APPENDIX 9.8-A
Construction and Terminal Activity Underwater Noise Modelling Study Technical Report

This page is intentionally left blank

ROBERTS BANK TERMINAL 2
TECHNICAL REPORT

Underwater Noise
Construction Activities and Terminal Vessel Operations Noise Modelling Study

TECHNICAL REPORT/TECHNICAL DATA REPORT DISCLAIMER

The Canadian Environmental Assessment Agency determined the scope of the proposed Roberts Bank Terminal 2 Project (RBT2 or the Project) and the scope of the assessment in the Final Environmental Impact Statement Guidelines (EISG) issued January 7, 2014. The scope of the Project includes the project components and physical activities to be considered in the environmental assessment. The scope of the assessment includes the factors to be considered and the scope of those factors. The Environmental Impact Statement (EIS) has been prepared in accordance with the scope of the Project and the scope of the assessment specified in the EISG. For each component of the natural or human environment considered in the EIS, the geographic scope of the assessment depends on the extent of potential effects.

At the time supporting technical studies were initiated in 2011, with the objective of ensuring adequate information would be available to inform the environmental assessment of the Project, neither the scope of the Project nor the scope of the assessment had been determined.

Therefore, the scope of supporting studies may include physical activities that are not included in the scope of the Project as determined by the Agency. Similarly, the scope of supporting studies may also include spatial areas that are not expected to be affected by the Project.

This out-of-scope information is included in the Technical Report (TR)/Technical Data Report (TDR) for each study, but may not be considered in the assessment of potential effects of the Project unless relevant for understanding the context of those effects or to assessing potential cumulative effects.

EXECUTIVE SUMMARY

The Roberts Bank Terminal 2 Project (RBT2 or Project) is a proposed new three-berth marine terminal at Roberts Bank in Delta, B.C. that could provide 2.4 million TEUs (twenty-foot equivalent units) of additional container capacity annually. The Project is part of Port Metro Vancouver's Container Capacity Improvement Program, a long-term strategy to deliver projects to meet anticipated growth in demand for container capacity to 2030.

Underwater noise produced by construction and operation of RBT2 has the potential to disturb or injure nearby marine fauna. JASCO Applied Sciences Ltd., under contract to Hemmera, performed a computer modelling study to predict the expected noise emissions and zones of potential disturbance from terminal construction and vessel operation activities associated with RBT2.

Fifteen modelling scenarios were considered, including ten pile driving scenarios (i.e., six impact and four vibratory pilling), a vibro-densification scenario, two dredging scenarios, and two vessel operation scenarios (i.e., container ship berthing and approaching terminal). Although vibratory methods are planned, impact piling methods were modelled because the need for this method cannot be ruled out at this stage of Project design. All modelling scenarios considered the influences of local bathymetry, ocean sound speed profiles, and seabed geoacoustics on waterborne sound propagation.

Impact pile driving was the only activity that had the potential to generate sound levels sufficiently high to injure marine mammals or fish. Several science-based injury thresholds were modelled for impact pile driving. For marine mammals, the U.S. National Marine Fisheries Service (NMFS) (MMPA 2007) thresholds for Level A harassment (potential to injure a marine mammal) and the Southall et al. (2007) thresholds for auditory injury were assessed. For fish, the Fisheries Hydroacoustic Working Group (FHWG 2008) interim injury criteria and the Halvorsen et al. (2011) experimental injury thresholds were assessed. Several injury thresholds are based on cumulative sound exposure; however, since pile driving duration (vibratory and impact) for individual piles are not yet known, distances to acoustic injury thresholds were modelled for three durations (i.e., 1 min, 10 min, and 100 min) over a single day for impact pile driving (see Table below).

The effectiveness of potential mitigation measures was considered. Using the example of bubble curtains, underwater sound levels generated by impact pile driving could be reduced such that modelling indicated that the average distance to injury thresholds could be reduced by 76% for marine mammals and 82% for fish.

Summary of Maximum Radii (R95%) to Injury Thresholds for Impact Pile Driving

Total Duration of Impact Pile Driving over 24 hours		1 min	10 min	100 min
Fish	206 dB peak SPL[a]	38 m	38 m	38 m
	210 dB SEL (flat)[b]	n/r[c]	n/r	50 m
	187 dB SEL (flat)[a]	70 m	250 m	1,020 m
Pinnipeds	190 dB rms SPL[d]	40 m	40 m	40 m
	218 dB peak SPL[e]	9 m	9 m	9 m
	186 dB SEL (M-weighted)[e]	80 m	270 m	1,170 m
Cetaceans	180 dB rms SPL[d]	120 m	120 m	120 m
	230 dB peak SPL[e]	2 m	2 m	2 m
	198 dB SEL (High-frequency cetaceans)[e]	n/r	50 m	210 m
	198 dB SEL (Low-frequency cetaceans)[e]	n/r	60 m	220 m
	198 dB SEL (Mid-frequency cetaceans)[e]	n/r	60 m	220 m

[a] Fisheries Hydroacoustic Working Group (2008) - Interim criteria for injury to fish from pile driving activities.
[b] Halvorsen et al. (2011) - Predicting and mitigating hydroacoustic impacts on fish from pile installations.
[c] "n/r" indicates threshold not reached by model.
[d] NMFS Level A take criteria for impulsive noise.
[e] Southall et al. (2007) - Marine mammal noise exposure criteria: initial scientific recommendations.
Note: SPL = Sound pressure level; SEL = Sound exposure level; rms = root mean square.

Other activities associated with RBT2 were not expected to generate sound levels capable of causing injury to aquatic organisms; however, behavioural disturbance and masking of sounds used for foraging and communication are possible. Although behavioural disturbance for marine mammals depends on many factors, including exposure duration, noise source type, habituation, and exposure context, the zone of potential disturbance is often considered as the place where continuous sound levels exceed 120 dB rms SPL. For RBT2, extent of the 120 dB rms SPL zone ranged between 640 m and 14.5 km for vibratory piling scenarios and between 960 m and 22 km for the continuous non-piling scenarios. Source level and bathymetry differences between scenarios are largely responsible for the variation in extent of the 120 dB rms SPL zone. Underwater noise modeling scenarios considered ambient wind-driven noise and existing noise from distant vessel traffic.

Southern resident killer whale (*Orcinus orca*) species-specific behavioural thresholds developed by SMRU Canada Ltd. (2014) were modelled for 5, 50, and 95% probability of low and moderate severity behavioural responses; thresholds ranged from 117 to 153 dB re 1 µPa. The extent of the zones for continuous sources ranged between 80 m and 22.2 km for the vibratory piling scenarios and between < 20 m and 29.2 km for the non-piling scenarios, i.e., vessel and dredging scenarios.

The maximum zone of audibility (ZOA) was modelled for three marine mammal species (i.e., killer whale, humpback whale (*Megaptera novaeangliae*), and Steller sea lion (*Eumetopias jubatus*)) and three fish species groups (i.e., salmon, herring, and flatfish) by comparing modelled sound levels to hearing threshold (audiogram) and measured ambient background in 1/3-octave bands. The largest overall ZOA radii (i.e., ~98 km) were produced by the container ship berthing scenario with killer whale, humpback whale, and Steller sea lion audiogram weighting. Radii were restricted by geography in the modelling area, with maximum range constrained by islands across the Strait of Georgia.

TABLE OF CONTENTS

List of Figures

List of Tables

LIST OF ABBREVIATIONS

dB	Decibels
DP3	Deltaport Third Berth Project
FHWG	Fisheries Hydroacoustic Working Group
HT	Hearing threshold
ITP	Intermediate transfer pit
MONM	Marine Operation Noise Model
NMFS	U.S. National Marine Fisheries Service
PE	Parabolic equation
PTS	Permanent threshold shift
RAM	Range-dependent acoustic model
RBT2	Roberts Bank Terminal 2 Project
rms	Root-mean-square
SEL	Sound exposure level
SMRU	Sea Mammal Research Unit
SPL	Sound pressure level
SRKW	Southern resident killer whale
SSP	Sound speed profile
TL	Transmission loss
TTS	Temporary threshold shift
ZOA	Zone of audibility

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 make up one octave. 1/3-octave-bands become wider with increasing frequency.
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., distant ships, precipitation, wave action, and biological activity. In this report, ambient noise refers the lower 5th percentile of SPL from long-term hydrophone measurements.
Audiogram	A graph of hearing threshold level (sound pressure level) as a function of frequency, which describes the hearing sensitivity of an animal over its hearing range.
Decibel (dB)	The dB scale is a measure of sound amplitude on a logarithmic scale that expresses a quantity relative to a predefined reference level, typically 1 µPa in underwater acoustics.
Ensonification	Area affected by a sound source.
Isopleth	A contour of constant sound level on a map.
M-weighting	The process of band-pass filtering loud sounds to reduce the importance of inaudible or less-audible frequencies for broad classes of marine mammals. "Generalised frequency weightings for various functional hearing groups of marine mammals, allowing for their functional bandwidths and appropriate in characterising auditory effects of strong sounds" (Southall et al. 2007).
Peak SPL	The maximum instantaneous sound pressure level in a stated frequency band attained by an acoustic pressure signal.
root mean square (rms)	Acoustic term indicating the manner in which sound amplitude is measured over time. An rms measure allows for average amplitude to be calculated for continuous sounds.
Sound exposure level (SEL)	A measure of the total sound energy contained in one or more pulses.
Source level (SL)	Acoustic term indicating the amplitude of a sound measured or modelled at a standardised 1 m from the source of the sound. Usually reported in units of dB re 1 µPa at 1 m.
Sound pressure level (SPL)	The sound pressure level is a logarithmic measure of the time-mean-square sound pressure relative to a reference value in a specified frequency band. It is a measure of only the pressure component of the sound and does not account for the duration of the sound. Unit: decibel (dB).
Time-average sound level (Leq)	A time-average sound level during a specified period. Equal to the corresponding sound exposure level according to $Leq = SEL - 10 \log(T)$ where T is the time period in seconds; measured in units of dB re 1 µPa.
Transmission loss	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.
Zone of audibility	The area where sound levels are above ambient noise level and the animal's hearing threshold.

