Sound Exposure of Southern Resident Killer Whales

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ABSTRACT

The Southern Resident killer whale, *Orcinus spp.*, population is listed as endangered in Canada. Underwater noise, resulting from human activity, is being recognized internationally as a serious form of environmental pollution. The purpose of this pilot project was to determine the effects of whale-watch noise on echolocation range of Southern Resident killer whales. This acoustic program sampled noise levels in the Southern Strait of Georgia using a calibrated hydrophone and digital audio recorder during whale-watch activities. A total of 200 1-min samples of Southern Resident killer whale acoustic habitat were recorded during 2005. Range of received sound levels was 106 to 146 dB RMS // 1μPa. The average annual decrease in foraging space due to increased noise levels ranged from 15% to 20%. This in combination with whale-watch

avoidance behaviours gives a total estimate of 18% to 23% in total carrying capacity reduction. This research project provides an important step in implementing future whale-watch guidelines for the Southern Strait of Georgia National Marine Conservation Area. Reducing the fraction of time the whales are exposed to increased ambient noise levels would increase effective foraging area. Managing the noise emitted from the commercial whale-watch industry is an important measure for the recovery of this population.

INTRODUCTION

There are four distinct populations of killer whales in British Columbia. These include two populations of fish eaters (northern and southern Vancouver Island summer residents), a population of meat eaters (transients), and a fourth population that rarely comes into coastal waters (offshores) (Ford & Ellis 1999). Resident killer whales live all their lives in stable social groups comprised of related family units. Matrilineal groups are comprised of the oldest female and her descendents (Bigg *et al.* 1990, Ford 1991). Pods are the usual social group of killer whales and are made up of related matrilines (Ford 1991). The Southern Resident killer whale population contains three pods (J, K, and L). There are about 90 Southern Residents compared to over 200 Northern Residents. The Southern Resident killer whale population frequents the trans-boundary waters of the Salish Sea from May to October (Figure 1).

