# Noise Impact Assessment

## Chapter Summary

- The two most common types of noise are point source and line source.
- Natural factors such as topography, vegetation, and temperature can reduce noise over distance. A hard site exists where sound travels away from the source over a generally flat, hard surface such as water, concrete, or hard-packed soil. When ground cover or normal unpacked earth is present between the source and receptor, the ground becomes absorptive to sound energy and is called a soft site.
- Topography, *v*egetation, and atmospheric factors can also affect the rate of sound attenuation.
- Existing ambient noise levels can serve as a baseline from which to measure potential disturbance caused by project activities. Baseline (ambient) noise levels vary greatly and depend on site-specific factors.
- Most transportation projects involve traffic noise. Identifying the amount and type of traffic helps to determine the baseline (ambient) noise conditions.
- One of the hardest things to quantify is noise associated with construction activities.
- Although noise from multiple sources at the same location results in louder levels than a single source alone, the decibel is on a logarithmic scale, so sound levels cannot be added by standard addition.
- For transportation projects, traffic noise typically determines the baseline noise level in the project area.
- In the absence of traffic, community or environmental noise levels may be important in project noise analysis.
- Defining the zone of noise impact requires the following steps:
    1. Estimate the equipment noise level for the project.
    2. Estimate the baseline (ambient) noise level. In most cases this can be done by defining traffic noise in the project area.
    3. Determine whether hard or soft site conditions exist.

4. Determine whether the noise is point source or line source noise.

5. Develop an attenuation table displaying distance and decibel level to compare traffic noise attenuation with construction noise. Graph the attenuation in a simple spreadsheet program, and plot a graph that linearly displays the attenuation rate for each source of noise. The point where the two lines cross represents the distance where construction noise is indistinguishable from traffic noise.

- Different species exhibit different hearing ranges, so appropriate sound metrics and frequency ratings should be used when possible.

- The threshold distance is defined as a known distance where noise at a given level elicits some response from a target species.

- Threshold distances and sound levels have been established to aid in making effect determinations for northern spotted owl and marbled murrelets.

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- Water currents bend underwater sound waves upward when propagated into the current and downward downstream. Sound waves bend toward colder, denser water.

- Underwater sound levels are measured with a hydrophone, or underwater microphone, which converts sound pressure to voltage, expressed in pascals (Pa), pounds per square inch (psi), or decibels (dB).

- Transmission loss (TL) underwater is the accumulated decrease in acoustic intensity as an acoustic pressure wave propagates outward from a source. The intensity of the source is reduced with increasing distance due to spreading.

- Noise reduction factors in water include hydrographic conditions that affect sound transmission, such as currents or tides, sediment types, bottom topography, structures in the water, slope of the bottom, temperature gradient, and wave height.

- Existing underwater noise levels serve as a baseline from which to measure potential disturbance associated with project activities.

- When analyzing the extent of the zone of noise impact, consider the area underwater through which the sound travels until it reaches ambient levels.

- The steps for defining the zone of noise impact are as follows:

1. Estimate the equipment noise level for the project.

2. Estimate the baseline (ambient) noise level.

3. Determine applicable noise reduction factors.

4. Use transmission loss models to determine the decrease in intensity of the sound away from the source.

5. Calculate the potential distance in which project noise will attenuate to ambient levels.

- The project biologist must analyze the effects of noise on all species addressed in the BA.
- For aquatic species, risk of injury or mortality resulting from noise is generally related to the effects of rapid pressure changes, especially on gas-filled spaces in the animal's body.
- Threshold distances and sound levels have been established aid in making effect determinations for salmon, bull trout, and diving marbled murrelets.

Noise from project activities can adversely affect wildlife in various ways. This chapter provides guidance on identifying construction-related noise and noise impacts in both terrestrial and in-water settings. Basic acoustic concepts are covered, including noise generation, transmission, and reduction. Identifying ambient or baseline noise levels for comparison with anticipated project-related noise can assist the project biologist in more accurately identifying the zone of impact for noise and, in turn, potential impacts on listed species.

Noise can be characterized as unwanted sound, and in this chapter, *sound* and *noise* are used interchangeably. Two other terms used in this chapter are *source* and *receptor*. In terms of hearing, the source is where a sound comes from, and the receptor is the perceiver or object (e.g., human, eagle, microphone, etc.) that is hearing or recording the sound.

For the project biologist's purpose, this discussion focuses on noise levels and the potential for impacts on wildlife. Noise transmission through air and impacts on terrestrial species are addressed first. Next, underwater noise, sound pressure levels, and their effects on fishes and diving marine birds are discussed.

# Terrestrial Noise

Sound is transmitted through air when an object moves, like water flowing over rocks, or air passing through vocal cords. This movement causes air waves, similar to ripples in water. When these waves reach human ears, they are transformed into sound. Sound is usually measured in decibels (dB). A decibel is a relative measure that is accompanied by a reference scale. Technically, sound pressure is 20 times the logarithm (base 10) of the ratio of the pressure level of any sound to the reference sound pressure in decibels. Table 7-1 shows typical sound levels generated by common indoor and outdoor activities, with human response.

**Table 7-1. Sound levels and human response.**

| Common Sounds | Noise Level (dB) | Effect |
|---|---|---|
| Rocket launching pad (no ear protection) | 180 | Irreversible hearing loss |
| Carrier deck jet operation<br>Air raid siren | 140 | Painfully loud |
| Thunderclap | 130 | Painfully loud |
| Jet takeoff (200 feet)<br>Auto horn (3 feet) | 120 | Maximum vocal effort |
| Pile driver<br>Rock concert | 110 | Extremely loud |
| Garbage truck<br>Firecrackers | 100 | Very loud |
| Heavy truck (50 feet)<br>City traffic | 90 | Very annoying<br>Hearing damage (8 hours) |
| Alarm clock (2 feet)<br>Hair dryer | 80 | Annoying |
| Noisy restaurant<br>Freeway traffic<br>Business office | 70 | Telephone use difficult |
| Air conditioning unit<br>Conversational speech | 60 | Intrusive |
| Light auto traffic (100 feet) | 50 | Quiet |
| Living room<br>Bedroom<br>Quiet office | 40 | Quiet |
| Library/soft whisper (15 feet) | 30 | Very quiet |
| Broadcasting studio | 20 | Very quiet |
| | 10 | Just audible |
| Threshold of hearing | 0 | Hearing begins |

From <http://www.nonoise.org/resource/educat/ownpage/soundlev.htm>.

In-air sound (which commonly is frequency-weighted to approximate human hearing) is measured on an A-weighted scale, denoted as dBA.[1] The A-weighted decibel scale begins at zero, which represents the faintest sound that humans can hear. How loud a sound is (or how loud it seems to humans) can vary from person to person. However, because decibels are measured on a logarithmic scale, a sound level of 70 dB is twice as loud to the listener as a sound of 60 dB (USDOT 1995).

1 For sound pressure in air, the reference amplitude is usually 20 micro-pascals (ΦPa). One pascal is the pressure resulting from a force of one newton exerted over an area of one square meter. Sound measured on an A-weighted scale is in reference to 20 ΦPa in this document.

## Noise Generation, Transmission, and Reduction

### *Noise Sources*

Sound is a pressure wave that decreases over distance from the source. Noise attenuation is typically described as a set reduction in decibel level per doubling of distance from the source. Depending on the nature of the noise source, sound propagates at different rates. Measures of sound level from a source should specify the distance from the source. The standard reference distance for sound levels at the source is 50 feet. The two most common types of noise are point source and line source. These are discussed in more detail below.

#### *Point Source Noise*

Point source noise is associated with noise that remains in one place for extended periods of time, such as with construction activities. A few examples of point sources of noise are pile drivers, jackhammers, rock drills, or excavators working in one location. Noise from a single traveling vehicle is also considered point source noise.

Point source noise is commonly measured in peak decibel levels, or the highest value of a sound pressure over a stated time interval (Harris 1991). Noise from a point source spreads spherically over distance. Think of this as a 3-dimensional model, where the wave spreading creates a dome effect, traveling in all directions equally from the source. The standard reduction for point source noise is 6 dB per doubling of distance from the source.

#### *Line Source Noise*

Line source noise is generated by moving objects along a linear corridor. Highway traffic is the best example of line source noise. Line source noise levels are measured as an average over time rather than peak levels measured in point source noise.

Noise from a line source spreads cylindrically, spreading outward along the length of a line. The standard reduction for line source noise is 3 dB per doubling of distance from the source (compared to 6 dB for point source noise).

Table 7-2 provides an example of noise attenuation of point and line source decibel levels based on distance from the source.

### *Noise Reduction Factors*

Natural factors such as topography, vegetation, and temperature can further reduce noise over distance. This section covers a few of the common factors and their applicability in increasing the noise reduction per doubling of distance from the source.

#### *Hard Site versus Soft Site*

A hard site exists where sound travels away from the source over a generally flat, hard surface such as water, concrete, or hard-packed soil. These are examples of reflective ground, where the ground does not provide any attenuation. The standard attenuation rate for hard site conditions is

6 dB per doubling of distance for point source noise and 3 dB per doubling of distance from line sources.

**Table 7-2. Example of noise reduction over distance from 95 dB source showing variation between point source and line source.**

| | Noise Attenuation | |
|---|---|---|
| Distance from Source (feet) | Point Source (–6 dB) | Line Source (–3 dB) |
| 50 | 95 dB | 95 dB |
| 100 | 89 dB | 92 dB |
| 200 | 83 dB | 89 dB |
| 400 | 77 dB | 86 dB |
| 800 | 71 dB | 83 dB |
| 1,600 | 65 dB | 80 dB |
| 3,200 | 59 dB | 77 dB |
| 6,400 | 53 dB | 74 dB |

When ground cover or normal unpacked earth (i.e., a soft site) exists between the source and receptor, the ground becomes absorptive to sound energy. Absorptive ground results in an additional noise reduction over distance of 1.5 dB per doubling of distance. Added to the standard reduction rate for soft site conditions, point source noise attenuates at a rate of 7.5 dB per doubling of distance, and line source noise decreases at a rate of 4.5 dB per doubling of distance.

*Topography, Vegetation, and Atmospheric Factors*

A break in the line of sight between the noise source and the receptor can result in a 5 dB reduction. Dense vegetation can reduce noise levels by 5 dB for every 100 feet of vegetation, up to a maximum reduction of 10 dB (USDOT 1995). Atmospheric conditions can also affect the rate of sound attenuation. Sound travels farther during periods of higher humidity and also in colder temperatures (USDI 2003). Wind can reduce noise levels by as much as 20 to 30 dB at long distances (USDOT 1995).

The influences of vegetation, topography, and atmospheric conditions as noise reduction factors can vary greatly and are often impossible to quantify. Therefore, these factors are generally not taken into account in environmental noise analyses, which likely results in predicted noise levels that are higher than actual noise levels.

## Baseline Noise Conditions

Existing ambient noise levels can serve as a baseline from which to measure potential disturbance caused by project activities.

### *Environmental Conditions*

Baseline (ambient) noise levels vary greatly and depend on site-specific factors. Environmental factors can elevate baseline noise near the source, masking construction noise. The same environmental factors occurring near the receptor can change the receptor's perception of how loud construction noise is, or hide it completely.

The few data that exist indicate baseline levels at known study sites of 35 to 88 dB for undisturbed forested areas. A WSDOT study on the Orcas Island ferry terminal identified a baseline of 58 to 61 dB (Bottorff and Schafer 1987). A WSDOT noise assessment on the San Juan Islands identified a baseline of about 35 dB at a bald eagle nest site, with regular noise intrusions from traffic and aircraft overflights ranging from 45 to 72 dB (WSDOT 1994). A study on the Mt. Baker-Snoqualmie National Forest listed forested baseline levels between 52 and 60 dB (USDA Forest Service 1996). The Olympic National Forest programmatic biological assessment uses an estimated baseline level of 40 dB for undisturbed forested areas (USDI 2003).

Weather conditions such as wind or rainfall can increase baseline noise. Locations near rivers or streams have higher baseline noise levels as well. As with the atmospheric conditions described above, these environmental factors are variable and may be impossible to quantify, so they are rarely taken into account in noise models.

The WSDOT project biologist should check with the WSDOT Air, Noise, and Energy Program to see if baseline noise data are available for the project or similar areas. If baseline information is not available and noise may be a major concern in the consultation, the biologist may wish to make onsite noise measurements with a hand-held noise meter.

### *Traffic Noise*

The majority of projects that the project biologist assesses encounters will involve traffic noise. Identifying the amount and type of traffic helps to determine the baseline (ambient) noise conditions. The level of highway traffic noise depends on the volume of traffic, the speed of the traffic, and the volume of trucks in the flow of traffic (USDOT 1995). Generally, the loudness of traffic noise is increased when traffic is heavier, when traffic speed is increased, and when a greater proportion of the traffic flow is heavy trucks.

For traffic volume, 2,000 vehicles per hour sounds twice as loud as (or is 10 dBA higher than) 200 vehicles per hour (USDOT 1995). As stated earlier, a noise that is increased by 10 dBA sounds twice as loud to the listener. For traffic speed, traffic at 65 miles per hour (mph) sounds twice as loud as traffic at 30 mph (USDOT 1995). In regard to the proportion of heavy truck traffic, one truck at 55 mph sounds as loud as 28 cars at 55 mph (USDOT 1995).

