Cumulative Noise Modelling in the Salish Sea

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Executive Summary

This report presents a study of shipping noise in the Salish Sea, located along the southern coast of British Columbia. This study used a cumulative noise modelling procedure to determine the contribution of vessel noise to the ambient sound level distribution in the Salish Sea and was funded by MEOPAR. The modelling was performed to estimate the acoustic energy distribution due to ship traffic during January and July 2015 and January 2016 chosen as representations for seasonal variation in sound propagation. The analysis considered transmission loss modelling results produced from JASCO’s MONM model, ship traffic densities determined through satellite AIS data from exactEarth 2016, and vessel sound source levels based on vessel class from various published sources to model cumulative sound energy. Received sound levels at chosen receiver depths representing natural vertical variation in sound propagation were calculated to evaluate the sound exposure of Southern Resident Killer Whales (SRKW) and other marine fauna in the Salish Sea. Resulting sound exposure levels were also weighted using the hearing sensitivity (audiogram) of the SRKW. This model was used to describe the contribution of shipping noise to the ambient sound levels in the Salish Sea and their potential impact on the ecological soundscape of Southern Resident Killer Whales and other marine fauna.

The results of the cumulative noise modelling showed that sound exposure levels vary with vessel density across the Salish Sea. Commercial vessel traffic is the main contributor to high ambient sound levels in the Salish Sea. The influence of ship noise on ambient sound levels differs, however, considerably between summer and winter in most of the Salish Sea due to sound propagation conditions driven by water temperature in the upper layers of the water column (< 25 m). This leads to lower exposure levels of SRKW from shipping noise as the sound refracts downward, away from the shallower water depths that these whales are known to frequent. Whereas, lower surface temperatures during the winter cause sound waves to refract upward into shallower water leading to higher sound exposure levels when the water is cooler. While SRKW are present in the Salish Sea throughout the year, higher numbers are present in the summer. During the winter one pod in particular, J-Pod, is more often seen within the Salish Sea than K- and L-pods. While sound exposure due to noise from large commercial ships is lower in the summer than the winter, it si still the main source of anthropogenic noise. Furthermore, there are many more small vessels on the water in the summer and smaller vessels can be encountered near the whales, often engaged in whale watching. Future cumulative noise modelling should therefore include estimates of sound produced by these smaller watercrafts.

The combination of AIS vessel density assessment and high resolution underwater acoustic modelling allowed highly accurate estimation of noise contribution to ambient sound levels from large commercial vessels. Unfortunately, most smaller vessels are not equipped with an AIS transmitter and vessel density of small vessels needs to be assessed differently.
1. Introduction

This technical report has been prepared for the Noise Exposure to Marine Environments from Ships (NEMES) project and describes sound level assessments conducted in the Northeast Pacific in the Salish Sea. The NEMES project is funded by NCE MEOPAR and is a collaboration of researchers from multiple universities, government agencies, and private enterprises with a goal to investigate the impact of shipping noise on the marine environment on the coast of British Columbia. Ship tracking data gathered via satellite Automated Identification System (AIS) was compared to underwater sound data and underwater sound modelling was performed to determine the contribution of ship noise to the ambient sound levels in the Salish Sea, which is a high vessel traffic area but also habitat for the critically endangered Southern Resident Killer Whales (SRKW) and other marine fauna.

1.1. Underwater Noise and Shipping

The adverse effect of underwater noise on marine wildlife due to commercial shipping is a growing concern worldwide (Nowacek et al. 2007, Tyack 2008, Allen et al. 2012), and possibly even greater in areas that show high levels of commercial and recreational vessel traffic, such as the Salish Sea (Figure 1).

It is expected that the construction of new marine terminals and other developments will attract more commercial and fishing vessel traffic to the Salish Sea. Larger numbers of vessels will generate increased levels of underwater sound that otherwise would not occur. One of the concerns is that many of the shipping routes of the new projects pass through key habitat of endangered, threatened or otherwise at-risk marine fauna. It is especially important to assess the potential impact of increased vessel traffic noise on marine fauna in areas that are considered critical for the survival of populations and species. Great parts of the Salish Sea has been designated critical habitat for SRKW and as such is protected under the Species of Risk Act (SARA) in Canada and the Endangered Species Act in the United States. Other marine fauna, such as members of a humpback whale population that makes increasing use of the Salish Sea during foraging, are also considered endangered in the United States and currently still listed under SARA in Canadian waters. Rockfish conservation areas and MPAs protecting other marine fauna can also be found within the boundaries of the Salish Sea.

