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Modelling Underwater Sound from Small Vessels in Southern Resident Killer Whale Critical Habitat

Noise Reductions for Increased Approach Distances of 400, 600, 800, and 1000 m and Changes in Listening Distances

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16. Abstract

A noise assessment was performed to evaluate the effects of increasing Southern Resident killer whale (SRKW) minimum vessel approach distances from the historic 200 m to the present 400 m and to longer potential distances. The acoustic model estimated the following average broadband reductions across all the scenarios investigated:

- 3.5 dB when increasing the approach distance from 200 to 400 m,
- 6.1 dB when increasing the approach distance from 200 to 600 m,
- 7.5 dB when increasing the approach distance from 200 to 800 m, and
- 9.7 dB when increasing the approach distance from 200 to 1000 m.

The model also predicted the listening distance could increase between approximately 55 and 140% in the SRKW communication frequency band and between 40 and 80% in the SRKW echolocation band by increasing the vessel approach distance from 200 to 400 m.

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16. Résumé

On a procédé à une évaluation du bruit afin de mesurer les effets de l'augmentation des distances minimales d'approche des navires pour les épaulards résidents du Sud, qui passeraient de 200 m (valeur historique) à 400 m (valeur actuelle) et à des distances potentielles plus longues. Le modèle acoustique a estimé les réductions moyennes suivantes de la bande passante pour tous les scénarios étudiés :

- 3,5 dB lorsque la distance d'approche passe de 200 à 400 m,
- 6,1 dB lorsque la distance d'approche passe de 200 à 600 m,
- 7,5 dB lorsque la distance d'approche passe de 200 à 800 m, et
- 9,7 dB lorsque la distance d'approche passe de 200 à 1000 m.

Le modèle a également prédit que la distance d'écoute pourrait augmenter d'environ 55 à 140 % dans la bande de fréquence de communication des épaulards résidents du Sud et de 40 à 80 % dans la bande d'écholocation des épaulards résidents du Sud en augmentant la distance d'approche des navires de 200 à 400 m.

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EXECUTIVE SUMMARY

Underwater noise from vessels has been identified as a contributing threat to the recovery of Southern Resident killer whales (SRKWs) (DFO 2018). As part of a coordinated effort to reduce the impact, the Government of Canada increased the whale-watching vessel approach distance from 200 to 400 m for SRKW in 2019 (Government of Canada 2020).This modelling study was conducted by JASCO Applied Sciences for Transport Canada to determine the changes in noise levels by implementing the 400 m stand-off distance. Longer potential distances of 600, 800, and 1000 m were also assessed using the same approach.

Noise levels for three vessel densities (10, 17, and 27 vessels) were assessed at three locations within the SRKW critical habitat in the Salish Sea, where killer whales could be subjected to commercial and recreational whale-watching vessel noise. Various vessel types were incorporated in the modelled assessment using underwater acoustic source levels derived from local systematic field measurements of several whale watch vessel types (Wladichuk et al. 2018) with the participation of the Pacific Whale Watch Association (PWWA). Median source levels for each vessel class (small and large commercial whale-watching, recreational, and small fishing vessels) travelling at speeds less than 7 knots, in accordance with the *Be Whale Wise* guidelines (BeWhaleWise.org 2019), were used in the model.

Changes in received noise levels at simulated whale positions at two depths (10 and 60 m), which represent travelling and foraging depths, were examined in the broadband (8.9 Hz to 64 kHz) frequency range as well as the listening distance in the SRKW communication (500 Hz to 14.1 kHz) and echolocation (14.1 to 64 kHz) bands. Listening distance is a fairly new concept that examines the relative reduction in the distance that a listener can detect an important sound when masking noise levels increase (Pine et al. 2018, Terhune and Killorn 2021). It also accounts for the absolute hearing sensitivity of the listener. Here we investigated the changes in listening distance when increasing the approach distance from 200 to 400 m, as well as for longer distances. We also calculated the listening distance changes due to whale watch vessel presence at the different approach distances relative to ambient noise conditions. Here the ambient noise was represented by the median noise levels in Boundary Pass.

There was a greater reduction in broadband levels when increasing the approach distance from 200 to 400 m at the deeper site (Haro Strait). However, there were minimal noise reductions when increasing from 600 to 800 m (for both receiver depths and all vessel densities). At the shallower sites (Swanson Channel and Race Rocks), there was a near-linear reduction in noise with increase in approach distance. The average broadband reductions across all the scenarios for the following approach distances were:

- 3.5 dB when increasing from 200 to 400 m,
- 6.1 dB when increasing from 200 to 600 m,
- 7.5 dB when increasing from 200 to 800 m, and
- 9.7 dB when increasing from 200 to 1000 m.

The ambient levels used here are from measurements made in Boundary Pass, near the shipping lanes, and are representative of noise levels close to the middle of Haro Strait. In quieter areas within the SRKW critical habitat, we would expect even greater reductions in the killer whales' listening distances when whale-watching vessels are present.

The modelling estimated that by increasing the approach distance from 200 to 400 m, the listening distance could increase between ~55 and ~140% in the SRKW communication frequency band and between 40 and 80% in the SRKW echolocation band. However, we must bear in mind that at 200 m, the listening distance in the communication band is only between 5 and 10% of that relative to ambient noise conditions, and in the echolocation band between 25 and 30% of that relative to ambient conditions.

The modelling also generally predicted greater noise reductions on the deeper (60 m) receiver from increasing the approach distance. Another interesting finding is that the listening distance in the echolocation band was estimated to be less affected than the communication band by vessel presence. This is due partly to reduced vessel source levels at high frequencies for slow speeds but primarily due to higher propagation loss for echolocation returns; echolocation signal propagation loss is approximately twice that in decibels of one-way sound transmission. For some of the scenarios (e.g., 10 and 17 vessels in Haro Strait at the 800 and 1000 m approach distances), the received levels in the echolocation band were comparable to ambient noise levels. However, most scenarios produced noise levels above ambient levels (median noise levels in Boundary Pass).

Lastly, the relative change in listening distance is similar across all vessel densities for each increase in approach distance, except for one scenario (10 m receiver in Haro Strait) where the model predicted greater noise reductions for higher vessel densities.

There were a few constraints of the model, primarily related to vessel specifics—only three different vessel densities (and composition of vessel types within each) were examined. Also, a single source signature was used per vessel type. It was also assumed that the vessels were randomly distributed in a 100-m wide annular area centred on the whales (the listeners). Additionally, the model assumed that vessels maintained a constant slow speed (less than 7 knots), which may not occur in practice. We note the PWWA has agreed to reduce speed to less than 7 knots within 1 km of SRKW. Non-PWWA vessels may not follow that guideline. The model did not consider vessels approaching and departing the whales at higher speeds.

In conclusion, our analysis demonstrated that whale-watching vessel noise can have a substantial impact on the SRKW listening distance in the communication frequency band, in particular, and that by increasing the minimum approach distance and reducing the number of vessels, there could be positive effects on reducing noise levels perceived by the whales.

RÉSUMÉ

Le bruit sous-marin des navires a été déterminé comme une menace pour le rétablissement des épaulards résidents du sud (ERS) (DFO 2018). Dans le cadre d’un effort coordonné pour réduire les répercussions, le gouvernement du Canada a augmenté la distance d’approche des navires d’observation de baleines de 200 à 400 m pour l’ERS en 2019 (Government of Canada 2020). Cette étude de modélisation a été menée par JASCO Applied Sciences pour Transports Canada afin de déterminer les changements dans les niveaux de bruit en appliquant la distance de sécurité de 400 m. Des distances potentielles plus longues de 600, 800 et 1 000 m ont également été évaluées en utilisant la même approche.

Les niveaux de bruit pour trois densités de navires (10, 17 et 27 navires) ont été évalués à trois endroits dans l’habitat essentiel de l’ERS dans la mer des Salish, où les épaulards pourraient être soumis au bruit des navires commerciaux et récréatifs d’observation de baleines. Divers types de navires ont été intégrés à l’évaluation modélisée à l’aide des niveaux de source acoustique sous-marine dérivés de mesures locales systématiques sur le terrain de plusieurs types de navires d’observation de baleines (Wladichuk et al. 2018) avec la participation de la Pacific Whale Watch Association (PWWA). Les niveaux de source médians pour chaque classe de navires (petits et grands navires commerciaux d’observation de baleines, navires de plaisance et petits navires de pêche) voyageant à des vitesses inférieures à 7 nœuds, conformément aux lignes directrices du partenariat *Be Whale Wise*, (BeWhaleWise.org 2019) ont été utilisés dans le modèle.

Les changements dans les niveaux de bruit détectés à des positions simulées de baleines à deux profondeurs (10 et 60 m), qui représentent les profondeurs de déplacement et de recherche de nourriture, ont été examinés dans la gamme de fréquences à large bande (de 8,9 Hz à 64 kHz) ainsi que la distance d’écoute dans la communication de l’ERS (de 500 Hz à 14,1 kHz) et des bandes d’écholocalisation (de 14,1 à 64 kHz). La distance d’écoute est un concept relativement nouveau qui examine la réduction relative de la distance à laquelle un auditeur peut détecter un son important lorsque le masquage des niveaux de bruit augmente (Pine et al. 2018, Terhune and Killorn 2021). Il rend également compte de la sensibilité auditive absolue de l’auditeur. Ici, nous avons étudié les changements de distance d’écoute lors de l’augmentation de la distance d’approche de 200 à 400 m, ainsi que pour des distances plus longues. Nous avons également calculé les changements de distance d’écoute dus à la présence de navires d’observation de baleines aux différentes distances d’approche par rapport aux conditions de bruit ambiant. Ici, le bruit ambiant était représenté par les niveaux de bruit médians dans le passage Boundary.

On a constaté une plus grande réduction des niveaux de large bande en augmentant la distance d’approche de 200 à 400 m sur le site le plus profond (détroit de Haro). Cependant, les réductions de bruit étaient minimes lorsque l’on passait de 600 à 800 m (pour les deux profondeurs de récepteur et toutes les densités de navires). Aux sites moins profonds (chenal Swanson et rochers Race), on a constaté une réduction presque linéaire du bruit avec l’augmentation de la distance d’approche. Les réductions moyennes de la large bande dans tous les scénarios pour les distances d’approche suivantes étaient de :

- 3,5 dB en passant de 200 à 400 m;
- 6,1 dB en passant de 200 à 600 m;
- 7,5 dB en passant de 200 à 800 m;
- 9,7 dB en passant de 200 à 1 000 m.

Les niveaux ambiants utilisés ici proviennent de mesures effectuées au passage Boundary, près des voies de navigation, et sont représentatifs des niveaux de bruit près du milieu du détroit de Haro. Dans les zones plus calmes de l'habitat essentiel de l'ERS, nous nous attendons à des réductions encore plus importantes des distances d'écoute des épaulards lorsque des navires d'observation de baleines sont présents.

La modélisation a permis d'estimer qu'en augmentant la distance d'approche de 200 à 400 m, la distance d'écoute pourrait augmenter de ~55 à ~140 % dans la bande de fréquence de communication de l'ERS et entre 40 et 80 % dans la bande d'écholocalisation de l'ERS. Il faut cependant garder à l'esprit qu'à 200 m, la distance d'écoute dans la bande de communication n'est que de 5 à 10 % de celle relative aux conditions de bruit ambiant, et dans la bande d'écholocalisation de 25 à 30 % de celle relative aux conditions ambiantes.

La modélisation a également généralement prédit de manière générale des réductions de bruit plus importantes sur le récepteur plus profond (60 m) en augmentant la distance d'approche. Un autre résultat intéressant est que la distance d'écoute dans la bande d'écholocalisation a été estimée comme étant moins affectée que la bande de communication par la présence de navires. Cela est dû en partie à la réduction des niveaux de source du navire à des fréquences élevées pour des vitesses lentes, mais surtout à une perte de propagation plus élevée pour les retours d'écholocalisation – la perte de propagation du signal d'écholocalisation est environ deux fois celle en décibels de la transmission sonore unidirectionnelle. Pour certains des scénarios (p. ex., 10 et 17 navires dans le détroit de Haro aux distances d'approche de 800 et 1 000 m), les niveaux détectés dans la bande d'écholocalisation étaient comparables aux niveaux de bruit ambiant. Cependant, la plupart des scénarios ont produit des niveaux de bruit supérieurs aux niveaux ambiants (niveaux de bruit médians dans le passage Boundary).

Enfin, le changement relatif de la distance d'écoute est similaire pour toutes les densités de navires pour chaque augmentation de la distance d'approche, à l'exception d'un scénario (récepteur de 10 m dans le détroit de Haro) où le modèle a prédit des réductions de bruit plus importantes pour des densités de navires plus élevées.

Le modèle comportait quelques contraintes, principalement liées aux spécificités des navires : seules trois densités de navires différentes (et la composition des types de navires au sein de chacune) ont été examinées. De plus, une seule signature de source a été utilisée par type de navire. On a également supposé que les navires étaient répartis de manière aléatoire dans une surface annulaire de 100 m de large centrée sur les baleines (les auditeurs). En outre, le modèle a supposé que les navires maintenaient une vitesse lente constante (moins de 7 nœuds), ce qui peut ne pas se produire hors simulation. Nous notons que la PWWA a accepté de réduire la vitesse de ces navires à moins de 7 nœuds à moins de 1 km de l'ERS. Les navires qui ne sont pas des navires de la PWWA peuvent ne pas suivre cette directive. Le modèle n'a pas pris en compte les navires approchant et s'éloignant des baleines à des vitesses plus élevées.

En conclusion, notre analyse a démontré que le bruit des navires d'observation de baleines peut avoir une incidence importante sur la distance d'écoute de l'ERS dans la bande de fréquences de communication, en particulier, et qu'en augmentant la distance d'approche minimale et en réduisant le nombre de navires, il pourrait y avoir des effets positifs sur la réduction des niveaux de bruit perçus par les baleines.

