150 Hz and 160 kHz, and high-frequency cetaceans with functional hearing estimated between 200 Hz and 180 kHz.

3.4 Pinniped Hearing

Pinnipeds have functional hearing both above and below the water, with broader functional hearing ranges in water (see Kastak and Schusterman 1998; Schusterman et al. 2000). Direct measurements of pinniped hearing have been obtained in less than a dozen different pinniped species (Southall et al. 2007; Mulsow and Reichmuth 2010; Mulsow et al. 2011) using both behavioral and electrophysiological measures. Southall et al. (2007) estimated functional hearing across all pinnipeds as extending between 75 Hz and 75 kHz underwater and between 75 Hz and 30 kHz in air. Hearing in phocids (i.e., seals) extends to much higher frequencies than otariids (i.e., sea lions, fur seals), especially in water.

3.5 Mustelid Hearing

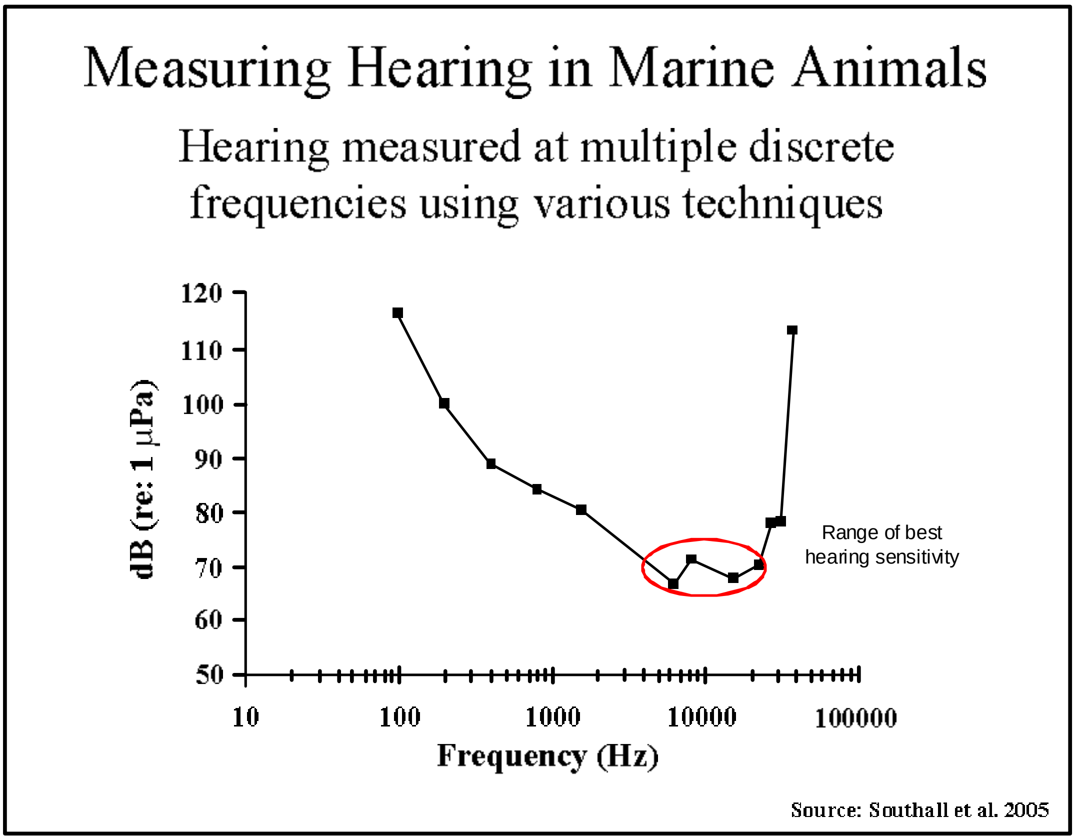
Only a few studies have characterized the bioacoustics of the sea otter. McShane et al. (1995) assessed sound production/vocalization and communication in sea otters. More recently, Ghoul and Reichmuth (2011) characterized both sound production and sound reception in the southern sea otter (*Enhydra lutris nereis*). Vocalizations appear to be restricted to airborne signals (Richardson et al. 1995), typically between mothers and pups; sound production underwater has never been observed. Ghoul and Reichmuth (2011) indicate that vocalizations (i.e., screams) in air were harmonic in structure and extremely broadband, with energy extending above 60 kHz. Dominant frequencies ranged from 6 to 8 kHz for adult females, and from 4 to 7 kHz for dependent pups. Source level measurements for all age and sex classes were variable, ranging from 50 to 113 dB SPL (re 20 µPa [in air]).

3.6 Marine Mammal Hearing

3.6.1 Sensitivity

Hearing has been measured using behavioral and/or electrophysiological methods in about a quarter of the known marine mammal species, although with a disproportional representation of species commonly found in captivity, and some entire groups (e.g., mysticetes) remain untested (Southall 2012). Hearing sensitivity is generally quantified by determining the quietest possible sound that is detectable by an animal either via a behavioral response or by quantifying an electrical response, based on exposure to an acoustic signal. By exposing an animal to a broad range of test frequencies, the overall hearing capability can be determined. The graphic depiction of the overall hearing capability of a test subject is known as an audiogram (**Figure H-3**).

Figure H-3. Audiogram from a California Sea Lion (From: Southall et al. 2005; Southall 2012)



Hearing sensitivity is greatest in those frequency ranges where the detection sound levels are lowest. Audiograms follow a U-shaped curve, with the lowest frequency measures indicating best hearing sensitivity, flanked by decreased sensitivity at frequencies above and below. The region where hearing thresholds are within some range from the lowest overall threshold is often referred to as the overall range of functional hearing. Audiograms quickly provide an indication of the range of frequencies where the best hearing capabilities are found.

3.6.2 Marine Mammal Hearing Weighting Functions

Because marine mammals do not hear equally well at all frequencies, frequency-weighting functions were developed by Southall et al. (2007) as a method for quantitatively compensating for differential frequency responses for different species. Weighting functions are commonly applied to assess the potential for the detection of a sound at a specific frequency and to assess the potential impact arising from noise exposure. **Table H-3** outlines the five functional hearing groups and estimated functional hearing ranges for marine mammals proposed by Southall et al. (2007).

Table H-3. Marine Mammal Functional Hearing Groups and Estimated Functional Hearing Ranges (Adapted from: Southall et al. 2007)

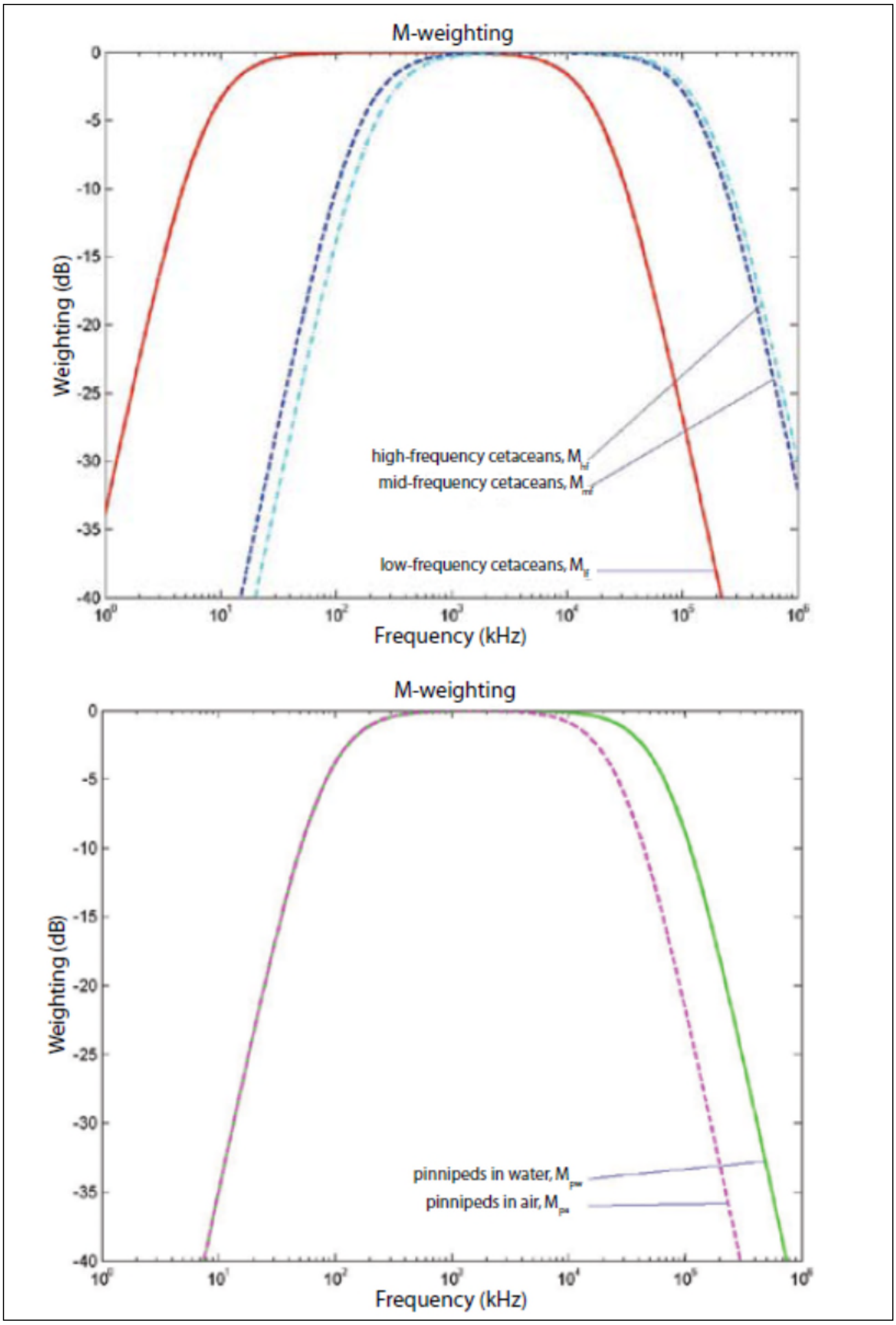
Functional Hearing Group	Estimated Auditory Bandwidth	Genera Represented (Number Species/Subspecies)	Frequency-Weighting Network
Low-frequency Cetaceans	7 Hz to 22 kHz	*Balaena, Caperea, Eschrichtius, Megaptera, Balaenoptera* (13 species/subspecies)	M_{lf}
Mid-frequency Cetaceans	150 Hz to 160 kHz	*Steno, Sousa, Sotalia, Tursiops, Stenella, Delphinus, Lagenodelphis, Lagenorhynchus, Lissodelphis, Grampus, Peponocephala, Feresa, Pseudorca, Orcinus, Globicephala, Orcacella, Physeter, Delphinapterus, Monodon, Ziphius, Berardius, Tasmacetus, Hyperoodon, Mesoplodon* (57 species/subspecies)	M_{mf}

Functional Hearing Group	Estimated Auditory Bandwidth	Genera Represented (Number Species/Subspecies)	Frequency-Weighting Network
High-frequency Cetaceans	200 Hz to 180 kHz	*Phocoena, Neophocaena, Phocoenoides, Platanista, Inia, Kogia, Lipotes, Pontoporia, Cephalorhynchus* (20 species/subspecies)	M_{hf}
Pinnipeds (in water)	75 Hz to 75 kHz	*Arctocephalus, Callorhinus, Zalophus, Eumetopias, Neophoca, Phocarctos, Otaria, Erignathus, Phoca, Pusa, Halichoerus, Histriophoca, Pagophilus, Cystophora, Monachus, Mirounga, Leptonychotes, Ommatophoca, Lobodon, Hydrurga, Odobenus* (41 species/subspecies)	M_{pw}
Pinnipeds (in air)	75 Hz to 30 kHz	*Arctocephalus, Callorhinus, Zalophus, Eumetopias, Neophoca, Phocarctos, Otaria, Erignathus, Phoca, Pusa, Halichoerus, Histriophoca, Pagophilus, Cystophora, Monachus, Mirounga, Leptonychotes, Ommatophoca, Lobodon, Hydrurga, Odobenus* (41 species/subspecies)	M_{pa}

Abbreviations: M_{lf} = low-frequency cetaceans; M_{mf} = mid-frequency cetaceans; M_{hf} = high-frequency cetaceans; M_{pw} = pinnipeds (in water); M_{pa} = pinnipeds (in air).

Using the estimated lower and upper frequency cut-off limits as 6-dB down points on an exponential roll-off for the frequency-weighting functions, Southall et al. (2007) developed frequency-weighting filters for each of the five functional hearing groups as shown in **Figure H-4**.

Figure H-4. Frequency-Weighting Functions for Cetaceans (Top) and Pinnipeds in Air and Water (Bottom) Proposed by Southall et al. (2007)



3.7 Thresholds and Exposure Criteria

3.7.1 Regulatory Thresholds

Within the U.S. Department of Commerce, the National Oceanic and Atmospheric Administration's (NOAA), National Marine Fisheries Service (NMFS) is responsible for the stewardship of the nation's living marine resources and their habitat, including the management, conservation, and protection of living marine resources within the U.S. Exclusive Economic Zone (EEZ) (i.e., waters from 3 to 200 nautical miles [nm] offshore).

Under the Marine Mammal Protection Act (MMPA) and the Federal Endangered Species Act (FESA), NMFS monitors the population status and recovery of protected marine species (i.e., whales, turtles), and oversees the permitting of incidental "take" of marine mammals. MMPA regulations make it illegal to "harass, hunt, capture or kill any marine mammal." The MMPA, as amended, defines "taking" to include harassment of marine mammals. Harassment is defined in the 1994 amendments to the MMPA as any act of pursuit, torment, or annoyance which has the potential to injure a marine mammal (Level A harassment) or disturb a marine mammal (Level B harassment) by causing disruption of behavioral patterns including migration, breathing, nursing, breeding, feeding, or sheltering.[3]

The history of the NMFS acoustic thresholds extends back to 1997. Based on interim guidelines put forth by the High Energy Seismic Survey (HESS) team, comprising staff from the CSLC, the U.S. Department of the Interior, Minerals Management Service (now the Bureau of Ocean Energy Management), and representatives of environmental groups (HESST 1999), NMFS established a 180 dB re 1 µPa rms threshold criterion for injury from sound exposure for cetaceans and a 190 dB re 1 µPa rms threshold criterion for pinnipeds. Additionally, Southall (2012) also notes that behavioral response criteria were developed as step-function (i.e., all-or-none) thresholds based solely on the rms value of received levels, and have been used by NMFS, although not entirely consistently. Thresholds for behavioral response from impulse sounds are 160 dB rms (received level) for all marine mammals, based on behavioral response data for marine mammals exposed to seismic airgun operations (Malme et al. 1983, 1984; Richardson et al. 1986). Thresholds for behavioral response from received "continuous" (non-impulsive) sounds have been set at 120 dB rms (for some but not all sound sources) based on the results of Malme et al. (1984) and Richardson et al. (1990).

Recognizing that the available data on hearing and noise impacts were rapidly evolving and that a more comprehensive and scientifically robust method of assessment would be required than these simplistic threshold estimates, NMFS supported an expert working group to develop more comprehensive and current criteria. This process ultimately resulted in the Southall et al. (2007) marine mammal noise exposure criteria.

[3] Note that the definition of "take" as used under the MMPA regulations differs from "take" as defined in section 86 of the California Fish and Game Code.

Noise exposure criteria currently utilized by NMFS's Office of Protected Resources (OPR) considers both continuous and intermittent sound sources based on SPL exposure, with differing thresholds for Level A (injury) and Level B (behavioral disruption) "harassment" thresholds depending upon the nature of the sound source (i.e., continuous versus intermittent [impulsive] noise sources).

As noted above, current acoustic exposure thresholds are based exclusively on the rms SPL metric, which is the square root of the average of the square pressure of the sound signal over a given duration; however, the duration over which the rms SPL is calculated can vary significantly for impulsive sounds (i.e., airguns). Pulse duration and other pulse characteristics (e.g., rise time) can have significant influence on the potential for injury (e.g. permanent and temporary threshold shifts [PTS, TTS]) (Madsen et al. 2006). Wood et al. (2012) notes that thresholds based on rms SPL values alone are not good predictive indicators of the likelihood of injury, and suggest using the SEL threshold, which measures the energy of sound, and depends on both amplitude, or loudness, and duration of exposure. The SEL is the time-integral of the instantaneous squared sound pressure normalized to a squared reference pressure over a 1-second period, using a unit of 1 μPa^2·s. The SEL metric is considered to be more biologically realistic in the sense that it incorporates the duration of the noise into the noise metric as well as the received level, unlike the rms SPL metric that only incorporates the received level.