Recent advances in computerized underwater noise modelling have led to the development of tools that can accurately predict the accumulation of sound from many vessels over time. A landmark computer modelling study (Erbe et al. 2012) examined yearly cumulative noise levels from all shipping activity over a large area of British Columbia’s coast. That study used relatively low-resolution vessel density data and its results were limited in its suitability to accurately assess noise effects on marine wildlife. However, Erbe et al.’s paper demonstrated that underwater noise models using higher-resolution vessel density data can be applied for that purpose. The results of this modelling can assist researchers and managers in the development of marine conservation plans.

For this study, JASCO Applied Sciences (JASCO) employed an advanced acoustic propagation model, Marine Operations Noise Model (MONM, by JASCO), in combination with high-resolution satellite AIS vessel tracking data provided by exactEarth to estimate cumulative noise in the Salish Sea, a key focus area within the NEMES project.

This report presents results from the assessment of ambient sound levels and ship contributions integrated in cumulative noise distribution maps of the Salish Sea.

1.1.1. Cumulative Ship Noise in the Salish Sea

The Salish Sea is one of the busiest ship traffic areas along the west coast of North America (Figure 1). There are also several whale species that inhabit the Salish Sea, such as the humpback, grey, minke, and false killer whales; however, the Southern Resident Killer Whale population (SRKW) is the only one listed as Endangered (in Canada and the US) and therefore receives the most attention. To assess the
noise impact on whales from shipping, reasonable predictions of shipping noise levels over time in areas important to the whales need to be determined.

Figure 1. Cumulative yearly ship traffic density in 2008 along the BC coast. The coordinates are in UTM in [10^5m] scale. Extracted from Figure 1 in Erbe et al. (2012). Red rectangle depicts the area that includes the Salish Sea.

Assessing noise impact on marine life from shipping requires the consideration of moving sound sources (ships) with varying sound source levels and moving receivers (e.g. whales). One way of approaching this problem is to create sound level maps of the entire study area based on information about ship densities and the variation thereof. For this study, a cumulative noise model (noise levels are integrated over a specific time period, e.g. a day, a week, a month, or a year) was chosen to provide sound level maps for the Salish Sea. The cumulation period was one month and the noise levels were modelled at two depths over two months representing two seasons, summer (July) and winter (January). Due to quite different weather patterns during summer and winter, considerable variances in sound propagation are expected for the two chosen months. The distribution of ambient sound levels and the ship noise contribution to these levels will be effected by different sound propagation. Furthermore the seasonal propagation effects will differ with water depths due to temperature, salinity and pressure gradients. The cumulative sound levels were modelled at two receiver depths during these two months. The sound propagation at the shallow depth (10m) is likely more effected by seasonal weather than the deeper receiver depth (50m) due to the prominent influence of water temperature on sound speed. At 10m depth water is considerable warmer during the summer than the winter and this will likely increase the sound speed during the summer (see Appendix 6.A.3.2) In addition, the two receiver depths (10 m and 50 m) represent typical diving depths of SRKW. To assess sound as it is perceived by SRKW, the modelled sound levels are reported as unweighted levels and killer whale audiogram weighted levels. Unweighted levels are
reported because they reflect the full frequency spectrum in which the ship noise appears. Holt et al. (2009) showed that SRKW responded to elevated noise levels with an increase of sound amplitude of their calls (Lombard response). The study did not specify which parts of the noise frequency spectrum may have been responsible for the response but most of the increased ambient sound levels was driven by low frequency noise in their study. Because it is currently unknown how noise in frequency bands outside the good hearing range of SRKW can affect them it is cautionary to consider that higher sound levels those frequency bands may impact the whales. Audiogram weighting is a frequency weighting of the noise signal that adjusts the received noise levels across the frequency range of the noise signal to match the hearing sensitivity curve of the receiver at each of the frequency bands in which noise occurs. Audiogram weighting is done to assess the potential of noise to mask important signals, such as communication and echolocation signals.
2. Methods

JASCO’s cumulative noise model (Figure 2) computed the total sound energy emitted by shipping for three temporal periods (Jan 2015, July 2015, Jan 2016) for a comparison between summer and winter. The model incorporated monthly databases of traffic density and speed from satellite AIS database (ExactEarth 2016). Appendix A describes the inputs and methods of the cumulative noise model in detail. The cumulative noise model was verified by comparing assorted measured received sound levels to the model received levels (Appendix A.6).

The boundaries of the modelling area (Figure 3) were selected to encompass the primary shipping lanes and regions that could be ensonified above ambient sound levels by vessel traffic, as well as to help quantify exposure of SRKWs to noise within the extent of their critical habitat.
Figure 3. Overview of cumulative noise modelling area. This location encompasses the boundaries of the Salish Sea, which wraps around the southern end of Vancouver Island, British Columbia.
3. Results

Long-term spatial distribution of sound energy from shipping activities in the Salish Sea in winter and summer are presented as monthly mean sound energy noise maps (Figure 4 to Figure 9). The maps depict cumulative shipping noise assessed for ship densities in a 800 m × 800 m grid cell size pattern over the study area. The colours show the average sound energy per grid cell over the period of a month for each temporal period (January 2015, July 2015, and January 2016) based on average sound exposure during a 24-hour period. Both unweighted sound levels and SRKW audiogram-weighted noise maps are shown. Audiogram-weighted maps reflect sound levels as they are perceived by SRKW.