Vehicle noise is a combination of noises produced by engines, exhaust, and tires. The loudness of traffic noise can also be affected by the condition and type of roadway, road grade, and the condition and type of vehicle tires. Predictions of noise from vehicles are usually based on *reference energy mean emission levels*, which correspond to the noise level expected from a single vehicle at the standard 50-foot distance. Figure 7-1 shows the reference energy mean emission levels in dBA for automobiles (two axles with four tires), medium trucks (two axles with six tires), and heavy trucks (three or more axles).

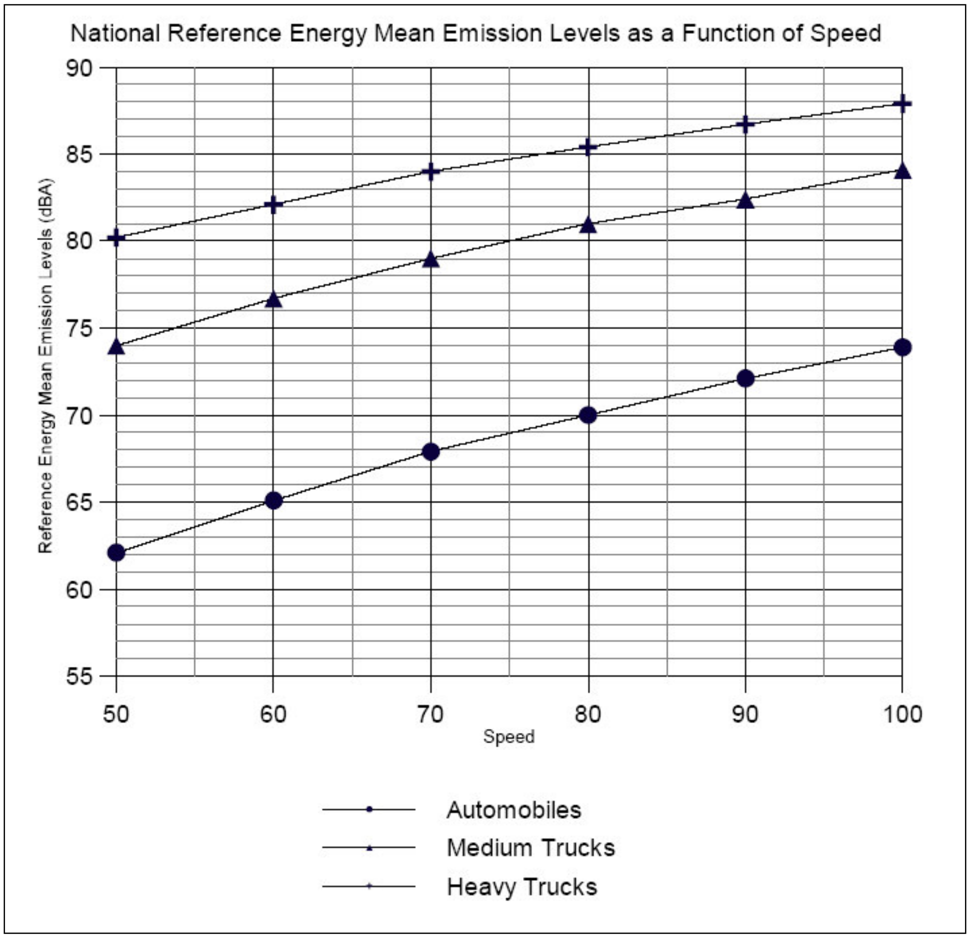



**Figure 7-1. Reference energy mean emission levels.**
(Note: Speed is in kilometers per hour.)

Table 7-3 lists typical traffic noise levels for a variety of roadway types, assuming heavy truck traffic and medium traffic volume. These numbers would be elevated as traffic volume increases.

**Table 7-3. Typical traffic noise levels.**

| Traffic Noise Levels | | | | |
|---|---|---|---|---|
| Traffic Speed and Type | Busy City Street | 35-40 mph Arterial (2-4 lanes, with stops and turn lanes) | 45-60 mph Highway (2 lanes) | 60+ mph Freeway (4-8 lanes) |
| Sound Level | 80 dB | 82 dB | 86 dB | 88+ dB |

## Construction Noise

One of the easiest things for the project biologist to identify and one of the hardest things to quantify is noise associated with the actual construction of the project. How much noise will construction generate, how often will it occur, and how long will it last are all questions that should be answered in the assessment. This section provides an introduction to equipment noise characteristics that the project biologist might expect for typical construction projects.

Construction is usually performed in a series of steps or phases, and noise associated with different phases can vary greatly. However, similarities in noise sources allow typical construction equipment to be placed into one of three categories: heavy equipment, stationary equipment, or impact equipment.

### *Heavy Equipment*

Heavy equipment can be defined as earth-moving equipment, such as excavating machinery like excavators, backhoes, and front loaders, as well as handling equipment like graders, pavers, rollers, and dump trucks. Noise levels at 50 feet from heavy equipment range from about 72 to 97 dB (Table 7-4). These numbers were identified from several studies, and represent the range of reported values. During the phase of construction using heavy equipment, noise is generated more or less at a constant level. Therefore, noise levels can be equated to an average hourly level.

**Table 7-4. Noise ranges at 50 feet from common construction equipment.**

| Equipment | dBA | Equipment | dBA |
|---|---|---|---|
| Heavy trucks (avg.) | 82–96 | Backhoe (avg.) | 72–90 |
| Grader (avg.) | 79–93 | Paver (+ grind) (avg.) | 85–89 |
| Excavator (avg.) | 81–97 | Front loader (avg.) | 72–90 |
| Crane (avg.) | 74–89 | Generator (avg.) | 71–82 |
| Pile driver (peak) | 81–115 | Jackhammers/rock drills (avg.) | 75–99 |
| Concrete mixer (avg.) | 75–88 | Roller (avg.) | 72–75 |
| Compressor (avg.) | 73–88 | Pumps (avg.) | 68–80 |

Sources: Bolt et al. (1971, 1987); Western Highway Institute (1971); WSDOT (1991); LSA Associates (2002).

Lacking onsite noise data, the project biologist can take the average of known equipment noise levels for the purpose of a noise assessment. Though it is not possible to average logarithmic functions, it is possible to take the average from the table above because the numbers represent a numeric value. For example, if the documented noise ranges of an excavators from four different studies are 81, 84, 87, and 90 dB at 50 feet, the biologist should assume a noise level of 86 dB to be typical.

### *Stationary Equipment*

Stationary equipment such as pumps, power generators, and air compressors generally runs continuously at relatively constant power and speed. Noise levels at 50 feet from stationary equipment can range from 68 to 88 dB, with pumps typically in the quieter range. The biologist can also assume an averaged noise level for stationary equipment because of its fixed location and constant noise pattern.

### *Impact Equipment*

This category includes pile drivers, jackhammers, pavement breakers, rock drills, and other pneumatic tools where a tool bit touches the work. The noise from jackhammers, breakers, rock drills, and pneumatic tools comes from the impact of the tool against the material. These levels can vary depending on the type and condition of the material. Noise levels at 50 feet from impact equipment, including jackhammers and rock drills, can range from 75 to 99 dB.

An impact pile driving hammer is a large piston-like device that is usually attached to a crane. The power source for impact hammers may be mechanical, air steam, diesel, or hydraulic.

In most impact drivers, a vertical support holds the pile in place, and a heavy weight, or ram, moves up and down, striking an anvil that transmits the blow of the ram to the pile. In hydraulic hammers, the ram is lifted by fluid, and gravity alone acts on the down stroke. A diesel hammer, or internal combustion hammer, carries its own power source and can be open-end or closed-end. An open-end diesel hammer falls under the action of gravity alone. A closed-end diesel hammer (double-acting) compresses air on its upward stroke and therefore can run faster than open-end hammers.

Vibratory hammers can also be used on projects. A vibratory pile driving hammer has a set of jaws that clamp onto the top of the pile. The pile is held steady while the hammer vibrates the pile to the desired depth. Because vibratory hammers are not impact tools, noise levels are not as high as with impact pile drivers. However, piles installed with a vibratory hammer must often be proofed, which involves striking the pile with an impact hammer to determine its load-bearing capacity, possibly with multiple impacts. In this case, noise is elevated to levels associated with impact pile driving. The project biologist should address proofing if vibratory hammers are used on a project.

The highest in-air noise from pile driving results from the impact of the hammer dropping on the pile, particularly when hollow steel piles are used. Noise assessments by WSDOT have documented peak levels of 110 dB (WSDOT 1994, 1995) and 105 dB (Bottorff and Schafer 1987) 50 feet away from driving steel piles.

Although stationary equipment noise and heavy equipment noise can be averaged over a period of time, pile driving noise consists of a series of peak events. Generally, noise from pile driving has been reported at peak levels. Therefore, the project biologist should assume that noise at the highest levels documented is commonly generated by pile driving and should avoid using an average in noise assessments.

For the purposes of this assessment, 110 dB is the best descriptor of typical peak noise levels associated with pile driving. Most of the documented studies have peak decibel levels between 95 and 110 dB, with only one documented level above 110 dB.

Noise from blasting should be included in the discussion on impact equipment. Since blast noise typically is infrequent and of short duration, blast noise is generally assessed using a different noise metric than those used for other more continuous types of noise. In assessing noise impact, peak instantaneous noise levels due to blasting (in $dB_{PEAK}$) cannot be compared to A-weighted noise levels (in dBA) for continuous noise sources, because noise from an impulse event such as blasting is perceived to be quieter than the unweighted peak level might imply. This is partly due to its short duration but mainly due to its very low frequency, in a range where human hearing is relatively insensitive.

Blasting can occur in different situations and is applied through a variety of methods. Due to the variability in blasting techniques and situations, noise from blasting is not addressed in this chapter. However, when addressing blasting, the project biologist should consider the following factors:

- Substrate – The location where blasting occurs partially determines the size of the charge and the duration of blasting. Blasting through bedrock requires more time and effort than blasting through less dense substrate.
- Size of charge – Blasting can use charges of less than a pound to over 200 pounds.
- Detonation system – Blasting may use a sequential delay system where each blast is subdivided into many smaller blasts, separated by a few milliseconds; or the blast may occur all at once.
- Directivity – Blasting above ground acts like point-source noise and spreads spherically from the source. Where blasting occurs below ground level, as in a shaft or pit, some directivity occurs, which directs the force of the blast upward more than horizontally, thereby lessening impacts.
- Use of BMPs – Best management practices may be used to lessen the energy of the blast. For example, when the charge is small enough, the use of heavy mats to cover the charge can significantly reduce the blast energy and contain any flying debris.

### *Rules for Decibel Addition*

Now that the project biologist can identify the type and level of construction equipment noise, it is important to discuss what happens when several pieces of equipment are operating at one time. Although noise from multiple sources at the same location results in louder levels than a single source alone, the decibel is on a logarithmic scale, so sound levels cannot be added by standard addition. Two sounds of equal level (±1 dB) combine to raise the noise level by 3 dB. However, if two sounds differ by more than 10 dB, there is no combined increase in the sound level; the higher output masks any other noise. The rules for decibel addition are shown in Table 7-5.

**Table 7-5. Rules for combining sound levels.**

| When two decibel values differ by: | Add the following to the higher decibel value: |
|---|---|
| 0 or 1 dB | 3 dB |
| 2 or 3 dB | 2 dB |
| 4 to 9 dB | 1 dB |
| 10 dB or more | 0 dB |

Source: USDOT (1995).

## Determining the Extent of Noise Impact

This discussion has introduced basic concepts and provided information on construction-related noise, traffic noise, and baseline noise levels. Using this information, the project biologist should be able to identify the extent of project-related noise to more accurately categorize the zone of noise impact, which represents one element of the project action area. This section provides instructions for establishing the extent of noise impacts and defining the noise element of the action area.

### *Community Noise or Environmental Noise*

For transportation projects, traffic noise typically determines the baseline noise level in the project area. However, it is also important to identify the project area baseline noise level in the absence of traffic. This noise level can be referred to as the environmental or community baseline noise level.

Baseline noise levels vary depending on the level of development. Urban areas have the highest baseline noise levels, with daytime levels of approximately 55 to 65 dB. Suburban or residential areas have baseline levels around 45 to 50 dB, while rural areas are the quietest with noise levels of 35 to 40 dB. Cavanaugh and Tocci (1998) identify typical urban residential noise at around 65 dB, high-density urban areas at 78 dB, and urban areas adjacent to freeway traffic at 88 dB. Community or environmental noise levels may be important in project noise analysis in the absence of traffic. In urban and developed areas, traffic noise and construction noise attenuate (decline) to baseline levels in less distance than in undeveloped or rural areas. For example, it may take 2 miles or more for construction noise to reach baseline levels in a rural area, but the same noise may attenuate to urban baseline levels in less than a mile. For most transportation projects, however, traffic noise determines the baseline noise level.

### *Steps for Defining the Noise Element or Zone of Impact*

The following subsection provides instruction on using noise analysis to determine the extent of impacts and define the noise element of the action area. This does not provide the biologist all of the information needed to describe the action area; noise is just one element of the project that must be considered. See Chapter 8 for guidance on determining the action area.

The following information is provided in a step-by-step format with an accompanying example project.