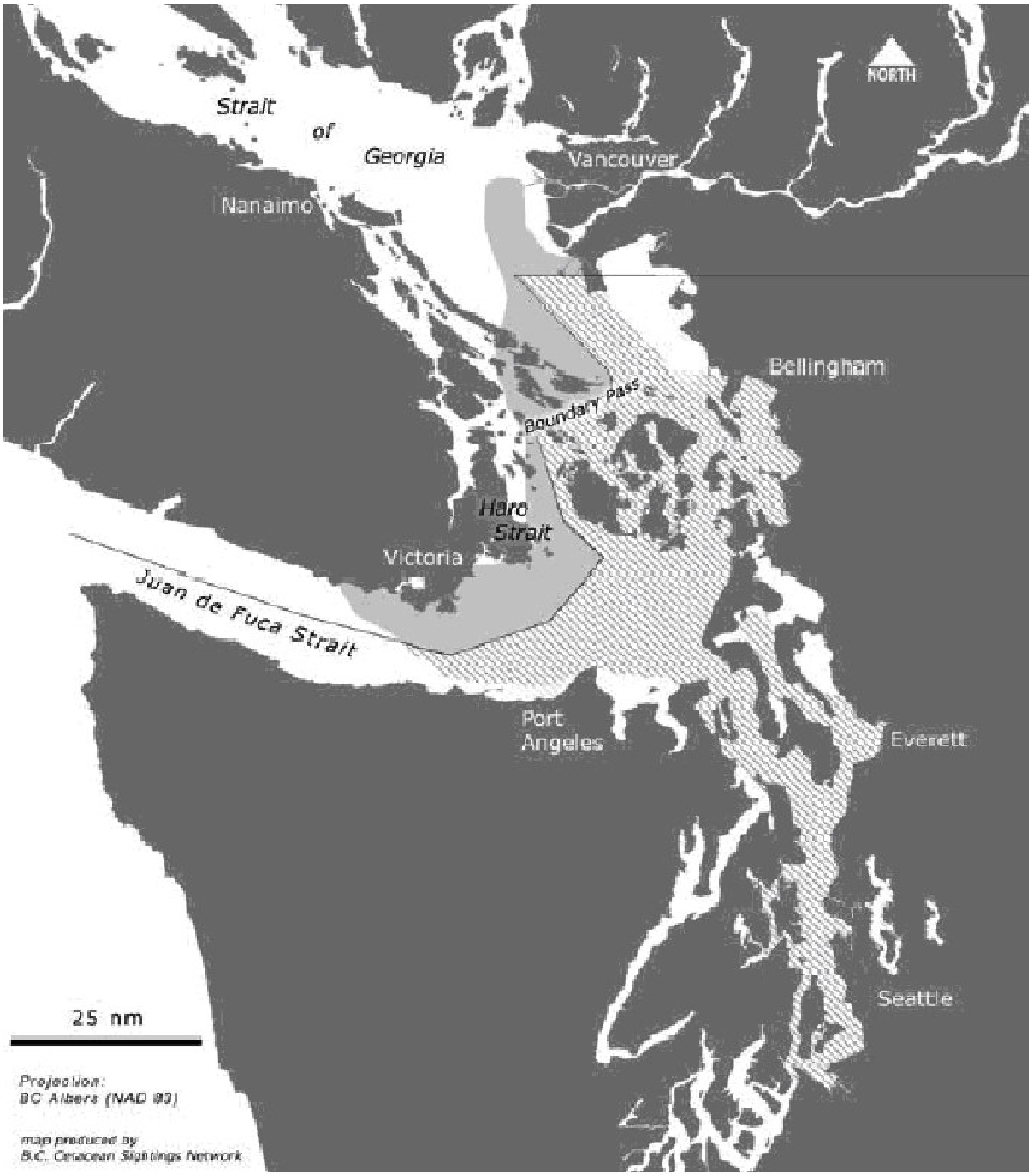


Figure 1. Critical habitat of endangered Southern Resident killer whale population (map modified from NRS 2005).

This area is proposed as Southern Resident killer whale critical habitat in the National Recovery Strategy of Canada for this population (NRS 2005). In 2001, the Committee on the Status of Endangered Species in Canada (COSEWIC) placed this population on its Endangered species list. The Southern Resident killer whale population is small and declined by 17% between 1995 and 2001 (NRS 2005). Marine wildlife in the area is increasingly threatened by toxic contamination, loss of habitat, declining food supply, global climate change, and disturbance from a high volume of vessel traffic. Commercial and recreational whale watching in this region has experienced tremendous growth over the past decade (Osborne *et. al.* 2002, Foote *et. al.* 2004).

This habitat consists of the proposed Southern Georgia Strait National Marine Conservation Area (Figure 2), existing Southern Gulf Island National Park Reserve (Figure 3), and San Juan Island Marine Stewardship Area (Figure 4).

Figure 2. Zoning considerations for the Southern Strait of Georgia National Marine Conservation Area (http://www.cpawsbc.org/marine/sites/ssg_map.php)