3.7.2 Marine Mammal Noise Exposure Criteria

Two key determinations were made as part of the Southall et al. (2007) analysis – the establishment of marine mammal "functional hearing groups" and the categorization of sound sources into "functional categories," based on their acoustic and repetitive properties. The review and recommendations offered by Southall et al. (2007) indicated that the lowest received levels of impulsive sounds (e.g., airgun pulses) that might elicit slight auditory injury (PTS), using the SEL metric, are 198 dB re 1 μPa^2·s in cetaceans and 186 dB re 1 μPa^2·s in pinnipeds.

As noted by Southall (2012), the noise criteria group also concluded that receipt of an instantaneous flat-weighted peak pressure exceeding 230 dB re 1 μPa (peak) for cetaceans or 218 dB re 1 μPa (peak) for pinnipeds might also lead to auditory injury even if the aforementioned cumulative energy-based criterion was not exceeded. While NMFS currently considers SEL in its incidental take authorizations, it has yet to establish formal SEL criteria. Proposed energy (SEL) criteria include:

- Level A harassment (Injury):
  - 198 dB re 1 μPa^2·s for cetaceans,
  - 186 dB re 1 μPa^2·s for pinnipeds;

- Use of flat and M-weighting; and
- Consideration of the site-specific environmental context for noise exposure, including factors such as seafloor type, temperature, salinity, and water column stratification.

Based on the HESS (1999) panel conclusions, the NMFS established behavioral response criteria as a step-function (all-or-none) threshold based solely on the rms value of received levels. The threshold for behavioral response from impulse sounds was based on behavioral response data for marine mammals exposed to seismic airgun operations (Malme et al. 1983, 1984; Richardson et al. 1986). Southall et al. (2007) developed a severity scaling for behavioral responses but did not propose alternative criteria for multi-pulse sources, due to the fact that behavioral responses resulting from multiple pulse sound exposures are simply too variable and context-specific to justify proposing single disturbance criteria for broad categories of either taxa or sound sources.

Southall (2012) noted that most of the earlier research addressing acoustic impacts was directed at determining exposure levels which produce injury (e.g., hearing/tissue damage; mass strandings). In recent years, there has been an increase in interest on population level effects (e.g., what constitutes a biologically significant behavior) and the overall acoustic ecology of marine life (NRC 2005; Southall et al. 2007).

As outlined in **Table H-3**, Southall et al. (2007) proposed explicit and numerical exposure level values for injury from sound exposure for each of the marine mammal functional hearing groups. Using measured TTS-onset levels where possible, and extrapolating for related species when measurements were not available, Southall et al. (2007) were able to estimate TTS and PTS levels for sound exposure. For SEL values, the frequency-weighting functions would be applied to the received sound to account for differential frequency sensitivity among the different marine mammal groups. The resulting thresholds for injury from sound exposure for different marine mammal groups, via these general methods and using all available relevant data as proposed by Southall et al. (2007), are summarized in **Table H-4**. Exceptions include SEL values of 192 dB re 1 $\mu Pa^2 \cdot s$ for low-frequency cetaceans (Cell 1) and 179 dB re 1 $\mu Pa^2 \cdot s$ for high-frequency cetaceans (Cell 7), both exposed to a single pulse; these revisions were derived from more recent efforts summarized by Wood et al. (2012).

Table H-4. Marine Mammal Noise Exposure Criteria for Injury for Different Marine Mammal Functional Hearing Groups, for Either Single or Multiple Exposures during a 24-Hour Period (From: Southall et al. 2007; Wood et al. 2012)

Marine Mammal Group	Sound Type		
	Single Pulses	Multiple Pulses	Non-Pulses
Low-frequency Cetaceans	Cell 1	Cell 2	Cell 3
SPL	230 dB_{peak} re 1 µPa (flat)	230 dB_{peak} re 1 µPa (flat)	230 dB_{peak} re 1 µPa (flat)
SEL	192 dB re 1 $µPa^2$-s (M_{lf})	198 dB re 1 $µPa^2$-s (M_{lf})	215 dB re 1 $µPa^2$s (M_{lf})
Mid-frequency Cetaceans	Cell 4	Cell 5	Cell 6
SPL	230 dB_{peak} re 1 µPa (flat)	230 dB_{peak} re 1 µPa (flat)	230 dB_{peak} re 1 µPa (flat)
SEL	198 dB re 1 $µPa^2$-s (M_{mf})	198 dB re 1 $µPa^2$-s (M_{mf})	215 dB re 1 $µPa^2$-s (M_{mf})
High-frequency Cetaceans	Cell 7	Cell 8	Cell 9
SPL	230 dB_{peak} re 1 µPa (flat)	230 dB_{peak} re 1 µPa (flat)	230 dB_{peak} re 1 µPa (flat)
SEL	179 dB re 1 $µPa^2$-s (M_{hf})	198 dB re 1 $µPa^2$-s (M_{hf})	215 dB re 1 $µPa^2$-s (M_{hf})
Pinnipeds (in water)	Cell 10	Cell 11	Cell 12
SPL	218 dB_{peak} re 1 µPa (flat)	218 dB_{peak} re 1 µPa (flat)	218 dB_{peak} re 1 µPa (flat)
SEL	186 dB re 1 $µPa^2$-s (M_{pw})	186 dB re 1 $µPa^2$-s (M_{pw})	203 dB re 1 $µPa^2$-s (M_{pw})
Pinnipeds (in air)	Cell 13	Cell 14	Cell 15
SPL	149 dB_{peak} re 20 µPa (flat)	149 dB_{peak} re 20 µPa (flat)	149 dB_{peak} re 20 µPa (flat)
SEL	144 dB re 20 $µPa^2$-s (M_{pa})	144 dB re 20 $µPa^2$-s (M_{pa})	144.5 dB re 20 $µPa^2$-s (M_{pa})

Acronyms and Abbreviations: SEL = sound exposure level; SPL = sound pressure level.

Based on the recent review of Southall (2012), several notable conclusions pertinent to these criteria were identified: (1) the predicted received levels necessary to induce injury are relatively high; and (2) all of the cetaceans have numerically-identical threshold values, with the exception of the frequency-weighting functions. The first conclusion is a function of the relatively high TTS-onset values in the marine mammal species tested to date. The second conclusion is a reflection of available data when the Southall et al. (2007) findings were published; there were no direct data on auditory fatigue in low- or high-frequency cetaceans, and the mid-frequency cetacean TTS-onset levels were used for these other groups. Subsequently, Lucke et al. (2009) have shown significantly lower onset values for TTS in high-frequency cetaceans.

Southall (2012) also notes that newer TTS measurements for mid-frequency cetaceans (Finneran and Schlundt 2010; Finneran et al. 2010a,b) will require reanalysis of the appropriate TTS onset and, correspondingly, injury onset for this category. Per Southall (2012), despite recent findings regarding TTS among several odontocete species, the Southall et al. (2007) approach to marine mammal noise exposure continues to represent a major evolution in the complexity and scientific basis for predicting the effects of noise on hearing in marine mammals over the extremely simplistic historical NMFS thresholds for injury.

In terms of behavioral impacts, the Southall et al. (2007) noise exposure criteria took a dual approach depending on the sound type (Southall 2012). For exposure to single impulses, the acoustic component of the event was considered sufficiently intense to constitute behavioral harassment at levels consistent with TTS onset (**Table H-5**).

Table H-5. Marine Mammal Noise Exposure Criteria for Behavior for Different Marine Mammal Functional Hearing Groups (From: Southall et al. 2007)

Marine Mammal Group	Sound Type		
	Single Pulses	**Multiple Pulses**	**Non-Pulses**
Low-frequency Cetaceans	Cell 1	Cell 2	Cell 3
SPL	224 dB_{peak} re 1 µPa (flat)	Variable[a], ranging from 110-180 dB rms re 1 µPa (flat)	Variable[f], ranging from 90-160 dB rms re 1 µPa (flat)
SEL	183 dB re 1 μPa^2-s (M_{lf})	Not applicable	Not applicable
Mid-frequency Cetaceans	Cell 4	Cell 5	Cell 6
SPL	224 dB_{peak} re 1 µPa (flat)	Variable[b], ranging from 100-180 dB rms re 1 µPa (flat)	Variable[g], ranging from 80-200 dB rms re 1 µPa (flat)
SEL	183 dB re 1 μPa^2-s (M_{mf})	Not applicable	Not applicable
High-frequency Cetaceans	Cell 7	Cell 8	Cell 9
SPL	224 dB_{peak} re 1 µPa (flat)	Variable[c], ranging from 80-160 dB rms re 1 µPa (flat)	Variable[c], ranging from 80-160 dB rms re 1 µPa (flat)
SEL	183 dB re 1 μPa^2-s (M_{hf})	Not applicable	Not applicable
Pinnipeds (in water)	Cell 10	Cell 11	Cell 12
SPL	212 dB_{peak} re 1 µPa (flat)	Variable[d], ranging from 150-200 dB rms re 1 µPa (flat)	Variable[h], ranging from 80-140 dB rms re 1 µPa (flat)
SEL	171 dB re 1 μPa^2-s (M_{pw})	Not applicable	Not applicable
Pinnipeds (in air)	Cell 13	Cell 14	Cell 15
SPL	109 dB_{peak} re 20µPa (flat)	Variable[e], ranging from 60-80 dB rms re 1 µPa (flat)	Variable[i], ranging from 60-120 dB rms re 1 µPa (flat)
SEL	100 dB re 20 μPa^2-s (M_{pa})	Not applicable	Not applicable

Acronyms and Abbreviations: SEL = sound exposure level; SPL = sound pressure level.

Note: SPLs noted as Variable show ranges which are species-specific, reflecting exposures to different sound sources. Southall et al. (2007) also characterized severity scores for exposures.

[a] see Southall et al. 2007, Tables 6 and 7; [b] see Southall et al. 2007, Tables 8 and 9; [c] see Southall et al. 2007, Tables 18 and 19; [d] see Southall et al. 2007, Tables 10 and 11; [e] see Southall et al. 2007, Tables 12 and 13; [f] see Southall et al. 2007, Tables 14 and 15; [g] see Southall et al. 2007, Tables 16 and 17; [h] see Southall et al. 2007, Tables 20 and 21; [i] see Southall et al. 2007, Tables 22 and 23.

The rationale for this determination rested with the nature of the sound – single impulse events are brief and transient. Any responses other than those affecting hearing would likely also be similar in nature, and would not affect the long-term health or fitness of the exposed mammal. Southall et al. (2007), however, did note that startle responses could trigger stress and other physiological responses, the biological significance of which remains poorly understood.

For all other sound types, Southall et al. (2007) did not propose explicit threshold criteria given the influences of “context-dependence” and other complexities inherent in behavioral responses. In lieu of explicit threshold criteria, it was concluded that significant behavioral effects would (1) likely occur at exposure levels below those required for TTS and PTS; and (2) that the simple step-function thresholds for behavior were inconsistent with the best available science. Southall et al. (2007) concluded that the type and magnitude of behavioral responses to noise exposure involve a multitude of factors, and cannot be as readily determined as thresholds for injury.

To begin addressing some of these issues, Southall et al. (2007) derived a severity scaling approach (**Table H-6**) to attempt to determine the likely significance of observed responses. This effort, in part, was intended to highlight the importance of those responses with the potential to affect vital rates and survivorship (*sensu* NRC 2005). An ordinal ranking of behavioral response severity was developed as an initial step in separating relatively minor and/or brief behaviors from those more likely to affect vital rates and survivorship. The observed behavioral responses in all 10 conditions for multiple pulses and continuous noise for each of the five functional hearing groups were reviewed in detail, and individual responses were assessed according to this severity scaling and measured or reasonably estimated exposure levels (Southall 2012).

Table H-6. Severity Scale Developed by Southall et al. (2007) to Rank Observed Behavioral Responses of Free-Ranging Marine Mammals to Various Types of Anthropogenic Sound

Response Score	Corresponding Behavior(s) for Free-ranging Subjects
0	• No observable response
1	• Brief orientation response (investigation/visual orientation)
2	• Moderate or multiple orientation behaviors • Brief or minor cessation/modification of vocal behavior • Brief or minor change in respiration rates
3	• Prolonged orientation behavior • Individual alert behavior • Minor changes in locomotion speed, direction, and/or dive profile but no avoidance of sound source • Moderate change in respiration rate • Minor cessation or modification of vocal behavior (duration < duration of source operation), including the Lombard Effect
4	• Moderate changes in locomotion speed, direction, and/or dive profile but no avoidance of sound source • Brief, minor shift in group distribution • Moderate cessation or modification of vocal behavior (duration ≈ duration of source operation)
5	• Extensive or prolonged changes in locomotion speed, direction, and/or dive profile but not avoidance of sound source • Moderate shift in group distribution • Change in inter-animal distance and/or group size (aggregation or separation) • Prolonged cessation or modification of vocal behavior (duration > duration of source operation)
6	• Minor or moderate individual and/or group avoidance of sound source • Brief or minor separation of females and dependent offspring • Aggressive behavior related to noise exposure (e.g., tail/flipper slapping, fluke display, jaw clapping/gnashing teeth, abrupt directed movement, bubble clouds) • Extended cessation or modification of vocal behavior • Visible startle response

Response Score	Corresponding Behavior(s) for Free-ranging Subjects
	• Brief cessation of reproductive behavior
7	• Extended or prolonged aggressive behavior • Moderate separation of females and dependent offspring • Clear anti-predator response • Severe and/or sustained avoidance of sound source • Moderate cessation of reproductive behavior
8	• Obvious aversion and/or progressive sensitization • Prolonged or significant separation of females and dependent offspring with disruption of acoustic reunion mechanisms • Prolonged cessation of reproductive behavior
9	• Outright panic, flight, stampede, attack of conspecifics, or stranding events • Avoidance behavior related to predator detection

As noted by Southall (2012), the primary advances made in the Southall et al. (2007) criteria in terms of behavioral response were to very clearly demonstrate that step-function thresholds for response using a single received level and no other considerations related to behavioral context are overly simplistic and outdated, and to develop at least a qualitative means of addressing behavioral response severity issues. The Southall et al. (2007) criteria for behavior represent a starting point in the development of a working framework to evaluate and characterize the type and magnitude of biologically-significant behavioral responses of marine mammals to noise.

Broad application of the Southall et al. (2007) criteria for both injury and behavior has been relatively slow in evolving, per Southall (2012) due, in part, to the increased complexity of the recommendations over the previous simplistic approaches (e.g., step-functions used by NMFS). However, NMFS has used exposure criteria consistent with the Southall et al. (2007) thresholds for injury from sound exposure for assessing potential impacts of Navy active sonar operations (*Federal Register* 2009a,b) for a variety of species, including large whales and pinnipeds. These regulations actually include higher exposure values for certain species for which higher TTS-onset values were directly measured than the more conservative values used in Southall et al. (2007). Additionally, NMFS regulations (*Federal Register* 2009a,b) have also begun to use a more graduated dose-function based approach to behavioral response rather than the historical step-function thresholds.

NMFS is preparing acoustic exposure guidelines that are expected to increasingly consider the increased complexity and context-dependence of responses of marine mammals to sound (Southall 2012).

3.8 Effects of Noise Exposure from Low Energy Geophysical Survey Equipment

Most studies addressing the effects of anthropogenic sound on marine mammals have focused on the effects of sound from airguns and similar high energy, low-frequency sources. Few studies have been directed specifically at the effects of low energy geophysical survey equipment.

However, the potential impacts of such sources have received increasing attention over the past several years, particularly in regards to research-based survey activity. For example, the National Science Foundation (NSF) issued an Environmental Impact Statement/Overseas Environmental Impact Statement (EIS/OEIS) which evaluated the effects of research-based seismic and oceanographic sonar emissions on marine mammals (NSF 2010); equipment evaluated included an airgun array, as well as oceanographic survey equipment previously thought be relatively benign (e.g., subbottom profiler, multibeam echosounder, pingers, and acoustic current profiler). Environmental analyses of similar equipment types have also considered the impacts to other marine fauna, including sea turtles, fishes, and invertebrates (e.g., NSF 2011). Summary study findings pertinent to low energy geophysical equipment noise exposure to marine mammals are provided in **Table H-7**.

