Aquatic Noise Pollution from Oil Tankers and Escort Vessels in Prince William Sound, Its Effects and Impacts on the Marine Environment of the Sound: Literature Search from 1980 to Present

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Report on Project 854.07.1

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Acronyms and Abbreviations

ADD	acoustic deterrent device
ADFG	Alaska Department of Fish and Game
AHD	acoustic harassment device
APSC	Alyeska Pipeline Service Company
ATOC	Acoustic Thermometry of Ocean Climate
ESA	Endangered Species Act of 1973
ETT	Enhanced Tractor Tug
EVOSTC	Exxon Valdez Oil Spill Trustee Council
dB	decibels
dwt	deadweight tons
GOA	Gulf of Alaska
HSWRI	Hubbs-SeaWorld Research Institute
Hz	hertz
IHA	incidental harassment authorizations
kHz	kilohertz
km	kilometer(s)
kph	kilometer per hour
kt	knot(s)
LFA	low-frequency active
m	meter(s)
MMPA	Marine Mammal Protection Act of 1972
NMFS	National Marine Fisheries Service
nmi	nautical miles
NOAA	National Oceanic and Atmospheric Administration
TAPS	Trans Alaska Pipeline System
PRT	Prevention and Response Tug
PTS	permanent threshold shift
PWS	Prince William Sound
PWS-RCAC	Prince William Sound Regional Citizens' Advisory Council
PWSSC	Prince William Sound Science Center
RMS	root-mean-square
SE	sound exposure
SEL	sound exposure level

SERVS	Ship Escort Response Vessel System
SPL	sound pressure level
TTS	temporary threshold shift
μPa	micropascal
U.S.	United States
U.S.FWS	United States Fish and Wildlife Service
VLCC	Very Large Crude Carrier
VMT	Valdez Marine Terminal

1.0 Executive Summary

This report summarizes the results of a review of available literature on the effects of anthropogenic (human-made) aquatic noise on fish and marine mammals of Prince William Sound, Alaska (PWS, the Sound). The review focused on potential effects of noise from vessel traffic associated with the Trans Alaska Pipeline System (TAPS), including oil tankers and their tug escorts. Other vessels operating in PWS, such as cruise liners, fishing boats, recreational boating, ferries, and ships used for scientific research were considered as potential contributors to the noise environment.

TAPS tankers and their escorts travel the Sound along a single shipping lane from the Hinchinbrook Entrance to the Port of Valdez. One to two transits by TAPS tankers and their escorts are made per day. Given this limited traffic, TAPS vessels are unlikely to be the only substantial contributor to the noise environment in the Sound. Therefore, noise from all vessels would have to be estimated to determine the contribution of TAPS vessels to any cumulative potential for impact on fish and marine mammals.

The level of noise produced by TAPS vessels has not been measured empirically. However, measured noise from similar vessels in other areas was likely to be a good model for TAPS noise. Although tankers produce the highest levels of any vessel type using the Sound (source levels estimated at up to 190 dB re 1 µPa), given the depth of the water in the shipping channel, tanker noise was expected to attenuate rapidly. In the channel, only moderate levels (150 dB re 1 µPa and below) were likely to be received at ranges greater than approximately 100 meters (m) based on transmission loss measurements made in other areas. Shadowing by islands on both sides of the shipping lane would reduce noise propagation to other areas of the Sound. Therefore, TAPS tankers and escort vessels would not be expected to produce high amplitude noise sufficient to cause biologically – significant effects on fish and marine mammals over large areas and long periods in the Sound.

Effects could be caused locally close to the Valdez Marine Terminal (VMT) or other ‘hot spots’ with high levels of noise in areas with concentrated vessel traffic. Possible hot spots include the narrow, shallow waters of the Valdez Arm and Port of Valdez, the cruise ship berths at Whittier, harbors used as staging areas by fishing vessels, and areas where fishing derbies occur. These areas should not be regarded as safe for fisheries, aquaculture, or wildlife without additional information regarding exposure. Measurements at selected locations and propagation modeling would be required to assess the potential for impact.

At long range, the most likely effect of tanker traffic would be masking of biologically significant sounds at moderate to low frequencies (particularly below 5 kHz). These sounds include social communication, signals used for navigation, sounds made by natural predators or prey, and possibly significant sounds made by humans (e.g., hunters). However, because TAPS vessels travel the Sound infrequently, they are unlikely to cause masking for a significant proportion of each day. Fish and mysticete whales will be most vulnerable to masking, as they hear and communicate at frequencies overlapping the greatest energy from ship noise.

Outside ‘hot spots’, changes in behavior might be observed during the passage of ships, but biologically-significant effects, such as abandonment of favored areas, is not expected. Both fish and marine mammals typically respond to vessels with behavioral strategies that minimize costs and risks to themselves. The review found little evidence that significant effects of noise could be expected unless fish and marine mammals were exposed to heavy and constant vessel traffic. Long-term effects of noise should be considered most likely in cases where behavioral or physiological adaptations are (1) not possible, for example when noise levels are high enough to cause hearing loss or chronic masking, or (2) when constant disturbance is accompanied by other stressors. Based on the available literature, these types of effects would not be expected as a consequence of infrequent TAPS traffic. However, collisions with whales should be considered a significant possibility where TAPS vessels exceed speeds of 14 kt.

An additional noise source should be considered important in areas where marine mammals with good high frequency hearing encounter large numbers of vessels. Sonars, including those used for fish-finding and navigation, produce extremely high signal levels, often in excess of 200 dB re 1 μPa. Frequencies of these sonars are in the range from 38-200 kHz, so they will be most likely to affect pinnipeds with good high frequency hearing (in PWS, the harbor seal) and small cetaceans. High frequency sonar signals attenuate rapidly, but animals that bow ride or approach boats for food, or that frequently use fishing harbors, could potentially be exposed to harmful levels often enough to damage hearing.

2.0 Introduction

2.1 Goals of Literature Review

This report summarizes the available literature on the effects of anthropogenic (human-made) aquatic noise on the marine environment of Prince William Sound, Alaska (PWS, the Sound). Of particular interest are measured and potential effects of noise from vessel traffic associated with the Trans Alaska Pipeline System (TAPS), including oil tankers and their tug escorts, the Alyeska Pipeline Service Company (APSC) Ship Escort Response Vessel System (SERVS). Other vessel traffic, such as cruise liners, fishing vessels, recreational boating, and scientific research vessels, were considered during the review because they have the potential to contribute significantly to the noise environment in PWS.

The review covers literature from approximately 1980 to the present (2007). Sections below review what is known about noise produced by various activities in PWS, describe briefly what is known about sound transmission in PWS, and outline possible effects on marine mammals and fish. The final section reviews what is known about the contribution of TAPS traffic to the overall noise environment in the Sound, the possible effects it may have on threatened and endangered marine mammals and fish, and recommends steps that could be taken to obtain information needed to further document effects.

2.2 Prince William Sound

PWS is the largest embayment in the North Pacific on the United States (U.S.) side, opening into the Gulf of Alaska (Figure 1). It is a shallow basin created by uplift of the surrounding mountains, the Chugach Range and its extensions on the Kenai Peninsula. The Sound is accessed by a major shipping channel through the shallow Hinchinbrook Entrance (~183 m) bounded on either site by two large islands, Montague and Hinchinbrook (Figure 2). The central Sound is a basin with a deep channel (reaching ~550 m in depth) extending westward and southward around a complex of islands to reconnect with the Gulf of Alaska through Montague Strait. The Port of Valdez is at the north end of the Sound, accessed through a shallow, narrow channel, the Valdez Arm. The boundaries of the Sound are a complex of many small islands and long embayments formed by glacial scour, including the Columbia Glacier at the north end of the Sound.

Valdez, Cordova, and Whittier are the major ports in the Sound, used by TAPS-related oil-industry traffic, fishing vessels, and cruise liners, respectively. Other smaller ports, used mainly by fishers, are scattered around the Sound.

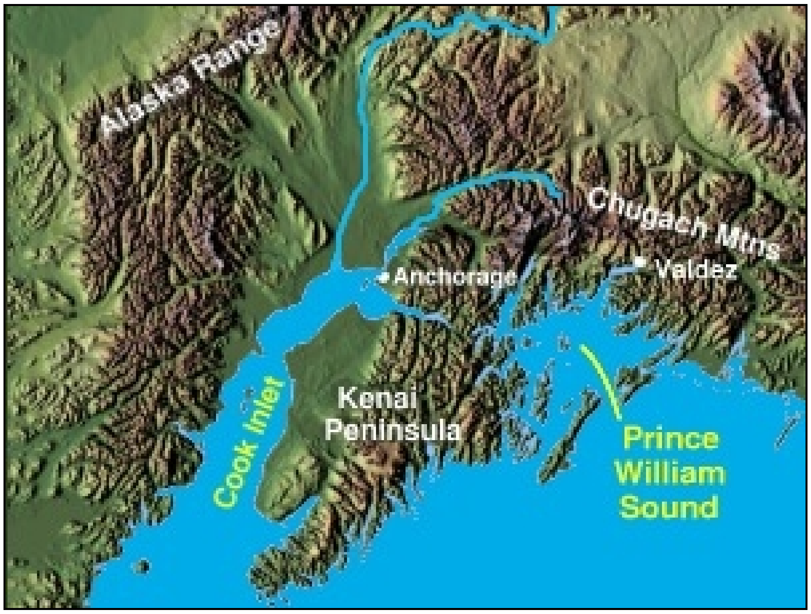

Figure 1. Map of the northern Gulf of Alaska, showing the locations of Cook Inlet, Prince William Sound and the surrounding topography.
Source: Wikipedia

The Sound supports large populations of marine mammals, birds, fish, and invertebrates. Glaciers and streams in the surrounding mountains provide runoff that contributes nutrients and habitat for anadromous fish. The 3,000 miles of shoreline support large fisheries for salmon and halibut as well as a recreational shrimp fishery (PWSSC, 2004). Although the ecosystem is still recovering from the consequences of the Exxon Valdez oil spill in 1989, the Sound and its natural resources possess unequalled beauty. Preservation of the PWS ecosystem is of great importance both locally and nationally for its intrinsic biodiversity, as a tourist attraction, and for its fisheries resources.

Anthropogenic noise is one byproduct of human activities that could potentially damage the environment in PWS. An important challenge for the future will be to accommodate activities such as the oil and fishing industries, tourism, local traffic, and subsistence uses, while still preserving the resources and beauty of the Sound. All these sources contribute to the anthropogenic noise environment, at least on a local scale. Therefore, although the primary focus of this review is the potential effects of exposure to TAPS-related noise, cumulative exposure from all the anthropogenic activity in the Sound is likely to be important. What follows is a brief summary.

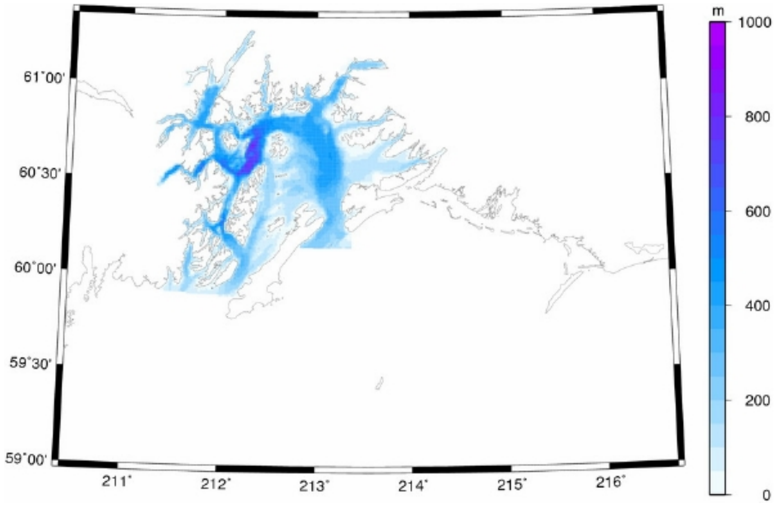

Figure 2. The bathymetry of Prince William Sound north of the Hinchinbrook Entrance and Montague Strait.
Source: AOOS

2.3 Activities in Prince William Sound that Produce Noise

2.3.1 TAPS Transport

The construction of the TAPS pipeline from Prudhoe Bay on the North Slope to the ice-free Port of Valdez began in March 1975 and was completed in June 1977. TAPS tankers carrying oil to the continental U.S. travel a shipping channel from the Hinchinbrook Entrance into the Port of Valdez that is used throughout the year, weather permitting. The U.S. Coast Guard controls the shipping lanes, shown in Figure 3, and the SERVS duty station monitors the progress of tankers and their escort tugs.

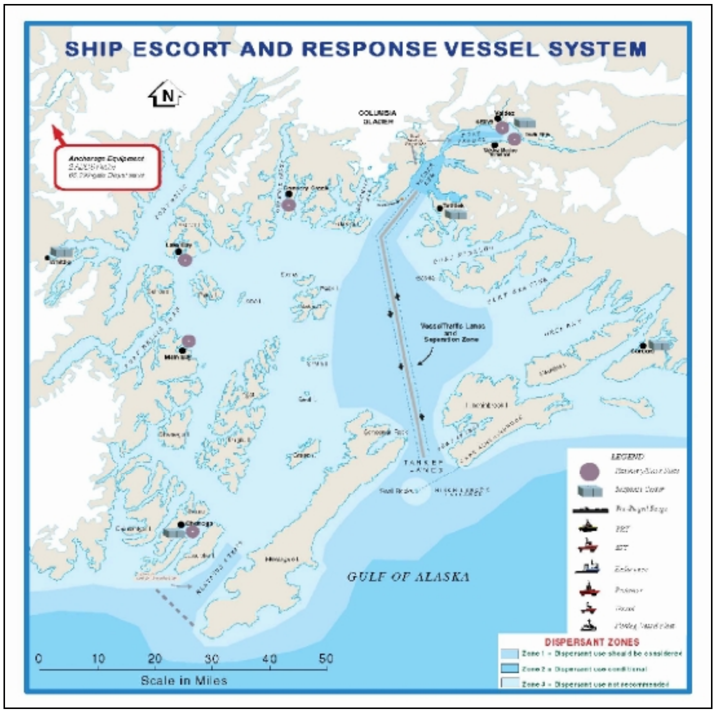

Figure 3. SERVS tanker traffic lanes.
Source: Alyeska Pipeline

The Valdez Marine Terminal (VMT), operated by Alyeska, is located in the Port of Valdez, a natural fjord 19 km long, 4 km wide, and up to 244 m deep. The shipping lanes through the Sound are 1.2 km wide and average 183-305 m deep with the minimum depth occurring in Valdez Narrows at 76 m (APSC, 2007).

The largest vessel that can be berthed at the VMT has a displacement of 270,000 deadweight tons (dwt), classified as a Very Large Crude Carrier or VLCC. In 1992, Congress required all oil tankers to be fitted with double hulls. This oil spill prevention measure has also served to dampen noise originating from engine rooms. SERVS currently maintains a fleet of ten tugs to escort laden oil tankers from the VMT to the Gulf of Alaska. Two vessels are required to escort each laden tanker. The primary escort must be either a PWS Class Enhanced Tractor Tug (ETT) or a Prevention and Response Tug (PRT). The secondary escort can be an Invader, Theriot or Utility Class tug. Vessels travel at speeds of 17 km per hour (kph) (12 knots [kt]) or less, with stringent requirements for the transit of the Sound and navigation of the Valdez Narrows into the Port of Valdez. In 2005, 399 tankers docked at the port, for an average of 1.1 per day, which indicates an average of slightly over 2 transits of the sound per day (MARAD, 2005). It takes an average of 22 hours and 20 minutes for a tanker to complete its visit at the Port of Valdez, including berthing, offloading ballast, loading crude oil, and deberthing. The transit of the sound takes approximately four and three-quarters hours.

Intense noise from ships in the traffic separation zone is likely to be confined largely to the central basin of the Sound. Transmission of lower levels will be reduced or blocked in many areas by shallow water at the margins, obstructing islands to the east and west, and the curved topography of the main channel at the north end of the Sound. However, to date, no empirical measurements or modeling studies have quantified the transmission noise from TAPS vessels in the Sound.

2.3.2 Exxon Valdez Oil Spill

In 1989 the Exxon Valdez, a fully-laden oil tanker leaving the Port of Valdez, veered out of the shipping lane to avoid ice and struck Bligh Reef, spilling 11 million gallons of crude oil into PWS. An estimated 149 km of the shoreline along the north end of the Sound were heavily oiled and an additional 459 km were considered “lightly oiled”. In 1993, the Exxon Valdez Oil Spill Trustee Council (EVOSTC) funded a survey that found subsurface (buried) oil to be persistent and not dispersing naturally, as originally predicted. Small-scale studies were conducted throughout the 1990s, reporting similar results. In 2001, EVOSTC funded another large-scale study by the National Marine Fisheries Service (NMFS) Auke Bay Laboratory, sampling 91 randomly selected sites along 8,000 m of shoreline. The study found that subsurface oil had remained dormant and highly toxic. Some “worst case” samples resembled oil found in the weeks immediately following the spill. Surface oil had hardened into an asphalt-like layer along the shore that did not present a risk to fish resources or wildlife. The study concluded that low level chronic effects of the spill were very likely, but would probably be restricted to populations in areas with isolated oil pockets (NOAA, 2001).

The consequences of the Exxon Valdez spill are important to a review of noise impact because the disaster stressed populations of marine mammals, birds, and fish over widespread areas of the upper Sound. Assessment of the effects of the spill on wildlife has developed slowly since the initial event. Fifteen years after the spill, a number of species have not as yet recovered, including the harbor seal (Phoca vitulina), a number of birds – the common loon (Gavia immer), three species of cormorants (Phalacrocorax spp.), pigeon guillemot (Cepphus columba), and harlequin duck (Histrionicus histrionicus), and Pacific herring (Clupea pallasi). Species considered to be recovering include killer whale (Orcinus orca), northern sea otter (Enhydra lutris kenyoni), marbled murrelet (Brachyramphus marmoratus), and several species of clams and mussels. Recovered species include river otter (Lutra canadensis), bald eagle (Haliaeetus leucocephalus), black oystercatcher (Haematopus bachmani), common murre (Uria aalge), pink salmon (Oncorhynchus gorbuscha), and sockeye salmon (O. nerka). Species of "unknown recovery" status include cutthroat (Oncorhynchus clarki) and Dolly Varden trout (Salvelinus malma Walbaum), Kittlitz's murrelet (Brachyramphus brevirostris), and a number of species of rockfish (EVOSTC, 2004).

Figure 4. Effects of the Exxon Valdez oil spill.
Source: Exxon Valdez Oil Spill Trustee Council

2.3.3 Fishing Industry

Alaska's commercial and sport fishing industries are essential to its economy. They have increased steadily in value in the past few years. Fishers received $1.3 billion from Alaskan harvests in 2005 (ADFG, 2006), contributing $53 million in government revenues. PWS fisheries averaged 24% of the Alaska salmon harvest by number of fish, 21% by weight, and 17% by dollar amount for 2002 through 2005. The average groundfish harvest for the same time period brought in over half a million dollars (Woodby et al., 2005).

There is no published summary of the total number of vessels using PWS, but a wide range of fishing vessels work the Sound and its environs, including purse seiners, gillnetters, trollers, longliners, recreational and sport fishing vessels. The fishing industry is active year-round and uses most of the inshore waters of the Sound, so its vessels are likely to be among the most pervasive noise sources. Engines, generators, and hydraulic hauling motors contribute to the noise produced by fishing vessels (ADFG, 2005a, 2007a). Of these, engine noise is the most likely to propagate over long ranges (Thode et al., 2007).