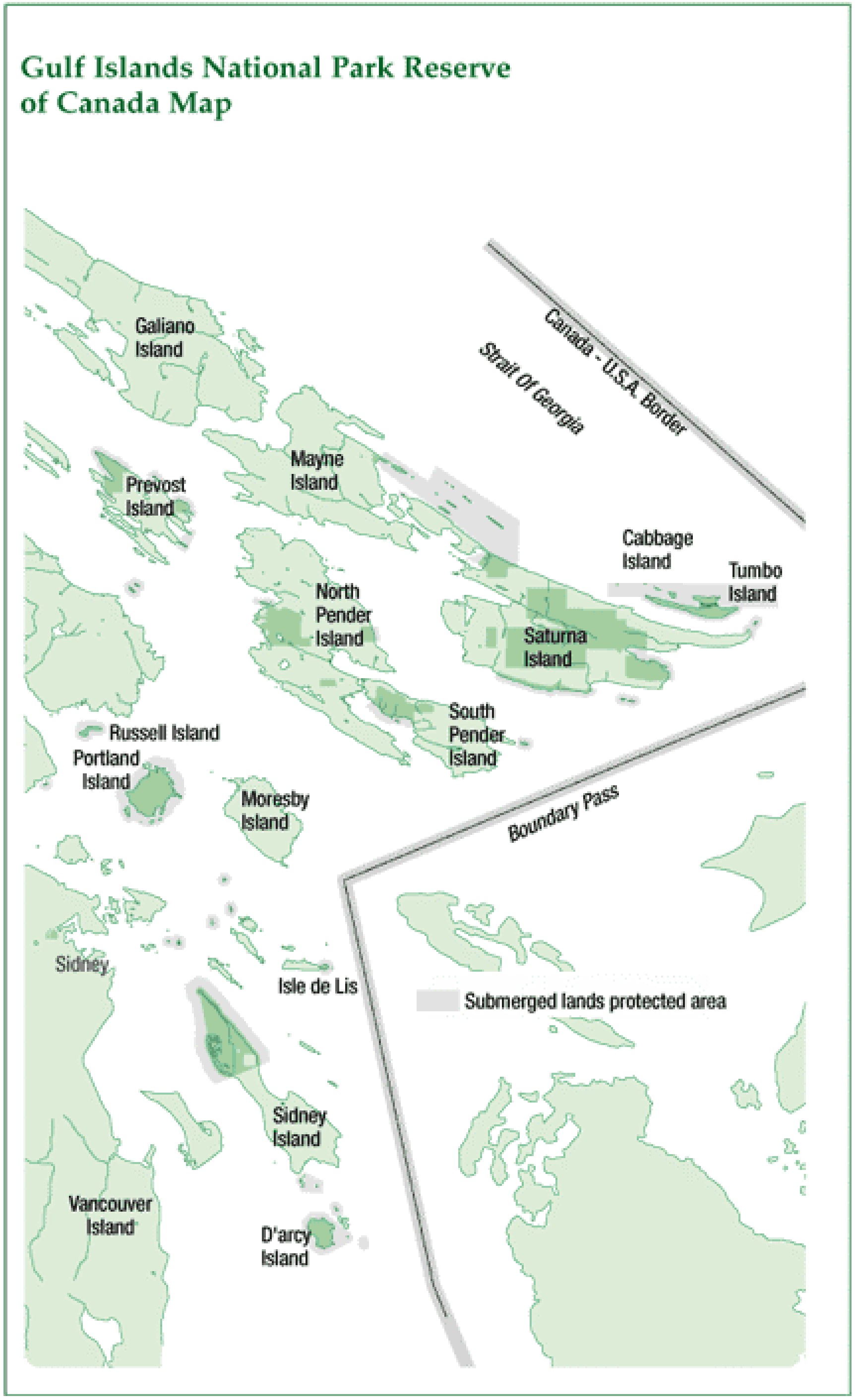


Figure 3. Southern Gulf Island National Park Reserve
(http://www.pc.gc.ca/voyage-travel/pv-vp/itm12-/page13_e.asp)

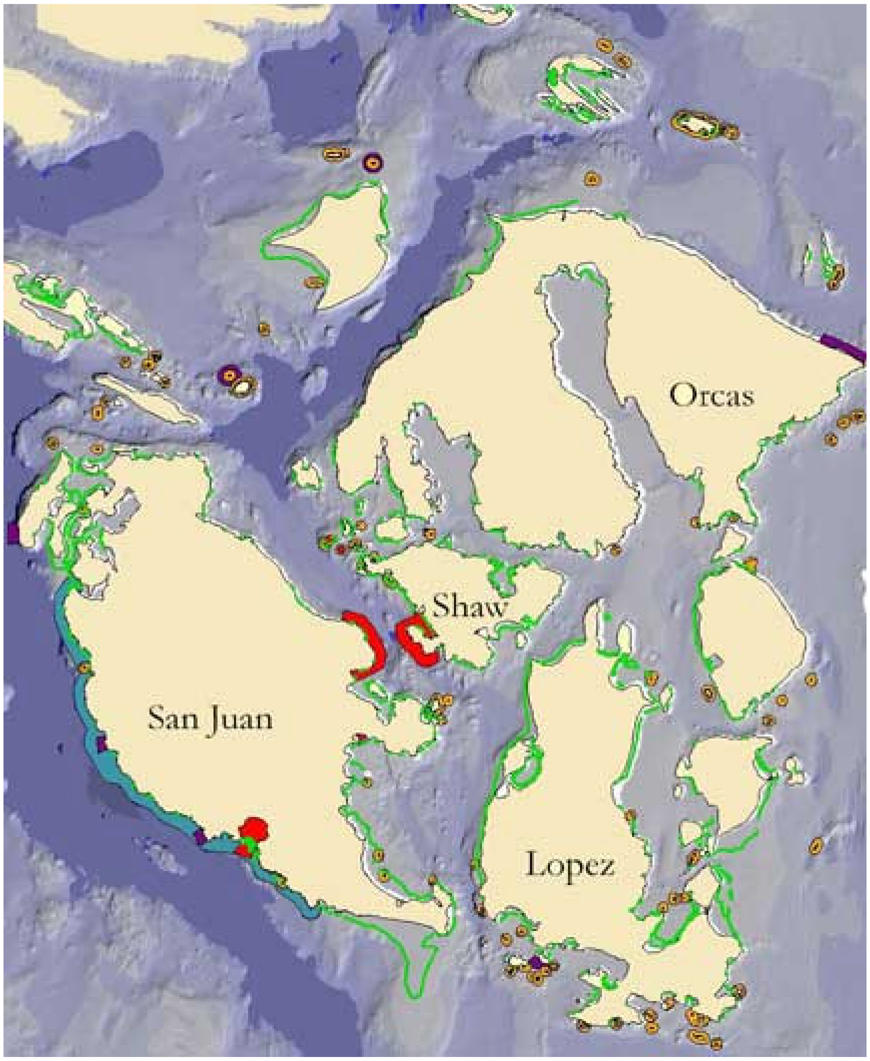
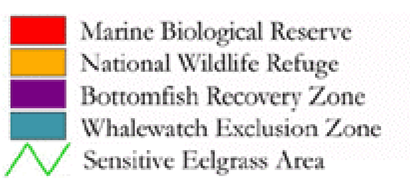