1. **Estimate the equipment noise level for the project**. In order to estimate the noise level of project activities, it is imperative to know and understand all equipment that will be used for the specific project. The project biologist should avoid assuming the types of equipment that may be used and ask the project design or engineering office for specific information. Once all project equipment is known, use the decibel levels for common construction equipment found in Table 7-4. This table shows the noise range for common construction equipment from several sources. Take the average noise level for at least the three noisiest pieces of equipment by taking the mid-value of the decibel levels listed in the table. For pile driving, use a value of 110 dB. Remember to use the rules of decibel addition for the final project noise level.

    - ***Example*** *– The equipment used will be an excavator, heavy trucks, finish grader, and paver. The estimated noise level for the construction equipment is: excavator, 89 dB; heavy trucks, 89 dB; grader, 86 dB, and; paver, 87 dB. Remembering the rules for decibel addition (see Table 7-5), the most noise will be produced by heavy trucks and/or excavators at 89 dB. The next highest noise level will be produced by the paver at 87 dB. Therefore, add two decibels to the higher value, and it can be assumed that construction noise will not exceed 91 dB.*

2. **Estimate the baseline noise level.** In most cases this can be done by defining traffic noise in the project area. There may be situations where baseline noise is greater than traffic noise, such as adjacent to airports. By using the information in Section 7.1.2.1, it is possible to estimate the baseline noise level for the project area by assessing traffic. The project biologist should define the type of roadway and the speed limit in the project area. If roadway type and speed limit are not obvious, consult the Washington State Highway Log (WSDOT 2005) for information. Using either the closest fit from Table 7-3 or the energy mean emission levels from Figure 7-1, estimate the decibel level of traffic in the project area. Remember that seasonality and the amount of heavy truck traffic can raise typical noise levels. The project biologist should also contact the WSDOT Air, Noise, and Energy program to ask if any acoustical monitoring has occurred in the project vicinity or in similar areas.

    - ***Example*** *- The project is located on a 2- lane state highway in an undeveloped forested area. The speed limit in the project area is 60 mph, and current traffic levels will be elevated because of the seasonal use and include heavy truck traffic. Table 7-3 lists the noise level as 86 dB for two-lane, 60 mph traffic, which is the best* *fit for the example. The 86 dB level already incorporates the 3 dB addition for more than one automobile.*

3. **Determine whether hard or soft site conditions exist.** Section 7.1.1.2 describes the difference between hard and soft site conditions. A hard site exists where sound travels away from the source over a generally flat, hard surface such as water, concrete, or hard-packed soil. When ground cover or normal unpacked earth exists between the source and receptor, the ground becomes absorptive to sound energy and soft site conditions are present. Most project areas, other than sites adjacent to water or in developed areas having more than 90 percent concrete or asphalt, exhibit soft site conditions. For soft site conditions, add 1.5 dB to the standard reduction factor.

   - ***Example*** *–Based on the location of the project in a forested setting, it can be assumed that soft site conditions exist. Therefore, add the additional 1.5 dB reduction on to the standard reduction factors.*

4. **Determine whether the noise is point source or line source noise –** Use Section 7.1.1.1 to determine whether construction noise and traffic noise are point or line source. Typically, construction noise has a point source, regardless of the activity. Even moving projects such as pavers attenuate noise in point source dynamics. Although construction activity may move, the noisy activity typically remains in one location.

   If multiple noisy activities are occurring at different locations throughout the project area, the zone of noise impacts should be described at each location. For example, pile driving could be occurring at one location in the project corridor, while pavement grinding or rock drilling may be occurring elsewhere.

   **Traffic noise is almost always line source noise.** The standard attenuation rate for point source noise is 6 dB, and the standard attenuation rate for line source noise is 3 dB. These standard attenuation rates do not take into account any reduction factors, such as soft sites, vegetation, or atmospheric factors.

   - ***Example*** *– All work on the project will occur at one location, and is considered point source noise. Therefore, adding the reduction for soft site conditions, construction noise will attenuate at a rate of 7.5 dB per doubling of distance. Traffic noise (line source) will attenuate at a rate of 4.5 dB per doubling of distance. This attenuation rate includes the 1.5 dB reduction for soft site conditions.*

5. **Develop an attenuation table** – The easiest way to compare traffic noise attenuation with construction noise attenuation is to construct a side-by-side table. Using the predicted levels, an attenuation table can be made displaying distance and decibel level. In noise assessments, 50 feet is the standard distance used to describe initial decibel levels. Therefore, the initial distance for known or predicted levels is 50 feet. The zone of noise impacts from construction activity is defined as the limit where noise from construction equipment is indistinguishable from noise generated by the roadway (baseline). An attenuation table can define the first estimate of the zone of noise impacts. Step 6 below describes how to develop an attenuation graph and use equations to further define the zone of noise impact.

   - ***Example*** *– Construction noise is estimated at 91 dB, and traffic noise is estimated at 86 dB. Table 7-6 was generated using the predicted construction and traffic noise levels and the attenuation rates for each. In this example project, it would be safe to define the extent of noise impacts at 200 feet, because it can be seen from the table that somewhere between 100 and 200 feet is where construction noise levels have attenuated to less than traffic noise levels.*

**Table 7-6. Example noise attenuation table.**

| Noise Attenuation Table (Example) | | |
|---|---|---|
| Distance from Roadway (ft) | Construction Noise (–7.5dB) | Traffic Noise (–4.5dB) |
| 50 | 91 dB | 86 dB |
| 100 | 83.5 dB | 81.5 dB |
| 200 | 76 dB | 77 dB |
| 400 | 68.5 dB | 72.5 dB |
| 800 | 61 dB | 68 dB |
| 1,600 | 53.5 dB | 63.5 dB |
| 3,200 | 46 dB | 59 dB |
| 6,400 | 38.5 dB | 54.5 dB |
| 12,800 | 31 dB | 40 dB |

The distance where construction noise has attenuated to less than baseline noise is somewhere between 100 and 200 feet.

6. **Graph the attenuation rates** – By developing the attenuation table above in a simple spreadsheet program, a graph can be made that linearly displays the attenuation rates for each source of noise. The point where the two lines cross represents the distance where construction noise is indistinguishable from traffic noise.

   Figure 7-2 graphically displays the attenuation rates for construction equipment noise and traffic noise. By using the trendline equation, the decibel level can be calculated at known distances. Note the trendline equation is specific for the set of variables that are input, and is not always the same as that listed here.

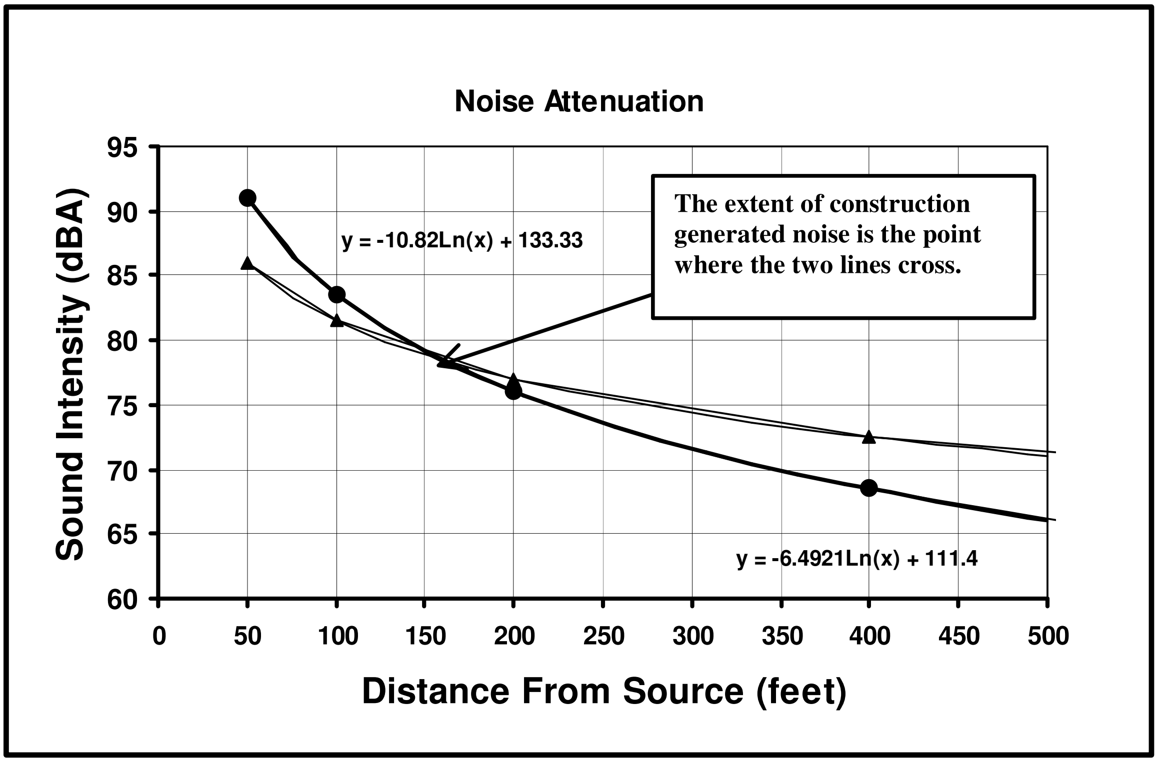



**Figure 7-2. Sound attenuation graph.**

- ***Example** – In this example, the equations for attenuation are:*

  Construction noise – noise level (dBA) = –10.82●ln(x) + 133)
  Traffic noise – noise level (dBA) = –6.4921●ln(x) + 111.4),

  *where x is the distance in feet from the origin of the sound. In the graph, the construction activity noise trend line crosses the traffic noise trend line at about 160 feet and about 79 dB. Using the equations and solving for distance can find this point more accurately. In this example, this distance is 150 feet. Therefore, the project biologist could define the noise zone of impact to be a radius 150 feet from the project activity. This assessment represents the worst-case scenario and does not take into account any interference such as topography or vegetation.*

If the project occurs in a developed area, the biologist can also use known baseline noise levels associated with the level of development, and determine when construction noise drops below that level to identify the noise zone of impact. For example, the Community Noise section above states an 88 dB baseline for those developed urban areas adjacent to freeway traffic. From the example project above, a 91 dB noise level was assumed. Using the equation for construction noise attenuation, construction noise would have attenuated to background levels at 66 feet from the project.

WSDOT is currently developing a noise model that can aid the project biologist in determining the extent of noise impacts. The model is intended for ease of use and to provide a definable extent of the noise until it diminishes to baseline levels. The user inputs the decibel levels for the three loudest pieces of equipment, traffic volume and type of vehicle, allowable speed limit, site surface characteristics, and target decibel level based on land use. The model calculates expected noise levels from these sources and the diminishing effects from vegetation, molecular absorption, atmospherics, and the physics of noise waves. The distance product is the worst-case scenario and does not take into account topography and naturally occurring noises such as water and wind. While the model will be applicable for most situations, it may not be appropriate to use the model for long linear projects that pass through numerous habitats or topographic features.

## Species and Noise

So far, this discussion has focused on noise dynamics, generation, and prediction. The ability to identify and measure noise is only part of the assessment. The project biologist is also tasked with addressing the effects of noise on the species addressed in the BA.

### *How Animals Hear*

Many animals can hear sounds with frequencies above and/or below the range of human hearing. Some animals have ears that can move and which are shaped to help localize the direction from which sound originates. Much is not known, but it is assumed that animals in general have better hearing than humans.

Not all animals respond the same way to similar noise sources, and not all individuals respond the same way within a species. Animal response to noise depends on a number of complicated factors, including sound level and frequency, distance and event duration, equipment type and condition, frequency of noisy events over time, slope, topography, weather conditions, previous exposure to similar sounds, hearing sensitivity, reproductive status, time of day, behavior during the noise event, and the animals location relative to the sound source (Delaney and Grubb 2003).

Different species exhibit different hearing ranges, so appropriate sound metrics and frequency ratings should be used when possible. For in-depth noise studies and hearing assessments, sound must be measured in a way that meaningfully correlates with the target species response. In this assessment, all decibel levels have been given as frequency weighted to approximate the way that humans hear. A-weighting (dBA) deemphasizes the upper and lower portions of the frequency spectrum, while emphasizing the middle portion of the spectrum (where humans have the greatest sensitivity). An audiogram (Figure 7-3) can describe the hearing range sensitivity for different species.

For example, an owl-weighted curve would emphasize the middle frequency range where owls have the highest hearing sensitivity. The information presented in this discussion only uses

A-weighted noise as a predictive factor. To describe effects on species, known threshold distances may constitute the best available science.

### *Threshold Distances and Effect Determinations*

Threshold distances are defined as a known distance where noise at a given level elicits some response from a target species. This response can be visual, as in head-turning or flushing from a nest, or the animal may show little reaction. Particularly in birds, little or no reaction does not mean that no effect has occurred.