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1. INTRODUCTION

Acoustic noise from vessels has been identified as a contributing threat to the recovery of Southern Resident killer whales (SRKW) (DFO 2018). While large commercial vessels are often the focus of underwater noise studies, Fisheries and Oceans Canada (DFO) has also identified underwater noise from small vessel traffic as potentially having a negative impact on SRKW. In 2018, the approach distance in the Marine Mammal Regulations was amended to 200 m from 100 m for all killer whales (*Orcinus orca*) in Canadian waters in the Pacific Ocean, and this regulation applies year round (BeWhaleWise.org 2019, Justice Laws 2020). In 2019, the Government of Canada implemented an increased approach distance for killer whales of 400 m from 1 Jun to 31 Oct 2019 in SRKW critical habitat (Government of Canada 2020). Starting June 2020, 400 m approach distance was applied year round in SRKW critical habitat and in an expanded area north of critical habitat identified as being within the SRKW range (DFO 2020). The Government of Canada is currently assessing the underwater noise exposure reduction achieved by implementing this increased approach distance and also for longer distances.

This analysis expands on three previous studies performed by JASCO Applied Sciences Ltd. (JASCO) for DFO and Transport Canada (TC) that considered an approach distance of 200 m (Wladichuk and Hannay 2017, Yurk et al. 2017, Wladichuk 2020). Yurk et al. (2017) modelled source levels from surrogate vessels, whereas Wladichuk and Hannay (2017) and Wladichuk (2020) modelled source levels from local whale watching vessels and other small vessels from field measurements conducted in the Salish Sea.

In this analysis, which applies similar modelling methodology as the previous studies, underwater noise exposure from small vessels was examined at three sites around southern Vancouver Island (Swanson Channel, Haro Strait near Lime Kiln Lighthouse, and Juan de Fuca Strait near Race Rocks) (Figure 3). The sites are within the SRKW critical habitat and represent important feeding and travelling areas (Hauser et al. 2007), as well as being popular whale watching spots (Hauser et al. 2006). A model-based approach for three vessel density scenarios (10, 17, and 27 vessels to represent low, medium, and high number of whale-watching vessels) was used to assess the reduction in underwater noise exposure, as perceived by killer whales, attained by increasing the approach distance to an interim distance of 400 m, as well as additional distances of 600, 800, and 1000 m. To examine absolute impacts on the killer whales, reductions in listening distance in the SRKW communication and echolocation frequency bands relative to ambient noise conditions (the median sound level in Boundary Pass) were also assessed.

1.1. Killer Whale Hearing and Sounds

SRKW produce various vocalizations including pulsed calls, whistles, and echolocation clicks. They use calls to communicate over distances that can extend up to 15 km under very quiet conditions and echolocation clicks to navigate and forage at shorter ranges (Au et al. 2004, Miller 2006). Their hearing sensitivity range is well suited for the sounds generated by members of their own species (Figure 1) and effective for detecting echolocation clicks (Barrett-Lennard et al. 1996). See additional killer whale audiogram information in Appendix A. The frequency ranges of pulsed calls that carry most of the sound energy range from 1–15 kHz, while whistles range from 7–17 kHz (Riesch et al. 2006). Echolocation clicks appear to have a bimodal distribution with a lower-frequency peak between 20 and 30 kHz and a high-frequency peak between 40 and 60 kHz (Au et al. 2004). In this study, vessel source levels were determined over a frequency band up to 64 kHz (limited by sampling rate) to enable assessing the effects on echolocation signals; however, it is noted that killer whale echolocation clicks extend to higher frequencies, but the majority of the energy is below 64 kHz.

Noise from small vessels can prevent whales from hearing vocalization and echolocation signals (i.e., auditory signal masking). The potential adverse effects of elevated noise levels on whales and other marine animals, especially the impact on listening distance, depend partly on the intensity and duration of the noise and partly on how sensitive the animal's hearing is to the frequency content of the noise (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

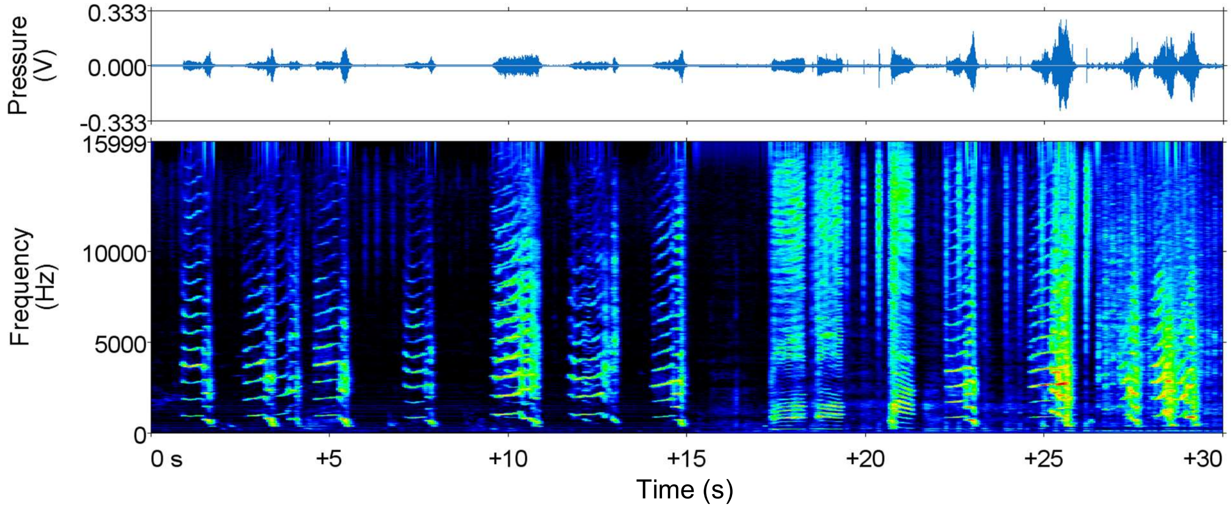


Figure 1. Spectrogram of Southern Resident killer whale (SRKW) calls (horizontal bands/curves) and clicks (vertical lines). The sound frequency changes are depicted over time (sound contours). Sound pressure levels are shown as pressure density in 1 Hz bands and are colour coded: blue and green are low levels, and yellow and red are high levels.

1.2. Critical Habitat of SRKW and Their Relative Habitat Use

The currently designated critical habitat of SRKW includes transboundary waters in southern British Columbia (Figure 2). The area encompasses the southern Strait of Georgia, Haro Strait, Juan de Fuca Strait, and waters surrounding Swiftsure and La Pérouse Banks (the latter was designated in 2018 for SRKWs and Northern Resident killer whales). The modelling sites chosen for this study represent areas of generally higher use by SRKWs, and, as a result, the sites also generally have high rates of whale watching activity.

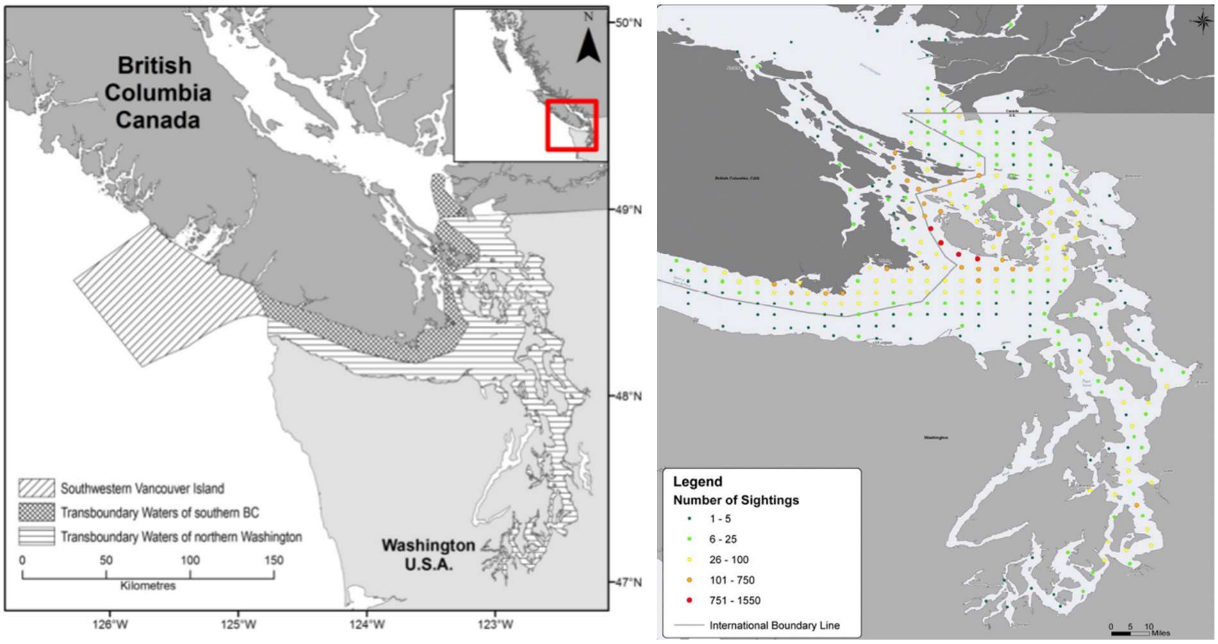


Figure 2. (Left) Critical habitat for Southern Resident killer whales (SRKW) (DFO 2011) and (right) distribution of SRKW sightings from 1990–2005 (Data from The Whale Museum 2005, NMFS 2008).

2. METHODS

2.1. Study Sites

This investigation, similar to the previous studies (Wladichuk and Hannay 2017, Yurk et al. 2017, Wladichuk 2020), modelled underwater vessel noise exposure of SRKW at the following three sites in the Salish Sea (Figure 3), all of which are in SRKW critical habitat:

- Swanson Channel west of North Pender Island
- Haro Strait near the Lime Kiln Lighthouse
- Near Race Rocks Lighthouse in Juan de Fuca Strait.

The geographic locations and water depth for each modelled site are shown in Table 1; water depths are based on bathymetry from the area (see Appendix B.2).

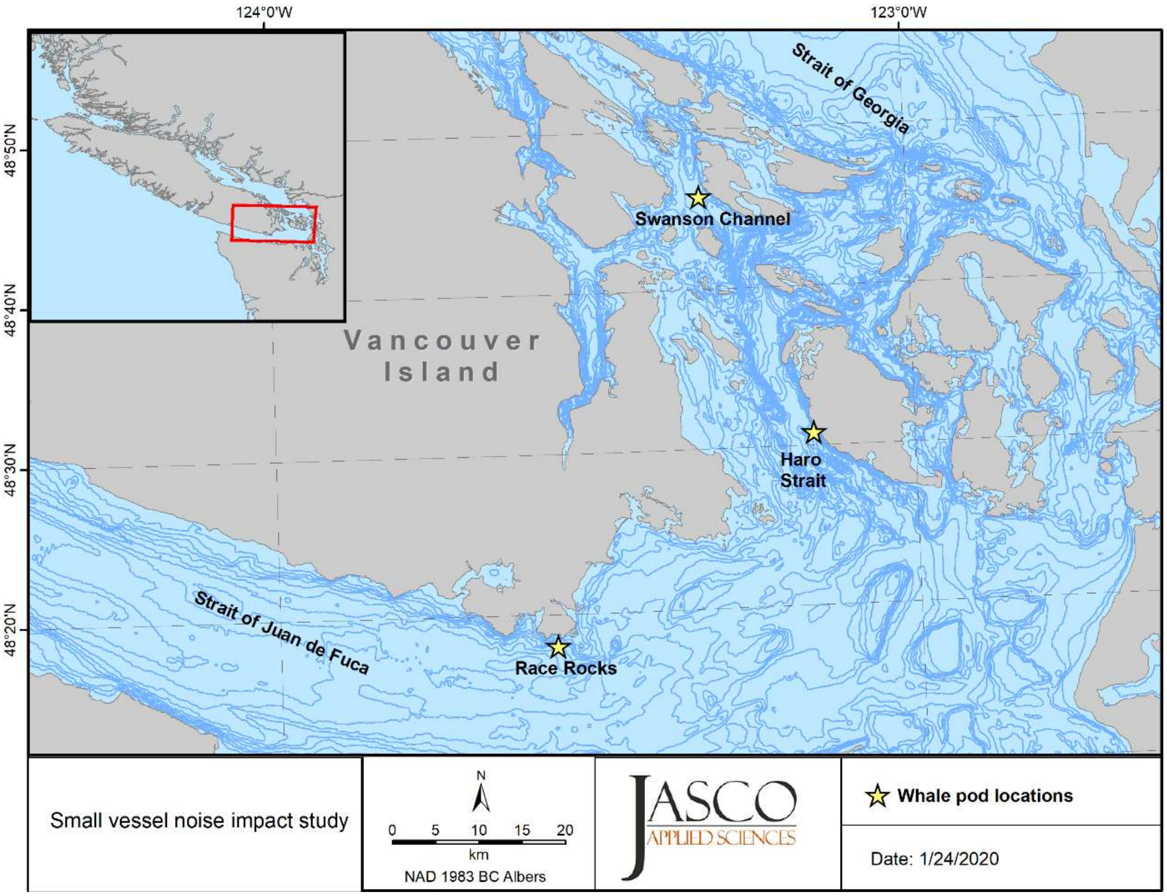


Figure 3. Model sites of killer whale pod locations, all of which are in Southern Resident killer whale (SRKW) critical habitat. Inset shows the study area (red box), which encompasses southern Vancouver Island.

Table 1. Modelled sites with geographic coordinates and water depth. Easting and northing are in UTM Zone 10N. These sites are the same as those used in the previous studies (Wladichuk and Hannay 2017, Yurk et al. 2017, Wladichuk 2020).

Site	Latitude	Longitude	Easting (m)	Northing (m)	Water depth (m)
1-Swanson Channel	48.76° N	123.33° W	476100	5401208	75
2-Haro Strait	48.51° N	123.16° W	488278	5373499	272
3-Race Rocks	48.30° N	123.57° W	457794	5349892	120

2.2. Vessel Noise Modelling

Underwater noise exposures were modelled at the three study sites for the five different approach distances (200, 400, 600, 800, and 1000 m) by distributing simulated vessels in three different configurations (10, 17, and 27 vessels) around a single listener location representing a SRKW pod. Each model scenario was iterated 1000 times in order to calculate an average sound level for various vessel configurations. This study uses the same methodology, described below and as the previous three studies (Wladichuk and Hannay 2017, Yurk et al. 2017, Wladichuk 2020).