Table H-7. Summary of Study Results for Marine Mammals Exposed to Low Energy Geophysical Equipment Emissions (Adapted from: NSF 2010)

Species/Group	Major Findings	Source
Mysticetes - Baleen Whales		
Humpback whale	Movement away from the source upon exposure to 3.3 kilohertz (kHz) sonar pulses; increased swimming speeds and track linearity in response to 3.1- to 3.6-kHz sonar sweeps	Maybaum 1990, 1993
Humpback whale	Documented changes in vocalization (songs) and swimming patterns upon exposure to low-frequency active (LFA) sonar transmissions	Miller et al. 2000; Clark et al. 2001
Gray whale	Migrating gray whales reacted to a 21 to 25 kHz whale-finding sonar (source level: 215 dB re 1 µPa at 1 meter [m]) by orienting slightly away from the source and being deflected from their course by approximately 200 m; responses were not obvious in the field and were only determined later during data analysis	Frankel 2005
Mysticetes, general	Reactions of marine mammals to a 38-kHz echosounder and a 150-kHz acoustic current profiler (ACP) were documented; results indicated that mysticetes showed no significant responses when the echosounder and ACP were transmitting	Gerrodette and Pettis 2005
Mysticetes, general	Whaling catcher boats reported that baleen whales showed strong avoidance of echosounders that were sometimes used to track baleen whales underwater	Richardson et al. 1995
Mysticetes, general	Ultrasonic pulses emitted by whale scarers during whaling operations tended to scare baleen whales to the surface	Richardson et al. 1995
Right, humpback, and fin whales	No reactions were noted following exposure to pingers and sonars at and above 36 kHz, although these species often reacted to sounds at frequencies of 15 Hertz (Hz) to 28 kHz	Watkins 1986

Species/Group	Major Findings	Source
Odontocetes - Toothed Whales		
Dolphins, beaked whales	When the echosounder and ACP were on, spotted and spinner dolphins were detected slightly more often and beaked whales less often during visual surveys	Gerrodette and Pettis 2005
Sperm whale	Some sperm whales stopped emitting pulses in response to 6 to 13 kHz pingers	Watkins and Schevill 1975
Sperm whale	Sperm whales usually continued calling and did not appear to otherwise react to continual pulsing from echosounders emitting at 12 kHz	Backus and Schevill 1966; Watkins 1977
Bottlenose dolphin	Behavior of captive, open-sea enclosed dolphins appeared to change in response to sounds from a close and/or approaching marine geophysical survey vessel operating a 1-kHz sparker, 375-kHz side-scan sonar, 95-kHz multibeam echosounder, and two 20-50 kHz singlebeam echosounders	van der Woude 2007
Killer whale	Occurrence was significantly lower during a 7-year period when acoustic harassment devices (10 kHz at 194 dB re 1 μPa m) were installed in the area; whales returned to baseline numbers when these sound sources were removed	Morton and Symonds 2002
Harbor porpoise	Acoustic alarms operating at 10 kHz with a source level of 132 dB re 1 μPa m were an effective deterrent	Kraus et al. 1997
Harbor porpoise	Subjected one harbor porpoise in a large floating pen to a continuous 50 kHz pure tone with a source level of 122 ± 3 dB re 1 μPa m rms; the porpoise moved away from the sound at an estimated avoidance threshold of 108 ± 3 dB re 1 μPa root mean square (rms) and did not habituate to it despite 66 exposures	Kastelein et al. 2008
Pinnipeds – Seals and Sea Lions		
Gray seal	Two gray seals, exposed to operation of a 375 kHz multibeam imaging sonar that included significant signal components down to 6 kHz, reacted by significantly increasing dive duration; no significant differences were found in swimming direction relative to the operating sonar	Hastie and Janik 2007

Ireland et al. (2005) noted numerous observations and acoustic detection of mysticetes, odontocetes, and pinnipeds during research surveys which utilized low energy geophysical equipment. Results suggest that marine mammals often appear to tolerate the presence of these sources when operating within several kilometers (km), and sometimes within a few hundred meters (m), of the source. Given the directional nature of the sounds from these sonars, only a fraction of the marine mammals seen by observers were likely to have been within the beams before or during the time of the sightings. Many of these mammals probably were not exposed to the sonar sounds despite the proximity of the ship (NSF 2010).

Little is known about reactions of odontocetes to underwater noise pulses, including sonar. Available data on responses to sonar are limited to a small number of species and conditions, including studies of captive animals. Most available data on odontocete responses to sonar are associated with beaked whales and high-intensity, mid-frequency military sonars, and are not applicable to the low energy geophysical equipment sources being utilized under permit in California state waters.

The U.S. Navy (2012), in a recent analysis of cetacean behavioral responses to mid-frequency sonar, noted that blue whales exposed to mid-frequency sonar in the Southern California Bight were less likely to produce low-frequency calls usually associated with feeding behavior (Melcón et al. 2012). It is not known whether the lower rates of calling actually indicated a reduction in feeding behavior or social contact since the study used data from remotely deployed, passive acoustic monitoring buoys. In contrast, blue whales increased their likelihood of calling when ship noise was present, and decreased their likelihood of calling in the presence of explosive noise, although this result was not statistically significant (Melcón et al. 2012). Additionally, the likelihood of an animal calling decreased with the increased received level of mid-frequency sonar, beginning at a sound pressure level of approximately 110 to 120 dB re 1 µPa (Melcón et al. 2012).

Preliminary results from the 2010–2011 field season of the ongoing behavioral response study in southern California waters indicated that in some cases and at low received levels, tagged blue whales responded to mid-frequency sonar but that those responses were mild and there was a quick return to their baseline activity (Southall et al. 2011). These preliminary findings from Melcón et al. (2012) and Southall et al. (2011) are consistent with the Navy's criteria and thresholds for predicting behavioral effects to mysticetes (including blue whales) from sonar and other active acoustic sources used in the quantitative acoustic effects analysis. The behavioral risk function predicts a probability of a substantive behavioral reaction for individuals exposed to a received sound pressure level of 120 dB re 1µPa or greater, with an increasing probability of reaction with increased received level as demonstrated in Melcón et al. (2012).

In addition to the lower energy levels emitted by permitted geophysical equipment, survey equipment is also highly directional in nature (i.e., directed downward, with narrow beam widths) when compared to either high energy seismic equipment or tactical sonar. Exposure risk to the highest sound source levels, therefore, occurs in close proximity to the equipment, and within the focused beam beneath the source.

Per NSF (2010), the behavioral reactions of free-ranging odontocetes to echosounders, pingers, and other acoustic equipment appear to vary by species and circumstance. Various dolphin and porpoise species have been seen bowriding while this equipment was operational during NSF-sponsored seismic surveys (e.g., see Smultea and Holst 2004; Smultea et al. 2008).

Very few data are available on the reactions of pinnipeds to sonar sounds at frequencies similar to those used during marine seismic operations. In addition, no studies were identified regarding exposure of mustelids (sea otters) to low energy geophysical equipment emissions.

NSF (2010) also addressed the potential for TTS and PTS to occur in marine mammals exposed to noise from geophysical survey operations. Important findings include:

- There has been no specific documentation of TTS in free-ranging marine mammals exposed to sonar pulses of the types used during marine seismic surveys.
- For mysticetes, there are no data, direct or indirect, on levels or properties of sound that are required to induce TTS from active sonar of any type. In general, auditory thresholds of mysticetes within their frequency band of best hearing are believed to be higher (less sensitive) than are those of odontocetes at their best frequencies (Clark and Ellison 2004). If so, their TTS thresholds may also be higher (Southall et al. 2007).
- The TTS threshold for the beluga whale and bottlenose dolphin has been measured in captivity to be approximately 195 dB re 1 $\mu Pa^2 \cdot s$ for exposure to a single non-impulsive tonal sound (Schlundt et al. 2000; Finneran et al. 2005; reviewed in Southall et al. 2007).
- Kremser et al. (2005), among others, have noted that the probability of a cetacean swimming through the area of exposure when a multibeam echosounder emits a pulse is small. The animal would have to pass the transducer at close range and be swimming at a speed and direction similar to the vessel in order to be subjected to repeated pulses and cumulative sound energy levels that could cause TTS.
- TTS thresholds for sounds of the types produced by multibeam echosounders, subbottom profilers, ACPs, and pingers have not been measured in pinnipeds, however, studies of TTS onset upon exposure to prolonged non-impulse sounds have been done in the harbor seal, California sea lion, and northern elephant seal (Kastak et al. 2005, 2008; Southall et al. 2007). Study results suggest that some pinnipeds (e.g., harbor seal) may incur TTS at somewhat lower received energy levels than do small odontocetes exposed for similar durations (Kastak et al. 1999, 2005; Ketten et al. 2001; Southall et al. 2007). In harbor seals, the TTS threshold for non-impulse sounds is approximately 183 dB re 1 $\mu Pa^2 \cdot s$, as compared with approximately 195 dB re 1 $\mu Pa^2 \cdot s$ in odontocetes (Kastak et al. 2005; Southall et al. 2007). TTS onset occurs at higher received energy levels in the California sea lion and northern elephant seal than in the harbor seal.

3.9 Assessment of Hearing Information for Marine Mammal Species in California State Waters

More than 40 marine mammal species have been documented in California waters (**Table H-8**). Most of the marine mammals likely to be present in California state waters are cetaceans, with several pinnipeds and a single mustelid also present.

Table H-8. Marine Mammals of California, including Minimum Population Estimates, Habitat, Hearing Group Classification, and Protected and Stock Status

Taxonomic Classification and Common Name	Scientific Name	Minimum Population Estimate and Presence/Stock	Habitat	Hearing Group	Protected Status	Stock Status
Mysticetes – Baleen Whales						
Order: Cetacea						
Family: Eschrichtiidae (gray whales)						
Gray whale	*Eschrichtius robustus*	Migrant; 18,017 (ENP stock)[a]	CN	M_{lf}	P	NS/ND
Family: Balaenopteridae (rorquals)						
Bryde's whale	*Balaenoptera edeni*	Vagrant; no estimate	O	M_{lf}	P	NS/ND
Minke whale	*Balaenoptera acutorostrata scammoni*	478 (CA/OR/WA stock)	CN, O	M_{lf}	P	NS/ND
Sei whale	*Balaenoptera borealis borealis*	126 (ENP stock)	O	M_{lf}	E	S, D
Blue whale	*Balaenoptera musculus musculus*	2,497 (ENP stock)	CN, O	M_{lf}	E	S, D
Fin whale	*Balaenoptera physalus physalus*	3,044 (CA/OR/WA stock)	CN, O	M_{lf}	E	S, D
Humpback whale	*Megaptera novaeangliae*	2,043 (CA/OR/WA stock)	CN, O	M_{lf}	E	S, D
Family: Balaenidae (right whales)						
North Pacific right whale	*Eubalaena japonica*	Vagrant; 31 (ENP stock)	CN, O	M_{lf}	E	S, D
Odontocetes – Toothed Whales						
Family: Delphinidae (dolphins)						
Short-beaked common dolphin	*Delphinus delphis*	411,211 (CA/OR/WA stock)	CN, O	M_{mf}	P	NS/ND
Long-beaked common dolphin	*Delphinus capensis capensis*	27,046 (CA stock)	CN	M_{mf}	P	NS/ND
Short-finned pilot whale	*Globicephala macrorhynchus*	760 (CA/OR/WA stock)	O	M_{mf}	P	NS/ND
Risso's dolphin	*Grampus griseus*	6,272 (CA/OR/WA stock)	CN, O	M_{mf}	P	NS/ND
Pacific white-sided dolphin	*Lagenorhynchus obliquidens*	26,930 (CA/OR/WA stock)	CN, O	M_{mf}	P	NS/ND
Northern right whale dolphin	*Lissodelphis borealis*	8,334 (CA/OR/WA stock)	CN, O	M_{mf}	P	NS/ND
Killer whale	*Orcinus orca*	86 (ENP southern resident) 240 (ENP offshore stock) 346 (ENP transient stock)	CN, O	M_{mf}	P	NS/ND
False killer whale	*Pseudorca crassidens*	Vagrant	CN, O	M_{mf}	P	NS/ND
Striped dolphin	*Stenella coeruleoalba*	10,908 (CA/OR/WA)	O	M_{mf}	P	NS/ND
Bottlenose dolphin	*Tursiops truncatus truncatus*	1,006 (CA/OR/WA offshore) 450 (Coastal CA population)	CN, O	M_{mf}	P	NS/ND
Family: Phocoenidae (porpoises)						
Dall's porpoise	*Phocoenoides dalli dalli*	42,000 (CA/OR/WA stock)	CN, O	M_{hf}	P	NS/ND
Harbor porpoise	*Phocoena phocoena vomerina*	40,000+ (NCA-SO)[b] 1,079 (Monterey Bay stock) 1,478 (Morro Bay stock)	CN, O	M_{hf}	P	NS/ND
Family: Physeteridae (sperm whales)						
Pygmy sperm whale	*Kogia breviceps*	579 (CA/OR/WA stock)	O	M_{hf}	P	NS/ND

Taxonomic Classification and Common Name	Scientific Name	Minimum Population Estimate and Presence/Stock	Habitat	Hearing Group	Protected Status	Stock Status
Dwarf sperm whale	*Kogia sima*	Unknown; Rare	O	M_{hf}	P	NS/ND
Sperm whale	*Physeter macrocephalus*	971 (CA/OR/WA stock)	O	M_{mf}	E	S, D
Family: Ziphiidae (beaked whales)						
Baird's beaked whale	*Berardius bairdii*	615 (CA/OR/WA stock)	O	M_{mf}	P	NS/ND
Hubbs' beaked whale	*Mesoplodon carlhubbsi*	907-2,143[c]	O	M_{mf}	P	NS/ND
Blainville's beaked whale	*Mesoplodon densirostris*	907-2,143[c]	O	M_{mf}	P	NS/ND
Ginkgo-toothed beaked whale	*Mesoplodon ginkgodens*	907-2,143[c]	O	M_{mf}	P	NS/ND
Perrin's beaked whale	*Mesoplodon perrini*	907-2,143[c]	O	M_{mf}	P	NS/ND
Pygmy beaked whale	*Mesoplodon peruvianus*	Single record; 907-2,143[c]	O	M_{mf}	P	NS/ND
Stejneger's beaked whale	*Mesoplodon stejnegeri*	907-2,143[c]	O	M_{mf}	P	NS/ND
Cuvier's beaked whale	*Ziphius cavirostris*	1,298 (CA/OR/WA stock)	O	M_{mf}	P	NS/ND
Pinnipeds – Seals and Sea Lions						
Order: Carnivora						
Family: Otariidae (eared seals)						
Guadalupe fur seal	*Arctocephalus townsendi*	7,408 total; several (N Channel Is.)	CN	M_{pw}	P, T, ST, FP	S, D
Northern fur seal	*Callorhinus ursinus*	9,968 (San Miguel Is. stock)	CN	M_{pw}	P	NS/ND
Northern (Steller) sea lion	*Eumetopias jubatus*	52,847 (Eastern U.S. stock) 2,497 (CA; site counts only)	CN, O	M_{pw}	P, T	S, D
California sea lion	*Zalophus californianus*	153,337 (U.S. stock)	CN	M_{pw}	P	NS/ND
Family: Phocidae (earless seals)						
Northern elephant seal	*Mirounga angustirostris*	124,000 (CA breeding stock)	CN, O	M_{pw}	P	NS/ND
Harbor seal	*Phoca vitulina richardsi*	30,196 (CA stock)	CN	M_{pw}	P	NS/ND
Mustelid – Sea Otter						
Order: Carnivora						
Family: Mustelidae (weasels)						
Southern sea otter	*Enhydra lutris nereis*	2,792	CN	Broad	P, T, FP	S, D

[a] Eastern North Pacific stock; [b] Northern California-southern Oregon stock; [c] For management purposes, several beaked whales inhabiting U.S. waters have been placed in the Alaska Stock and California/Oregon/Washington Stock by NOAA, NMFS, Office of Protected Resources (OPR). The estimated population for Blainville's, Perrin's, Pygmy, Gingko-toothed, Hubb's, and Stejneger's beaked whales in the California/Oregon/Washington stock is 907 to 2,143 animals.