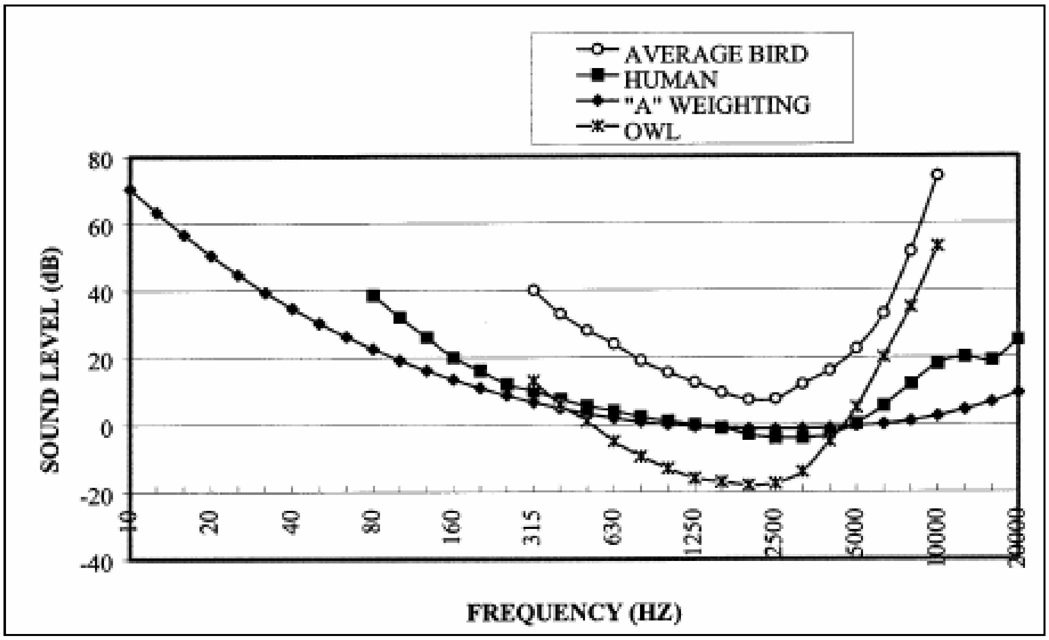



**Figure 7-3. Example audiograms.**
Source: Pater et al. (1999).

The U.S. Fish and Wildlife Service (USFWS) has provided WSDOT a copy of its biological opinion for the Olympic National Forest program of activities (USDI 2003). The USFWS updated Appendix 1 of the biological opinion in September 2004. Appendix 1 provides estimates of distance at which incidental *take* of marbled murrelets and northern spotted owls is expected to occur due to harassment from noise-generating activities. The biological opinion establishes harassment distances for noise-generating activities, specific to marbled murrelets and northern spotted owls. This document may present the best available science regarding thresholds and sound-only harassment distance for these species.

Harassment distance is the distance from an activity at which incidental *take* occurs due to harassment. Within the biological opinion, harassment distances and effect determinations for activities including but not limited to blasting, pile driving, and heavy equipment operation are defined (see Chapter 13 for effect determination guidance). In a previous biological opinion for the Olympic National Forest, the USFWS used a standard 0.25-mile distance from most noise generating activities and a one-mile distance for blasting and aircraft operation. In this biological opinion, distances in most cases are reduced significantly, based on noise analysis provided in Appendix 1.

Appendix 1 included the ESA definition of harassment; *an intentional or negligent act or omission which creates the likelihood of injury by annoying it to such an extent as to significantly disrupt normal behavior patterns which include, but are not limited to, breeding, feeding, and sheltering.* It also described behaviors indicating harassment including adult flushing from the nest, or aborting a feeding attempt. USFWS determined that a postponed feeding (when an adult successfully feeds young with the same prey item) is considered disturbance, not harassment.

In Appendix 1, the USFWS states the following: "we are concerned with the distances at which sound results in injury to murrelets, not the distance at which noise attenuates to ambient levels." The analysis cites several studies and personal communications regarding marbled murrelet responses to disturbance. Such studies are lacking for spotted owls, but some relevant information was available for Mexican spotted owls. The discussion seems to suggest that owls are most vulnerable to disturbance if the nest site is approached on foot. Mexican spotted owls seem to be most sensitive when activities and hiking traffic were conducted within 60 meters of the nest.

The analysis determined noise levels at a distance by using a 7.5 dB doubling distance reduction from noise-generating activities. They estimated the sound-only injury threshold for murrelets and owls is approximately 92 dB at nest sites. Disturbance thresholds were estimated at 70 dB. Detectability thresholds were estimated at 44 dB. Injury threshold distances for spotted owls and marbled murrelets are shown in Table 7-7. The process that was used to determine the sound-only detectability, alert, disturbance, and injury threshold distances is outlined below:

- ***Sound-only detectability threshold*** (where the sound is detectable, but a murrelet or spotted owl does not show any reaction) – The detectability threshold was identified as being 4 dB above the baseline noise level. For example, in the Olympic National Forest biological opinion, baseline noise levels were identified at 40 dB; therefore the detectability threshold was 44 dB. This number varies based on baseline noise levels. Dooling and Hulse (1989) noted that 16 species of birds showed an average sensitivity of 4 dB to detect a sound (in USDI 2003).

- ***Sound-only alert and disturbance thresholds*** (alert is where the murrelet or spotted owl shows apparent interest by turning the head or extending the neck; disturbance is where the murrelet or spotted owl show avoidance of the sound by hiding, defending itself, moving the wings or body, or postponing a feeding) – These threshold levels could not be documented with any precision, so they were subjectively placed between the detectability threshold and the injury threshold. The alert threshold is 57 dB and the disturbance threshold is defined as 70 dB.

- ***Sound-only injury threshold*** (where the murrelet or spotted owl is actually injured, defined as an adult flushed from the nest or the young missing a feeding) - This distance was estimated using known data from several studies that documented sound-only flushes for several bird species. Based on the results of the studies, the sound-only injury threshold is 92 dB. The detectability threshold differs as baseline noise differs, but this 92 dB level remains constant.

**Table 7-7. Threshold distances for spotted owl and marbled murrelet.**

| Activity | Combined Injury Threshold Distances: Murrelet / Spotted Owl |
|---|---|
| A blast, a large helicopter, or a large airplane | 1 mile / 1 mile |
| A small helicopter or a single-engine airplane | 120 yards / 120 yards |
| An impact pile driver, a jackhammer, or a rock drill | 60 yards / 60 yards |
| Chainsaws (firewood cutting, hazard trees, pre-commercial thinning, and commercial thinning) | 45 yards / 65 yards |
| Heavy equipment | 35 yards / 35 yards |

Source: USDI (2003, revised September 2004), Appendix 1.

### *Zone of Noise Impacts versus Effects on Species*

One of the biggest mistakes made in writing a BA is to define the action area in terms of the extent of impacts on species rather than the zone of impact for noise.

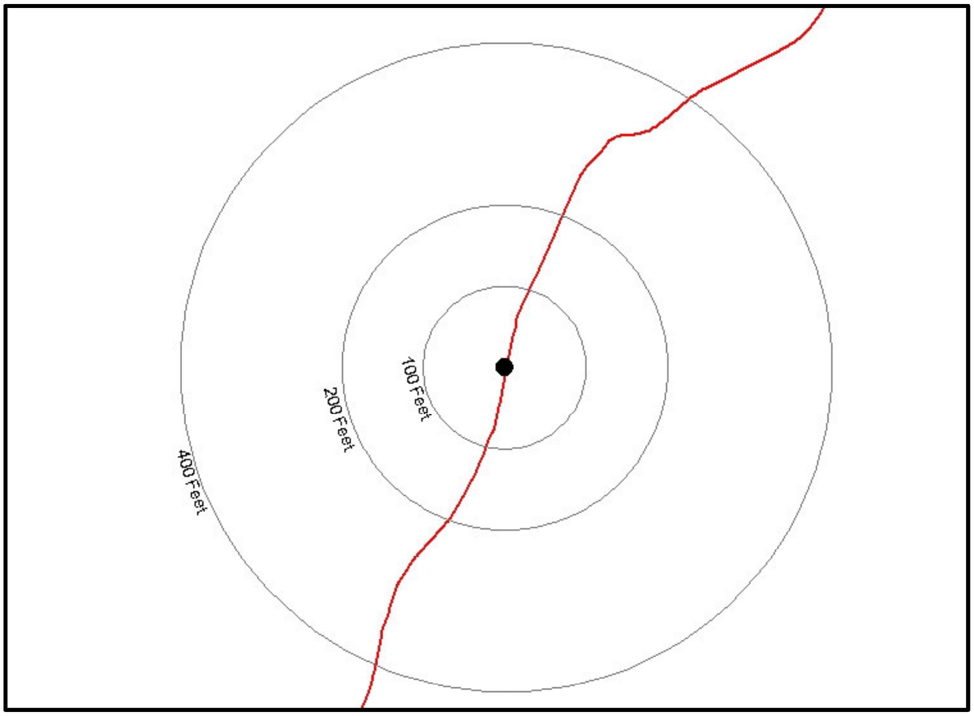
To illustrate the concept of action area versus impacts on species, this section combines the noise assessment information from Section 7.1 through Section 7.1.4.1 with threshold distances to reach an effect determination. The following figures are based on the example project presented in Section 7.1.4.2.

In Figure 7-4, the project area is the dot in the center of the figure. The concentric circles show the noise attenuation distances for construction and traffic noise. The two small tables with the figure show the noise levels and distances from the example for construction and traffic noise attenuation.

Figure 7-5 displays the example project area in relation to a bald eagle nest site, a spotted owl nest site, and a marbled murrelet suitable habitat/occupied stand. These locations are placed only for the purposes of the example.

Remember from the example, the extent of noise impact was estimated to be 150 feet. This distance is shown in Figure 7-5 as the heavier line. For this example, assume that the noise element is the farthest-reaching impact from construction activities; therefore, this distance represents the project action area.

These effect determinations assume that noise is the only construction-related impact on the species at these distances. See Chapter 13 for guidance on effect determinations for all elements of construction.




| Construction dBA | |
|---|---|
| 100 feet | 83.5 dB |
| 200 feet | 76 dB |
| 400 feet | 68.5 dB |

| Traffic dBA | |
|---|---|
| 100 feet | 81.5 dB |
| 200 feet | 77 dB |
| 400 feet | 72.5 dB |

**Figure 7-4. Example project area.**

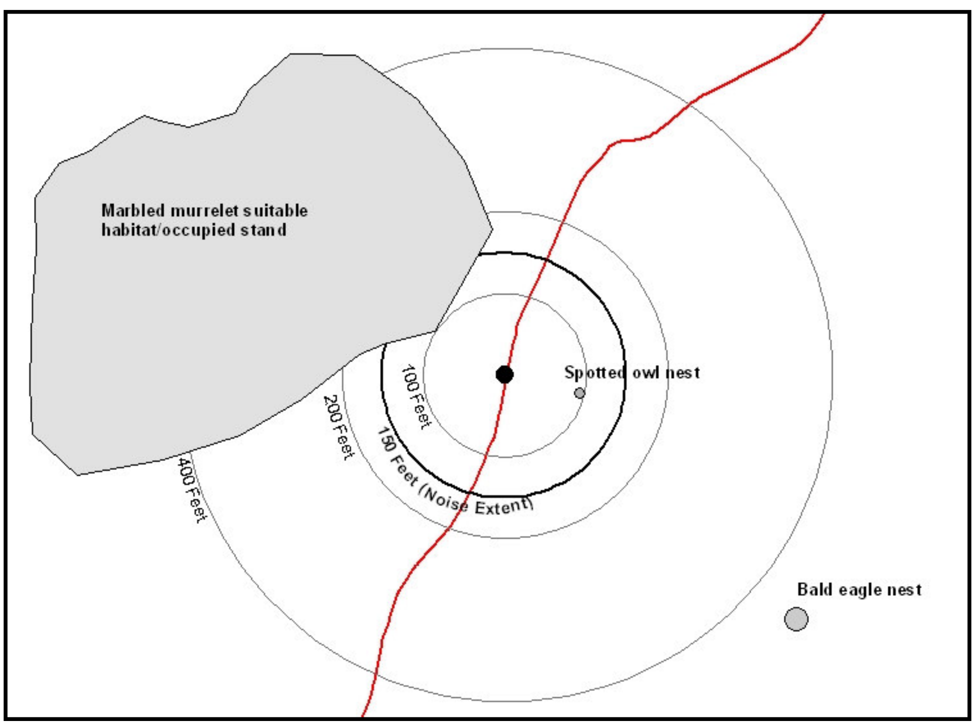



**Figure 7-5. Species and habitat occurrence.**

- **Bald eagle** – The bald eagle nest is located over 400 feet from the project area. The darker circle represents the point where construction noise has attenuated to baseline levels based on traffic. Therefore, the determination for bald eagle is *no effect*. (This assumes noise as the only element causing impacts; see Chapter 13 for additional guidance on determining impacts on foraging or roosting.)

- **Northern spotted owl** – The spotted owl nest site is located about 90 feet from the project area. Based on the example model above, the decibel level from construction noise at the nest is about 84 dB. This is above the disturbance threshold (70 dB), and below the injury threshold of 92 dB. This project example also assumes that the nest is not in line-of-sight of construction activities. The project biologist should always address the potential for visual disturbance as well. The determination would be *may affect, not likely to adversely affect* for spotted owl based on noise-only disturbance. Noise from construction activities may be at a high enough level to delay a feeding attempt or cause avoidance behavior, but noise will not reach the level of causing injury.

- **Marbled murrelet** – Suitable murrelet habitat exists about 100 feet from construction activity. In the absence of a survey to protocol, the project biologist must assume that suitable habitat is occupied habitat. By the time noise from construction enters suitable murrelet habitat, levels have attenuated to around 83 dB. This level is again between the disturbance and injury thresholds. The determination for murrelet in this example is *may affect, not likely to adversely affect*, for reasons similar to spotted owl.

If, for example, suitable habitat or a nest site were located immediately adjacent to the project area (within 35 yards and line-of-sight or with noise levels above 92 dB), the determination would be *adverse effect*, because based on these thresholds, noise levels would be high enough for injury to occur.