The simulated vessels consisted of commonly encountered types of commercial whale watching vessels and pleasure craft (Table 2). Vessel source levels were determined from systematic field measurements of vessels transiting at a range of speeds at the Haro Strait modelling site (Appendix B.3) (Wladichuk et al. 2018). Median source levels (SLs) of each vessel type measured in the field study (Wladichuk et al. 2018) were computed for the slow speed transects, which were for vessel speeds less than 7 knots (the median speed of all vessels was 5 knots). SLs were grouped based on the vessel types identified in the Yurk et al. (2017) modelling study. The modelling assumed that all vessels travelled at slow speeds (<7 knots) in accordance with the marine mammal viewing guidelines.

Table 2. Types of modelled vessels and their characteristics (Yurk et al. 2017, Wladichuk et al. 2018, Wladichuk 2020).

Vessel type	Vessel size	Average length (m)	Source depth (m)	Measured vessels
Whale watching	Small	7.0	0.5	Rigid-hulled inflatable boats (RHIB)
	Large	14.0	1.3	Large monohulls
Pleasure craft	Small	11.0	0.5	Sailboats
	Large	14.5	0.5	Catamarans
Fishing vessel	Small	9.0	1.3	Charter fishing vessels

For each noise exposure scenario, vessels were placed at random positions around the whales inside a 100 m wide area with an inside radius equal to the approach distance (either 400, 600, 800, or 1000 m) and an outer radius 100 m greater (Figure 4). For each approach distance, we modelled three different vessel scenarios at each site, representing 10, 17, and 27 vessels (Table 3).

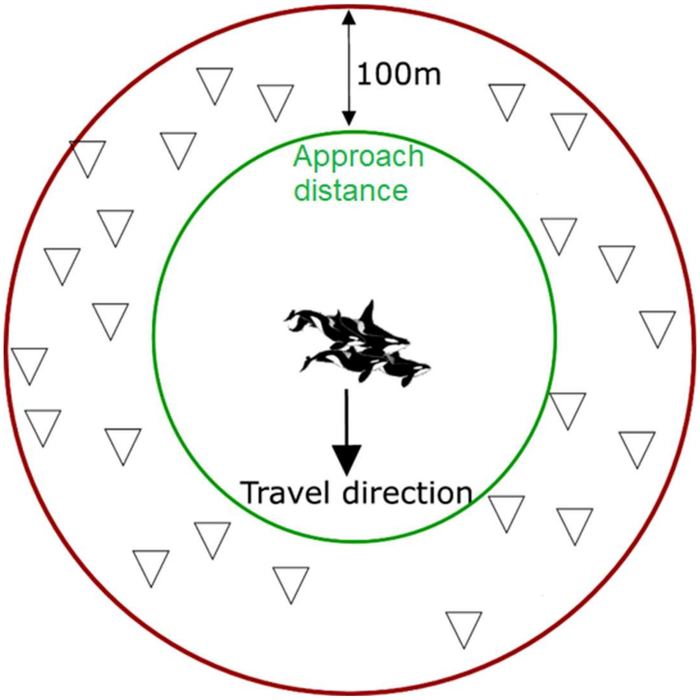


Figure 4. Diagram showing simulated vessel locations (triangles) in relation to a Southern Resident killer whale (SRKW) pod (not to scale). Distances of individual vessels were chosen at random from a uniform distribution between the approach distance (green circle) and 100 m farther from the whales (red circle).

Table 3. Number of simulated vessels of each type for the three scenarios considered at each site. Numbers are based on values provided by Fisheries and Oceans Canada (DFO).

Vessel type	Vessel size	10 Vessels	17 Vessels	27 Vessels
Whale watching	Small	3	4	5
	Large	2	4	7
Pleasure craft	Small	2	4	8
	Large	1	3	5
Fishing vessel	Small	2	2	2

Noise exposures were modelled in terms of sound pressure level (SPL) as received by the whales, in units of decibels (dB), and noise levels at the whales' locations were calculated using JASCO's Marine Operations Noise Model (MONM; see Appendix B.1). The model computed the acoustic field in three dimensions by calculating propagation loss (reduction in sound level with distance from the source) within each modelling area by incorporating the following site-specific environmental properties:

- Bathymetry,
- Water sound speed profile (which affects sound refraction in the water column), and
- Geo-acoustic properties of the seabed (which affect acoustic reflection and refraction in the seabed).

Source levels were then added to the propagation loss to calculate sound levels that would be received at a given location.

Spatial distributions of noise levels for each of the three modelled sites (Swanson Channel, Haro Strait, and Race Rocks; see Figure 3) were calculated for a flat sea bottom with water depths representative of the respective sites as listed in Table 1. Although the model could easily have handled a realistic bathymetry for each site, the flat bottom assumption was made to yield more generally applicable estimates unaffected by localized sea bottom features. The modelling was performed using temperature and salinity profiles representing July conditions, because whale watching activity is most intense in summer. These environmental conditions, along with pressure, affect sound propagation and change very little over the June to September period when most whale-watching and pleasure boating occur.

Noise levels were modelled at two depths, 10 and 60 m, representing a shallower travelling depth and a deeper foraging depth. The foraging depth is between the median foraging depths presented in Wright et al. (2017) and Tennessen et al. (2019). Appendix B provides a detailed description of the acoustic modelling used in this study.

2.3. Calculation of Listening Distance

This study, along with the previous studies (Wladichuk and Hannay 2017, Yurk et al. 2017, Wladichuk 2020), considered the vessel noise emissions in relation to the frequency-dependent hearing acuity of killer whales and the frequency spectrum of the background ambient noise.

We first calculated the received noise level in each frequency band and evaluated it relative to the hearing threshold of killer whales in that band as defined by their audiogram (Appendix A). We then applied a relatively new approach to examine the effects of the noise exposures on the ability of killer whales to use sound for communicating and echolocating/foraging. The approach is referred to as the listening distance (LD) method, which is similar to communication space methods (e.g., Hatch et al. 2012) without being limited to communication calls. This method considers masking from the perspective of the listener and the corresponding change in distance within which the listener can detect audible biologically important sounds (Barber et al. 2010, Matthews et al. 2016, Pine et al. 2018).

The LD method examines relative changes in the distances over which important sounds, such as communication calls and echolocation sounds, can be detected by a listener (here a killer whale) in the presence of differing background noise environments. An important benefit of the LD method is that it does not require knowledge of sound source levels (i.e., the loudness of the original sound of interest when it was produced), listener detection thresholds, or the directionality of received signals. The method only requires knowledge of the hearing sensitivity (audiogram) of the species and the *received* levels of the noise that could potentially mask sounds of interest. The LD method, however, does not yield *absolute* distances over which a sound could be detected; it only provides the *relative change* in detection distance for different signal masking scenarios, e.g., the change of detection distance resulting from changes in distance between listener and noise source. There are also a few assumptions made in this analysis such as, a 1/3-octave band auditory filter shape holds true across the hearing range or recorded frequency range, the fact that animals probably do not spend time at only two depths, and the assumption that vessel sound sources are distributed randomly around the whales.

An animal's ability to detect a sound at a given frequency is limited most fundamentally by the subject's hearing ability in the presence of noise. As a result, a sound whose received level is below the animal's absolute hearing threshold cannot be perceived. For a sound whose received level is above the animal's hearing threshold, detectability is then limited by the background noise of the environment, i.e., the background noise level becomes the ultimate threshold for detectability. The LD method therefore uses a threshold, called the equivalent masking level, that combines the influence of hearing threshold (audiogram) with the background noise level on signal detectability (see Figure 7). The ambient sound levels used to represent the background noise levels are specific to the study location under realistic conditions. Realistic ambient sound levels include sounds resulting from natural sources, such as precipitation, wind, and waves, as well as persistent anthropogenic sources, such as vessels.

The ambient noise levels used for all three sites in this assessment are the 50th percentile (median) levels from July 2020 collected on an Underwater Listening Station (ULS) in Boundary Pass (Figures 5 and 6). The frequency resolved ambient sound level is shown in Figure 7 along with the SRKW hearing threshold-the greater of the two levels in each frequency band is the combined threshold or equivalent masking level.

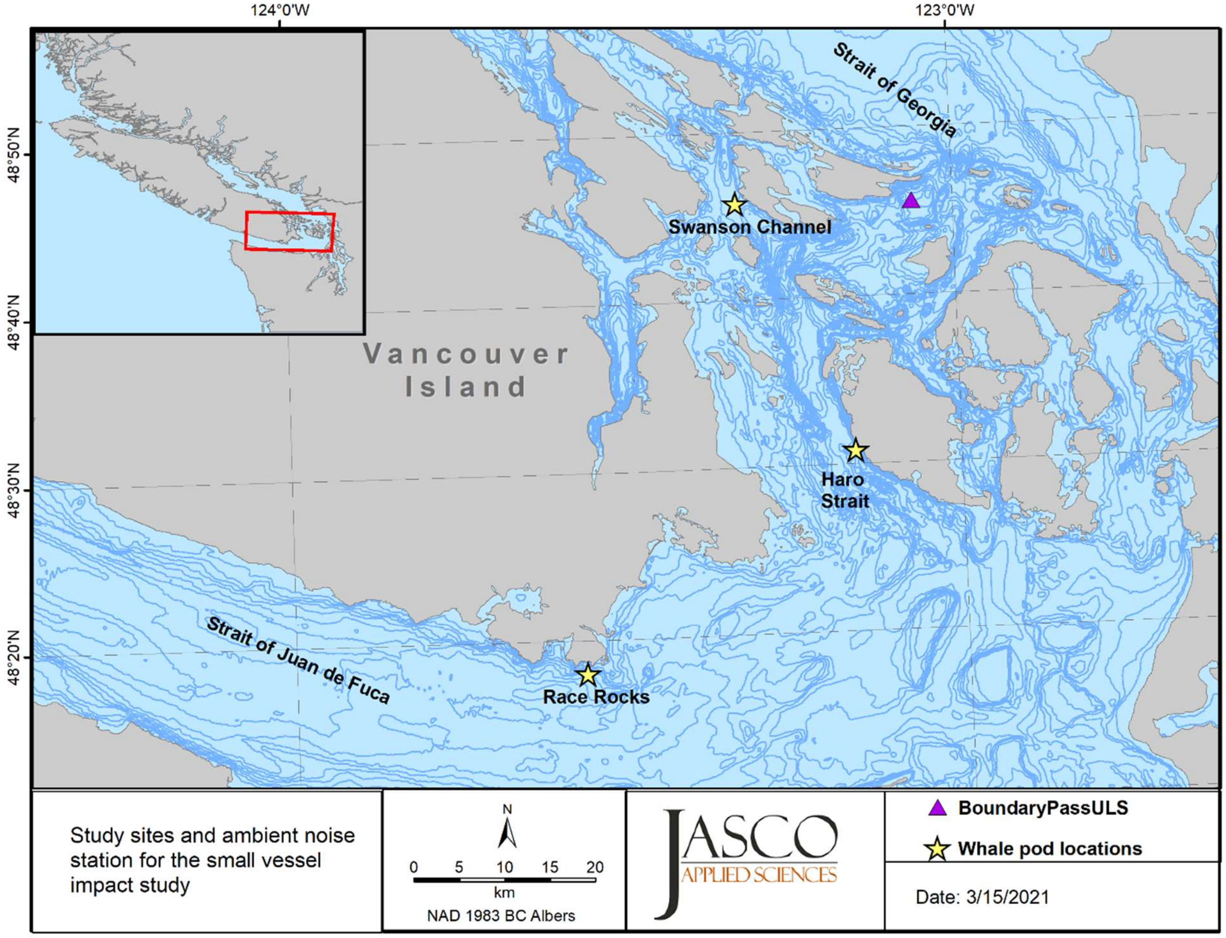


Figure 5. Map of the model sites (yellow stars) and ambient noise station (purple triangle).

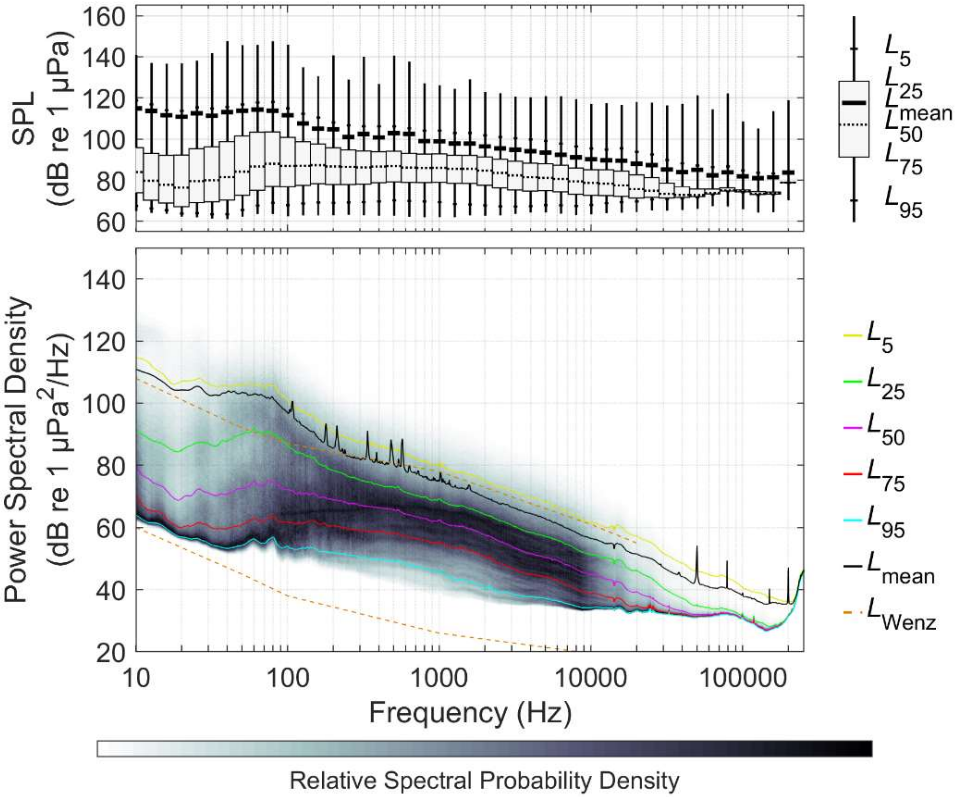


Figure 6. Exceedance percentiles of ambient noise power spectral density (PSD; 1 min average) at the Boundary Pass Underwater Listening Station (ULS) for July 2020.

