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Assessment of Vessel Noise within the Southern Resident Killer Whale Interim Sanctuary Zones

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Assessment of Vessel Noise within Southern Resident Killer Whale Interim Sanctuary Zones

Final Report
Version 2.0

By:

Marie-Noël R. Matthews
Connor Grooms

JASCO Applied Sciences (Canada) Ltd

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The Government of Canada, aiming to reduce SRKW exposure to underwater noise from vessels, implemented Interim Sanctuary Zones around Saturna and Pender Islands (Salish Sea) from 1 June to 31 October 2019. JASCO Applied Sciences (JASCO) performed a study to quantify vessel noise both with and without the implementation of these zones to estimate their effectiveness in reducing vessel noise levels within the zones. JASCO's cumulative noise model was applied for each zone to predict monthly averaged noise levels associated with vessel traffic conditions before and during the implementation of the sanctuary zones. The effectiveness of these zones is assessed quantitatively according to the estimated changes in noise levels.

The results, which consider multiple commercial, government and recreational vessel classes, show that this mitigation approach would result in a decrease of unweighted noise levels by, on average, 0.5 (±0.4) dB within the Saturna Island Interim Sanctuary Zone and 3.0 (±1.0) dB within the Pender Island Interim Sanctuary Zone. The decrease is greater for audiogram-weighted noise levels: 2.2 (±1.1) dB and 4.6 (±1.3) dB, respectively. These results are based on an idealized level of compliance by vessels in the area, and accounts for the exemptions stated in the 2019 Interim Order.

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16. Résumé

Dans le but de réduire l'exposition des épaulards résidents du Sud au bruit sous-marin des navires, le gouvernement du Canada a mis en œuvre des zones de refuge provisoires autour des îles Saturna et Pender (mer des Salish) du 1er juin au 31 octobre 2019. JASCO Applied Sciences (JASCO) a réalisé une étude pour quantifier le bruit des navires avec et sans la mise en œuvre de ces zones de refuge afin d'estimer leur efficacité à réduire les niveaux de bruit des navires au sein de ces zones. Le modèle d'exposition cumulative au bruit de JASCO a été appliqué pour chaque zone afin de prévoir les niveaux de bruit moyens mensuels associés aux conditions de trafic maritime avant et pendant la mise en œuvre des zones de refuge. L'efficacité de ces zones est évaluée sur le plan quantitatif en fonction des changements estimés des niveaux de bruit. Les résultats, qui tiennent compte de plusieurs classes de navires commerciaux, gouvernementaux et de plaisance, montrent que cette approche d'atténuation entraînerait une diminution des niveaux de bruit non pondérés de 0,5 (±0,4) dB en moyenne dans la zone de refuge provisoire de l'île Saturna et de 3,0 (±1,0) dB dans la zone de refuge provisoire de l'île Pender. La diminution est plus importante pour les niveaux de bruit pondérés par les audiogrammes : 2,2 (±1,1) dB et 4,6 (±1,3) dB, respectivement. Ces résultats sont fondés sur un niveau idéalisé de conformité des navires dans la zone, et reflètent les exemptions énoncées dans l'Arrêté d'urgence de 2019.

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EXECUTIVE SUMMARY

The Salish Sea is an important habitat for several marine mammal species and populations, including the endangered Southern Resident Killer Whales (SRKWs; SARA 2002). Man-made noise, including vessel noise, has the potential to disturb or injure marine animals, and it has been identified as a factor hindering recovery of the SRKW population (DFO 2011). The Government of Canada, aiming to reduce SRKW exposure to underwater noise from vessels, implemented Interim Sanctuary Zones around Saturna and Pender Islands in the Salish Sea from 1 June to 31 October 2019 (DFO 2019).

JASCO Applied Sciences (JASCO) performed a study to quantify the vessel noise both with and without the implementation of these Interim Sanctuary Zones to try to determine the effectiveness in reducing vessel noise levels in the zones. JASCO's cumulative noise model was applied for each zone to predict monthly averaged noise levels associated with vessel traffic conditions before and during the implementation of the sanctuary zones. The effectiveness of these zones is assessed quantitatively according to the estimated changes in noise levels.

Vessel traffic information for multiple commercial, government, and recreational vessel classes in the Salish Sea were derived from a high-resolution AIS dataset that contains the locations of many thousands of vessels (MarineTraffic 2020). Since not all vessels are required to be fitted with AIS, the vessel densities for these classes (e.g. recreational and sailing vessels) were scaled up based on the estimated proportions of those vessels that are not fitted with AIS.

The vessel traffic information was computed for two 1-month periods—July 2018 and July 2019—with the aim of representing conditions before and during the implementation of the sanctuary zones, respectively. AIS data for July 2019 showed in fact a minimum level of compliance (avoidance of sanctuary zones) by most vessel classes. To provide meaningful information about the possible effect of implementing such sanctuary zones, and to avoid influences from natural variations in vessel traffic between years, we synthesized a set of vessel traffic data to represent conditions of due compliance with the sanctuary zones.

The results show that this mitigation approach would result in a decrease of unweighted noise levels by, on average, 0.5 (±0.4) dB within the Saturna Island Interim Sanctuary Zone and 3.0 (±1.0) dB within the Pender Island Interim Sanctuary Zone. The decrease is greater for audiogram-weighted noise levels 2.2 (±1.1) dB at Saturna Island and 4.6 (±1.3) dB at Pender Island). These results are based on an idealized level of compliance by vessels in the area, which takes into account the exemptions stated in the 2019 Interim Order (DFO 2019). The reduction in levels effectively achieved in 2019 is expected to have been significantly less than modelled here, and likely negligible, because of poor compliance by vessels as shown by AIS.

SOMMAIRE

La mer des Salish est un habitat important pour plusieurs espèces et populations de mammifères marins, y compris l'épaulard résident du sud (ERS), en voie de disparition (SARA 2002). Le bruit d'origine humaine, y compris le bruit des navires, a le potentiel de perturber ou de blesser les animaux marins, et il a été déterminé comme étant un facteur entravant le rétablissement de la population d'ERS (DFO 2011). Dans le but de réduire l'exposition des ERS au bruit sous-marin des navires, le gouvernement du Canada a mis en œuvre des zones de refuge provisoires autour des îles Saturna et Pender, dans la mer des Salish, du 1er juin au 31 octobre 2019 (DFO 2019).

JASCO Applied Sciences (JASCO) a réalisé une étude pour quantifier le bruit des navires avec et sans la mise en œuvre de ces zones de refuge provisoires afin d'essayer de déterminer leur efficacité à réduire les niveaux de bruit des navires au sein de ces zones. Le modèle d'exposition cumulative au bruit de JASCO a été appliqué pour chaque zone afin de prévoir les niveaux de bruit moyens mensuels associés aux conditions de trafic maritime avant et pendant la mise en œuvre des zones de refuge. L'efficacité de ces zones est évaluée quantitativement en fonction des changements estimés des niveaux de bruit.

Les renseignements sur le trafic maritime pour plusieurs classes de navires commerciaux, gouvernementaux et de plaisance dans la mer des Salish ont été dérivés d'un ensemble de données précises du SIA qui contient les emplacements de plusieurs milliers de navires (MarineTraffic 2020). Étant donné que tous les navires ne sont pas tenus d'être équipés d'un SIA, les densités de navires pour ces classes (p. ex., les navires de plaisance et les voiliers) ont été mises à l'échelle en fonction des proportions estimées de ces navires qui ne sont pas équipés d'un SIA.

Les renseignements sur le trafic maritime ont été calculés pour deux périodes d'un mois – juillet 2018 et juillet 2019 – dans le but de représenter les conditions avant et pendant la mise en œuvre des zones de refuge, respectivement. Les données du SIA de juillet 2019 indiquaient en effet un niveau minimum de conformité (évitement des zones de refuge) par la plupart des classes de navires. Pour fournir des renseignements significatifs sur l'effet possible de la mise en œuvre de telles zones de refuge et pour éviter les influences des variations naturelles du trafic maritime d'une année à l'autre, nous avons synthétisé un ensemble de données sur le trafic maritime afin de représenter les conditions de conformité aux zones de refuge.

Les résultats montrent que cette approche d'atténuation entraînerait une diminution des niveaux de bruit non pondérés de 0,5 (±0,4) dB en moyenne dans la zone de refuge provisoire de l'île Saturna et de 3,0 (±1,0) dB dans la zone de refuge provisoire de l'île Pender. La diminution est plus importante pour les niveaux de bruit pondérés par les audiogrammes : 2,2 (±1,1) dB pour l'île Saturna et 4,6 (±1,3) dB pour l'île Pender. Ces résultats sont fondés sur un niveau idéalisé de conformité des navires dans la zone, qui tient compte des exemptions énoncées dans l'Arrêté d'urgence de 2019 (DFO 2019). La réduction des niveaux réalisée efficacement en 2019 devrait être nettement inférieure à celle modélisée ici, et probablement négligeable, en raison de la faible conformité des navires, comme le montrent les données du SIA.

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GLOSSARY

1/3-octave-band
Non-overlapping passbands that are one-third of an octave wide (where an octave is a doubling of frequency). Three adjacent 1/3-octave-bands comprise one octave. One-third-octave-bands become wider with increasing frequency. Also see octave.

absorption
The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

ambient noise
All-encompassing sound at a given place, usually a composite of sound from many sources near and far (ANSI S1.1-1994 R2004), e.g., shipping vessels, seismic activity, precipitation, sea ice movement, wave action, and biological activity.

automated identification system (AIS)
A radio-based tracking system whereby vessels regularly broadcast their identity, location, speed, heading, dimensions, class, and other information to nearby receivers.

broadband sound level
The total sound pressure level measured over a specified frequency range. If the frequency range is unspecified, it refers to the entire measured frequency range.

cavitation
A rapid formation and collapse of vapor cavities (i.e., bubbles or voids) in water, most often caused by a rapid change in pressure. Fast-spinning vessel propellers typically cause cavitation, which creates a lot of noise.

cetacean
Any animal in the order Cetacea. These are aquatic, mostly marine mammals and include whales, dolphins, and porpoises.

decibel (dB)
One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 (R2004)).

draft (of a vessel)
The vertical distance between the waterline and the bottom of the hull (keel), including the thickness of the hull

ECHO
Enhancing Cetacean Habitat and Observation Program.

frequency
The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: *f*. 1 Hz is equal to 1 cycle per second.

Global Positioning System (GPS)
A satellite based navigation system providing accurate worldwide location and time information.

geoacoustic
Relating to the acoustic properties of the seabed.

hertz (Hz)
A unit of frequency defined as one cycle per second.

monopole source level (MSL)
A source level that has been calculated using an acoustic model that accounts for the effect of the sea-surface and seabed on sound propagation, assuming a point-like (monopole) sound source. See related term: radiated noise level.

octave
The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

parabolic equation method
A computationally-efficient solution to the acoustic wave equation that is used to model propagation loss. The parabolic equation approximation omits effects of back-scattered sound, simplifying the computation of propagation loss. The effect of back-scattered sound is negligible for most ocean-acoustic propagation problems.

power spectrum density
The acoustic signal power per unit frequency as measured at a single frequency. Unit: $\mu Pa^2/Hz$, or $\mu Pa^2 \cdot s$.

power spectral density level
The decibel level ($10\log_{10}$) of the power spectrum density, usually presented in 1 Hz bins. Unit: dB re 1 $\mu Pa^2/Hz$.

pressure, acoustic
The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: *p*.

propagation loss (PL)
The decibel reduction in sound level between two stated points that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also called propagation loss.

received level
The sound level measured at a receiver.

rms
root-mean-square.

shear wave
A mechanical vibration wave in which the direction of particle motion is perpendicular to the direction of propagation. Also called secondary wave or *S*-wave. Shear waves propagate only in solid media, such as sediments or rock. Shear waves in the seabed can be converted to compressional waves in water at the water-seabed interface.

sound
A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

sound exposure level (SEL)
A cumulative measure related to the sound energy in one or more pulses. Unit: dB re 1 µPa^2·s. SEL is expressed over the summation period (e.g., per-pulse SEL [for airguns], single-strike SEL [for pile drivers], 24-hour SEL).

sound pressure level (SPL)
The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 (R2004)).

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 µPa) and the unit for SPL is dB re 1 µPa:

$$\mathrm{SPL} = 10\log_{10}\left(p^2/p_0^2\right) = 20\log_{10}\left(p/p_0\right)$$

Unless otherwise stated, SPL refers to the root-mean-square sound pressure level. See also 90% sound pressure level and fast-average sound pressure level.

source level (SL)
The sound level measured in the far-field and scaled back to a standard reference distance of 1 metre from the acoustic centre of the source. Unit: dB re 1 µPa @ 1 m (sound pressure level) or dB re 1 µPa^2·s (sound exposure level).

spectrum
An acoustic signal represented in terms of its power (or energy) distribution compared with frequency.

sound speed profile
The speed of sound in the water column as a function of depth below the water surface.

ULS
Underwater Listening Station.

wavelength
Distance over which a wave completes one oscillation cycle. Unit: meter (m). Symbol: λ.