1.0   INTRODUCTION

This section provides project background information, an overview of the study, and study components and major objectives.

1.1   PROJECT BACKGROUND

The Roberts Bank Terminal 2 Project (RBT2 or Project) is a proposed new three-berth marine terminal at Roberts Bank in Delta, B.C. that could provide 2.4 million TEUs (twenty-foot equivalent units) of additional container capacity annually. The Project is part of Port Metro Vancouver's Container Capacity Improvement Program, a long-term strategy to deliver projects to meet anticipated growth in demand for container capacity to 2030.

Port Metro Vancouver (PMV) has retained Hemmera to undertake environmental studies related to the Project. JASCO Applied Sciences (JASCO) has been subcontracted by Hemmera to conduct modelling studies to assess underwater noise associated with RBT2 to ensure that adequate information is available to inform a future effects assessment for the Project. This technical report describes the results of the Construction Activities and Terminal Vessel Operations Noise Modelling Study.

Marine construction and vessel operations associated with RBT2 may generate sounds that have the potential to disturb or injure nearby marine mammals and fish. Construction operations modelled in this study include pile driving (i.e., impact and vibratory driving of cylindrical and sheet pilings), vibro-densification, and dredging. Although vibratory methods are planned, impact piling methods were modelled because the need for this method cannot be ruled out at this stage of Project design. Vessel operations modelled including container ship approaches to, and berthing at, the terminal.

Underwater noise was modelled for 15 scenarios with each scenario comprised of one or more specific sound sources (see **Section 3.2**). Noise footprints of the scenarios are presented as sound field contour maps and in tables listing distances to specified sound level thresholds. Audiogram weighting was applied to modelled sound levels to account for hearing sensitivity of killer whales (*Orcinus orca*), humpback whales (*Megaptera novaeangliae*), Steller sea lions (*Eumetopias jubatus*), herring, salmon, and flatfish.

1.2   CONSTRUCTION AND TERMINAL VESSEL OPERATIONS NOISE MODELLING OVERVIEW

A review of available information and state of knowledge was completed to identify key data gaps and areas of uncertainty within the general RBT2 area. This technical report describes the study findings for key components identified from this gap analysis. Study components, major objectives, and a brief overview are provided in **Table 1-1**.

Table 1-1 Study Components and Major Objectives

Component	Major Objective	Brief Overview
Modelling of underwater sound levels around planned construction activities and terminal vessel operations within PMV jurisdiction.	Predict potential areas where injury or disturbance to marine mammals and fish could occur resulting from Project construction activities and terminal vessel operations.	Utilise computer acoustic models and baseline data collected to predict the noise footprints of construction and terminal vessel activities.

2.0 REVIEW OF EXISTING LITERATURE AND DATA

This section provides a review of available literature and data considered in the Construction Activities and Terminal Vessel Activities Noise Modelling Study.

2.1 ACOUSTIC METRICS

Underwater sound amplitude is commonly measured in decibels (dB). The dB scale is a logarithmic scale that expresses a quantity relative to a predefined reference level. Sound pressure, in dB, is expressed in terms of the sound pressure level (**SPL**):

$$L_p = 20\log_{10}(P/P_{ref})$$

(1)

where P is the pressure amplitude and P_{ref} is the reference sound pressure. For underwater sound, the reference pressure is 1 µPa (10^{-6} Pa or 10^{-11} bar).

Sounds composed of single frequencies are commonly referred to as tones. Most sounds are generally composed of a broad range of frequencies (broadband sound) rather than pure tones.

2.1.1 CONTINUOUS SOUND

Continuous sound is characterised by gradual changes of sound pressure levels over time (e.g., propeller noise from a transiting vessel). Given a measurement of the time-varying sound pressure, $p(t)$, for a given noise source, the **root-mean-square (rms) SPL** (symbol L_p) is computed according to the following formula:

$$L_p = 10\log_{10}\frac{1}{T}\int_T p(t)^2\,dt / P_{ref}^{\;2}$$

(2)

In this formula, T is the time over which the measurement was obtained. **Figure A–1** shows an example of a continuous sound pressure waveform and the corresponding rms sound pressure.

2.1.2 IMPULSIVE SOUND

Sounds with short durations (less than a few seconds) are referred to as impulsive, and are typically characterised by abrupt increases of sound pressure (less than a second), followed by rapid decay back to pre-existing levels (within a few seconds). Noise from impact pile driving is typically considered impulsive.

The zero-to-peak, or **peak SPL** (L_{pk}, dB re 1 µPa) is the maximum instantaneous sound pressure level in a stated frequency band attained by an acoustic pressure signal, $p(t)$, and is defined as:

$$L_{pk} = 20\log_{10}\left(\max|p(t)|/P_{ref}\right)$$

(3)

In this formula, $p(t)$ is the instantaneous sound pressure as a function of time, measured over the pulse duration $0 \le t \le T$. This metric is commonly quoted for impulsive sounds, but does not take into account the duration or bandwidth of the noise. At high sound pressures (e.g., for shock fronts), peak SPL can be a valid criterion for assessing whether a sound is potentially injurious; however, because peak SPL does not consider pulse duration, it is not a good indicator of perceived loudness.

The rms SPL of an impulsive sound can be calculated using the same equation as a continuous source **(Equation 2)**; however, some ambiguity remains in how the duration T is defined because the beginning and end of a pulse can be difficult to identify precisely. In studies of impulsive noise, T is often accepted as the interval over which the cumulative energy curve rises from 5% to 95% of the total energy. This interval contains 90% of the total pulse energy (T_{90}), and the SPL computed over this interval is commonly referred to as the 90% rms SPL (L_{p90}, dB re 1 µPa). The energy, $E(t)$, of the pulse is computed from the time integral of the square pressure by:

$$E(t) = \int_0^t p(\tau)^2 \, d\tau$$

(4)

According to this definition, if the time corresponding to n% of the total energy of the pulse is denoted t_n, then the 90% energy window is defined such that $T_{90} = t_{95} - t_5$. **Figure A–2** shows an example of an impulsive noise pressure waveform, with the corresponding peak pressure, rms pressure, and 90% energy time interval.

Sound exposure level (SEL) measures the total sound energy contained in one or more pulses. The SEL (L_E, dB re 1 µPa^2·s) for a single pulse is computed from the time-integral of the squared pressure over the full pulse duration (T_{100}) according to the formula:

$$L_E = 10\log_{10}\left(\int_{T_{100}} p(t)^2 \, dt / P_{ref}^2 t_{ref}\right) = 10\log_{10}\left(E(t_{100})/E_{ref}\right) \tag{5}$$

SELs for impulsive noise sources (i.e., impact pile driving) presented may refer to single pulse or multiple pulse SELs. Total SEL from a train of N pulses may be calculated by summing the sound energy (in linear units) of the N individual pulses (L_{Ei}) as follows:

$$L_E = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{Ei}}{10}}\right) \tag{6}$$

where N is the total number of pulses and L_{Ei} is the SEL of the ith pulse event. Alternatively, given the mean (or expected) SEL for single pulse events, $\overline{L_E}$, the cumulative SEL from N pulses may be computed according the following formula:

$$L_E = \overline{L_E} + 10\log_{10}(N) \tag{7}$$

2.2   FREQUENCY WEIGHTING AND ACOUSTIC IMPACT CRITERIA

2.2.1   AUDIOGRAM WEIGHTING

The potential for anthropogenic noise to affect a marine animal is reduced when the animal cannot hear the sound well, except for injurious effects at high sound pressures. For sound levels too low to cause physical injury, 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 (i.e., single-frequency sinusoidal signals) as a function of 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. Since the auditory filter shape of marine mammals is not well understood, 1/3-octave-band levels are still commonly used for hearing assessments and are used in this study for all investigated audiograms. Using 1/3-octave bands for audiogram analysis assumes that the hearing threshold and sound level are all approximately constant within each 1/3-octave band, which are realistic assumptions when considering broadband sounds that cover a wide frequency range; therefore, the error associated with this assumption is expected to be small. Audiogram-weighted levels are expressed in units of dB re HT, which is the dB level of sound above hearing threshold (HT). Sound levels

less than 0 dB re HT are below the typical hearing threshold for a species and are, therefore, expected to be inaudible. Sound levels above 0 dB re HT represent auditory sensation levels, which relate to the perceived loudness of different sounds by a particular species. While this analysis does not directly relate to potential for behavioral response or auditory injury, weighting sounds according to hearing sensitivity permits a comparison of different sound sources in terms of species-specific hearing abilities.