Habitat: CN = coastal and/or nearshore; O = offshore and/or deep water. Status: P = protected (Marine Mammal Protection Act [MMPA]); FP = State fully protected; E = endangered (Federal Endangered Species Act [FESA]); T = threatened (FESA); ST = threatened (California Endangered Species Act [CESA]); NS/ND = not strategic stock/not depleted (MMPA); S = strategic stock (MMPA); D = depleted (MMPA).

Hearing Groups per Southall et al. (2007) for all marine mammals except the southern sea otter: M_{lf} = low-frequency cetacean (7 Hz to 22 kHz); M_{mf} = mid-frequency cetacean (150 Hz to 160 kHz); M_{hf} = high-frequency cetacean (200 Hz to 180 kHz); M_{pw} = pinnipeds in water; (75 Hz to 75 kHz); Broad = sea otter (0.125 to 32 kHz, per Ghoul and Reichmuth [2011]).

For some of these species (e.g., bottlenose dolphins), relatively good information exists about hearing and behavioral responses to some types of sounds (e.g., Nowacek et al. 2001). For most of the mid-frequency cetacean species, including the endangered sperm whale, the injury criteria proposed by Southall et al. (2007) and general conclusions on behavioral response are considered to be applicable; direct recent information on behavioral responses in sperm whales to other forms of anthropogenic noise are available as well (e.g., Miller et al. 2009).

For the endangered mysticetes that occur in offshore California waters (e.g., blue, fin, humpback, and sei whales), as for all low-frequency cetaceans, no direct information regarding hearing is available. Current exposure criteria for injury are based on assumptions and extrapolations from mid-frequency cetacean data that may need to be reassessed to some degree based on the subsequent measurements of lower TTS-onset levels in bottlenose dolphins within their range of best hearing sensitivity (Finneran and Schlundt 2010).

In terms of behavioral response, substantial effort has been made and data are available for anthropogenic impulsive noise sources (e.g., seismic airguns, sonars) for mysticetes, though not for all of the species present offshore California. Recently, Southall et al. (2011) demonstrated behavioral responses, and an apparent context-dependence in response based on behavioral state, in some blue and fin whales exposed to simulated sonar sounds off the coast of California.

3.10 Marine Mammal Sound Research

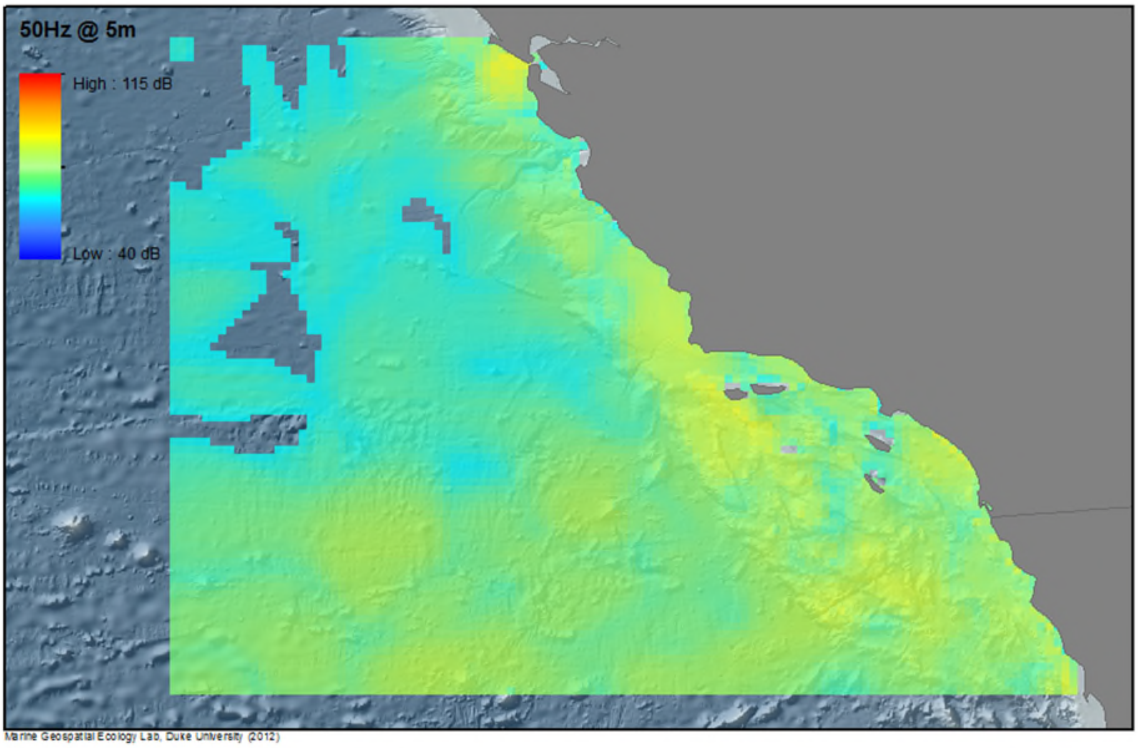
In January 2010, NOAA committed to improving the tools used by the agency to evaluate the impacts of human-induced noise on cetaceans. As a result, two data and product-driven working groups were convened in January 2011: the Underwater Sound-field Mapping Working Group (SoundMap) and the Cetacean Density and Distribution Mapping Working Group (CetMap). In May 2012, the working groups presented their products at a symposium where potential management applications were discussed with a large multi-stakeholder audience. The final report for the symposium can be found at: http://cetsound.noaa.gov/pdf/CetSound_Symposium_Report_Final.pdf. The following summaries of working group scope and progress outline the tools which are now available.

3.10.1 Sound Field Data Availability

The specific objective of the NOAA SoundMap is to create mapping methods to depict the temporal, spatial, and spectral characteristics of underwater noise. Of specific interest to the working group is the development of tools to map the contribution of human sound sources to underwater ocean noise in U.S. waters. These tools use environmental descriptors and the distribution, density, and acoustic characteristics of human activities within U.S. waters to develop first-order estimates of their contribution to ambient noise levels at multiple frequencies, depths, and spatial/temporal scales.

SoundMap has focused its efforts on developing feasible methods that could be implemented within a one-year analytical effort. A variety of informed approximations were necessarily applied to enhance computational feasibility and to bridge data gaps. All extrapolations and assumptions made in producing these products have been explicitly documented in methodology summaries. These summaries are intended to assist users in understanding the current status of the available sound field data, the methodologies applied, and the requirements for producing different or higher resolution products in the future. For this first release, SoundMap is providing preliminary mapping products as images with the goal of making the underlying data available in subsequent releases. An example is provided in **Figure H-5**.

Figure H-5. Noise Levels off the Southwest U.S. Coast from Passenger Vessels (From: NOAA 2012)



NOAA (2012) outlines the following data characteristics for SoundMap modeling:

- Spectral resolution: The emphasis of SoundMap modeling on broad-scale and long-term (seasonal to annual) noise exposure resulted in a focus on low-frequencies, ranging from 50 to 1,000 Hz (with several specific exceptions), since higher frequencies are subject to strong absorption effects and are more local in effect. Broader band levels (1/3rd–octave) were estimated based on modeled frequencies to assist interpretation relative to mammalian hearing systems.

- Spatial resolution: SoundMap modeling focused on coastal waters at least 5 m in depth out to the 200 nm U.S. EEZ boundary at a 0.1° x 0.1° (approximately 100 square kilometers [km^2] at the equator) grid size. Additionally, due to the emphasis on low-frequencies and the lack of a hard boundary for noise at 200 nm, some sources of chronic noise at greater ranges were modeled for larger portions of ocean basins at 1° x 1° (approximately 10,000 km^2 at the equator). To capture differences in sound propagation and how this can influence interactions with marine wildlife that spend time at different depths, modeling was conducted at discrete depths between 5 m and (up to) 1,000 m.
- Temporal resolution: The central SoundMap products are predicted noise level maps for U.S. EEZ waters of the continental U.S., Hawaii, and Alaska. These maps depict predictions of wide-ranging contributions from “chronic” anthropogenic sources of underwater noise, including vessels (e.g., merchant shipping; ocean-going passenger vessels; mid-sized service, fishing and passenger vessels) in regions where data were available, and sustained areas of offshore energy exploration (i.e., seismic surveys). Predicted received levels are expressed as equivalent, unweighted SPLs (Leq), which are averages of aggregated sound levels. Averaging time varies according to the appropriate timescales for the activities of interest, with a focus on annual averages from year-round activities (e.g., merchant shipping in most regions), and shorter scales for activities or events which are seasonal (e.g., in sometimes ice-covered areas).

Additionally, mapping efforts were conducted for four localized and transient events that are more episodic or seasonal; these were selected to reflect major acute sources of human-induced noise in areas of biological importance to marine mammals, including: (1) a military active sonar training exercise in Hawaii; (2) a period of seismic exploration in the Beaufort Sea; (3) the installation of an alternative energy platform off New England; and (4) the decommissioning of an oil platform in the Gulf of Mexico.

Key discussions of the working group focused on each of the transient event scenarios, in particular methods for summing energy from chronic and intermittent sources during the events, and presenting cumulative energy averages over days to months when some sources were intermittent during those time periods. The group wanted to avoid averaging over “dead periods” between noisy events (especially very long events) and not retaining duration information, given the ultimate goal of integrating this meaningfully with biologics.

As a result, events were divided into an appropriate number of acoustic “states” characterized by combinations of sources that are coincident over discrete time periods (e.g., staging prior to driving a pile, then driving a pile, then a break, then driving a pile, etc.). Duration information associated with these “states” can be retained and exemplary output maps can be created for each.

3.10.2 Cetacean Density and Distribution Mapping Working Group

The specific objective of the CetMap is to create comprehensive and easily accessible regional cetacean density and distribution maps that are time- and species-specific, ideally using survey data and models that estimate density using predictive environmental factors. In order to depict the best comprehensive cetacean density and distribution maps, the CetMap attained the following goals:

- Identified a hierarchy of preferred density and distribution model or information types;
- Conducted a cetacean data availability assessment that included making previously less accessible data available through this effort;
- Modeled or re-modeled density using first-tier habitat-based density models in some critical areas, based upon updated methods and/or new data;
- Created standardized geographic information system (GIS) files from the new modeling results and other existing modeling results; and
- Developed a NOAA website interface that organizes these datasets and maps to highlight the best available information type, making them searchable by region, species, and month, and making many of the GIS files available for download.

The Tier 1 species-specific CetMap products presented (i.e., the habitat-based density models) are predominantly at a spatial resolution of 10 km^2, with a few at 25 km^2, based on the manner in which the data were initially collected or modeled. Products are organized by month, but depicted in a manner that reflects when model results are predicting only seasonal resolution. The CetMap products can be viewed and downloaded, with accompanying metadata, at the NOAA Cetacean Sound/CetMap website (cetsound.noaa.gov).

Separately, to augment the more quantitative density and distribution mapping described above and to provide additional context for marine mammal impact analyses, the CetMap also identified (through literature search, current science compilation, and expert consultation) known areas of importance for cetaceans. Important areas included areas used for reproduction, feeding, and migration, as well as areas in which small or resident populations are concentrated.

CetMap efforts, as noted by NOAA (2012), include development of an information hierarchy, completion of a cetacean data availability assessment, and completion of initial density modeling. Each of these milestones are outlined below.

For the information hierarchy task, CetMap identified and broadly evaluated the information-types and modeling methods available for estimating marine mammal density and distribution and ranked them in “tiers” based on their expected ability to accurately predict presence, distribution, or density in a spatially and temporally explicit manner. Tiers include:

- Habitat-based density models, which allow fine-scale predictions of density (individuals per 10 or 25 km^2) throughout a survey region using regression-based models that relate habitat variables to species encounter rates and group sizes;
- Stratified density models, which assume uniform animal density within each stratum (area), for which boundaries are determined based on survey coverage, the number of sightings, and prior knowledge of cetacean distribution and habitats;
- Probability of occurrence models, which indicate areas where a species is likely to occur based on statistical models that relate habitat variables to the presence/absence of a species, but do not provide absolute density estimates;
- Records of presence, which include visual observations, acoustic detections, or satellite tagging indicators; and
- Expert knowledge, which reflects a lack of spatio-temporally explicit data for a species, but indicates if a species is believed to be present or likely absent by regional experts.

A more detailed description of the information tiers, as well as the factors considered in evaluating them and deciding which data should be included in any given model, are available at the Cetacean Sound webpage.

The cetacean data availability assessment has fulfilled the following objectives:

- Identified and compiled existing cetacean density models, some of which were not previously available to the public;
- Identified and compiled existing indicators of cetacean presence, including visual observations, acoustic detections, and satellite tagging data, some of which were not previously available to the public, and several of which expand the known range of certain species; and
- Organized the available modeling results and data in a manner that allows the user to quickly identify what type of data is available for a species/region/month and where data gaps exist.

The Cetacean Data Availability page shows the available information for each species/region/month, and also serves as the link to the downloadable products.

For the density modeling task, CetMap identified and undertook two key modeling efforts to meaningfully improve the understanding of cetacean density and distribution in the U.S. EEZ in several key U.S. areas, including the Beaufort and Chukchi Seas, Atlantic coast, Gulf of Mexico, and U.S. west coast. Of relevance to California, CetMap is presently working with NOAA's Southwest Regional Office to showcase an effort that uses shore-based visual sighting data for grey whales along the U.S. west coast, combined with their swim speed, to model the estimated location and density of the majority of migrating gray whales on any date within the migration period. A summary of this west coast gray whale model and the associated products can be viewed on the CetMap webpage.

For the mapping and product accessibility task, select CetMap members affiliated with Duke University's Marine Geospatial Ecology Lab have created standardized GIS files for the new modeling results produced by the CetMap, as well as for several existing model results compiled for this effort, but for which GIS maps had not previously been generated.

4.0 TURTLES

4.1 Life History

Sea turtles use a broad range of marine habitats depending upon their developmental stage. They spend most of their lives at sea, with only limited excursions on land during those periods where they return to natal beaches for egg deposition, and following hatching. Once hatchlings reach the sea, they are pelagic, moving primarily with ocean currents. After a period of years, which varies both among species and within populations, a critical ontogenetic habitat shift occurs whereby most sea turtles actively recruit to a demersal, neritic habitat and are considered juveniles. Finally, upon reaching maturity, all sea turtles maintain a discrete foraging area which frequently overlaps with the area occupied by juveniles (Bolton 2003).

4.2 Overview of Sea Turtle Hearing

Few studies have examined the role acoustic cues play in the ecology of sea turtles (Mrosovsky 1972; Samuel et al. 2005; Nunny et al. 2008). It has been suggested that sea turtles use sound to navigate, locate prey, avoid predators, and sense their environment (Piniak et al. 2011). There is evidence that sea turtles may use sound to communicate; the few vocalizations described for sea turtles are restricted to the "grunts" of nesting females. These sounds are low-frequency and relatively loud, thus leading to speculation that nesting females use sounds to communicate with conspecifics (Mrosovsky 1972).

While little is known regarding the extent to which sea turtles use acoustic cues to sense and monitor their environment, it is recognized that a turtle's ambient and passive acoustic environment changes with each ontogenetic habitat shift. In the inshore environment where juvenile and adult sea turtles generally reside, the ambient environment is noisier than the open ocean environment of the hatchlings; this inshore environment is dominated by low-frequency sound (Hawkins and Myrberg 1983). In areas with high levels of vessel traffic, low-frequency noise from shipping, recreational boating, and seismic surveys compound the potential for acoustic impact (Hildebrand 2005).