## Underwater Noise

In-water work activities contribute to noise in the marine and freshwater environments. Recently, underwater noise from pile driving activities has become an issue of concern to NOAA Fisheries and the U.S. Fish and Wildlife Service (referred to here as the Services). The Services are concerned with recent fish kills that have resulted from in-water pile driving activities in Puget Sound, San Francisco Bay, and British Columbia, Canada.

Noise behaves in much the same way in air and in water. (The information and concepts presented here apply to both fresh and saltwater environments.) Water currents bend sound waves upward when propagated into the current and downward downstream. Sound waves bend towards colder denser water. Bottom topography and underwater structures can block or refract sound waves.

Underwater sound levels are measured with a hydrophone, or underwater microphone, which converts sound pressure to voltage, expressed in pascals (Pa), pounds per square inch (psi), or decibels (dB).[2]

Sound levels measured in air are typically used to assess impacts on humans and thus are weighted (A-weighting) to correspond to the same frequency range that humans hear. Sound levels underwater are not weighted and thus measure the entire frequency range of interest, which may extend below and above audible range of many fish. Generally, to determine an equivalent sound level in air from an underwater noise level, subtract 62 dB from the underwater noise level. To calculate an equivalent underwater noise level from an airborne noise level, add 62 dB. This is due to the different acoustical properties of water and air.

## Noise Generation, Transmission, and Reduction

Transmission loss (TL) underwater is the accumulated decrease in acoustic intensity as an acoustic pressure wave propagates outwards from a source. The intensity of the source is reduced with increasing distance due to spreading. Spreading can be categorized into two models, spherical spreading and cylindrical spreading models.

### *Attenuation Models for Underwater Noise Levels*

Spherical (free-field) spreading occurs when the source is free to expand with no refraction or reflection from boundaries (e.g., the sediment or water surface). The TL for spherical spreading is defined by the formula:

$$TL = 20 \log(R)$$

where R is the range or distance from the source given by $\pi r2$. Spherical spreading results in a general 6 dB decrease in the intensity of the sound per doubling of distance.

Cylindrical spreading applies when sound energy spreads outwards in a cylindrical fashion bounded by the sediment and water surface. Cylindrical spreading is defined by the formula:

2. Measurements are typically recorded electronically for analysis later. Pascals, or psi, can easily be converted to decibels (dB). To convert sound pressure energy to dB in air or water we use the same formula:

$$dB = 20 \log(p/pref)$$

Where dB is decibels, p is the pressure in micropascals (pascal multiplied by 106), pref is a reference pressure. When converting air pressure levels a reference pressure of 20 micropascals is used. The 20 micropascal reference for sound in human studies was selected because it is near the threshold of hearing at 1kHz for the average young person. When converting underwater pressure levels a somewhat arbitrary reference pressure of 1 micropascal is used. Thus in many reports in the literature, underwater decibels are reported as decibels re: 1 micropascal, indicating that the decibels are referenced to 1 micropascal. All underwater sound pressure levels given in this chapter are in decibels (dB) referenced to 1 micropascal (μPa).

$$TL = 10 \log(R)$$

This results generally in 3 dB per doubling of distance transmission loss of underwater sound. However sound in shallow water, where many construction projects exist, reflections from the sediment or water surface can reduce spreading considerably. Because of the complexity of these reflections it is difficult to define. Since sound energy is not perfectly contained by reflection and refraction most experts agree that the true spreading is often somewhere between 3 and 6 dB per doubling of distance, or approximately 4.5 dB per doubling of distance (Vagle 2003).

Currently, the Services are using a practical spreading loss model as described by Davidson (<http://freespace.virgin.net/mark.davidson3/TL/TL.html>), where:

$$TL = 15\text{Log}(R_1/R_2)$$

This model assumes that sound energy decreases at a rate of 4.5 dB re: 1µPa per doubling of distance.

Illingworth and Rodkin (personal communication) state that the underlying characteristic of transmission loss for pile driving in marine environments is spherical spreading, however, like propagation in air, a number of other factors, such as temperature gradients and currents, modify this characteristic. The common occurrence of decreasing temperature with depth can create significant shadow zones (sound refracts or bends towards the colder deeper water as it does in air) where the sound pressure level can be as much as 30 dB lower than that given by spherical spreading. In shallow water (less than 200 meters depth), reflections from the surface and bottom combine in such a way that the sound level transitions from spherical spreading of 6 dB per doubling of distance to cylindrical spreading at 3 dB per doubling of distance. Where this transition occurs depends on the distance from the source, water depth, acoustic wavelength, and the reflective properties of the bottom and surface conditions. Thus, underwater sound propagation has a large amount of uncertainty.

Nedwell and Edwards (2002) measured underwater sound levels between 2 and 652 meters from the piles in the River Arun, England. The authors used the peak-to-peak values collected for each pile to estimate the transmission loss at their measurement site. The transmission loss was estimated to be 0.07 dB per meter.

The authors found that the standard geometric transmission loss formula did not fit well to the data. Therefore, because the losses are mainly due to absorption a better fit is given by the formula below. SL is the source sound level measured at some distance from the pile, $N_a$ is the transmission loss rate or 0.07 dB per meter, and R is the range or distance from the pile in meters.

$$SPL = SL - N_a (R)$$

Nedwell et al. (2003) measured underwater sound levels generated from 20-inch and 36-inch steel piles at a ferry terminal project in Southampton England, similar to conditions found in Puget Sound. Sound levels were monitored 96.3, 233.8, and 417.4 meters from the piles simultaneously. The authors used the peak to peak values collected for each pile to estimate the transmission loss at their measurement site. The transmission loss rate was estimated to be 0.15 dB per meter (Figure 7-6). The reason this transmission loss rate was approximately twice as high as the previous study (Nedwell and Edwards 2002) could be due to differences in sediment type, density gradients between fresh and salt water in the estuary, existing piles shielding the sound, or tidal or river currents in the River Arun influencing sound propagation. However, without further study it is unclear why the differences exist.

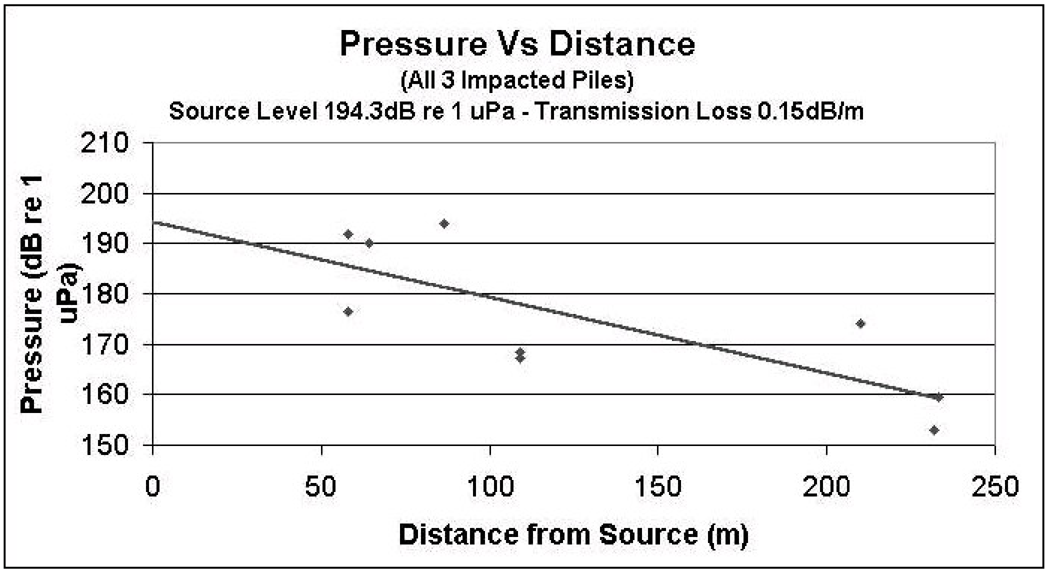



**Figure 7-6. Sound transmission loss over distance.**
Source: Nedwell et al. (2003).

Rearranging the terms to determine the distance in meters at which the sound levels drop off to ambient levels (action area), the following formula can be used.

$$R = \frac{SL - SPL}{N_a}$$

SL is the sound level at the source (dB), SPL is the ambient sound level (dB), and either 0.07 dB per meter (in river systems; Nedwell and Edwards 2002) or 0.15 dB per meter (in marine environments; Nedwell et al. 2003) can be used for $N_a$.

***Noise Reduction Factors***

*Hydrographic Conditions that Affect Sound Transmission*

In a current or tidal flux, sound propagated into the current would be refracted toward the surface where it would be quickly attenuated. However, this would depend on the velocity of the current and would occur on a scale of several hundred feet or more. This has not been researched adequately to make definitive determinations.

The water depth in which frequencies propagate must be greater than one-quarter the wavelength or $h = \lambda/4$ where h = water depth and $\lambda$ = wavelength (Urick 1983). Wavelength is determined by $\lambda = c/f$ where f = frequency in Hz and c = speed of sound in water (approximately 5000 feet/sec). Since the dominant frequencies generated in pile driving are between 50 and 1000 Hz, most of the energy is not propagated in water depths of 0.4 meters (1.3 feet) or less. However, some sound propagates through the sediment, especially the harder sediments, such as clay and rock, escaping into the water column somewhere else (albeit at a lower level than the source) through *sound flanking*.[3] Sound flanking is a common occurrence and has been observed by Burgess and Blackwell (2003) and WSDOT (2004d).

*Bottom Topography*

The method of determining how sound spreads as it moves away from the source can be difficult and site specific. It is dependent on sediment types, bottom topography, structures in the water, slope of bottom, temperature gradients, currents, and wave height. In the Puget Sound region the sediments are relatively soft and the bottom slopes away from the shore relatively quickly. Depending on location and season, there can also be a relatively strong tidal flux in Puget Sound. Therefore, it is clear that general conclusions about spreading cannot be drawn without the likelihood of violating several assumptions.

## Baseline Underwater Noise Conditions

Existing underwater noise levels can serve as a baseline from which to measure potential disturbance impacts associated with project activities. Both environmental or natural noise sources and mechanical or human generated noise contribute to the baseline or ambient noise conditions of a project site.

### *Environmental Noise*

Carlson et al. (2005)[4] measured the underwater baseline for the Hood Canal to range from 115 to 135 $dB_{RMS}$. Heathershaw et al. (2001) reported open-ocean ambient noise levels to be between 74 and 100 dB off the coast of central California with a sea state of 3-5.

There are numerous contributing sources to baseline noise conditions. Noise levels produced by natural sources include snapping shrimp (71 dB) (Urick 1983), lightening strikes (260 dB), waves breaking on the ocean surface (65–85 dB), and gray whales (185 dB) (CRS Report 95-603 1995; Heathershaw et al. 2001).

3. *Sound flanking* refers to paths by which sound travels around an element, such as in water surrounding a piling. For example, a sound generated by pile driving can be flanked to another location by the ocean floor if the substrate is relatively uniform and uninterrupted from one location to another.

4. Carlson, T.J., D.A. Woodruff, G.E. Johnson, N.P. Kohn, G.R. Plosky, M.A. Weiland, J.A. Southard, and S.L. Southard. 2005. Hydroacoustic Measurements During Pile Driving at the Hood Canal Bridge, September through November. 2004. Battelle Marine Sciences Laboratory, Sequim, Washington.

### *Mechanical Noise*

Ambient noise levels can range louder in areas of high human usage. Feist et al. (1992) measured ambient levels at Everett Home Port to be between 80 and 90 dB (SPL). Anchor Environmental (McKenzie personal communication) measured ambient levels at the Mukilteo ferry terminal to be approximately 145 dB peak in the absence of ferry traffic. Greene (2003) measured ambient sounds in the Duwamish River averaged over 20 seconds to 5 minutes and varied between 110 to 130 dB (SPL).

Noise levels produced by human or mechanical sources include large tankers and naval ship engines (up to 198 dB) and 180+ dB for depth sounders (CRS Report 95-603, 1995; Heathershaw et al. 2001). Commercial sonar devices operate in a frequency range of 15 kHz to 200 kHz and in an acoustical range of 150 to 215 dB (Stocker 2002).

## Underwater Construction Noise

Although there are many sources of noise in the underwater environment, the most common sources of noise associated with construction activities are impact hammers. Underwater noise from pile driving is generated using different types and diameters of piles, types of hammers, and by driving the piles into different types of substrates. Each configuration can produce different sound levels and waveform characteristics.

Sound generated by impact pile driving is impulsive in nature. Impulsive sounds have short duration and consist of a broad range of frequencies. Impulsive wave forms are characterized by a rapid pressure rise time (the time in milliseconds it takes the wave form to rise from 10 percent to 90 percent of its highest peak) that occurs within the first few milliseconds followed by rapid fluctuation (underpressure and overpressure) about the ambient pressure.[5]

### *Impact Equipment*

There are four pile driving hammer types that are commonly used. Vibratory hammer, diesel hammer, air or steam hammer, and hydraulic hammer. Wave forms generated by each of these hammer types are described below.

Vibratory hammers vibrate the pile into the sediment by use of an oscillating hammer placed on top of the pile. The vibratory action causes the sediment surrounding the pile to liquefy and the pile can be driven through the sediment. In most cases piles cannot be driven by vibratory hammers to a depth where they can reach load bearing capacity. In these cases an impact hammer must be used to finish driving the pile to the proper depth also known as proofing the pile.