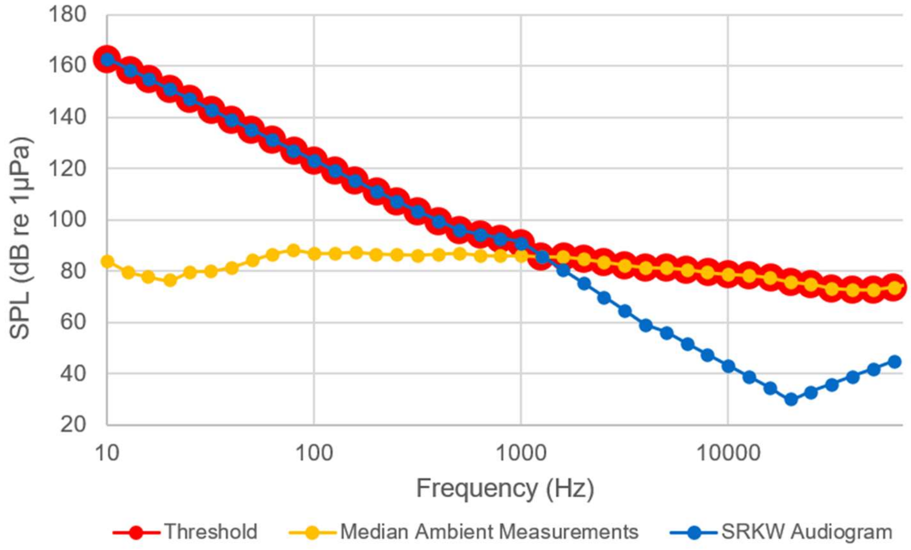


Figure 7. Combined threshold (red dots) versus frequency representing the greater of the ambient noise levels (yellow line) and Southern Resident killer whale (SRKW) audiogram (blue line) in 1/3-octave frequency bands. This combined threshold determines the equivalent masking level for SRKW under median ambient conditions measured at the Boundary Pass Underwater Listening Station (ULS) and the killer whale audiogram (Appendix A).

As mentioned previously, the LD method assumes that the relative change in distance over which a sound can be heard depends only on the change in the equivalent masking level, which is the greater of the hearing threshold and the background sound level and is represented by the red dots in Figure 7. The calculation of LD assumes that a change in the equivalent masking level entails a proportional adjustment of the listener's distance from the sound source if the received level of the sound of interest is to remain at the threshold of detectability, i.e., when noise levels increase, a listener must move closer to the sound source to be able to detect it. The relative amount of listening distance reduction, due to an increase in the number of vessels for example, requires knowledge of the frequency-dependent propagation loss of the call, the change in masking noise levels (i.e., ambient noise levels), and the species' audiogram (Barber et al. 2010, Matthews et al. 2016).

The amount by which sound levels decrease with increasing distance from a sound source is known as acoustic propagation loss. Thus, the previous argument may be restated to say that in order for the sound of interest to remain at the threshold of detectability, the change in propagation loss between the source and the listener must equal the change in equivalent masking level. Over distances less than a few water depths, we can assume a simple propagation loss function (in decibels) of $N \log r$, where r is the source-listener distance and N is a spreading loss parameter. Then the relationship between LD and the change in equivalent masking level can be shown to be:

$$N \log (r_2/r_1) = -\Delta \,, \tag{1}$$

where Δ is the change in equivalent masking level, r_1 represents the initial LD and r_2 represents the final LD. For example, if the equivalent masking level increases by 6 dB ($\Delta = 6$), and if $N = 20$ (a common value for short distance propagation and verified by the propagation loss model to be valid for frequencies >1 kHz), then from Equation 1 the relative change in LD is $r_2/r_1 = 1/2$. This means that the source must be at half its original distance from the listener to remain acoustically detectable.

The only parametric assumption required for applying this method is the choice of a suitable rate of sound propagation loss N. It must also be assumed that other ambient factors affecting masking of a sound remain the same in the before and after scenarios. An important factor to consider when determining absolute masking levels is the directivity index of the signal and the noise, which defines how well an animal can resolve a sound arriving from a given direction in the presence of masking noise arriving from a different direction, e.g., by orienting itself to face the sound of interest. This parameter can only be neglected under the premise that spatial distribution of masking noise does not change with orientation, which is valid for the present study because the noise is assumed to arrive from vessels positioned all around the animals. Only the distance of the vessels from the animal's changes when increasing the approach distance.

As the separation between vessels and whales increases, sound levels received by the whales decrease. This reduction is biologically important from a masking standpoint if it results in an increase of LD at sound frequencies that are important to the whales. We calculated the equivalent masking level by summing the individual changes in equivalent masking level from small vessel sounds across 1/3-octave-bands (an approximation of a critical band) within frequency ranges that are important to SRKW. We then calculated the relative change in LD (as a percentage of the original LD) that would result from increasing the approach distance. We analyzed the effect of masking over two frequency ranges determined to be of importance to SRKW (Heise et al. 2017):

1. 500 Hz to 15 kHz, which includes the typical frequency range of SRKW communication calls. We used a modified band of 500 Hz to 14.1 kHz and assumed that the rate of propagation loss for these calls was 20 log (r).
2. 15 kHz to 100 kHz, which includes the typical frequency range of echolocation clicks. We calculated this band from 14.1 kHz to 64 kHz. We also calculated relative change in foraging distance using a propagation loss rate of 40 log (r) to account for the two-way propagation loss of echolocation signals (away from and back toward the whale).

At frequencies where SRKW hearing sensitivity is below the masking sound levels, increases to the approach distance are expected to reduce equivalent masking levels. So, over these frequencies we expect an increase in the relative LD, i.e., an improvement in the acoustic environment for SRKW. While the LD can be calculated separately for each 1/3-octave frequency band (which approximate critical SRKW hearing bands), we instead summed the 1/3-octave equivalent masking levels through the two frequency ranges described above (500 Hz to 14.1 kHz, or 14.1 kHz to 64 kHz) to obtain changes in the *wide-band* equivalent masking level for use with Equation 1. The relative LD results are obtained using the wide-band approach, and results are then expressed as a percentage of the original LD: i.e., 100% × (r_2/r_1 – 1).

3. RESULTS

Figure 8 presents the reductions in noise levels at each of the three study sites for the different whale-watching approach distances, relative to an approach distance of 200 m. Corresponding values are listed in Tables C-1 and C-2 along with modelled broadband vessel noise levels (not reductions) as well as the difference in sound levels between vessel noise for an approach distance of 200 m relative to ambient noise.

The plots in Figure 8 show that water depth influences received vessel noise levels. For example, at the deeper site (Haro Strait), there are greater reductions in noise levels when the approach distance is increased from 200 to 400 m (for both receiver depths) than at the two shallower sites (Swanson Channel and Race Rocks). However, there are minimal reductions in noise when approach distance is increased from 600 to 800 m. In contrast, at the two shallower sites, there is almost a linear decrease in noise with increasing approach distance from 200 m to 1000 m. Additionally, there generally appears to be greater reductions in noise levels with increasing approach distance at the deeper (60 m) receiver. An expected finding is that the noise levels scale proportionately with vessel density, therefore, the SPL reductions are almost equal between the vessel densities as is shown in Figure 8. The only exception to this occurs at the 10 m receiver depth in Haro Strait, where there appears to be greater reductions in noise levels for the 27-vessel scenario when increasing the approach distances.

The average broadband reductions across all scenarios for the following approach distance changes were:

- 3.5 dB when increasing from 200 to 400 m,
- 6.1 dB when increasing from 200 to 600 m,
- 7.5 dB when increasing from 200 to 800 m, and
- 9.7 dB when increasing from 200 to 1000 m.

The average broadband increase above ambient levels when vessels are at an approach distance of 200 m was 22.5 dB across all 3 sites and vessel densities.

Due to the presence of low-frequency (<100 Hz) noise artifacts in the field measurements of vessel source levels used as inputs to the model, the broadband SPL are expected to be slightly high estimates. The *differences* in the received sound levels between two approach distances, however, are not influenced by this spurious contribution. Nor are the listening distance calculations due to the SRKW communication and echolocation bands being above this frequency.

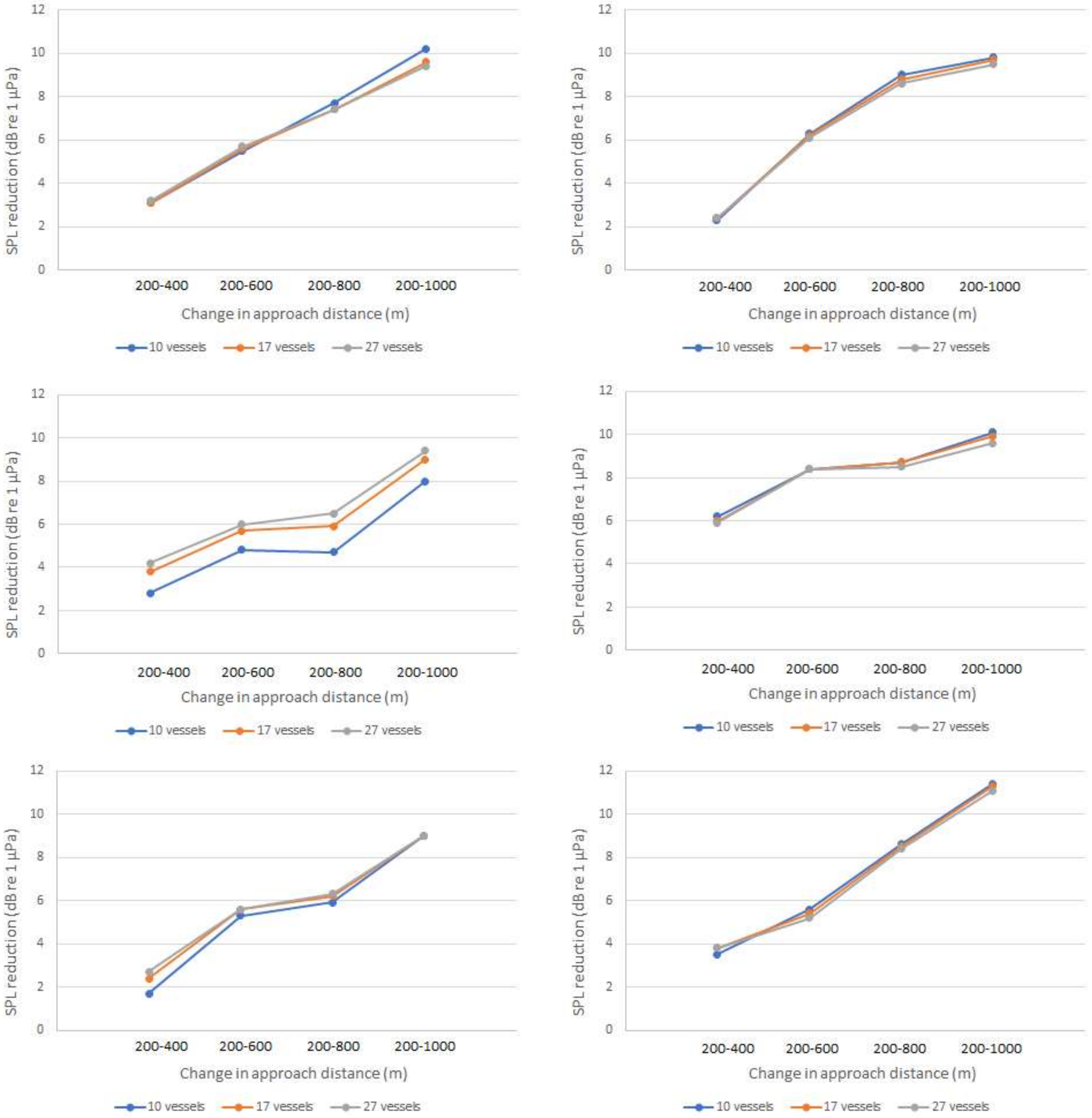


Figure 8. Reductions in broadband noise levels with increase in whale-watching approach distance for three vessel densities. The left column presents results for the 10-m receiver, and the right column is the 60-m receiver. Top row: Swanson Channel (water depth 75 m), middle row: Haro Strait (270 m), and bottom row: Race Rocks (120 m).

Figure 9 shows frequency-dependent noise levels from the highest vessel density (27) scenario at Site 2 (Haro Strait) in relation to ambient noise and the SRKW audiogram. The plots, one for each receiver depth, illustrate the decrease in masking across frequencies for the various approach distances. Resident killer whale calls travel farthest based on the energy located in frequencies 800 Hz-5 kHz with a peak around 2 kHz (Mouy et al. 2020). This band contains a significant portion of the perceived noise from whale watch vessels. None of the modelled approach distances will reduce the levels below median ambient noise levels except for the 1000 m distance for frequencies above ~30 kHz.

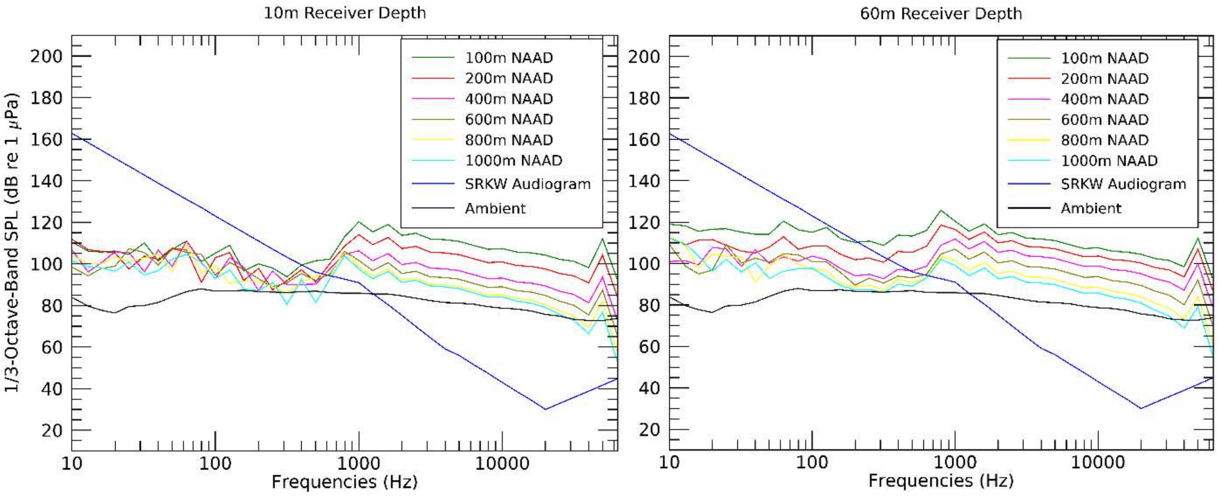


Figure 9. Modelled 1/3-octave-band vessel noise versus frequency from 27 vessels for all approach distances at Site 2 – Haro Strait. Vessel SPL was modelled at a listener depth of 10 m (left) and 60 m (right).