Figure 5. Fishing boat.
Source: Virtual Alaska

2.3.4 Tourism, Transportation, and Other Vessel Traffic

Vessels associated with tourism, local transportation, and government activities can be locally important in the Sound as well. Of these, cruise ships have the most widespread influence on the noise environment. The cruise ship industry has shown constant growth worldwide since 1980. By the end of 2005, the North American cruise industry was operating 192 vessels disembarking 8.6 million passengers in U.S. ports, an increase of 6.3 percent over 2004. Alaska is the premier cruise destination in the U.S., with 3.2 million visiting passengers and just over 5,000 resident passengers visiting in 2005 (BREA, 2006). Cruise ships visit PWS in the spring and summer. In the summer of 2006, 71,000 passengers traveled to Whittier (MARAD, 2007). The total for the year was 108,000. That number of passengers translates to approximately one cruise ship every three days during the 180 days of the spring and summer seasons. Also, cruise ships can travel through the Sound without calling at Whittier, so the number of passages may be somewhat higher. The traffic of cruise ships in and out of the Gulf of Alaska, mainly into the ports of Whittier and Seward, contributes to anthropogenic underwater noise in the Hinchinbrook Entrance, Montague Strait, and the deep channel around Knight Island.

Ferries transport vehicles and residents to and from offshore islands and settlements on the coast of PWS. Ferry routes are a locally-important noise source. Privately owned boats and local tour boats operate widely throughout the Sound. Vessels used for fisheries research, enforcement, and government functions also operate in the Sound, but are sufficiently uncommon that they are typically not major sources of noise. Exceptional cases might include bathymetric surveys and construction projects.

Figure 6. Cruise ship in Prince William Sound.
Source: Prince William Sound Science Center

2.3.5 Alaska Subsistence Uses

Alaska Native Americans were granted exceptions to the Marine Mammal Protection Act of 1972 (MMPA) and the Endangered Species Act of 1973 (ESA) to allow for the continuation of their traditional hunting and fishing practices. Subsistence uses include fishing and hunting for food, clothing, fuel, transportation, construction, home goods, sharing, trading, ceremony, and crafts. At least 65 percent of the state's subsistence food harvest by weight is fish; including salmon, halibut, herring, Dolly Varden trout, and Pacific cod (Gadus macrocephalus). Marine mammals make up 9.7 percent of the total. Takes are managed, but represent an additional pressure on populations. Machinery such as boats or snowmachines may be used by native hunters and fishers in conjunction with more traditional forms of transportation. They are likely to make a small contribution to the overall noise in the Sound, but may be locally important because animals associate the noise with hunting. Since many areas that have been protected as "wilderness" are also traditional homelands, subsistence activities can be the major source of anthropogenic noise in remote wilderness areas (Wolfe, 2003).

2.4 Threatened and Endangered Species in Alaska

Figure 7. Steller sea lion Eumetopias jubatus
Source: NOAA

The effects of anthropogenic activities on threatened, endangered, and specially-managed species are of particular concern. U.S. Fish and Wildlife Service (USFWS) currently lists twelve threatened and endangered species in Alaska, one plant and eleven vertebrates (USFWS, 2007). Of the eleven vertebrates, seven are marine animals and four are birds. No fish species are currently listed. All the marine mammals in the area are also managed under the Marine Mammal Protection Act regardless of their abundance.

For the purposes of this report, the threatened and endangered species of concern are the humpback whale (Megaptera novaeangliae), fin whale (Balaenoptera physalus), Steller sea lion (Eumetopias jubatus), and northern sea otter (USFWS, 2007). Harbor seal populations that have been reduced in several areas of the Gulf of Alaska will also be considered. The Eastern North Pacific population of the gray whale (Eschrichtius robustus), which occurs from the Bering Sea to Baja California, recovered from the effects of overexploitation early in the 20th century, and was delisted in 1994; however, recent trends in ice cover in the Bering Sea have raised concerns that their resource base may be impacted significantly in the future. The population estimate declined to 18,000 whales in the winter of 2001 – 2002 from the population maximum of approximately 29,800 in 1997 – 1998 (Angliss and Outlaw, 2006). The decline was associated with a decline in their prey base in the Bering Sea beginning in 1997 and resulting in a mortality event marked by thin whales and a large increase in the number of whales stranded in 1999 and 2000 (Angliss and Outlaw, 2006; Grebmeier et al., 2006; Moore et al., 2003). In response, gray whales have begun to exploit resources in coastal areas of the North Pacific, including around Kodiak Island (Calambokidis et al., 2002; Moore et al., 2007). The population is apparently beginning to recover somewhat, but changes in Arctic ice cover could cause similar alterations in their food supply in the future. If resources are available within PWS, the Sound and its environs could become increasingly important to them.

One highly endangered species, the North Pacific right whale (Eubalaena japonica), occurs in the northern Gulf of Alaska (Appendix B). These whales are very rare in the eastern Pacific, with only 2-3 sightings per year (71 FR 77694), and they appear to prefer shelf waters rather than embayments. Therefore, they are highly unlikely to be detected in PWS.

A few highly visible species in PWS are not endangered, but have populations listed as endangered in other areas. Therefore, an understanding of the factors affecting their populations is important to predicting future trends in the Sound. The Southern resident killer whale is listed as endangered in California, Oregon, and Washington. Both resident and transient killer whales are closely-monitored in PWS, particularly since the population underwent an apparent decline or displacement after the Exxon Valdez spill. The sperm whale (Physeter macrocephalus) is endangered in California, North Carolina, Puerto Rico, and the Virgin Islands (USFWS, 2007), but is widespread in the Pacific. This deep diving species is unlikely to use the shallow waters of PWS, but it is capable of entering embayments to exploit fish catches, a challenge faced by fishers in other parts of Alaska (Thode et al., 2007).

2.5 Fish Species of Concern

Currently, there are no threatened or endangered fish species in the state of Alaska (USFWS, 2007). However, some species are critical food for endangered marine mammals such as the fin whale and humpback whales (Pacific herring, sand lance [Ammodytidae spp.] and capelin [Mallotus villosus]), and Steller sea lion (walleye pollock [Theragra chalcogramma], Pacific herring, and Pacific cod) (Reeves et al., 2002). Recent evidence has related declines of the Steller sea lion and harbor seal to conflict with human use of the same fisheries resources (Guenette et al., 2006; Merrick and Loughlin, 1997), although the evidence is still difficult to interpret and controversial. Alternatively, changes in predatory behavior of killer whales have been implicated in declines of some species (Estes et al., 2006).

In addition to fish species exploited by both humans and endangered marine mammals, there are also many species of commercial importance, including salmon (chinook [Oncorhynchus tshawytscha], sockeye, coho [O. kisutch], chum [O. keta], and pink), halibut (Hippoglossus stenolepis), and groundfish (sablefish [Anoplopoma fimbria] and rockfish [Sebastes spp., Sebastolobus spp.]) (ADFG, 2006).

2.6 Fish Habitat Use

In addition to any direct effects of anthropogenic noise on fish, concerns regarding effects on fish habitat must be addressed. Essential Fish Habitat is defined as any area on which fish are critically dependent, directly or indirectly, during any stage of their life cycle, including but not limited to areas of spawning, rearing, food supply, overwintering, or migration (ADFG, 2007b). Extensive areas of Essential Fish Habitat have been identified for special protection in the Gulf of Alaska, particularly around Kodiak Island, throughout PWS, and in Southeast Alaska. The areas used by the species of greatest importance are as follows:

- *Pacific herring*. In April and May, Pacific herring enter PWS in great numbers to spawn around the coastal islands, after which they move offshore to feed (ADFG, 2005b).
- *Pacific cod*. Pacific cod feed in shallow water throughout the Sound, migrating into deeper waters to spawn (ADFG, 1985).

- *Pacific salmon.* All species of Pacific salmon are anadromous, and therefore dependent on access to the freshwater rivers and streams of coastal PWS.
- *Pacific halibut.* Pacific halibut spawn off the edge of the continental shelf in deep waters, after which the eggs and larvae are carried to the surface by currents, often ending up in the shallower waters of PWS where they metamorphose into their adult, bottom-dwelling forms.
- *Rockfish.* Rockfish live throughout much of the Gulf of Alaska, including nearshore shallow waters with rocky bottoms (including PWS), nearshore continental shelf waters, and in deep water on the edge of the continental shelf (ADFG, 2005b).

3.0 Anthropogenic Ocean Noise

As described above, there are many anthropogenic sources in PWS that could contribute to the noise environment. The level at the source, frequency range, and time-varying characteristics of the noise will all have a large influence on the potential for effects, but the most important factors will be distance from the noise source to the receiver and the effect of topography and oceanographic conditions on noise propagation. A brief introduction to the terminology and acoustic concepts is provided in the next section.

3.1 Acoustics in the Marine Environment: Relevant Concepts

A detailed description of the principles of noise in the marine environment is outside the scope of this document. However, a few basic concepts will be important for the sections that follow. A brief introduction is provided herein. These concepts include a description of noise measurements, estimation of source levels, the time-varying statistical properties of sound, typical levels in the marine environment, and propagation in water of moderate to shallow depth.

3.2 Noise Measurements

There are a number of standardized measures developed over the last half century to assess noise impact on humans (Harris, 1994). No similar effort or body of research has been invested in developing noise metrics for marine wildlife, although NOAA has recently initiated the process of developing formal noise exposure criteria (e.g., Miller et al., 2007). In the absence of standards, a range of ad hoc measures and guidelines have been used. Those applied by NOAA to marine mammal permits and incidental harassment authorizations (IHAs) are also summarized below.

Sound is produced by a traveling pressure wave that alternately compresses and rarefies the medium in which it travels. The pressure is represented by positive values when the medium is compressed and negative values when it is rarefied. This alternating pressure is sensed by the ear as sound as long as the rate of compressions and rarefactions (the frequency) is within the range that the animal can perceive. Frequency is expressed in units of cycles per second (Hz). The perceptual equivalent of this measure for humans is pitch.

The magnitude of the compressions and rarefactions, called the amplitude of the moving wave, is another important property of sounds. It corresponds approximately to human perception of loudness. Amplitude is usually quantified on a decibel scale. In the following example (Equation 1), level is calculated in units of sound pressure level (SPL):

Equation 1 $$\mathrm{dB} = 20*\log_{10}(p/p_0)$$

where p is the instantaneous pressure of the sound and p_0 is the reference pressure (more on this below). In practice, SPL in decibels (dB) is calculated by taking root-mean-squared (RMS) of a series of pressure samples. This is done to quantify the magnitude of the wave regardless of whether the pressure is positive (compression) or negative (rarefaction). Otherwise, the sum of all the pressures would sum to a value close to zero. Thus, in practice, the equation is written

Equation 2 $$p_{RMS} = \sqrt{\frac{p_1^2 + p_2^2 + p_3^2 + \ldots + p_n^2}{n}}$$

for a sample of n pressure measurements. In words, it is the square root of the average of all the pressure measurements squared. For the simplest kind of sound, a constant tone, the RMS pressure is 0.707 times the maximum pressure. Based on this equation, RMS SPL in decibels is calculated as follows:

Equation 3 $$\mathrm{dB} = 20*\log_{10}(p_{RMS}/p_0)$$

the important things to note are that decibels are measured on a logarithmic scale and expressed relative to a reference value. This type of measure is called a level. The mathematics of logarithms can result in some counterintuitive results when noise from multiple sources are combined. For example, when two sounds of equal level are added, the result is always 3 dB higher. Thus 72 dB + 72 dB = 75 dB and 0 dB + 0 dB = 3 dB. If two sources differ by more than 10 dB, the outcome of adding them is essentially equal to the higher of the two levels, e.g., 72 dB + 50 dB = 72 dB.

The reference pressure also causes confusion. In air, the reference pressure is the nominal lower limit of human hearing (20 µPa), also called the threshold of hearing. This value was selected to make 0 dB the threshold of hearing at frequencies that humans hear well. Negative numbers indicate that a level is inaudible to humans, although other animals may be able to hear it. In water, the reference pressure was selected to be 1 µPa for mathematical convenience. Thus, sound pressure levels measured in the two media are not directly comparable.

The final source of confusion is the type of physical quantity being measured. The decibel unit is applied to a number of physical quantities in acoustics, including pressure, power, intensity, and energy, which are all expressed as levels in dB. Simply knowing the value in dB is not sufficient to interpret a level. The crucial characteristics that must be specified are (1) the physical quantity (pressure, etc.), (2) the associated reference value, (3) the range of frequencies over which the measurement was made (for human applications this is often a filter function referred to as A-weighting), and (4) the time interval over which the sound was measured.

Those who are not familiar with decibels are often surprised by the apparently high levels of sound reported in water. The cause of this confusion is partly the difference in reference pressure between air and water described above. It translates to a 26 dB difference in the level for a sound of the same pressure ($dB_{water} = dB_{air} + 26$ dB). Another source of confusion is that air and water have very different densities. From a physics point of view, this impedance mismatch means that levels cannot be compared directly, even if the difference in reference level is accounted for. They can only be compared using a measure that takes density into account. Ketten (2000) and NRC (2003) provide lucid descriptions of the calculations used to make the comparison using intensity as a measure (Watts/m^2). After accounting for reference pressure and impedance mismatch, the difference in levels of sounds of the same intensity in air compared with water is 62 dB. That is, a sound of comparable intensity in air and water will have a measured SPL in water 62 dB higher. To put the difference in perspective, the minimum level typically encountered in air is about -20 dB (that is, about 20 dB below the threshold of human hearing). In water, the comparable minimum is about 40 dB re 1 µPa, or about 60 dB higher.

To add to the confusion, reference pressure is not specified when reporting levels in air, whereas it is specified in all other media. This is a very anthropocentric perspective, but it is currently standardized, so readers must simply be aware of the difference.

Another important factor is the distance between the source and location where it is received. Source level, the estimated level of a sound source at the point where it is produced, is arbitrarily expressed as level at 1 m distance (@ 1 m). Received levels vary with the distance from the source. The equation describing transmission loss with distance is:

Equation 4 $$RL = SL - C_L * \log_{10}(R)$$

where RL is the received level measured at range R, SL is the source level, and C_L is the spreading coefficient. C_L is 20 in the ideal case, where sound travels unobstructed in every direction. Note that in this case the range term in Equation 4 could also be written as $\log_{10}(R^2)$, demonstrating that sound from an unobstructed point source declines in relation to the square of the range.

Figure 8 shows two sample representations of a series of acoustic events to illustrate how the basic concepts above are turned into metrics characterizing real-world sound. The upper panel is a spectrogram, a graph that shows time (x-axis), frequency (y-axis) and level (a color scale with yellow indicating the highest level). The spectrogram is a good visual representation of changes in sound over time as they would be perceived by the ear. The example in Figure 8 was collected off the Pioneer Seamount offshore of Central California (Bland and Garfield, 2002). It spans a 40 min period, which begins with a blue whale calling, followed by the noise from one pass by a ship. There is also an oceanographic beacon operating in the vicinity, visible as a narrowband tone lasting several minutes (RAFOS beacon). Even though the beacon overlaps in time with the blue whale calls and has a level high enough to appear as an event on the spectrogram, it is separated in frequency and lower in level, and thus is clearly distinguishable. Similar sounds are unlikely to make whale calls undetectable (masking). The ship noise, on the other hand, is so intense that the whale's call is effectively masked, at least from the perspective of the receiving station. The whales' behavior cannot be determined in the presence of this masking sound, so it is unclear how they responded. The issue of masking is an important one, and will be discussed as a possible effect in later sections. An inset shows the spectrogram of an intense natural source, an earthquake, as a point of comparison.

All of the sounds in this 40 min period can be represented solely in terms of time and level, with values for all the frequencies that were measured added to produce a single number. This representation is referred to as a time-history (integrated level vs. time). The lower panel in Figure 8 shows a sketch of the time-history of events in the upper panel, with whale calls and ship noise appearing as intense peaks (noise events) against a background of ambient noise, the ensemble of all the indistinguishable signals with lower amplitudes that make up the background. The whale calls produce short individual peaks, whereas the ship event is prolonged and of greater amplitude. Thus, one measure for assessing the potential impact of sound on whale calls is the period that the calls would be masked by ships.

Some of the metrics used to describe ship noise are shown in the lower panel of Figure 8. The sample with the highest value is referred to as the peak. For some types of signals (e.g., explosions), the peak may be produced by either a positive or negative change in pressure. Therefore, if there is any possibility of confusion, the type of peak must be specified. For complex sounds such as ship noise, the maximum positive pressure is typically assumed.

Root-mean-square [RMS] sound pressure level [SPL] is usually used to represent the level of events. It is calculated by taking the square root of the sums of the squared pressures over the course of the entire sound. This approach is taken rather than simply summing pressures because pressures may be either positive or negative, and a level might add to zero if only the raw measurements were used. The RMS level represents absolute magnitude. It is accumulated over the duration of the noise event (e.g., the ship passing), and typically has a value within a few dB of the peak.

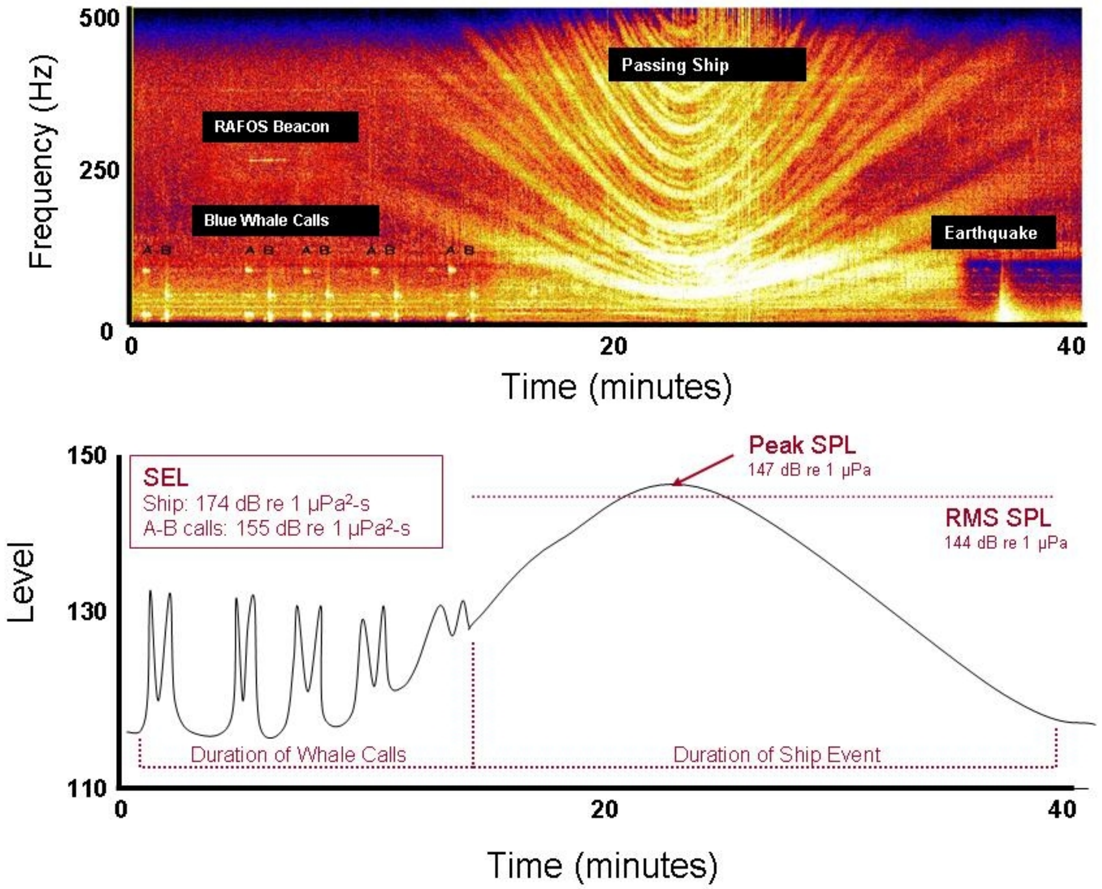

Figure 8. An example of noise including the passage of a ship [image from Bland and Garfield (2002)]. The upper panel shows the spectrogram of the noise, with sources identified. The lower panel is a sketch of changing level over time, as received at an arbitrary point. Noise metrics used to represent ship and whale sounds are illustrated.