4.3 Morphology

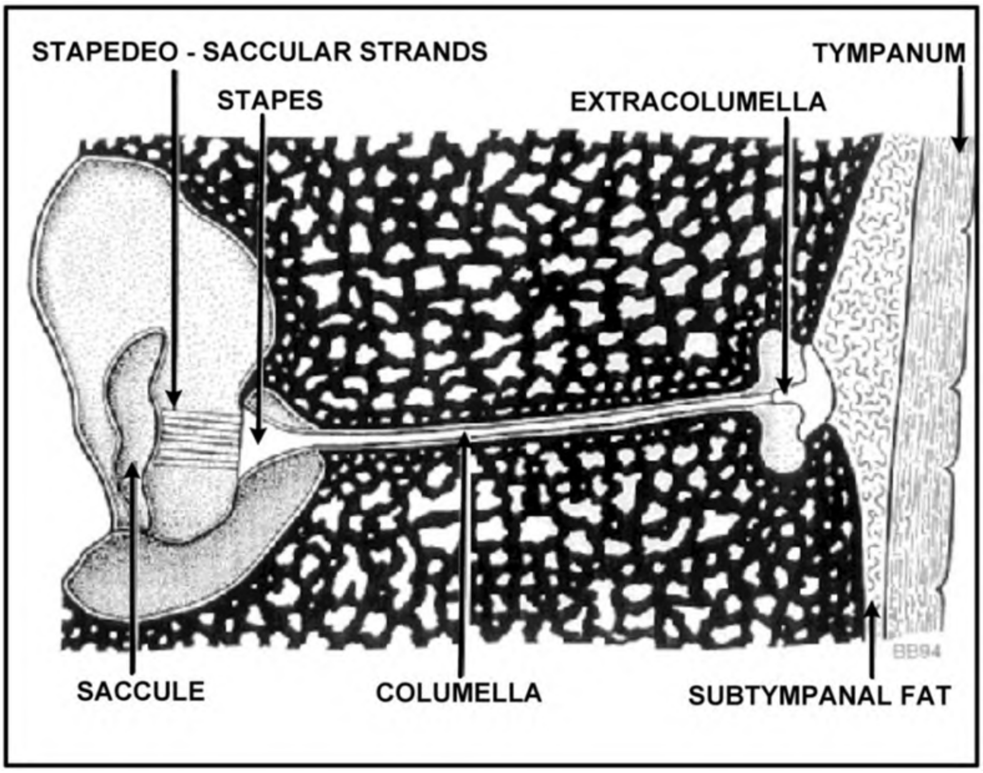
A majority of the research conducted on sea turtle hearing has been restricted to gross morphological dissections (e.g., Wever 1978; Lenhardt et al. 1985). Moein (1994) notes several important components of the turtle ear, identified in **Figure H-6**:

- Tympanum – a continuation of the facial tissue; distinguishable only by palpitation of the area.
- Subtympanal fat – lying beneath the tympanum, this thick fat layer distinguishes sea turtles from both terrestrial and semi-aquatic turtles. Ketten et al. (1999)

suggests that this layer of fat is similar to the fats found in the jaws of odontocete whales, and functions as a low-impedance channel for sounds to the ear.

- Middle ear cavity – lying posterior to the tympanum, it is connected to the throat by the eustachian (Wever 1978; Lenhardt et al. 1985). The middle ear is small and encased by bone.
- Extracolumella and Columella – these two structures comprise the ossicular mechanism. The extracolumella is a cartilaginous disk under the tympanic membrane attached to the columella by ligaments. The columella, or stapes, consists of a long rod with the majority of its mass concentrated at each end. The columella extends medially from the middle ear cavity through a narrow bony channel and expands within the oval window to form a funnel shaped end.

Figure H-6. Middle Ear Anatomy of the Juvenile Loggerhead Sea Turtle (From: Moein 1994)



The columella is free to move only longitudinally within this channel so when the tympanum is depressed directly above the middle of the extracolumella, the columella moves readily in and out of the oval window, without any flexion of the columella. The stapes and oval window are connected to the saccular wall by fibrous strands. It is thought that these stapedo-saccular strands relay vibrational energy of the stapes to the saccule (Wever and Vernon 1956; Wever 1978; Lenhardt et al. 1985).

For semi-aquatic turtles, the columella is the main pathway for sound input to the inner ear; when the columella is clipped while leaving the tympanum intact, the animal displayed an extreme decrease of sensitivity of hearing (Wever and Vernon 1956).

The auditory sense organ within the inner ear of the sea turtle cochlea is the basilar papilla (basilar membrane). This membrane is large and composed of dense connective tissue in sea turtles (rather than a thin basilar membrane found in terrestrial turtles) (Wever 1978; Hetherington 2008). This basilar papilla is positioned opposite the round window and lies within the pathway of fluid displacement due to columella motion. In most reptiles, and presumably in sea turtles as well, the tectorial membrane lays over the hair cells of the basilar papilla. For sea turtles, the innervations of the hair cells may be accomplished through the movement of the overlying tectorial membrane rather than the movement of the papillae (Hetherington 2008).

As summarized by Bartol (2012), sea turtles are thought to receive sound through the standard vertebrate tympanic middle ear path. However, an important distinction is made when comparing the functional morphology of the middle ear of terrestrial vertebrates and sea turtles. In terrestrial vertebrates, the middle ear is an impedance transformer between sound in air (environment) and sound in fluid (inner ear). This impedance mismatch can be overcome by having a high convergence ratio between the tympanic membrane and oval window (thus amplifying the force acting on the inner ear) and by having a multiple bone ossicular mechanism that acts as a lever system to amplify force. The convergence ratio of the tympanic membrane to oval window in sea turtles is reported to be lower than other semi-aquatic turtles (Lenhardt et al. 1985), and sea turtles lack an osscicular mechanism that acts as a lever (having only a single straight columella). Thus, the sea turtle ear appears to be a poor receptor for aerial sounds. However, this ear is well adapted to water conduction sound. The dense layer of fat under the tympanum acts as a low-impedance channel for underwater sound, similar to that pathway found in odontocetes (Ketten et al. 1999). Furthermore, the retention of air in the middle ear of these sea turtles suggests that they are able to detect sound pressures.

Lenhardt et al. (1983) also identifies the potential for bone-conducting hearing in loggerhead and Kemp's ridley turtles, noting that both the skull and shell act as receiving surfaces. The ability to recognize bone-conducted sound was implicated in the reception of low-frequency sounds from natal beaches and may serve as one of the cues in nesting returns.

4.4 Sea Turtle Hearing

The characterization of sea turtle hearing can be broadly organized into two study types – measurements of the electrophysiological responses to sound exposure and observations of the behavioral responses to sound exposure. The following summaries have been derived from a recent synthesis effort completed by Bartol (2012).

4.4.1 Electrophysiological Response to Sound

Electrophysiological studies on hearing have been conducted on juvenile green turtles (*Chelonia mydas*) (Ridgway et al. 1969; Bartol and Ketten 2006), juvenile Kemp's ridley turtles (*Lepidochelys kempii*) (Bartol and Ketten 2006), juvenile loggerhead turtles (*Caretta caretta*) (Bartol et al. 1999; Lavender et al. 2010, 2011a,b), and hawksbill turtles (*Eretmochelys imbricata*) (Yudhana et al. 2010a). Kemp's ridley is a congener for the olive ridley (*Lepidochelys olivacea*) found in California waters. Electrophysiological responses, specifically auditory evoked potentials (AEPs), are the most widely accepted technique for measuring hearing in situations in which normal behavioral testing is impractical. Auditory brainstem response (ABR) measurements of sea turtles exposed to sound have also been reported.

AEPs reflect the synchronous discharge of large populations of neurons within the auditory pathway and, thus, are useful monitors of the functioning of the throughput of the auditory system. Most AEP research has concentrated on the use of responses occurring within the first 10 milliseconds (ms) following presentation of click or brief tone burst stimuli. This response has been termed the ABR and consists of a series of five to seven patterned and identifiable waves. AEP measurements are noninvasive and can be performed on conscious subject animals (Bullock 1981; Corwin et al. 1982).

Ridgway et al. (1969) measured auditory cochlear potentials of green turtles using both aerial and vibrational stimuli. Thresholds were not measured; instead, cochlear response curves of 0.1 µV (microvolts) potential were plotted for frequencies ranging from 50 to 2,000 Hz. Green turtles detect a limited frequency range (200 to 700 Hz) with best sensitivity at the low tone region of about 400 Hz. Though this investigation examined two separate modes of sound reception (i.e., air and bone conduction), sensitivity curves were relatively similar, suggesting that the inner ear is the main structure for determining frequency sensitivity.

Bartol et al. (1999) collected ABRs from juvenile loggerhead turtles to measure electrophysiological responses to sound stimuli. Thresholds were recorded for both tonal and click stimuli. Best sensitivity was found in the low-frequency region of 250 to 1,000 Hz. The decline in sensitivity was rapid after 1,000 Hz, and the most sensitive threshold tested was at 250 Hz.

Bartol and Ketten (2006) collected underwater ABRs from hatchling and juvenile loggerhead and juvenile green turtles. For these experiments, the speaker was suspended in air while the turtle's tympanum remained submerged underwater. All turtles tested responded to sounds in the low-frequency range, from at least 100 Hz (lowest frequency tested) to no greater than 900 Hz. Interestingly, the smallest turtles tested, hatchling loggerheads, had the greatest range of hearing (100 to 900 Hz) while the larger juveniles responded to a much narrower range (100 to 400 Hz). Hearing sensitivity of green turtles also varied with size; smaller greens had a broader range of hearing (100 to 800 Hz) than that detected in larger subjects (100 to 500 Hz).

Lavender et al. (2010, 2011a,b) have recorded underwater AEPs for loggerhead turtles, with ages ranging from yearlings to subadults, using an underwater speaker as the sound source. Loggerheads were found to respond to frequencies between 50 and 1,000 Hz.

ABR measurements of hawksbill turtles were reported by Yudhana et al. (2010a). Best response in the two test subjects occurred between 50 and 500 Hz.

4.4.2 Behavioral Responses to Sound

Multiple studies have attempted to examine the behavioral responses of juvenile loggerheads to sound in their natural environment, both in controlled settings (O'Hara and Wilcox 1990; Moein et al. 1995; McCauley et al. 2000; Lavender et al. 2011a) and as observed *in situ* (Holst et al. 2007; Weir 2007; DeRuitter and Doukara 2010). Behavioral audiograms have been collected from multiple size classes of loggerhead turtles (Lavender et al. 2011b). Behavioral audiograms require the animal to perform a task in the presence of auditory stimuli. Though time consuming, behavioral audiograms are a more sensitive measure of hearing threshold than electrophysiological responses and ascribe a critical behavioral component to hearing trials.

Lavender et al. (2011a) recorded audiograms using a two-response, forced-choice approach, whereby the turtles were required to vary behavior according to presence or absence of sound, permitting a behavioral measure of acoustic sensitivity. Lavender et al. (2011b) found that while loggerheads respond to similar frequencies as previous studies (50 to 1,000 Hz), their threshold levels are actually more sensitive than reported using electrophysiological methods.

Several sea turtle behavioral studies have been initiated to assist in the development of an acoustic repelling device for sea turtles. O'Hara and Wilcox (1990) attempted to create a sound barrier for loggerhead turtles at the end of a canal using seismic airguns. The test results indicated that airguns were effective as a deterrent for a distance of about 30 m when the sound output of this system was approximately 220 dB re 1 μPa at 1 m in the 25 to 1,000 Hz range. However, this study did not account for the reflection of sound by the canal walls, and the stimulus frequency and intensity levels are ambiguous.

Moein et al. (1995) investigated the use of airguns to repel juvenile loggerhead turtles from hopper dredges. A net enclosure was erected in the York River, Virginia to contain the turtles, and an airgun was stationed at each end of the net. Sound frequencies of the airguns ranged from 100 to 1,000 Hz at three decibel levels (175, 177, and 179 dB re 1 μPa at 1 m). Avoidance of the airguns was observed upon first exposure. However, after three separate exposures to the airguns, the turtles habituated to the stimuli.

McCauley et al. (2000) examined the response of sea turtles (one green and one loggerhead turtle) to an airgun signal. For these trials, the turtles were placed in cages, and behavior was monitored as a single airgun approached and departed. During these trials, the turtles showed a noticeable increase in swimming behavior when the airgun level was above 166 dB re 1 μPa at 1 m and became erratic and increasingly agitated above 175 dB. Because these animals were caged, avoidance behavior could not be monitored. However, the researchers speculated that avoidance would occur at 175 dB re 1 μPa at 1 m, the point at which the animals were acutely agitated (McCauley et al. 2000).

Researchers have also attempted to monitor sea turtle avoidance to sound during an active seismic survey (Weir 2007; DeRuiter and Doukara 2010). Weir (2007) observed 240 animals during a 10-month seismic survey off the coast of Angola. Behaviors were recorded at time of first sighting and as the vessel and towed equipment moved in relation to the turtle. Fewer turtles were observed near the airguns as they were firing (as opposed to the “gun-off” state). However, the source of agitation for the turtle could not be identified; the turtle could have reacted to the ship and towed equipment rather than specifically to the airgun (Weir 2007).

DeRuiter and Doukara (2010) observed turtles during active operation of an airgun array as well and found a startle response (rapid dive) to the airgun. However, again, these authors could not distinguish the stimulus source of the startle response as they did not perform a control with the airguns off.

4.4.3 Summary of Sea Turtle Hearing

Sea turtles are low-frequency hearing specialists, typically hearing frequencies from 30 to 2,000 Hz, with a range of maximum sensitivity between 100 and 800 Hz (Bartol and Ketten 2006; Bartol et al. 1999; Lenhardt 1994; Ridgway et al. 1969). Hearing below 80 Hz is less sensitive but may be important biologically (Lenhardt 1994). By species, hearing characteristics of sea turtles which may be present in California waters include:

- Green sea turtles: greatest sensitivities are 300 to 400 Hz (Ridgway et al. 1969); juveniles and sub-adults detect sounds from 100 to 500 Hz underwater, with maximum sensitivity at 200 and 400 Hz (Bartol and Ketten 2006) or between 50 and 400 Hz (Dow et al. 2008); peak response at 300 Hz (Yudhana et al. 2010b);
- Loggerhead sea turtle: greatest sensitivities approximately 250 Hz or below for juveniles, with the range of effective hearing from at least 250 to 750 Hz (Bartol et al. 1999);
- Olive ridley sea turtles: juveniles of a congener (Kemp’s ridley) found to detect underwater sounds from 100 to 500 Hz, with a maximum sensitivity between 100 and 200 Hz (Bartol and Ketten 2006); similar functional hearing capabilities are assumed;
- Hawksbill sea turtles: greatest sensitivities at 50 to 500 Hz (Yudhana et al. 2010a); and

- Leatherback sea turtles: a lack of audiometric information noted; anatomy suggests hearing capabilities similar to other sea turtles, with functional hearing assumed to be 10 to 2,000 Hz.

4.5 Effects of Anthropogenic Noise

Sounds have the potential to impact a sea turtle in several ways: trauma to hearing (temporary or permanent), trauma to non-hearing tissue (barotraumas), alteration of behavior, and masking of biologically significant sounds (McCarthy 2004).

Hearing damage is usually categorized as either a temporary or permanent injury. TTSs are recoverable injuries to the hearing structure and can vary in intensity and duration. Normal hearing abilities return over time; however, animals often lack the ability to detect prey and predators and assess their environment during the recovery period. In contrast, PTSs constitute a permanent loss of hearing through loss of sensory hair cells (Clark 1991). Few studies have looked at hair cell damage in reptiles, and it is still unknown if sea turtles are able to regenerate hair cells (Warchol 2011). There are almost no data on the effects of intense sounds on marine turtles and, thus, it is difficult to predict the level of damage to hearing structures. Clear avoidance reactions to seismic signals at levels between 166 and 179 dB re 1 µPa have been observed (Moein et al. 1995; McCauley et al. 2000); however, both of these studies were done in a caged environment, so the extent of avoidance could not be monitored. Moein et al. (1995) did observe a habituation effect to the airguns; the animals stopped responding to the signal after three presentations. This lack of behavioral response could be a result of TTS or PTS.

Anthropogenic noise even below levels which may cause injury has the potential to mask relevant sounds in the environment. Masking sounds can interfere with the acquisition of prey, affect the ability to locate a mate, diminish the ability to avoid predators, and, particularly in the case of sea turtles, adversely affect the ability to properly identify an appropriate nesting site (Nunny et al. 2008). Sea turtles appear to be low-frequency specialists and, thus, the potential masking noises would fall within at least 50 to 1,000 Hz. These maskers could have diverse origins, ranging from natural to anthropogenic sounds (Hildebrand 2005). There are no quantitative data demonstrating masking effects for sea turtles.