In this study, audiogram weighting was applied to three marine mammal species (i.e., southern resident killer whale (SRKW), Steller sea lion, and humpback whale) and three fish groups (i.e., salmon, herring, and flatfish). Audiograms were based on the following sources: killer whale (Yurk and Wood, pers comm.) Steller sea lion (Kastelein et al. 2005), humpback whale (Erbe 2002), salmon (Hawkins and Johnstone 1978), herring (Enger 1967), sole (Zhang et al. 1998), and dab (Chapman and Sand 1974). The flatfish audiogram is a composite of dab and sole audiogram data (i.e., dab below 200 Hz, from Chapman and Sand 1974) and sole above 200 Hz. The killer whale audiogram was extrapolated below 100 Hz down to 10 Hz using a 12 dB/octave slope that 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, animals likely have a higher hearing threshold at frequencies outside their hearing range than the terminal trend of their audiogram would predict. Humpback whale, sea lion, salmon, herring, and flatfish thresholds were extrapolated to the lower and upper modelled frequencies by fixing the threshold at the most extreme value, which is likely a conservative approach. **Figure A–3** shows the estimated audiograms for the three marine mammal species and **Figure A–4** the estimated audiograms for the three fish species groups.

2.2.2 MARINE MAMMAL FREQUENCY WEIGHTING (M-WEIGHTING)

Based on a literature review of marine mammal hearing, and on physiological and behavioural responses to anthropogenic sound, Southall et al. (2007) proposed standard frequency weighting functions, referred to as M-weighting functions, for four functional hearing groups of marine mammals:

- Low-frequency cetaceans (LFC) - mysticetes (baleen whales);
- Mid-frequency cetaceans (MFC) - some odontocetes (toothed whales);
- High-frequency cetaceans (HFC) - odontocetes specialised for using high-frequencies; and
- Pinnipeds in water - seals, sea lions, and walrus (in-air hearing not addressed here).

At the upper and lower limits of the hearing range, M-weighting functions do not discount sound levels as much as the corresponding audiograms (where available) for member species of these hearing groups. The rationale for applying a smaller discount than suggested by audiograms is due in part to an observed characteristic of mammalian hearing, where loudness perception increases more rapidly with sound level at the limits of the audible range. Additionally, less-audible frequencies can still cause physical injury if pressure levels are sufficiently high. The M-weighting functions are, therefore, primarily intended to be

applied when sound levels are high, which is when effects such as temporary or permanent hearing threshold shifts may occur. **Figure A–5** shows the decibel frequency weighting of the four underwater M-weighting functions.

The M-weighting functions apply no discount to sound levels between their high and low frequency cut-off frequencies. Past the cut-off frequencies, sound levels are discounted by approximately −12 dB per octave. The amplitude response in the frequency domain of the M-weighting functions is defined by the following formula:

$$G(f) = -20\log_{10}\left[\left(1+\frac{f_{lo}^2}{f^2}\right)\left(1+\frac{f^2}{f_{hi}^2}\right)\right] \tag{8}$$

The shape of these weighting functions are controlled by the two parameters f_{lo} and f_{hi}, which correspond to the estimated upper and lower hearing limits specific to each functional hearing group (**Table 2-1**). M-weighting is typically applied to evaluate potential auditory injury and onset of temporary threshold shift (TTS) from exposures to sounds of high amplitude, such as those from impact pile driving (Southall et al. 2007). Sound levels produced from vessels and other construction activities are typically well below injury or TTS thresholds based on SEL. Consequently, M-weighting is not commonly applied in these cases.

Table 2-1 Low- and High-frequency Cut-off Frequency of M-weighting Curves for each Marine Mammal Functional Hearing Group

Functional Hearing Group	f_{lo} (Hz)	f_{hi} (Hz)
Low-frequency cetaceans	7	22,000
Mid-frequency cetaceans	150	160,000
High-frequency cetaceans	200	180,000
Pinnipeds in water	75	75,000

2.2.3 ACOUSTIC IMPACT CRITERIA

For marine mammals, there are two widely-acknowledged sets of injury and disturbance criteria for sound exposure:

1. The regulatory criteria applied by the U.S. National Marine Fisheries Service (NMFS) (MMPA 2007).
2. The recommended criteria of Southall et al. (2007).

Both sets distinguish between continuous and impulsive sounds, and injury thresholds are based on the estimated onset of PTS (permanent threshold shift, i.e., permanent loss of hearing sensitivity) for marine

mammals. Although the NMFS auditory injury threshold criteria are not based on the best available science, they are currently still being implemented until newly-proposed criteria are revised and formally accepted by the agency.

NMFS specifies separate injury criteria (i.e., Level A harassment under the MMPA) for two groups of marine mammals: cetaceans and pinnipeds. The NMFS injury criteria are based on the maximum rms SPL, averaged over the pulse duration, to which a marine mammal may be safely exposed before injury occurs. NMFS has not established injury criteria for exposure to continuous sounds. NMFS behavioural disturbance criteria (level B harassment), which are based on a limited set of behavioural data, are widely applied. **Table 2-2** lists the NMFS auditory injury and disturbance criteria.

Southall et al. (2007) employ a dual criteria based on peak SPL and cumulative M-weighted SEL thresholds, where the cumulative injury criteria (SEL) are specified as originating from single or multiple exposure events over a 24-hour period. A received sound exposure is assumed to cause injury if it exceeds either the peak SPL or the SEL criterion, or both. **Table 2-2** lists the Southall et al. (2007) auditory injury criteria. Southall et al. (2007) did not recommend specific SPL thresholds for marine mammal disturbance criteria.

Table 2-2 Auditory Injury and Disturbance Thresholds for Marine Mammals

Marine Mammal Group	NMFS Thresholds rms SPL (dB re 1 µPa)				Southall et al. (2007) M-weighted 24-Hour SEL Thresholds (dB re 1 µPa^{2}s)	Southall et al. (2007) peak SPL Thresholds (dB re 1 µPa)
	Continuous Sounds		Impulsive Sounds		Impulsive Sounds	Impulsive and Continuous Sounds
	Injury	Disturbance	Injury	Disturbance	Injury	Injury
Cetaceans (LFC, MFC, HFC)	-	120	180	160	198	230
Pinnipeds in water	-	120	190	160	186	218

In 2008, the Fisheries Hydroacoustic Working Group (FHWG) developed interim criteria for injury to fish from pile driving noise (FHWG 2008). This dual criteria includes a peak level of 206 dB re 1 µPa and a cumulative SEL of 187 dB re 1 µPa^2·s for fishes 2 g or more, and a cumulative SEL of 183 dB re 1 µPa^2·s for fish smaller than 2 g. In this study, the effects on fish (>2 g) were investigated using the FHWG criteria and more recent SEL threshold recommended by Halvorsen et al. (2011). **Table 2-3** lists these two sets of injury criteria.

Table 2-3 Auditory Injury Thresholds for Fish (>2 g)

Reference	Peak SPL (dB re 1µPa)	Cumulative SEL (dB re 1 µPa^{2}s)
FHWG (2008)	206	187
Halvorsen et al. (2011)	-	210[a]

[a] Threshold for fish exposed to fewer than 960 pile strikes.

2.2.4 SOUTHERN RESIDENT KILLER WHALE BEHAVIOURAL DISTURBANCE DATA

Because free-ranging marine mammals are difficult to observe experimentally, there are comparatively few published studies documenting underwater noise exposure effects on killer whales; therefore, SMRU Canada Ltd. was contracted by Hemmera to gather input from outside experts and reanalyse three existing data sets to quantify unweighted broadband SPLs where behavioural responses were observed. For the current study, radii were computed for the SMRU low-severity and moderate-severity response thresholds at the 5%, 50%, and 95% probability levels (**Table 2-4**).

Table 2-4 Behavioural Response Thresholds (unweighted broadband SPL, dB re 1µPa) for SRKW (SMRU Canada Ltd. 2014)

Severity of Response	Probability of Response		
	5%	50%	95%
Low	117	129	146
Moderate	126	137	153

2.3 AMBIENT NOISE

Ambient underwater noise levels near the existing Roberts Bank terminals were measured in 2012 by Mouy et al. (2012) and in 2013 by Warner et al. (2013). The latter study also measured ambient noise in the Strait of Georgia in 2013. The levels near Roberts Bank terminals and in Strait of Georgia from 2013 were similar to those near Roberts Bank terminals from the longer duration measurements in 2012; therefore, for this study, the lowest 5th percentile levels from the 2012 measurements were used for determining the audibility zones for marine mammals (i.e., where sound levels are above both the threshold of hearing and ambient noise). The lowest 5th percentile levels include the ambient noise contribution from all anthropogenic and natural sources present in the study area, including wind, waves, and distant vessels. This provides a conservative estimate of the zone of audibility; 95% of the time the ambient noise will be louder and the zone of audibility will be smaller. Measurements were extrapolated to the 50 and 63 kHz 1/3-octave bands by setting the levels equal to those of the 40 kHz band. **Figure A–6** shows the ambient levels.

3.0 METHODS

Descriptions of the spatial and temporal scopes of the Construction Activities and Terminal Vessel Operations Noise Modelling Study, plus model scenarios and parameters are provided below.

3.1 STUDY AREA

Roberts Bank is located 40 km south of Vancouver in Delta, B.C., at the mouth of the Fraser River estuary and within the Strait of Georgia. Proposed construction of RBT2 will take place adjacent to the existing Roberts Bank terminals (**Figure A-7**). The study area included Project-related construction and operational noise sources within PMV jurisdiction (**Figure A-8**). No study area boundary was imposed on the spatial extent of noise propagation modelled from these sources.