RMS SPL is often taken as the default metric for level, but it does not represent the accumulated energy of exposure over an entire event (e.g., the total duration of a ship's passage). For example, a short sonar ping or a long tonal from an oceanographic source could have the same RMS SPL, but would expose animals to very different amounts of noise energy. An integrated measure that allows events of varying duration to be compared is sound exposure level (SEL), expressed in dB referenced to one micropascal squared-second (1 μPa^2-s). This measure is usually conceptualized as the energy of exposure, but sound exposure (E) is not energy (measured in joules), but rather a highly correlated measure that can be calculated using easily-obtained pressure measurements (NRC, 2003).

Peak SPL, RMS SPL, and SEL are potentially useful predictors of effect for hearing damage and alterations in animal behavior. However, other effects, such as masking, are best predicted by the duration or proportion of time that noise exceeds some reference level or signal, such as a call. Effects caused by long-term exposure to time-varying real-world noise, such as masking, may be better-characterized by metrics that represent the statistical properties of sound. In studies of environmental noise, statistical measures typically used include:

- *Median* – the level exceeded by half the sample, usually expressed as the level at the 50th percentile (L_{50})
- L_{90} – the level exceeded by 90% of the sample, a measure of the background or ambient level
- L_5 or L_{10} – the level of high-amplitude noise, typically measured by the level exceeded by 5% to 10% of the sample.
- *Exceedence time* – the proportion or duration of samples exceeding a criterion level, for example the total time in the sample exceeding 120 dB re 1 µPa.

Unfortunately, peak and RMS SPL have historically been the only measurements of noise provided in studies of anthropogenic sources. Without additional information, long-term average exposure and the potential for noise masking cannot be determined.

One final representation of noise is important to predicting effects, the spectrum of a sound (Figure 9) (plural: spectra). It shows the relationship between frequency and level. The important points for the purposes of this document are that (1) duration can dramatically affect relative level with frequency across a spectrum, so it must be at least implicit for the spectrum to be interpretable, and (2) the physical quantity (in Figure 9, power spectral density in units of uPa^2 per Hz) varies depending on the application for the information and the type of sound being measured. The rationale for spectral representations is described in more detail by Richardson et al. (1995b). Typically, spectra are made from samples of sound collected under known conditions, e.g., a 5-min sample of the noise produced by a vessel with known distance and aspect.

The spectrum in Figure 9 shows frequency on a logarithmic scale, a typical method for representing anthropogenic noise, which has most of its energy at low frequencies. Figure 9 indicates that the tug docking operation represented by the spectrum has most of its power in the range from 200 Hz to approximately 4 kiloherz (kHz) and from 50 Hz to below 10 Hz, that there is a tonal (sound with narrow bandwidth) at 50 Hz, and that there is relatively little energy in the sound above 10 kHz.

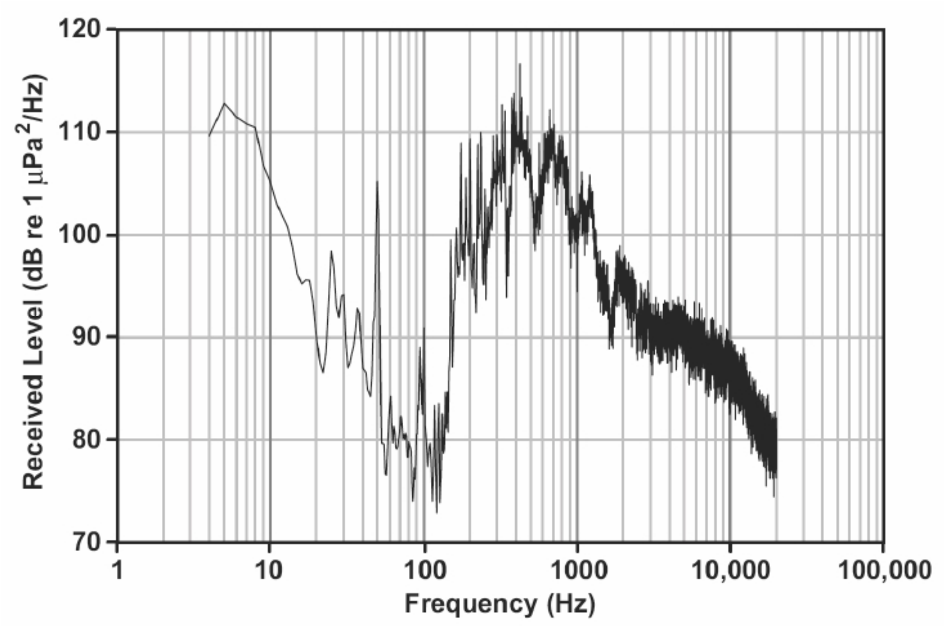

Figure 9. Underwater narrowband spectrum from the recording of tug docking a barge in Cook Inlet, Alaska Blackwell & Greene (2002).

3.2.1 Estimation of Source and Received Level

In the simple transmission loss model given above (Equation 4), the source was presumed to be a point radiating sound in all directions. If a sound is being produced by a whale or small boat in relatively deep water, this assumption is reasonable at even moderate distances (e.g., 100 m) from the source. However, if the source is a ship 450 m in length, there may be considerable separation between the various places where sound is emitted, such as propellers, engine plant, and generators. In addition, the body of the vessel may shadow noise produced at the rear, reducing the received level at the front (e.g., Blue and Gerstein, 2005). The estimation of received level will be complicated further if the ship is escorted by support vessels. Within several hundred meters of a ship with escorts, propagation will vary considerably based on ship aspect and the location and behavior of support vehicles.

The spreading coefficient (C_L in Equation 4) varies greatly depending on bottom, water depth, and the density of the water column. As a rule of thumb, a coefficient of 20 indicates that sound is spreading spherically in three dimensions away from the source (usually called spherical spreading), the simplest case. When the range R is greater than depth, sound can no longer spread spherically, and begins to spread in a plane. This is called cylindrical spreading, with a spreading coefficient of 10. Intermediate values (10-20) can be found depending on variations in water density, currents, and bottom topography. Coefficients below 10 can be found in very shallow water and areas with reflective sides and bottom, such as rocky canyons. In addition, once the sound wave begins to encounter obstacles (e.g., a change in water density, the surface, or a rocky prominence), it is reflected or refracted and the relationship between distance and level becomes much more complex. The different paths traveled by sound are modeled as rays emanating from the source. There is extensive literature describing sophisticated mathematical models for predicting propagation of sound, for example based on ray tracing; a description of these methods is outside the scope of this document (see Medwin and Clay, 1998).

Because propagation in marine mammal habitat is often complex, it is usually wise to obtain empirical measurements of transmission loss directly. This information can be used directly at specific locations (e.g., the level received close to a Steller sea lion haul out). Empirical measurements are also essential for determining whether models represent the propagation in a given environment well. Finally, they are used in estimating source levels, which must be back-calculated from measurements made at a distance (Figure 10).

When the noise of interest is produced by vessels in complex environments such as the Sound, there is no substitute for direct measurements of received level. Figure 10 gives an example from Blackwell and Greene (2002). These investigators made measurements of transmission loss and source levels from various large vessels operating in Anchorage harbor.

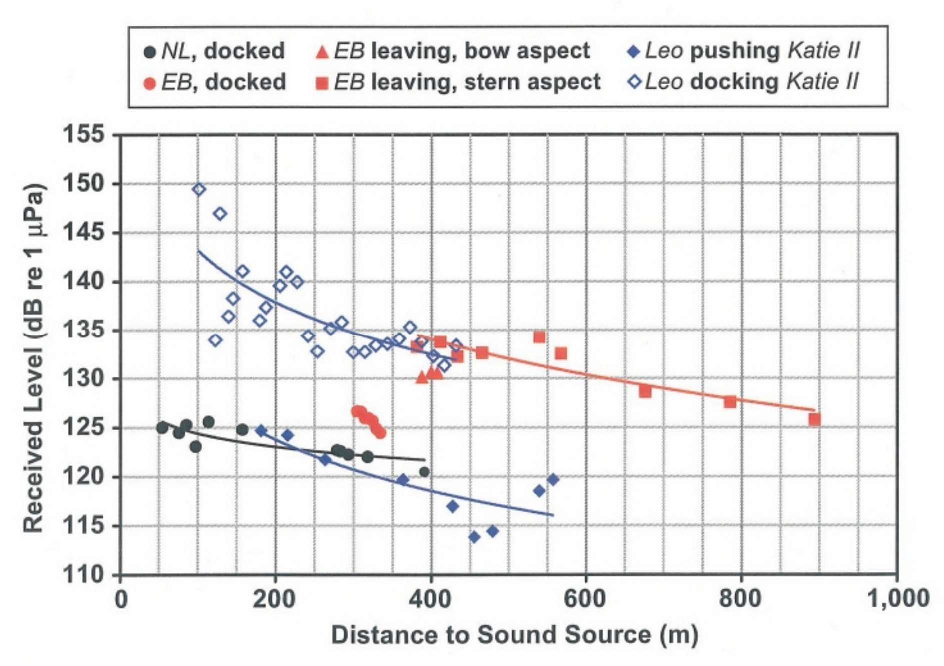

Figure 10. Broadband underwater SPLs as a function of distance to sound source for various large vessels operating in Anchorage harbor. (Blackwell and Greene, 2002)
NL = Northern Lights (cargo ship); EB = Emerald Bulker (bulk carrier); Leo (tug0; Katie II (barge)

The results of Blackwell & Greene (2002) are summarized in the section on ship noise below. The important point for introductory purposes is that these measurements were made at ranges from 100 m to about 1 km from large vessels under real-world conditions to obtain transmission loss equations, and that the source level was back-calculated by fitting regressions to the individual datapoints. Therefore, source level should be viewed as an idealized representation of the level produced by a source such as a tanker, rather than an estimate of what would actually be experienced by a marine animal at close range.

As an example, the transmission loss equation for the cargo ship Northern Lights while docked was

Equation 5 $RL = 133.5 – 4.5*\log_{10}(R)$

In this equation, estimated source SPL was 133.5 dB re 1 µPa, while transmission loss with distance was minimal (C_L only 4.5). Blackwell & Greene (2002) reported source levels as high as 188.8 dB re 1 µPa from the cargo ship Emerald Bulker underway in open water, with C_L of

21. The importance of the spreading coefficient is clear in these two examples – despite a difference of several orders of magnitude in the source level (a 20 dB increase in SPL corresponds to a 10-fold increase in sound pressure), the received level from the two ships would have been equal at a range of approximately 1 km.

At long ranges, oceanographic conditions also have an important effect on the transmission of noise. Salinity, temperature, and pressure vary with depth, affecting the density of the water substantially in the water column. If the density gradient is steep, sound can reflect from the gradient, just as it does from the sharp density gradient at the surface of the water. In addition, some frequencies are absorbed more efficiently by water than others. High frequencies are subject to an important effect from absorption, and they are also reflected more efficiently by all types of barriers. Thus, a 10 ms high intensity sound with substantial energy at moderate to high frequencies (e.g., a seismic survey pulse) in water can 'smear' over distance as different frequencies are absorbed, reflected, and refracted differentially. It would be received at long range (10s-100s of kilometers) as a transient lasting hundreds of milliseconds with little remaining high frequency energy.

3.2.2 Noise in the Marine Environment

Noise in the ocean varies greatly depending on proximity to high-amplitude sources such as ships and whales, topography, bottom composition, presence of concentrations of marine organisms and bubbles in the water, and the sound speed profile of the water. Ocean noise has been studied extensively for military, fishery, and oceanographic applications for many years. Useful introductions to the subject can be found in Wenz (1962), Richardson et al. (1995b), and Dohl et al. (2007). However, intensive efforts to assess impact on marine mammals and fish are recent. The relative contributions of various sources to the noise environment they experience are still poorly understood.

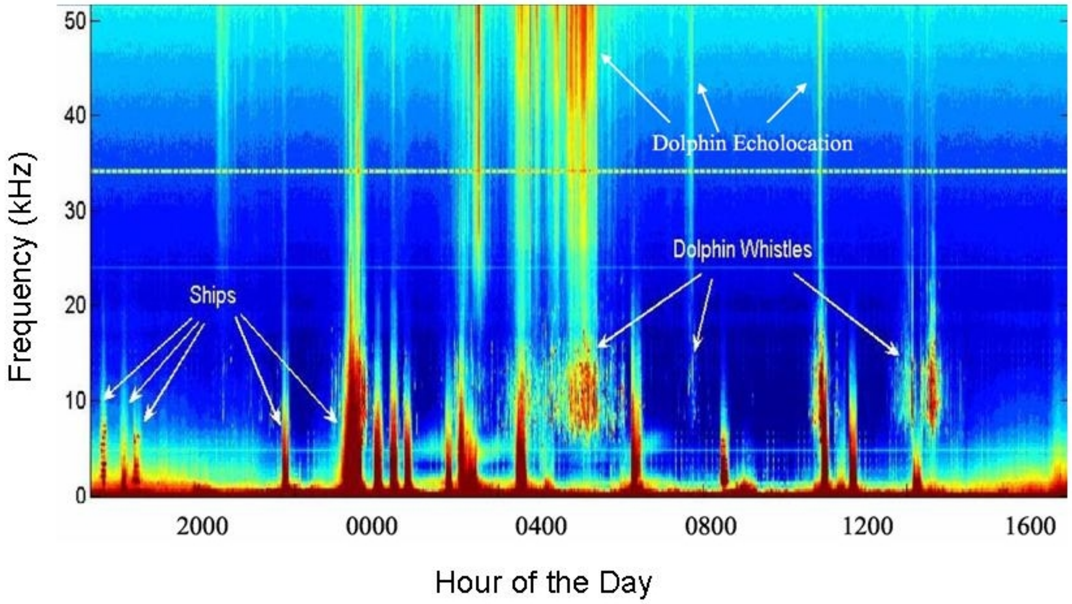

Figure 11. A one-day segment of noise collected in the Santa Barbara Channel off California at frequencies up to 50 kHz (Hildebrand, 2007).
Ship events and the vocalizations of dolphins occur intermittently over the course of the day-night cycle.

Figure 11 shows an example of a long-term spectrogram of ocean noise collected by Hildebrand (2007) in the Santa Barbara Channel off California. The site was located in a shipping lane. At least 15 ship events occurred over the course of the day-night cycle. The figure also shows noise produced at 35 kHz by an echo-sounder. Schools of small dolphins are evident in the spectrogram, whistling and echolocating, particularly at night. Two important points emerge from the figure. First, although traffic in the shipping lane was reasonably heavy, the total proportion of time when vessel noise could have masked whistling dolphins was not high (10%-20% at the receiver). Second, the frequency band of dolphin signals was high, limiting the effectiveness of the ship noise as a masker. If the sound had been represented as an average over time, the ships might have been seen to mask dolphin whistles effectively. However, when viewed over time, it is clear that they had many periods of quiet in which to communicate. This figure shows the importance of knowing not only the frequency and level of the noise, but also its statistical properties in time, the characteristics of signals produced by the animals, and the range of their hearing sensitivity.

3.3 Acoustic Characteristics of Sources in Prince William Sound

This review uncovered no systematic efforts to monitor the noise in PWS or to characterize the contribution of the various sources identified in Section 2.0. What follows is a summary of the characteristics of noise likely to be produced by the important sources in PWS based on studies of similar sources in other areas, including measurements made nearby in Cook Inlet. Although criteria used by the National Marine Fisheries Service for protecting marine species from noise are usually specified in terms of level, other characteristics, such as the frequency range of noise and duration of exposure, are also important predictors of effect, and will be considered in the review where information is available. Relevant characteristics of fish and marine mammal hearing and vocalizations are described in Appendix A and Appendix B.

3.3.1 Heavy Shipping: Tankers and Bulk Carriers

Generally speaking, noise from large commercial vessels (tankers, bulk carriers, and cruise ships) is the dominant source of anthropogenic noise at low frequencies in the ocean. This noise is omni-present, continuous, and has increased steadily over the last half century. The characteristics and trend in ship noise have been considered in a few recent studies because the noise has a significant potential to mask sounds produced by whales that depend on the low frequency band for communication and navigation (Mazzuca, 2001). A recent study conducted west of San Nicolas Island, California, showed that average ambient noise levels in the 30-50 Hz range used by large baleen whales such as fin and blue whales had increased at a rate of 2.5-3 dB per decade between 1964 and 2004 (McDonald et al., 2006). This increase was associated with a doubling of commercial vessel traffic during the same period. Generally speaking, commercial shipping has raised ambient low frequency noise primarily in the 10-40 Hz frequency band by as much as 10-16 dB compared to that of the pre-industrial era. However, these authors only collected long-term averages of noise produced by ships at long range. They did not describe the statistical properties of the sound received by whales over time.

The level and frequency characteristics of ship noise correspond roughly to ship size and speed. Oil tankers and bulk dry transport vessels represent nearly 50% of the total gross tonnage presently operating in the marine environment, but less than 19% of the total number of vessels in the world’s commercial fleet (Lloyd's Register). It has been argued that the larger vessels are the greatest contributors to shipping noise, particularly the largest and fastest ships. As a rule of thumb, horsepower to the 4/3-power is correlated with noise power. Engine type is also a contributing factor. Slow-speed diesel engines (< 250 rpm), such as those of container ships, large tankers, and freighters, are relatively quiet compared to medium- and high-speed diesel engines (Ross, 2005). The majority of noise produced by slow-speed diesel engines is a result of propeller cavitation, which creates tones from approximately 100 to 1,000 Hz (Richardson et al., 1995b). Large ships typically produce the greatest noise at low frequencies, in the 10-300 Hz frequency band (Ross, 1993). The noise consists of narrowband tonal sounds below 50 Hz and broadband sounds that have greatest energy between 50-150 Hz.

Commercial vessels (> 135 m) typically cruise at speeds between 16-17 knots and emit noise with estimated source levels between 155-190 dB re 1µPa at 1 m (Table I). Noise data from Scrimger and Heitmeyer (1991) for three ship classes (1) passenger/ferries (2) cargo ships and (3) tankers show that mean spectra lie within 2 dB of each other over the 70 to 700 Hz frequency band, except between 570 and 700 Hz, where the mean spectrum for tankers is approximately 4 dB lower. The mean spectra for the three classes was reported to be within one-half of a standard deviation, suggesting that source spectrum statistics for a given region should be largely independent of the makeup of large ship traffic in a given area.

Figure 12 shows some examples of transmission loss from bulk carriers, tugs, and barges reported by Blackwell & Greene (2002) in Cook Inlet and the port of Anchorage. In deep water, decays of 60 dB occur within the first 500 m of distance from a large ship, with the majority of decay within the first 100 m. However, for some vessel configurations and in shallow water, noise attenuates slowly, and may remain constant at long ranges from the vessel (e.g., Northern Lights, Figure 9). Tugs produce more moderate levels, but have higher energy frequencies (Table I).