1. INTRODUCTION

The International Maritime Organization (IMO) recognizes that underwater noise from ships may have short- and long-term negative consequences on marine life, especially for marine mammals that rely on the use of sound for life-critical purposes. The Salish Sea is an important habitat for several marine mammal species and populations, including the endangered Southern Resident Killer Whales (SRKWs; SARA 2002).

Man-made noise, including vessel noise, has the potential to disturb or injure marine animals, and it has been identified as a factor hindering recovery of the SRKW population (DFO 2011). Strategic management of future vessel traffic will be necessary to ensure marine animals in the region are not exposed to substantial increases in underwater noise.

The Government of Canada’s June 2019 *Interim Order for the Protection of Killer Whales (Orcinus orca) in the Waters of Southern British Columbia* implemented Interim Sanctuary Zones around Saturna and Pender Islands in the Salish Sea, effective from 1 June to 31 October 2019 (DFO 2019). These zones aimed to reduce SRKW exposure to underwater noise from vessels. JASCO Applied Sciences (JASCO) performed the present study to quantify the vessel noise both with and without the implementation of these Interim Sanctuary Zones to try to determine the effectiveness of their implementation.

This study uses the acoustic modelling techniques and some of the model input parameters from a previous assessment study by JASCO for Transport Canada (Matthews et al. 2018).

1.1. Study Overview

JASCO’s cumulative noise model was used to examine the effectiveness of the implementation of Interim Sanctuary Zones in reducing vessel noise exposures of SRKW habitat near Saturna and Pender Islands, in the Salish Sea. The model was applied for each zone to predict monthly averaged noise levels associated with vessel traffic conditions before and during the implementation of the sanctuary zones. The effectiveness of these zones is assessed quantitatively according to the estimated changes in noise levels.

The cumulative noise model requires several inputs, including the traffic densities, the noise emission levels, and the transit speeds for each vessel class. The model also incorporates oceanographic data such as ocean temperature and salinity profiles, water depth variations, and seabed properties.

The frequency range examined, from 10 Hz to 63 kHz, covers most of the frequencies used by killer whales for communication and echolocation (although echolocation click frequency content can extend weakly to 100 kHz). Killer whale hearing sensitivity is best between 15–30 kHz (Branstetter et al. 2017), whereas most vessel sound energy is concentrated below 1 kHz. Nevertheless, vessel noise emissions do extend to several tens of kHz so can interfere with killer whales’ use of sound. The frequency distribution of vessel noise, therefore, was assessed in the analyses in relation to killer whales’ hearing spectral sensitivity, which is represented by an audiogram.

For this study, vessel density and speed information for multiple commercial, government, and recreational vessel classes in the Salish Sea were derived from a high-resolution AIS dataset that contains the locations of many thousands of vessels (MarineTraffic 2020). Since not all vessels are required to be fitted with AIS, the vessel densities for the classes of smaller vessels (e.g. recreational and sailing vessels) were scaled up based on the estimated proportions of those vessels that are not fitted with AIS (see Section 2.1.1). This vessel information was computed for two 1-month periods—July 2018 and July 2019—with the aim of representing conditions before and during the implementation of the sanctuary zones, respectively. When we compared the AIS data between July 2019 and July 2018, however, we found a very low rate of compliance for many vessel classes, i.e., the number of vessels within the sanctuary zones did not decrease significantly between 2018 and 2019 (see Section 2.1.2). Performing modelling using the 2019 data would therefore provide no meaningful information about the possible effect of implementing such sanctuary zones. For this reason, as well as to avoid influences from natural variations in vessel traffic between years, we chose to synthesize a set of vessel data to represent conditions of due compliance with the sanctuary zones.

The noise emission levels of the vessel classes were obtained from a previous JASCO study that reported average source levels from over 2700 vessel measurements recorded in 2015 to 2018 by an Underwater Listening Station (ULS) for the Enhancing Cetacean Habitat Observations (ECHO) program (MacGillivray et al. 2018). These data were supplemented with those from a few additional sources to include smaller vessel classes not covered by the ULS data (see Section 2.3).

For each sanctuary zone, the modelled sound levels are presented over an 8 × 8 km study area encompassing the zone. The modelled region, however, extended well beyond the study area to account for noise contributions from vessels near but outside the area (Figure 1).

The aggregate vessel noise was assessed as a monthly average; the results are presented as maps showing the spatial distribution of equivalent continuous underwater noise levels (L_{eq}; see Appendix A.1) and tabulated at fixed sample locations in the sanctuary zones (these locations are shown in Figure 2 and listed in Table 1). This monthly L_{eq} is calculated like the 8-hour L_{eq} used for human workplace noise assessments but using a much longer averaging time (31 days versus 8 hours). Since L_{eq} is a time average, it does not provide information about noise level variations over time within the averaging period. Time variability is important for certain analyses, such as for estimating how often sound levels exceed marine mammal effects thresholds; this type of analysis, however, was not within scope for this project.

This report is divided into three main sections. Section 2 presents an overview of the methods, with more detailed descriptions provided in Appendix A. Section 3 presents the results. Section 4 discusses the study results in terms of the overall effectiveness of the implementation of the sanctuary zones in reducing sound exposures.

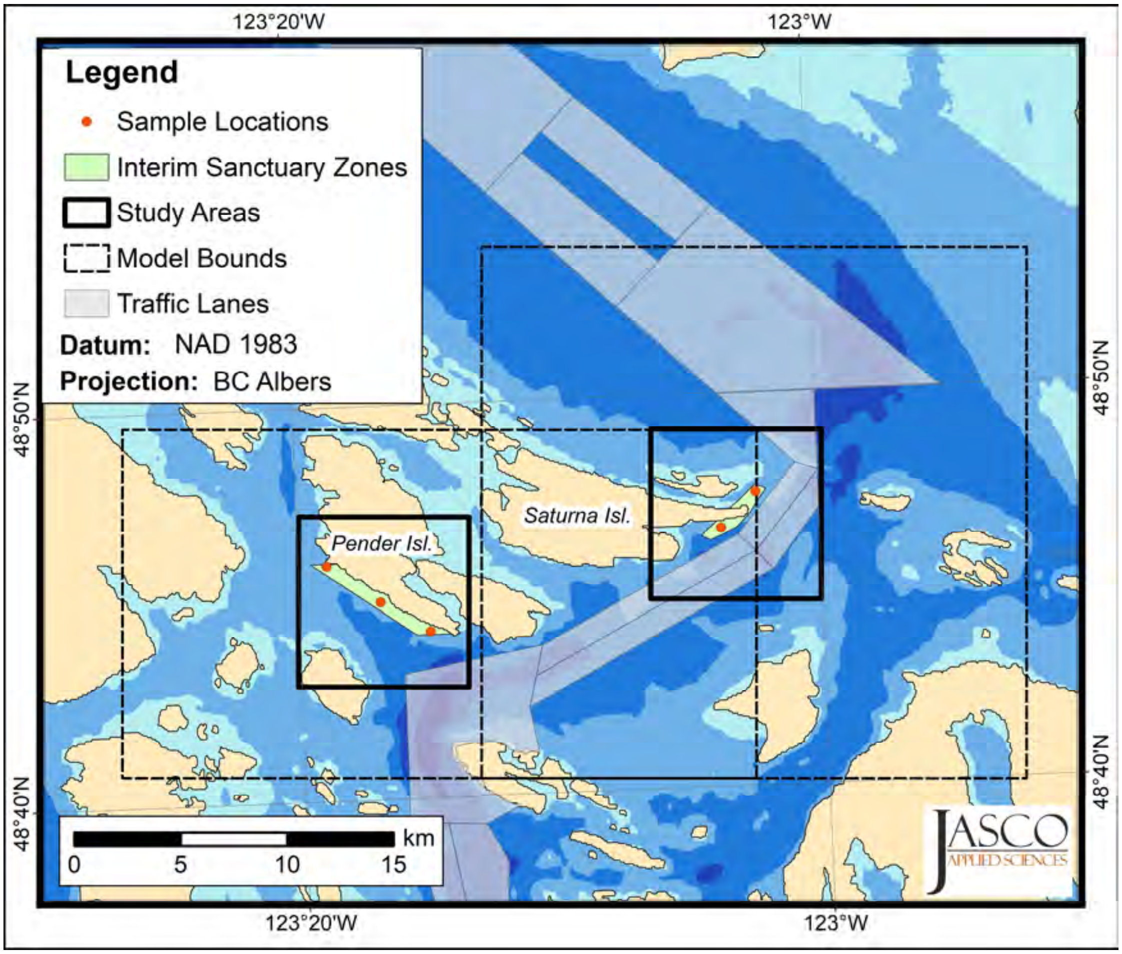

Figure 1. Overview of the bounds of the modelled regions, which extend beyond the study areas for which sound level results are provided. The study areas are shown in greater detail in Figure 2.

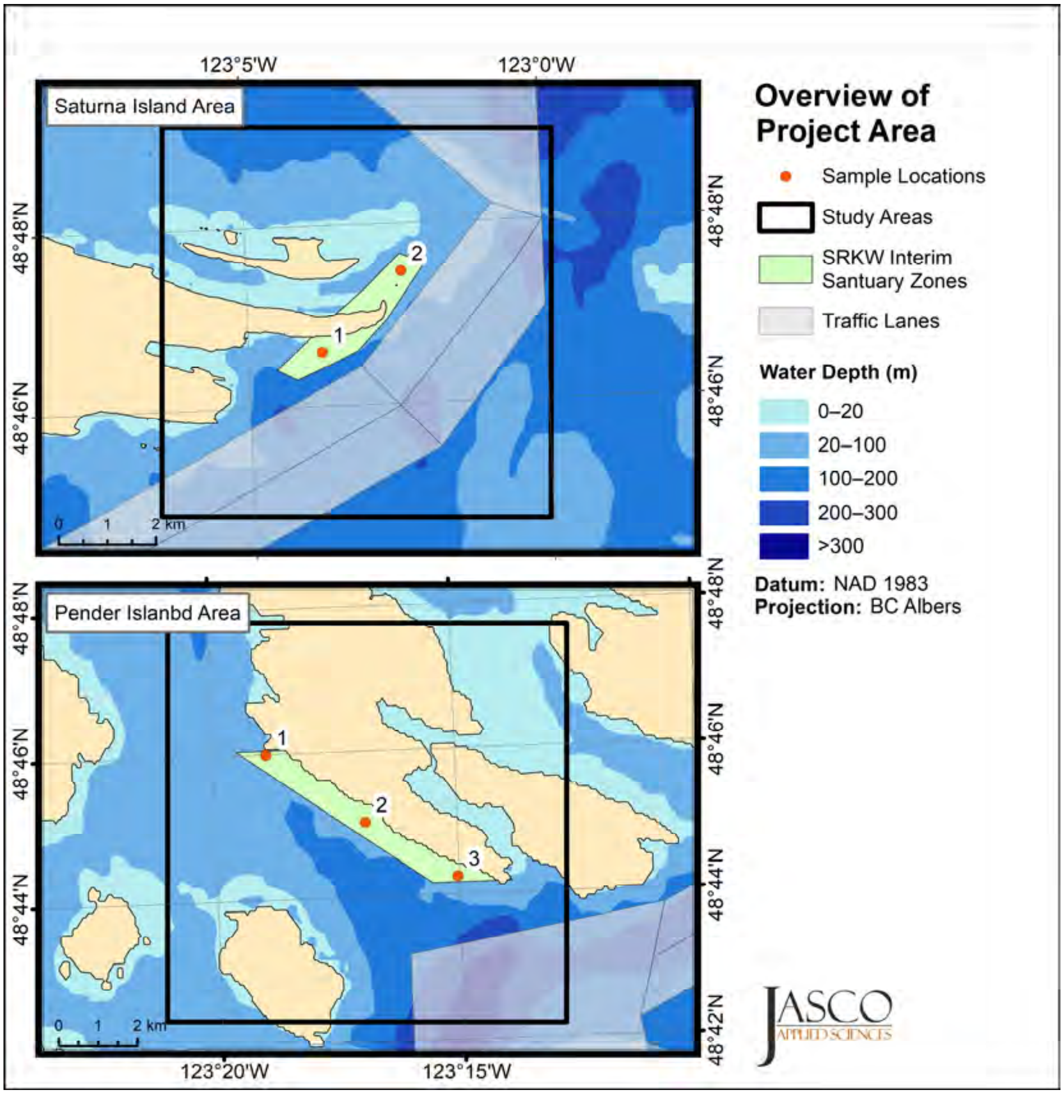

Figure 2. Extent of the study areas around the Interim Sanctuary Zones and the five sample locations.

Table 1. Noise field sample locations in the two study areas.