3.2 MODELLED SCENARIOS

Construction and operation of RBT2 will involve several activities that produce underwater sound. To determine appropriate modelling scenarios for construction activities, Project engineers were consulted regarding preliminary terminal and tug basin designs, probable construction activity locations, and likely construction equipment. A navigation study (AECOM Canada Ltd. 2012) was also conducted and approved by local pilots to determine the routes and speeds of container ships approaching the terminal and tugs assisting in berthing. Unberthing a container ship was considered comparable to berthing and was therefore, not investigated separately. Similarly, loading a container ship while under shore power was not modelled as there were no available measurements of this operation; however, source level was assumed to be lower than container ship loading without shore power (SL of 167 dB re 1 µPa at 1 m). The following scenarios were modelled in this study (**Table B–1** lists the details of each scenario and **Figure A–8** provides a map of the source locations for each scenario):

1. Impact piling a cylindrical pile at the mooring dolphin;
2. Impact piling a cylindrical pile with confined bubble curtain mitigation at the mooring dolphin;
3. Impact piling a cylindrical pile at the tug basin;
4. Impact piling a cylindrical pile at the perimeter dyke;
5. Vibratory piling a cylindrical pile at the mooring dolphin;
6. Vibratory piling a cylindrical pile at the tug basin;
7. Impact piling a sheet pile at the west end caisson;
8. Vibratory piling a sheet pile at the west end caisson;
9. Impact piling a sheet pile at the east end caisson;
10. Vibratory piling a sheet pile at the east end caisson;
11. Vibro-densification at the dredge basin (consisting of berth pocket, approaches, and caisson trench);
12. Dredging of the dredge basin;

13. Dredging of the intermediate transfer pit (ITP);

14. Berthing of an E-class container ship (*Emma Maersk* design vessel) with three tugs and a line boat at 4 knots (kts); and

15. E-class container ship approaching terminal at 6 kts with four tugs approaching container ship at 12 kts.

3.3 SOUND PROPAGATION MODEL

3.3.1 MARINE OPERATIONS NOISE MODEL

Sound levels for each noise source of concern were modelled using JASCO's Marine Operations Noise Model (MONM). MONM predicts underwater sound propagation in range-varying acoustic environments through a wide-angled parabolic equation (PE) solution to the acoustic wave equation (Collins 1993). The PE method has been extensively benchmarked and is widely employed in the underwater acoustic community. The PE code used by MONM is based on a version of the Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for an elastic seabed.

MONM computes acoustic fields in three dimensions by modelling transmission loss (TL) along evenly spaced 2-D radial traverses covering a 360° swath from the source, an approach commonly referred to as $N \times$ 2-D. The model fully accounts for depth and/or range dependence of several environmental parameters including bathymetry and sound speed profiles for the water column and the sea floor. It also accounts for the additional reflection loss at the seabed due to partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces through a complex density approximation (Zhang and Tindle 1995). Wave attenuation in all layers is also included. The acoustic environment is sampled at a fixed range step along radial traverses. MONM treats frequency dependence by computing acoustic TL at the centre frequencies of 1/3-octave bands. Broadband received levels are summed over the received 1/3-octave band levels, which are computed by subtracting band TL values from the corresponding source levels. MONM's predictions have been validated against experimental data from several underwater acoustic measurement programs (Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010, Hannay et al. 2013). For this study, MONM was used to compute TL for the 28 1/3-octave-bands centred between 10 Hz and 5 kHz.

The TL computed by MONM was further corrected to account for attenuation of acoustic energy by molecular absorption in seawater. The volumetric sound absorption is quantified by an attenuation coefficient, expressed in units of decibels per kilometre (dB/km). The absorption coefficient depends mainly on the sound frequency, but also on the temperature, salinity, and hydrostatic pressure of the water. In general, the absorption coefficient increases with the square of frequency. The absorption of acoustic wave energy has a noticeable effect (> 0.05 dB/km) at frequencies above 1 kHz. At 10 kHz, the absorption loss over 10 km distance can exceed 10 dB. The absorption coefficient for seawater can be computed according to the formulae from François and Garrison (1982) which consider the contribution of

pure seawater, magnesium sulfate, and boric acid. In this study, absorption coefficients were calculated based on water temperature at 7.5 °C and salinity of 29 parts per thousand (ppt) and a depth of 10 m, and applied to the modelled TL (see **Table B–2**).

Because it is computationally inefficient to model TL using the PE method above several kHz, TL was approximated for bands between 6.3 and 63 kHz by computing the TL at 5 kHz and applying the correct frequency-dependent absorption coefficient to each band. This approach is valid because high-frequency predictions from the PE model will approach a limiting value that is consistent with geometrical absorption.

A 10 m radial step size was used for the PE model computational grid, and sound levels were modelled at 18 receiver depths, distributed vertically in the water column, as follows:

- Five receivers were spaced 2 m apart, 2 to 10 m below the water's surface;
- Nine receivers were spaced 10 m apart, 20 to 100 m below the water's surface;
- Three receivers were spaced 100 m apart, 200 to 400 m below the water's surface; and
- One receiver was on the sea floor.

Modelled received levels were gridded separately in each horizontal plane (i.e., at each modelled receiver depth). To generate a conservative estimate, the modelled results in this study were obtained by collapsing the stack of grids into a single plane using a maximum-over-depth rule, which means that the sound levels at each planar point are taken to be the maximum value from all modelled depths in the water column for that point.

To model continuous sources such as container ships, tugs, dredgers, and vibratory pile drivers, MONM predicted the SPLs on the $N \times$2-D grid. For impulsive sources (i.e., impact pile driving), MONM modelled the single-strike SELs and then converted the SELs to SPLs based on the conversion curve described in **Section 3.3.2**. Predicted received SPLs (in dB re 1 µPa) were contoured to show the estimated acoustic footprint (area of ensonification) for each scenario, and noise contours were converted to GIS layers for rendering on thematic maps. For each scenario, the 95th percentile radius, $R_{95\%}$, and the maximum radius, R_{max}, for each noise threshold level were tabulated. The $R_{95\%}$ is the radius of a circle that encompasses 95% of grid points whose value equals, or is greater than, the threshold value. For a given threshold level, this radius always provides a range beyond which no more than 5% of a uniformly distributed population would be exposed to sound at or above that level, regardless of the geometrical shape of the noise footprint. The R_{max} is the maximum distance from the source to the given noise threshold in any direction (equivalent to $R_{100\%}$). R_{max} can be a reference for the most conservative case compared to using $R_{95\%}$. For cases where the isopleth of a specific sound level is discontinuous and small pockets of higher received levels occur far beyond the main ensonified volume (e.g., due to convergence of sound rays), R_{max} would be much larger than $R_{95\%}$ and could be misleading if not given alongside $R_{95\%}$.

3.3.2 ESTIMATING 90% RMS SPL AND PEAK SPL FROM SEL

For impulsive sound sources, MONM computes per-pulse SEL in 1/3-octave-bands, but does not directly predict the 90% rms SPL or peak SPL. Although the 90% rms SPL and peak SPL are easily measured in situ, these metrics are generally more difficult to model than per-pulse SEL. In addition, the adaptive integration period to model rms SPL, implicit in the definition of the 90% rms SPL, is highly sensitive to the specific multipath arrival pattern from an acoustic source and can vary greatly with distance from the source or with receiver depth. Nonetheless, because per-pulse SEL and SPL are related, the former metric can be used to estimate the latter.

In this study, empirical measurements of the range-dependent difference between SPL and per-pulse SEL for impact pile driving, obtained in environments similar to this study, were used to predict peak and rms SPL from the modelled per-pulse SEL. **Figure A–9** shows measurement data for rms SPL to per-pulse SEL offset and peak SPL to per-pulse SEL offset as a function of distance for impact driving of cylindrical and sheet piles (MacGillivray et al. 2007, Oestman et al. 2009) and data calculated from logarithmic regression estimated by Blackwell (2005). Maximum offsets of rms SPL and peak SPL are at the source (15 dB, red line, and 30 dB, pink line, in **Figure A–9**). Offsets decreased beyond 10 m range so an empirical function was used to approximate the trend of the higher offset data, which decreased by approximately 2.4 dB per 10 times increase in range. These offsets were applied to the per-pulse SEL model results to estimate peak and rms SPL.

3.3.3 CUMULATIVE SOUND EXPOSURE

Lengthy exposures to high-intensity anthropogenic noise can lead to a temporary or permanent reduction of hearing sensitivity in marine animals. Cumulative noise exposure is generally measured as the total sound energy an organism receives over some period, calculated by **Equation 6** or **7** (see **Section 2.1.2**).

Cumulative SEL for impact pile driving was computed for sequences of pile driving blows that could occur over 24 hours. Since details of the pile driving for potential construction activities had not been confirmed at time of writing this report, it was assumed that the cylinder and sheet impact pile driving would typically operate at 35 and 44 blows per minute, respectively, based on source levels and hammer specifications from measurements of similar piling activities. The number of strikes required to drive each pile was unknown; therefore, three durations of pile driving activity (i.e., 1 min, 10 min, and 100 min) were modelled over a 24-hour period for each scenario.

3.4 MODEL PARAMETERS

3.4.1 ACOUSTIC SOURCES

Several operations were modelled including impact and vibratory piling of cylindrical and sheet piles, impact piling with confined bubble curtain mitigation, vibro-densification, dredging, container ship berthing, and vessel transiting. These operations were modelled in various combinations for the 15 scenarios (see scenario descriptions in **Section 3.2**). The 1/3-octave band source levels for each operation, discussed below, were derived from the literature.