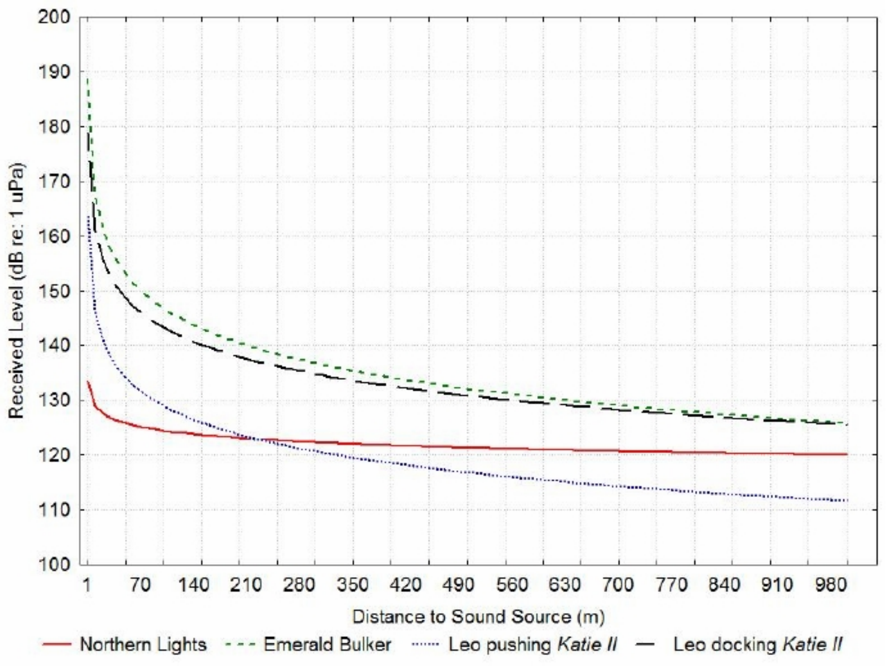

Figure 12. Transmission loss of vessels that are models for oil-industry activities in PWS. Broadband underwater SPLs are plotted as a function based on data of Blackwell and Greene (2002). Northern Lights is a cargo ship, Emerald Bulker a bulk carrier, Leo a tug, and Katie II a barge. The levels were calculated using the formulaRL = SL + B*log(R) where RL is the received level, SL is the hypothetical extrapolated source level at 1 m, B is spreading loss term, and R is range in m.

Table I. Estimated source levels of noise components from vessels.

Vessel Type	**Dominant Frequency (Hz)**	**Source Level (dB re 1μPa-m)**	**Frequency Range**
Outboard*	630	156	100 Hz - 3 kHz
Trawler*	100	158	50 Hz - 1 kHz
Conventional Tug†	1,000	164	10 Hz - 1 kHz
Tanker‡	60	180	-
Bulk Carrier*	100	173	-
Supertanker‡	6.8	190	50 Hz - 300 Hz

* Source level of dominant 1/3-octave band ‡ Source level of dominant tone.† Pulling an empty barge.
Source: Richardson et al., (1995b)

3.3.2 Other Vessel Traffic

Cruise ships are the other type of large vessel that frequently use PWS. There has been little effort to measure the characteristics of noise produced by large cruise vessels, nor has their impact on wildlife been considered often. They are likely to produce noise similar to that of bulk carriers and tankers (Richardson et al., 1995b).

The noise produced by medium- and high-speed diesel engines typically used for fishing is due mainly to the revolutions of connecting rods and not to propeller cavitation as in large bulk carriers (Richardson et al., 1995b). These sources are less intense than heavy shipping, but have tonal components across a broad frequency range and substantially more energy at higher frequencies. Locally, they are likely to be important sources of masking noise.

3.3.3 Navigation and Fish-finding Sonar

Military sonar systems exist across the range of frequencies, but civilian systems (e.g. fish finder or echosounder) operate at higher frequencies, typically in the range from 38 kHz to around 200 kHz. Most echosounders operate at two frequencies, 50 kHz and 200 kHz, which are above the range that most fish can hear, but within the hearing range of many marine mammals (NRC, 2003). Other types of active sonars include systems used for oceanographic and fisheries applications to measure depth, currents, bathymetry, and plankton. All of these sonars produce narrowband tonal signals at very high level, often with source levels in excess of 200 dB re 1 µPa. Because the frequencies are high, pings attenuate quickly, but marine mammals such as Steller sea lions or porpoises that are in the habit of following vessels are likely to be exposed at high levels. Surprisingly, these intense sources have generated little interest as potential hazards to marine mammals and empirical measurements have been made only rarely.

4.0 Impact on Fish Species

The sections that follow describe potential effects of TAPS traffic and other noise sources on fish and marine mammals. Supporting literature describing the characteristics of fish hearing and acoustic signaling is extensive, and has been summarized for the purposes of this report in Appendix A-2. The review sections are broken down by potential effect type, on distribution, hearing, behavior, and physiology. Data on species of concern in PWS have been given priority during the review where data were available. Because the number of fish species of importance in the Sound is large and the data on potential impacts fairly limited, the information available regarding potential impact on any one species was always limited. Available information on other fish species were used as an alternative as needed.

4.1 Anthropogenic Noise Effects on Fish

Effects of noise on fish have been studied in the context of fisheries resources for many years, typically to determine the effect on catches. However, efforts to understand effects on fish hearing and health have only been initiated in recent years.

4.1.1 Distribution

If noise were to cause changes in fish distribution, the entire fishing industry of Alaska could be affected. However, no systematic studies have been conducted on changes in fish distribution due to noise from heavy shipping, such as tankers. The available information comes from studies of movements in relation to fishing and seismic survey vessels.

Observations of in changes of fish behavior have documented short-term movements in response to vessel noise (see section on behavior below) but have not shown long-term effects on distribution of species. Unfortunately, none of these studies have collected information on the relative locations of individual fish with relation to the range and bearing of the noise source. Fish have reasonably good hearing (Appendix A-2) and appear to respond in a flexible and dynamic manner to noise sources. Thus, while they may learn to avoid specific sources, such as fishing vessels, they have not been shown to avoid favored habitat over the long term in the presence of vessel noise. Instead, they appear to move out of the area when the vessel is present, and return to their normal activities when it has gone by.

None of the studies reviewed the potential for noise masking of biologically-important signals, such as communication or navigation signals in fish exposed to vessel noise or other continuous sources. Most of the fish species in the Sound hear in a narrow range, between 125 Hz and approximately 4 kHz, which is also the range where noise from vessels is most prominent. The effects are unlikely to be important at long range, as most species have low hearing sensitivity (thresholds in the best range in excess of 90 dB re 1 μPa) (Appendix A-2).

4.1.2 Hearing Damage

Studies of physiological changes in fish ears have been uniformly concerned with short-term exposures to high-intensity transients (e.g. impulses from airguns, tone bursts). Nothing is known regarding fish susceptibility to noise-induced hearing loss due to long-term exposure under free-ranging conditions. What follows is a summary of the literature on hearing damage after exposure to short-term high-intensity transients. This literature cannot be extrapolated to effects of ship noise easily. First, impulses are poor models for chronic broadband noise. Second, variability in susceptibility to impulse noise is very high across individuals and species. Finally, there are large anatomical differences among fish taxa. Some fish are hearing 'specialists' with anatomical structures that give them greater sensitivity or a wider frequency range of hearing (Appendix A-2). However, most marine species are 'generalists' having relatively low sensitivity and a narrow range.

Effects of noise on hearing are measured in several ways. First, the threshold for temporary changes in sensitivity can be measured (temporary threshold shift or TTS) and treated as a conservative measure of the threshold for injury. Second, the noise required to produce permanent threshold shifts (PTS) can be measured directly. Third, the threshold for PTS can be approximated using the level at which TTS becomes maximal. Finally, histological examination of the inner ear can be used to determine whether damage has occurred. Unfortunately, functional loss and physical damage observed histologically are often difficult to relate.

Exposures using broadband and tonal noise in the laboratory suggest that there is a threshold of injury after exposure to continuous noise at levels on the order of 150-170 dB re 1 µPa (about 60 dB above threshold in the midrange of hearing). Popper and Clarke (1976) exposed goldfish (Carassius auratus) to tonal signals for 4 hr at 149 dB re 1 µPa. These exposures caused TTS lasting 2-4 hr, but the shifts recovered completely. Similar findings were reported by Scholik and Yan (2002) for the bluegill sunfish (Lepomis macrochirus). Cox et al. (1987) stimulated goldfish with pure tones at levels of 197 and 204 dB re 1 µPa for 2 hr and found evidence of significant hair cell damage, although functional shift was not studied. Smith et al. (2004b) exposed goldfish to broadband noise at levels of 160-170 dB re 1 µPa for one to 21 days. They experienced TTS of up to 28 dB after exposure that recovered substantially over an 18 day period after exposure. Hair cells in the ears of a freshwater fish, the oscar (Astronotus ocellatus), were exposed to levels ranging from 100-180 dB re 1 µPa for 1 hr. Damage was detectable in the inner ear of four out of five fish after exposures at the highest level, 180 dB re 1 µPa, four days after exposure (Hastings et al., 1996).

Results of exposure to impulse noise varied substantially from species to species. For example, Popper et al. (2005) studied TTS in several species of lake fish exposed to seismic airgun pulses. In two of their study species (broad whitefish [Coregonus nasus], young-of-the-year northern pike [Esox lucius]), they found no effect on hearing after five or twenty impulses from the airgun. Lake chub (Couesius plumbeus) and adult northern pike both exhibited TTS within a few minutes of exposure, but 18 hours after exposure all thresholds returned to levels close to those of controls. Fish were observed for 24 hours post-exposure and no further TTS was observed. No histological examinations were performed.

Comparable evidence of damage has been obtained in studies of marine fish, even though these species. These data are at least consistent with what has been found in laboratory-raised and freshwater species. Enger (1981) exposed Atlantic cod (Gadus morhua) to continuous noise in their midrange for 1-5 hr at 180 dB re 1 µPa. They found that sensory cells in the saccule were destroyed. McCauley et al. (2003) conducted experiments on Australian pink snapper (Pagrus auratus), a hearing generalist, using pulses from an airgun (received levels 150-180 dB re 1 µPa RMS SPL at 6 pulses/min for over 3 hr). Fish sacrificed 18 hours after exposure showed damage to the membranes of the inner ear and loss of hair cells compared with the control group. A third group of fish, sacrificed 58 days after exposure to the air-gun array, showed significantly ($p << 0.001$) more holes in the membrane than the other two groups, suggesting that the fish did not recover from the damage over nearly two months , and may have experienced growth of damage instead.

In the experiments described above, the relationship between TTS and damage to the inner ear great enough to cause permanent loss (PTS) could not be determined. TTS caused by exposure at levels above the threshold of hearing is used as a rough measure of the threshold for hearing loss in animals that cannot be damaged experimentally. Smith et al. (2004a) plotted data on the relationship between TTS and the level of noise above threshold, showing that there is an approximately linear relationship between TTS and level above threshold (SL) (Figure 13). In mammals, the relationship is steep, and permanent losses becomes much more likely if TTS values in excess of approximately 40-50 dB are observed (SL > 80 dB). However, the slope of the TTS/SL correlation is much lower in fish. The lower slope may reflect a narrower dynamic range in the fish ear. If so, PTS would be predicted for the greatest values of TTS even though they were substantially lower than those found at the onset of PTS in birds and mammals. The ensemble of available data on fish supports this hypothesis, but the relationship between TTS and PTS has not been studied systematically.

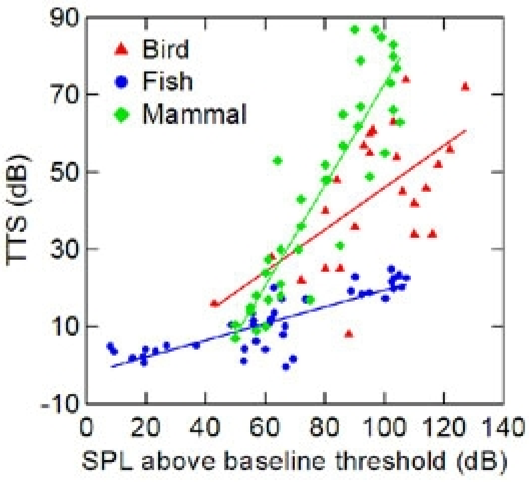

Figure 13. Relationship between TTS and PTS in mammals, birds and fish. Data from Smith et al. (2004a).

There are other reasons for treating the limited data on hearing loss in fish with caution. Prediction of effects on hearing fish hearing is complicated by a variety of factors that can affect sensitivity. First, while mammalian hair cell loss it usually permanent, in other vertebrates, including birds, fish, reptiles, and amphibians, hair cell regeneration occurs (Corwin and Overholtzer, 1997). This capability persists throughout life in fish. Fish auditory sensitivity is also likely to be affected by temperature. Finally, recent evidence (Sisneros et al., 2004) suggests that auditory sensitivity of some fish may be under hormonal control, with sensitivity increasing in both sexes during breeding. Until there are better data on PTS in marine fishes, a conservative approach should be taken where noise levels are above ~150 dB re 1 µPa for long periods.

4.1.3 Noise Masking

While some fish are specialized to produce complex, high-amplitude sounds, the commercially-important species in PWS are not known to be acoustic specialists. Fish produce acoustic signals using a variety of structures, including specialized gill arches, muscles that drum the swimbladder, and the jaw. They produce broadband transient sounds that are variously described as clicks, claps, and pops, or series of such sounds described as hums, drumming, grunts or buzzes. To the extent that fish source levels have been measured, they are usually low to moderate (70-135 dB re 1 µPa) (Sprague and Luczkovich, 2004; Wahlberg and Westerberg, 2005), raising the concern that masking produced by constant vessel traffic might be surprisingly important in fish. However, there have been no studies on the impact of masking by broadband anthropogenic noise on fish, such as interference with social signals or predator-prey interactions.

4.1.4 Behavioral Responses

A theoretical literature is now developing that interprets disturbance responses of vertebrates as expressions of a strategy for defense against predators (Frid and Dill, 2002; Gill et al., 2001; Ydenberg and Dill, 1986). This approach is useful because it explains many of the apparent contradictions in the literature on vertebrate responses to anthropogenic noise. It interprets choice of response as a behavioral strategy that depends on the risk posed by the noise source, familiarity with similar noise, and environmental context, rather than as a simple, reflexive reaction to a loud noise.

The literature on short-term behavioral responses of fish are certainly consistent with the defensive strategy model. Fish of several species avoided vessels that were actively fishing. Handegard and Tjøstheim (2005) measured the behavior of fish using a remote sonar station during the passage of trawling vessels. They found that fish began diving 15 min before the passage of a trawler, during the period when noise and the change in noise level were greatest. They swam ahead ('herding') or to the side depending on their location relative to the vessel. Draštik and Kubečka (2005) found that smaller fish exhibit avoidance behaviors to survey boats but that larger fish did not. They suggested that the behavior was an anti-predator defense. Røstad et al. (2006) were surprised to find their subject fish congregating underneath and around stationary research vessels, apparently using them as a refuge. They swam away from the research vessel to approach a passing commercial ship, returning to their original location once the noisier ship had passed. Thus, their findings could be interpreted as evidence that fish are attracted to noisy sources. The possible reasons for this attraction are unclear.

De Robertis and Wilson (2006) examined the behavior of walleye pollock (Theragra chalcogramma) in response to vessels while free-running and trawling to improve survey methodology. They examined sonar returns and found that average backscatter was greater while the vessel was free-running than while trawling, indicating that schools of pollock avoided the vessel while trawling. However, they were not able to measure the signal received by the fish, so they did not estimate a threshold for avoidance. Misund et al. (1996) measured the responses of Atlantic herring to noise from a survey vessel using an echosounder. Like Handegard and Tjøstheim (2005), they found that the fish appeared to be 'herded' in front of the vessel, possibly as a result of the greater received noise to the side of the vessel. More schools reacted to the side (50%) as opposed to the front (20%).

Studies have generally failed to find evidence that behavioral responses lead to long-term changes in fish density, at least in the range of detection available to experimental vessels. When examining acoustic backscatter data from fish schools, Draštik and Kubečka (2005) found no significant difference between fish biomass before, during, and after a vessel had passed. Jørgensen et al. (2004) saw no significant influence on capelin (Mallotus villosis) density during vessel transits but did note changes in diving behavior.

Laboratory experiments were conducted by Klimley and Beavers (1998) on three species of rockfish, exposing them to playback sounds similar to the signals produced by an intense low-frequency oceanographic source (ATOC). The fish did not spend significantly more time closer to or further from the playback sound when compared with silent control times. However, the signals produced had received levels that would be typical of exposure at moderate to long range, 123-153 dB re 1 µPa, so it is not clear what fish would have done close to the source.

4.1.5 Survivorship of Eggs and Fry

In general, early-life mortality of fish is high. Research into the effects of noise on eggs, larvae and fry is still limited, and results have been highly contradictory due to flaws in experimental design (e.g. Banner and Hyatt, 1973; Lagardere, 1982). One recent study (Sandstrom et al., 2005) examined the effects of boating and navigational activities on fish recruitment, focusing on young-of-the-year. Fish eggs that survived best on vegetation, such as Pacific herring (ADFG, 2005b), were found to be more abundant in undisturbed inlets (Sandstrom et al., 2005) than those with high boating traffic. However, the effect was most likely resulted from impact on the grass substrate or changes in flow rather than noise per se.

4.1.6 Physiological Effects of Noise

There is a limited literature on physiological responses of fish to noise. As yet, none have shown an association with biologically-significant effects, such as loss of health Smith et al. (2004b) measured plasma cortisol and glucose levels during exposure to broadband noise in the goldfish. They found a short-term spike in cortisol secretion during exposure to noise at levels 160-170 dB re 1 µPa. However, long-term elevation in cortisol levels did not result; cortisol concentrations returned to pre-exposure values an hour after the onset of exposure. Interpretation of these results is somewhat difficult without additional information on the regulation of stress in fish, however, as animals that show limited stress responses can be susceptible to different effects from those exhibiting strong ones (McEwen and Wingfield, 2003).

Wysocki et al. (2006) measured cortisol concentrations in fish in the Danube River and two Austrial lakes. The fish were exposed to levels of ship noise at 153 dB re 1 µPa for 30 min, the typical duration of exposure to passing shipping. They were also exposed to continuous broadband noise at 156 dB re 1 µPa for long enough to produce TTS in the two hearing specialists, carp (Cyprinus carpio) and gudgeon (Gobio gobio). They also examined European perch (Perca fluviatalis). All three species showed increased cortisol secretion in response to ship noise, but not to the broadband noise. The authors attributed the difference in responses to the time-varying characteristics of the ship noise, but it is also possible that previous experience with ships had an influence on cortisol levels. These authors did not determine the duration of increased cortisol secretion nor the increase that might have caused longer term effects.

5.0 Impact on Marine Mammals

Possible effects of anthropogenic noise on marine mammals are reviewed in this section. The subsections below review the background information on distribution, followed by a review of possible effects on distribution, survivorship, and reproduction; hearing; perception of biologically-significant sounds; and behavior. Supporting data on characteristics of marine mammal hearing and vocalizations can be found in Appendix A. Possible physiological or psychological effects, for which the literature is very limited, are considered in association with behavior (Section 5.5) because the effects of noise on physiology, psychology, and behavior are strongly interlinked. Effects on reproduction and health will be discussed in the same section.

5.1 Regulations and Guidelines Regarding Exposure of Marine Mammals

Under the Marine Mammal Protection Act of 1972 (MMPA), take ("harass, hunt, capture, or kill") of marine mammals is prohibited except under certain permitted circumstances. Thus, from a legal point of view, it is not permissible to disturb any of the marine mammals in the Sound. In addition to the threatened and endangered species described above, there are several other marine mammal species that might be found in PWS, including the gray whale, minke whale (Balaenoptera acutorostrata), sperm whale, beluga whale, killer whale, Dall's porpoise (Phocoenoides dalli), harbor porpoise (Phocoena phocoena), and harbor seal.

The MMPA defines takes due to harassment in two categories. Level A harassment applies to activities with the potential to injure an animal, which in the context of noise usually refers to temporary or permanent hearing loss. Level B harassment applies to activities that have the potential to disturb (disrupt behavioral patterns). NMFS Office of Protected Resources (NMFS/OPR) has used a number of ad hoc guidelines for limiting noise exposure since 1997 during consultations for IHAs and permits for research. The limits for "acoustic takes" relevant to TAPS ship traffic have been (70 FR 1871):

1. 120 dB re 1 μPa RMS SPL for prevention of Level B take during exposure to continuous or intermittent noise
2. 160 dB re 1 μPa RMS SPL for prevention of Level B take during exposure to impulse noise
3. 180 dB re 1 μPa for prevention of Level A take in all marine mammals

Because the agency does not specify duration of exposure or any frequency weighting procedures for these limits, they are subject to interpretation on a case by case basis. More formal guidelines are currently under development (Southall et al., 2007).