---

5. The total duration of the impulse varies based on several factors, which include the force applied to the pile, the nature of the pile (i.e., wood, concrete, or steel as well as diameter) and the substrate into which the pile is being driven. In general, most of the energy associated with each impulse occurs within the first 30 to 50 msec. Recent measurements of underwater sound generated by impact pile driving have shown that most of the energy is contained in a frequency range between approximately 25Hz and 1.6 kHz. Within this frequency band the highest energy densities are found between 50 and 350 Hz (Reyff et al. 2002).

Peak sound levels can exceed 180 dB; however, the rise time is relatively slow (Figure 7-7). Vibratory driving sound levels are generally 10 to 20 dB lower than impact hammer driving.

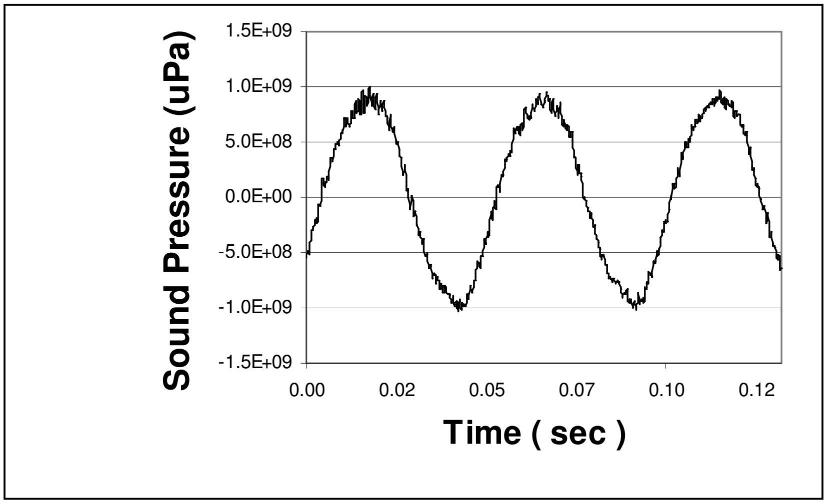



**Figure 7-7. Typical vibratory hammer wave form.**

Impacts on fish have not been observed in association with vibratory hammers. This is because of the slower rise time and the fact that the energy produced is spread out over the time it takes to drive the pile. As a result, vibratory driving of piles is generally the preferred method.

Air or steam-driven impact hammers use air to lift a heavy piston and then use gravity to drop the piston onto the top of the pile. The height of the piston can be varied somewhat allowing more potential energy to be put into the piston and then transferred as kinetic energy into the pile. Air hammers produce underwater sound waveforms with each pile strike that are similar to diesel hammers (Figure 7-8). Therefore, sound levels and rise time are similar for air hammers and diesel hammers.

Diesel-driven impact hammers ignite diesel fuel to lift a heavy piston and then use gravity to drop the piston onto the top of the pile. The height of the piston can be varied somewhat by varying the amount of diesel fuel going into the combustion chamber. Diesel hammers produce underwater sound waveforms with each pile strike that are similar to air hammers (Figure 7-9).

Hydraulic driven impact hammers use hydraulics to lift a heavy piston and then use gravity to drop the piston onto the top of the pile. In addition, with some hydraulic hammers, hydraulic pressure is used to drive the hammer into the pile instead of using gravity. Hydraulic hammers produce a somewhat different waveform signature with a much more rapid rise time (Figure 7-10). It is in part because of this rapid rise time that diesel hammers are often preferred over hydraulic.

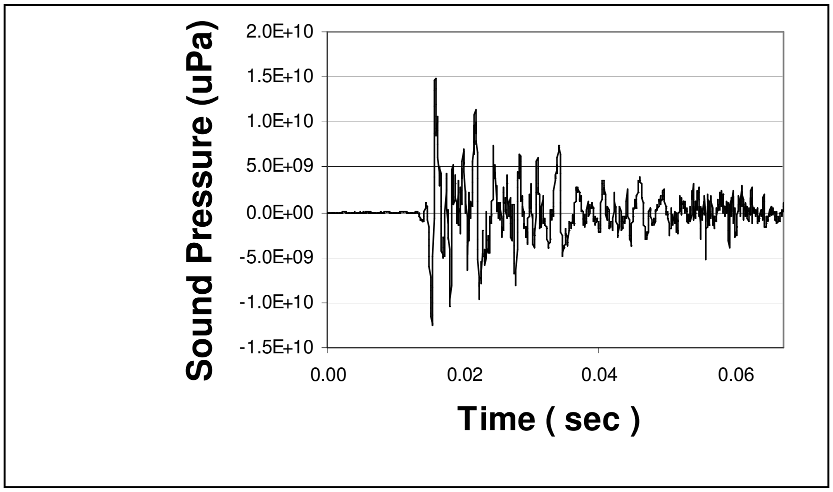



**Figure 7-8. Typical air hammer wave form for a single pile strike.**

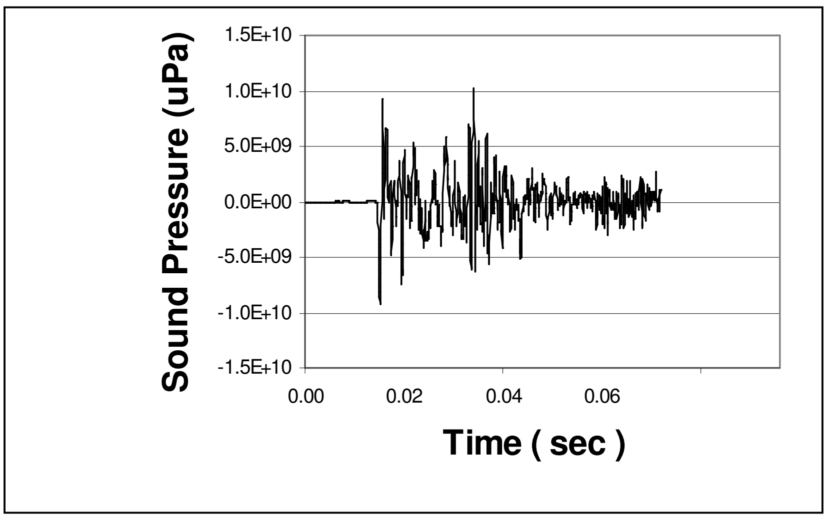



**Figure 7-9. Typical diesel hammer wave form for a single pile strike.**

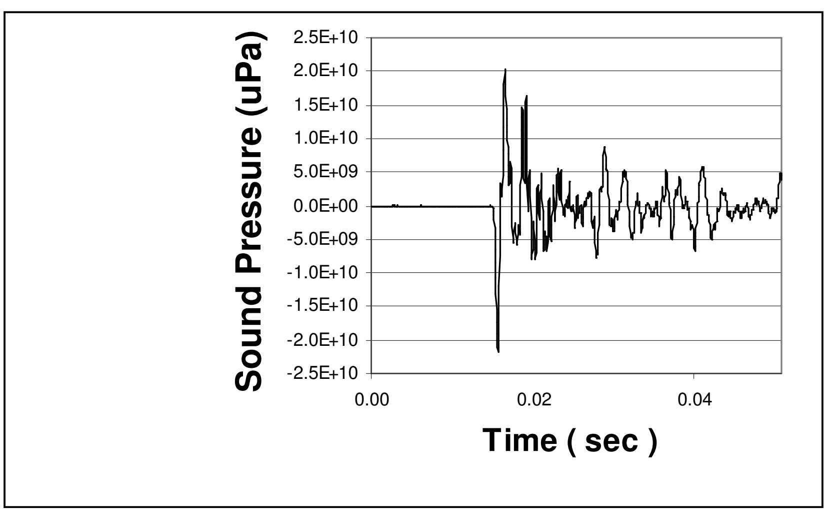



**Figure 7-10. Typical hydraulic hammer wave form for a single pile strike.**

### *Different Pile Types*

Different types and diameters of piles can also affect the noise generated by pile-driving activities. There are three different materials piles can be made of timber, concrete, and steel. Noise levels associated with each of these types of piles are summarized in the list below. These are denoted as either peak or RMS, and show the distance measured, if known:

- Wood piles:[6] < 200 $dB_{PEAK}$
- Concrete piles:[7] 190 and 205 $dB_{PEAK}$
- Steel H-piles: < 180 $dB_{PEAK}$
- 12-inch steel piles[8]: 175-177 $dB_{RMS}$ @ 10m
- 14-inch steel piles: 180 $dB_{RMS}$ @ 30m
- 16-inch steel piles9: 187 $dB_{RMS}$ @ 9m
- 24-inch steel piles[10]: 178-195 $dB_{RMS}$ @ 10m

---

6. Timber piles, of variable diameter, have been measured underwater by the Port of Vancouver (POV) in British Columbia to achieve a peak level of 200 dB. The POV has compared the shape of the sound wave between steel piles and timber piles and found that the timber pile produced a more 'rounded' wave than with steel piles. This means that although the peak sound levels may be similar the waveform appears more stretched out than for steel piles and the rise time is relatively slower. A slower rise time means that the shock wave produced with each pile strike is not as severe resulting in less damage to the fish. The effect is similar to the difference between a push and a punch.

7. Concrete piles with 24-inch diameter have been measured by POV, and sound levels range between 190 and 205 dB (DesJardin 2003 personal communication). In California, although there have been no documented fish kills with the installation of concrete piles, the Services have not exempted concrete piles from possible sound mitigation strategies or monitoring because of the lack of formally documented effects (CalTrans 2003 personal communication). The POV achieved a 0-5 dB reduction with a bubble curtain on a 24-inch concrete pile (DesJardin 2003 personal communication). The POV has compared the shape of the sound wave between steel piles and concrete piles and found that the concrete piles produced a more rounded wave than the steel piles.

8. CalTrans (2003 personal communication) has measured the sound energy emanating from driving 12-inch diameter steel piles to range between 180 – 190 dB, and 14-inch diameter steel piles to range between 195 and 200 dB. Illingworth and Rodkin (2004 personal communication) measured 10-inch steel H-piles in a slough approximately 6 feet deep at 10 meter distance from the pile to range between 180 – 195 dB (160-177 dB RMS). They also measured 10-inch steel H-pile at Noyo Bridge with peak levels at 180 dB (165 dB RMS) at 30 meters from the pile. An H-pile driven on shore next to the water produced peak levels in the water of 170-175 dB (155-162 dB RMS) at 23 meters from the pile. The measurements at Noyo Bridge were highly variable due to the shallow water. Vibratory driving has been shown to be 10 – 20 dB lower than impact driving steel piles of similar diameter (CalTrans 2003 personal communication).

9 Laughlin, Jim. 2004. Underwater Sound Levels Associated with the Construction of the SR 240 Bridge on the Yakima River at Richland. WSDOT, Office of Air Quality and Noise, Seattle, WA. September 2004. 33 pages.

10. Sound pressure levels generated from pile driving of 24-inch diameter steel piles have been measured by POV to range between 201 – 214 dB, and 36-inch steel piles at approximately 224 dB (DesJardin 2003 personal communication). The highest sound pressure levels were observed at a range of 4-5 meters from the pile and the sound pressure level was found to depend most on the type of substrate. They found that sound levels would range between 201 dB to 214 dB within a 2-foot change in substrate depth of the pile due to change in substrate

- 30-inch steel piles: 194-212 $dB_{RMS}$ @10m
- 66-inch dia. steel piles: 185 $dB_{RMS}$ @ 30m
- 126-inch dia. steel piles: 180-206 $dB_{RMS}$ @ 11m
- 150-inch dia. steel piles: 192 $dB_{RMS}$ @ 50m
- 8-foot dia. steel piles: 183-207 $dB_{PEAK}$
- Peak levels are generally 10 to 15 dB higher than RMS levels
- Peak pressures occur between 1 millisecond (msec) very close to the pile and 5 to 6 msec after the strike at a distance of 20 meters from the pile
- The greater the pile surface exposed under the water, the more acoustic energy radiates. Shallower water (e.g., water less than about 3 feet deep) does not propagate sound energy effectively, especially at lower frequencies.

***Noise Reduction Strategies***

An air bubble curtain is a device used during pile driving that infuses the area surrounding piles with air, thereby generating a bubble screen. The purpose is to attenuate peak underwater sound pressure levels (SPLs), which may adversely affect fish, marine mammals, and seabirds in the marine environment.

The components of a bubble curtain typically include a high volume air compressor, primary and secondary feed lines, and air distribution manifolds. Longmuir et al (2001) recommended that manifolds should have 1/16-inch air release holes every ¾-inch along their entire length (Figure 7-11). The air distribution manifolds are placed surrounding the piling below the water surface where the pile meets the sediment. An effective bubble curtain system should distribute air bubbles that completely surround the perimeter of a pile to the full depth of the water column. Reducing the size of the bubbles greatly enhances the sound attenuation of the bubble curtain (Vagle 2003).

In areas where currents exist, where the seafloor or substrate is not level, or piles are being driven at an angle other than 90 degrees to the water surface, the size or number of manifolds should increase to provide coverage throughout the water column. In some of these cases, bubble curtains may prove ineffective.

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composition. POV also recorded peak pressure measurements at the bottom and 5-7 meters from the water surface. In Canada, there are currently no mitigation or monitoring requirements for steel piling less than 18-inches in diameter as they assume there will be no impacts. The Canadian government has agreed on a 30 kPa (210 dB) threshold for piles larger than 18-inches to protect small fish (DesJardin 2003 personal communication).