Study area	Sample location	Easting/Northing (m), BC Albers Projection		Latitude	Longitude
Saturna Island	1	1216170 E	422320 N	48° 46' 36.0460" N	123° 03' 45.7644" W
	2	1217784 E	424006 N	48° 47' 28.4988" N	123° 02' 23.4381" W
Pender Island	1	1197651 E	420467 N	48° 45' 59.8486" N	123° 18' 54.1408" W
	2	1200186 E	418784 N	48° 45' 02.1902" N	123° 16' 53.4760" W
	3	1202538 E	417420 N	48° 44' 15.0204" N	123° 15' 01.2166" W

2. METHODS

The cumulative noise model was used to compute noise maps based on vessel traffic over a one-month period before and during the implementation of SRKW Interim Sanctuary Zones near Saturna and Pender Islands. To produce these time-averaged noise maps, the model requires three main sets of input parameters (Figure 3):

- A representation of the vessel traffic, including individual vessels' type, sail tracks (position versus time), and speed throughout the modelled area (Vessel Traffic Data),
- A description of how sound propagates away from a vessel at any location in the study area (Sound Propagation Curves, which require environmental parameters as input), and
- A description of the noise emitted by each vessel (Vessel Source Levels).

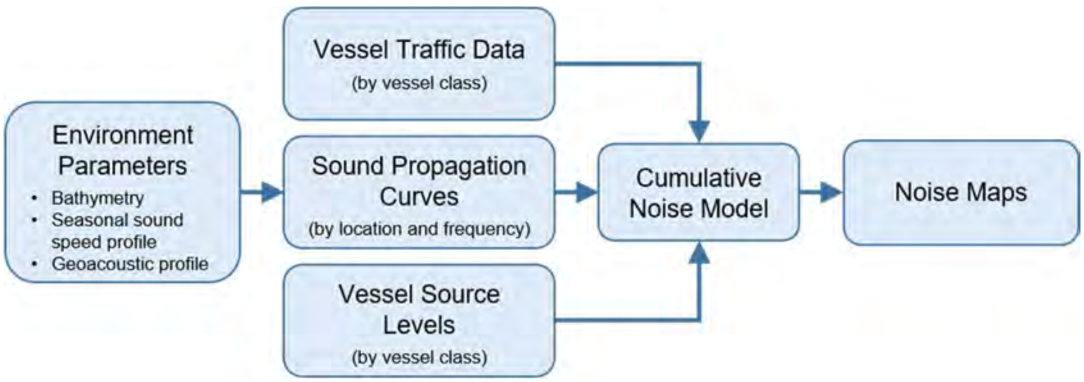

Figure 3. High-level flowchart of the inputs and outputs of the cumulative noise model.

In this section, we describe the model input parameters specific to the current study. Details relating to underwater acoustics terminology, vessel sounds, and sound propagation modelling can be found in Appendix A.

2.1. Estimating Vessel Traffic

2.1.1. Vessel Traffic before Implementation of Sanctuary Zones

To assess the effectiveness of implementing SRKW Interim Sanctuary Zones in the Gulf Islands, noise levels were first calculated from recent historical vessel traffic data to get a baseline understanding of vessel noise in each sanctuary zone. For that purpose, AIS data for July 2018 (MarineTraffic 2020), the year before the sanctuary zones were implemented, were analysed. July was selected since it is one of the months with the highest recreational vessel traffic in the area.

For this study, the various vessel types in the AIS data (there are more than 60 types) were grouped into 14 vessel classes. Ten of those classes match those used by the measurement study from which we obtained most of the vessel source levels (see Section 2.3). The other four classes represent non-commercial vessels and ecotourism. The vessel classes are listed in Table 2, and the AIS vessel types associated with each class are listed in Appendix B. Ecotourism vessels don't have a specific AIS vessel type but rather belong to multiple types that are also associate with various vessel classes. To estimate the number of ecotourism vessels in the AIS data, we researched vessel names and their Maritime Mobile Service Identity (MMSI) number from companies operating in the area. We also retrieved available images of vessels tracked on AIS based on their MMSI number to confirm their class. We then reclassified all AIS records associated with MMSI numbers we found to be ecotourism vessels.

Not all vessels are fitted with AIS, however. Many recreational vessels, for example, are not required to do so under Canadian Laws. The AIS data therefore do not represent the true number of vessels present for such vessel classes. To account for this, a scaling factor can be applied to the AIS vessel densities for each class, based on estimates of the proportion of those vessels that aren't fitted with AIS transmitters. This is equivalent to uniformly increasing the number of vessels (in that class) throughout the modelled area. Few studies, however, have estimated the percentage of AIS versus non-AIS vessels. We determined the density scaling factors, one for each vessel class (as presented in Table 2), after analysing visual observation estimates of non-AIS vessels in the region (Serra-Sogas et al. 2018, Le Baron et al. 2019a, Warner et al. 2019), as described below, and comparing the 2018 and 2019 AIS data (MarineTraffic 2020). The values in Table 2 represent the best estimates for the region, based on the available data and approach described below.

Two observational studies of vessel traffic off East Point (Saturna Island) have determined percentages of non-AIS vessels in the region. The first study captured images from a land-based camera deployed at East Point (Saturna Island) in August 2017 (Warner et al. 2019). By comparing the camera imagery against AIS records, Warner et al. estimated that, in daytime in August, on average 72% of the vessels were not fitted with AIS—a substantial majority. More specifically, it was estimated that only 45% of ecotourism vessels observed were fitted with AIS. Even lower numbers were found for motorboats (i.e., recreational vessels), at 22%, and sailboats (i.e., sailing vessels), at 16%. The second study, conducted by the University of Victoria using areal observations from August 2015 through December 2017, found that between 8 and 33% of recreational vessels in the Gulf Islands and Boundary Pass area were fitted with AIS (Serra-Sogas et al. 2018).

We also performed a preliminary analysis of a more recent set of observation data. This dataset consists of daytime counts of observed vessels in 5-minute intervals, by vessel class, off East Point, from July 27th to August 1st, 2019 (Le Baron et al. 2019b). We compared the daily mean number of vessels to the number of AIS records for the area for July 2019. This preliminary comparison estimated that in 2019, less than 4% of vessels in the observed area were fitted with AIS. This very low number disagrees with the two observational studies mentioned previously. Le Baron et al. (2019b) aimed at comparing the total count of vessels in the area to recorded noise levels within the same timeframe as the observations. Thus, vessels may have been counted multiple times throughout the observations, yielding an underestimation of the number of AIS-fitted vessels. We therefore ignored these results and used the 2017 study values (Warner et al. 2019) to estimate the proportions and factors in Table 2.

In the current study, like in the AIS datasets, the fishing vessel class represents commercial fishing; vessels engaged in recreational fishing are classified as recreational vessels. We suspect that the observation data from 2017 included recreational fishing vessels in the commercial fishing class and therefore overestimated the number of non-AIS vessels in this class. New Canadian AIS requirements were implemented in June 2019 (Navigation Safety Regulations 2005, Sec. 65). The changes affected vessels operating outside sheltered waters that are certified to carry more than 12 passengers or that are 8 m or more in length (carrying any number of passengers). This means that by June 15th, 2019, most commercial fishing vessels were required to be fitted with AIS. By comparing the number of unique fishing vessels in the July 2018 AIS records to the July 2019 records, we estimated that 91% of commercial fishing vessels in July 2018 were fitted with AIS.

Table 2. Estimated percentage by vessel class of vessels fitted with AIS (in July 2018 for the southern Gulf Islands) and density scaling factor applied to the AIS data to account for vessels without AIS. A scaling factor > 1.0 means that the number of vessels in that class was increased.

Vessel class	Proportion fitted with AIS	Density scaling factor
Container	100%	1.0
Cruise ship	100%	1.0
Ecotourism	45%	2.2
Ferry	100%	1.0
Fishing (commercial fishing only)	91%	1.1
Government	100%	1.0
Merchant	100%	1.0
Passenger (less than 100 m in length)	100%	1.0
Recreational and Sailing		
Recreational (including recreational fishing)	22%	4.6
Sailing (under power)	16%	6.3
Tanker	100%	1.0
Tug	100%	1.0
Vehicle carrier	100%	1.0
Other/miscellaneous	100%	1.0

2.1.2. Vessel Traffic during Implementation of Sanctuary Zones

The Interim Sanctuary Zones in the Gulf Islands were implemented from 1 June to 31 October, 2019 (DFO 2019). The Interim Order applied to all vessels, regardless of the method of propulsion, except for:

- Local traffic that needs access to a residence, business … or a mooring buoy within the sanctuary, where travel by water is the only means of access;
- Vessels in distress or providing assistance to vessels or person in distress;
- Vessels avoiding immediate or unforeseen danger;
- Employees of the Government of Canada and peace officers performing their duties or functions, persons assisting them, or persons that are present at the request of the Government of Canada;
- Person undertaking certain activities, including scientific research, as authorized under either the *Species at Risk Act, Marine Mammal Regulations, or Fishery (General) Regulations*;
- Persons fishing for food, social or ceremonial purposes or for domestic purposes pursuant to a treaty within the meaning of section 35 of the *Constitution Act, 1982*, in accordance with a licence issued under the *Aboriginal Communal Fishing Licence Regulations*; and
- Indigenous persons exercising an existing right for non-commercial purposes, other than fishing, under section 35 of the *Constitution Act, 1982* (Transport Canada 2019).

AIS data for July 2018 and July 2019 were compared to evaluate how vessel traffic changed with the implementation of the sanctuary zones. For this comparison, we defined a vessel track (or transit) as a group of AIS records for the same vessel (same Maritime Mobile Service Identity (MMSI) number) with consecutive time stamps (i.e., with less than 10 minutes between time stamps), thus evidencing the main routes followed by each vessel class. The outcome was that no obvious changes in the routes could be discerned between the July 2018 and 2019 data, i.e., the vessels did not appear to alter their courses to avoid entering the sanctuary zones.

Table 3 compares the number of times an AIS-fitted vessel entered a sanctuary zone in July of each year, as well as the number of vessel tracks within an arbitrary 500 m boundary around the zones. At Saturna Island, the number of vessels entering the sanctuary zone did not change significantly between 2018 and 2019; this difference is expected to have little effect on the cumulative noise levels for the month of July. At Pender Island, the numbers of ecotourism and fishing vessels decreased significantly in the zone and within 500 m of the zone; a substantial increase was recorded, however, for many other vessel classes (government, passenger, recreational, sailing, tug and other/miscellaneous). Therefore, as for Saturna Island, the AIS 2019 data do not point to a level of compliance high enough to significantly change the cumulative noise levels over the month of July. Even without an exploratory modelling, we assessed that using the July 2019 data as input would provide no meaningful representation of the effect on noise levels of implementing such sanctuary zones in a scenario of due compliance.

In addition, by using vessel data from two different years, we would be introducing natural variations in vessel traffic across years into the comparison rather than strictly comparing the differences between having and not having sanctuary zones.

To address these problems and provide a meaningful comparison of noise levels without and with the sanctuary zones in effect, we chose to synthesize a set of vessel data to represent modified traffic patterns after the zones were implemented. We synthesized the data by making the following adjustments to the July 2018 AIS data:

- For recreational and sailing vessels, 95% of vessels within a sanctuary zone were modified to transit around the zone;
- All government vessel tracks were left unmodified;
- For all other vessel classes, 100% of vessels transiting through a sanctuary zone were modified to transit around the zone.

This scenario represents an idealistic level of compliance, considering the exemptions stated in the 2019 Interim Order (DFO 2019), which include local traffic accessing residences or businesses, Government of Canada employees and peace officers performing their duties, and indigenous persons exercising a legal right.

Table 3. Changes in the number of tracks of AIS-fitted vessel (July 2018 versus July 2019), in and around the sanctuary zones.

Sanctuary Zone	Vessel Class	Tracks crossing the zone			Tracks within 500 m of the zone		
		July 2018	July 2019	Difference	July 2018	July 2019	Difference
Saturna Island	Container	0	0	n/a	2	1	-1 (-50%)
	Cruise ship	0	0	n/a	0	0	n/a
	Ecotourism	33	33	0 (0%)	44	56	+12 (+27%)
	Ferry	0	0	n/a	0	0	0 (0%)
	Fishing	0	1	+1 (+100%)	1	6	+5 (+500%)
	Government	2	0	-2 (-100%)	7	2	-5 (-71%)
	Merchant	0	0		8	9	+1 (+13%)
	Passenger (less than 100 m in length)	9	11	+2 (+22%)	19	15	-4 (-21%)
	Recreational	22	21	-1 (-5%)	36	39	+3 (+8%)
	Sailing	12	11	-1 (-8%)	17	16	-1 (-6%)
	Tanker	0	0	n/a	1	3	+2 (+200%)
	Tug	0	0	n/a	5	6	+1 (+20%)
	Vehicle carrier	0	0	n/a	0	1	+1 (+100%)
	Other/miscellaneous	0	1	+1 (+100%)	1	1	0 (0%)
Pender Island	Container	0	1	+1 (+100%)	0	2	+2 (+200%)
	Cruise ship	0	0	n/a	0	0	n/a
	Ecotourism	97	24	-73 (-75%)	121	45	-76 (-63%)
	Ferry	0	0	n/a	3	0	-3 (-100%)
	Fishing	16	7	-9 (-56%)	23	12	-11 (-48%)
	Government	10	31	+21 (+210%)	30	53	+23 (+77%)
	Merchant	12	9	-3 (-25%)	25	25	0 (0%)
	Passenger (less than 100 m in length)	32	35	+3 (+9%)	51	69	+18 (+35%)
	Recreational	338	412	+74 (+22%)	605	709	+104 (+17%)
	Sailing	99	160	+61 (+62%)	195	301	+106 (+54%)
	Tanker	0	0	n/a	0	0	n/a
	Tug	2	18	+16 (+800%)	41	42	+1 (+2%)
	Vehicle carrier	0	0	n/a	0	0	n/a
	Other/miscellaneous	3	9	+6 (+200%)	5	19	+14 (+280%)

2.2. Modelling the Sound Propagation Curves

The sound propagation loss curves (sometimes referred to as acoustic transmission loss curves) are computed by the noise model's internal algorithms. These calculations are independent of the source levels (vessel noise emission) and account solely for the sound weakening effect of the 3-dimensional ocean environment.