Figure 4. San Juan Island Marine Stewardship Area
(http://sjcmrc.org/programs/stewardship_MPAs.htm)



National Marine Conservation Areas (NMCA) are types of marine protected areas managed by Parks Canada for the sustainable use of recreation, education, and research. National Marine Conservation Areas are established under the Canada National Marine Conservation Areas Act. Marine conservation areas are implemented to preserve the structure and function of their unique ecosystems. The NMCA program was designed to represent Canada's biodiversity, encourage monitoring, and protect depleted species. These areas include both the water column and submerged lands, and can include adjacent lands. National Marine Conservation Areas include at least one zone that allows ecologically sustainable use of marine resources and at least one zone that fully protects special features or sensitive ecosystems elements. The Southern Strait of Georgia consists of the area between Vancouver and Victoria. It is among the most productive of all marine ecosystems in the world. Upwelling causes the mixing of fresh and oceanic water, resulting in a nutrient rich highly productive marine environment. Scientists, fisherman, and community members have identified marine biodiversity hotspots in this area (Figure 2). These zones include important areas for the protection of the Southern Resident killer whale population. The National Park Reserve was established in the Southern Gulf Islands and offers the opportunity for the public to learn and experience these spectacular coastal ecosystems. San Juan County developed the Marine Stewardship Area to protect their unique and valuable marine resources while allowing sustainable use of marine resources.

Recovery plans for the endangered Southern Resident killer whale population include investigation into their acoustic habitat. Vessel noise has been identified as a possible factor in the decline of abundance of this population (Federal Register 2004, Krahn *et. al.* 2004, Bain *et. al*. 2002). Vessel traffic is known to increase the energy expenditure of killer whales (Williams *et. al.* 2002ab). Similar responses have been observed in bottlenose dolphins, *Tursiops truncaus* (Nowacek *et. al.* 2001). In the 1990s, the effects of whale watching may have exceeded changes in fish abundance accounting for a correlation between fleet size and population size (Figure 5).