4.6 Effects of Noise Exposure from Low Energy Geophysical Survey Equipment

No studies have been identified which address the effects of low energy geophysical equipment noise on sea turtles. NSF (2011), in its analysis of research-based oceanographic survey equipment (i.e., subbottom profiler, multibeam echosounder, pingers, and acoustic current profiler) determined that significant impacts to sea turtles through masking, disturbance, or hearing impairment would not be expected to occur. Mitigating factors supporting this determination include equipment frequencies well above the optimal hearing range of sea turtles, low source levels, the directional and narrow-beam characteristics of the acoustic signals, and/or brief signal duration and exposure periods.

4.7 Noise Exposure Criteria

There currently are no noise exposure criteria for sea turtles. NMFS has, however, implemented *de facto* use of the marine mammal exposure protocols when addressing impacts and implementing mitigation for sea turtles. NMFS has established the following SPL criteria for marine mammals:

- Injury, cetaceans: 180 dB re 1 µPa rms for impulsive sound, cetaceans;
- Behavioral response, all marine mammals: 160 dB re 1 µPa rms for impulsive sound; and
- Behavioral response, all marine mammals: 120 dB re 1 µPa rrms for continuous (non-impulsive) sound.

Currently, there are no SEL thresholds in place for sea turtles.

4.8 Assessment of Hearing Information for Sea Turtle Species Present in California Waters

Five sea turtle species have been documented in California waters (**Table H-9**).

Table H-9. Sea Turtles of California, including Summary Life History Information and Hearing Sensitivities

Taxonomic Classification and Common Name	Scientific Name	Status	Presence, Habitat, and Diet	Hearing
Family: Cheloniidae				
Loggerhead sea turtle	*Caretta caretta*	E[a]	Rare in CA; occupies three different habitats – oceanic, neritic, and terrestrial (nesting only), depending upon life stage; omnivorous	Low-frequencies (optimal: 250 to 750 Hz)
Green sea turtle	*Chelonia mydas*	E	Common In CA; resident populations in San Diego County; aquatic, but known to bask onshore; juvenile distribution unknown; omnivorous	Low-frequencies (optimal: 200 to 400 Hz)
Pacific hawksbill sea turtle	*Eretmochelys imbricata bissa*	E	Rare in CA; pelagic; feeding changes from pelagic surface feeding to benthic, reef-associated feeding mode; opportunistic diet	Low-frequencies (optimal: 50 to 500 Hz)
Olive ridley sea turtle	*Lepidochelys olivacea*	T[b]	Rare in CA; primarily pelagic, but may inhabit coastal areas, including bays and estuaries. Most breed annually, with annual migration (pelagic foraging, to coastal breeding/nesting grounds, back to pelagic foraging); omnivorous, benthic feeder	Low-frequencies (optimal: 100 to 200 Hz; congener)

Taxonomic Classification and Common Name	Scientific Name	Status	Presence, Habitat, and Diet	Hearing
Family: Dermochelyidae				
Pacific leatherback sea turtle	*Dermochelys coriacea*	E	Frequent in CA; pelagic, living in the open ocean and occasionally entering shallower water (bays, estuaries); omnivorous (jellyfish; other invertebrates, vertebrates, kelp, algae)	Low-frequencies (estimated: 10 to 2,000 Hz)

[a] North Pacific Ocean Distinct Population Segment (DPS); [b] coastal Mexico population endangered; threatened elsewhere.

Status (under FESA): E = endangered; T = threatened.

Green and leatherback sea turtles are the most likely species to be present offshore California, with loggerheads, hawksbill, and olive ridley sea turtle presence considered to be rare.

As noted previously, sea turtles are low-frequency hearing specialists. Typically hearing frequencies are in the range of 30 to 2,000 Hz, with best hearing sensitivities varying by species.

5.0 FISHES

5.1 Overview

The effects of anthropogenic sound on fishes have been summarized by several authors, including Popper (2003), Hastings (2008), Popper and Hastings (2009a,b), Slabbekoorn et al. (2010), and Popper and Hawkins (2011). Popper (2012) has also recently prepared a summary of fish hearing and sound-related impacts.

Popper (2012) initiated his hearing summary with the following definitions:

- <u>Injury</u>: any effect on the physiology of the animal that leads to immediate or potential death. Behavioral effects, such as moving from a site of feeding, would not be considered an injury.
- <u>Fish</u>: generally refers to three groups of vertebrates: (a) Agnatha or jawless vertebrates; (b) cartilaginous fishes (sharks, rays); and (c) bony fishes. Nelson (2006) provides a complete review of fishes and their evolutionary relationships; more than 32,000 known living fish species have been documented.

5.2 Overview of Bioacoustics

Sound plays a major role in the lives of all fishes (e.g., Zelick et al. 1999; Fay and Popper 2000). Fishes acquire information about biotic (living) and abiotic (environmental) sources via sound and sound interpretation (Fay and Popper 2000; Popper et al. 2003; Fay 2005; Slabbekoorn et al. 2010).

In addition to listening to their environment, many bony fishes species use sound to communicate. Anthropogenic sound may interfere with normal behavior of fishes and has the potential to adversely affect the survival of individuals and/or populations. Detailed discussions of fish bioacoustics can be found in Webb et al. (2008), Fay and Megela-Simmons (1999), Zelick et al. (1999), and Popper et al. (2003). A broad discussion of interactions of anthropogenic sounds and fishes can be found in Popper and Hastings (2009a,b) and Popper and Hawkins (2011).

Cartilagenous fishes do not utilize sound for communication. Popper (2012) notes that virtually nothing is known about effects of human-generated sound on cartilaginous fishes, but there is concern about potential effects since these animals are integral to the ecosystem in many parts of the marine environment (Casper et al. 2011a).

5.3 The Fish Ear

The fundamental structure for hearing by fishes is the inner ear, as summarized by Popper (2012). The inner ear has three otolith organs – the saccule, lagena, and utricle – each containing a dense structure, the otolith. The otolith lies in close proximity to a sensory surface – the sensory epithelium. Each epithelium contains sensory hair cells that are very similar to those found in the mammalian ear. On their top surfaces, sensory hair cells have hair-like projections (cilia) that bend when the epithelium and otolith move out of phase from one another (i.e., when sound stimulates the ear). The sensory cells respond physiologically to the bending of the cilia and send signals on to the brain.

5.4 Hearing Sensitivity

Per Popper (2012), hearing thresholds have been determined for approximately 100 fish species. Data on hearing thresholds for fishes can be found in Fay (1988), Popper et al. (2003), Ladich and Popper (2004), Nedwell et al. (2004), Ramcharitar et al. (2006), and Popper and Schilt (2008). Available data indicate that fishes cannot hear sounds above approximately 3 to 4 kHz, with the majority of species only able to detect sounds to 1 kHz or below; however, several fish genera in the family Clupeidae can hear frequencies greater than 120 kHz but with limited sensitivity. Recent studies have demonstrated that some species can detect sounds below 50 Hz (i.e., infrasound), but it remains unclear as to whether these sounds are sensed by the ear or via the lateral line (Karlsen 1992; Knudsen et al. 1994; Popper 2012).

There have been a limited number of studies on cartilaginous fishes, with results suggesting that they detect sounds to no more than 600 or 800 Hz (e.g., Myrberg et al. 1976; Myrberg 2001; Casper et al. 2003; Casper and Mann 2006). Available data suggest that the majority of marine species do not have specializations to enhance hearing, probably relying on both particle motion and sound pressure for hearing. Hearing capabilities vary considerably between different bony fish species (**Figure H-7**; **Table H-10**).

Figure H-7. Audiograms for Select Bony Fishes (From: Popper 2012)

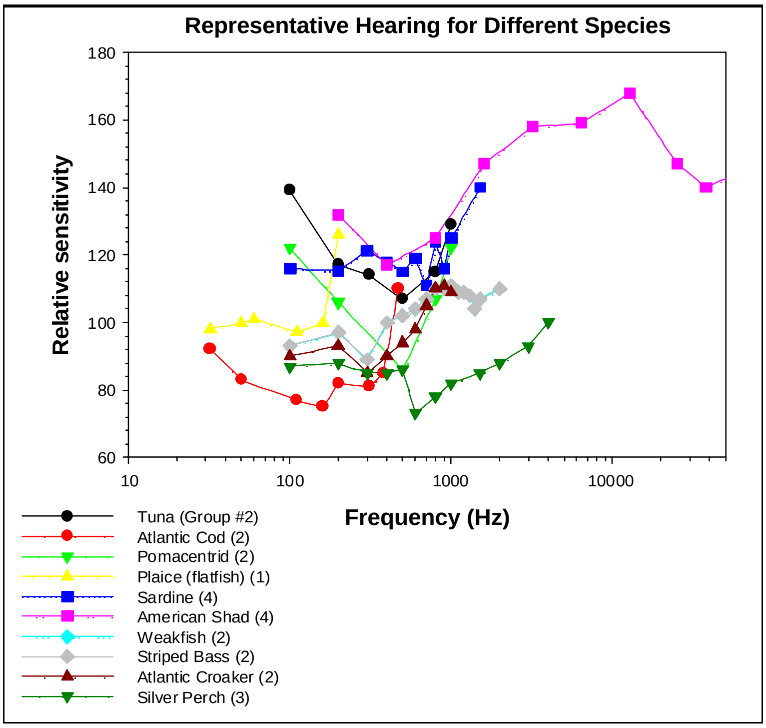


Table H-10. Marine Fishes Hearing Sensitivity, by Family, with Representative California Marine Species

Family	Common Name of Taxa	Highest Frequency Detected (Hz)	Hearing Category	Reference	California Marine Species	Notes
Asceripensidae	Sturgeon	800	2	Lovell et al. 2005; Meyer et al. 2010	Green sturgeon	Several different species tested. Relatively poor sensitivity
Anguillidae	Eels	300	2	Jerkø et al. 1989	N/A	Poor sensitivity
Batrachoididae	Toadfishes	400	2	Fish and Offutt 1972; Vasconcelos and Ladich 2008	Plainfin midshipman	
Clupeidae	Shad, menhden	>120,000	4	Mann et al. 1997, 2001	Pacific herring, Pacific sardine	Ultrasound detecting, but sensitivity relatively poor
	Anchovy, sardines, herrings	4,000	4	Mann et al. 2001	Northern Anchovy	Not detect ultrasound, and relativley poor sensitivitiy
Chondrichthyes [Class]	Rays, sharks, skates	1,000	1	Casper et al. 2003	California skate, Longnose skate, Spiny dogfish	Low-frequency hearing, not very sensitive to sound
Gadidae	Atlantic cod, haddock, pollack, hake	500	2	Chapman and Hawkins 1973; Sand and Karlsen 1986	Hundred-fathom codling	Probably detect infrasound (below 40 Hz). Best hearing 100 to 300 Hz
	Grenadiers		3?	Deng et al. 2011	Giant grenadier, California rattail	Deep sea, highly specialized ear structures suggesting good hearing, but no measures of hearing
Gobidae	Gobies	400	1 or 2	Lu and Xu 2009	Bluebanded goby, blackeye goby	
Labridae	Wrasses	1,300	2	Tavolga and Wodinksy 1963	Senorita, California sheepshead	
Lutjanidae	Snappers	1,000	2	Tavolga and Wodinksy 1963	N/A	
Malacanthidae	Tilefish		2	NA	Ocean whitefish	No data
Moronidae	Striped bass	1,000	2	Ramcharitar unpublished	N/A	
Pomacentridae	Damselfish	1,500 to 2,000	2	Myrberg and Spires 1980	Blacksmith	
Pomadasyidae	Grunts	1,000	2	Tavolga and Wodinsky 1963	Salema, Sargo	

Family	Common Name of Taxa	Highest Frequency Detected (Hz)	Hearing Category	Reference	California Marine Species	Notes
Polyprionidae	Wreckfish		2	NA	Giant sea bass	No data
Sciaenidae	Drums, weakfish, croakers	1,000	2	Ramcharitar et al. 2006	White seabass, Queenfish	Hear poorly
	Silver perch	3,000	3	Ramcharitar et al. 2004, 2006	N/A	
Serranidae	Groupers		2	NA	Kelp bass, barred sand bass	No data
Scombridae	Yellowfin tuna	1,100	2	Iversen 1967	Yellowfin tuna	With swim bladder
	Tuna	1,000	1	Iversen 1969	Pacific bonito	Without swim bladder
	Bluefin tuna	1,000	2	Song et al. 2006	Bluefin tuna	Based only on ear anatomy

Source: Popper (2012), as compiled from Fay (1988) and Nedwell et al. (2004).

There is no clear correlation between hearing capability and environment. There is also broad variability in hearing capabilities within fish groups. **Table H-10** also identifies representative fish species, by phylogenetic group (e.g., families or class), that occur in California waters. Only four of the 17 groups noted do not have representative California fish species and corresponding hearing data.

Table H-10 identifies the highest frequency measurements for fish hearing, but does not identify the lowest frequencies heard. Popper (2012) notes that low-frequency hearing is often a function of the equipment used in a study and not what the fish actually hears. Fishes hear below 100 Hz, and there are some species studied (e.g., cod, salmon, plaice) where fishes have been shown to respond to sounds below 40 Hz.

Species within a group may differ substantially in terms of their hearing structures. For example, tuna species may or may not have a swim bladder, the latter of which is involved in pressure detection. While the hearing range of species with and without swim bladders is quite similar, it is likely that the sensitivity is poorer in the species without this structure (Popper 2012).

Fish groups have been categorized based on hearing capability by Popper (2012), as follows:

- Group 1: Fishes that do not have a swim bladder; these fishes are likely to use only particle motion for sound detection. The highest frequency of hearing is likely to be no greater than 400 Hz, with poor sensitivity compared to fishes with a swim bladder. Fishes within this group include flatfish, some gobies, some tunas, and all sharks and rays and their relatives.
- Group 2: Fishes that detect sounds from below 50 Hz to perhaps 800 to 1,000 Hz, although several are predicted to only detect sounds to 600 to 800 Hz. These fishes have a swim bladder but no known structures in the auditory system that would enhance hearing; hearing sensitivity is limited. These species detect both particle motion and pressure, and the differences between species are related to how well the species can use the pressure signal. A wide range of species fall into this category, including tuna with swim bladders, sturgeons, and salmonids, among others.
- Group 3: Fishes that have some kind of structure that mechanically couples the inner ear to the swim bladder (or other gas bubble), thereby resulting in detection of a wider bandwidth of sounds and lower intensities than fishes in other groups. These fishes detect sounds to 3,000 Hz or more, and their hearing sensitivity, which is pressure driven, is better than in fishes of Groups 1 and 2. There are not many marine species known to fit within Group 3, but this group may include some species of sciaenids (Ramcharitar et al. 2006). It is also possible that a number of deep sea species fall within this category, based on morphology of the auditory system (e.g., Popper 1980; Deng et al. 2011). Other members of this

group would include all of the Otophysan fishes, though few of these species other than catfishes are found in marine waters.

- Group 4: All of these fishes are members of the herring family and relatives (Clupeiformes). Their hearing below 1,000 Hz is generally similar to fishes in Group 1, but their hearing range extends to at least 4,000 Hz (e.g., sardine), and some species (e.g., American shad) are able to detect sounds to over 180 kHz (Mann et al. 2001).

To gain a full understanding of the effects of sound on fishes, it may be necessary to measure or estimate particle motion. Based on outcomes from a recent hydroacoustic workshop for fish and invertebrates hosted by the Bureau of Ocean Energy Management (BOEM), and other efforts (e.g., CEF Consultants Ltd. 2011; Worchester 2006), particle motion may be a more appropriate metric to assess the potential impact of noise exposure for many fish species. Key studies addressing species- or group-specific particle motion include Popper et al. (2003), Horodysky et al. (2008), Popper and Fay (2011), and Zeddies et al. (2011, 2012).