Acoustic propagation loss is the decrease in intensity of a sound as it travels away from a source through an environment. JASCO's Marine Operations Noise Model (MONM) was used to calculate the propagation loss field throughout the modelled regions. MONM uses multiple environmental parameters (Section 2.2.1) to compute the reduction in sound levels with distance and depth for each frequency band out to a given distance from the source, in this case 30 km (Appendix A.5.1). The resulting propagation loss fields are then sampled at a specific receiver depth (10 m in the current study, deemed to be representative for SRKW interaction) to yield propagation loss curves as a function of distance. The MONM predictions have been validated against measurements from propagation loss field studies (see e.g., JASCO Applied Sciences 2015).

2.2.1. Ocean Environmental Parameters

Sound propagation through the ocean depends on properties of the water column itself, such as the temperature, salinity, and water depth profiles, as well as geological properties of the seabed beneath the water, including the sediment type (e.g., sand, silt, bedrock) and the thickness of each sediment layer.

The study area was divided into several environmental zones (see Figure B-5), which lie in the distinct geoacoustic regions of Haro Strait, Rosario Strait, and portions in the Strait of Georgia (see Figure B-6). Various zones have different water depths, as highlighted in Table B-2. Propagation loss was modelled for each zone using the average sound speed profile for July (see Figure A-4; ONC and UVic 2017). More information on the environmental parameters is provided in Appendix A.4.

2.3. Vessel Noise Emission Levels (Source Levels)

The main sources of underwater noise from a vessel are propeller cavitation and hull vibrations from internal machinery. Different types of vessels will have different spectral characteristic because of their design and operating conditions (vessel sounds and cavitation noise are further described in Appendix A.3).

To model noise from a large number of vessels over a large area during a one month period, we used omnidirectional source level spectra which represent the mean levels for each vessel class (NRC 2003). In the cumulative noise model, the noise emissions of each vessel class were represented by frequency-dependent source levels, resolved in 1/3-octave frequency bands from 10 Hz to 63.1 kHz (Figure 4). For each vessel location over the modelled period, the cumulative noise model adjusts the vessel's source levels based on the vessel's speed at the modelled location and time.

The source levels for 10 of the vessel classes were sourced from the ECHO program ULS (see Appendix A.3.2). Source levels for four additional vessel classes, not covered by the ULS data (Ecotourism, Passenger (<100 m in length); Recreational and Sailing, and Other/miscellaneous), were obtained from other sources (see Appendix A.3.2). The sources were placed at one of six depths (from 1 to 6 m; see Appendix A.5.1) dependent on the modelled vessel class, representing the nominal acoustic emission centre of that class.

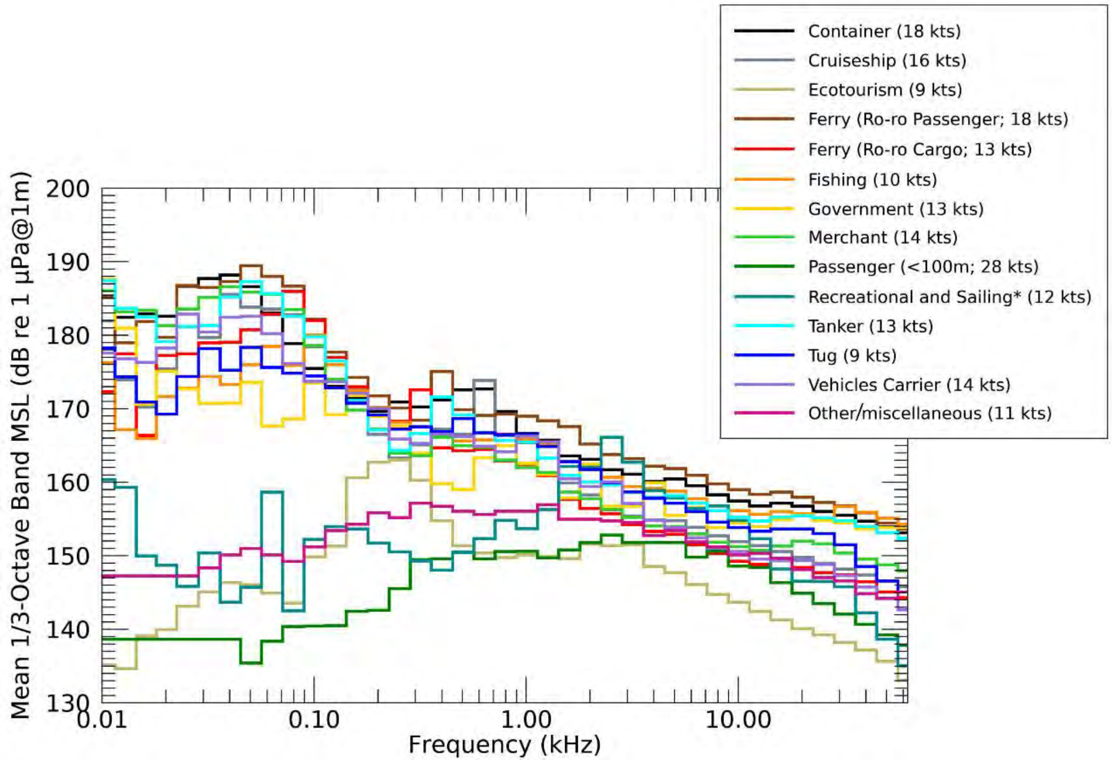

Figure 4. Frequency-dependent source levels used in the model for each vessel class, in 1/3-octave-bands. The reference speed (average transit speed, in knots) for each class is indicated in the legend. *Sailing vessels under power (not under sail).

2.4. Modelling Cumulative Noise and Applying Audiogram Weighting

The Cumulative Noise Model combines the sound propagation curves described in Section 2.2 with the vessel noise emission level described in Section 2.3. The computations are based on a grid representing a model region divided into equally sized square cells. For each vessel class, the vessel density data and average speed (described in Section 2.1) is assigned to each cell; the associated noise level is propagated outwards into neighbouring cells, over several kilometres (30 km in the current study).

The results representing vessel traffic conditions before and during the implementation of the Interim Sanctuary Zones are presented as maps of equivalent continuous noise levels (L_{eq}). L_{eq} is calculated by dividing the cumulative sound exposure level (SEL) by the averaging period, in seconds. The L_{eq} metric is useful for presenting geographic distributions of mean noise levels. In the present study, L_{eq} is calculated over the 31 days of July.

The model bounds cover large regions around Saturna and Pender Islands to encapsulate vessel traffic noise from many of the distant shipping lanes that might influence sound levels in the sanctuary zones. We used a fine resolution grid (50 m × 50 m) to determine the fine sound structures within the narrow Interim Sanctuary Zones. The results are presented over 8 × 8 km areas, each encompassing the sanctuary zone.

2.4.1. SRKW Audiogram Weighting

When assessing the effectiveness of any mitigation approach, the frequencies of the noise must be considered relative to the animal's hearing ability. For instance, it is less likely that man-made noise will affect a marine animal if the animal cannot perceive the sound well, unless the sound pressure is high enough to cause physical injury (not a likely situation for vessel noise). For noise levels that are below physical injury thresholds, frequency weighting based on audiograms can be applied to scale the importance of noise levels at each frequency in a manner reflective of an animal's sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

This audiogram weighting, described in Appendix A.6.1, is applied to the final received sound levels generated by the cumulative noise model. The resulting audiogram-weighted levels represent sound levels above an animal's hearing threshold (dB re HT), and they cannot be directly compared with unweighted levels nor compared to any impact threshold levels mentioned in the literature. It is not well understood at what dB re HT levels the onset of behavioural disturbance in killer whales may occur, but Williams et al. (2014) suggested that responses can start at between 56 and 64 dB re HT.

In the current report, audiogram-weighted equivalent continuous noise level (L_{eq}) represents the mean noise level perceived by a SRKW at any time in July.

3. RESULTS

In this section, the results for each model scenario are presented both without and with the SRKW audiogram-weighting applied. The two types of results are easily identified in the noise exposure maps by the different colour scales used to represent the equivalent continuous noise levels (L_{eq}): blue/yellow/red for the broadband/unweighted levels, and purple/yellow/fuchsia for the audiogram-weighted levels. A third colour scale, blue/white/red, is used to map the difference in L_{eq}, which compares the noise levels before and after the implementations of the Interim Sanctuary Zones.

Maps of noise levels (L_{eq}) before and during the implementation of the Interim Sanctuary Zones, and the associated changes in L_{eq}, are presented in Figure 5 for the Saturna Island area and Figure 6 for the Pender Island; unweighted results are presented on the left, and SKRW audiogram-weighted are presented on the right. These one-month average levels were sampled at the key locations in each sanctuary zone; these results are presented in Table 4. The spatial analysis of the changes in noise level within each sanctuary zone yield the values presented in Table 5.

Table 4. Unweighted (left) and audiogram-weighted (right) equivalent continuous noise levels (L_{eq}), changes in levels (dB), and changes in acoustic intensity (%) at five sample locations in the sanctuary zones.

Area	Sample location	Unweighted				Audiogram-weighted			
		Before (dB re 1 µPa)	During (dB re 1 µPa)	Change		Before (dB re HT)	During (dB re HT)	Change	
				dB	%			dB	%
Saturna Island	1	116.8	116.6	-0.2	-4.5	58.6	56.6	-2.0	36.9
	2	113.7	111.9	-1.8	-33.9	59.9	54.9	-5.0	68.4
Pender Island	1	122.6	118.7	-3.9	-59.3	71.0	64.7	-6.3	-76.6
	2	119.6	115.5	-4.1	-61.1	68.0	62.0	-6.0	-74.9
	3	120.3	116.1	-4.2	-62.0	69.1	63.8	-5.3	-70.5

Table 5. Spatial analysis of the changes in noise level (dB) and acoustic intensity (%). The values indicate the percentile or mean of the changes over all grid cells within the sanctuary zone.

Area	Frequency weighting	5th	50th	95th	Mean
Saturna Island	Unweighted	-1.3 (-25.7%)	-0.3 (-7.4%)	-0.1 (-1.4%)	-0.5±0.4 (-10.0%)
	Audiogram-weighted	-4.2 (-62.0%)	-2.1 (-38.1%)	-0.6 (-13.1%)	-2.2±1.1 (-39.6%)
Pender Island	Unweighted	-4.3 (-62.7%)	-3.2 (-52.2%)	-1.1 (-21.8%)	-3.0±1.0 (-49.5%)
	Audiogram-weighted	-6.2 (-75.9%)	-5.0 (-57.4%)	-2.2 (-40.1%)	-4.6±1.3 (-65.3%)