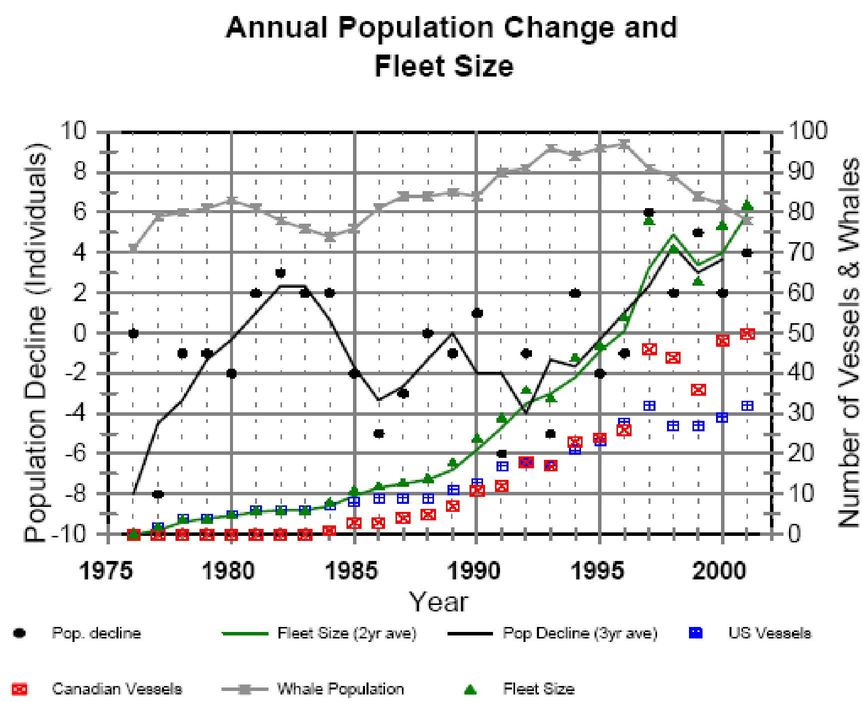


Figure 4. Relationship between fleet size and whale population changes. July 1 counts of Southern Resident population size are shown (after Wade et al. 2000 with unpublished data from Balcomb). The total number of commercial vessels actively engaged in whale watching, along with the number based in American and Canadian ports, are shown (after Otis and Osborne 2001). Annual changes in whale population size are plotted in the year of the latter count. A three year moving average of annual whale population change is plotted along with a two year moving average of total fleet size. Fleet size is used as an index of exposure to whale watching, although other actors not represented in this graph that affect overall exposure may include: efficiency of whale watch operators in locating whales; hours per day spent with whales; number and type of engines employed, operating speed, distance, orientation, and relative position. Note the tight fit of smoothed whale population change with smoothed fleet size beginning in the early 1990's. Also note that the number of vessels in the commercial whale watching whale fleet exceeded the number of whales in the population in 2001 (although typically, not all vessels operated simultaneously).

Figure 5. Southern Resident killer whale population numbers and commercial whale-watch growth (figure from Bain 2002b).

Killer whale vocalization consists of whistles, pulsed calls, and echolocation clicks. Whistles are tones used for close-range communication (Thomsen *et al*. 2001) and are predominantly between 6 to 12 kHz (Richardson *et al*. 1995). Killer whales use calls to maintain group cohesion and integrity (Ford *et. al*. 2000). The fundamental frequencies of discretely pulsed calls range from 300Hz to 6 kHz and have source levels of 160dB (Richardson *et. al*. 1995, Miller 2002). Echolocation is the active detection and ranging of prey and marine environment. Killer whales generate trains or pulses of broad-frequency clicks for very short durations and listen for the reflected echoes before emitting the next pulse (Berta and Sumich 1994). Center frequencies of echolocation clicks range from 45 to 80kHz, bandwidths are between 35 to 50kHz, and have source levels from 195 to 224dB // 1µPa (Awbrey *et. al.* 1982, Au *et. al*. 2004).

Vessels produce underwater noise within the hearing range of killer whales. Engines operating at high RPM produce higher intensity sounds and are distributed over a higher frequency range than vessels traveling at low RPM. Source levels for small boats range from 141dB to 161dB with frequency ranges from 0.86kHz to 8.0 kHz (Williams *et. al*. 2002a). Outboard motors operating at high speeds create source levels around 165 to 175dB, including frequencies above 20kHz (Bain 2002b). Large commercial ships produce source levels of 180dB to 188dB with a frequency range of 100 Hz to 8.0 kHz (Galli *et. al.* 2003). These frequency ranges overlap with killer whale vocalization ranges.

There are several considerations in terms of sound interfering with killer whale ability to hear biologically meaningful signals. These include masking of emitted sounds and damage to hearing. The later could be temporary (Temporary Threshold Shifts, TTS) or permanent (Permanent Threshold Shifts, PTS). Permanent threshold shifts occur at higher exposure levels than the onset of TTS. In urban zones, masking effects would be most significant on killer whale hearing (Bain 2002b). Noise can mask killer whale vocalizations (Szymanski *et. al.* 1998, 1999, Bain and Dahlheim 1994). Auditory masking resulting from sound exposure may have long-term biological significance on the fitness of killer whales. Masking occurs with the greatest of magnitude directly in front of the killer whales (Bain and Dahlheim 1994). The extent of noise interference with signal detection depends on the loudness of received levels. The volume of space actively searched by echolocation decreases with increases in noise levels.

Active space is the area over which echolocation can function. Increase from quiet ambient noise reduces the amount of transmission loss in an echolocation pulse that can be tolerated by the whales. As noise levels increase, range of clicks decrease, to reduce maximum detection range of prey with echoes from the sound pulse. An increase in 12dB in received noise level from ambient decreases foraging distance approximately by a half (Figure 6).