The NMFS/OPR guidelines have not been applied to activities widespread before the passage of the MMPA, including noise produced by vessels used in fisheries, recreation, and transport. Thus, most of the noise produced in PWS has not been subject to the existing guidelines. The agency is currently considering methods for limiting these widespread sources of noise (e.g., Southall, 2004) because they have the potential to produce biologically-significant effects over the long-term, but no formal rules have been developed as yet.

5.2 Abundance, Distribution, and Habitat Use

While abandonment of favored habitat is raised frequently as a potential impact of noise and vessel activity, the evidence for the effect is surprisingly limited. As was the case for fish, the limited available data indicate that marine mammals are flexible in their strategies for coping with noisy disturbances, minimizing costs to themselves in loss of habitat and additional energy expenditure while also limiting risk. Most studies that have quantified vessel noise as a source of disturbance have been short-term, focusing on behavioral responses (see Section 4.1.4), while those demonstrating that marine mammals can abandon favored habitat permanently in the face of disturbance have failed to show the characteristics of the stimuli that produced the effect. The best information has been collected with respect to stationary industrial sources, such as oil drilling platforms, rather than vessels.

5.2.1 Cetaceans

The best-documented case of abandonment due to disturbance was reported by Bryant et al. (1984) in a mysticete, the gray whale. Bryant et al. documented the decline and reoccupation of wintering gray whales (calving females, breeding adults) in Laguna Guerrero Negro in Baja California. The whales were exposed to heavy and uncontrolled commercial shipping and dredging activities from a salt mining operation starting in 1957. They had largely abandoned the lagoon as a breeding area by 1964. Once the vessel traffic and dredging activity was stopped in 1967, the whales began to use the area again and were present in numbers by the time Bryant et al. began surveys in the 1980s. This ‘unplanned experiment’ showed that gray whales can abandon critical breeding habitat in response to heavy vessel traffic and possibly habitat modification by industrial activity, but the stimuli producing the behavior were not documented.

5.2.2 Pinnipeds

Three haul-out areas in PWS are considered critical habitat for the Steller sea lion, located on Perry Island, Point Eleanor, and the Needle. None of these sites occur within the TAPS shipping lane, Valdez Arm, or Port of Valdez. However, the one on Perry Island is close to the channel used by cruise ships entering the port of Whittier. Within the marine mammal research community, Steller sea lions have a reputation for strong responses to disturbance, and concerns have been expressed regarding the impact of disturbance on the recovery of the species (Kucey and Trites, 2006). In the short-term they are capable of mass abandonment of hauling areas in the face of directed approach by vessels. However, there is little systematic information on behavior over time, e.g., abandonment of hauling areas. The available experimental evidence (Kucey, 2005) indicates that, like other otariids, they abandon hauling sites readily in the short-term, but do not abandon hauling areas as a result, at least when exposed to occasional disturbances. Some of their reactivity to approach may be explained by conflicts with fishers and hunters. Sea lions are still occasionally shot in PWS (Angliss and Outlaw, 2006), despite their protected status.

There has been no systematic effort to study the susceptibility of PWS harbor seals to disturbance, even though they have been the object of a subsistence hunt for many years (Appendix B). Harbor seals have a reputation for responsiveness to disturbance, but the ensemble of data available supports the hypothesis that they adopt a flexible defensive strategy based on experience. The literature on their responses has been reviewed recently (Grella et al., 2001) for the heavily-populated San Francisco Bay area. The authors found that harbor seals abandoned areas where they experienced persistent intrusions on hauling sites and breeding beaches, e.g., by fishers and clammers, but tolerated non-invasive approaches, such as passing kayakers or walking humans in areas where visitor activity was controlled (e.g., Children’s Pool in La Jolla, CA [Bowles pers obs.]). Lelli and Harris (2001) examined the factors that affected numbers of hauled harbor seals in the Gulf of Maine. They reported that close approach by motorized vessels explained 27% of the variance in counts of hauled seals.

The reputed sensitivity of both the Steller sea lion and harbor seal in PWS may be a product of experience. Unlike seals living in the vicinity of major metropolitan areas, harbor seals in more remote areas are highly responsive to disturbance (e.g. Bowles and Stewart, 1982), possibly because they are unfamiliar with the disturbances or more likely to be attacked by humans.

5.2.3 Otters

There is some evidence that sea otters may alter their use of habitat in areas with heavy boat traffic. Sea otters avoided southern Alaskan waters during periods with heavy boat traffic, but re-inhabited them during seasons with less traffic (Garshelis et al., 1984). Their behavior was suggestive of a dynamic response to disturbance, abandoning areas when disturbed persistently and returning when the disturbance ceased.

5.3 Hearing Damage

Hearing loss may be temporary (TTS) or permanent (PTS). In experiments exposing marine mammals to noise, levels have been increased gradually to ensure that only small shifts occurred. Recovery from loss was rapid in these experiments, as expected given small shifts. In humans and laboratory animals, large shifts, on the order of 40 dB or more, are needed to produce permanent hearing loss. However, TTS must be used as an estimate of the threshold for auditory injury in marine animals because (1) there are no good animal models that could be used in PTS experiments, (2) chronic exposure to levels that produce small shifts may cause permanent loss in the long-term, and (3) TTS is the only available conservative measure.

5.3.1 Cetaceans

As described in Appendix A, the hearing of mysticete cetaceans is difficult to study and poorly understood. There is no information on threshold of noise-induced temporary or permanent threshold shift any large whale.

Research on small odontocetes has shown that noise-induced hearing loss is possible if individuals are exposed to noise with substantial energy within the range of frequencies they hear well. However, levels required to produce temporary loss of sensitivity (TTS) were relatively high (more than 130 dB above threshold). Finneran et al. (2000) exposed two bottlenose dolphins and one beluga to pulses from an array of piezoelectric sound projectors that generated pressure waveforms resembling distant underwater explosions. The sounds had substantial energy in the subjects' midrange. No substantial (i.e., 6 dB or larger) threshold shifts were observed in any of the subjects at the highest received exposure levels (70 kPa [10 psi]; 221 dB re 1μPa peak to peak; and SEL of 179 dB re 1μPa^2-s).

Finneran et al. (2002b) repeated this experiment using single pulses from a seismic watergun. Experimental subjects were one beluga and one bottlenose dolphin. Values of TTS measured two seconds after exposure to pulses a few ms in duration were 7 and 6 dB in the beluga at 0.4 and 30 kHz, respectively (226 dB re 1μPa peak to peak; and 186 dB re 1μPa^2-s SEL). Thresholds could not be distinguished from the pre-exposure value within four minutes of exposure. No TTS was observed in the bottlenose dolphin at the highest exposure conditions (228 dB re 1μPa peak to peak, and 188 dB re 1μPa^2-s SEL]. These studies showed that, for short duration impulsive sounds, high sound pressures were required to induce TTS.

Schlundt et al. (2000) reported TTS in five bottlenose dolphins and two belugas exposed to 1-s pure tones. At frequencies of 3, 10, and 20 kHz, levels necessary to induce measurable amounts (6 dB or more) of TTS were between 192-201 dB re 1μPa RMS SPL (SEL: 192 to 201 dB re 1μPa^2-s). The mean level for TTS onset was 195 dB re 1μPa RMS SPL (195 dB re 1μPa^2-s). At 0.4 kHz, no subjects exhibited shifts after exposures up to 193 dB re 1μPa RMS SPL. The data at 75 kHz were inconclusive – one dolphin exhibited measurable TTS after exposure at 182 dB re 1μPa RMS SPL but not at higher exposure levels. The other dolphin did not show any shift after exposure to maximum levels of 193 dB re 1μPa RMS SPL.

Finneran et al. (2005; 2003) measured TTS in bottlenose dolphins exposed to 3 kHz tones with durations of 1, 2, 4, and 8 seconds. Small amounts of TTS (3-6 dB) occurred in one dolphin after exposure to between 190-204 dB re 1μPa^2-s. These results are consistent with those of Schlundt et al. (2000). These results also confirmed that for tonal noise of variable duration, the amount of TTS was best correlated with sound exposure level rather than RMS sound pressure level.

Additional research on cetacean TTS was performed by Nachtigall et al. (2004) using continuous band-limited noise. They exposed a bottlenose dolphin to octave-band noise with 7.5 kHz center frequency for 30 min and measured TTS 10-15 min after exposure. They found shifts of approximately 11 dB (maximum SPL: 179 dB re 1µPa and SEL ~212-214 dB re 1µPa^2-s). The total experimental time exceeded the net exposure time because the subjects had to surface to breathe during experiments. This time was measured and factored into the SEL measurement. No TTS was observed after exposure at a maximum sound pressure level of 165 and 171 dB$_{RMS}$ re 1µPa (~ 198-200 dB re 1 µPa^2-s and 204-206 dB re 1µPa^2-s respectively). They also measured TTS five minutes after exposure using evoked potentials (Nachtigall et al., 2004) (maximum SPL: 160 dB re 1µPa and ~193-195 dB re 1µPa^2-s). The difference in results (slightly lower TTS for exposures of much lower SEL) was attributed to faster post-exposure threshold measurement, and thus less opportunity for recovery.

These findings support the use of SEL in estimating the potential for TTS after exposure to sounds of varying duration. Using most conservative values obtained, an estimate of the threshold for TTS in SEL would be 190 dB re 1µPa^2-s. The shifts after exposure at this level were of short duration and small (3-11 dB). Low to moderate TTS results primarily from the fatigue of cochlear hair cells and supporting structures rather than damage and is completely recoverable. Higher levels would be required to produce PTS. In humans, when threshold shift magnitudes for single exposures exceed approximately 40 dB, the likelihood of PTS begins to increase substantially (Kryter, 1994) whereas no permanent loss is expected after substantially smaller shifts.

Note that the experiments described above were conducted using sounds with frequencies in the mid-range of the subjects' hearing, so that SEL values could be compared directly without the need for frequency weighting procedures. Sounds with broader bandwidths are likely to require weighting, but there are no formal procedures available as yet.

A received level of 180 dB_{RMS} re 1 μPa has been used for some years as an ad hoc limit to prevent auditory injury to marine mammals to seismic survey pulses (70 FR 1871). At the time the limit was set, there was no specific evidence that exposure to higher levels would cause auditory or other injury. Instead, the value was a conservative informed guess made by experts using data from terrestrial animals, and based on the available evidence above, it is probably conservative. Research effort since that time has shown that for both small cetaceans (especially Schlundt et al., 2000, reviewed above) and pinnipeds (e.g., Kastak et al., 2005) the equal-energy approach used develop damage risk criteria for human hearing will be useful for marine mammals as well.

5.3.2 Pinnipeds

Small threshold shifts after exposure to noise have been measured in the California sea lion (a model for the Steller sea lion) and harbor seal (Kastak and Schusterman, 1996; Kastak et al., 2005). Together, the two studies exposing sea lions to continuous noise underwater indicated TTS of approximately 6 dB after 25 min of exposure to 2.5 kHz octave-band noise with SPL of 174 dB re 1μPa (SEL=206 dB re 1μPa^2-s).

Data on underwater TTS in pinnipeds exposed to pulses are limited to a single study. Finneran et al. (2003) exposed two California sea lions to single underwater pulses from an arc-gap transducer. They found no measurable TTS following exposures up to 183 dB re 1μPa (peak-to-peak; SEL=163 dB re 1μPa^2-s); the absence of loss is consistent with the expected threshold obtained using SEL in the Kastak et al. (2005) study. For the harbor seal, which has more sensitive hearing, the threshold of TTS was 183 dB re 1μPa^2-s (Kastak et al., 2005), or ~10-20 dB lower than TTS-onset in the California sea lion.

5.4 Noise masking

Underwater, sound provides much of the information obtained using vision in air. In addition to the function of sound in communication, marine mammals use it to monitor their environment and each other, navigate, locate prey, and avoid predators. Therefore, masking or distortion of these biologically-significant sounds is likely to have a relatively greater impact in the marine environment than it would in the terrestrial environment. Masking can occur if animals are exposed to constant broadband anthropogenic noise, such as ship noise. Unlike behavioral and physiological effects, which can only affect animals through the intermediary of their own perception and psychology, masking occurs inevitably if animals are exposed to noise in frequency ranges similar to those that they produce or hear with sufficient level to obscure biologically-important sounds. Thus, masking may be one of the most significant and pervasive effects of increasing ambient ocean noise. Surprisingly, it is also one of the least-studied.

Noise is effective at masking a target signal if it is lies within a critical band around the frequency of the signal and has a greater level. Critical bandwidth increases at low frequencies, so low frequency signals are more effectively masked than high frequency ones. Sources with energy in a broad, low frequency band are expected to be the most efficient maskers. Among these, shipping noise has been cited repeatedly as an important source of masking noise over large areas (NRC, 2003) with the potential to affect animal movements and social communication. For example, increases in ambient levels as a result of shipping noise could effectively decrease the range that receptive female fin whales hear male vocal displays, ultimately impeding species recovery by reducing encounter rates (Croll et al., 2002; Richardson et al., 1995b).

5.4.1 Cetaceans

Anti-masking behavior has been observed in humpbacks, gray whales, killer whales, and beluga whales. In response to experimental vessel approaches, singing humpbacks shortened song units, resulting in increased song tempo. Similarly, gray whales improved the signal-to-noise ratio of their calls by altering call duration, varying bandwidth, increasing call rates, and modulating signal frequency (Ollervides, 2001).

Like other behavioral responses to disturbance, responses to masking noise are likely to be dynamic depending on context and motivational state. There is almost certainly a threshold level of noise at which cetaceans respond by employing anti-masking strategies, and below which they do not. For example, they may stop calling to reduce energy use when noise levels are so high that communication is impossible. Fin whales are reported to continue calling in the presence of noise from vessels but tend to be silent when ships are very near (Watkins, 1986). However, the relationship has not been examined systematically. In a study by Foote (2004), killer whales reportedly increased call duration in the presence of boat noise during the 2001 – 2003 period, but showed no significant differences in call duration in the previous two study periods (1977 – 1981 and 1989 – 1992). Foote et al. (2004) hypothesized that killer whales adjusted their behavior to compensate for noise based on acoustic differences during the three periods.

Another recent study used measurements of underwater noise produced by boats to model acoustic impacts on the Southern Resident killer whale community (Erbe, 2002). This study predicted that fast moving vessels (100-200 kHz band) with source levels between 145-169 dB re 1 μPa @ 1 m would be audible over ranges of 16 km, mask calls at ranges of 14 km, and elicit behavioral avoidance at ranges of 200 m. The expected range of impact of slow moving vessels was much lower. Slow moving vessels were expected to be audible and mask calls at 1 km and elicit behavioral responses at 50 m. It is important to note that these estimates are worst-case scenarios and that actual response zones could be expected to depend on a number of factors including, ambient noise levels, the context of whale behavior, whale orientation and location relative to the vessel, habituation to vessel presence, and so on, which Erbe did not measure. Thus, while providing a useful indication of the ranges at which vessels might affect killer whales, her predictions were not confirmed by empirical test.

5.4.2 Pinnipeds

No studies have measured masking of biologically-significant signals in pinnipeds. In addition, other than vocal communication, their use of sound is poorly-understood, including navigation and prey localization. If vessel noise is likely to be a significant masker in areas of PWS, additional information on masking effects would be needed to assess the potential impact.

5.5 Behavioral Responses

The term ‘disturbance’ has two meanings in the literature on human impact. First, it is used to describe direct modifications of habitat, such as forest fires, introduction of an invasive species, or dams. Second, it refers to sensory stimuli that cause behavioral or physiological changes (responses). The study of disturbance with this second meaning is still in the early stages of formalization, with major concepts (including 'disturbance') still imprecisely defined (Taylor and Knight, 2003). Vessels can modify habitat by producing widespread masking noise, as discussed above. They can also modify it locally by posing the danger of collision (see section below) and releasing pollutants into the environment. However, when the cause of the effect is the stimuli associated with the vessel passage, impact is likely to be greatest during the period of vessel passage and determined by the coping strategy chosen by marine mammals. Throughout the rest of this review, disturbance will be defined in the sense implied by the relevant legislation (MMPA, NEPA), as a disruption of behavior or physiology that results from perception of a stimulus. In this usage, effect is measured by responses, and is considered significant only if the responses can be related ultimately to biologically-significant consequences, such as abandonment of favored hauling or breeding habitat or loss of opportunity to feed that could not be regained by short-term compensatory behaviors.

The body of research on biologically-significant effects of anthropogenic disturbance is still small. Current theory posits that animals respond to human disturbances using species-typical behaviors used for defense (Frid and Dill, 2002; Ydenberg and Dill, 1986). In this view, approaching vessels would be conceptualized as potential predators. The defensive repertoire also includes behaviors designed to protect individuals from startling and dangerous environmental events such as lightning strikes, falling rocks, or earthquakes, which in the ocean are signaled by intense acoustic transients. Responses to startling anthropogenic noises cannot yet be related to this generalized defensive repertoire, which has not been studied for natural stimuli.

Ultimately, the effects of disturbance must be analyzed by determining the costs and benefits of the behaviors that animals chose out of the repertoire of possible behaviors (Ydenberg and Dill, 1986). For large-brained animals with good memories, like birds and mammals, responses such as the distance at which animals flee from approach can be treated as species-typical traits (e.g., Blumstein et al., 2005), but environmental factors and experience alter both the intensity of responses and choice of behavior. It is quite likely that the variability in behavioral responses seen in many studies is explained by varying strategies, the context in which choices are made, and experience.

Extrapolation of short-term behavioral or physiological responses to longer-term biologically-significant impacts (e.g., reproductive losses or abandonment of habitat) is problematic. Immediate responses are easy to measure, but may not directly predict biologically-significant effects (Gill et al., 2001). Most authors freely speculate that their short-term observations could be extrapolated to long-term effects, but they can rarely demonstrate a connection based on their data. For example, (Green and Green, 1990) suggested that humpback whales could be employing anti-predator defenses in response to vessels. As a result, they suggested that vessels may be a source of stress to the whales that could have long-term negative effects on health and population viability. However, their data did not support any of these possibilities. Without data on the ensemble of response costs incurred by whales over time (e.g., over the course of a whale-watching season), short-term avoidance responses are more parsimoniously interpreted as an indication that the whales have made an intelligent assessment of the situation (e.g., the trajectory and speed of a vessel) and selected the least costly response needed to prevent injury to themselves or their young.

5.5.1 Cetaceans

A large body of research has documented short-term cetacean behavioral responses to vessels. A thorough review is outside the scope of the present analysis. The summary that follows focuses on responses to larger vessels, with information on responses to other types of vessels or noise included as appropriate. In general, studies of vessels measure exposure using approach distance and the response as the distance at which marine mammals begin to exhibit defensive responses such as avoidance. Noise data are collected concurrently only infrequently.

Humpback whale responses are among the best-studied. They exhibit behavioral responses to vessels (Frankel and Clark, 1998; Richardson et al., 1995a), aircraft (Richardson et al., 1995a), active sonar (3.1-3.6 kHz), oceanographic sources (ATOC) (Frankel and Clark, 2000), M-sequence signals from low-frequency active (LFA) military sonar (Frankel and Clark, 1998), and possibly seismic exploration (Richardson et al., 1995a). The responses in these studies were variable. They included decreased dive intervals and surface blow rate (Frankel and Clark, 1998), increased dive times (Green and Green, 1990), no change in respiration (Corkeron, 1995), and decreased swim speed as a function of vessel size (Frankel and Clark, 1998). The best interpretation of the available information is that humpbacks have multiple strategies for coping, including (1) horizontal avoidance (moving away from the vessel), (2) vertical avoidance (decreased time spent at the surface), and (3) agonistic surface-active behaviors, apparently an attempt to warn off the vessel, just as they would warn off other animals. These findings are consistent with the hypothesis that marine mammals respond to disturbance in a dynamic and flexible manner.