The design of an air bubble curtain directly relates to the effectiveness at reducing sound pressure levels. Curtains should be designed to maximize the potential for noise reduction. When properly designed and implemented, reductions of 3 to 24 dB have been documented.

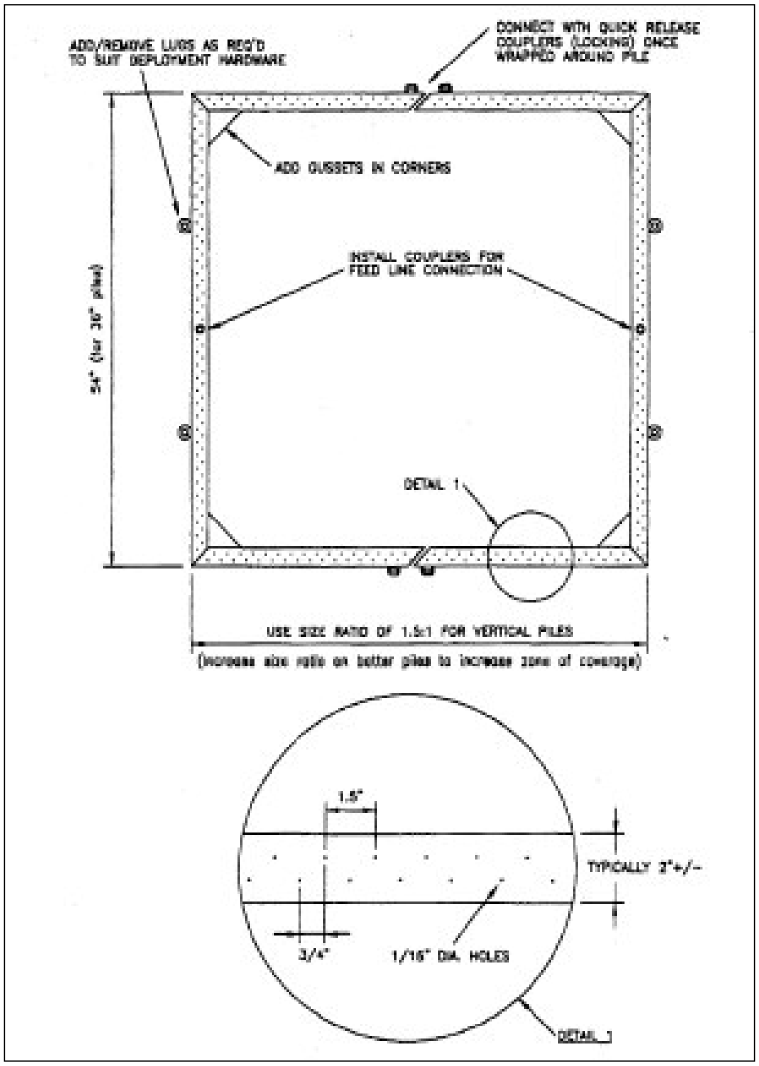


**Figure 7-11. Air manifold design.**
Source: Longmuir et al. (2001).

## Determining the Extent of Underwater Noise Impacts

The action area for a project is defined as the extent of the physical, chemical, and biological effects of the action. When considering the extent of the noise element of the action area (i.e., zone of impact associated with noise), consider the area underwater through which the sound travels until it reaches ambient levels.

### *Steps for Defining the Noise Element or Zone of Impact*

The following subsection provides instruction on using noise analysis to determine the extent of impacts and define the noise element of the action area. This is not meant to provide the project biologist with all of the information needed to describe the action area; noise is just one element of the project that must be considered when defining the action area.

A brief example of how one would use the concepts discussed above to define the zone of impact associated with noise is provided here.

- Assume the simplest situation where sound levels decrease at a rate of 0.07 dB per meter from the source in a freshwater river system (Nedwell and Edwards 2002), or 0.15 dB per meter from the source in a marine environment (Nedwell et al. 2003). Also assume that a typical peak sound level produced by driving a steel pile with a diesel hammer is 205 dB at a distance of 10 meters (33 feet) from the pile. The calculation shows that the sound level drops off to an ambient level of 130 dB at 1,071 meters (0.7 miles) in a freshwater river system (i.e., 0.07 dB per meter); or at 500 meters (0.3 miles) (i.e., 0.15 dB per meter) in a marine environment such as Puget Sound.
- Most calculations for determining at what point the project noise becomes indistinguishable from ambient noise assume a 3 dB decrease with doubling of distance. At this rate of loss, the sound level from the source described above drops off to 130 dB at 983,000 meters (611 miles). However, common sense would dictate that the sound levels would drop to ambient levels long before it reached 611 miles because there are other noise sources in the environment that can mask noise levels or attenuate levels more quickly. As mentioned above, temperature gradients, bottom topography, and currents can cause sound levels to attenuate more quickly. Therefore, it is often difficult to accurately determine the extents of noise impacts using a standard geometric spreading model.
- In addition, the use of a bubble curtain can reduce the levels at the source. Assuming a 5 dB reduction at the source described above from use of an air bubble curtain, the distance at which the sound reaches an ambient level (130 dB) is reduced to about 467 meters (0.3 miles) using the formula from Nedwell et al. (2004). In other words, a 5 dB reduction at the source translates into approximately a 7 percent reduction of the zone of impact.

The following example will use both the Nedwell model and the Practical Spreading Loss model in use by the Services to illustrate the procedure for determining the zone of noise impact.

1. **Estimate the equipment noise level for the project**. Though there are many types of equipment potentially used during underwater construction, pile driving is one of the most probable activities in underwater environments and is one of the best understood. To determine the noise levels associated with pile driving determine the hammer type as well as

the type of pile being used. Peak decibels associated with different types of piles are listed in the DIFFERENT PILE TYPES section above.

For other equipment types to calculate an equivalent underwater noise level from an airborne noise level, add 62 dB. Tables 7-1 and 7-4 can be used to determine noise levels for equipment that may be used for underwater construction.

- ***Example*** *– A 205 dB peak sound level is estimated 5 feet from the pile, as a result of driving a concrete pile with a diesel hammer.*

2. **Estimate the baseline noise level**. Determine if there have been any noise studies in the vicinity of your project that may be able to specifically define ambient underwater noise levels. If not, based on some of the information cited above, you could estimate a reasonable baseline noise level.

   - ***Example*** *– The project takes place in Puget Sound and no noise studies have been completed in the vicinity of the project. However, based on the study in Hood Canal reported earlier and the similarity of properties with Puget Sound, a baseline noise level of 115* $dB_{RMS}$ *is assumed.*

3. **Determine applicable noise reduction factors**. Identify if there are any noise reduction factors that are present either as a result of the physical location of the project (shallow water, confined harbor, soft-bottom substrates, currents, etc.) or impact minimization measures that will be implemented during construction.

   - ***Example –*** *The project site is bordered on the east by shoreline and upland habitats. As a result, underwater noise associated with pile-driving activities will dissipate 100-200 meters to the east of the locations where piles will be installed. To the west shorelines are located 5 miles away. The terminus of the harbor is located 2 miles to the north and the mouth of the harbor is located 5 miles to the south. A bubble curtain will also be used. This will reduce the anticipated underwater construction noise by 15 to 190 dB.*

4. **Use the Nedwell Model to determine the zone of aquatic impact**.

   - ***Example –*** *Because this example takes place within a harbor, shallow water depths are assumed, with noise intensity decreasing at 0.15 dB per meter.* ***From above, R = (SL-SPL)/Na.*** *SL is the sound level at the source (dB), SPL is the ambient sound level (dB), and 0.15 dB per meter can be used for* $N_a$*. (190 – 115)/.07 = 1,071 meters. Therefore, according to the Nedwell model, construction noise will attenuate to ambient levels in open water at 1,071 meters from the pile.*

□

5. **Use the Practical Spreading loss model to determine the zone of aquatic impacts.**

   □ ***Example – Now use the same example assumptions and the Practical Spreading Loss model to determine the zone of impact. TL = 15Log(R1/R2), or solved for R1, R1 = ($10^{(TL/15)}$)(R2).*** *R1 is the distance where noise attenuates to ambient levels, R2 is the range of the known sound level, and TL is the amount of spreading loss (known sound level – ambient sound level). ($10^{(190\text{-}115/15)}$)(10) =1,000,000 meters. Therefore, according to the Practical Spreading Loss model, noise will attenuate to ambient levels in open water at 1 million meters (621 miles). This is likely an unreasonable distance, and true attenuation to ambient levels likely happens somewhere between these two models.*

## Species and Noise

As is stated in the first section of this chapter, one task the project biologist must complete is identifying and measuring noise to determine the noise element of the action area. Another task the project biologist must complete is analyzing the effects of noise on the species that are addressed in the BA.

### *How Fish Hear*

The main sensory organ in fish is the lateral-line system that detects low-frequency (<100 Hz) particle motion in water. The lateral-line organ is likely involved in acoustic repulsion when the source is within a few body lengths of the fish. The inner ear located within the skull of the fish is sensitive to vibration rather than sound pressure.[11] In fish species that are hearing specialists, the gas-filled swim bladder acts as a transducer that converts sound pressure waves to vibrations, allowing the fish to detect sound and vibration.

Fish species with a reduced or no swim bladder tend to have a relatively low auditory sensitivity. Fish having a fully functional swim bladder tend to be more sensitive. Fish with a close coupling between the swim bladder and the inner ear are most sensitive.

Most audiograms of fishes indicate a low threshold (higher sensitivity) to sounds within the 100 Hz to 2 kHz range (Stocker 2002) (Figure 7-12).[12] Anderson (1992) states that juvenile fish may

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11. Fish have three symmetrically paired structures in the inner ear associated with bony otoliths: the lagena, sacculus, and utriculus. In most species the saccule and lagena detect acoustic pressure and acoustic particle motion (Popper and Fay 1973) and the utricle is involved in sound detection by several species of clupeids and perhaps other species (Popper and Fay 1993).

12. Cod has a hearing threshold of 75-80 dBrms between 100 and 200 Hz (Chapman and Hawkins 1973). Atlantic salmon have a sensitivity of 95 to 100 dBrms between 100 and 200 Hz (Hawkins and Johnstone 1978). Since both species have their best sensitivity between 100 and 200 Hz one would expect to see damage of hair cells in salmon occurring with exposure to continuous sound at about 200 dBrms (Hastings 2002).

have less developed hearing abilities so the distance at which they could detect pile driving sounds might be much less than adults. Audiograms developed for various fish species are based on sound pressure. However, fish do not hear with sound pressure. They hear with particle motion. Therefore, the thresholds and frequency ranges listed above and in Figure 7-12 will likely be revised when those data are available.

High-intensity sounds may temporarily or permanently damage the hearing of fish.[13] However, damage to hearing by intense sound depends on auditory threshold and will thus vary from species to species (Popper and Fay 1973, 1993).[14] Popper et al. (unpublished) exposed three species of fish to sounds from a seismic airgun, having sounds similar to pile driving. Peak sound levels ranged between 205 and 209 $dB_{PEAK}$. They exposed a hearing generalist (broad whitefish), a hearing specialist (lake chub), and a species that is intermediate in hearing (northern pike). They found that the hearing generalist had no significant effects from air gun exposure, the lake chub indicated the most effect in temporary threshold shift, and the northern pike showed a significant hearing loss but less than that of the lake chub. Lake chub and northern pike returned to their respective normal thresholds after 18 to 24 hours.

13. Popper and Clarke (1976) found that gold fish (*Carassius auratus*) demonstrated up to a 30 dB decrease in hearing sensitivity when exposed to 149 dB for four hours, but hearing returned to normal after 24 hours. Enger (1981) used a sound level of 180 dB to destroy bundles of cilia on the saccular maculae of codfish as evidenced by scanning electron microscopy and assumed permanent hearing loss.

14. Enger (1981) exposed 26 cod (*Gadus morhua*) to continuous tones of 180 dBrms at frequencies from 50 to 400 Hz for 1 to 5 hours and found destruction of auditory hair cells in the saccule. Hastings (1995) found destruction of auditory sensory cells when she and her colleagues exposed goldfish (*Carassius auratus*) to continuous tones of 189, 192, and 204 dBpeak at 250 Hz and found destruction of ciliary bundles correlate with sound pressure level at a 95% confidence level. Hastings et al. (1996) found destruction of sensory cells in the inner ears of Oscars (*Astronotus ocellatus*) 4 days after being exposed to continuous sound for 1 hour at 180 dBpeak and 300 Hz. Fish exposed to 180 dBpeak sounds at 60 Hz either continuous or 20% duty cycle (impulsive) or to 180 dBpeak sounds at 300 Hz and 20% duty cycle for 1 hour had no apparent damage. The authors also found no damage in fish allowed to survive for only 1 day after exposure, suggesting that damage may develop slowly.

Hastings et al. (1996) also examined the sensory cells of the lateral line and semicircular canals of the inner ear in the Oscars and found no damage. The authors speculated that this could be related to the fact that these sensory hair cells do not have an overlying otolith.

McCauley et al. (2003) exposed caged pink snapper (*Pagrus auratus*) to air gun sound levels as the ship passed by the caged fish, producing damaged hair cells that did not regenerate up to 58 days after exposure.