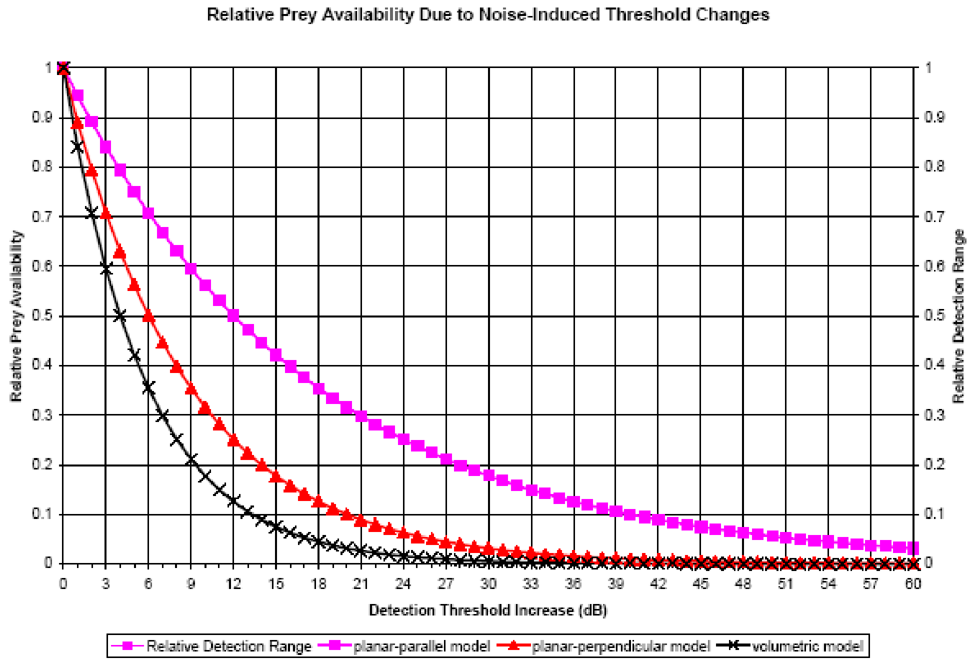


Figure 5. Detection Range and Detection Efficiency when hearing is impaired. The upper curve shows the relationship between relative detection range and magnitude of hearing impairment. This is also the curve for relative prey detection efficiency for the search within the plane model. The middle curve shows relative prey detection efficiency for the perpendicular to prey plane search model. The lower curve shows the relative prey detection efficiency for the volumetric search model. It is important to note that small elevations in detection thresholds (e.g., 3 dB) can have large effects on the proportion of prey that remain detectable. Points of interest include 6 dB (proposed PTS), 12 dB (proposed TTS), and 30 dB (typical ambient above sea state 0).

Figure 6. Relative change in echolocation transmission range at different environmental noise levels (figure from Bain 2002b).

The sonar equation allows for quantitative determination of the decrease in echolocation transmission distance due to increased noise levels.

DT – maximum echolocation detection threshold
SL – echolocation source levels (independent of noise)
TL – transmission loss of click (TL = 20 log R); R = transmission distance (Au 1993)
TS – target strength (independent of noise)
NR – received noise level
NR_o – minimum ambient level
ΔR – ratio of detection ranges for an echolocation click in presence and absence of noise

$DT = SL - 2TL + TS - NR$ => $\mathbf{\Delta R = 10^{[-0.025\,(NR-NRo)]}}$

Change in foraging efficiency depends on foraging tactics (Bain 2002a). The foraging method used by killer whales to locate prey, determines the total reduction in active space searched. These strategies can be broken down into separate models (Bain 2002b). The

Fixed Location Model, occurs when the whales know the location of prey. The Linear Search Model, happens when the whales and fish are on the same path. If the whales travel faster than the fish their foraging capability will be unchanged due to noise levels, or effect could be linearly proportional to echolocation range. In the Planar Model, prey are in a two-dimensional fixed location. For example, fish at a certain depths or along the bottom of the ocean. There are two ways that the whales can hunt for prey in the Planar Model. First, when whales swim through the same plane as the prey the effect on active space is linear. Second, when the whales swim perpendicular to the plane of prey the effect is proportional to the square of the range. In a Volumetric Model, prey could be anywhere in the water column. The main food for resident killer whales is chinook salmon (*Oncorhynchus tshawytschu*) making up over 60% of their diet (Ford *et. al.* 1998). Chinook salmon are distributed in such a way that would require volumetric searches (Bain 2002b). The two and three-dimensional foraging tactics would be affected by increases in noise levels.