Tables 4–7 present the increase in listening distance (LD), in both the communication and echolocation frequency bands, for the approach distances of 400, 600, 800, and 1000 m, compared to 200 m for each site and vessel scenario. The increase in LD was calculated from the change in detectable vessel noise levels for SRKW, as described in Appendix D. These results show that the vessel sounds have a greater effect on LD for animals at 60 m than at 10 m depth, except at the closest vessel distance of 400 m. This could be due to acoustic shadowing by the surface at farther ranges from the source. Site 2, the deepest site, consistently has the largest increase in LD across all approach distances and vessel scenarios.

Table 4. 200 to 400 m: Percent (%) increase in listening distance for all modelled scenarios, that would result from increasing the approach distance. Results are provided for the two frequency ranges that killer whales use in acoustic signaling: 500 Hz to 14.1 kHz (covering the range of calls and lower-frequency whistles) and 14.1 kHz to 64 kHz (upper frequency range of whistles and echolocation clicks). A value of 0% corresponds to no change, a value of 100% corresponds to a doubling of the listening distance, and 200% to a tripling of the distance.

Site	**Listening distance (LD)**					
	500 Hz to 14 kHz Communication-Type			**14 kHz to 64 kHz Echolocation-Type**		
	10 vessels	17 vessels	27 vessels	10 vessels	17 vessels	27 vessels
10 m listener depth						
1-Swanson Channel	64.1	66.0	66.0	51.4	53.1	52.2
2-Haro Strait	137.1	137.1	134.4	80.9	79.9	80.9
3-Race Rocks	111.3	111.3	111.3	72.8	73.8	73.8
60 m listener depth						
1-Swanson Channel	56.7	58.5	58.5	40.4	40.4	40.4
2-Haro Strait	82.0	82.0	82.0	48.8	48.8	48.8
3-Race Rocks	77.8	75.8	75.8	46.2	47.1	46.2

Table 5. 200 to 600 m: Percent (%) increase in listening distance for all modelled scenarios, that would result from increasing the approach distance. Results are provided for the two frequency ranges that killer whales use in acoustic signaling: 500 Hz to 14.1 kHz (covering the range of calls and lower-frequency whistles) and 14.1 kHz to 64 kHz (upper frequency range of whistles and echolocation clicks). A value of 0% corresponds to no change, a value of 100% corresponds to a doubling of the listening distance, and 200% to a tripling of the distance.

Site	**Listening distance (LD)**					
	500 Hz to 14 kHz Communication-Type			**14 kHz to 64 kHz Echolocation-Type**		
	10 vessels	17 vessels	27 vessels	10 vessels	17 vessels	27 vessels
10 m listener depth						
1-Swanson Channel	88.4	90.5	90.5	79.9	80.9	80.9
2-Haro Strait	254.8	246.7	246.7	151.2	152.6	152.6
3-Race Rocks	131.7	134.4	134.4	112.6	113.8	113.8
60 m listener depth						
1-Swanson Channel	139.9	139.9	142.7	96.1	96.1	96.1
2-Haro Strait	227.3	227.3	227.3	127.8	127.8	127.8
3-Race Rocks	160.0	157.0	157.0	107.7	107.7	106.5

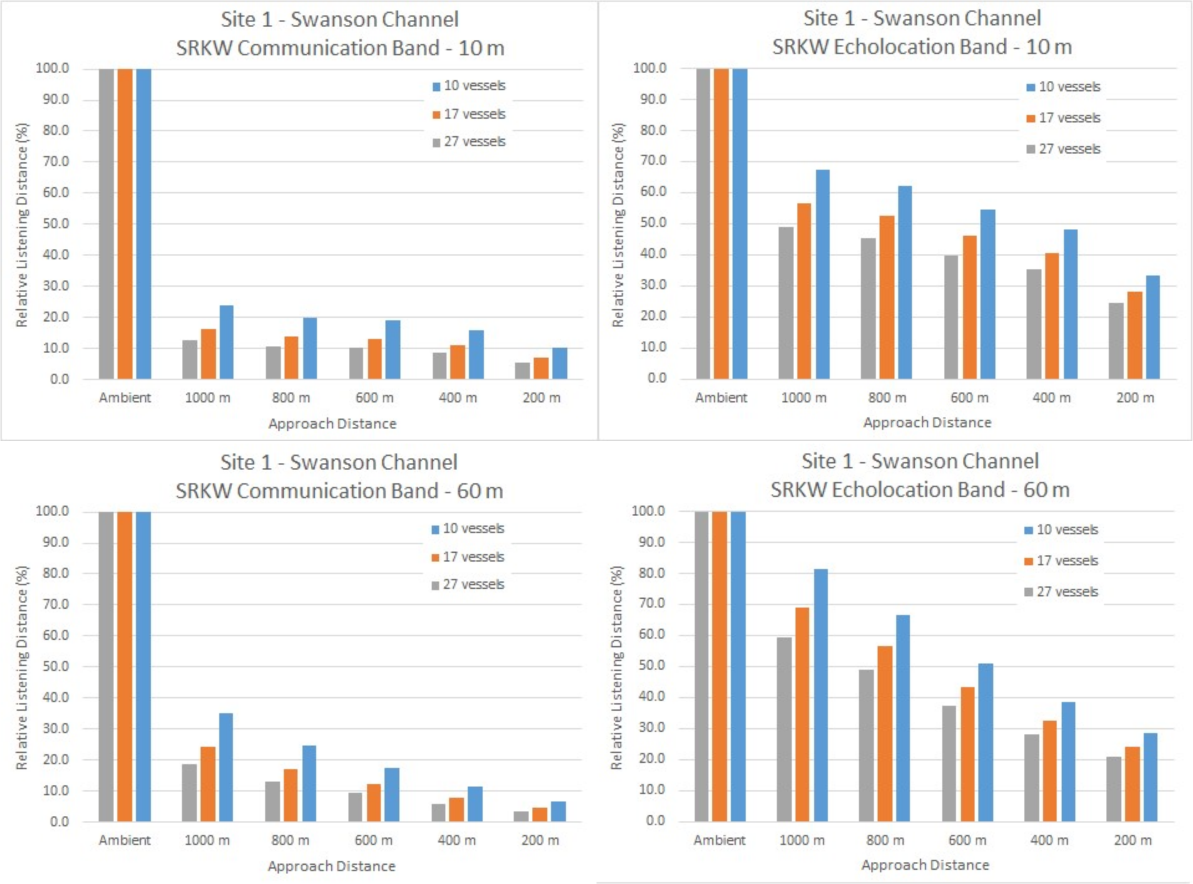
Table 6. 200 to 800 m: Percent (%) increase in listening distance for all modelled scenarios, that would result from increasing the approach distance. Results are provided for the two frequency ranges that killer whales use in acoustic signaling: 500 Hz to 14.1 kHz (covering the range of calls and lower-frequency whistles) and 14.1 kHz to 64 kHz (upper frequency range of whistles and echolocation clicks). A value of 0% corresponds to no change, a value of 100% corresponds to a doubling of the listening distance, and 200% to a tripling of the distance.

Site	**Listening distance (LD)**					
	500 Hz to 14 kHz Communication-Type			**14 kHz to 64 kHz Echolocation-Type**		
	10 vessels	17 vessels	27 vessels	10 vessels	17 vessels	27 vessels
10 m listener depth						
1-Swanson Channel	106.5	108.9	108.9	113.8	115.0	113.8
2-Haro Strait	357.1	351.9	351.9	238.8	238.8	238.8
3-Race Rocks	129.1	131.7	134.4	148.3	151.2	149.7
60 m listener depth						
1-Swanson Channel	242.8	242.8	242.8	170.7	170.7	170.7
2-Haro Strait	455.9	449.5	449.5	242.8	244.7	242.8
3-Race Rocks	250.8	246.7	246.7	178.6	178.6	178.6

Table 7. 200 to 1000 m: Percent (%) increase in listening distance for all modelled scenarios, that would result from increasing the approach distance. Results are provided for the two frequency ranges that killer whales use in acoustic signaling: 500 Hz to 14.1 kHz (covering the range of calls and lower-frequency whistles) and 14.1 kHz to 64 kHz (upper frequency range of whistles and echolocation clicks). A value of 0% corresponds to no change, a value of 100% corresponds to a doubling of the listening distance, and 200% to a tripling of the distance.

Site	**Listening distance (LD)**					
	500 Hz to 14 kHz Communication-Type			**14 kHz to 64 kHz Echolocation-Type**		
	10 vessels	17 vessels	27 vessels	10 vessels	17 vessels	27 vessels
10 m listener depth						
1-Swanson Channel	131.7	131.7	131.7	141.3	142.7	141.3
2-Haro Strait	430.9	430.9	430.9	316.9	316.9	316.9
3-Race Rocks	181.8	185.1	185.1	193.4	196.8	195.1
60 m listener depth						
1-Swanson Channel	373.2	373.2	373.2	248.7	250.8	248.7
2-Haro Strait	624.4	624.4	624.4	334.0	336.5	334.0
3-Race Rocks	293.6	289.0	293.6	231.1	233.0	231.1

Figures 10–12 present the percent of LD remaining relative to ambient, in both the communication and echolocation frequency bands for all scenarios and receiver depths. Corresponding values are listed in Table C-3.



Site 1 - Swanson Channel SRKW Communication Band - 10 m

Site 1 - Swanson Channel SRKW Echolocation Band - 10 m

Site 1 - Swanson Channel SRKW Communication Band - 60 m

Site 1 - Swanson Channel SRKW Echolocation Band - 60 m

Figure 10. Relative listening distance (to ambient) at Site 1 (Swanson Channel) in the SRKW communication band (500 Hz to 15 kHz) (left) and echolocation band (15–64 kHz) (right) for the 10 m receiver (top) and 60 m receiver (bottom). A value of 100% corresponds to no change to the listening distance (i.e., Same LD as under ambient conditions), a value of 50% corresponds to a halving of the listening distance, and 10% corresponds to 10% of the original LD (under ambient conditions).

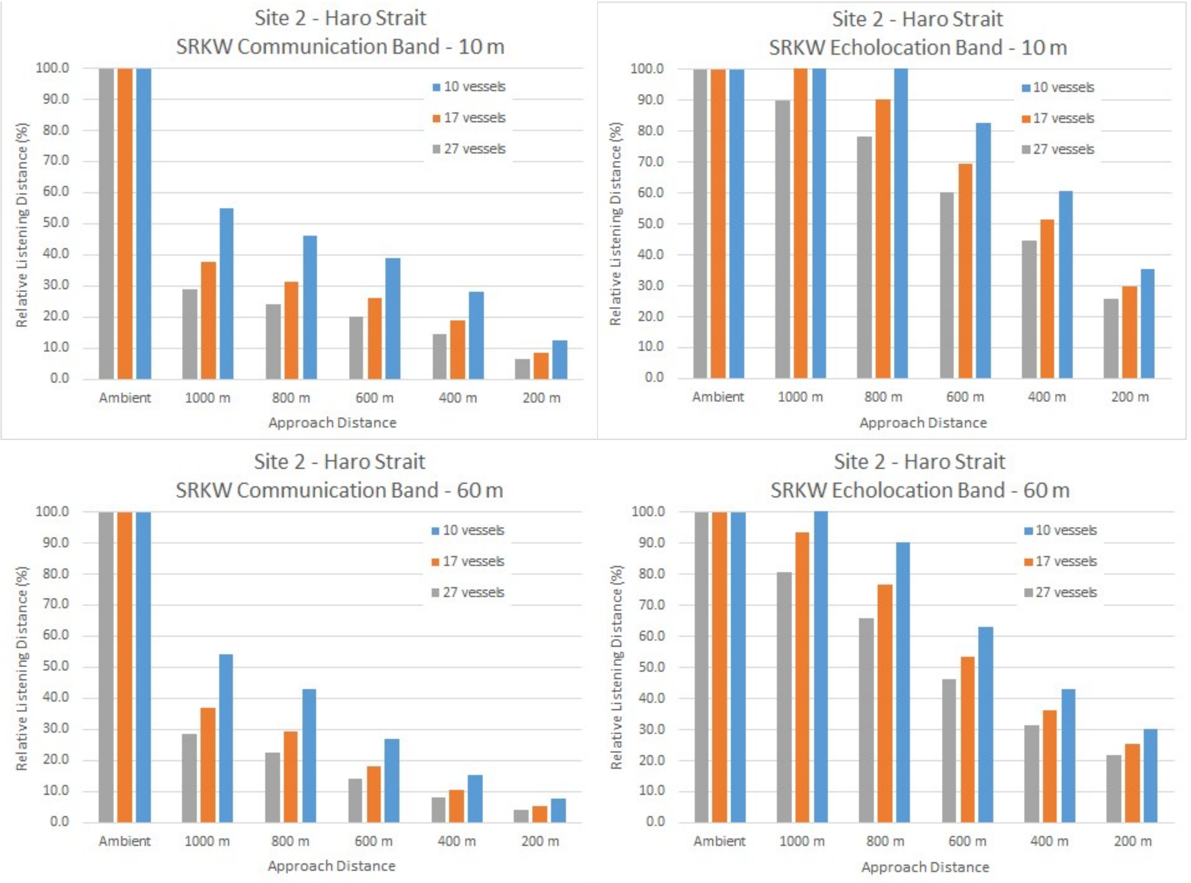


Figure 11. Relative listening distance (to ambient) at Site 2 (Haro Strait) in the SRKW communication band (500 Hz to 15 kHz) (left) and echolocation band (15–64 kHz) (right) for the 10 m receiver (top) and 60 m receiver (bottom).