5.5 Anthropogenic Sound Effects on Fishes

Anthropogenic sound effects may include behavioral effects, masking, physiological effects, and, in extreme cases, mortality (Popper and Hastings 2009b; Popper and Løkkeborg 2008). Fish response to sound may occur in several sequential and progressive steps, per Popper (2012):

1) Fishes do not hear the sound – the sound is too low and/or is masked.
2) The sound is at a higher level detectable to the fish, but it is sufficiently low that the sound is dismissed as not being biologically relevant or important.
3) The sound is somewhat higher than threshold, but the fish cannot discriminate it from ambient sounds and does not respond (e.g., informational masking).
4) The sound is clearly audible to the fish and recognizable, but the fish does not respond, or makes an initial, small response (e.g., startle), then returns to normal behavior. After multiple presentations of the sound, the fish may determine that the sound is not biologically important; the fish habituates and no longer shows a startle response.
5) Sound is even louder, and the fish recognizes it as something that may be biologically relevant and may change behavior (e.g., swim away or change swimming course). When the sound ends or after the fish habituates to the sound, the fish returns to normal behavior.
6) The fish may totally avoid the very loudest signals if those sounds are perceived as being potentially harmful; fish may permanently change location or migratory pattern.

5.5.1 Behavioral Effects

Popper (2012) notes several points pertinent to behavioral responses to sound, and emphasizes the variability in the type of sound-induced response among fishes:

1) Context of sound exposure: Fish vary in their response to sound, depending upon the context of the exposure and other factors (e.g., activity at time of exposure; prior habituation, etc.).

2) Variability in response: Responses of animals vary widely (see review by Brumm and Slabbekoorn 2005). These may include movement from the area of maximum sound level, as shown for several fish species (Engås et al. 1996; Slotte et al. 2004), to changing the intensity of calls so they can be heard over the background sounds (Bee and Swanson 2007) or changing the spectrum of the emitted sounds so they are no longer masked, as has been shown in a variety of species (Brumm and Slabbekoorn 2005; Dooling et al. 2009; Parris et al. 2009; Laiolo 2010; Slabbekoorn et al. 2010).

3) Thresholds: Sounds generally have to be well above the minimal detectable level in order to elicit behavioral responses.

Doksaeter et al. (2009) showed no responses of free-swimming herring (*Clupea*) when exposed to naval sonars. Similarly, sounds at the same received level that had been produced by major predators of the herring (killer whales) elicited strong flight responses. Sonar sound levels received by the fishes ranged from 197 to 209 dB re 1 µPa rms at 1 to 2 kHz. The hearing threshold for herring is approximately 125 to 135 dB re 1 µPa (Mann et al. 2005); fishes exposed to sonar showed no reactions to a sound that is biologically irrelevant at a level that was 84 dB above the herring hearing threshold. Other key references regarding impacts of sonars on fishes include Kvadsheim and Sevaldsen (2005), Halvorsen et al. (2006, 2012), and Kane et al. (2010).

Fewtrell and McCauley (2012) used various species of captive marine fish and one species of squid, exposing each species to the noise from a single airgun. Six trials were conducted off the coast of Western Australia with each trial using a different noise exposure regime. Noise levels received by the animals ranged between 120 and 184 dB re 1 $\mu Pa^2 \cdot s$ (SEL). Behavioral observations of the fish and squid were made before, during, and after airgun noise exposure. Results indicate that as airgun noise levels increase, fish respond by moving to the bottom of the water column and swimming faster in more tightly cohesive groups. Significant increases in alarm responses were observed in fish and squid to airgun noise exceeding 147 to 151 dB re 1 $\mu Pa^2 \cdot s$ (SEL). An increase in the occurrence of alarm responses was also observed as noise level increased.

5.5.2 Auditory Masking

Masking is a key issue for potential effects of human-generated sound on all vertebrates, including fishes (reviewed in Fay and Megela-Simmons 1999; Popper et al. 2003). Masking occurs when there are sounds in the environment that are in the same frequency range as the sound of biological relevance to the animal and/or within the hearing range of the fishes. Thus, if a fish has a particular threshold for a biologically relevant sound in a quiet environment and a background noise in the same frequency range is introduced, this will decrease the ability of the fish to detect the biologically relevant signal. In effect, the threshold for the biologically relevant signal will become poorer. Thus, if background noise increases, it may be harder for a fish to detect the biologically relevant sounds that it needs to survive. Specifically, if the ambient noise (or masker) is raised by 10 dB, the threshold of the fish will increase by about 10 dB in the frequency range of the masker. Reviews of auditory masking include Zelick et al. (1999) and Ramcharitar et al. (2006).

Popper (2012) noted several studies where larval fishes may rely on natural, reef-based sounds for location and settling (e.g., Leis et al. 2003; Wright et al. 2005, 2011). These studies have suggested that if there is an increase in ambient (masking) noise, larval fish would be less likely to hear the sounds of the reef and, thus, less likely find a place to settle. Reef sounds could be produced by a variety of sources, including snapping shrimp, water moving over reefs, other fishes, etc. and would be subject to masking by anthropogenic sounds within the hearing range of fishes.

5.5.3 Threshold Shifts

Sound exposure can result in a temporary loss of hearing sensitivity (TTS). Recovery from TTS follows termination of the noise, allowing damage to the sensory cells of the inner ear to be repaired (Smith et al. 2006). Permanent hearing loss (PTS) is not known to occur in fishes due the ability of fishes to repair and regenerate the sensory cells of the ear (e.g., Lombarte et al. 1993; Smith et al. 2006).

Data on TTS in fishes are reviewed in Popper and Hastings (2009b). Data suggest that TTS occurs after long-term exposure to sounds that are as high as 170 to 180 dB re 1 µPa rms, but only in species that have specializations that result in their having relatively wide hearing bandwidths (to over 2 kHz) and lower hearing thresholds than fishes without specializations. For example, TTS of 10 to 20 dB has been demonstrated in goldfish (*Carassius auratus*) and lined Raphael catfish (*Platydoras costatus*) (e.g., Scholik and Yan 2002; Smith et al. 2004a, 2006; Wysocki and Ladich 2005), but little or no TTS has been found in fishes such as cichlids, sunfishes, and perch (e.g., Scholik and Yan 2001; Amoser and Ladich 2003; Smith et al. 2004a,b; Wysocki and Ladich 2005). Moreover, studies of the effects of exposure to 150 dB re 1 µPa rms (received level) for 9 months showed no effect on hearing or on survival and growth of young rainbow trout (*Oncorhynchus mykiss*) (Wysocki et al.

2007). Significantly, in those species where TTS was found, hearing returned to normal starting well within 24 hours after the end of exposure (e.g., Smith et al. 2004b, 2006).

While TTS is not as likely to be particularly relevant with regard to repetitive sound sources, concerns have still arisen that fishes may temporarily have impaired hearing as a result of exposure to loud sounds (e.g., Popper et al. 2005, 2007; reviewed in Popper and Hastings 2009b). Several studies show varying results, but overall, if TTS occurs as a result of exposure to loud sounds, it is not necessarily very great and recovery seems to be within 24 hours in most cases (Popper et al. 2005, 2007; Hastings et al. 2008; Hastings and Miskis-Olds 2011).

The potential effects of TTS are similar to those of masking. If the hearing ability of an affected fish decreases, then the likelihood of detecting predators, prey, or mates (or a reef) decline, thus decreasing the potential fitness of the receiver until normal hearing returns (Popper 2012).

5.5.4 Stress

There have been few studies of sound-induced stress on fishes (e.g., Smith et al. 2004b; Remage-Healey et al. 2006; Wysocki et al. 2006, 2007). Results of several studies suggest that physiological effects may occur among fishes, including changes in hormone levels and altered behavior (Pickering 1981; Smith et al. 2004a,b; Wysocki et al. 2007). Sverdrup et al. (1994) found that Atlantic salmon subjected to up to 10 explosions to simulate seismic airguns released primary stress hormones, adrenaline and cortisol, as a biochemical response. There was no mortality. All experimental subjects returned to their normal physiological levels within 72 hours of exposure. Popper (2012) determined that the available information is too limited to adequately address the issue.

5.5.5 Summary

Data obtained to date on the effects of sound on fishes are very limited both in terms of the number of well-controlled studies and in the number of species tested. Moreover, there are significant limits in the range of data available for any particular type of sound source. While new data have become available on physiological effects of very intense pile driving (e.g., Casper et al. 2012a; Halvorsen et al. 2011, 2012a,b), these data are limited and can only be extrapolated to other sound sources and species with caution (Popper 2012). Comparable data are needed for other sound sources and other species. Further, the proper extrapolation of sound exposure findings from caged fishes to fish in the natural environment remains an issue.

Popper and Hastings (2009) noted that select fish species, when exposed to certain sounds, may produce a range of effects. They caution, however, that extrapolation of these results to either other untested sound sources or fish species is problematic. A comprehensive understanding of the effects of various sound sources on all fish species remains undetermined.

5.6 Effects on Eggs and Larvae

There have been a few studies on effects of sound on eggs and larvae, as recently reviewed by Popper and Hastings (2009b). Jørgensen et al. (2005) examined effects of high intensity pure tones from 1.5 to 6.5 kHz on the survival and behavior of larval and juvenile fishes of several species placed in small plastic bags. The study used herring (*Clupea harengus*) (standard lengths 2 to 5 centimeters [cm] [0.8 to .9 inches (in.)]), Atlantic cod (*Gadus morhua*) (standard length 2 to 6 cm [0.8 to 2.4 in.]), saithe (*Pollachius virens*) (4 cm [1.6 in.]), and spotted wolffish (*Anarhichas minor*) (4 cm [1.6 in.]) at different developmental stages. Both tissue pathology and survival were studied in response to sounds from 150 to 189 dB, and the only effects found were 20% to 30% mortality in one group of herring larvae at the highest sound levels. A lack of replication of exposure protocols in this experiment has been noted.

Most recently, a group in the Netherlands exposed larvae of common sole (*Solea solea*) to simulated pile driving sounds in an apparatus that is very similar to that used by Halvorsen et al. (2011a,b) for larger fish (de Jong et al. 2011; Popper 2012). The larvae of different stages were exposed to sound with cSEL of up to 206 dB re 1 µPa^2·s without any affect on fish mortality. There were no differences in mortality between fish exposed to the simulated pile driving sound and fish that served as controls. The authors did not, however, look at effects on fish tissue or larval growth, and it is possible that either or both of these would have shown an effect of sound exposure (Popper 2012).

5.7 Current Exposure Criteria

Interim noise exposure criteria for fishes exist (Woodbury and Stadler 2008; Stadler and Woodbury 2009), based on concerns over the effects of pile driving. These criteria, established on the U.S. west coast, are for the onset of physiological effects (Popper et al. 2006; Carlson et al. 2007; Popper 2012). The current interim criteria[4] are dual in nature, based on fish weight, and include:

1) Physiological onset (fish 2 g/0.07 oz and above): 206 dB re 1 µPa (peak SPL), or 187 dB re 1 µPa^2·s (cSEL); and
2) Physiological onset (fish <2 g/0.07 oz): 206 dB re 1 µPa (peak SPL), or 183 dB re 1 µPa^2·s (cSEL).

Behavioral criteria have also been implemented by NMFS (Caltrans 2009), however, behavioral studies are limited. Where data are available, observations have been conducted using caged fishes. Interpretation of study results remain problematic, with concerns as to whether the sound stimulus was the measured sound pressure or particle motion arising in complex tank acoustics.

[4] The original “interim criteria” was established at 208 dB re 1 µPa (peak SPL) based on Popper et al. 2006. It was revised to 206 dB re 1 µPa (peak SPL) in 2009 based on Stadler and Woodbury 2009.

Popper (2012) notes that the current thresholds, particularly for cumulative exposure, may be too low. The inadequacy of the interim criteria has now been documented in a recent quantified study on the effects of pile driving on the onset of physiological effects in Chinook salmon (Halvorsen et al. 2011a,b) and several other species (Casper et al. 2011b). These studies, which demonstrated that a cSEL below approximately 207 dB re 1 µPa^2·s will not result in the onset of injury and that cSEL as high as 210 dB re 1 µPa^2·s produces physiological effects that are inconsequential (e.g., minor external bleeding). While these data need to be replicated for other species and other sounds, they have been shown to be appropriate for three very different species, suggesting that there may be reasonably broad applicability of these values for setting future interim criteria.

Per Popper (2012), it is not clear which attributes of sound result in physiological onset, but it is likely that the rise time (onset time) of the signal may be of consequence. Thus, signals with slower rise times than pile driving may have even higher onset levels whereas sounds with faster rise times (e.g., from explosives) may have somewhat lower criteria.

Popper (2012) also notes that recovery time needs to be built into future criteria. For example, the accumulation of exposure (cSEL) is returned to zero after 12 hours without exposure (Carlson et al. 2007; Stadler and Woodbury 2009).

6.0 INVERTEBRATES

6.1 Overview

Many invertebrates are capable of producing sound, including barnacles, amphipods, shrimp, crabs, and lobsters (Au and Banks 1998; Tolstoganova 2002). Invertebrates typically produce sound by scraping or rubbing various parts of their bodies, although they also produce sound in other ways. There are few data indicating how invertebrates may use sound in behavior, although a number of species make sounds for communication (e.g., Budelmann 1992; Popper et al. 2001), territorial behavior (Tolstoganova 2002), mating (Pye and Watson 2004; Henninger and Watson 2005), courtship, and aggression. Snapping shrimp (*Synalpheus parneomeris*) are among the major sources of biological sound in temperate and tropical shallow water areas (Au and Banks 1998). By rapidly closing one of its frontal chelae, a snapping shrimp generates a forward jet of water and associated cavitation to generate sound, the latter of which functions in feeding and territorial behaviors of alpheidae shrimp. Measured source SPLs for snapping ship were 183 to 189 dB re 1 μPa_{p-p} and extended over a frequency range of 2 to 200 kHz.

No physical structures have been discovered in aquatic invertebrates that are stimulated by the pressure component of sound. However, vibrations (i.e., mechanical disturbances of the water) are also characteristic of sound waves. Rather than being pressure sensitive, aquatic invertebrates appear to be most sensitive to the vibrational component of sound (Breithaupt 2002). Statocyst organs may provide one means of vibration detection for aquatic invertebrates.

More is known about the acoustic detection capabilities in decapod crustaceans than in any other marine invertebrate group, although cephalopod acoustic capabilities are now becoming a focus of study. For example, Kaifu et al. (2008) determined that the cephalopod *Octopus ocellatus* can detect particle motion with its statocyst. Studies by Packard et al. (1990), Rawizza (1995), and Komak et al. (2005) have tested the sensitivities of various cephalopods to water-borne vibrations, some of which were generated by low-frequency sound. Using the ABR approach, Hu et al. (2009) showed that auditory evoked potentials can be obtained in the frequency ranges 400 to 1500 Hz for the squid *Sepiotheutis lessoniana* and 400 to 1000 Hz for the octopus *Octopus vulgaris*, higher than frequencies previously observed to be detectable by cephalopods.

Few studies have been directed at determining impacts of sound on invertebrates (e.g., Boudreau et al. 2009; Lagadère 1982; Lagardère and Régnault 1980). There are no data that indicate whether masking occurs in invertebrates.

6.2 Synthesis Studies

Several past and recent synthesis efforts have addressed the question of hearing and the impacts of sound exposure on invertebrates. Moriyasu et al. (2004) conducted a critical review of 20 studies completed through 2003 which addressed seismic and marine noise effects on invertebrates. They determined that among the nine studies that were quantitative, the effects of sound on marine invertebrate species were mixed. Normandeau Associates, Inc. (2012) identified the most critical information needs and data gaps on the effects of various anthropogenic sound on fish, fisheries, and invertebrates resulting from the use of sound-generating devices by the energy industry through development of a literature synthesis that summarized current knowledge of the topic as of January 2012. Popper (2012) developed a summary of the potential effects of sound on invertebrates (e.g., crabs, cephalopods) as part of an analysis of fish and invertebrate hearing capabilities and pertinent study results for a programmatic impact analysis of geological and geophysical sound sources being considered on the Atlantic Outer Continental Shelf (OCS).

The consensus of these reviews indicate that few data regarding hearing have been compiled for aquatic invertebrates (e.g., André et al. 2011). Available data suggest invertebrate hearing in the low-frequencies and only to the particle motion component of the sound field (e.g., Mooney et al. 2010). In other words, based on the few studies that have been conducted on the sensitivity of certain invertebrate species to underwater sound, available data suggest that they are capable of detecting vibrations but they do not appear to be capable of detecting pressure fluctuations. Normandeau Associates, Inc. (2012) concluded that, although there is evidence that a range of invertebrates are sensitive to low-frequency sounds, it is not yet clear whether any of them are sensitive to sound pressure, or whether they show the same level of sensitivity to sounds as other aquatic organisms (e.g., fishes).