3.4.1.1 Impact Driving of Cylindrical Piles

Several sizes of cylindrical steel piles will be used during RBT2 construction, of which the largest is anticipated to be 914 mm in diameter. Impact piling source levels were based on the largest piles, which typically require the most hammer energy to drive and have higher source levels. Specifications of impact hammers that may be used during RBT2 construction have not been determined; therefore, estimated source levels were based on published measurements for similar piling activities. Impact piling is most often carried out using hydraulic or diesel impact hammers. A representative broadband source level for impact piling of 914 mm diameter steel cylindrical piles was based on measurements of impact piling of 914 mm diameter piles in 10 m of water using a Delmag diesel D36-32 hammer with ram weight of 3,600 kg (Humboldt Bay Bridges, Oestman et al. 2009). The maximum impact energy of the Delmag hammer is 123 kJ at a drop height of 3.4 m with a rate of 35 strikes/min.

The per-pulse sound exposure level measured at 10 m range was 183 dB re 1 µPa. Assuming spherical spreading (20✕Log r), the source level would be 203 dB re 1 µPa at 1 m. These measurements did not include 1/3-octave band levels, so this broadband level was split into 1/3-octave band levels using the averaged spectrum for impact piling of 4 to 6 foot diameter piles (MacGillivray et al. 2011). The spectrum was extrapolated beyond 16 kHz using the trend of the spectrum from 6.3 to 16 kHz. **Figure A–10** shows the resulting 1/3-octave band source levels. The modelled source depth for all piling sources was taken to be the mid-water column depth at the piling location.

Bubble curtain mitigation may be used during pile driving, so the average attenuation from a confined bubble curtain on impact piling levels was applied to the unmitigated piling source levels. MacGillivray et al. (2011) averaged confined bubble curtain attenuation values from several studies. The 1/3-octave band attenuation was extrapolated beyond 6.3 kHz with a constant value of the attenuation of 6.3 kHz (i.e., 12.9 dB). Confined bubble curtains are more effective at attenuating high frequencies, so this approach is expected to be conservative. Source levels for mitigated impact piling of cylindrical piles were calculated by subtracting the attenuation from the source levels of unmitigated impact piling. **Figure A–10** shows the resulting 1/3-octave band source levels.

3.4.1.2   Vibratory Driving of Cylindrical Piles

Specifications of vibratory hammers that will be used during RBT2 construction have not yet been determined; therefore, source levels for vibratory piling of the 914 mm diameter steel cylindrical piles were based on published vibratory piling 1/3-octave band source levels (Racca et al. 2007) and measurements for similarly sized piles (Blackwell 2005). The Racca at al. (2007) measurements were from an APE 300 vibro-hammer with 1,842 kN centrifugal force driving a 900 mm diameter pile. The Blackwell measurements were from an APE model 400B hammer driving a 914 mm pile. The Blackwell measurements were back-propagated from 10 m to 1 m using spherical spreading and were averaged with the Racca source level measurements over their common frequency range of 10 Hz to 5 kHz. The Blackwell measurements extended to 16 kHz so the levels between 6.3 and 16 kHz were shifted by +6.9 dB to match the trend of the averaged spectrum. The levels were then extrapolated to 63 kHz using the trend of the 12.5 and 16 kHz levels. Resulting 1/3-octave band source levels are shown in **Figure A– 10**.

3.4.1.3   Impact and Vibratory Driving of Sheet Piles

Impact piling of AZ46 sheet piles may occur during RBT2 construction. As with the cylindrical piles, hammer specifications were not specified in the Project design; therefore, the broadband source level for impact piling sheet piles was based on measurements of impact piling of a 0.6 m wide sheet pile at 10 m range in 15 m of water with an ICE 60S diesel impact hammer (Berth 23 Port of Oakland, Oestman et al. 2009). The per-pulse sound exposure level was 179 dB re 1 µPa at 10 m range, so the source level would be 199 dB re 1 µPa at 1 m assuming spherical spreading. The spectrum was taken to be the same as for impact piling of cylindrical piles and was adjusted to the 199 dB broadband level. The resulting 1/3-octave band source levels are shown in **Figure A–10**. A review of the published literature found no suitable source level measurements for vibratory piling of sheet piles; therefore, source levels were taken to be the same as vibratory piling of cylindrical piles. A driving rate of 44 strikes/min was used based on the source level and hammer specifications.

3.4.1.4   Vibro-densification

Source levels for two vibro-densifiers were measured at Roberts Bank terminals for the Deltaport Third Berth Project (DP3) for 1/3-octave bands between 10 Hz and 40 kHz (Austin 2007). Source levels for vibro-densification in this study were taken from the maximum of the two measurements in each 1/3-octave band. The source levels were extended to 63 kHz by extrapolating the trend of the source levels in the bands between 20 and 40 kHz (see **Figure A–11**). The modelled source depth for vibro-densification was taken to be mid-water column.

3.4.1.5   Cutter Suction Dredging

Source levels for dredging operations were derived from source level measurements of the dredge *Columbia* measured at DP3 (Zykov et al. 2007). Source levels were extrapolated beyond 40 kHz to 63 kHz using the trend of source levels in bands between 20 and 40 kHz. Robinson et al. (2011) found that underwater noise from marine dredges in the 1 to 2 kHz frequency range were generated near the cutter head on the seafloor and that below 500 Hz, noise levels were similar to those generated by transiting cargo ships. Modelled dredge source levels were therefore, split between the vessel (below 1 kHz) and the cutter head (1 kHz and above) with the acoustic source depth for the vessel and cutter head at 2.14 m below the sea surface (the *Columbia's* draught) and 1 m above the seafloor, respectively (see **Figure A–11**).

3.4.1.6   Container Ship Berthing

Container ship berthing consists of an E-class container ship, plus three berthing tugs and a line boat which assist in manoeuvring the container ship into the terminal. Specifics of the berthing operation are described in more detail in the CCIP ship navigation report (AECOM Canada Ltd. 2012). Source levels for berthing of an E-class container ship by three berthing tugs were derived from measurements of the *Vienna Express* (length 335 m) berthing with the two tugs *Seaspan Resolution* and *Seaspan Raven* (Warner et al. 2013). Source levels used in the modelling were based on measured sound levels from the highest two minutes of recording. Sound levels during the berthing operation were assumed to originate primarily from the tugs, not the container ship, since tugs produced high levels of cavitation noise as they pushed the container ship into its berth. Modelled source levels for an individual berthing tug were determined by splitting the measured sound power from the berthing operation equally between the two tugs (i.e., reducing the aggregate source levels by 3 dB) and extrapolating to lower frequencies (10 to 40 Hz) using the source level of the 50 Hz band (169.4 dB re 1 µPa at 1 m). This source level was applied to each of the three tugs in the berthing operation; the spectrum is shown in **Figure A–12**. Modelled source depths were taken to be 3.6 m for two of the berthing tugs (*Seaspan Resolution* as surrogate) and 3.4 m for the other berthing tug (*Seaspan Kestrel* as surrogate), based on the specified propeller depths. Source levels for the line boat involved in the berthing operation are discussed in **Section 3.4.1.8**.

3.4.1.7   Container Ship Transiting

Source levels for extremely large container ships (e.g., Maersk E-class and Triple-E-class, approximately 400 m LOA) were not available for modelling a transiting E-class container ship. Modelled source levels for an E-class container ship approaching RBT2 at 6 kts were therefore derived from container ship transiting measurements at 10 kts (Warner et al. 2013). Source levels for the *CMA CGM Attila* and *Zim Los Angeles* transiting at 10.6 and 11.1 kts, respectively, were averaged in each 1/3-octave band. The levels were then adjusted for a slower speed and larger ship of the scenario. The source level was

adjusted from the average 10.85 kts to the reference speed of 6 kts using the following sixth-power dependence of radiated sound power on ship speed (Ross 1976):

$$L_s(v) = L_s(v_{ref}) + 60\log_{10}\left(v/v_{ref}\right)$$

(9)

where $L_s(v)$ is the adjusted source level at speed v and $L_s(v_{ref})$ is the mean source level at reference speed v_{ref}. This resulted in a decrease of 15.4 dB in source level.

Modelled source levels were increased from the 336 m length of the *CMA CGM Attila* and *Zim Los Angeles* to the reference length 398 m for an E-class container ship using the following squared-power dependence of radiated sound power on ship length (Ross 1976):

$$L_s(l) = L_s(l_{ref}) + 20\log_{10}\left(l/l_{ref}\right)$$

(10)

Where $L_s(l)$ is the adjusted source level for length *l* and $L_s(l_{ref})$ is the mean source level at reference length l_{ref}. Source levels were, therefore, increased by 1.5 dB. Resulting source levels for an E-class container ship transiting at 6 kts are shown in **Figure A–12**. Modelled source depth was taken to be 9.3 m, which was estimated by subtracting 80% of the propeller diameter from the maximum vessel draught of 16.5 m, following the procedure in (Wright and Cybulski 1983).

3.4.1.8 *Tugs and Line Boats Transiting*

Modelled source levels for the tugs and line boat transiting at 4 and 12 kts were taken from the measurements of the *Seaspan Resolution* near Roberts Bank terminals (Warner et al. 2013). The *CH Cates IV* is the design vessel for the line boat operation, but acoustic measurements of this vessel were not available. Using the modelled tug source levels as a surrogate vessel for the line boat is expected to be conservative since the *CH Cates IV* is smaller and less powerful than the *Seaspan Resolution*. Modelled source levels for the tugs transiting at 4 kts were extrapolated to frequencies between 10 and 15.8 Hz using a constant value of the level in the 20 Hz 1/3-octave band. Modelled source levels for transiting tugs are shown in **Figure A–12**.