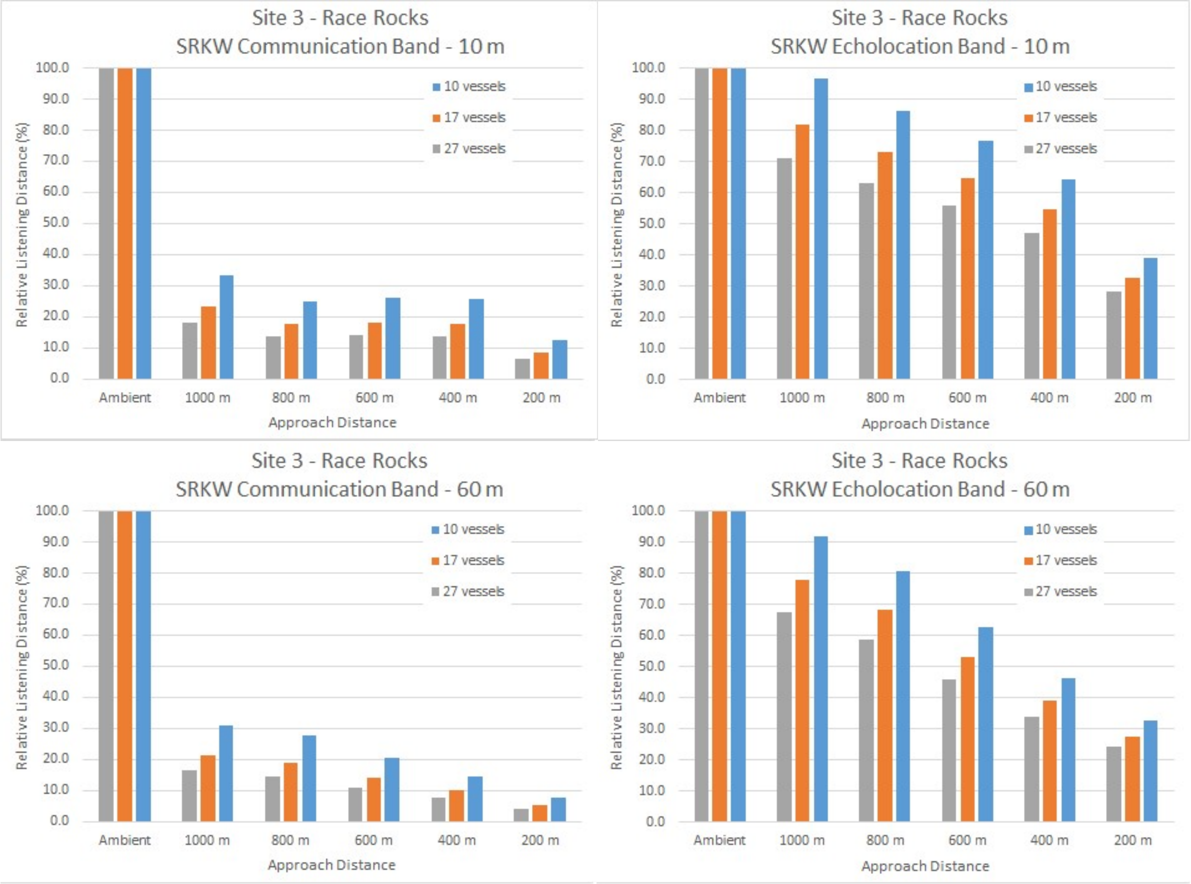


Figure 12. Relative listening distance (to ambient) at Site 3 (Race Rocks) in the SRKW communication band (500 Hz to 15 kHz) (left) and echolocation band (15–64 kHz) (right) for the 10 m receiver (top) and 60 m receiver (bottom).

4. DISCUSSION AND CONCLUSIONS

Noise from vessels has been identified as a contributing threat to the recovery of endangered Southern Resident killer whales (SRKW); because of this, in 2019 and 2020 the Government of Canada increased the minimum approach distance to all killer whales in SRKW critical habitat (with expanded range for 2020) from 200 to 400 m as an interim measure. In this study, we modelled the noise reductions at simulated whale pod locations achieved by this increase in the approach distance as well as longer increases of 600, 800, and 1000 m. Three vessel scenarios (10, 17, and 27 vessels) at two listener depths (10 and 60 m) were analyzed at three sites within the critical habitat (Swanson Channel, Haro Strait, and Race Rocks). This work expands on previous modelling studies for DFO, which examined smaller approach distances of 100 and 200 m (Wladichuk and Hannay 2017, Yurk et al. 2017).

In this assessment, we applied a relatively new approach known as the listening distance method, to examine the effects of noise exposures on the ability of killer whales to hear communication and echolocation signals under different noise conditions resulting from the presence of vessels in the whales' vicinity. The LD method determines the relative changes in the distances over which important sounds could be detected by a listener (here, a whale) in the presence of differing amounts of noise.

The modelling predicted the reductions in vessel noise levels that the whale perceived resulting from adopting a 400 m approach distance relative to the previously prescribed 200 m, as well as increasing it to 600, 800, and 1000 m. The reductions in the modelled vessel noise levels for all of the approach distances were investigated over three important frequency bands to the SRKW – broadband (10 Hz to 64 kHz), communication (500 Hz to 15 kHz) and echolocation (15 to 64 kHz, note full bandwidth is referenced up to 100 kHz) (Heise et al. 2017).

In general, the results showed a near-linear increase in noise level reductions with an increase in the vessel approach distance. However, there were a couple scenarios where there were minimal reductions by increasing the approach distance from 600 to 800 m, mainly at the deeper modelling site (Haro Strait). Interestingly though, there were greater noise reductions at the Haro Strait site when increasing the approach distance from 200 to 400 m.

The broadband noise reductions from increasing the approach distance from 200 m to the longer distances, varied by different amounts depending on location, listener depth and number of vessels (Tables 1–2). Overall, the average broadband reductions across all scenarios examined were 3.5 dB when increasing the approach distance from 200 to 400 m, 6.1 dB when increasing from 200 to 600 m, 7.5 dB when increasing from 200 to 800 m, and 9.7 dB when increasing from 200 to 1000 m. And the average broadband increase above ambient levels (median noise levels in Boundary Pass) when a 200 m minimum approach distance was used was 22.5 dB across the 3 sites and all vessel density scenarios. Even using a 1000 m approach distance, the broadband noise levels were still approximately 12 dB above ambient noise levels in Boundary Pass.

The relative change in listening distances (LD) is similar across all vessel densities for each increase in approach distance. The largest reduction in LD compared to ambient noise conditions, occurred with the greatest number of modelled vessels (27) present at the shortest approach distance (200 m), as was expected. The reduction in LD in the communication band was 96%, meaning only 4% of the original LD, corresponding to no whale watch vessels present, remained. This maximum reduction occurred in Swanson Channel - the shallowest study site. The greater effect in shallow water is attributed to the influence of vessel noise that is reflected from the seabed and surface, increasing the masking noise levels more than would occur in deeper water. As a result, the deepest site (Haro Strait) showed the smallest LD reductions. Still, at this site there remained only 55% of the ambient-only LD in the communication band when 10 vessels were near the 1000 m approach distance.

Interestingly, there were minimal increases in LD in the communication band between the 600 and 800 m scenarios, particularly at the 10 m receiver at the two shallower sites (Swanson Channel and Race Rocks) due to propagation characteristics in shallow-water environments. This result is attributed to a lower rate of decrease of vessel noise with distance in shallow water relative to deeper water. Essentially the seabed and surface reflect the vessel noise, trapping sound energy in a disk-shaped volume that grows proportionately with distance. In deeper water the energy expands in a spherical shape and the increase is squared with distance, so the energy density decrease with distance in deep water is more rapid.

As noted previously, reduction in LD in the echolocation/foraging band was always less than in the communication band. That is partly due to the spectral content of the vessel noise which has more energy below 10 kHz at slow speeds (Wladichuk et al. 2018), but this result is primarily due to inherent differences in acoustic propagation loss between passive listening and echolocation. Echolocation propagation loss in decibels is twice that of passive listening for the same listener-to-source (or target) distance. That is because echolocation sounds experience two-way propagation loss: on the paths from the source animal to the target and then from the target back to the source animal, which in the case of echolocation is also the listener. Consequently, the same change in distance causes a greater change in echolocation sound level than to a passive listening sound level. These distance increases must balance the increase in vessel noise. Therefore, a smaller reduction in echolocation distance will produce the same decibel savings as a larger increase in passive source distance from the listener.

The largest reduction in LD in the echolocation band was by 79% (27 vessels at 200 m in Swanson Channel). In contrast, there were no reductions in LD for some of the longer approach distance scenarios (ex. 10 and 17 vessels at 1000 m in Haro Strait). With the present 400 m minimum approach distance, the remaining echolocation distances ranged from 35% to 64% of the LD with no vessels present. It is noted that even the ambient noise levels, used here as a reference, includes vessel noise: it is based on the median ambient noise level in Boundary Pass. Larger LD reduction percentages would be predicted using ambient noise statistics representative of the natural acoustic environment only. Another notable finding is that there were generally greater noise reductions from increasing the approach distance on the deeper (60 m) receiver than on the shallower (10 m) receiver. This suggests that there is less impact while the whales are foraging at depth but has a greater impact while they are travelling, resting, and searching for prey near the surface.

LD estimations are specific to the given propagation conditions and ambient sound levels. They also vary with the source levels and frequencies of the signals that the whales are attempting to detect. For example, source levels of killer whale calls can vary by more than 20 dB (Miller 2006, Holt et al. 2011). So, a change in relative LD from increasing the approach distance imparts more absolute benefit to some calls than others, depending on the ambient sound levels and propagation loss: a loud sound will have a longer initial detection distance than a quiet sound, so an improvement or impairment of relative LD will cause a *greater* change in the absolute detection distance for the louder sound.

Finally, vessel speed influences both the loudness and frequency spectrum of radiated noise (Erbe 2002, Wladichuk et al. 2018). This study used only a single source level spectrum for each vessel type, and thereby assumed the vessels were travelling at a fixed speed, roughly equal to 5 knots. This is a typical average speed for vessels engaged in active whale watching, but likely the vessels would be adjusting their speed frequently. Different vessel speeds lead to different masking sound levels and therefore different relative LDs. So, variations in vessel speed, at different distances from the whales, could be considered in future impact studies. Attention might be focussed on the speeds of vessels as they approach and depart from whales, which are generally much higher than when they are alongside. Additionally, vessel orientation might be a factor that could affect noise levels due to the origin of the noise source and subsequent radiation patterns (Arveson and Vendittis 2000) and was not considered here. However, whale-watching vessels are more likely to parallel the whales, in accordance with the *Be Whale Wise* guidelines (BeWhaleWise.org 2019), and not position themselves directly in front or behind the whales. With that in mind, the vessel source levels used here are anticipated to be good representations of actuals given they were calculated at the vessels' closes point of approach (ie. Broadside to the recorder) as outlined by the [ISO] International Organization for Standardization (2016). Another recommendation for future studies, is to use different combinations of vessel types and to examine more vessel densities to understand other possible real-life scenarios. It would also be useful to compare reductions in listening distance between the different vessel densities rather than the same vessel density at different approach distances to consider the effects increasing the number of whale-watching vessels. Furthermore, it could also be valuable to examine changes in listening distance under different ambient noise conditions to investigate the possible range in reductions throughout SRKW critical habitat.

In conclusion, our analysis demonstrates that whale watch vessel noise can have a substantial impact on the SRKW listening distance in their communication frequency band, in particular, and that by increasing the minimum approach distance and reducing the number of vessels, there can be positive effects on reducing noise levels perceived by the whales. The listening distance analysis reveals additional important information about the relative reduction in the distance that a listener can detect an important sound when masking noise levels increase. It also accounts for the absolute hearing sensitivity of the listener, therefore can have more meaningful results than broadband noise levels.

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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.

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APPENDIX A. KILLER WHALE AUDIOGRAM

All mammalian hearing evolved for a terrestrial ecosystem. Adaptations of the hearing apparatus and marine mammal physiology, especially for fully aquatic cetaceans, extended these animals' hearing ranges to include higher frequencies (e.g., 150 Hz to 200 kHz in odontocetes versus 20 Hz to 80 kHz in most terrestrial mammals) but reduced their ability to hear low frequencies (< 1 kHz).

The SRKW audiogram used in this and the previous studies (Figure A-1) is based on data published for captive killer whales by Branstetter et al. (2017), Szymanski et al. (1999), and Hall and Johnson (1972). It accounts for pool noise influences and uses the best reported sensitivity at each tested frequency. It incorporates augmentations by H. Yurk and J. Wood to extend the hearing threshold to the lower frequencies outside the range of the reported measurements (pers. comm.).

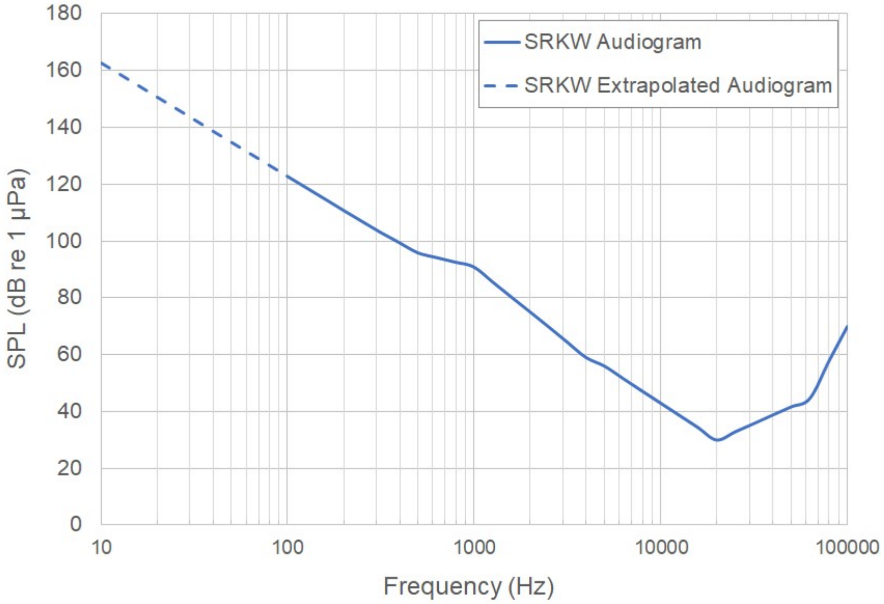

Figure A-1. Modelled resident killer whale hearing threshold (i.e., audiogram) versus frequency, based on data for killer whales from Branstetter et al. (2017), Szymanski et al. (1999), and Hall and Johnson (1972) with extrapolation by H. Yurk and J. Wood.