One study addressing the effects of seismic exploration (i.e., airguns) on shrimp suggests no behavioral effects at sound levels with a source level of approximately 196 dB re 1 µPa rms at 1 m (3.3 feet [ft]) (Andriguetto-Filho et al. 2005).

Among the studies completed on the effects of sound on invertebrates, the vast majority have focused on the impact of seismic surveys (i.e., airgun arrays), primarily using crustaceans and cephalopods. Crustaceans appear to be most sensitive to sounds less than 1 kHz, although some species are able to detect sounds up to 3 kHz (Lovell et al. 2005). Cephalopods appear to be sensitive to the low-frequency particle motion component of the sound field and not pressure (Mooney et al. 2012), and are sensitive to water movement stimuli in a range between less than 20 and 1500 Hz (Packard et al. 1990; Hu et al. 2009)

6.3 Hearing Sensitivity

While sounds known to be produced by marine invertebrates have frequencies ranging from 87 Hz to 200 kHz, depending on the species, it remains unclear as to the hearing sensitivity of aquatic invertebrates. Rather than being pressure sensitive, aquatic invertebrates appear to be most sensitive to the vibrational component of sound (Breithaupt 2002).

6.4 Effects of Sound Exposure

Acute injury or mortality of invertebrates as a result of exposure to sound appears to depend on two features of the sound source: (1) the received peak pressure, and (2) the time required for the pressure to rise and decay. Generally, the higher the received pressure and the less time it takes for the pressure to rise and decay, the greater the chance of acute pathological effects (NSF and USGS 2011). Considering the peak pressure and rise/decay time characteristics of high energy sound sources (e.g., seismic airgun arrays), the associated pathological zone for invertebrates would be expected to be small (i.e., within a few meters of the seismic source). Lower peak pressures and rise/decay times associated with low energy geophysical sources suggest that even smaller ranges for pathological changes would be evident.

NSF and USGS (2011) have summarized the effects of seismic survey noise, providing summary information regarding previous studies which have assessed the pathological, physiological, and behavioral responses of marine invertebrates exposed to seismic sources (**Table H-11**). NSF and USGS (2011) have also noted that the three categories should not be considered as independent of one another and are likely interrelated in complex ways.

There are only limited data on high anthropogenic sound levels and corresponding physiological effects on invertebrates. Potentially relevant data are limited to results from a study on the effects of seismic exploration on snow crabs on the east coast of Canada (Boudreau et al. 2009) and controlled exposure of cephalopods to low-frequency sound. Results from Boudreau et al. (2009) showed no short-term or long-term effects of seismic exposure in adult or juvenile crabs or crab eggs.

Andre et al. (2011) conducted controlled exposure experiments on four cephalopod species (*Loligo vulgaris*, *Sepia officinalis*, *Octopus vulgaris,* and *Illex coindetii*), subjecting them to low-frequency sound. Exposure to low-frequency sounds resulted in permanent and substantial alterations of the sensory hair cells of the statocysts, the structures responsible for the animals' sense of balance and position. The exposure level (received SPL) was 157 ± 5 dB re 1 µPa, with peak levels at 175 dB re 1 µPa.

Study results presented by Andre et al. (2011) have been critically reviewed (Popper 2012), with concerns raised over lack of scientific control (i.e., control specimens being handled and treated to identical conditions, absent sound exposure) and the absence of an assessment of particle motion (i.e., invertebrates are detectors of particle motion, with no specializations coupling an air-filled structure to the ear). While there is uncertainty regarding the biological importance of particle motion sensitivity versus acoustic pressure, recent electrophysiological studies confirmed cephalopod sensitivities to frequencies under 400 Hz (*Octopus vulgaris*, Kaifu et al. 2008; *Sepioteuthis lessoniana*, *Octopus vulgaris*, Hu et al. 2009; *Loligo pealei*, Mooney et al. 2010).

1 **Table H-11. Summary of Seismic Noise Exposure Studies on Invertebrates (Adapted from: NSF and USGS 2011)**

Species	Test Subject(s)	Exposure	Determinations	Reference(s)
Pathological Effects				
Snow crab (*Chionoecetes opilio*)	Captive adult males, egg-carrying females, and fertilized eggs	Variable sound pressure levels (SPL) (191-221 dB re 1 μPa_{0-p}) and sound exposure levels (SELs) (<130-187 dB re 1 μPa^2·s)	Neither acute nor chronic (12 weeks post-exposure) mortality was observed for the adult crabs. A significant difference in development rate was noted between the exposed and unexposed fertilized eggs/embryos. The egg mass exposed to seismic energy had a higher proportion of less developed eggs than did the unexposed mass. Both egg masses came from a single female and any measure of natural variability was unattainable.	Christian et al. 2003, 2004
Snow crab (*Chionoecetes opilio*)	Caged egg-bearing females	Maximum received SPL was ~195 dB re 1 μPa_{0-p}. Crabs were exposed for 132 survey hr	Neither acute nor chronic lethal or sub-lethal injury to female crabs or crab embryos was indicated. Some exposed individuals had short-term soiling of gills, antennules and statocysts, bruising of the hepatopancreas and ovary, and detached outer membranes of oocytes; these differences could not be linked conclusively to exposure to seismic survey sound. Study design problems impacted interpretation of some of the results (Chadwick 2004).	DFOC 2004
American lobster (*Homarus americanus*)	Adult	Exposed either 20 to 200 times to 202 dB re 1 μPa_{p-p}, or 50 times to 227 dB re 1 μPa_{p-p}	Monitored for changes in survival, food consumption, turnover rate, serum protein level, serum enzyme levels, and serum calcium level. Results showed no delayed mortality or damage to the mechano-sensory systems associated with animal equilibrium and posture.	Payne et al. 2007
Dungeness crab (*Cancer magister*)	Stage II larvae	Single discharges from a seven-airgun array	No statistically significant differences were found in immediate survival, long term survival, or time to molt between the exposed and unexposed larvae, even those exposed within 1 meter (m) of the seismic source.	Pearson et al. 1994
Squid (*Sepioteuthis australis*)	Adult	Exposed to noise from a single 20-in^3 airgun with maximum SPLs of >200 re 1 μPa_{0-p}.	No squid or cuttlefish mortalities were reported as a result of these exposures.	McCauley et al. 2000a,b

Species	Test Subject(s)	Exposure	Determinations	Reference(s)
Physiological Effects				
Snow crab (*Chionoecetes opilio*)	Captive adult males	Variable SPLs (191-221 dB re 1 μPa_{0-p}) and SELs (<130–187 dB re 1 μPa^2·s)	No significant acute or chronic differences were found between exposed and unexposed animals in which various stress indicators (e.g., proteins, enzymes, cell type count) were measured.	Christian et al. 2003, 2004
American lobster (*Homarus americanus*)	Adult	Exposed either 20 to 200 times to 202 dB re 1 μPa_{p-p} or 50 times to 227 dB re 1 μPa_{p-p}	Noted decreases in the levels of serum protein, particular serum enzymes and serum calcium, in the haemolymph of animals exposed to the sound pulses. Statistically significant differences (P=0.05) were noted in serum protein at 12 days post-exposure, serum enzymes at 5 days post-exposure, and serum calcium at 12 days post-exposure.During the histological analysis conducted 4 months post-exposure, noted more deposits of periodic-acid Schiff (PAS)-stained material, likely glycogen, in the hepatopancreas of some of the exposed lobsters. Accumulation of glycogen could be due to stress or disturbance of cellular processes.	Payne et al. 2007
Blue mussels (*Mytilus edulis*)	Small and large mussels	10 kHz pure tone continuous signal	Decreasing respiration. Smaller mussels did not appear to react until exposed for 30 minutes (min) whereas larger mussels responded after 10 min of exposure. The oxygen uptake rate tended to be reduced to a greater degree in the larger mussels than in the smaller animals.	Price 2007
Behavioral Effects				
Snow crab (*Chionoecetes opilio*)	Eight adults	Received SPL and SEL were ~191 dB re 1 μPa_{0-p} and <130 dB re 1 μPa^2·s, respectively. The crabs were exposed to 200 discharges over a 33-min period	Equipped with ultrasonic tags, released, and monitored for multiple days prior to exposure and after exposure. None of the tagged animals left the immediate area after exposure to the seismic survey sound. Five animals were captured in the snow crab commercial fishery the following year, one at the release location, one 35 kilometers (km) from the release location, and three at intermediate distances from the release location.	Christian et al. 2003
Snow crab (*Chionoecetes opilio*)	Seven pre-exposure and six post-exposure trap sets	SPLs and SELs were not measured directly; expected to be similar to levels noted above	Investigated the pre- and post-exposure catchability of snow crabs during a commercial fishery using remote video camera. Results indicated that the catch-per-unit effort did not decrease after the crabs were exposed to seismic survey sound.	Christian et al. 2003
Rock lobster (*Jasus edwardsii*)	Variable	Commercial catches and seismic surveying in Australian waters from 1978-2004.	No evidence that lobster catch rates were affected by seismic surveys.	Parry and Gason 2006

Species	Test Subject(s)	Exposure	Determinations	Reference(s)
Snow crab (*Chionoecetes opilio*)	Caged females	Airgun sound associated with a recent commercial seismic survey	Exhibited a higher rate of "righting" than those crabs not exposed to seismic survey sound. "Righting" refers to a crab's ability to return itself to an upright position after being placed on its back. Christian et al. (2003) made the same observation in their study.	J. Payne unpublished; reported in NSF and USGS 2011
American lobster (*Homarus americanus*)	Adult	Exposed either 20 to 200 times to 202 dB re 1 μPa_{p-p} or 50 times to 227 dB re 1 μPa_{p-p}	Noted a trend for increased food consumption by the animals exposed to seismic sound.	Payne et al. 2007
Shrimp	Variable	Seismic survey sound	Bottom trawl yields of Brazil artisanal shrimp were measured before and after multiple-day shooting of an airgun array. Water depth in the experimental area ranged between 2 and 15 m. Results of the study did not indicate any significant deleterious impact on shrimp catches.	Andriguetto-Filho et al. 2005
Brown shrimp (*Crangon crangon*)	Variable	Not specified	Shrimp reared under different acoustical conditions exhibited differences in aggressive behavior and feeding rate	Lagardère 1982
Squid (*Sepioteuthis australis*) and cuttlefish (*Sepia officinalis*)	Adults – 50 squid and 2 cuttlefish	Exposed to noise from a single 20-in^3 airgun with maximum SPLs of >200 dB re 1 μPa_{0-p}.	The two-run total exposure times during the three trials ranged from 69 to 119 min. at a firing rate of once every 10–15 seconds (s). Some of the squid fired their ink sacs apparently in response to the first shot of one of the trials and then moved quickly away from the airgun. In addition to the above-described startle responses, some squid also moved towards the water surface as the airgun approached. Researchers reported that the startle and avoidance responses occurred at a received SPL of 174 dB re 1 μPa root mean square (rms). They also exposed squid to a ramped approach-depart airgun signal whereby the received SPL was gradually increased over time. No strong startle response (i.e., ink discharge) was observed, but alarm responses, including increased swimming speed and movement to the surface, were observed once the received SPL reached a level in the 156–161 dB re 1 μPa rms range.	McCauley et al. 2000a,b
Cuttlefish (*Sepia officinalis*)	Juveniles	Exposed to local sinusoidal water movements of different frequencies between 0.01 and 1000 Hz	Responses included body pattern changing, movement, burrowing, reorientation, and swimming.	Komak et al. 2005
Octopus (*Octopus ocellatus*)	Adults	Non-impulse sound, level of 120 dB re 1 μPa rms, at 50, 100, 150, 200 and 1000 Hz.	The respiratory activity of the octopus changed when exposed to sound in the 50–150 Hz range but not for sound at 200–1,000 Hertz (Hz). Respiratory suppression by the octopus might have represented a means of escaping detection by a predator.	Kaifu et al. 2007

There are few data indicating if and how invertebrates may use sound in behavior, although a number of species make sounds and so, presumably, use such sounds for communication (e.g., Budelmann 1992; Popper et al. 2001). Invertebrate species capable of producing sounds include barnacles, amphipods, shrimp, crabs, lobsters, mantis shrimps, sea urchins, and squid (Au and Banks 1998; Iversen et al. 1963; Radford et al. 2008; Staaterman et al. 2011). However, there are no data that indicate whether masking occurs in invertebrates or suggest whether anthropogenic sound would have any impact on invertebrate behavior. A study assessing the effects of seismic exploration on shrimp suggests no behavioral effects at sound levels with a source level of about 196 dB re 1 µPa rms at 1 m (Andriguetto-Filho et al. 2005).

Direct observation of squid exposed to airgun sound showed both a strong startle response involving ink ejection and rapid swimming at 174 dB re 1 µPa rms and avoidance behavior (McCauley et al. 2000a,b). Sensitivity to low-frequencies indicates that marine invertebrates, like squid (Packard et al. 1990; Urick 1983), are likely to be susceptible to anthropogenic sources of underwater sound such as shipping, offshore industrial activities (e.g., wind or tidal turbines), and seismic surveys. As a result, invertebrates sensitive to low-frequencies may be susceptible to masking or other physiological or behavioral impacts of anthropogenic noise (McCauley et al. 2000). In addition, statocyst or lateral line hair cells may be affected by sound energy (either long duration or brief, high-intensity noise). Such hair cell damage and related temporary hearing loss has been demonstrated in fishes (McCauley et al. 2003), and this has been suggested for squid which possess a lateral line analogue (Budelmann 1994).

Recent studies have indicated that offshore seismic survey activity has no effect on catch rates of crustaceans in the surrounding area (Andriguetto-Filho et al., 2005; Parry and Gason, 2006).

Stocks et al. (2012) examined the responses of larvae of temperate invertebrates to three sound treatments: natural ambient sound (shallow rocky reef), anthropogenic sound (vessel engine), and no sound (control). Species analyzed included larvae of two mollusks (gastropod *Bembicium nanum*; oyster *Crassostrea gigas*), an echinoderm (echinoid *Heliocidaris erythrogramma*), and a bryozoan (*Bugula neritina*). Larvae of the gastropod increased their swimming activity in response to both natural and anthropogenic sound, while larvae of the bryozoan decreased swimming activity when exposed to engine noise, but not recordings from the natural reef. Considerable variation was observed in the swimming behavior of larvae of the echinoid, with no evidence of differences in response among the treatments. The behavior of oyster larvae was dependent on its nutritional status, with unfed larvae not responding to sound, whereas fed larvae increased swimming activity, but only in response to natural sound.

6.5 Noise Exposure Criteria

There are no noise exposure criteria for invertebrates. Interim criteria for the onset of injury in fish (i.e., physiological effects) were established at a peak SPL level of 208 dB re 1 µPa, based on the work of Popper et al. (2006); this threshold was also applied in recent analyses (e.g., Central California Coast Seismic Imaging Project, CSLC 2012) to both fish and invertebrates. This threshold was originally derived from studies of fish and invertebrates exposed to pile driving noise (Popper et al. 2006) and included a SEL threshold of 187 dB re 1 $\mu Pa^2 \cdot s$.

In 2009, the interim criteria, as applicable to fish and by inference to invertebrates, were revised to account for the onset of physical injury (i.e., TTS) when either (1) the peak SPL exceeds 206 dB re 1 µPa (peak) or the SEL, accumulated over all pile strikes generally occurring within a single day; or (2) exceeds 183 or 187 dB re 1 $\mu Pa^2 \cdot s$, depending upon fish weight (Stadler and Woodbury 2009). However, Popper (2012) notes that the interim criteria have being closely scrutinized, and that recent pile driving effects studies (Halvorsen et al. 2011, 2012a, 2012b; Casper et al. 2011, 2012a,b) have introduced further concerns regarding acceptable exposure levels. Given these concerns and the absence of revised criteria, the current MND analysis has used the approach outlined in CSLC (2012), adopting the SPL threshold of 208 dB re 1 µPa and the lower current SEL threshold of 183 dB re 1 µPa.

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