Figure 4. January 2015: unweighted monthly mean shipping SPL noise levels for receiver depth of (left) 10 m and (right) 50 m. Grid coordinates are BC Albers (NAD83).

Figure 5. July 2015: unweighted monthly mean shipping SPL noise levels for receiver depth of (left) 10 m and (right) 50 m. Grid coordinates are BC Albers (NAD83).
Figure 6. January 2016: unweighted monthly mean shipping SPL noise levels for receiver depth of (left) 10 m and (right) 50 m. Grid coordinates are BC Albers (NAD83).

Figure 7. January 2015: SRKW audiogram-weighted monthly mean shipping SPL noise levels for receiver depth of 10 m (left) and 50 m (right). Grid coordinates are BC Albers (NAD83).

Figure 8. July 2015: SRKW audiogram-weighted monthly mean shipping SPL noise levels for receiver depth of (left) 10 m and (right) 50 m. Grid coordinates are BC Albers (NAD83).
Linear mean and interquartile range (IQR) sound levels and total average squared sound pressure were computed over the entire cumulative study area and within 4 km distance of the inbound and outbound shipping routes (Table 1) and (Table 2). The four kilometer distance was chosen to delineate a maximum distance at which noise from passing vessels could have levels rising above typical ambient levels. These values are used to quantitatively compare the contribution of shipping noise between two years (January 2015 and January 2016) and two seasons (between January 2015 and July 2015).

Table 1. Linear mean and interquartile range (IQR) of shipping noise levels over the entire cumulative noise study area and within 4 km distance of shipping lanes in the Strait of Georgia.

<table>
<thead>
<tr>
<th>Receiver depth (m)</th>
<th>Monthly Leq (dB re 1 µPa)</th>
<th>SRKW Audiogram-weighted Leq (dB re HT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>IQR</td>
</tr>
<tr>
<td>Entire cumulative noise study area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>116.41/116.60</td>
<td>9.67/10.36</td>
</tr>
<tr>
<td>50</td>
<td>113.91/114.03</td>
<td>10.32/10.93</td>
</tr>
<tr>
<td>Within 4 km of Roberts Bank shipping routes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>118.53/118.54</td>
<td>2.18/2.15</td>
</tr>
<tr>
<td>50</td>
<td>116.80/116.76</td>
<td>3.56/3.66</td>
</tr>
</tbody>
</table>

Table 2. Total average squared sound pressure for entire study area and within 4 km distance of the shipping lanes in the Strait of Georgia

<table>
<thead>
<tr>
<th>Receiver Depth (m)</th>
<th>Average Total Mean Squared Sound Pressure (kPa²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entire Study Area</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.17/1.22</td>
</tr>
<tr>
<td>50</td>
<td>0.66/0.68</td>
</tr>
<tr>
<td>Within 4 km of Shipping Lanes in Strait of Georgia</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.91/1.91</td>
</tr>
<tr>
<td>50</td>
<td>1.28/1.27</td>
</tr>
</tbody>
</table>
Figure 10: Average Level Equivalents (Leq) for different vessel classes (VC) during January 2015, July 2015, and January 2016. Top two diagrams show levels for the entire study area at 10 and 50 meters respectively. The bottom two diagrams show levels within 4 km of the shipping lanes in the Strait of Georgia at 10 and 50 meters respectively.
4. Discussion and Conclusion

The noise maps (Figure 4 to Figure 9) show the modelled spatial distribution of underwater noise originating from shipping traffic throughout in the study area. Brightly-coloured regions on the noise maps generally correspond to locations with high densities of vessel traffic, such as shipping lanes and ferry routes. Ferry routes are the most prominent features on the cumulative noise maps, due to the large number of vessel trips concentrated in relatively small areas. Shipping lanes are also clearly visible in the noise maps along corridors where merchant traffic is concentrated. On the audiogram-weighted maps, shipping noise decays more rapidly around ferry routes and shipping corridors than on the unweighted maps. This is a frequency-dependent effect, which is a consequence of the stronger sound attenuation (i.e. higher TL) at frequencies where killer whales have their best hearing sensitivity.

By comparing results from January 2016 to January 2015, the overall increase in cumulative shipping noise levels is very small (< 1 dB, Table 1). This is due to the large amount of existing vessel traffic in the study area.