3.5 ENVIRONMENTAL PARAMETERS

3.5.1 BATHYMETRY

High-resolution (10 m) bathymetry data within several kilometres of Roberts Bank terminals were provided to JASCO by Hemmera. The bathymetry was extended to cover the entire modelling area (up to 120 km from Roberts Bank terminals) using NOAA digital elevation model data (NGDC 2013) and Canadian Hydrographic Service data provided by Nautical Data International Inc. Bathymetry data from the three datasets were re-projected onto a 20 × 20 m grid in UTM zone 10N for use with MONM.

Some of the modelled construction scenarios involved changing the bathymetry near the port (e.g., dredging); therefore, scenario-specific bathymetry datasets were generated according to the construction schedule to accurately model sound propagation. **Table 3-1** lists the construction activities associated with bathymetry changes and the corresponding modifications to the original bathymetry dataset and model scenarios. The bathymetry in the ITP was not modified to account for sediments temporarily deposited during dredging. This approach is conservative since decreased water depth will reduce sound propagation. Scenario 13, which involves dredging the ITP, uses the pre-existing water depth in this area to model dredging of the last portion of temporary deposits. **Figure A–13** shows the locations of the planned dredging areas and the ITP.

Table 3-1 Construction Activities and the Corresponding Bathymetry Modifications

Construction Activity	Bathymetry Modifications	Bathymetry Dataset #	Scenarios Using Dataset
Piling temporary piles at perimeter dyke	None	1	4
Dredging dredge basin (berth pocket, approaches and caisson trench) to −30 m CD	Depth within berth pocket set to 30 m	2	12
Fill berth pocket to approx. −21.6 m CD and dredge tug basin to −7.6 m CD*	Depth within berth pocket set to 21.6 m. Depth within tug basin set to 7.6 m CD	3	1–3, 5–11, 13
Construction of the terminal	Depth within RBT2 set to 0 m (i.e., land)	4	14, 15

*based on preliminary project information. Tug basin redesign has a depth of −6.5 m CD and is expected to be larger in size than the original design. The modelling results are not expected to be affected much by these changes.

3.5.2 GEOACOUSTIC PROPERTIES

Sound propagation is influenced by the geoacoustic properties of the sea floor, including density, compressional wave (P-wave) speed, shear wave (S-wave) speed, compressional wave attenuation, and shear wave attenuation of seabed sediments. 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 article of typical properties for many common seabed materials (Hamilton 1980). **Table 3-2** lists the geoacoustic parameters for the modelled scenarios in this study.

Table 3-2 Geoacoustic Profile for the Noise Estimation Model

Depth (mbsf)	Sediment Type	Density (g/cm3)	P-wave Speed (m/s)	P-wave Attenuation (dB/λ)	S-wave Speed (m/s)	S-wave Attenuation (dB/λ)
0 to 100	Fluvial silt deposits	1.4 to 1.9	1502 to 1602	1.61 to 0.1	125	2.2
> 100	Compact sand and rock	1.9	2275	0.1		

3.5.3 SOUND SPEED PROFILE

The sound speed profile (SSP) in the water column was based on data measured near Roberts Bank terminals in February 2007 that was applied during a previous modelling study for DP3 (McHugh et al. 2007). The profile reached 28 m depth and was extrapolated to 400 m (deeper than the maximum depth in the modelling area) using the depth-dependence of sound speed given by (Coppens 1981):

$$c(z) = c(z_0) + 0.016 \cdot (z - z_0) \tag{11}$$

where c is sound speed (m/s), z_0 is the reference depth (m), and z is the extrapolation depth (m). **Figure A–14** shows the extrapolated SSP used for this study. The SSP in this study is more upward refracting than that measured in the spring/summer (Warner et al. 2013) where more sunlight heats the surface layer. Because of this, and because upward refraction reduces the loss of energy due to bottom interaction, the SSP in this study is expected to generate more conservative threshold distances.

3.6 METHOD FOR COMPUTING ZONE OF AUDIBILITY

The areas of ensonification show the estimated absolute sound levels from the modelled sources but do not represent areas where animals can hear the sounds. If sound levels from a noise source are lower than the ambient underwater noise level or fall below the hearing threshold of an animal, that animal will not hear that sound and will not react unless the disturbance is also non-acoustic (e.g., visual). Regions where sound levels were greater than ambient noise and species-specific audiograms, referred to as zones of audibility (ZOA), indicate areas where an animal may detect noise from the modelled sound source. The ZOAs for each scenario were computed where an animal was assumed to detect noise only if the SPL exceeded the ambient noise and the audiogram in any 1/3-octave frequency band. This assumption is conservative since, audibility is computed over all modelled frequency bands, ambient noise was the lowest 5th percentile of measured levels, and SPLs are the maximum over all modelled depths.

4.0 RESULTS

Model outputs for the Construction Activities and Terminal Vessel Operations Noise Modelling Study are presented in this section as SEL isopleth maps for impact pile driving scenarios, and as rms SPL isopleths for all continuous sound sources. The SEL metric is used for impact pile driving to permit calculation of cumulative exposure injury thresholds for marine mammals and fish. Nevertheless, rms SPLs, and peak SPLs for impact pile driving pulses were derived from the corresponding single-pulse SELs using an empirical conversion method (**Section 3.3.2**). The approach is based on assigning a pulse duration within which most (90%) of the pulse energy arrives. The resulting level is commonly referred to as 90% rms SPL, a metric often applied for assessing pile driving sound effects on marine mammals.

In the radii tables mentioned below, $R_{95\%}$ is the radius of a circle centred at the source that encompasses 95% of the area ensonified above the threshold value. R_{max} is the maximum distance from the source to the given noise threshold in any direction.

4.1 IMPULSIVE NOISE SOURCES

Table B–3 to **Table B–5** present 95th percentile isopleth radii of 24-hr cumulative (1, 10, and 100 min piling) SEL M-weighted injury threshold contours for marine mammals, and un-weighted SEL injury threshold contours for fish, for impact piling scenarios (S1, S2, S3, S4, S7, and S9). Corresponding isopleth maps for S1 (impact piling at the mooring dolphin) are provided in **Figure A–15** to **Figure A–19**. **Table B–6** and **Table B–7** present 95th percentile rms SPL (for marine mammals) and peak SPL radii (for marine mammals and fish), respectively, to injury thresholds for impact piling scenarios. Corresponding isopleth maps of rms SPL for all impact piling scenarios are provided in **Figure A–20** to **Figure A–25**.

Salmon ZOA, audiogram-weighted SPL radii and areas of ensonification for impact piling scenarios are presented in **Table B–18** to **Table B–20**. A representative audiogram-weighted isopleth map for salmon for impact piling at the mooring dolphin is provided in **Figure A–46**. Corresponding tables for herring are presented in **Table B–27** to **Table B–29** and a representative isopleth map for impact piling at the mooring dolphin is provided in **Figure A–47**. Flatfish results are presented in **Table B–33** to **Table B–35**, and a representative isopleth map for impact piling at the mooring dolphin is provided in **Figure A–48**.

Peak SPL radii less than 10 m (the minimum MONM model resolution) were extrapolated to shorter distances using spherical spreading. A plot of the modelled peak SPL with range is provided in **Figure A–51**.

4.2 CONTINUOUS NOISE SOURCES

Table B–8 and **Table B–9** present 95th percentile and maximum isopleth radii for vibratory piling scenarios (S5, S6, S8, and S10), and **Table B–10** and **Table B–11** present 95th percentile and maximum radii for continuous non-piling scenarios (S11 to S15). Corresponding isopleth maps are located in **Figure**

A–26 to **Figure A–34**. Killer whale ZOA radii for vibratory piling scenarios are presented in **Table B–12** and **Table B–13**. **Table B–14** and **Table B–15** present the killer whale ZOA radii for the continuous non-piling scenarios. Corresponding isopleth maps are located in **Figure A–35** to **Figure A–43**. **Table B–16** and **Table B–17** present radii to unweighted broadband thresholds (SMRU Canada Ltd. 2014) for killer whale behavioural response for vibratory piling scenarios and non-piling scenarios, respectively. Isopleth maps of the killer whale behavioural response thresholds for terminal operations scenarios (S14 and S15) are shown in **Figure A–44** and **Figure A–45**.

Salmon ZOA, 95th percentile and maximum SPL radii, and areas of ensonification for vibratory piling scenarios are presented in **Table B–21** to **Table B–23**. **Table B–24** to **Table B–26** present the corresponding salmon results for continuous non-piling scenarios.

Herring ZOA , 95th percentile and maximum SPL radii, and areas of ensonfication for vibratory piling scenarios are presented in **Table B–30** to **Table B–32**, and corresponding results for flatfish are presented in **Table B–36** to **Table B–38**.

Humpback whale results for continuous non-piling scenarios (S14 and S15) are presented in **Tables B–39** and **Table B–40**, and **Figure A–49** gives a representative isopleth map for container ship berthing. Corresponding results for Steller sea lion are presented in **Table B–41** and **Table B–42**, with a representative isopleth map provided in **Figure A–50** for container ship berthing.

5.0   DISCUSSION

Key findings from the Construction Activities and Terminal Vessel Operations Noise Modelling Study and data gaps are discussed.