During vessel approaches, noise level and approach are highly correlated, so it is unclear whether marine mammals respond to their perception of approach or the level of the noise per se. The relationship of level to response has been studied with sources at fixed locations in several cases. These have shown that there is an effect of level independent of approach. For example, in experiments with oceanographic sources (ATOC), slight increases in distance and time between successive humpback whale surfacings corresponded to increases in estimated received sound level (98-130 dB re 1 µPa), suggesting that received sound level was the important predictor (Frankel and Clark, 1998; Frankel and Clark, 2000).

Whale experience with vessels can also alter responses. In response to approaching speed boats, fin whales were observed to stop feeding, increase travel speed and decrease surface intervals (Jahoda et al., 2003). Responses may have been stronger than usual in this study because the boats were approaching fin whales deliberately and closely to collect biopsy samples. Decreased behavioral reactions to the presence of vessels were observed over time from fin whales in Cape Cod waters (Watkins, 1986). Watkins' data suggested that fin whales can habituate to vessel presence. The fin whales could have learned to react with increasing efficiency as they gained experience with approaches that did not result in direct approach or harm.

Gray whale reactions to anthropogenic disturbance are also among the most thoroughly studied. Gray whales have shown varied behavioral responses to vessels, ranging from short-term escape responses to attraction (Richardson et al., 1995b), depending on context. Short-term behavioral responses, such as increased reorientation and decreased swim speed have been linked to vessel presence in breeding lagoons (Ollervides, 2001). Gray whales have also been reported to change course more often with increasing numbers of whale-watching boats along migration routes

(Richardson et al., 1995b). Summering gray whales, which are hunted for subsistence purposes in the Bering and Chukchi seas, have been reported to actively avoid vessels within 350-550 m and to exhibit snorkeling behavior (exposing their blowholes only to inhale) in response to whaling vessels (Richardson et al., 1995b). This behavior is consistent with an accurate assessment of the danger posed by whalers.

Direct and indirect approaches by boats appear to elicit different behavioral responses, also suggesting flexible and intelligent responses. Avoidance behaviors, such as submerging and changes in heading were observed significantly more during direct approaches by whale-watching vessels (Ollervides, 2001). In response to stationary or idling vessels, behavioral responses ranged from no response to very close approaches by 'friendly' whales (Dahlheim et al., 1984). In some cases gray whales in the calving lagoons have been attracted to noise from idling out-board engines (Dahlheim et al., 1984; Dahlheim et al., 1981), as though 'curious' (motivated to obtain information about the vessels) or soliciting contact. Response to whale watching vessels in wintering lagoons decreases throughout the winter, suggesting habituation (Richardson et al., 1995b), but without data on individual whale interactions with boats over time, seasonal changes in behavior are also a reasonable alternative explanation.

Limited research has been conducted on the effects of anthropogenic noise on minke whales. In general, minke whales do not approach and sometimes actively avoid vessels. However, ship-seeking behavior has been observed in response to stationary or slow moving vessels (Richardson et al., 1995b).

Vessel noise can attract whales if it is associated with food resources. A multiyear study off the coast of Sitka, Alaska, is examining the interactions between sperm whales and sablefish longline fishermen. Recent results indicate that the whales are attracted to the acoustic cues generated by engaging and disengaging the ship's propeller (Thode et al., 2007).

There is also an extensive literature on the behavior of odontocete cetaceans. The response of beluga whales to vessels has depended on a number of intrinsic and extrinsic factors, such as behavioral state, prior experience, age, habitat, vessel type, and vessel behavior. Observed reactions range from tolerance to active avoidance, consistent with the model that the whales altered their behavioral choices depending on internal state, context, and experience. For example, belugas have shown tolerance to large vessels traveling along predictable routes, but actively avoid fast, unpredictable movement of smaller boats. This may be a good explanation for the common observation that small cetaceans react more strongly to variable engine noise – if they associate changes in engine noise with maneuvering, their behavior should reflect the greater risk posed by unpredictable vessel behavior.

Beluga whales also reacted differently depending on behavioral context. Young belugas and those engaged in feeding or traveling were less likely to show a strong reaction to vessels compared with older belugas and those engaged in other activities. The general context of risk was also a factor. For example, belugas in the heavily-traveled St. Lawrence River estuary and Bristol Bay were habituated to vessel presence, whereas belugas in the Canadian high arctic have consistently shown strong reactions to vessels at long range, 35-50 km (Richardson et al., 1995b), i.e. close to the limits of detection. Beluga whales in Bristol Bay were described as being “extremely leery” of passing boats that had engines running, but were seen to pass near drifting or anchored boats with the engines turned off without hesitation (Stewart et al., 1982). Arctic belugas are hunted from small vessels, a likely explanation for their greater wariness. Beluga whales in Cook Inlet did not appear to be bothered by the sounds from a passing cargo-freight ship (Blackwell and Greene, 2002). They are also hunted in this area, but only from small vessels that can be easily distinguished from freighters using acoustic cues.

Both behavioral and physiological responses of killer whales to vessels have been observed. In a study by (Jelinski et al., 2002) they increased swim speed and moved into open water, both of which are good defensive responses. Williams et al. (2002) found sex differences in evasive responses to an experimental vessel used to model whale-watching vessels. The vessel leap-frogged the predicted path of killer whales at distances greater than 100 m. Male killer whales adopted a less predictable path, whereas females tended to swim faster and increase successive changes in angle between dives.

The population of Northern Resident killer whales in this study is frequently approached by whale-watching boats. Although occasional evasive responses are unlikely to have significant energetic consequences for large, fast-swimming oceanic carnivores, the incidence of encounters with boats in this population is very high. The same can be said for the Southern Resident killer whales that, in the summer, spend over 90% of the daylight hours in the presence of boats. It is an excellent example of a situation in which concerns about the energetic consequences of evasive responses could be justified. Based on the analysis of Williams et al. (2002) the presence of boat traffic resulted in significant changes to the activity budgets of Northern Resident killer whales, corresponding to an estimated increase of 3-4% in energetic demand. In addition, decreased time spent feeding was observed frequently, which could have resulted in an 18% decrease in energy uptake. Unfortunately, actual energy intake could not be measured to determine whether whales were able to compensate behaviorally (e.g., by hunting at night more frequently). If whales in PWS are targeted by whale-watching vessels with high frequency in the future, such concerns should be addressed as research questions.

For porpoises, the effects of vessel sonars may be more important than engine noise. These species appear to be particularly responsive to tonal signals at mid- to high-frequency. In a study by Hatakeyama (1994), Dall’s porpoises exhibited avoidance reactions to pulsed sounds between 20-143 kHz at ranges of 100-700 m. Reaction thresholds at exposure levels of 116-130 dB re 1 µPa for signals with frequencies greater than 100 kHz were reported. On the other hand, they have also been reported to approach or ignore vessels (Watkins et al., 1981). Since navigation sonars are ubiquitous, it is likely that marine mammals familiar with them.

Harbor porpoises are more wary of boats. They have shown avoidance responses at up to 1.5 km distance, such as changes in behavioral state, avoidance (swimming away), and decreased surfacing intervals (Barlow, 1988). It is unclear how general these responses are. However, there has been a great deal of research in recent years on the effects of acoustic alarms (or pingers) on harbor porpoises. These ‘warning’ devices emit short, high frequency tones (pings) that have proven to be effective at reducing by-catch in gillnets. Studies in the laboratory indicate that harbor porpoises are repelled by pingers. Pingers typically emit frequencies with the majority of their energy between 2-12 kHz and source levels of ~ 130 dB re 1 µPa @ 1 m

(Kastelein et al., 2001). Negative responses include horizontal and vertical avoidance, increased swim speed, bradycardia, and reduced echolocation (Teilmann et al., 2006). Under free ranging conditions, they may abandon large areas (Culik et al., 2001) if nets are equipped with pingers. Specific reactions depend on the frequency, structure, duration, and source level of the signal (Kastelein et al., 2000). However, recent evidence suggests that harbor porpoises can habituate to pingers over time (Teilmann et al., 2006).

5.5.2 Pinnipeds

In general, Steller sea lions appear to respond differently to vessels when they are in the water versus hauled on land. In the water, they are tolerant of vessels or even approach them. They congregate around fishing vessels (Richardson et al., 1995b), possibly with the expectation of being fed, or possibly as part of an opportunistic search strategy for prey. However, when hauled out on land they react strongly to vessel approaches within 100-200 m. Strong reactions among hauled sea lions are more common if motor noise varies in level (Bowles and Stewart, 1982; Richardson et al., 1995b). In both cases, the stimuli could be interpreted as signals for intrusion, so it is not clear whether the stronger responses were a consequence of fear of attack or sensitivity to noise. Captive Steller sea lions have been repelled from fishing nets by impulsive sounds and pure tones (8 kHz and 1-4 kHz sweeps) at high source levels (210 dB re 1 µPa at 1 m and 165 dB re 1 µPa at 1 m), but these reactions are likely to be of short-term if the sounds are associated with access to prey in nets (Shaughnessy et al., 1981).

Vessel approaches within 100 m have been shown to displace harbor seals from haul-out sites for up to 3 hours (Bowles and Stewart, 1982). However, like the Steller sea lion, responses to approach may be associated with fear of intrusions. Similar reactions have been observed in response to non-powered boats (Allen et al., 1984), so noise level per se is unlikely to be the salient stimulus. In areas of California where harbor seals have been approached by boats or humans without harassment over long periods, increased tolerance to all types of disturbance is observed (e.g., in Elkhorn Slough and Children's Cove in La Jolla).

5.5.3 Sea Otters

Variable reactions of sea otters to vessels have been documented, ranging from mild interest to avoidance and displacement (Richardson et al., 1995b). For example, rafting sea otters off California showed only mild interest in boats passing within hundreds of meters (Riedman, 1983). Sea otters in Alaskan waters, however, moved away from approaching survey vessels (Udevitz et al., 1995). On land, sea otters had reactions similar to those of pinnipeds, flushing in response to vessels approaching 100 m parallel to shore (Garrott et al., 1993).

The ensemble of data on pinnipeds and sea otters is consistent with the data from cetaceans, suggesting flexible and dynamic responses to vessel disturbance. Because previous experience can have a substantial effect on the strategy chosen by animals, the most useful research has been conducted on animals with known history of exposure to disturbance. Unless disturbances are associated with intrusions or attack (e.g., capture for examination and tagging, vessel collisions), marine mammals appear to learn to tolerate vessel disturbances well. They also return to areas where they have been disturbed once the source has disappeared.

5.6 Non-Auditory Physiological Effects

The non-auditory physiological effects of greatest concern in the literature were (1) energetic effects and (2) physiological ‘stress’. Strandings of deep-diving beaked whales have also been attributed to physiological effects of noise, although the mechanism of injury is not proven. All three potential effects are mediated by the perceptual and behavioral responses of marine mammals. Evidence for these effects is reviewed below.

5.6.1 Energetic effects

Responses to vessels can certainly consume energy and divert time and attention from biologically important behaviors such as feeding. However, the evidence of effect depends not only on reporting the behavior, but also showing that it represents a significant drain on marine mammal resources and that they do not have strategies to compensate. For example, in the study of Northern resident killer whales by Williams et al. (2002) evidence suggested that vessel interactions could result in additional energetic costs on the order of 3-4%. Their subjects experienced some of the greatest exposure to vessel activity of any marine mammal, so the finding was certainly plausible. However, empirical measurements would be needed to determine whether the whales had opportunities to compensate for these costs and what level of exposure was sufficient to overtax them. Until such evidence is collected, it is unclear whether the energetic costs projected by Williams et al. represent a significant drain on the whales' resources.

Increased activity has been documented in a number of marine mammals exposed to vessels. Increased occurrence of surface-active behaviors has been demonstrated in humpback whales (e.g., breaches, fluke swipes) correlated with sudden changes in sound level during direct vessel approaches (Watkins, 1986). These behaviors are agonistic displays used in conflicts with other whales, so they could have been attempts to warn off the approaching vessel. From an ethical point of view, arousing agonistic gestures from whales may be a sufficient argument for restricting approaches, but from an energetic point of view occasional displays would not be a significant drain on the energy budget of a large, active carnivore. The behavior must be stimulated repeatedly. The whales could be expected to change their response strategy if they experienced significant drain on their energetic resources, but this possibility has not been studied in the whales. In a now-classic study of birds, Beale and Monaghan (2004) showed that artificially-provisioned oystercatchers flew at much greater distances than those dependent on naturally available energy resources because they could afford to be more wary.

5.6.2 Physiological stress

When faced with an acute challenge, such as a predator attack, the body releases regulatory hormones called catecholamines and glucocorticoids to mobilize energy reserves, shuts down non-essential functions (e.g., digestion), and activates neurophysiological and muscular systems in preparation for defense or flight. Glucocorticoids are also released to regulate responses to long-term challenges, such as bad weather or starvation. Under normal conditions, these hormones are crucial to an animal's adaptive responses to environmental change, but chronic release of glucocorticoids can result in symptoms of the syndrome commonly called 'stress', including digestive dysfunction, psychological effects (irritability, depression), compromised response to immune challenges, and neurophysiological disfunction, particularly failures of attention and memory loss (Sapolsky, 1996). In extreme cases, growth may be slowed and reproduction suppressed.

Historically, all physiological changes in response to environmental challenges have been viewed as deviations from homeostasis, the maintenance of a constant internal state, and reported as ‘stress’. In this sense, any response to a challenge could be interpreted as potentially damaging. However, animals constantly experience changes in their environment that stimulate behavioral and physiological responses, most of which do not result in any measurable negative effect on health or reproductive success. A more sophisticated approach recognizes that animals cope successfully with a range of conditions and internal states. Allostasis, meaning ‘maintenance of stability through change’ (McEwen, 1998), is a recent theoretical construct that accounts for dynamic behavioral and physiological accommodation to the environment. Symptoms of stress become detectable only when the ensemble of changes and adjustments (allostatic load) experienced by an animal exceeds its ability to adjust. For example, variation in blood pressure is a normal part of animal activities. However, when there is persistent increase of blood pressure, health effects occur. An example has been documented in dominant male macaques vying for position in an unstable dominance hierarchy; constant elevation of blood pressure accelerated atherosclerotic plaque formation in these animals (Manuck et al., 1995), a significant health effect.

There are important corollaries of the concept of allostasis. First, non-linear relationships between challenges and response are expected, so empirical data will be needed to determine the relationship between exposure and effect. Simply extrapolating from short term responses is unlikely to be a successful predictive tool. Second, there will be a strong relationship between physiology and behavior. Not only do animal behavioral strategies have physiological costs (e.g., increased energy consumption), but they can also have benefits, such as restoring a balanced internal environment. For example, animals in captive settings are often given objects to manipulate as a stress-reduction measure. In wild animals, movement and displacement activities may serve the similar functions.

To date, there has been very little work on stress responses of marine mammals in the presence of disturbance. Romano (2004) studied the physiological responses of a beluga whale and a bottlenose dolphin during exposure to impulses from an airgun. The beluga whale showed significant changes in catecholamines, but not the bottlenose dolphin, while the dolphin showed an increase in aldosterone and monocytes. The study was short-term, so the consequences of these changes could not be determined. However, the data support earlier work showing that cetacean regulatory hormones do not always function like those of terrestrial animals. They have ‘co-opted’ regulatory mechanisms for somewhat different physiological functions, such as maintenance of the blubber layer (St. Aubin et al., 1996). Therefore, empirical studies of their stress responses will be needed before the physiological effects of noise can be predicted.

5.6.3 Injury Produced by High-intensity, Narrowband Sounds

Narrowband sounds, such as sonar signals, not only stimulate strong behavioral responses, but there is growing evidence that some can cause or intensify dangerous behavioral or physiological responses that result in strandings. There is increasing evidence that exposure to high intensity tonal signals produced by at least some types of sonar can cause stranding in beaked whales (Ziphiidae, Mesoplodontidae). The beaked whale species occurring in the vicinity of PWS are listed in Appendix B. Strandings of beaked whales have been associated with tests of high-intensity mid-frequency (1-10 kHz, typically 2-4 kHz) military sonars on several occasions (Evans and England, 2001; Frantzis, 1998; Jepson et al., 2003). Deep-diving beaked whales appear to be particularly susceptible to stranding when exposed to these sounds, but the mechanism of injury is still not understood. Therefore, susceptibility of other deep diving species, such as sperm whales, is unknown.

Studies of freshly-beached whales were conducted after stranding events in the Bahamas (Evans and England, 2001) and in the Canary Islands (Jepson et al., 2003). The whales in the Bahamas incident were exposed to mid-frequency sonar signals, with pings at frequencies around 3.5 kHz with source levels up to 235 dB re 1 μPa peak SPL. Only a few of the whales were in good enough condition for examination; these showed evidence of subarachnoid hemorrhage, but not damage to the inner ear. The range at which they would have been exposed to levels sufficient to cause auditory damage was very close to the pinging vessel, so few whales would have been exposed. However, but whales would have been exposed to more moderate received levels (150-

160 dB re 1 µPa RMS SPL) throughout the channel where the sonar exercise was conducted. Beaked whales examined after a similar naval sonar exercise in the Canary Islands found acute and chronic tissue damage that they attributed to in vivo gas bubbles (Jepson et al., 2003). However, baseline incidence of similar histological results was unknown. Stranded animals begin to decompose immediately after death, particularly in tropical climates, which might have influenced the results.

There is a theoretical possibility that bubbles could be produced in vivo as a when tissue supersaturated with nitrogren is brought to the surface to quickly. This condition is called the bends. Houser et al. (2001) demonstrated that marine mammals can become supersaturated with nitrogen while diving to depth in a repetitive sequence, a behavior pattern typical of beaked whales. Exposure to high intensity sound could potentiate bubble formation (Cox et al., 2005). Studies of beaked whale diving suggest that these cetaceans normally wait below the surface for a time, perhaps to 'decompress' after a series of dives. On theoretical grounds, this behavior could leave them susceptible to nitrogen bubble formation (Zimmer and Tyack, 2007), lending further support to the notion that they strand because they get the bends. However, the hypothesis is not yet proven, nor does it apply to many of the strandings for which concerns have been raised in recent years. Bradshaw et al. (2006) have made a strong plea for a science-based approach to stranding incidents until the mechanism of injury can be established.

All the strong evidence for effects of mid-frequency sonars on whales has been found in deep-diving beaked whale species, primarily Cuvier's, Blainville's and Gervais' beaked whales (Ziphius cavirostris, Mesoplodon densirostris, M. europaeus). Cuvier's beaked whales could potentially enter PWS, but they are primarily found in deeper pelagic waters. Other beaked whales are unlikely to enter the Sound and sperm whales are not known to be susceptible. Thus, it is unclear whether any of the cetacean species in PWS could be affected. Also, neither military sonars nor seismic airgun arrays, the two sources that have been implicated in strandings, used in the Sound. Broadband noise from tankers or other vessels is not suspected to cause these types of effects. Navigation and fish-finding sonars are ubiquitous, but they produce very different and much higher frequency signals. These sonars are sufficiently widespread that strandings would probably have been associated with them previously if there were a strong effect. At present, they are not considered likely to cause strandings.

One other caveat should be noted regarding navigation and fish finding sonars. There is excellent evidence that both small cetaceans and pinnipeds experience aversion when exposed to high intensity pings (e.g., Kastelein et al., 2001). In addition, the levels produced by all sonars are sufficiently high that auditory effects are a possibility if individuals spend long periods in close proximity to the devices, such as while bow-riding. Until better evidence is available, areas where vessel densities are high around marine mammals (e.g., during fishing derbies) should also be considered 'hot spots' for physical effects of sonars.