Except along seasonal ferry routes, sound levels were generally higher in January than in July. This is mainly because of differences in the sound speed profiles between these months, rather than the changes in vessel traffic density.

In winter (January), the thermocline in the surface layer (i.e. typically above 25 m depth in the Salish Sea) has a very strong effect on sound transmission. In January, low water temperatures near the sea surface create a surface sound channel where sound waves introduced near the surface bend upward while propagating through the water. This concentrates sound energy in the upper layers of the water column.

In summer (July), higher temperatures in the upper water column create a downward refracting (sound wave bending) layer that directs sound energy towards the seabed where it is absorbed. The seasonal propagation effect is greatest in the Strait of Georgia, where softer, more acoustically absorptive sediments combined with the downward-refracting sound speed profile in July increase the rate of sound transmission loss relative to January conditions.

As a result of the sound speed differences in the upper layer, shipping noise levels are predicted to be higher in winter than in summer throughout the study area. This effect is more pronounced due to the 10 m receiver depth used in the TL model. The seasonal change in transmission loss is expected to be smaller for deeper receiver depths, below the surface layer, as shown in the results of 50 m receiver depth.

This difference in depth-dependent sound energy distribution is generally beneficial for SRKW who spend more time in the Salish Sea during the summer and fall when Chinook salmon return to the area to spawn in the Fraser River system. Some SRKW pods, however, appear to spend time in the Salish Sea both in summer and winter and those pods are likely exposed to higher shipping sound energy during the winter. Furthermore, small vessel traffic such as whale watch vessels and recreational boats as well as fishing vessels are not included in the cumulative noise model. Noise from those vessels, particularly the noise generated during whale watching activities, needs to be considered to get a more accurate picture of noise exposure.
5. Acknowledgements

JASCO Applied Sciences would like to acknowledge the Institute of Ocean Sciences for CTD data to calculate sound speeds, MEOPAR for funding to support this work, and Casey Hilliard from ExactEarth for supplying the satellite AIS data.
6. 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 conversion of acoustic energy into heat, which is captured by insulation.

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.

attenuation
The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium.

audiogram
A graph of hearing threshold level (sound pressure levels) as a function of frequency, which describes the hearing sensitivity of an animal over its hearing range.

audiogram weighting
The process of applying an animal’s audiogram to sound pressure levels to determine the sound level relative to the animal’s hearing threshold (HT). Unit: dB re HT.

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.

compressional wave
A mechanical vibration wave in which the direction of particle motion is parallel to the direction of propagation. Also called primary wave or P-wave.

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).

duty cycle
The time when sound is periodically recorded by an acoustic recording system.

ensonified
Exposed to sound.

fast Fourier transform (FFT)
A computationally efficiently algorithm for computing the discrete Fourier transform.

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.
geoacoustic
Relating to the acoustic properties of the seabed.

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

hydrophone
An underwater sound pressure transducer. A passive electronic device for recording or listening to underwater sound.

Interquartile range (IQR)
A measure of statistical dispersion, equal to the difference between the 75th and 25th percentiles.

mysticete
Mysticeti, a suborder of cetaceans, use their baleen plates, rather than teeth, to filter food from water. They are not known to echolocate, but use sound for communication. Members of this group include rorquals (Balaenopteridae), right whales (Balaenidae), and gray whales (Eschrichtius robustus).

noise
Any kind of disruption that interferes with the transmission and interpretation of information from a sender to a receiver.

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

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

pressure, hydrostatic
The pressure at any given depth in a static liquid that is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid. Unit: pascal (Pa).

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.

signature
Pressure signal generated by a source.

sound
A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.
**sound channel**
A horizontal layer of water where due to the water properties, sound waves become “trapped” in a propagation path.

**sound exposure**
Time integral of squared, instantaneous frequency-weighted sound pressure over a stated time interval or event. Unit: pascal-squared second (Pa²·s) (ANSI S1.1-1994 R2004).

**sound exposure level (SEL)**
A cumulative measure related to the sound energy in one or more pulses. Unit: dB re 1 µPa²·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 field**
Region containing sound waves (ANSI S1.1-1994 R2004).

**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:

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

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. Non-rectangular time window functions may be applied during calculation of the rms value, in which case the SPL unit should identify the window type.

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

**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 µPa²·s (sound exposure level).

**spectrogram**
A visual representation of acoustic amplitude compared with time and frequency.

**surface duct**
The upper portion of a water column within which the sound speed profile gradient causes sound to refract upward and therefore reflect off the surface resulting in relatively long range sound propagation with little loss.