5.1   MARINE MAMMALS

5.1.1   IMPULSIVE SOURCES

The Southall et al. (2007) injury threshold (198 dB SEL) was not reached for any cetacean species groups (HFC, MFC, and LFC) for 1 min of total piling (**Table B-3** and **Figure A–15** to **Figure A-17**); however, it was reached for all scenarios for 100 min of piling, with Scenario 4 (impact piling at the perimeter dyke) generating the largest radii (210 to 220 m) (**Table B–5** and **Figure A–15** to **Figure A–17**). Scenario 2, (impact piling at the mooring dolphin with a confined bubble curtain), which modelled the effectiveness of bubble curtain mitigation, had substantially reduced radii compared to Scenario 1 (impact piling at the mooring dolphin). On average, for both SPL and SEL marine mammal thresholds, radii were reduced by 76% by applying a bubble curtain (**Table B–3** to **Table B–5**).

For pinnipeds, the radii to the injury threshold (186 dB SEL) for 1 min of piling were similar for all unmitigated scenarios (50 to 80 m) (**Table B–3**). For the most conservative case modelled—100 min of piling—the largest radii (1,170 m) were produced by impact piling at the mooring dolphin (Scenario 1) for pinniped M-weighting (**Table B–5** and **Figure A–18**).

With respect to the Southall et al. (2007) peak SPL injury threshold for cetaceans (230 dB SPL), all impact piling scenarios produced injury radii ≤ 2 m (**Table B–7**). For pinnipeds (218 dB SPL), impact piling at the tug basin and perimeter dyke (Scenarios 3 and 4 respectively) produced the largest injury radii at 9 m, followed by impact piling at the mooring dolphin (Scenario 1) at 7 m (**Table B–7**). Note that, the potential for injury exists whenever the SEL or peak SPL dual-criteria are exceeded.

Disturbance zones for the NMFS injury and behavioural thresholds were also considered in this study (**Table B–6**). For the NMFS cetacean injury threshold (180 dB rms SPL), impact piling at the perimeter dyke (Scenario 4) produced the largest radii (120 m) (**Figure A–23**); however, the disturbance radii (160 dB rms SPL) were largest for impact piling at the mooring dolphin (Scenario 1; 1,320 m) (**Figure A–20**). For pinnipeds, the largest injury radii (190 dB rms SPL) were generated by impact piling at tug basin and perimeter dyke (Scenario 3 and 4 respectively, both 40 m) (**Figure A–22** and **Figure A–23**). The largest disturbance radii (160 dB rms SPL) were produced by impact piling at the mooring dolphin (1,320 m) (**Figure A–20**).

Model results show that impact piling at shallower locations produced the largest radii for the high-level injury thresholds, due to constructive interference from seabed reflections in shallow water. Impact piling close to the steep bank at the edge of the terminal generated the largest radii for the lower-level

disturbance thresholds and zones of audibility because these locations were exposed to open water of the Strait of Georgia.

5.1.2 CONTINUOUS SOURCES

For vibratory piling scenarios, the cetacean and pinniped disturbance radii under NMFS criteria (120 dB rms SPL) were largest for Scenario 8 (vibratory sheet piling at west caisson) at 14,520 m ($R_{95\%}$) (**Table B-8** and **Figure A–28**). The killer whale ZOA for this scenario was approximately 58 km (**Table B–12** and **Figure A–37**). For non-piling scenarios (**Table B–10**), Scenario 14 (ship berthing) generated the largest radii (22 km) (**Figure A–33**), while dredging at the ITP (Scenario 13) produced the smallest radii (960 m) (**Figure A–32**). The killer whale ZOA for ship berthing was estimated at approximately 98 km (**Table B–14**).

Humpback whale and Steller sea lion audiogram-weighting was also applied to selected scenarios to determine which activity produced the largest radii. For both species, Scenario 14 (container ship berthing) produced the largest ZOA of approximately 98 and 99 km, respectively (**Table B–39**, **Table B–41**, **Figure A–49**, and **Figure A–50**).

Sound levels were similar for vibratory piling at the east and west sides of the proposed terminal expansion because their water depths and proximity to open water were similar. Vibratory piling at the tug basin produced the smallest radii (≤ 640 m) for a continuous source (120 dB SPL) because it was enclosed in shallow water behind the existing terminal (**Table B–8**).

5.2 FISH

5.2.1 IMPULSIVE SOURCES

For 1 min of continuous impact piling, the FHWG SEL injury radii (187 dB SEL) were similar between all scenarios, except for impact piling with a bubble curtain, where the threshold was not reached (**Table B-3**). None of the impact piling scenarios reached the Halvorsen et al. (2011) injury criteria (210 dB SEL) for 1 min of piling. For 100 min of piling, the FHWG radii (187 dB SEL) were largest for impact piling at the mooring dolphin (Scenario 1; 1,020 m). For the Halvorsen et al. (2011) injury threshold, all impact piling scenarios had radii 50 m or less for 100 min of piling (**Table B–5** and **Figure A–19**).

The largest peak SPL radii under the FHWG (2008) criteria (206 dB re 1 μPa) were generated by impact piling at the tug basin (Scenario 3) at 38 m, followed by piling at the perimeter dyke at 36 m, and then at the mooring dolphin at 29 m, which was reduced to 9 m with the application of the confined bubble curtain (**Table B–7**). The radii for all SPL and SEL fish thresholds were reduced by an average of 82% by applying a confined bubble curtain.

Salmon, herring, and flatfish audiogram-weighting were applied to the impact piling scenarios to calculate ZOA, 95th percentile and maximum radii, and areas of ensonification. The largest radii ($R_{95\%}$) for the salmon ZOA was produced by impact piling at the mooring dolphin (**Figure A–46**) and impact sheet piling at the west caisson (Scenarios 1 and 7; both approximately 39 km) (**Table B–18**), whereas for herring and flatfish impact sheet piling at the west caisson produced the largest radii (approximately 55 and 41 km, respectively) (**Table B–27** and **Table B–33**, respectively).

5.2.1.1 *Continuous Sources*

Audiogram-weighting for salmon, herring, and flatfish was also applied to calculate ZOA, 95th percentile and maximum radii, and areas of ensonification for vibratory piling scenarios. For salmon, the largest ZOA radii ($R_{95\%}$) were produced by vibratory piling at the mooring dolphin (Scenario 5; approximately 24 km) (**Table B–21**), and for the continuous non-piling scenarios, container ship berthing (Scenario 14; approximately 23 km) (**Table B–24**). For herring, the largest ZOA radius for vibratory piling scenarios was sheet piling at the west caisson (Scenario 8; approximately 49 km) (**Table B–30**), while for flatfish it was piling at the mooring dolphin (Scenario 5; approximately 30 km) (**Table B–36**).

5.3 CHANGE IN EXISTING CONDITIONS DUE TO PROJECT OPERATIONS

The long-term change in noise levels in the study area was calculated by taking existing noise levels from hydrophone measurements and adding time-average sound levels from RBT2 terminal operations. Existing noise levels in the study area were estimated from PAMbuoy recordings performed at Roberts Bank from 2013-2014 (SMRU et al. 2014). The broadband (111 Hz to 112 kHz) time-average sound level (*Leq*) measured at Roberts Bank over the nine-month PAMbuoy deployment was 119.5 dB re 1 µPa.

Time-average sound levels from terminal operations were computed from berthing (S14) and approach (S15) scenarios, based on the proportion of time these activities are expected to occur inside PMV jurisdiction. Typical durations for these activities were calculated based on the following assumptions:

- 260 container ship calls per year at RBT2
- 1 hour combined berthing and unberthing activity per call
- 0.75 hours combined approach and departure per call

Under these assumptions, berthing and unberthing noise (S14) would be present in the study area 2.97% of the time, and approach and departure noise (S15) would be present in the study area 2.23% of the time. Time-average sound levels for the terminal operations were calculated by weighting the modelled SPLs according to the proportion of the time (*P*) the activities would be present in the study area:

$$Leq(\text{model}) = \text{SPL}(\text{model}) + 10\log(P)$$

Noise levels in the study area were calculated by adding time-average sound levels for the terminal operations to existing noise levels:

$$Leq(\mathrm{RBT2}) = 10\log\left(10^{Leq(\mathrm{existing})/10} + 10^{Leq(\mathrm{S14})/10} + 10^{Leq(\mathrm{S15})/10}\right)$$

The long-term change in existing noise levels was taken to be the time-average difference between RBT2 noise levels (*Leq*(RBT2)) and existing noise levels (*Leq*(existing)). **Figure A–52** shows a contour map of the long-term change in existing noise levels from RBT2 terminal operations; **Table B–43** shows distances to the contours from the terminal. This calculation is expected to be conservative because (1) terminal operations were based on an E-class containership, which is largest class of vessel capable of calling at RBT2, and (2) the broadband PAMbuoy measurements do not include noise below 111 Hz.

5.4   DATA GAPS AND LIMITATIONS

At the time of writing, specific equipment associated with construction activities (i.e., pile driving hammers and vibro-densifier) and vessel specifications had not been confirmed. As such, model scenarios were based on reasonable, but conservative, assumptions. Source levels were based on the best available information obtained from a review of past measurements. Actual source levels can vary for a given activity, depending on the specific equipment used, how it is operated, and other environmental factors. Acoustic source depth for vessels were based on fully-loaded ships since deeper sources more efficiently radiate underwater sound, and consequently produce more conservative model results.

Other conservative assumptions associated with the model include application of a winter sound speed profile, which traps energy near the sea surface (i.e., in a surface duct), and favours longer-range propagation. In the acoustic model, sound levels were sampled at numerous receiver depths spanning the entire water column. The radii and contour maps were computed using maximum sound level over all depths to ensure conservative estimates. Furthermore, ambient underwater noise used in calculation were from the lower 5th percentile measured levels that include noise from natural sources (e.g., wind) and anthropogenic sources (e.g., existing commercial and recreational vessel traffic). The lower 5th percentile levels may underestimate ambient levels if nearby vessels mask construction or terminal vessel operation sounds.