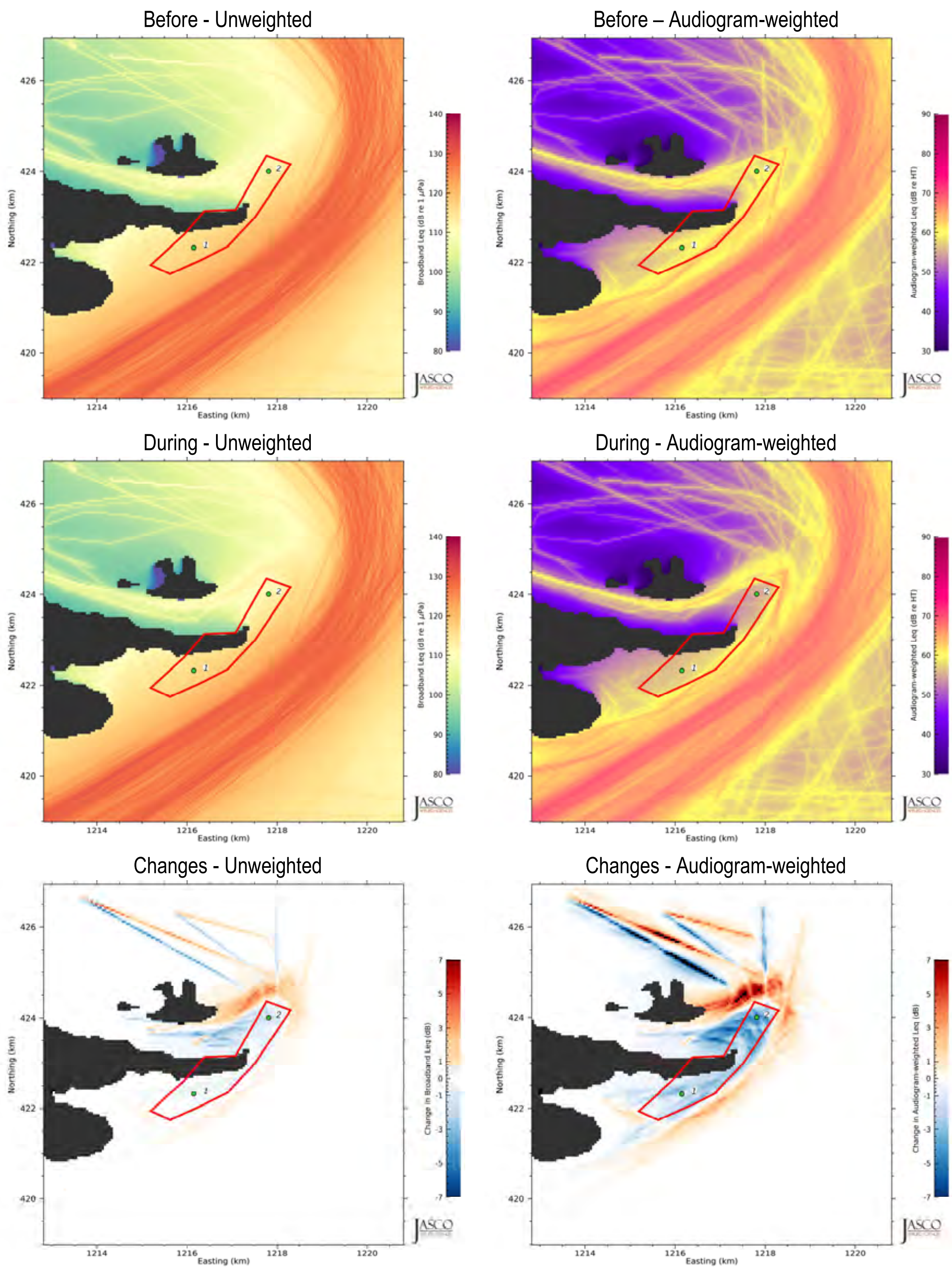

Figure 5. *Saturna Island Area*: Unweighted (left) and audiogram-weighted (right) equivalent continuous noise levels (L_{eq}) representing conditions before (top) and after (middle) the implementation of the Interim Sanctuary Zone, and changes in L_{eq} (bottom). Grid resolution is 50 × 50 m. The red outline shows the boundary of the interim sanctuary zone. The green dots show the sample locations within the sanctuary zone.

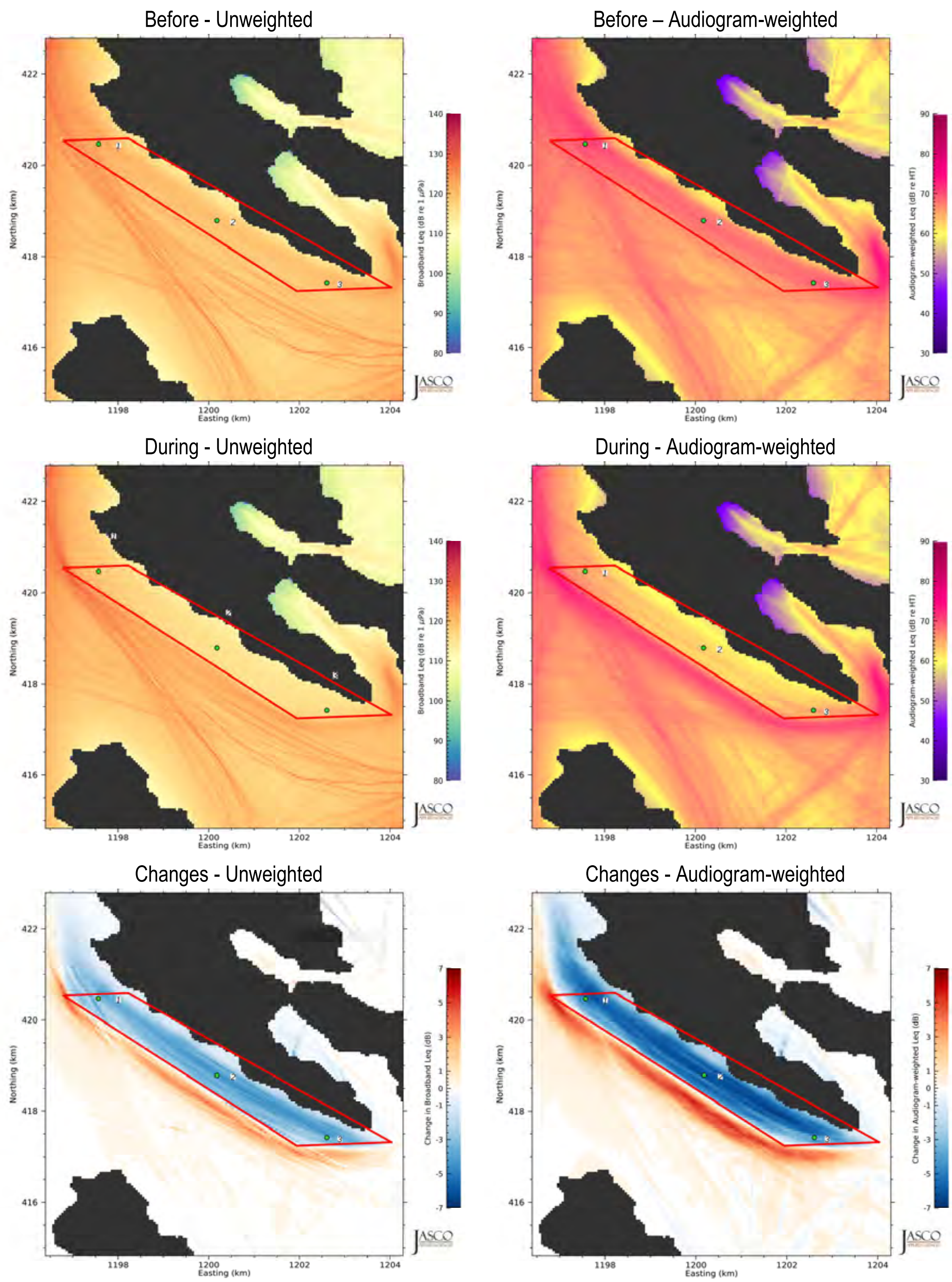

Figure 6. *Pender Island Area*: Unweighted (left) and audiogram-weighted (right) equivalent continuous noise levels (L_{eq}) representing conditions before (top) and during (middle) the implementation of the Interim Sanctuary Zone, and changes in L_{eq} (bottom). Grid resolution is 50 × 50 m. The red outline shows the boundary of the interim sanctuary zone. The green dots show the sample locations within the sanctuary zone.

4. DISCUSSION

We modelled equivalent continuous underwater noise levels (L_{eq}) around Saturna and Pender Islands to assess the effectiveness of the implementation of sanctuary zones in reducing noise levels for Southern Resident Killer Whales (SRKW). Our results show that this mitigation approach would result in a decrease of unweighted noise levels by, on average, 0.5 (±0.4) dB and 3.0 (±1.0) dB within the Saturna Island and the Pender Island Interim Sanctuary Zones respectively. The decrease is greater for audiogram-weighted noise levels (2.2 (±1.1) dB at Saturna Island and 4.6 (±1.3) dB at Pender Island).

These results are based on an idealized level of compliance by vessels in the area, which takes into account the exemptions stated in the 2019 Interim Order (DFO 2019). AIS data for July 2019 showed in fact a minimum level of compliance (avoidance of sanctuary zones) by most vessel classes. The reduction in levels effectively achieved in 2019 is therefore expected to have been significantly less than modelled here, and likely negligible.

The reduction in noise level is significantly greater at Pender Island than at Saturna Island. This is due to the fact a larger number of vessels would normally transit within the zone at Pender Island than at Saturna Island, so that the rerouting of those vessels removes a larger percentage of the total noise level in the zone. Note that the changes in noise levels in the Strait of Georgia (north of the Saturna Island sanctuary zone) are artefacts caused by a few (3) vessels' simulated displacement while transiting at high speed; in practice, no significant variations in monthly-averaged noise levels due to implementing the sanctuary zone at Saturna Island are expected in the Strait of Georgia.

The greater absolute drop in audiogram-weighted noise levels compared to unweighted noise levels during implementation of the sanctuary zones is related to the noise emission spectra of the vessels that were excluded from entering. Most of the vessels displaced belong to the classes of ecotourism, passenger (less than 100 m in length), recreational and sailing vessels. These are generally smaller vessel whose noise emissions have more energy at higher frequencies than for other classes (see Figure 4). Their exclusion has a greater influence on the sound field at frequencies greater than ~2 kHz, where killer whale hearing sensitivity is greater (see Appendix A.6.1).

The exclusion of vessels from the sanctuary zones also results in a significant increase in noise levels just outside the zones. Vessels would normally transit along the shortest routes between ports. One of these routes crosses the sanctuary zone south of Pender Island, whilst vessels transiting in the sanctuary zone east of Saturna Island are mainly smaller vessels avoiding the shipping lanes. Analysis of the July 2019 AIS data did not show preferred alternative routes due to the implementation of the Interim Sanctuary Zones, but it is expected that most vessels complying with the exclusion would circumnavigate the zones along the prescribed boundaries, as was modelled in this study. This results in an increase in vessel density and therefore, an increase in noise levels just outside the zones. A wider spread of the displaced routes would reduce the noise concentration along the boundaries and further decrease levels within the zones compared to the results presented.

With the implementation of, and due compliance to, the sanctuary zones, marine animals (including SRKW) would experience lower noise levels while within their boundaries. They would have to pass through areas of likely enhanced noise levels, however, to travel in and out of the sanctuary zones. It is expected that SRKW would transit rapidly through the modelled areas of higher noise levels, limiting their exposure time, and remain for longer periods (e.g., for foraging) within the zones. This would result in an overall net reduction in noise exposure to the SRKW.

There are relatively small spatial various in the changes in noise levels within the sanctuary zones (see Table 5). The modelled variations are due to currently preferred routes to navigate around the islands (see the bottom maps in Figures 5 and 6). They depend slightly on the selected vessel tracks used to simulate the exemptions (i.e. the vessels allowed in the zones; see Section 2.1.2).

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AUTHORIZED RELEASE

The undersigned confirms that this report meets the scope of work and has undergone all quality control checks and report reviews required by JASCO's QMS Policies and Procedures.

Role: Project Manager
Name: Holly Sneddon
Date:
Signature:

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APPENDIX A. METHODS IN DETAIL

A.1. Acoustic Metrics

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa. Because the perceived loudness of sound, especially pulsed noise such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate noise and its effects on marine life. We provide specific definitions of relevant metrics used in the accompanying report. Where possible we follow the ANSI and ISO standard definitions and symbols for sound metrics, but these standards are not always consistent.

The sound pressure level (SPL; dB re 1 μPa) is the rms pressure level in a stated frequency band over a specified time window (*T*, s) containing the acoustic event of interest. It is important to note that SPL always refers to an rms pressure level and therefore not instantaneous pressure:

$$L_p = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_0^2\right) \quad \text{(B-1)}$$

where $g(t)$ is an optional time weighting function. The SPL represents a nominal effective continuous sound over the duration of an acoustic event, such as the emission of one acoustic pulse, a marine mammal vocalization, the passage of a vessel, or over a fixed duration. Because the window length, *T*, is the divisor, events with similar sound exposure level (SEL) but more spread out in time have a lower SPL.

The sound exposure level (SEL, dB re 1 μPa^2·s) is a measure related to the acoustic energy contained in one or more acoustic events (*N*). The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (*T*):

$$L_E = 10\log_{10}\left(\int_T p^2(t)dt \Big/ T_0 p_0^2\right) \quad \text{(B-2)}$$

where T_0 is a reference time interval of 1 s. The SEL continues to increase with time when non-zero pressure signals are present. It therefore can be construed as a dose-type measurement, so the integration time used must be carefully considered in terms of relevance for impact to the exposed recipients.

SEL can be calculated over periods with multiple acoustic events or over a fixed duration. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, the SEL can be computed by summing (in linear units) the SEL of the *N* individual events:

$$L_{E,N} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right) \quad \text{(B-3)}$$

Energy equivalent SPL (dB re 1 μPa) denotes the SPL of a stationary (constant amplitude) sound that generates the same SEL as the signal being examined, $p(t)$, over the same period of time, *T*:

$$L_{eq} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_0^2\right) \quad \text{(B-4)}$$

The equations for SPL and the energy-equivalent SPL are numerically identical; conceptually, the difference between the two metrics is that the former is typically computed over short periods (typically of one second or less) and tracks the fluctuations of a non-steady acoustic signal, whereas the latter reflects the average SPL of an acoustic signal over times typically of one minute to several hours.