The objectives of this project were to identify received sound levels of the Southern Resident killer whales and to determine the potential impacts of increased sound levels on their prey detection range. Studies have been conducted to measure ambient noise and source levels from commercial whale-watch vessels (Bain 2002a, Erbe 2002, Galli *et. al.* 2003), this project is the first to measure received noise levels. The data collected from this study facilitated the calculation of reduction in energy acquisition resulting from commercial whale-watch noise. The energy cost of noise level exposure assisted the estimation of total effect whale watching has on killer whales. This information is important for developing whale-watch regulations and to promote the continuation of vital community economic industries while ensuring the recovery of the endangered Southern Resident killer whale population.

METHODS

The study was conducted in Southern Resident habitat from Saturna to Lopez Islands using a 19.4' rigid-hull inflatable zodiac from July to September and a 42' cutter catamaran in October, 2005. The hydrophone was lowered to 10m depth and recordings were made with engines off in the presence of both whales and boats. Standardized notes were taken on sea-state, location, killer whale behaviour, and vessel traffic for each sixty-second sample. Samples were made with a Brüel & Kjær 8105 hydrophone, Brüel & Kjær 2635 amplifier, and Marantz PMD660 portable digital recorder. The B&K hydrophone is spherical, omnidirectioanl, and has a voltage sensitivity of -205 dB // 1V/Pa. Frequency range of the transducer is 0.1 Hz to 100 kHz. The B&K amplifier is equipped with a push button activated test oscillator, which applies a calibrated sinusoidal signal to the input. Samples were made directly into wav files and onto a flash card with 16-bit resolution and 44.1kHz sampling frequency. Files were analyzed with OVAL (Orca Vocalization and Localization) acoustic software. The computer program was used to calculate loudness level (root-mean square, RMS) of sample waveforms. Recordings were made during whale-watch activity and therefore recordings were above sea state and other natural noise level factors. Measurements were analyzed to determine distribution of noise exposure experienced by the Southern Resident killer whales during commercial whale-watching practices. The reduction in energy acquisition was calculated resulting from vessel noise. Commercial whale-watching vessels have been reported to be with the whales for approximately 90% of daylight hours (Bain 2002b). By estimating that whales are accompanied 25% of the time (50% of a six month whale-watch season) change in carrying capacity is approximately 3% due to whale-watch vessel avoidance. Carrying capacity (K) is the number of animals of a population that can be supported on a given area (Berta and Sumich 1999).

RESULTS

The total number of samples recorded was 200. The minimum value of received levels was 106 dB RMS // 1μPa. Median and maximum values were 128 and 146 dB RMS // 1μPa respectively (Figure 7).