A similar comment may be made regarding pingers and other devices used by fishers and aquaculturists. Acoustic deterrent devices (ADD) and acoustic harassment devices (AHD) have helped to reduce fisheries bycatch and attacks by marine mammals on aquaculture operations, but concerns have arisen regarding the effect of these ADD and AHD devices on marine mammals. The problem is particularly acute in the case of AHDs associated with aquaculture operations, where attractive food resources are paired with damaging levels of noise. Unfortunately, pinnipeds exposed to these devices in areas such as the Ballard Locks have not been tested to determine whether hearing loss occurred. There is also a possibility that some species, such as harbor porpoises, may be excluded from favored habitat in the presence of both types of devices (NRC, 2003; Olesiuk et al., 2002).

5.6.4 Ship Strikes

One of the most significant effects of vessel traffic is not a direct consequence of noise, but rather of the passage of the vessel. If a vessel is moving too fast to see or avoid a marine mammal, or if the animal's behavior suddenly brings it into the path of the oncoming vessel, a collision is likely to occur. These collisions are a significant source of mortality in some whale populations, most notoriously that of the northern right whale (Eubalaena glacialis), which migrates along heavily-traveled shipping lanes on the east coast of the United States (Vanderlaan and Taggart, 2007).

An extensive review of documented and anecdotal accounts by (Laist et al., 2001) revealed that one-third of all fin and right whale strandings involve ship strikes. They plotted the proportion of strikes against estimated vessel speed and found that ships traveling at 14 knots or faster accounted for 89% of the collisions in cases where the vessel's speed was known. They observed that ship strikes were more dangerous to threatened and endangered species whose population numbers are already low (Laist et al., 2001) because strikes were typically fatal to adults, which normally have very high survivorship in the wild. In a review of more recent data, Vanderlaan and Taggart (2007) provide evidence that vessels traveling at more than 12 kt are likely to hit whales.

Behavioral reactions of marine mammals can inadvertently place them in the path of oncoming vessels, making the possibility of equipping vessels with alarms less practical than it might seem. Playback experiments in the Bay of Fundy examined the response of Northern Atlantic right whales to sounds, including conspecific calls, vessel noise, a signal intended to alert them to danger, and a silent control stimulus. The whales showed no significant response to the control silence, vocalizations, or vessel noise, but five of the six study animals exhibited strong response to the alert signal. They terminated their ongoing foraging dives prematurely, making a rapid ascent at a shallow angle. They surfaced and remained near the surface or immediately below for abnormally long periods. Responses to the alarm would probably have increased rather than decreased the risk of being hit by a passing ship (Nowacek et al., 2004). These data indicate that any effort to develop alarms must be preceded by experimental research on whale behavioral responses.

6.0 Conclusions

The level of noise produced by TAPS vessels has not been the subject of directed measurements in PWS. However, studies of other vessels in the same size class are likely to be good models for TAPS traffic, and these data (reviewed above) show that TAPS tankers are likely to produce high levels relative to other anthropogenic sources in the low frequency band. However, they are not likely to produce widespread permanent injury to fish or marine mammals (e.g., hearing damage) for the following reasons:

1. Tankers and associated vessels do not travel the route frequently (one passage up and down the shipping lane every 1-2 days on average);
2. The tankers and associated vessels are confined to a narrow channel in the center of the sound, where noise is likely to attenuate most rapidly, and well away from shallow-water resources important to marine mammals and fish;
3. In the channel, tanker noise is expected to attenuate rapidly away from the source, producing moderate levels (150 dB re 1 μPa and below) at ranges greater than approximately 100 m;
4. Shadowing by islands on both sides of the shipping lanes will block noise from TAPS vessels, despite the greater efficiency of propagation at low frequencies

TAPS-related vessel traffic is unlikely to affect the use of the Sound by marine mammals and fish because their activity is infrequent. For example, effects on the herring spawn, or abandonment of favored areas by groundfish and spawning salmon are not expected based on the available information.

However, there are likely to be local ‘hot spots’ with high levels of noise in areas with concentrated vessel traffic, particularly in the Valdez Arm, Valdez Narrows, and Port of Valdez, the cruise ship berths at Whittier, around harbors used as staging areas by fishing vessels, and in areas where fishing derbies occur. These areas should not be regarded as safe for fisheries resources, aquaculture, or marine mammals without further analysis. For example, aquaculture facilities should not be established where heavy vessel traffic is expected without estimates of exposure and possibly tests of effects on eggs and fry.

Conclusions

Short-term behavioral responses, such as avoidance or approach, are expected close to vessel traffic for both marine mammals and fish. However, there is no evidence that TAPS vessels could cause abandonment over the long term. Fish may avoid vessels that are actively fishing, but they do not appear to abandon areas used by fisheries in the long-term. However, because study effort on fish has not involved long-term monitoring of individuals or schools, caution should be used in areas with high vessel traffic.

For marine mammals, the little data available suggests that abandonment is unlikely in areas where traffic is low and vessels travel a predictable route. Abandonment is most likely to be detected where marine mammals are exposed to vessels or intrusions frequently in a context where habituation is disadvantageous (e.g., when they are likely to be hit or approached closely). In such cases, animals could be expected to switch strategies, e.g., by abandoning favored habitat. TAPS traffic in PWS shipping lanes outside the Port of Valdez is highly predictable and not heavy enough to produce long-term behavioral effects.

The species most vulnerable to current levels of TAPS vessel activity will be those that use the SERVS shipping channel a large proportion of their time, particularly close to or within the Valdez Arm, Valdez Narrows, and Port of Valdez. In these narrow embayments, animals may be confined close to ships. Reverberation is likely to change transmission loss characteristics substantially, resulting in greater relative exposure at distance than in open water. However, vessels also operate with engines turned off and generators running at the VMT, so exposures are likely to be most important within the Valdez Arm as vessels approach the terminal.

At greater ranges, the most likely effect of tanker traffic will be masking of biologically significant sounds at moderate to low frequencies (5 kHz and below, particularly in the range below 500 Hz) over fairly large areas of PWS. These sounds include social communication, signals used for navigation, sounds made by natural predators or prey, and possibly significant sounds made by humans (e.g., outboard motors of hunters). Fish and mysticete whales will be most vulnerable. Phocoenids will be the least susceptible, as their communication and navigation are specialized for high frequencies.

As described above, many different sources contribute to the noise environment in PWS. In areas away from the channel other sources are expected to dominate. The most important sources are cruise ships, which generate noise comparable to that produced by tankers, and fishing vessels, which have high-speed diesel engines with greater high-frequency content than tanker noise and are numerous throughout the sound. It is the cumulative effect of all sources that should be considered when estimating the potential for significant masking or damage to hearing in both fish and marine mammals.

To date, experimental studies of the effects of masking have demonstrated adaptive behavior (changes in vocalizations), but not longer-term, biologically significant effects. Noise masking and other disturbances that may be caused by vessels (interference with rest, for example) are challenges that animals are likely to meet with flexible behavioral and physiological responses; often, these measures will be successful and no permanent effect will be detectable Therefore, long term effects of noise should be considered most likely in cases where behavioral or physiological acclimation are (1) not possible, for example when noise levels are high enough to create chronic masking or hearing loss, or (2) outside the animals' limits of adaptability, for example when frequent near-misses with boats cause them to judge an area unsafe regardless of available resources. Unfortunately, the available body of research has generally focused on short-term responses, so 'tipping points' at which animals change their strategies are not currently predictable. However, there is no evidence that the limited traffic due to TAPS activities is sufficient to cause such long-term effects.

An additional noise source should be considered important in areas where marine mammals with good high frequency hearing encounter large numbers of vessels. Sonars, including those used for fish-finding and navigation, produce extremely high signal levels, often in excess of 200 dB re 1 μPa. In general, the level produced is not known. Frequencies are in the range from 38 kHz-200 kHz, so they will be most likely to affect pinnipeds with good high frequency hearing (in PWS, the harbor seal) and all odontocete cetaceans. High frequency sonar signals attenuate rapidly because absorption and refraction become particularly significant at higher frequencies. However, animals that bow ride, or approach boats for food, or frequently use fishing harbors could potentially be exposed to harmful levels.

7.0 Recommendations

Based on this review, noise from tanker traffic is unlikely to pose a significant hazard to fish and marine mammals except at very close range. However, potential effects on fish are less predictable in confined areas such as the Valdez Arm and Port of Valdez. If additional management requirements related to noise are published or there are increases in TAPS vessel traffic in the Sound, PWS-RCAC should consider the following efforts to analyze noise effects, particularly:

1. Document existing vessel activity in the Sound through the use of official records (e.g., PWS-RCAC databases, vessel registries, and records of commercial and recreational fishing licenses)
    a. Vessel data could be used to generate predictions about exposure to vessels in critical areas, such as close to Steller sea lion hauling sites or areas used by feeding humpback whales
    b. If high densities of vessels are found in areas where large whales congregate, speed limits could be kept below 12 kt to prevent collisions
2. Using the acoustic characteristics of vessels and the data on vessel traffic, develop a map describing the anticipated noise exposure in areas of concern
    a. Identify any ‘hot spots’ where unusual predicted exposure levels coincide with important marine mammal and/or fish populations or aquaculture facilities
    b. Develop methods to characterize expected statistical properties of high amplitude noise over time (e.g., vessel passages should be modeled in time rather than treated as constant sources)
3. Develop an approximate noise budget for TAPS tankers and associated vessels for critical areas of the sound
    a. Outside the shipping channel, Valdez Arm, Valdez Narrows, and Port of Valdez, TAPS traffic is likely to be less important than other sources
    b. The recommended effort would enable PWS-RCAC and port planners to suggest scheduling or regulatory measures as appropriate
4. If analysis of vessel activity indicates that areas critical to marine mammals, particularly mysticete whales, are likely to experience large increases in vessel activity over time, populations should be monitored frequently to ensure that they are not being excluded
5. Effects of noise on hearing of both fish and marine mammals should be considered in areas predicted to have chronic high noise levels

a. PWS-RCAC could promote experimental studies using federal, state, or industry monies to develop methods for measuring loss of hearing in large whales

b. PWS-RCAC could promote experimental studies of hearing loss in fish using federal, state, or industry monies

c. The possible risks posed by navigation and fish-finding sonars should be considered in addition to ship noise; risks could be estimated using empirical measurements of sonar noise and available data on animal movements in the vicinity of heavy boat traffic (e.g., exposure of Steller sea lions prone to ‘mooch’ from boats)

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Appendix A Hearing and Vocalizations of Marine Mammals and Fish

A-1 Introduction to Hearing

Animals do not hear all sound frequencies equally well. Changes in sensitivity with frequency are characterized using the auditory threshold function (also called an audiogram), a curve that describes the just-detectable level of sound across the range of frequencies that an animal can hear (Figure 14). Generally, sensitivity is low at the high and low end of the range and greatest in the middle. The shape of the curve varies greatly by taxonomic group (taxon) and species. The important features of the curve are best sensitivity (the lowest audible level), best frequency (the frequency of best sensitivity), hearing range (the bandwidth from minimum to maximum, generally measured at 60 dB above best sensitivity), and best range (the range of frequencies heard well). For example, humans hear in the range from 20 Hz to 20 kHz, with best frequency at 1-2 kHz, best sensitivity at 0 dB, and best range between 500 Hz and 8 kHz.

Figure 14 shows some example auditory threshold functions (ATF) collected from a variety of marine fish. These curves are typical of data that can be obtained from most marine animals. Only a limited number of trials can be collected from a small number of subjects and data are limited to a few frequencies that bracket the range of audibility. Thresholds tend to vary substantially based on experimental conditions and the noise in the test environment, which is often not quantified. Most ATFs show the expected shape, however, with a best range, upper and lower limit, and best sensitivity in the middle of the best range.

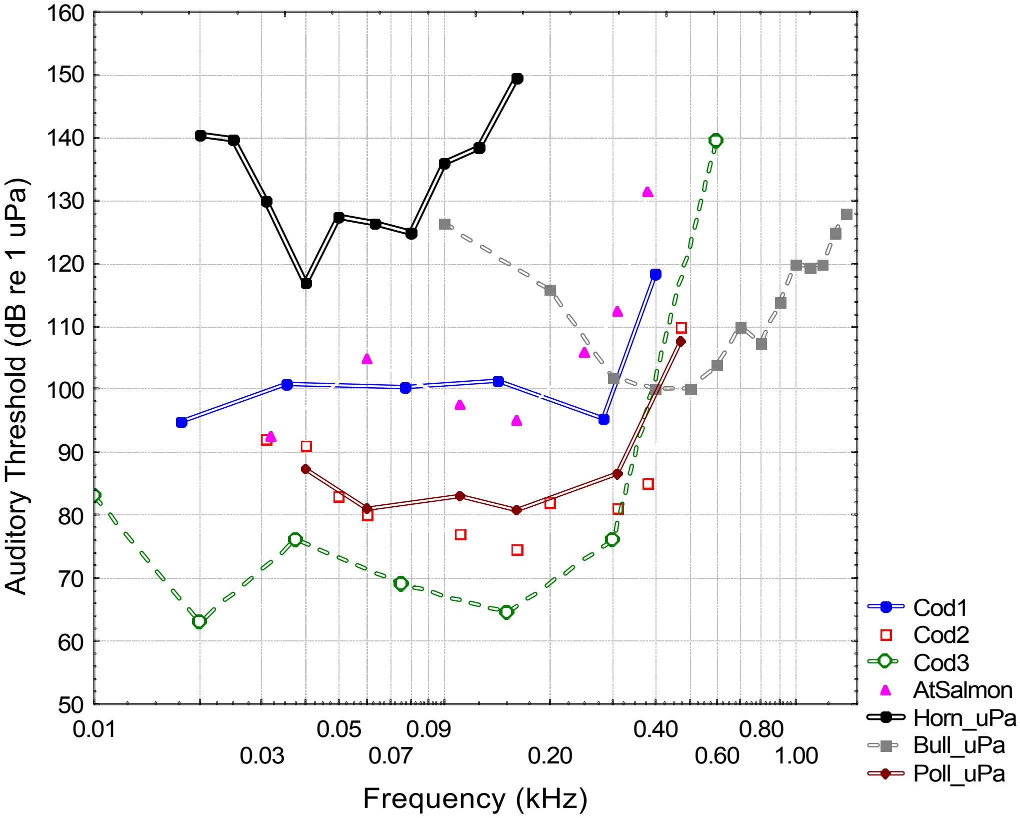

Figure 14. Selected auditory threshold functions of fish.
Data from Fay (1988). Cod: All data from Gadus morhua (Atlantic cod); Cod1= 10 fish studied by Buerkle (1967); Cod2 = 43 fish studied by Chapman and Hawkins , 1973 #538}; Cod3 = 20 fish studied by Offutt (1973); AtSalmon: Data from Salmo salar (Atlantic salmon), 5 fish studied by Hawkins and Johnstone (1978); Horn: Data from Heterodontus francisci (horn shark), 4 fish studied by Kelly and Nelson (1975); Bull: Data from Carcharhinus leucas (bull shark), 1 fish studied by Kritzler and Wood (1961); Poll: Data from Pollachius pollachius (Atlantic pollack), 1 fish studied by Chapman (1973).

In fish, measurement of the audiogram is complicated by the fact that fish can detect particle motion per se in addition to sound pressure (Popper et al., 1988). When sound travels through water, there is a small amount of particle motion locally as the moving pressure wave passses. Fish detect it using the relative motion of dense, calcareous otoliths (literally, “ear stones”) riding over sensory epithelium. Cetaceans have been reported to detect particle motion at low frequencies (Turl, 1993), but more recent systematic research by Finneran et al. (2002a) has shown that the cetacean ear is functionally a pressure transducer. Fish may also be able to detect low-frequency particle motion using the lateral line. Thus, it is possible for fish to respond to sounds that they cannot ‘hear’, particularly at very low frequencies. Measurements of their sensitivity to sound must thus be made with appropriate controls.

The dynamic range of hearing, the range from the minimum audible level to the maximum level the ear can tolerate, is not well-defined for animals. In humans, the upper limit of the range is defined by the level causing strong discomfort or pain, which relates reasonably well to the level at which acute auditory injury begins to occur. Chronic exposure begins to cause hearing loss at levels in excess of those normally encountered in natural habitats (under 60 dB in the range humans hear best), and at which humans begin to object strongly to exposure. In animals, there is no comparable reliable behavioral measure. The upper end of the dynamic range could be defined by the threshold for hearing loss, but for most species, there is little information regarding hearing loss. Therefore, this important characteristic of hearing typically cannot be specified, particularly in fish. Considering the variability of fish hearing by taxon and the paucity of data on hearing loss in any taxon, the potential for hearing damage should be managed using conservative criteria. There is better evidence regarding the threshold for hearing loss in marine mammals (summarized in Section 5.3).

In theory, animal species should be adapted to cope with the types of noise they encounter in nature, so it might be possible to determine the range of exposures likely to cause hearing loss by comparing statistical properties of natural and human-made noise. However, little is known about the typical noise environment experienced by most species over their lifetime. For example, even though considerable noise is encountered close to the sea surface, species living on the bottom may experience very quiet conditions. On the other hand, marine mammals living in quiet embayments may expose one another to very high levels of their own noise.

A-2 Fish Hearing

Fish hearing is characterized by a wide range of specializations that affect their auditory sensitivity and potentially susceptibility to noise. The main structures of the fish inner ear are the three semicircular canals, which are used in maintaining balance in three dimensions, and the otolithic organs, the utriculus, sacculus and lagena. These structures are responsible for sensitivity to sound pressure and contribute to localization of sound sources (Corwin and Overholtzer, 1997). In bony fishes, the otoliths are stones of calcium carbonate that ride on the sensory hair cells of the inner ear, while in more primitive fish and elasmobranches, they are replaced by small spherules called otoconia. These small stones move freely relative to the hair cells when a fish is exposed to pressure waves, exciting the sensory epithelium and producing the sensation of hearing.

Beyond these generalizations, it is difficult to characterize fish hearing in a short summary. There are many fish species from diverse taxa and this diversity is reflected in their auditory anatomy (Popper et al., 1998; Tavolga et al., 1981). Structures outside the ear, particularly the swim bladder, may be used to amplify sound entering the ear. Some species are hearing specialists with an anatomical connection between the inner ear and swimbladder that improves sensitivity and frequency range. Other species have no swim bladder at all and generally little hearing sensitivity. Fish with swimbladders, but no specialized structures coupling the swimbladder to the ear, can have low or intermediate sensitivity. Other species have different structures for improving sensitivity within the inner ear itself. In addition, the majority of species that have been studied are small fishes that are easy to hold in the laboratory, so there is only limited information on commercially-important marine species from controlled laboratory studies.

Fay (1988) published a compendium of the data available on fish auditory thresholds and sensitivity to particle motion. More recently, Nedwell et al. (2004) have reviewed the available data on the hearing of fishes for the purposes of predicting sensitivity to anthropogenic noise. The information available for commercially-important species in PWS or similar species are summarized briefly below. Readers are referred to Nedwell et al. (2004) for source data and greater detail regarding the studies. Most of the fish were studied using electrophysiological rather than behavioral measures of hearing, which may have reduced the estimated sensitivities somewhat, but there has generally been less difference between electrophysiological and behavioral measures in fish than in marine mammals because fish are difficult to condition.

Based on these reviews, a few generalizations can be made regarding fish hearing. First, the frequency range tends to vary greatly by taxon, but most of the commercially important species hear in the range from about 10 Hz to under 1 kHz. Unless they have special adaptations for good sensitivity, measured best sensitivities have been high (at least relative to marine mammals), in the range 70-100 dB re 1 µPa. However, the background noise in many studies was either not reported or was high enough that the thresholds could have been masked in the range below 500 Hz (see especially the three cod curves in Figure 14). Thus, the thresholds reported in these studies should be interpreted with caution.

Two species of bottom fishes, the dab (Limanda limanda) and plaice (Pleuronectes platessa) have been studied. The findings are expected to be similar for other flatfishes. They have no swimbladder, so it is not surprising that they have a narrow hearing range (best at 100 Hz) and poor hearing sensitivity (best sensitivity at 100 dB re 1 µPa).