APPENDIX B. MODELLING METHODS AND PARAMETERS

B.1. Marine Operations Noise Model

As in the two previous studies, underwater propagation loss of vessel noise was predicted with JASCO's Marine Operations Noise Model (MONM).

MONM computes acoustic propagation at frequencies of 10 Hz to 2 kHz 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 a solid seabed (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 accounts for the additional reflection loss at the seabed, which results from partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. MONM incorporates the following site-specific environmental properties: a bathymetric grid of the modelled area, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

MONM computes acoustic propagation at frequencies higher than 2 kHz using a Gaussian beam acoustic ray-trace model (Porter and Liu 1994), based on the widely used BELLHOP model. This version of MONM accounts for sound attenuation due to energy absorption through ion relaxation and viscosity of water in addition to acoustic attenuation due to reflection at the medium boundaries and internal layers (Fisher and Simmons 1977). The former type of sound attenuation is significant for frequencies higher than 5 kHz and cannot be neglected without noticeably affecting the model results.

MONM computes acoustic fields in three dimensions by modelling propagation loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as *N*×2-D. These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding $N = 360°/\Delta\theta$ number of planes (Figure B-1).

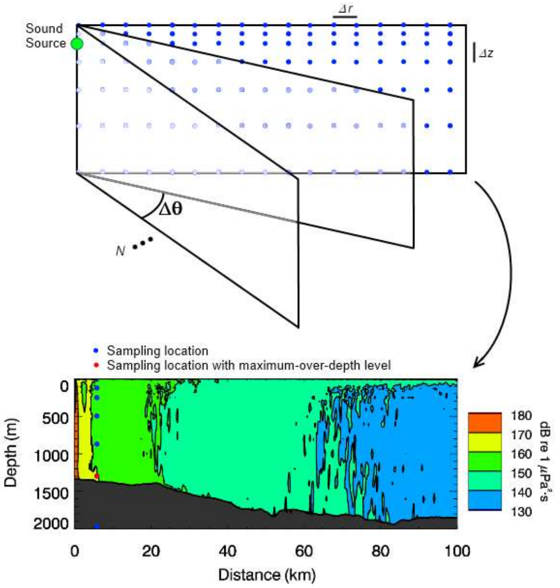

Figure B-1. The *N*×2-D and maximum-over-depth modelling approach used by MONM.

MONM treats frequency dependence by computing acoustic propagation loss at the centre frequencies of 1/3-octave-bands. Sufficiently many 1/3-octave-bands, starting at 10 Hz, are modelled to include most of the acoustic energy emitted by the source. At each centre frequency, the propagation loss is modelled within each of the *N* vertical planes as a function of depth and range from the source. The 1/3-octave-band received sound levels are computed by subtracting the band propagation loss values from the directional source level in that frequency band. Composite broadband received levels are then computed by summing the received 1/3-octave-band levels.

The received sound field within each vertical radial plane is sampled at various ranges from the source, generally with a fixed radial step size. At each sampling range along the surface, the sound field is sampled at various depths, with the step size between samples increasing with depth below the surface. The step sizes are chosen to provide increased coverage near the depth of the source and at depths of interest in terms of the sound speed profile. For areas with deep water, sampling is not performed at depths beyond those reachable by marine mammals. The received sound level at a surface sampling location is taken as the maximum value that occurs over all samples within the water column, i.e., the maximum-over-depth received sound level. These maximum-over-depth sound levels are presented as colour contours around the source.

MONM’s predictions have been validated against experimental data from several underwater acoustic measurement programs conducted by JASCO (Hannay and Racca 2005, Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010, Racca et al. 2012a, Racca et al. 2012b, Martin et al. 2015).

B.2. Environmental Parameters

This section describes the environmental parameters that were used in MONM to simulate the effect of the water and seabed on sound propagation in the study area.

B.2.1. Bathymetry

A flat bathymetry was used in the modelling of the three study areas, with water depth equal to that at each of the three modelling sites as obtained from the following two sources (Figure B-2):

- Data south of latitude 49°N were obtained from the NOAA digital elevation model (NGDC 2013);
- Data north of latitude 49°N were obtained from a Canadian Hydrographic Service (CHS) digital elevation map from Nautical Data International Inc. (NDI).

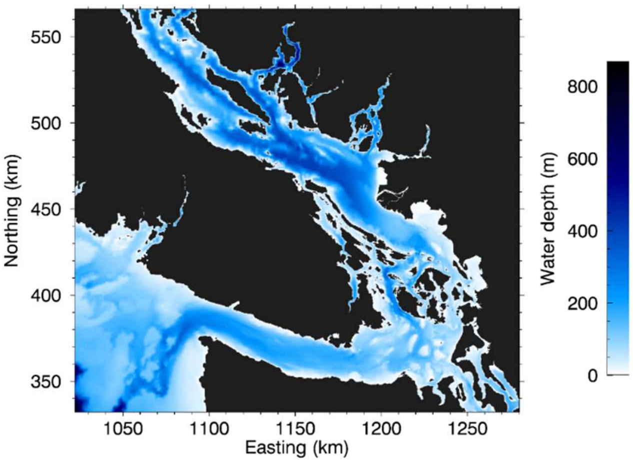

Figure B-2. Bathymetry in the region of the modelled areas.

B.2.2. Geoacoustics

The geoacoustic properties of the seabed strongly influence propagation loss because reflection and absorption of sound energy at the seabed is a dominant loss mechanism in shallow water (Urick 1983). The seabed geoacoustic properties for the study area were obtained from Wladichuk et al. (2014) and a review of the scientific literature (Hamilton 1980, Erbe et al. 2012).

Considering the geographic variation across the study area, the modelled sites fall into two distinct geoacoustic regions based on the bottom substrate: Sites 1 and 2 in one region, and Site 3 in another (Table B-1). Seafloor sediments with higher sound speed values will reflect sound energy more strongly back into the water column; therefore, higher sound levels are received by marine fauna nearby. Whereas lower seafloor sound speed allows for more sound energy to be absorbed into the substrate and will therefore reduce the amount that is received by marine mammals nearby.

Table B-1. Geoacoustic profiles for the three modelled sites based on Wladichuk et al. (2014). Within the top layer, the compressional speed varies linearly with depth within the stated range.

Site	Depth below seafloor (m)	Sediment type	Density (g/cm^3)	Compressional wave		Shear wave	
				Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
1-Swanson Channel 2-Haro Strait	0–50	Sand-silt-clay	1.80	1,541–1,591	0.72	250	1.2
	>50	Bedrock	1.90	2,275	0.10		
3-Race Rocks	0–50	Silt	1.64	1,558–1,608	0.83	500	3.4
	>50	Bedrock	1.90	2,275	0.10		

B.2.3. Sound Speed Profiles

Seasonal changes of water temperature and salinity influence the corresponding water sound speed profile. The sound speed profile can have a large effect on the propagation loss throughout the entire water column and needs to be considered accordingly. Water column sound speed profiles for the study area for July were computed from historical temperature and salinity data obtained from DFO Institute of Ocean Sciences (Patricia Bay) Ocean Sciences Division. A monthly average sound speed profile was computed from approximately 120 historical temperature-salinity casts for July, collected between the years of 2006 to 2010 (Figure B-3). Depth profiles of temperature and salinity were converted to speed of sound in water (c [m/s]) using the following formula (Clay and Medwin 1977):

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016z \tag{B-1}$$

In this formula, z is depth in metres, T is temperature in degrees Celsius, and S is salinity in parts per thousand.

The monthly sound speed profiles exhibited the greatest variability in the upper 80 m of the water column. Solar heating in summer results in a downward-refracting profile, which is less favourable for long-range propagation of vessel noise. The mean sound speed profiles for July were used to represent the acoustic properties of the water column in the models. Analysis of the sound speed profiles showed no strong north-south trend in the data; therefore, one single sound speed profile was assumed throughout the study area and for all modelled sites.

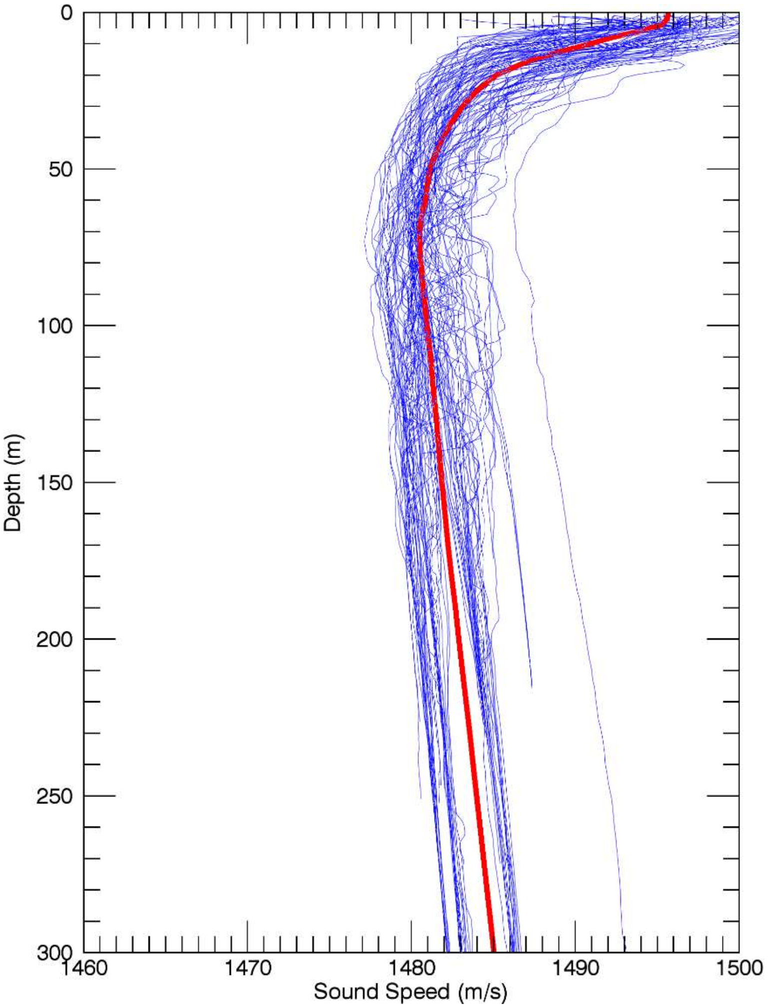

Figure B-3. Sound speed profiles (SSPs) from Fisheries and Oceans Canada's (DFO) database during the month of July from 2006 to 2010 and the average sound speed profile (SSP) (red bold line), which was used in the models.

B.3. Vessel Source Parameters

Propeller cavitation and hull-borne machine vibration are the predominant sources of underwater noise from vessels. Different types of vessels have characteristic source level (SL) spectra (i.e., variations of sound emission levels with sound frequency) because of their specific design and operating conditions.

Vessel SLs were obtained from a systematic field study of 20 different small vessels (whale watching, pleasure, and fishing vessels), in which transects were conducted at a range of speeds near Site 1 (Haro Strait) (Wladichuk and Hannay 2017). Median levels for each vessel type were computed in 1/3-octave-bands from 10 Hz to 63 kHz, covering the frequency range where most vessel sound energy emissions overlap with killer whale hearing.

The SLs (Figure B-4) for each vessel category were computed from the field study transects that had speeds of less than 7 knots in accordance with the *Be Whale Wise* guidelines (BeWhaleWise.org 2019).

When modelling acoustic propagation loss, the sound from a vessel is assumed to radiate from a point source. The water depth of that point source was chosen for each vessel type based on its length overall (LOA) following Erbe et al. (2012). For vessels with an LOA greater than 10 m, we placed the source at 1.3 m depth, and for smaller vessels, at 0.5 m depth (Table 2).

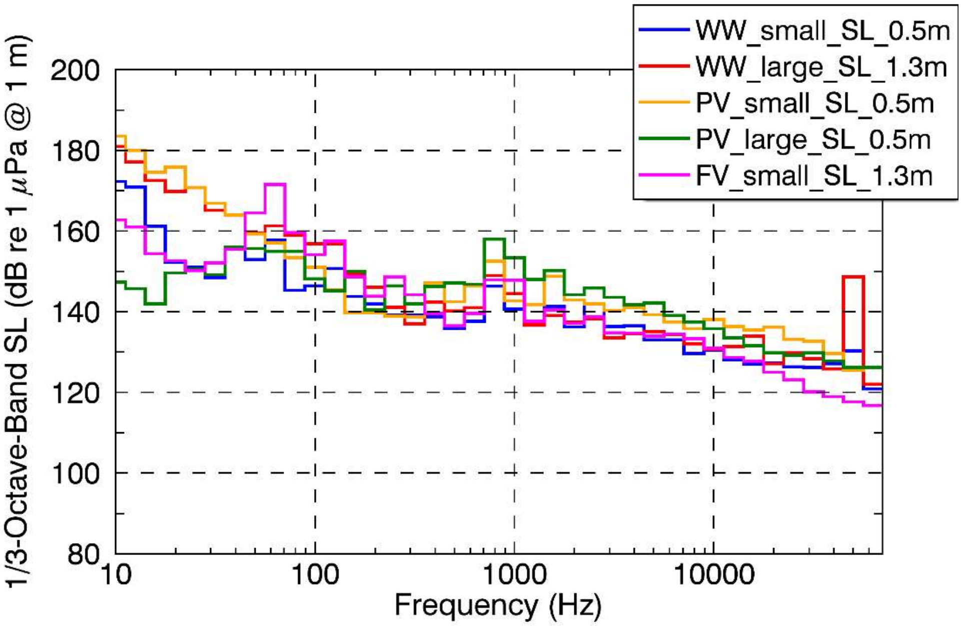

Figure B-4. Modelled 1/3-octave-band source levels (SLs) computed from the median of the slow speed (<7 knots) transects conducted in the field SL measurements study (Wladichuk and Hannay 2017). WW: whale watching, PV: pleasure vessel, FV: fishing vessel. Flow noise artifacts from water currents are present below around 100 Hz.