A.2. 1/3-Octave-Band Analysis

The distribution of a sound's power with frequency is described by the sound's spectrum. The sound spectrum can be split into a series of adjacent frequency bands. Splitting a spectrum into 1 Hz wide bands, called passbands, yields the power spectral density of the sound. This splitting of the spectrum into passbands of a constant width of 1 Hz, however, does not represent how animals perceive sound.

Because animals perceive exponential increases in frequency rather than linear increases, analyzing a sound spectrum with passbands that increase exponentially in size better approximates real-world scenarios. In underwater acoustics, a spectrum is commonly split into 1/3-octave-bands, which are one-third of an octave wide; each octave represents a doubling in sound frequency. The centre frequency of the ith 1/3-octave-band, $f_c(i)$, is defined as:

$$f_c(i) = 10^{i/10} \tag{B-5}$$

and the low (f_{lo}) and high (f_{hi}) frequency limits of the ith 1/3-octave-band are defined as:

$$f_{lo} = 10^{-1/20} f_c(i) \text{ and } f_{hi} = 10^{1/20} f_c(i) \tag{B-6}$$

The 1/3-octave-bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure B-1).

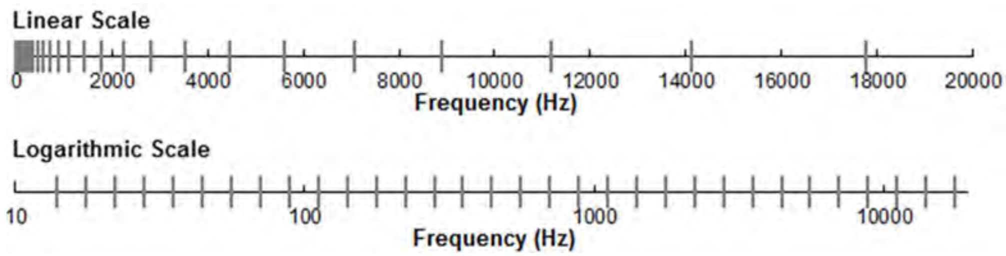

Figure B-1. One-third-octave-bands shown on a linear frequency scale and on a logarithmic scale.

The sound pressure level in the ith 1/3-octave-band $(L_b^{(i)})$ is computed from the power spectrum $S(f)$ between f_{lo} and f_{hi}:

$$L_b^{(i)} = 10\log_{10}\left(\int_{f_{lo}}^{f_{hi}} S(f)df\right) \tag{B-7}$$

Summing the sound pressure level of all the 1/3-octave-bands yields the broadband sound pressure level:

$$\text{Broadband SPL} = 10\log_{10}\sum_i 10^{L_b^{(i)}/10} \tag{B-8}$$

Figure B-2 shows an example of how the 1/3-octave-band sound pressure levels compare to the power spectrum of an ambient noise signal. Because the 1/3-octave-bands are wider with increasing frequency, the 1/3-octave-band SPL is higher than the power spectrum, especially at higher frequencies. Acoustic modelling of 1/3-octave-bands require less computation time than 1 Hz bands and still resolves the frequency-dependence of the sound source and the propagation environment.

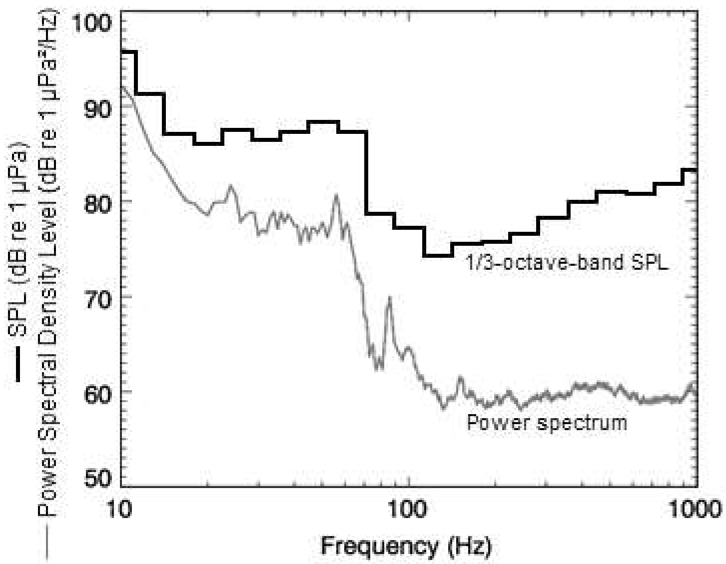

Figure B-2. A power spectrum and the corresponding 1/3-octave-band sound pressure levels of example ambient noise shown on a logarithmic frequency scale.

A.3. Vessel Sounds and Source Levels

Underwater sound that radiates from vessels is produced mainly by propeller and thruster cavitation, with a smaller fraction of noise produced by sound transmitted through the hull, such as from engines, gearing, and other mechanical systems. Sound levels tend to be the highest when thrusters are used to position a vessel and when a vessel is transiting at high speeds. A vessel's sound signature depends on the vessel's size, power output, propulsion system (e.g., conventional propellers vs. Voith Schneider propulsion), and the design characteristics of the given system (e.g., blade shape and size). Sounds produced by vessels are broadband with most of the sound energy emitted below a few kilohertz. Sound from onboard machinery, particularly sound below 200 Hz, dominates the sound spectrum at slower speeds before cavitation begins—normally around 8–12 knots for many commercial vessels (Spence et al. 2007). Noise from vessels typically raises the background sound level by 10 dB or more (Arveson and Vendittis 2000).

A.3.1. Cavitation Noise

The term cavitation refers to streams of vapour bubbles that form on the surface of marine propellers when the vessel is moving quickly. Cavitation bubbles make a lot of underwater noise when they collapse in the vessel's wake. Cavitation occurs when the propeller tip speed exceeds a certain onset threshold, which depends on the propeller design and wake field. Generally, the onset of cavitation is between 8–12 knots, although it may occur at even lower vessel speeds for heavily loaded propellers (Spence et al. 2007). The lowest speed cavitation occurs at is known as the Cavitation Inception Speed (CIS).

Cavitation noise is very broadband (5 Hz to 100 kHz) and may therefore be of important when considering effects on SRKWs, which have their best hearing at frequencies above 10 kHz. The spectrum of cavitation noise typically has a peak between 40−300 Hz and a steady −6 dB/decade roll-off at higher frequencies (Ross 1976). Cavitation noise increases rapidly with vessel speed: the difference between cavitation onset and full cavitation may be up to 30 dB (Spence et al. 2007). Cavitation also results in the phenomenon of blade-rate tonals, which are strong, low-frequency tones appearing at harmonics of the blade-passing frequency (Arveson and Vendittis 2000). Most control treatments for propulsion noise are therefore concerned with delaying the onset of cavitation.

A.3.2. Vessel Source Levels from the ECHO ULS

Vessel source levels for 10 of the 14 vessel classes were obtained from a previous JASCO study by MacGillivray et al. (2018). They reported average source level spectra by vessel class based on measurements from the ECHO Underwater Listening Station (ULS). From September 2015 to April 2018, this ULS measured vessel noise emissions (i.e., source levels) in the Strait of Georgia, as part of the Enhancing Cetacean Habitat Observations (ECHO) program. The ULS was situated in the inbound shipping lane, on the VENUS East Node (Figure B-3), a collaboration between JASCO. Vancouver Fraser Port Authority and Ocean Networks Canada. It captured noise emissions from merchant vessels bound for the Port of Vancouver, as well as ferry traffic along several passenger and cargo routes. Automated processing of vessel source levels had been performed by JASCO's ShipSound software, which used AIS data to detect when vessels transited through the measurement funnel of the ULS. Valid vessel tracks, as selected by the automated system, were used for the vessel source level analysis, which conformed approximately to the ANSI standard for ship sound measurements (ANSI/ASA S12.64/Part 1 2009).

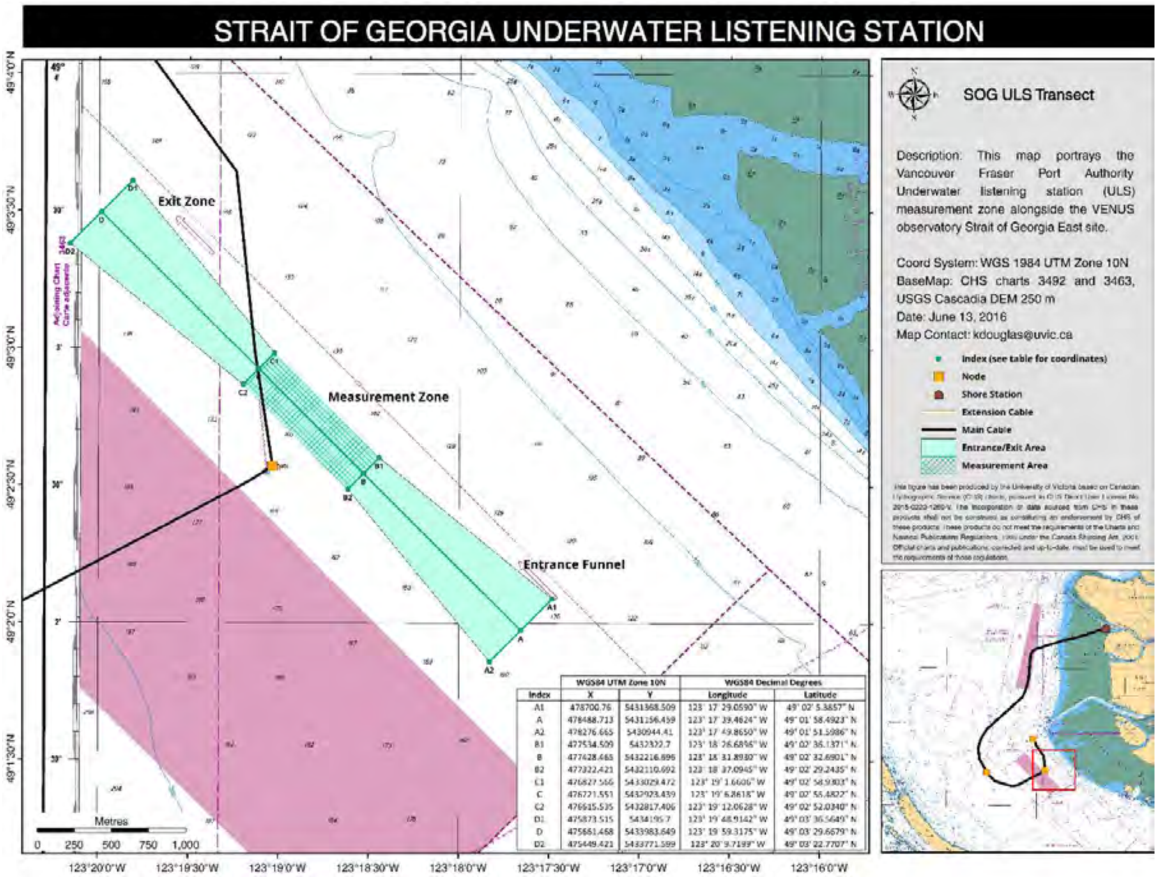

Figure B-3. Underwater Listening Station (ULS) location (yellow circle) at the VENUS East Node in Georgia Strait. Pilots use the measurement funnel (cyan) to ensure vessel source level measurements are accurate. Figure reproduced from MacGillivray et al. (2018).

MacGillivray et al. (2018) assigned the source level measurements from the ULS to ten different classes, according to vessel class information embedded in the AIS logs. They then calculated average frequency-dependent source levels for each class. Their analysis included over 2700 unique measurements from the Strait of Georgia ULS (Table B-1).

For the current study, we used these source levels to represent noise emissions of corresponding vessels in the cumulative noise model. For each vessel class, we compiled the average source levels (i.e., monopole source levels; MSL) in 1/3-octave frequency bands, which spanned from 10 Hz to 31 kHz. We then extrapolated these source levels to 63.1 kHz to cover the frequency range over which noise emissions from vessels overlap the hearing sensitivity of the marine mammals and fish inside the study area. The extrapolation was done based on the terminal slope of the 1/3-octave-band level curves. The resulting average source level for each vessel class is presented in Figure 4 in Section 2.3.

Table B-1. Number of measurements used by MacGillivray et al. (2018) to calculate mean (power average) source levels for each vessel class represented in the ULS data. The Merchant category includes both Bulk Carriers and General Cargo. The Government category includes Navy and Research vessels. Ferries measurements were grouped before averaging to properly account for repeat vessel passes.