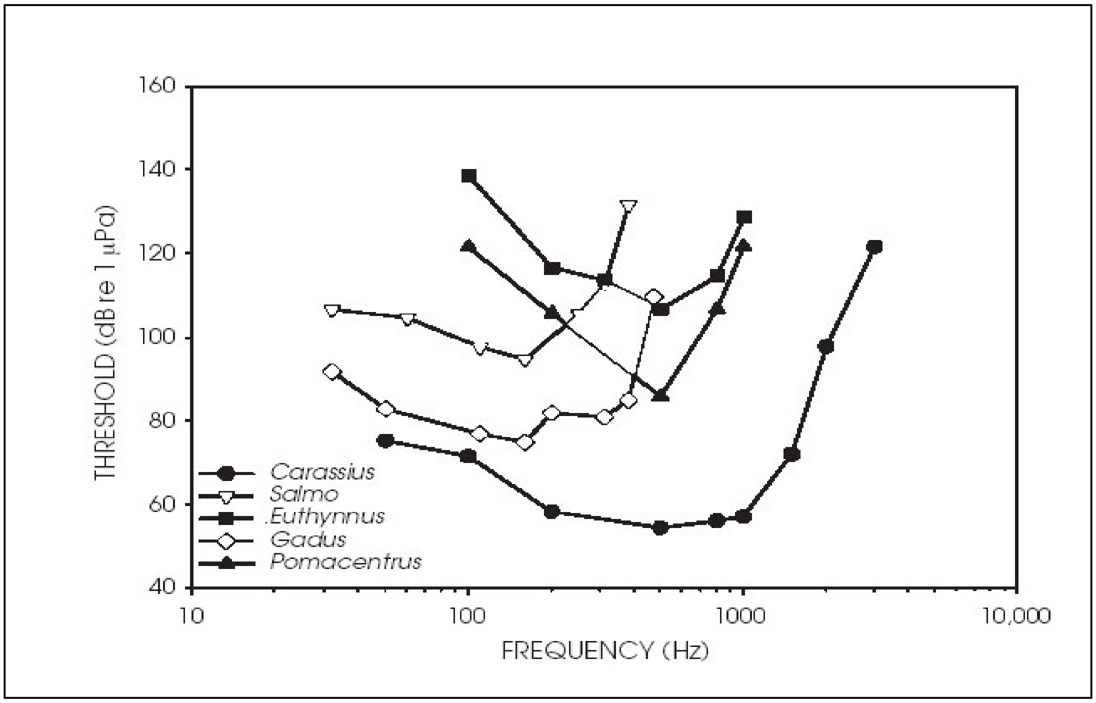


**Figure 7-12. Audiogram for several fish species.**
Source: Burgess and Blackwell (2003).

One study completed by Feist et al. is particularly pertinent to species potentially occurring in Washington. Feist et al. (1992) looked at the effects of concrete pile driving activities on the behavior and distribution of juvenile pink and chum salmon in Puget Sound. The authors found that juvenile pink and chum salmon (1–2 inches total length) did not change their distance from shore or cease feeding in response to pile driving. However, they did find that there were substantial differences in the distributions and sizes of fish schools on pile-driving days versus non-pile-driving days.

*Lethal Impacts Associated with Noise*

Risk of injury or mortality for aquatic species and fish associated with noise, in general, is related to the effects of rapid pressure changes, especially on gas filled spaces in the body. Rapid volume changes of the swim bladder may cause it to tear, reducing hearing sensitivity in some hearing specialist species, and loss of hydrostatic control.

According to Illingworth and Rodkin (2001) the effects of underwater sounds created by pile driving on fish may range from a brief acoustic annoyance to instantaneous lethal injury depending on many factors including:

- Size and force of the hammer
- Distance from the pile
- Depth of the water around the pile

- Depth of the fish in the water column
- Amount of air in the water
- The texture of the surface of the water (amount of waves on the water surface)
- The bottom substrate composition and texture
- Size of the fish
- Species of the fish
- Physical condition of the fish.

Physostomus fishes, such as salmonids, regulate the air in their swim bladders through a direct connection to the esophagus. Salmonids acclimate their swim bladders by gulping air at the surface, and as they swim deeper the swim bladder becomes compressed. When exposed to a sudden positive pressure, or overpressure, the swim bladder compresses further. When exposed to a sudden negative pressure, or underpressure, the swim bladder may expand beyond its original volume at depth but may not suffer or injure any other organs because it has some room to expand. Physostomus fishes acclimated to the surface atmospheric pressure may suffer less injury or mortality the deeper they are in the water column, whereas those acclimated to deeper water pressure may suffer more injury in shallow areas (Carlson 2003 personal communication).

Physoclistus fishes, such as bluegill, regulate air in the swim bladder through the circulatory system. In a physoclistus fish, the swim bladder will roughly maintain its volume at depth. During exposure to underpressure the swim bladder will expand, possibly tearing and causing damage to other organs. The magnitude of the expansion of the swim bladder is dependent on the magnitude of the underpressure. It is simply an example of Boyle's law: The volume of a confined amount of gas at constant temperature is inversely proportional to the pressure applied to the gas (Carlson 2003 personal communication).

There have been numerous studies addressing the effects of pile driving on fish, a few of which are described here, and others are summarized in the footnotes.[15] Illingworth and Rodkin (2001)

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15. Diver observations made by the Port of Vancouver (POV) in Canada following pile driving 36-inch steel piles into sandstone bedrock found higher mortality rates on the bottom than observed on the surface although no counts were reported (DesJardin 2003 personal communication). Fish mortalities at the POV included herring, juvenile salmon, rockfish, and tomcod.

Experiments conducted by the Pacific Northwest National Laboratory (PNNL) placed Bluegill in a hyperbaric chamber and acclimated to simulated ambient surface pressures of 101 kilopascals (kPa) in one group and simulating ambient pressures at 30ft depth of 191 kPa in another group inside a hyperbaric chamber. The fish were then exposed to 400 kPa for 30 to 60 seconds then pressure was rapidly decreased to 2 to10 kPa respectively within 0.1 seconds. The fish were then held for 48 hours for observation (Carlson 2003 personal communication). The results for Bluegill indicated 90% injury and 21% mortality to the 30ft acclimated group and 35% injury and 5% mortality to the surface acclimated group (after 48 hours). Carlson (2003 personal communication) found that both acclimation (Pa) and exposure (Pe) pressures are important and the ratio of Pe to Pa is an important predictor to mortality and possible injury. In the example below it shows the percentage increase in bluegill swim bladder found that there was not only a relationship between distance from the pile but an increase in the degree of damage and number of fish impacted with increasing duration of exposure to pile-driving activities.[16] Illingworth and Rodkin (2001) found that both a smaller hammer size and bubble curtains reduced injuries to fish.[17] Hastings and Popper (2005) found that smaller fish were more likely to be harmed than larger fish during pile driving operations.

*Behavioral Impacts Associated with Noise*

According to Feist et al. (1992) broad-band pulsed sound (e.g., pile driving sound) rather than continuous, pure tone sounds are more effective at altering fish behavior.[18] However, the sound level must be at least that of the minimum audible field of the fish for the frequencies of interest (1 to 100 Hz for pile driving), ambient noise should be at least 24 dB less than the minimum audible field of the fish, and the pile driving sound levels had to be 20 to 30 dB higher than ambient sound levels in order to produce a behavioral response (in herring) (Feist et al. 1992).

Behavioral sensitivity is lowest in flatfishes that have no swim bladder and also in salmonids (brown trout) in which the swim bladder is present but somewhat remote from the inner ear. Gadoid fishes (cod, whiting) in which the swim bladder is closely associated with the inner ear display a relatively high sensitivity to sound pressure (Turnpenny et al. 1994).

Hastings and Popper (2005) present a summary of different sound levels and effects on fish based on the findings of the best available science from citations that have most relevance to pile

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volume during the 0.1 second drop in pressure (Carlson 2003 personal communication). Similar unpublished work has been done with rainbow trout and results indicated no mortality and minimal injury.

16. In one experiment all fish exposed to driving for one minute were unaffected while 80 percent of fish exposed for six minutes exhibited significant tissue damage. In a second experiment only fish exposed for 40 minutes or longer were seriously injured.

17. The authors put fish in cages at various distances from 8-foot diameter steel piles and 60% of fish were found with damage to their internal organs as far as 150 meters (492 feet) from the pile with the large hydraulic hammer (1,700 kJ maximum) and no bubble curtain. With a smaller hydraulic hammer (750 kJ maximum) and a bubble curtain in operation only 40% were damaged at this distance. In general they found that the greatest impacts were observed within a 30-meter (98-foot) radius of the pile. It is assumed that there would be a decrease of 3 dB with halving of the hammer energy.

18. Hastings (1995) reported that 13 out of 34 goldfish exposed for 2 hours to pure tones ranging from 192 to 204 dBpeak at either 250 or 500 Hz experienced equilibrium problems including swimming backwards/upside down and wobbling from side to side. These fish recovered within one day suggesting that the damage was not permanent. These behaviors could have been caused by post-traumatic vertigo similar to that experienced by humans after a severe blow to the body or head.

Hastings (1995), Hult (1982), and Norris and Møhl (1983) found that captive dolphins disorient schooling fish with a series of clicks at times over a two-hour period. Although the sound levels were not measured in these studies. Norris and Møhl (1983) reported that in captivity dolphins usually produce clicks at levels from 140 to 180 dBpeak with peak energy in frequency bands around 1-5 kHz.

Avoidance behavior using pure tones was detected at 128 dB for one fish species (bass) which is 32 dB below the lowest avoidance threshold detected for air gun sounds but comparable with other species when exposed to specially developed deterrent signals (Turnpenny et al. 1994). Low duty cycle air gun sounds generally elicit high avoidance thresholds (approximately 160 dB or higher) while the high duty cycle (100%) acoustic deterrent signals elicit low avoidance thresholds (128 dB or higher).

driving. However, the study does not include Pacific Salmon species or bull trout, the species project biologists would need to address in their BAs.

Jorgensen (unpublished) from Fisheries and Oceans Canada recently presented preliminary data suggesting that that sound generated by an air gun at sound levels between 205 and 209 $dB_{PEAK}$ indicated no significant difference in startle response in the vertical direction or vertical velocity and a possible slight difference in the horizontal direction. The author also indicates that the fish observed did not actively avoid the sound, and there appeared to be no hearing loss. The fishes studied included broad whitefish, northern pike, and lake chub.

### *Threshold Levels*

In 2002, Hastings recommended 180 $dB_{PEAK}$ and 150 $dB_{RMS}$ as the thresholds for protecting salmon.[19] The recommendations were adopted by the Services and have been used in numerous biological opinions. Hastings and Popper (2005) have since revised the 180 $dB_{PEAK}$ threshold and now propose a 194 dB sound exposure level (SEL) as the new threshold to be protective of harm to fish. However, the Services have not implemented the new proposed criterion.

It is unlikely that most standard WSDOT pile driving activities using 30-inch or smaller steel pile would exceed the 194 dB SEL threshold. However, WSDOT has observed fish kills at some of its pile driving operations. Many of the killed fish observed were pile perch.

As mentioned above, the Services currently recognize 180 $dB_{PEAK}$ as the threshold for injury to salmon and bull trout (NOAA/USFWS 2005). They anticipate the potential for barotraumas to occur in salmon and bull trout at SPLs greater than or equal to 180 $dB_{PEAK}$. The 180 $dB_{PEAK}$ threshold is conservative because most of the studies described evaluated transmitted signals of longer duration than is anticipated to result from pile driving.

The Services also currently recognize a 150 $dB_{RMS}$ level as the threshold for disturbance to salmon and bull trout. Based on their assessment, sound pressure levels in excess of 150 $dB_{RMS}$ are expected to cause temporary behavioral changes, such as elicitation of a startle response or avoidance of an area. Those levels are not expected to cause direct permanent injury.

The USFWS (2004) has also identified underwater threshold sound levels for foraging marbled murrelets. As with bull trout, the injury threshold remains at 180 $dB_{PEAK}$. The USFWS established the underwater disturbance threshold based on the 92 dB level identified in the Olympic National Forest biological opinion (USDI 2003). It was assumed that murrelet hearing underwater is the same as above water. Therefore, after converting the pressure level to underwater sound metrics, the disturbance threshold for underwater murrelet foraging is 153 $dB_{RMS}$.

19. These recommendations were based on long-term exposure to a pure tone.

### *Effect Determinations and Zone of Impact*

The threshold levels established above can be used as a basis for effect determinations for salmon, bull trout, and diving marbled murrelets. For example, the zone of impact for a *not likely to adversely affect* determination for all species would occur in areas below the 180 $dB_{PEAK}$ level and above the 150 $dB_{RMS}$ level (153 $dB_{RMS}$ for murrelet) identified above. If pressure levels are higher than this, direct mortality is likely to occur, and a *likely to adversely affect* determination must be made for species in that zone.

Even if a species is outside the zone of behavioral disruption (i.e., located below 150 dB for salmon and trout and below 153 dB for murrelet), a *no effect* determination may not be warranted. For a *no effect* determination, the species must be located in a zone where all underwater sound has attenuated to ambient levels.

**The important thing to realize when using the threshold levels identified above is that the injury and disturbance thresholds are measured in two different metrics, $dB_{PEAK}$ and $dB_{RMS}$. When using the models, it is crucial to compare like values to ensure accuracy. For example, a noise level measured in PEAK should not be used to determine the distance of the disturbance threshold, which is measured in RMS. Likewise, using an RMS noise level to identify the injury threshold (PEAK) will lead to incorrect results.**