APPENDIX C. RESULTS TABLES

Tables C-1 and C-2 list the modelled broadband vessel noise levels received at the whales' positions at 10 and 60 m depths, respectively, for all scenarios considered in this study (i.e., three sites, each with 10, 17, or 27 vessels, for approach distances of 100, 200, 400, 600, 800, and 1000 m). The tables also present the reductions in received sound levels achieved, from the average of the 1000 iterations for each scenario, by using the longer approach distances compared to the previously considered one of 200 m, as well as the difference between 200 m and ambient.

Table C-1. 10 m listener depth: Modelled broadband vessel noise levels (SPL in dB re 1 µPa) and reduction with approach distance at the SRKW location for all scenarios at each site. The dB differences (grey rows) show the difference between ambient and vessels at 200 m and the reductions when the approach distance is increased from 200 m to longer distances.

Site	**Approach distance (m)**	**SPL (dB re 1 µPa) 8.9 Hz to 64 kHz**		
		10 vessels	17 vessels	27 vessels
1-Swanson Channel	100	124.2	126.6	128.6
	200	120.3	122.5	124.5
	400	117.2	119.4	121.3
	600	114.8	116.9	118.8
	800	112.7	115.1	117.1
	1000	110.1	112.9	115.1
	Difference, ambient vs 200 m (dB)	20.6	22.8	24.8
	Difference, 200 vs 400 m (dB)	3.1*	3.1	3.2
	Difference, 200 vs 600 m (dB)	5.5	5.6	5.7
	Difference, 200 vs 800 m (dB)	7.7	7.4	7.4
	Difference, 200 vs 1000 m (dB)	10.2	9.6	9.4
2-Haro Strait	100	121.4	124.4	126.6
	200	116.5	119.4	121.6
	400	113.7	115.6	117.4
	600	111.7	113.7	115.6
	800	111.8	113.5	115.1
	1000	108.5	110.4	112.2
	Difference, ambient vs 200 m (dB)	16.8	19.7	21.9
	Difference, 200 vs 400 m (dB)	2.8	3.8	4.2
	Difference, 200 vs 600 m (dB)	4.8	5.7	6.0
	Difference, 200 vs 800 m (dB)	4.7	5.9	6.5
	Difference, 200 vs 1000 m (dB)	8.0	9.0	9.4
3-Race Rocks	100	121.3	124.3	126.5
	200	117.3	119.8	121.8
	400	115.6	117.4	119.1
	600	112.0	114.2	116.2
	800	111.4	113.6	115.5
	1000	108.3	110.8	112.8
	Difference, ambient vs 200 m (dB)	17.6	20.1	22.1

Site	**Approach distance (m)**	**SPL (dB re 1 µPa) 8.9 Hz to 64 kHz**		
		10 vessels	17 vessels	27 vessels
	Difference, 200 vs 400 m (dB)	1.7	2.4	2.7
	Difference, 200 vs 600 m (dB)	5.3	5.6	5.6
	Difference, 200 vs 800 m (dB)	5.9	6.2	6.3
	Difference, 200 vs 1000 m (dB)	9.0	9.0	9.0

* To calculate the difference in sound level between 10 vessels at 400 m and ambient: 20.6 dB − 3.1 dB = 17.5 dB.

Table C-2. 60 m listener depth: Modelled broadband vessel noise levels (SPL in dB re 1 µPa) and reduction with approach distance at the SRKW location for all scenarios at each site. The dB differences (grey rows) show the reduction in vessel noise levels when the approach distance is increased from 200 m to longer distances.

Site	**Approach distance (m)**	**SPL (dB re 1 µPa) 8.9 Hz to 64 kHz**		
		10 vessels	17 vessels	27 vessels
1-Swanson Channel	100	127.7	130.3	132.4
	200	122.4	125.1	127.3
	400	120.1	122.7	124.9
	600	116.1	118.9	121.2
	800	113.4	116.3	118.7
	1000	112.6	115.4	117.8
	Difference, ambient vs 200 m (dB)	22.7	25.4	27.6
	Difference, 200 vs 400 m (dB)	2.3	2.4	2.4
	Difference, 200 vs 600 m (dB)	6.3	6.2	6.1
	Difference, 200 vs 800 m (dB)	9.0	8.8	8.6
	Difference, 200 vs 1000 m (dB)	9.8	9.7	9.5
2-Haro Strait	100	127.1	129.6	131.7
	200	120.8	123.4	125.5
	400	114.6	117.4	119.6
	600	112.4	115.0	117.1
	800	112.1	114.7	117.0
	1000	110.7	113.5	115.9
	Difference, ambient vs 200 m (dB)	21.1	23.7	25.8
	Difference, 200 vs 400 m (dB)	6.2	6.0	5.9
	Difference, 200 vs 600 m (dB)	8.4	8.4	8.4
	Difference, 200 vs 800 m (dB)	8.7	8.7	8.5
	Difference, 200 vs 1000 m (dB)	10.1	9.9	9.6
3-Race Rocks	100	127.3	129.8	131.8
	200	121.0	123.7	125.8
	400	117.5	119.9	122.0
	600	115.4	118.3	120.6
	800	112.4	115.2	117.4
	1000	109.6	112.4	114.7
	Difference, ambient vs 200 m (dB)	21.3	24.0	26.1
	Difference, 200 vs 400 m (dB)	3.5	3.8	3.8
	Difference, 200 vs 600 m (dB)	5.6	5.4	5.2
	Difference, 200 vs 800 m (dB)	8.6	8.5	8.4
	Difference, 200 vs 1000 m (dB)	11.4	11.3	11.1

Table C-3. Percent (%) of listening distance relative to ambient for all modelled scenarios. Results are provided for the two frequency ranges that killer whales use in acoustic signaling: 500 Hz to 14.1 kHz (covering the range of calls and lower-frequency whistles) and 14.1 kHz to 64 kHz (upper frequency range of whistles and echolocation clicks). A value of 100% corresponds to no change to the listening distance (i.e., Same LD as under ambient conditions), a value of 50% corresponds to a halving of the listening distance, and 10% corresponds to 10% of the original LD (under ambient conditions).

Site	**NAAD (m)**	**Listening distance (LD)**					
		500 Hz to 14 kHz Communication-Type			**14 kHz to 64 kHz Echolocation-Type**		
		10 vessels	17 vessels	27 vessels	10 vessels	17 vessels	27 vessels
10 m listener depth							
1-Swanson Channel	100	5.5	3.8	2.9	22.7	19.1	16.5
	200	10.1	6.9	5.3	33.4	28.1	24.3
	400	16.0	11.1	8.6	48.3	40.6	35.2
	600	19.0	13.2	10.1	54.5	46.1	39.9
	800	19.9	14.0	10.8	62.2	52.6	45.3
	1000	24.0	16.4	12.7	67.4	56.7	49.1
2-Haro Strait	100	6.1	4.2	3.2	23.2	19.6	16.9
	200	12.4	8.4	6.5	35.4	29.8	25.8
	400	28.2	19.0	14.6	60.8	51.4	44.5
	600	38.9	26.0	19.9	82.5	69.4	60.1
	800	46.2	31.2	24.0	100	90.4	78.3
	1000	54.9	37.6	28.8	100	100	89.9
3-Race Rocks	100	6.2	4.3	3.3	25.6	21.6	18.6
	200	12.6	8.6	6.7	39.0	32.8	28.4
	400	25.7	17.6	13.6	64.4	54.5	47.2
	600	26.3	18.2	14.1	76.5	64.7	56.1
	800	25.1	17.6	13.6	86.3	73.1	63.3
	1000	33.5	23.2	18.0	96.9	82.0	71.0
60 m listener depth							
1-Swanson Channel	100	3.8	2.7	2.0	22.2	18.6	16.2
	200	6.8	4.7	3.7	28.6	24.2	20.8
	400	11.3	7.8	6.0	38.3	32.4	28.1
	600	17.6	12.2	9.4	51.1	43.3	37.5
	800	24.5	17.0	13.2	66.6	56.4	48.8
	1000	35.0	24.2	18.8	81.5	69.0	59.4
2-Haro Strait	100	4.1	2.8	2.2	22.8	19.1	16.6
	200	7.6	5.2	4.1	30.1	25.3	21.9
	400	15.1	10.3	7.9	43.0	36.2	31.3
	600	26.9	18.2	14.0	62.9	53.2	46.1
	800	43.1	29.1	22.6	90.4	76.5	65.9
	1000	54.3	37.1	28.5	100	93.6	80.6

Site	NAAD (m)	Listening distance (LD)					
		500 Hz to 14 kHz Communication-Type			14 kHz to 64 kHz Echolocation-Type		
		10 vessels	17 vessels	27 vessels	10 vessels	17 vessels	27 vessels
3-Race Rocks	100	4.1	2.8	2.2	24.8	21.0	18.1
	200	7.7	5.3	4.1	32.8	27.6	24.1
	400	14.6	10.1	7.8	46.1	39.0	33.8
	600	20.6	14.3	11.1	62.5	52.9	45.8
	800	27.5	19.0	14.6	80.6	68.2	58.7
	1000	30.9	21.4	16.6	92.0	77.8	67.4

APPENDIX D. DETECTION THRESHOLD RESULTS

The modelled sound levels were analyzed in terms of a killer whale's effective detection threshold to determine whether changes in vessel noise levels were likely to be perceptible by SRKW. The detection threshold in each 1/3-octave-band was assumed to be the greater of the ambient noise level and the SRKW audiogram. Weighted sound levels were calculated by subtracting the detection threshold from the modelled vessel noise level in each 1/3-octave frequency band. The weighted sound pressure levels from all bands were summed together to yield a single weighted sound level above the detection threshold (Tables D-1 and D-2). Weighted vessel noise levels above 0 dB can reduce the SRKW LD, whereas levels below 0 dB cannot. The relative increase in LD between the approach distances was calculated according to the following formula, which assumes spherical spreading of sound:

$$\frac{\Delta d}{d} = 10^{\Delta L / 20} - 1 \tag{D-1}$$

where $\Delta d/d$ is the relative increase in LD and ΔL is the reduction in the sound level above the detection threshold.

Table D-1. Sound levels at 10 m receiver depth: Sound levels above detection threshold (dB re threshold) at the Southern Resident killer whale (SRKW) pod location for all the approach distances modelled and the 100 and 200 m results from Wladichuk and Hannay (2017). Results are provided for the two frequency ranges that killer whales use in acoustic signaling: 500 Hz to 14.1 kHz (typical range of calls) and 14.1 to 64 kHz (upper frequency range of whistles and echolocation clicks).

Site	Approach distance (m)	Sound levels above detection threshold (dB re threshold)					
		447 Hz to 14 kHz Communication-type range			14 kHz to 64 kHz Echolocation-type range		
		10 vessels	17 vessels	27 vessels	10 vessels	17 vessels	27 vessels
1-Swanson Channel	100	28.3	31.5	33.8	35.7	38.8	41.3
	200	22.9	26.1	28.4	28.8	31.9	34.3
	400	18.6	21.7	24.0	21.6	24.5	27.0
	600	17.4	20.5	22.8	18.6	21.6	24.0
	800	16.6	19.7	22.0	15.6	18.6	21.1
	1000	15.6	18.8	21.1	13.5	16.5	19.0
2-Haro Strait	100	27.6	30.9	33.2	35.4	38.5	41.0
	200	21.5	24.7	27.0	27.8	30.8	33.3
	400	14.0	17.2	19.6	17.5	20.6	23.0
	600	10.5	13.9	16.2	11.8	14.7	17.2
	800	8.3	11.6	13.9	6.6	9.6	12.1
	1000	7.0	10.2	12.5	3.0	6.0	8.5
3-Race Rocks	100	27.1	30.3	32.6	33.9	37.0	39.5
	200	21.0	24.3	26.6	26.3	29.4	31.8
	400	14.5	17.8	20.1	16.8	19.8	22.2
	600	13.7	16.9	19.2	13.2	16.2	18.6
	800	13.8	17.0	19.2	10.5	13.4	15.9
	1000	12.0	15.2	17.5	7.6	10.5	13.0

Table D-2. Sound levels at 60 m receiver depth: Sound levels above detection threshold (dB re threshold) at the Southern Resident killer whale (SRKW) pod location for all the approach distance modelled and the 100 and 200 m results from Wladichuk and Hannay (2017). Results are provided for the two frequency ranges that killer whales use in acoustic signaling: 500 Hz to 14.1 kHz (typical range of calls) and 14.1 to 64 kHz (upper frequency range of whistles and echolocation clicks).

Site	**Approach distance (m)**	**Sound levels above detection threshold (dB re threshold)**					
		447 Hz to 14 kHz Communication-type			**14 kHz to 64 kHz Echolocation-type**		
		10 vessels	17 vessels	27 vessels	10 vessels	17 vessels	27 vessels
1-Swanson Channel	100	30.1	33.4	35.7	36.3	39.3	41.7
	200	25.8	29	31.3	31.6	34.6	37.0
	400	21.9	25.0	27.3	25.7	28.7	31.1
	600	18.2	21.4	23.6	19.9	22.9	25.3
	800	15.1	18.3	20.6	14.3	17.3	19.7
	1000	12.3	15.5	17.8	9.9	12.8	15.3
2-Haro Strait	100	29.6	32.8	35.1	35.8	38.8	41.3
	200	24.8	28.0	30.3	30.7	33.7	36.1
	400	19.6	22.8	25.1	23.8	26.8	29.2
	600	14.5	17.7	20.0	16.4	19.4	21.8
	800	9.9	13.2	15.5	9.3	12.2	14.7
	1000	7.6	10.8	13.1	5.2	8.1	10.6
3-Race Rocks	100	29.3	32.5	34.8	34.4	37.4	39.9
	200	24.5	27.6	29.9	29.4	32.4	34.8
	400	19.5	22.7	25.0	22.8	25.7	28.2
	600	16.2	19.4	21.7	16.7	19.7	22.2
	800	13.6	16.8	19.1	11.6	14.6	17.0
	1000	12.6	15.8	18.0	8.6	11.5	14.0