Gadids appear to have moderate sensitivity, but a narrow range of hearing. Atlantic cod (Gadus morhua) have a swimbladder and moderate sensitivity to sound. There are no data available from the Pacific cod. Atlantic cod hear best in the range 50-600 Hz, with best sensitivity from 65-100 dB re 1 µPa based on the results of three separate studies (Figure 14) (Nedwell et al., 2004). Another gadid, the haddock (Melanogrammus aeglefinus) heard best in the range 60-310 Hz, with best sensitivity at 80 dB re 1 µPa.

The hearing of other non-specialists are similar. Atlantic pollock (Pollachus pollachius) hear best in the range 60-300 Hz, with best sensitivity at 81 dB re 1 µPa. Atlantic salmon (Salmo salar) hear in the same range, but have even lower best sensitivity, 95 dB re 1 µPa.

Clupeids, including herring (Clupea harengus) and the American shad (Alosa sapidissima) are hearing specialists. They have a structure in the inner ear (the prootic auditory bulla) that gives them moderate sensitivity to environmental noise and enough sensitivity at high frequencies to detect marine mammal echolocation (Mann et al., 1997). In the shad, there are two regions of best sensitivity, at around 400 Hz and another at 40-130 kHz, with best sensitivity at 118 dB re 1 µPa. While their sensitivity is poor in the higher range, it is good enough to allow them to detect high-amplitude echolocation clicks from approaching odontocete cetaceans. It is unclear whether high frequency hearing is widespread in the taxon, as earlier authors did not measure frequencies above 10 kHz. Herring had the best sensitivity of the gadid species that have been studied, at 75 dB re 1 µPa in the best range 100-1,000 Hz (measurements made to 10 kHz).

A-3 Marine Mammal Hearing

A-3.1 Mysticete hearing

Auditory thresholds of mysticete whales have not yet been measured directly. However, the threshold of response to band-limited sounds has provided limited information about their capabilities. The gray whale, for example, has been found to react to mitigation sonars at 21-25 kHz (Frankel, 2005) and tonal sounds at frequencies as low as 200 Hz (Dahlheim and Ljungblad, 1990). The responses in these experiments have been observed at levels down to the local noise ambient, so their sensitivity cannot be estimated with any accuracy.

The range of their hearing has been estimated to lie between around 7 Hz and 22 kHz based on anatomical characteristics of a limited sample of mysticete ears collected from freshly dead specimens (Ketten, 1994, 1998, 2000) (one each bowhead, fin, humpback, blue, right, and minke whale). The estimated best frequency lay below 5 kHz in every case. One attempt was made to measure the hearing thresholds of a captive orphaned gray whale using electrophysiological measures, but the results were more a testament to the difficulty of obtaining electrophysiological data from mysticetes than an indication of hearing range (Ridgway and Carder, 2001). The results were consistent with the range estimated on anatomical grounds.

A number of authors have suggested using vocal range as a proxy for the range of hearing. If this method were used, the mysticete best range would be estimated to lie below 5 kHz in most species, and would be maximal at approximately 20 kHz (see summary of vocal range in Richardson et al., 1995b). Vocal range of spotted dolphins matched the range of hearing (e.g. Lammers et al., 2003). However, in both cases there was an alternate source of information that could be used to confirm the estimates based on vocalizations. When used as an estimator a priori, vocal range should not be over-interpreted. It is a poor predictor of the best range of hearing. Many species produce vocalizations with substantial energy at frequencies below their range of best sensitivity, possibly because they have been optimized for signal transmission over longer distances than would be possible if all the vocal energy were in the midrange. For example, the dominant energy in killer whale vocalizations is often below 500 Hz even though their auditory sensitivity, like that of most delphinids, declines rapidly below 10 kHz (Bowles pers. obs. Richardson et al., 1995b; Szymanski et al., 1999). They hear very poorly at 500 Hz. In addition, it is not clear that conclusions can be drawn about the upper limit of hearing based on vocalizations because harmonics may extend well above the range of hearing. The best that can be said is that vocal range is a useful first-order approximation of the limits of hearing.

A-3.2 Small cetacean hearing

Many small delphinid cetaceans have similar hearing. Of these, the hearing of the bottlenose dolphin (Tursiops truncatus) and beluga whale have been studied best. Bottlenose dolphins and beluga whales (Delphinapterus leucas) hear in the range between 40 Hz-160 kHz, but their sensitivity begins to decline rapidly below 10 kHz and they are insensitive below 1 kHz. They hear best within the 10 kHz-80 kHz range (Richardson et al., 1995b).

The killer whale (Orcinus orca) has somewhat better hearing below 10 kHz based on a study of one animal with possible high-frequency hearing loss (Hall and Johnson, 1972), but they are still 40 dB less sensitive at 1 kHz than in the midrange. Based on electrophysiological evidence, killer whales hear frequencies in the range of 1-120 kHz and are most sensitive in the range of 18-42 kHz (Szymanski et al., 1999). To date, no studies have examined their susceptibility to noise-induced hearing loss.

Harbor porpoises (Phocoena phocoena) are representative of a group of small cetaceans with good high frequency hearing, the porpoises (the Dall's porpoise [Phocoenoides dalli] is also in this group). They have an extremely wide range of hearing, between 0.25-180 kHz, with greatest sensitivity between 16-140 kHz (Kastelein et al., 2002). They produce low frequency clicks at ~ 2 kHz and pulsed sounds (Richardson et al., 1995b) in addition to high frequency echolocation clicks. Above 32 kHz this species' hearing shows a second rage of high sensitivity, suggestive of a specialized 'acoustic fovea' designed for perception of echolocation clicks. Their upper limit is the highest of any odontocete species studied to date (Kastelein et al., 2002). Dall's porpoises are also in this group of high-frequency specialists, and may be expected to have a range of hearing similar to the harbor porpoise, but their auditory thresholds have not been measured.

A-3.3 Pinniped and sea otter hearing

Auditory thresholds have been measured in both Steller sea lions and harbor seals, but there are currently no published hearing data available for sea otters. The underwater hearing range for the Steller sea lion is 800 Hz-25 kHz for males and 800 Hz-30 kHz for females (Kastelein et al., 2005) . It is unclear whether the difference in range is actually the result of sex differences or simply the small sample of animals that have been studied to date. Maximum sensitivity for males is in the 1-16 kHz range and 1-25 kHz range for females.

Harbor seal hearing is among the best studied of any pinniped species. Harbor seals are capable of hearing underwater in the 1-70 kHz range, but sensitivity is poor above 60 kHz (Kastak and Schusterman, 1996). In-air sensitivity is optimal between 2 kHz and 20 kHz (Richardson et al., 1995b), but the range extends down to 100 Hz (Kastak and Schusterman, 1996).

A-4 Marine Mammal Vocalizations

What follows is a short summary of the vocalizations produced by the marine mammals most commonly encountered in the Sound. For more detailed information, readers are referred to the extensive literature review in Richardson et al. (1995b) and to Tyack and Clark (2001).

A-4.1 Mysticete whales

Balaenopterid rorquals are known for their low-frequency vocalizations. In PWS, the fin whale is the most commonly encountered large balaenopterid, and therefore the most likely to be impacted by noise from TAPS activities. Fin whales produce intense (184-186 dB re 1 μPa @ 1 m), low frequency (15-30 Hz) moans and downsweeps optimally suited for long distance communication in deep water. These calls are produced only by male fin whales (Croll et al., 2002), which suggests that they may function as breeding displays. More complex sounds have also been recorded in the presence of fin whales, including rumbles and clicks with greater broadband energy, up to ~2500 Hz (Richardson et al., 1995b).

Minke whales are the other common balaenopterid in the Sound. They produce a variety of vocalizations, including down sweeps, moans, grunts, ratchets, and thump trains, with dominant frequencies between 60-850 Hz and click trains with dominant frequencies of 12 kHz

(Richardson et al., 1995b). Source levels of these sounds can reach 175 dB re 1 μPa @ 1 m. Recently, they have also been found to produce the 'boing', a mysterious echoing transient that plagued submariners in the North Pacific for many years (Gedamke et al., 2001; Rankin and Barlow, 2005).

Unlike the balaenopterids and humpback whales, the gray whale has a relatively limited repertoire and is unlikely to produce sounds at high source levels. Data on gray whale vocalizations are limited from the Gulf of Alaska and PWS. Little is known about the function of gray whale calls. The major concentration of energy in gray whale signals is below 2 kHz, except for calves, which produce clicks at dominant frequencies between 3,400-4,000 Hz (Richardson et al., 1995b). This frequency range lies below the broadband noise produced by snapping shrimp, which is ubiquitous in shallow water throughout the temperate and tropical zones, so their vocalizations may be adapted for the noise environment encountered throughout most of their range. The measured source levels of these calls can reach 185 dB re 1 μPa @ 1 m (Richardson et al., 1995b), but are usually on the order of 110 to 130 dB re 1 μPa @ 1 m (Cummings et al., 1968).

Humpback whales are famed for the complex songs they produce during the breeding season. Song typically has its greatest energy in the range up to 4 kHz (Richardson et al. 1995), but components can be detected up to 24 kHz (Au et al., 2006). However, while summering in the North Pacific, humpback whales typically produce a variety of non-song sounds, including moans, shrieks, pulses, trains of grunts, and impact noise associated with surface activity. These vocalizations generally have their greatest energy in the range from 20 Hz to about 2 kHz (Thompson et al., 1986). In addition, they produce stereotyped, rhythmic 'feeding calls', series of cries typically associated with the formation of bubble curtains while feeding. In combination with the bubble curtains, these sounds are thought to 'herd' or frighten prey species into tight schools. They range in frequency from 360 to 988 Hz and are frequency modulated (Cerchio and Dahlheim, 2001). Summering humpback whales continue to sing, but only to a limited extent (Clark and Clapham, 2004; McSweeney et al., 1989). The source level of song has been measured at 151-173 dB re 1 μPa @ 1 m (Au et al., 2006). Surface-active impulses (fluke and pectoral slaps) can reach levels of 192 dB re 1 μPa @ 1 m (Thompson et al., 1986).

A-4.2 Odontocete Cetaceans

In keeping with their higher-frequency hearing, the vocalizations of odontocete cetaceans are generally much higher in frequency than those of mysticetes, although there can be considerable overlap. Killer whales produce whistles and pulsed calls with dominant frequencies in the range 0.5-12 kHz. Echolocation clicks have a dominant frequency range of 12-25 kHz (Richardson et al., 1995b). Many of the pulsed calls are stereotyped elements of a vocal dialect that distinguishes members by pod, clan, community and predatory lifestyle. Of the odontocetes, they are probably the most vulnerable to TAPS-related noise because much of their repertoire has significant energy below 5 kHz.

Harbor porpoises are likely to experience high levels of vessel noise because they occur in harbors, embayments, and inshore waters throughout PWS. However, as phocoenids (porpoises), they are among the cetaceans least susceptible to low-frequency anthropogenic noise because their vocalizations have the majority of their energy at high frequencies. They have been reported to produce low frequency clicks at ~ 2 kHz, but the function of these signals is unclear. Usually, they produce high frequency pulsed sounds that are thought to function as social signals in the range from , in addition to high frequency echolocation clicks (Richardson et al., 1995b). Source levels of their echolocations clicks have been measured at 167 dB re 1 µPa @ 1 m and 186 dB re 1 µPa @ 1 m (Au et al. 2007).

The vocal behavior of Dall's porpoises has not been studied frequently. They reportedly produce whistles and clicks between 0.04-12 kHz (Richardson et al., 1995b) at moderate source levels (120-148 dB re 1 µPa @ 1 m). However, the acoustic characteristics of their echolocation has not been measured, and their high frequency repertoire is unlikely to have been documented adequately.

A-4.3 Pinnipeds

Vocalizations of harbor seals and Steller sea lions are produced at mid to low frequencies (< 8 kHz) (Kastelein et al., 2005). Harbor seal pups produce a high-pitched cry to attract the mother's attention, but otherwise the species is silent on land. In water, they produce growls, snorts, chirps, barks, and a sound like a creaking door (Beier and Wartzok, 1979; Hanggi and Schusterman, 1994). The calls function in territory maintenance and attracting mates.

Steller sea lions produce barking threat displays, used in self defense and the defense of territories (Poulter, 1968). They also produce underwater clicks and bleating sounds.

Appendix B Marine Mammal Distribution

B-1 Cetaceans

Humpback whales occur seasonally in PWS during the summer, primarily distributed in the southwest portion of PWS. The Sound is an important foraging habitat. They are considered to be the most abundant whales in the area, with estimates of between 60 and 100 reported for the area (von Ziegesar et al., 1994). The whales are part of the North Pacific stock, estimated at 4,000 individuals and known to winter near the Hawaiian Islands (Angliss and Outlaw, 2006).

Whales of the genus Balaenoptera are widely distributed in the Pacific. The fin whale is the most likely to be encountered in PWS. Fin whales tend to concentrate in coastal and shelf waters (Reeves et al., 2002) wherever prey are available. Other large rorquals such as the blue and sei whale may occur occasionally, but are not known to use the Sound as an important feeding ground.

Gray whales travel along the coast of Alaska during their migration to and from their feeding grounds. They prefer inshore waters, typically appearing in the Sound during late spring and early fall. They are part of the eastern, or California, stock that migrates from Baja California in the winter to the Bering, Chukchi and Beaufort Seas in the summer (Reeves et al., 2002). A small proportion of the population has been found year-round off Oregon, Washington, and the coastal waters of the Gulf of Alaska (Angliss and Outlaw, 2006), particularly around Kodiak Island (Calambokidis et al., 2002). The number of these whales appears to be increasing, but it is not yet clear how much of the change in feeding areas can be attributed to the decline in their prey base and associated mortalities in 2000-2001.

Minke whales occur seasonally in the Gulf of Alaska during the summer months. This small rorqual is dependent on abundant stocks of krill and small fish (Reeves et al., 2002). Of the mysticetes, it is the most likely to be found in small embayments throughout the sound.

North Pacific right whales occur in coastal and shelf waters of the north Pacific, Gulf of Alaska, and southern Bering Sea, but are more likely to be found between Japan and Alaska, with anecdotal accounts of sightings along the west coast of the U.S. and Baja California (Reeves et al., 2002). After heavy exploitation by Russian whalers in the 1960s, this sub-species of right whale was feared extinct. Prior to exploitation, it was abundant around the Aleutians and in the Sea of Okhotsk. Over the past forty years, there have been occasional sightings in the eastern North Pacific of single whales. Recently, small groups have been found and one confirmed sighting of a calf, suggesting that a slow recovery may be underway. Because the few remaining whales are sparsely distributed, some of the best information has been obtained using acoustic surveys. Surveys using moored hydrophone arrays and buoys have found North Pacific right whales around Kodiak Island in the Gulf of Alaska, Southeast Alaska, and the Bering Sea (McDonald and Moore, 2002; Moore et al., 2006). They are apparently rare in the eastern North Pacific, however (71 FR 77694). Therefore, they are unlikely to be detected in PWS. Their prey requirements and movements are still poorly understood.

Sperm whales inhabit deep ice-free marine waters in all oceans to the edge of the polar pack ice. Adult males travel widely, but females and immature males do not occupy the higher latitudes (Reeves et al., 2002). Sperm whales feed primarily on squid in deep water, and are therefore only likely to be found in the deepest channels in PWS. However, they have recently begun to attack the longline fishery for sablefish in Southeast Alaska (Thode et al., 2007). There is therefore some likelihood that they could begin to attack the fishery in the Sound as well.

Beluga whales have a circumpolar distribution in Arctic waters. Populations exhibit high site fidelity, often returning to the areas where they were found in their first year of life (Reeves et al., 2002). They are rarely seen in PWS, but a small, isolated, genetically distinct population of belugas inhabits the nearby waters of Cook Inlet (Angliss and Outlaw, 2006; O'Corry-Crowe et al., 2002). Between 1994 and 1998, a 50% decline in this population was observed, primarily attributed to subsistence hunting. Subsistence hunts are now regulated and since 1998 the population has stabilized somewhat (Hobbs et al., 2000), but has recently been proposed for listing. Therefore, any individuals straying into PWS would be of great importance.

Killer whales are abundant year round in PWS (Angliss and Outlaw, 2006). Two distinct types occur in the Sound, residents and transients. Resident killer whales are seen primarily within the Sound and feed on fish, mainly coho salmon, during the summer months. Their movements in the winter are not known. Transient killer whales move in and out of the sound and feed primarily on other species of marine mammals, including harbor seals, Dall's porpoises, Steller sea lions, and harbor porpoises (Saulitis et al., 2000). Killer whales are known to attack sablefish longliners to steal their catch in both PWS and the Bering Sea. This behavior is probably mediated by the noise of the vessels (Francine and Awbrey, 1995; Thode et al., 2007), so the impact of masking noise could potentially be positive, at least from the perspective of the fishers. Recently, the impact of killer whales on other marine mammals has come under scrutiny, as they may be contributing to declines in sea otter, harbor seal, and Steller sea lion populations (Estes et al., 2006).

The Dall's porpoise is considered an abundant species in the Sound, especially during the summer months (Harvey and Dahlheim, 1994). They feed on both fish and squid and generally occur along the continental shelf and slope (Reeves et al., 2002) in the outer areas of the Sound.

Although, less common than Dall's Porpoise, the harbor porpoise is still considered abundant in PWS (Calkins, 1986). These shy, coastal porpoises feed on fish and occasionally cephalopods. They are found primarily in bays, harbors, and river mouths (Reeves et al., 2002) where they frequently encounter vessel noise.

B-2 Pinnipeds

Steller sea lions are locally abundant in the Gulf of Alaska (Angliss and Outlaw, 2006) and are the only sea lions to occur there (Reeves et al., 2002). Foraging habitats of the Steller sea lion are not completely understood but they are known to eat mainly walleye pollock in the Gulf of Alaska and Bering Sea (Reeves et al., 2002). Recent evidence indicates that some age classes may also be dependent on herring, and that the vertical migration of these fish is an important factor in access to the resource. Both an eastern and a western stock of the Steller Sea Lion are recognized in U.S. waters. Eastern stock rookeries occur in Southeast Alaska and western stock rookeries range from Prince William Sound across the Aleutian Island chain. While the eastern stock has shown an annual rate of increase of 5.9% between 1979-1997, the western stock has shown a general decline, up to a 90% decline at some sites over the same time span (Kruse et al., 2001). The western stock is listed as endangered under the ESA and depleted under the MMPA and has a minimum population estimate of 34,600 individuals, of which an estimated 3,500-4,000 are considered to occur in PWS (Angliss and Outlaw, 2006).

Three haul-out areas in PWS are considered critical habitat for the Steller sea lion. They are located on Perry Island, Point Eleanor, and the Needle. None of these sites occur within the shipping lanes, Valdez Arm, or Port of Valdez. The one on Perry Island is close to the channel used by cruise ships to enter the port of Whittier.

Harbor seals are abundant year round in PWS. They are considered part of the Gulf of Alaska stock. Although harbor seals are not currently listed under the MMPA or the ESA, the PWS population declined by 57% between 1984 and 1992 and is considered to be at risk. One possible explanation for the decline is overexploitation; an estimated 791 animals are taken per year by subsistence hunters in the Sound (Angliss and Outlaw, 2006). However, changes in fish resources are also considered a possible factor, as the hunt has been in existence for many years. The highest numbers of harbor seals occur in haul-outs during the pupping (May – Jun) and molting (Aug – Sep) seasons. The largest concentrations are found in the Copper River Delta near Cordova and mainland glacial fjords at the north and west points of the Sound.

B-3 Otters

Sea otters range from the Aleutian Island to California, with the majority of the worlds' population belonging to the Alaskan subspecies. In PWS, sea otters mainly feed on bivalves, crustaceans, and other invertebrates in near-shore waters. The minimum population estimate is approximately 100,000 individuals, of which an estimated 14,352 occur in the Sound (Angliss and Outlaw, 2006).