Category	Measurements	Unique vessels
Container	233	118
Cruise ship	17	11
Ferry (Ro-ro Passenger)	1505	8
Ferry (Ro-ro Cargo)	134	3
Fishing	23	20
Government	6	5
Merchant	464	445
Tanker	86	50
Tug	206	67
Vehicle carrier	31	28
Total	**2705**	**755**

A.3.3. Vessel Source Levels from Other Sources

Source levels for four additional vessel classes not covered by the ULS data (Ecotourism (whale watching vessels); Passenger (<100 m in length); Recreational and Sailing, and Other/Miscellaneous) and were obtained from other sources. The source levels associated with the Recreational and Sailing, and Other/Miscellaneous vessel classes were based on a prior review of published vessel measurements carried out for the Roberts Bank Terminal 2 cumulative modelling assessment (MacGillivray et al. 2014). The source levels for vessels in the Passenger (<100 m) and Ecotourism classes (mainly whale watching vessels) were based on spectra presented by Erbe (2002), Wladichuk et al. (2018), and Wladichuk et al. (2019).

A.4. Environmental Parameters

Sound propagation models incorporate the sound speed profile of the seawater, which describes how the speed of sound varies with depth in the water column. Sound speed profiles are calculated from temperature and salinity profiles, which change over the seasons.

The water column sound speed profiles for the study area for July were computed from historical temperature and salinity data (MacGillivray et al. 2014). Solar heating in summer increases the surface water temperature, which increases the sound speed at the top of the water column and, therefore, redirects sound toward the seafloor. The computed sound speed profiles did not vary significantly with geographical location, so a single sound speed profile was assumed for both study areas for the month of July (Figure B-4).

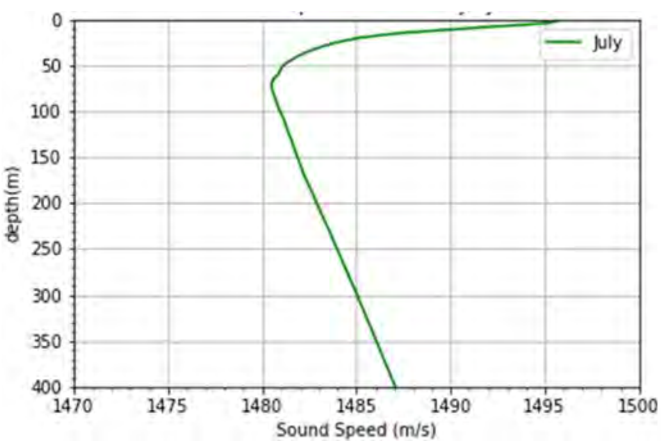

Figure B-4. Sound speed profile for July, used for modelling in both study areas in the Salish Sea.

The bathymetry (i.e., water depth contours) inside the study areas was compiled from the following sources:

1. NOAA digital elevation model (NGDC 2013) for data south of latitude 49°N.
2. Canadian Hydrographic Service digital elevation map from Nautical Data International Inc. for data north of latitude 49°N.

The water depths in the study areas range from 0 to 370 m.

The geoacoustic properties of the seabed strongly influence how sound travels through the water over long distances. Reflection and absorption of sound energy at the seabed is the dominant mechanism by which sound is attenuated in shallow water (Urick 1983). The seabed geoacoustic properties for the study area were adapted from MacGillivray et al. (2014), who divided the Salish Sea into 20 zones (Figure B-5) based on four unique geoacoustic regions (Figure B-6**)** and five water depth ranges. For the two regions of interest, Pender Island and Saturna Island, we selected the appropriate zones (Table B-2) to conduct propagation loss estimates (see Appendix A.5.1). We accounted for geographic variation in the southern Gulf Island region by dividing it into four geoacoustic regions of similar bottom types; a different set of geoacoustic properties was used to represent each region (Table B-3).

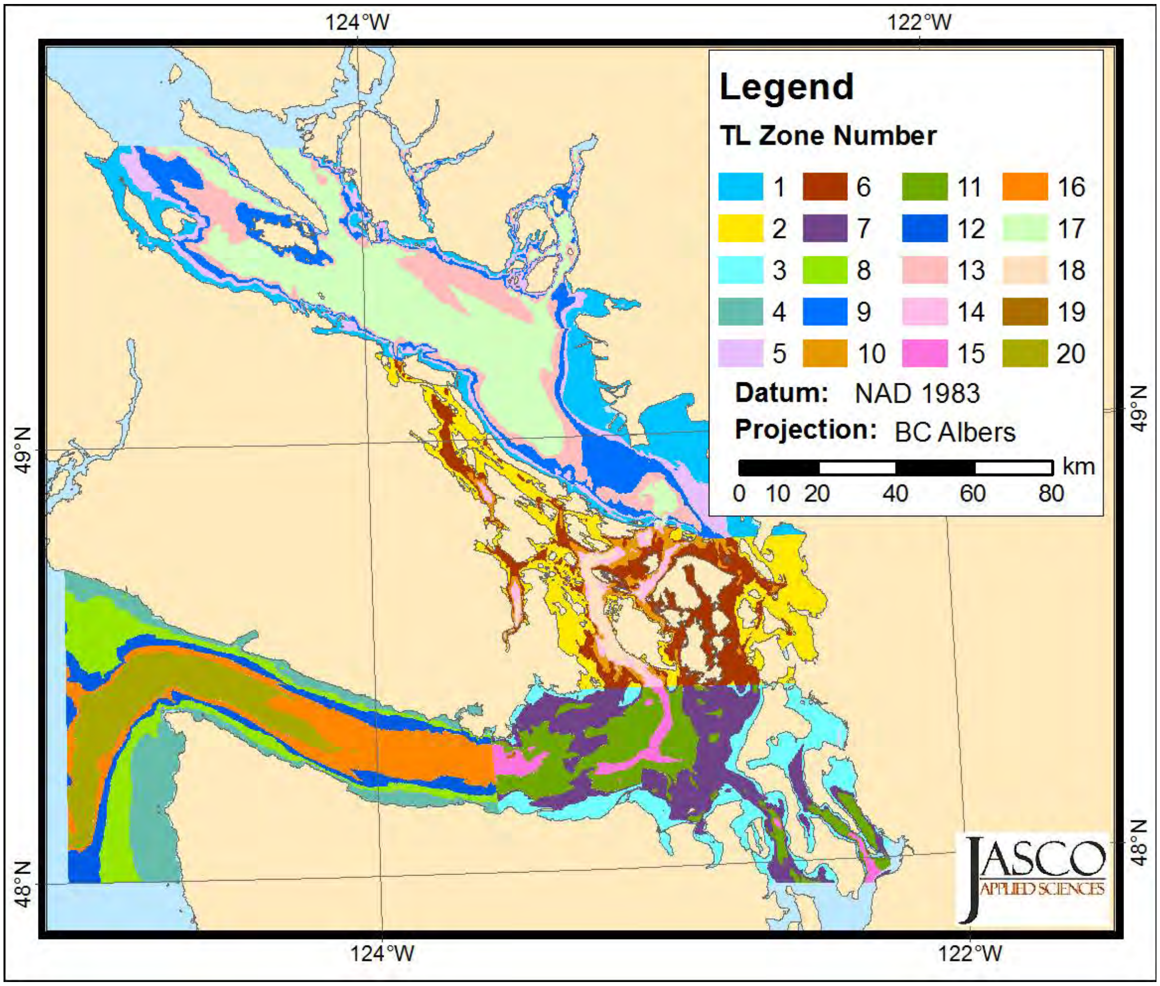

Figure B-5. Map of the 20 propagation loss (equivalent to transmission loss; TL), zones used by MacGillivray et al. (2014) to model sound propagation in the southern Gulf Islands. The current study used a subset of these zones to model sound in the regions surrounding the Saturna and Pender Island Interim Sanctuary Zones.

Table B-2. Geoacoustics regions and propagation loss (or transmission loss; TL) zones used for each water depth range in the study areas. The properties of each geoacoustic region are listed in Table B-3; the TL zones are shown in Figure B-5.

Study area	Geoacoustic region	Water depth range (m)	Modelled water depth (m)	TL Zone
Saturna Island (northern portion)	Strait of Georgia	0–50	25	1
		50–100	75	5
		100–150	125	9
		150–200	175	13
		>200	225	17
Saturn Island (southern portion) Pender Island	Haro Strait and Rosario Strait	0–50	25	2
		50–100	75	6
		100–150	125	10
		150–200	175	14
		>200	225	18

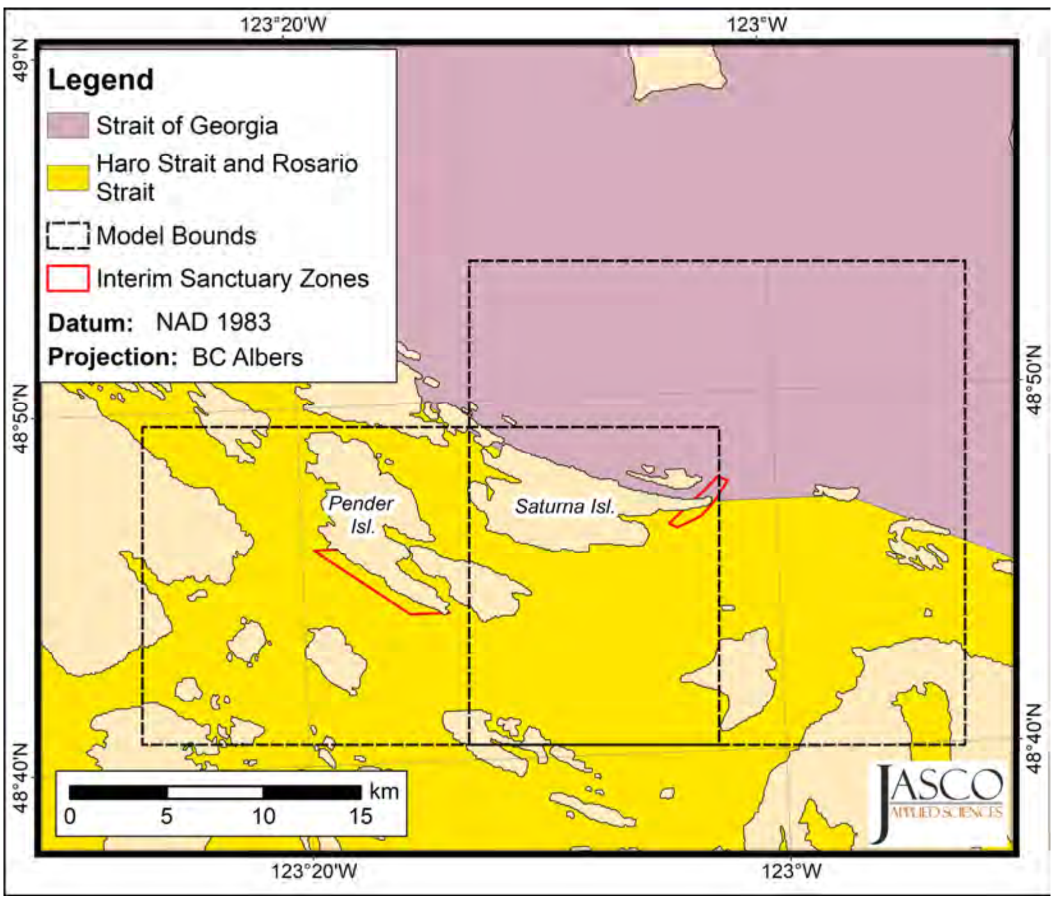

Figure B-6. Map of geoacoustic regions used to represent the study areas in the sound propagation models.

Table B-3. Seabed geoacoustic profiles for the geoacoustic regions of interest. Within each depth range, the compressional speed varies linearly within the stated range of speeds.

Depth below seafloor (m)	**Sediment type**	**Compressional speed** (m/s)	**Density** (g/cm^3)	**Compressional attenuation** (dB per wavelength)	**Shear speed** (m/s)	**Shear attenuation** (dB per wavelength)
Strait of Georgia						
0–100	Clayey-silt	1502–1602	1.54	0.61	125.0	2.2
>100	Bedrock	2275	1.90	0.10		
Haro Strait and Rosario Strait						
0–50	Sand-silt-clay	1541–1591	1.80	0.72	250	1.2
>50	Bedrock	2275	1.90	0.10		

A.5. Sound Propagation Models

A.5.1. Propagation Loss Model

The propagation of sound through the environment was modelled by predicting the acoustic propagation loss (also known as transmission loss)—a measure, in decibels, of the decrease in sound level between a source and a receiver some distance away. Propagation loss occurs predominantly from geometric spreading of the acoustic waves as they expand, moving outward from the source; additional loss mechanisms arise from the sound being absorbed and scattered by the seawater as well as absorbed, scattered, and reflected at the water surface and within the seabed. Therefore, the propagation loss depends on the acoustic properties of both the ocean water and the seabed, and it is frequency dependent.

If the acoustic source level (SL), expressed in dB re 1 µPa @ 1 m, and propagation loss (PL), in units of dB, at a given frequency are known, then the received level (RL) at a receiver location can be calculated in dB re 1 µPa @ 1 m by:

$$RL = SL - PL \qquad \text{(B-9)}$$

Propagation loss was calculated using JASCO's Marine Operations Noise Model (MONM). MONM computes acoustic propagation via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for elastic seabed properties (Zhang and Tindle 1995). The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996).