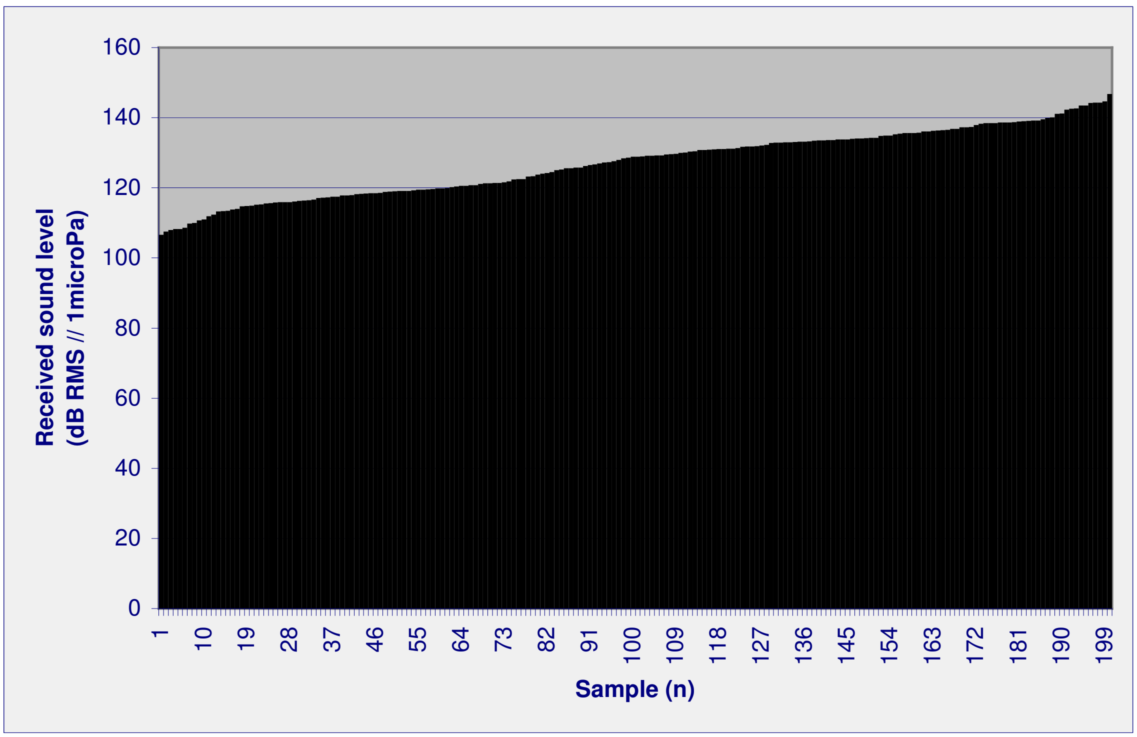


Figure 7. Received sound level (dB RMS // 1μPa) recorded per sample.

The total reduction in echolocation range was determined from decreased transmission distance of echolocation clicks. Table 1 shows noise level effects on the echolocation ability of Southern Resident killer whales for planar and volumetric foraging tactics. The annual whale-watch noise level effect on Southern Resident foraging efficacy was on average 15% for linear, 19% for planar, and 20% for volumetric the search model.

Table I. Noise impacts on resident killer whale foraging space during whale-watch activities.

Foraging Model	Average active space reduction (%)	Average annual whale-watch effect (%)
Linear	64	15
Planar	83	19
Volumetric	90	20

DISCUSSION

The Southern Resident killer whale population is threatened with extinction. This project sampled the acoustic environment of Southern Resident killer whale summer habitat. The objective of this research was to determine the received noise levels the Southern Resident killer whales are exposed to and to what effect it has on their population growth. The minimum received sound level was 106 dB RMS // 1µPa. This is near reported levels for the area; 95 dB RMS // 1µPa (Galli *et. al.* 2003) and 108 dB RMS // 1µPa (Bain 2002a). The median and maximum received levels were 128 dB and 146 dB RMS // 1µPa respectively. Noise levels increased from minimum ambient level by 40 dB RMS // 1µPa. The estimated reduction in foraging area searched due to increased noise levels was from 15% to 20%. This in combination with decrease in energy costs due to avoidance behaviour equals 18% to 23% in total potential reduction in Southern Resident carrying capacity due to whale-watch avoidance behaviours and reduction in active foraging space. Actively managing the acoustic environment is essential for the protection of this endangered population of whales.

Acoustic management is an important factor in the establishment of a NMCA in the Southern Strait of Georgia. The Southern Resident killer whales are an important top predator for this unique ecosystem. Their summer habitat is increasingly threatened by the continual growth of the commercial whale-watch industry. Measuring the actual received sound levels that the whales are exposed to can estimate long-term effects on population growth. Acoustic whale-watch guidelines are important to reduce masking of killer whale vocalizations. This could be accomplished by 1) decreasing the number of boats below the number of matrilines so not all whales are watched all the time, or having boats close together to accomplish the same affect, 2) decreasing noise from vessels by reducing noise produced (propulsion types, operating speeds) and increasing distance between vessels and whales, 3) limiting the time vessels spend with whales through seasonal closures, time of day limitations, and/or area closures. Closing quiet areas to commercial whale watching would increase foraging space up to 80% while the whales are in the protected areas.

Further research is necessary to make strong conclusions on the effects of commercial whale watching on killer whale foraging efficiency. Future investigations involve sampling areas when no boats are present to determine the complete range of received noise levels. Areas need to be investigated to determine relative amounts of shipping, recreational, commercial whale-watch, and ambient noise levels. Obtaining commercial whale-watch logbooks would determine actual time the whales are exposed to industry. Determining source levels of makes of commercial whale-watch vessels and engines would reveal quiet models. These studies would increase the resolution of the estimated effects on killer whale energy costs.

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