**thermocline**
A layer in a body of water with a steep vertical temperature gradient.

**transmission loss (TL)**
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.
upward refraction
When sound rays bend upward while propagating through the water.
Literature Cited


Appendix A. Cumulative Noise Model

In the modelled area, the acoustic sources and receivers were assumed to be at the center of each 800 × 800 m grid cell. The 1/3-octave-band SEL in each map cell was computed as the total ship noise energy originating from all adjacent map cells within a 75 km radius. The maximum propagation range from the sources was limited to 75 km to cover the width of channels where vessels transited. SEL is a measure of the total acoustic energy that is received at some location over a specific time duration, and it is the standard metric for quantifying the total sound exposure of marine organisms.

To compute TL between pairs of cells, geometric rays were projected from each cell where the density in a given vessel class was non-zero (the source cell) to all nearby cells (the receiver cells) not blocked by land within 75 km. The 1/3-octave-band TL between source and receiver cells was then interpolated from the tabulated TL versus range curves, based on the midpoint separation of the cells and the TL 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 TL was computed as the weighted-average value:

$$\text{TL}_{ij} = -10 \log_{10} \sum_{n}\left(10^{-\text{TL}^{(n)}(r_j)/10} \times d_n / r_{ij}\right)$$

(4)

In the above equation, $r_{ij}$ is the source-receiver separation, $\text{TL}^{(n)}$ is the tabulated transmission 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, TL 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:

$$\text{TL}_{ii} = 10 \log_{10} \left(4 \pi / D^2\right) = 20 \log_{10} D - 11$$

(5)

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

The total ship noise energy transmitted from each source cell $i$ to receiver cell $j$ was computed using the SL and corresponding cell-to-cell TL values summed over all vessel classes and adjusted for vessel speed and cumulative vessel class time in each source cell:

$$E_{ij} = \sum_{k}10^{\left(SL_k - \text{TL}_{ij}\right)/10} \times \left(v_k / v_{\text{ref}}\right)^6 \times T_k$$

(6)

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 sixth-power law. 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 75 km range, plus the 1/3-octave-band contribution of wind-driven ambient noise:

$$\text{SEL}_j = 10 \log_{10} \left[\frac{T_{\text{mon}} \times 10^{\text{AN}/10} + \sum_{j}E_j}{\text{SEL}_{mon}}\right]$$

(7)

In the above equation, $T_{\text{mon}}$ is the number of seconds in the month and $AN$ is the SPL of the ambient noise. The mean monthly $\text{Leq}$ was equal to the total noise energy in all 1/3-octave-bands divided by the number of seconds in the month (i.e., $\text{Leq} = \text{SEL} - 10 \times \log_{10}(T_{\text{mon}})$).
A.1. Vessel Data

Monthly maps of ship traffic density and speed were provided by University of Victoria based on satellite AIS database ExactEarth, for January 2015 and 2016, and July 2015. Monthly data for all 21 vessel classes (Table 3) were provided on an 800 m x 800 m grid in BC Albers projection, including cumulative time occupied by vessels in a specific class per each grid cell, and corresponding average speed. Example plots of density and average speed are shown in Figure 11.

Vessel source levels (SLs) were compiled in 1/3-octave-bands from 10 Hz to 63.1 kHz (Figure 12) – the frequency range that captures the hearing sensitivities of marine mammals and fishes found in the study area. The broadband SL for each vessel class is given in Table 3.

Table 3. Vessel code classification categories, modelled source depths, and SLs.