MONM incorporates the following site-specific environmental properties: a bathymetric grid of the model area; underwater sound speed as a function of depth; and a geoacoustic profile based on the overall stratified composition of the seafloor. Measurements obtained from dedicated propagation loss studies are used to validate MONM predictions (see e.g. JASCO Applied Sciences 2015).

MONM was used to compute curves of propagation loss compared to range for each zone in 1/3-octave-bands between 10 Hz and 63 kHz, out to a maximum distance of 30 km from the source (Figure B-7). Propagation loss for each zone of interest was modelled assuming uniform bathymetry (i.e., range-independent water depth) for a receiver depth of 10 m. At high frequencies, mean propagation loss computed by MONM is expected to converge to a high frequency (i.e., ray-theoretical) limit; therefore, propagation loss values for bands above 5 kHz are approximated by adjusting propagation loss at 5 kHz to account for frequency-dependent absorption at higher frequencies (François and Garrison 1982a, 1982b).

For each zone, propagation loss was modelled using the single sound speed profile for July (see Figure B-4), and six source depths (1 to 6 m, in 1 m steps), representing the nominal acoustic emission centres of small and large draft vessels. Figure B-7 presents plots that help visualizing how the modelled propagation loss varies by distance from the source and frequency, as well as with zones and seasons.

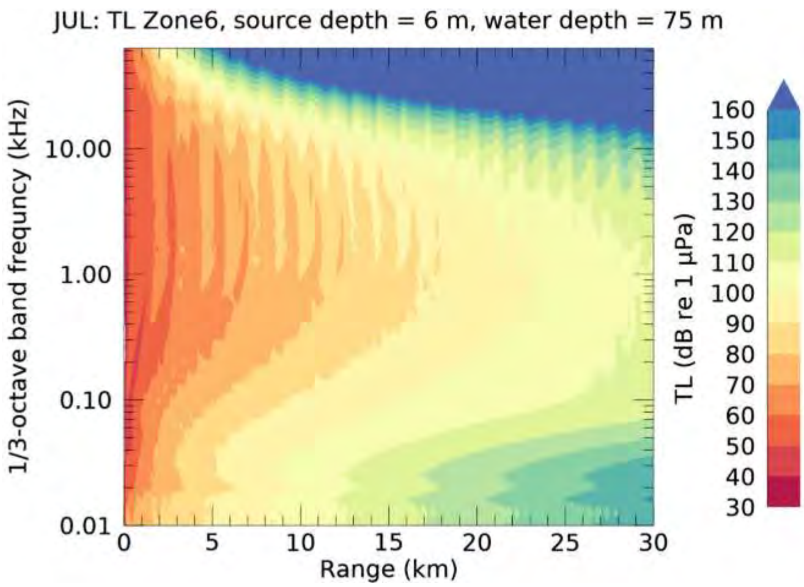

Figure B-7. Example plot of modelled propagation loss (or transmission loss; TL) for a source at 6 m depth and a receiver at 10 m depth, as a function of distance from the source and sound frequency.

A.5.2. Cumulative Noise Model

The total noise from multiple vessels was modelled with JASCO's cumulative noise model (MacGillivray et al. 2014, Joy et al. 2019). It considers a given model area as square cells within which vessels are located. Each cell contains information about the density of vessels, the vessel speeds, and the time they spent in each cell.

To compute propagation loss between pairs of cells, geometric rays were projected from each cell where the density for a given vessel class was non-zero (the source cell) to all nearby cells (the receiver cells) not blocked by land within maximum propagation range. The 1/3-octave-band propagation loss between source and receiver cells was then interpolated from the tabulated propagation loss vs. range curves, based on the midpoint separation of the cells and on the propagation loss zone traversed by the ray. For the range-dependent case, where the ray between a source cell *i* and a receiver cell *j* traverses more than one zone, the propagation loss was computed as the weighted-average value:

$$PL_{ij} = -10\,log_{10} \sum_n 10^{-PL^{(n)}(r_{ij})/10} \times d_n/r_{ij}\ . \qquad \text{(B-10)}$$

In the above equation, r_{ij} is the source-receiver separation, $PL^{(n)}$ is the tabulated propagation loss in zone *n*, and d_n is the distance traversed by the ray in zone *n*. For the special case where the source and receiver cell are identical, propagation loss was estimated by assuming that the sound power radiated by all sources in a cell is distributed evenly over the cell's area, resulting in a horizontally uniform sound field. For a square cell of size *D*, this assumption results in the following expression:

$$PL_{ii} = 10\,log_{10}(\,4\pi/D^2) = 20\,log_{10}\,D - 11. \qquad \text{(B-11)}$$

For an 800 m square cell, the corresponding PL_{ii} value is 47.1 dB.

The total ship noise energy transmitted from each source cell *i* to receiver cell *j* was computed using the source level and corresponding cell-to-cell propagation loss values summed over all vessel categories and adjusted for vessel speed and cumulative vessel class time in each source cell:

$$E_{ij} = \sum_k 10^{(SL_k - PL_{ij})/10} \times \left(\frac{v_k}{v_{ref}}\right)^{C_{v,k}} \times T_k \, . \quad \text{(B-12)}$$

In the above equation, the source level for each vessel class *k* is computed by adjusting the reference source level SL_k for speed v_k according to the power-law model (Ross 1976). The power of the ratio of speeds, $C_{v,k}$, depends on the modelled vessel class. The source energy is then computed by multiplying the source power by the cumulative time T_k that vessels from class *k* occupied the source cell. The total SEL in the receiver cell *j* was then computed as the sum of the sound energy transmitted from all cells with vessels within maximum propagation range:

$$SEL_j = 10 \log_{10}\left(\sum_j E_j\right) . \quad \text{(B-13)}$$

The mean monthly equivalent continuous noise level (L_{eq}) was equal to the total noise energy in all 1/3-octave-bands, divided by the number of seconds in the month, T_{mon}, that is:

$$L_{eq} = SEL - 10 \log_{10}(T_{mon}) . \quad \text{(B-14)}$$

A.6. Marine Mammal Frequency Weighting

The potential for noise to affect animals depends on how well the animals can hear it. Noises are less likely to disturb or injure an animal if they are at frequencies that the animal cannot hear well. An exception occurs when the sound pressure is so high that it can physically injure an animal by non-auditory means (i.e., barotrauma). For sound levels below such extremes, the importance of sound components at particular frequencies can be scaled by frequency weighting that is relevant to an animal's sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

A.6.1. SRKW Audiogram-Weighting

Audiograms represent the hearing threshold for tonal sounds (i.e., single-frequency sinusoidal signals) as a function of the tone frequency. These species-unique sensitivity curves are generally U-shaped, with higher hearing thresholds at low and high frequencies. Noise levels above hearing threshold are calculated by subtracting species-unique audiograms from the received 1/3-octave-band noise levels. The audiogram-weighted 1/3-octave-band levels are summed to yield broadband noise levels relative to each species' hearing threshold. Audiogram-weighted levels are expressed in units of dB re HT, which is the decibel (dB) level of sound above hearing threshold (HT). Sound levels less than 0 dB re HT are below the typical hearing threshold for a species and are likely inaudible to those animals.

SRKW use sound actively when foraging to echolocate their prey. The echolocation signals range in frequency from 15 and 100 kHz (Au et al. 2004). SRKW also produce communication calls when foraging. Groups can spread out over several kilometres while foraging, but the area they cover is limited by the distance where they can detect calls. Calls typically range in frequency from 500 Hz to 40 kHz (Miller 2006). Although substantially louder below 1 kHz, ship noise reaches above 60 kHz. Thus, shipping noise may determine the distance between SRKW while foraging.

The SRKW audiogram used in this study is presented in Figure B-8. Based on values from Szymanski et al. (1999) and Branstetter et al. (2017), it was extrapolated from the lowest measured frequency down to 10 Hz using a 12 dB/octave slope, which represents the hearing roll-off toward the infrasound range for mammals (Marquardt et al. 2007). Although the validity of the extrapolation for marine mammals is not physiologically confirmed, it is likely that these animals have a higher hearing threshold at frequencies outside their hearing range than the terminal trend of their audiogram predicts.

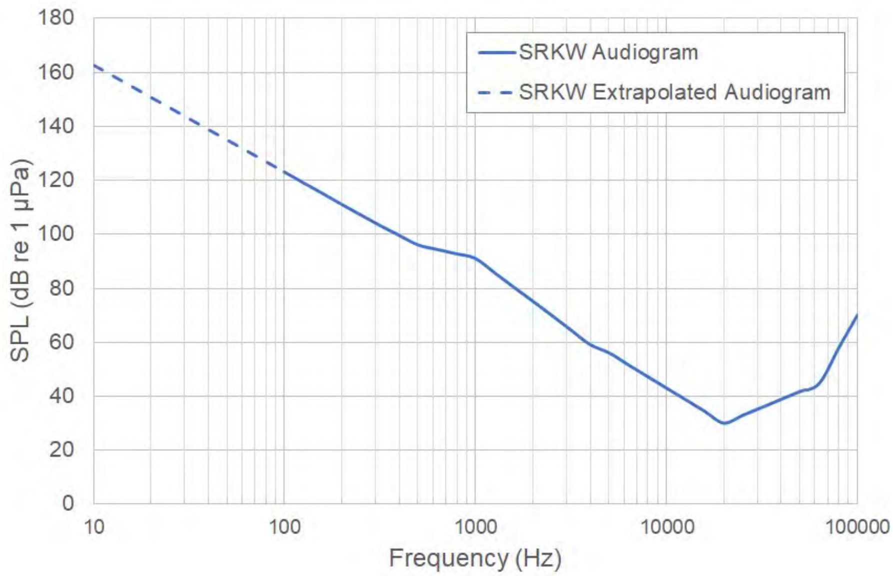

Figure B-8. Southern Resident Killer Whale (SRKW) audiogram used for this study, based on Szymanski et al. (1999) and Branstetter et al. (2017). The dashed curve is extrapolated low-frequency threshold.

APPENDIX B. AIS VESSEL CLASS ASSIGNMENTS

Table B-1 shows how vessel type codes from the Marine Traffic AIS dataset (Vessel type) were assigned to the vessel classes in the cumulative noise model. Note that roll-on/roll-off vessels in the Seaspan Ferries fleet were manually assigned to the Ferry category. Sailing vessels were included in the model and assumed to be under power.

Table B-1. Assignment of vessel type from the Marine Traffic AIS dataset to the vessel classes used for modelling.

Assigned vessel class	AIS vessel type code
Container	Cargo/containership
	Container ship
Cruise Ship	Passenger
	Passenger Ship
	Inland, Passenger Ship, Ferry, Cruise ship
Ferry	Ro-Ro/Passenger ship
	Seaspan Ro-Ro
Fishing	Factory trawler
	Fish carrier
	Fish factory
	Fishing
	Fishing vessel
	Trawler
Government	Buoy-Laying Vessel
	Fire Fighting Vessel
	Fishery Patrol Vessel
	Fishery Research Vessel
	Government
	Inland, Service Vessel, Police Patrol
	Law Enforce
	Logistics Naval Vessel
	Military Ops
	Patrol Vessel
	Replenishment Vessel
	Research/Survey Vessel
	SAR
	Special Vessel

Assigned vessel class	AIS vessel type code
Miscellaneous	Air Cushion Patrol Vessel
	Anti-Pollution
	Buoy-Laying Vessel
	Cable Layer
	Dive Vessel
	Dredger
	Drill Ship
	High Speed Craft
	Hopper Dredger
	Icebreaker
	Inland, Unknown
	Local Vessel
	NULL
	Other
	Pilot Vessel
	Port Tender
	Reefer
	Reserved
	Special Craft
	Suction Dredger
	Tender
	Tender
	Unspecified
	Unspecified
	Utility Vessel
	Wing In Grnd

Table B-1 (cont'd). Assignment of vessel type from the Marine Traffic AIS dataset to the vessel classes used for modelling.

Assigned vessel class	AIS vessel type code
Merchant	Bulk Carrier
	Cargo
	Cargo - Hazard A (Major)
	Chemical Tanker
	General Cargo
	Heavy Lift Vessel
	Heavy Load Carrier
	Inland Ro-Ro Cargo Ship
	LPG Tanker
	Rail/Vehicles Carrier
	Reefer
	Ro-Ro/Container Carrier
	Self Discharging Bulk Carrier
	Timber Carrier
	Wood Chips Carrier
Passenger	Passenger
	Passengers ship

Assigned vessel class	AIS vessel type code
Recreational	Pleasure craft
	Yacht
Tanker	Crude oil tanker
	Oil products tanker
	Oil/Chemical tanker
	Tanker
Tug	Anchor Handling Vessel
	Articulated Pusher Tug
	Multi Purpose Offshore Vessel
	Offshore Supply Ship
	Pusher Tug
	Towing Vessel
	Tug
	Pollution Control Vessel
	Seaspan Tug
	Tug/Supply Vessel
Vehicles Carrier	Vehicles Carrier
	Ro-Ro Cargo