<table>
<thead>
<tr>
<th>Vessel type</th>
<th>Class ID</th>
<th>Modelled source depth (m)</th>
<th>Broadband SL (dB re 1 µPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferries &lt; 50 m</td>
<td>C1A</td>
<td>2</td>
<td>173.3</td>
</tr>
<tr>
<td>Ferries &gt; 50 m</td>
<td>C1B</td>
<td>2</td>
<td>173.3</td>
</tr>
<tr>
<td>Passenger &lt; 100 m</td>
<td>C2A</td>
<td>6</td>
<td>152.3</td>
</tr>
<tr>
<td>Passenger &gt; 100 m</td>
<td>C2B</td>
<td>6</td>
<td>166.3</td>
</tr>
<tr>
<td>Container ships &lt; 200 m</td>
<td>C3A</td>
<td>6</td>
<td>178.6</td>
</tr>
<tr>
<td>Container Ships &gt;200 m</td>
<td>C3B</td>
<td>6</td>
<td>178.6</td>
</tr>
<tr>
<td>Bulk Carriers &lt; 200 m</td>
<td>C4A</td>
<td>6</td>
<td>167.1</td>
</tr>
<tr>
<td>Bulk Carriers &gt; 200 m</td>
<td>C4B</td>
<td>6</td>
<td>170.9</td>
</tr>
<tr>
<td>Crude Oil Tankers &lt; 200 m</td>
<td>C5A</td>
<td>6</td>
<td>161.2</td>
</tr>
<tr>
<td>Crude Oil Tankers &gt; 200 m</td>
<td>C5B</td>
<td>6</td>
<td>161.2</td>
</tr>
<tr>
<td>Reefers</td>
<td>C6</td>
<td>6</td>
<td>170.9</td>
</tr>
<tr>
<td>Chemical Products Carriers</td>
<td>C7</td>
<td>6</td>
<td>170.9</td>
</tr>
<tr>
<td>Vehicle Carriers</td>
<td>C10</td>
<td>6</td>
<td>170.9</td>
</tr>
<tr>
<td>Tankers</td>
<td>C12</td>
<td>6</td>
<td>161.2</td>
</tr>
<tr>
<td>Fishing Vessels</td>
<td>C13</td>
<td>2</td>
<td>146.2</td>
</tr>
<tr>
<td>Government/Research</td>
<td>C14</td>
<td>2</td>
<td>146.7</td>
</tr>
<tr>
<td>Naval Vessels</td>
<td>C15</td>
<td>2</td>
<td>146.7</td>
</tr>
<tr>
<td>Recreational Vessels</td>
<td>C16</td>
<td>2</td>
<td>144.3</td>
</tr>
<tr>
<td>Tug &lt; 50 m</td>
<td>C17A</td>
<td>2</td>
<td>167.5</td>
</tr>
<tr>
<td>Tug &gt; 50 m</td>
<td>C17B</td>
<td>2</td>
<td>167.5</td>
</tr>
<tr>
<td>Dredgers</td>
<td>C18</td>
<td>2</td>
<td>167.5</td>
</tr>
<tr>
<td>High Speed Ferry</td>
<td>C19</td>
<td>2</td>
<td>166.3</td>
</tr>
<tr>
<td>Other</td>
<td>C21</td>
<td>2</td>
<td>145.8</td>
</tr>
</tbody>
</table>
Figure 11. Vessel monthly density (left) and average speed (right) for Class C3B (Container Ship >200 m) of January 2015 (top), July 2015 (middle), and Jan 2016 (bottom).
Figure 12. Modelled 1/3-octave-band source levels for all vessel classes. Descriptions of vessel classes are shown in Table 3 (sources: Cybulski (1977), Arveson and Vendittis (2000), MCR International (2011), McKenna et al. (2012), Mouy et al. (2012), (MacGillivray et al. 2014), Veirs et al. (2016))

Table 4: References listed by vessel class

<table>
<thead>
<tr>
<th>Vessel class</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>MacGillivray, et al. (2014), Mouy et al. (2012)</td>
</tr>
<tr>
<td>C3</td>
<td>McKenna et al. (2012), MacGillivray, et al. (2014)</td>
</tr>
<tr>
<td>C5, C12</td>
<td>Cybulski (1977), McKenna et al. (2012), MacGillivray, et al. (2014)</td>
</tr>
<tr>
<td>C13</td>
<td>Veirs et al. (2016)</td>
</tr>
<tr>
<td>C14, C15</td>
<td>Veirs et al. (2016)</td>
</tr>
<tr>
<td>C16</td>
<td>Veirs et al. (2016)</td>
</tr>
<tr>
<td>C17, C18</td>
<td>MacGillivray, et al. (2014)</td>
</tr>
<tr>
<td>C21</td>
<td>Veirs et al. (2016)</td>
</tr>
</tbody>
</table>
A.2. Transmission Loss Model

The study area was divided into 20 zones (Figure 13 and
Table 5) based on the four geoacoustic regions and five different water depth ranges. MONM was used to compute curves of TL versus range for each zone in 1/3-octave-bands between 10 Hz and 5 kHz, out to a maximum distance of 100 km from the source (Figure 14). TL for each zone was modelled assuming uniform bathymetry (i.e., range-independent water depth) for a receiver depth of 10 m and 50 m. TL was averaged over five frequencies inside each 1/3-octave-band and the TL versus range curves were smoothed inside a 200 m window to remove fine-scale interference effects. At high frequencies, mean TL computed by MONM is expected to converge to a high frequency (i.e., ray-theoretical) limit; therefore, TL values for bands above 5 kHz were approximated by adjusting TL at 5 kHz to account for frequency-dependent absorption at higher frequencies (François and Garrison 1982a, François and Garrison 1982b). For each zone, TL was modelled using two different sound speed profiles, representing July and January conditions, and two source depths of 2 m and 6 m, representing the nominal acoustic emission centres of small and large draft vessels (see Table 3).
Table 5. Description of zone numbers and corresponding geoacoustics and water depths.

<table>
<thead>
<tr>
<th>Zone Number</th>
<th>Water Depth Range (m)</th>
<th>Modelled Water Depth (m)</th>
<th>Geoacoustic Region</th>
<th>Zone Number</th>
<th>Water Depth Range (m)</th>
<th>Modelled Water Depth (m)</th>
<th>Geoacoustic Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-50</td>
<td>25</td>
<td>Strait of Georgia</td>
<td>11</td>
<td>100-150</td>
<td>125</td>
<td>East Strait of Juan de Fuca</td>
</tr>
<tr>
<td>2</td>
<td>0-50</td>
<td>25</td>
<td>Haro Strait and Rosario Strait</td>
<td>12</td>
<td>100-150</td>
<td>125</td>
<td>West Strait of Juan de Fuca</td>
</tr>
<tr>
<td>3</td>
<td>0-50</td>
<td>25</td>
<td>East Strait of Juan de Fuca</td>
<td>13</td>
<td>150-200</td>
<td>175</td>
<td>Strait of Georgia</td>
</tr>
<tr>
<td>4</td>
<td>0-50</td>
<td>25</td>
<td>West Strait of Juan de Fuca</td>
<td>14</td>
<td>150-200</td>
<td>175</td>
<td>Haro Strait and Rosario Strait</td>
</tr>
<tr>
<td>5</td>
<td>50-100</td>
<td>75</td>
<td>Strait of Georgia</td>
<td>15</td>
<td>150-200</td>
<td>175</td>
<td>West Strait of Juan de Fuca</td>
</tr>
<tr>
<td>6</td>
<td>50-100</td>
<td>75</td>
<td>Haro Strait and Rosario Strait</td>
<td>16</td>
<td>150-200</td>
<td>175</td>
<td>West Strait of Juan de Fuca</td>
</tr>
<tr>
<td>7</td>
<td>50-100</td>
<td>75</td>
<td>East Strait of Juan de Fuca</td>
<td>17</td>
<td>&gt; 200</td>
<td>225</td>
<td>Strait of Georgia</td>
</tr>
<tr>
<td>8</td>
<td>50-100</td>
<td>75</td>
<td>West Strait of Juan de Fuca</td>
<td>18</td>
<td>&gt; 200</td>
<td>225</td>
<td>Haro Strait and Rosario Strait</td>
</tr>
<tr>
<td>9</td>
<td>100-150</td>
<td>125</td>
<td>Strait of Georgia</td>
<td>19</td>
<td>&gt; 200</td>
<td>225</td>
<td>East Strait of Juan de Fuca</td>
</tr>
<tr>
<td>10</td>
<td>100-150</td>
<td>125</td>
<td>Haro Strait and Rosario Strait</td>
<td>20</td>
<td>&gt; 200</td>
<td>225</td>
<td>West Strait of Juan de Fuca</td>
</tr>
</tbody>
</table>
Figure 13. Map of TL zones (1-20) used for modelling sound propagation in the study area.
Figure 14. Example plots of modelled TL vs. range and 1/3-octave-band frequency for zone 5. Receiver depths of 10 m (top) and 50 m (bottom) for January (left) and July (right). Source depth is 6 m.

A.3. Environment parameters

A.3.1. Bathymetry

Bathymetry for the study area was obtained from NOAA digital elevation model (NGDC 2013) and Canadian Hydrographic Service (CHS) digital elevation map from Nautical Data International Inc. (NDI). The bathymetry was modelled on a 20 m resolution BC Albers grid (Figure 3).

A.3.2. Sound speed profiles

Water column sound speed profiles for the study area for January and July were computed from historical temperature and salinity data obtained from the DFO Institute of Ocean Sciences (Patricia Bay) Ocean Sciences Division. Monthly average sound speed profiles (Figure 15) were computed from approximately 120 historical temperature-salinity casts for January and July, collected from 2006 to 2010. Depth profiles
of temperature and salinity were converted to speed of sound in water (units m/s) using the following formula (Clay and Medwin 1977):

\[
c = 1449.2 + 4.6 \times T - 0.055 \times T^2 + 0.00029 \times T^3 + (1.34 - 0.01 \times T)(S - 35) + 0.016 \times z
\]  

(3)

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

Figure 15. January and July sound speed profile data for the study area.

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, whereas wind-driven mixing in winter combined with atmospheric cooling in results in a strong surface-duct profile. The mean sound speed profiles for January and July were used to represent the acoustic properties of the water column in the model. Analysis of the sound speed profiles showed no strong north-south trend in the data, therefore single sound speed profiles were assumed throughout the study area for each month.

A.3.3. Geoacoustics

The geoacoustic properties of the seabed strongly influence transmission 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 a combination of geoacoustic inversion results from transmission loss measurements (Warner et al. 2013) and a review of the scientific literature (Hamilton 1980, Erbe et al. 2012). The study area was divided into four geoacoustic regions based on bottom type, to account for geographic variation inside the study area: Strait of Georgia, Haro Strait, East Strait of Juan de Fuca, and West Strait of Juan de Fuca. A different set of geoacoustic properties was used to represent each region (}
Table 6).
Table 6. Seabed geoacoustic profiles for the four geoacoustic regions.

<table>
<thead>
<tr>
<th>Depth (mbsf)</th>
<th>Sediment Type</th>
<th>Compressional Speed (m/s)</th>
<th>Density (g/cm$^3$)</th>
<th>Compressional Attenuation (dB/λ)</th>
<th>Shear Speed (m/s)</th>
<th>Shear Attenuation (dB/λ)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strait of Georgia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-100</td>
<td>clayey-silt</td>
<td>1502-1602</td>
<td>1.54</td>
<td>0.61</td>
<td>125.0</td>
<td>2.2</td>
</tr>
<tr>
<td>&gt; 100</td>
<td>bedrock</td>
<td>2275</td>
<td>1.90</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Haro Strait and Rosario Strait</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-50</td>
<td>sand-silt-clay</td>
<td>1541-1591</td>
<td>1.80</td>
<td>0.72</td>
<td>250</td>
<td>1.2</td>
</tr>
<tr>
<td>&gt; 50</td>
<td>bedrock</td>
<td>2275</td>
<td>1.90</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>East Strait of Juan de Fuca</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-50</td>
<td>silt</td>
<td>1558-1608</td>
<td>1.64</td>
<td>0.83</td>
<td>250</td>
<td>3.4</td>
</tr>
<tr>
<td>&gt; 50</td>
<td>bedrock</td>
<td>2275</td>
<td>1.90</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>West Strait of Juan de Fuca</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0-50</td>
<td>sand</td>
<td>1713-1763</td>
<td>1.94</td>
<td>0.90</td>
<td>500</td>
<td>3.4</td>
</tr>
<tr>
<td>&gt; 50</td>
<td>bedrock</td>
<td>2275</td>
<td>2.20</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For more information on bottom classification please consult the British Columbia Marine Ecological Classification: Marine Ecossections and Ecounits report available from the Province of British Columbia [https://www.crownpub.bc.ca/Product/Details/7680000657_S](https://www.crownpub.bc.ca/Product/Details/7680000657_S). A map of bottom classifications is also available in Erbe et al. (2012).

### A.4. Ambient Noise

In shallow water, with the absence of vessel traffic, ambient noise is dominated by wind-driven surface noise at all frequencies (Urick 1984). The spectrum of wind-generated ambient noise was based on the measurements by (Warner et al. 2013). Ambient noise spectrum levels at the 95% exceedance level ($L_{95}$), corresponding to the lowest fifth percentile of the data, were averaged between the two measurement locations (Warner et al. 2013) to obtain a representative spectrum for wind-generated noise (Figure 16).
A.5. Audiogram Weighting

The potential for anthropogenic noise to affect a marine animal is reduced when the animal cannot hear the sound well, with an exception for sound pressures high enough to cause physical injury. For sound levels that are below physical injury thresholds, frequency weighting based on audiograms may be applied to weight the importance of sound levels at particular frequencies in a manner reflective of an animal’s sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

Audiograms represent the hearing threshold for tonal sounds (single-frequency sinusoidal signals) as a function of the tone frequency. These species-specific sensitivity curves are generally U-shaped, with higher hearing thresholds at low and high frequencies. Noise levels above hearing threshold were calculated by subtracting species-specific audiograms from the received 1/3-octave-band noise levels. The audiogram-weighted 1/3-octave-band levels were 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. Sound levels less than 0 dB re HT are below the typical hearing threshold for a species and are, therefore, likely inaudible to those animals.

In this study, audiogram weighting was applied for resident killer whales (Orcinus orca) (Figure 17) to sound levels generated by the cumulative noise model. The resident killer whale audiogram 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 these animals have a higher hearing threshold at frequencies outside their hearing range than the terminal trend of their audiogram would predict.
A.6. Cumulative Noise Modelling Validation

To validate the cumulative noise model results, modelled received sound levels were compared to assorted vessel measurements in the Salish Sea, as shown in Figure 18. Most of the modelled sound levels were representative of the measured levels. Modelled received levels of two fishing vessels were lower than the measured levels at ranges greater than 1500 m. One of the measured bulk carriers had higher measured levels than modelled levels at all ranges. Bulk carriers also have a large difference between aft and forward received levels, unlike tugs, which were the most similar of all compared vessel types.
Figure 18. Modelled and measured received sound levels in the Salish Sea. The two lines of measured results on each plot represent the aft and forward direction from the vessel, with the higher levels usually occurring in the aft direction.