No source levels were available for E-class container ships so SLs were estimated by scaling measurements of somewhat smaller container ships by the length ratio. In the absence of source level measurements for this class of vessel, it is unknown whether the scaled measurements accurately represent their noise emissions.

Because it is unclear exactly how many sections would be in place when sheet piling occurs at both the east and west ends of the structure, a conservative approach of having no caisson sections in place was chosen when these scenarios were modelled. The effect on the sound propagation of the entire caisson

structure, including the berm, was tested. Results showed a relatively small change in the 95% rms SPL radii (largest decrease was 12% at the 150 dB level; largest increase was 20% at the 190 dB level, which is an increase from 20 m to 24 m).

Structure placement for the new terminal will vary with time so to be conservative, the model excluded any obstructions from ongoing construction activities (e.g., no caisson structure in place).

Despite the above limitations, this report successfully reported adequate information to include in a future effects assessment for the Project.

6.0 CLOSURE

Major authors and reviewers of this technical report are listed below, along with their signatures.
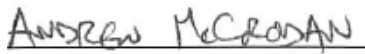
Report prepared by:
JASCO Applied Sciences

Jennifer Wladichuk, Project Scientist

Graham Warner, Project Scientist

Andrew McCrodan, Project Scientist

Alexander MacGillivray, Lead Scientist

Report peer reviewed by:
Hemmera

Sonya Meier, Msc, RPBio
Senior Biologist

7.0 REFERENCES

AECOM Canada Ltd. 2012. *Container Capacity Improvement Program (CCIP) – Phase 2 Roberts Bank Terminal 2 Fast-time Ship Navigation Simulation Study.* http://www.aecom.ca/.

Aerts, L., M. Blees, S. Blackwell, C. Greene, K. Kim, D. Hannay, and M. Austin. 2008. *Marine mammal monitoring and mitigation during BP Liberty OBC seismic survey in Foggy Island Bay, Beaufort Sea, July-August 2008: 90-day report.* Document Number LGL Report P1011-1. Report by LGL Alaska Research Associates Inc., LGL Ltd., Greeneridge Sciences Inc. and JASCO Applied Sciences for BP Exploration Alaska. 199 pp. http://www.nmfs.noaa.gov/pr/pdfs/permits/bp_liberty_monitoring.pdf.

Austin, M. 2007. Vibro-densification source level study and killer whale acoustics impact report. *In* Jacques Whitford AXYS and JASCO Research Ltd. (eds.). *Appendix F: Marine Mammal Monitoring Program Reports.* Technical report prepared by JASCO Research Ltd, Victoria BC, for Vancouver Port Authority http://www.robertsbankterminal2.com/wp-content/uploads/DP3-Pre-Operations-EAC-Compliance-Report-Appendix-F.pdf.

Blackwell, S.B. 2005. *Underwater Measurements of Pile driving Sounds during the Port MacKenzie Dock Modifications, 13-16 August 2004.* . Report from Greeneridge Sciences, Inc., and LGL Alaska Research Associates, Inc., in association with HDR Alaska, Inc. for Knik Arm Bridge and Toll Authority, Department of Transportation and Public Facilities, and Federal Highway Administration. . 33 pp.

Chapman, C.J. and O. Sand. 1974. Field studies of hearing in two species of flatfish *Pleuronectes platessa* (L.) and *Limanda limanda* (L.) (family pleuronectidae). *Comparative Biochemistry and Physiology Part A: Physiology* 47(1): 371-385.

Collins, M.D. 1993. A split-step Padé solution for the parabolic equation method. *Journal of the Acoustical Society of America* 93: 1736-1742.

Coppens, A.B. 1981. Simple equations for the speed of sound in Neptunian waters. *Journal of the Acoustical Society of America* 69(3): 862-863. http://link.aip.org/link/?JAS/69/862/1.

Enger, P.S. 1967. Hearing in herring. *Comparative Biochemistry and Physiology* 22(2): 527-538.

Erbe, C. 2002. *Hearing abilities of baleen whales.* DRDC Atlantic Report CR2002-065. Defence Research & Development Canada—Atlantic. http://pubs.drdc.gc.ca/PDFS/unc09/p519661.pdf.

Fisheries Hydroacoustic Working Group. 2008. *Agreement in Principle for Interim Criteria for Injury to Fish from Pile Driving Activities.* June 12, 2008 edition. http://www.dot.ca.gov/hq/env/bio/files/fhwgcriteria_agree.pdf.

Funk, D., D. Hannay, D. Ireland, R. Rodrigues, and W. Koski (eds.). 2008. *Marine mammal monitoring and mitigation during open water seismic exploration by Shell Offshore Inc. in the Chukchi and Beaufort Seas, July–November 2007: 90-day report.* LGL Report P969-1. Prepared by LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Research Ltd. for Shell Offshore Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. 218 pp. http://www-static.shell.com/static/usa/downloads/alaska/shell2007_90-d_final.pdf.

Halvorsen, M.B., B.M. Casper, C.M. Woodley, T.J. Carlson, and A.N. Popper. 2011. *Hydroacoustic impacts on fish from pile installation.* NCHRP Research Results Digest 363, Project 25-28. National Cooperative Highway Research Program, Transportation Research Board, National Academy of Sciences, Washington DC, USA. http://www.trb.org/Publications/Blurbs/166159.aspx.

Hamilton, E.L. 1980. Geoacoustic modeling of the sea floor. *Journal of the Acoustical Society of America* 68: 1313-1340.

Hannay, D.E., J. Delarue, X. Mouy, B.S. Martin, D. Leary, J.N. Oswald, and J. Vallarta. 2013. Marine mammal acoustic detections in the northeastern Chukchi Sea, September 2007–July 2011. *Continental Shelf Research* 67: 127-146. http://www.sciencedirect.com/science/article/pii/S0278434313002483.

Hawkins, A.D. and A.D.F. Johnstone. 1978. The hearing of the Atlantic salmon, *Salmo salar*. *Journal of Fish Biology* 13(6): 655-673. http://dx.doi.org/10.1111/j.1095-8649.1978.tb03480.x.

Ireland, D.S., R. Rodrigues, D. Funk, W. Koski, and D. Hannay. 2009. *Marine mammal monitoring and mitigation during open water seismic exploration by Shell Offshore Inc. in the Chukchi and Beaufort Seas, July–October 2008: 90-Day Report*. Document Number LGL Report P1049-1. 277 pp.

Kastelein, R.A., R. van Schie, W.C. Verboom, and D. de Haan. 2005. Underwater hearing sensitivity of a male and a female Steller sea lion (*Eumetopias jubatus*). *Journal of the Acoustical Society of America* 118(3): 1820-1829. http://link.aip.org/link/?JAS/118/1820/1.

MacGillivray, A., E. Ziegler, and J. Laughlin. 2007. Underwater Acoustic Measurements from Washington State Ferries 2006 Mukilteo Ferry Terminal Test Pile Project. Technical report prepared by JASCO Research, Ltd for Washington State Ferries and Washington State Department of Transportation. 27.

MacGillivray, A., G. Warner, R. Racca, and C. O'Neill. 2011. *Tappan Zee Bridge Construction Hydroacoustic Noise Modeling: Final report*. Report by JASCO Applied Sciences for AECOM. 63 pp. http://www.newnybridge.com/documents/feis/vol2/f-4a-tzb-construction-hydroacoustic-noise-modeling.pdf.

Marine Mammal Protection Act of 1972 as Amended. 2007. United States Pub. L. No. 92-522, 16 U.S.C. 1361 (Oct. 21, 1972). http://www.nmfs.noaa.gov/pr/laws/mmpa/text.htm.

Marquardt, T., J. Hensel, D. Mrowinski, and G. Scholz. 2007. Low-frequency characteristics of human and guinea pig cochleae. *Journal of the Acoustical Society of America* 121(6): 3628-3638. http://link.aip.org/link/?JAS/121/3628/1.

McHugh, O., M. Fraker, B. Wheeler, M. Austin, M. Zykov, and M. Laurinolli. 2007. *Potential Acoustic Impacts to Killer Whales Associated with Construction Dredging at DP3*. Document Number PROJECT NO. 1021281. Report prepared for Vancouver Port Authority by Jacques Whitford-AXYS and JASCO Research Ltd. 53 pp.

Mouy, X., A. MacGillivray, J. Vallarta, B. Martin, and J. Delarue. 2012. *Ambient Noise and Killer Whale Monitoring near Port Metro Vancouver's Proposed Terminal 2 Expansion Site: July–September 2012*. Version 2.0, Document 00476. Technical report by JASCO Applied Sciences for Hemmera.

National Geophysical Data Center. 2013. High resolution NOAA digital elevation model. *U.S. Coastal Relief Model (CRM)*. National Oceanic and Atmospheric Administration, U.S. Department of Commerce. http://www.ngdc.noaa.gov/dem/squareCellGrid/download/655.

Nedwell, J.R. and A.W. Turnpenny. 1998. The use of a generic frequency weighting scale in estimating environmental effect. *Workshop on Seismics and Marine Mammals*. 23–25th June, London, U.K.

Nedwell, J.R., A.W.H. Turnpenny, J. Lovell, S.J. Parvin, R. Workman, and J.A.L. Spinks. 2007. *A validation of the dB$_{ht}$ as a measure of the behavioural and auditory effects of underwater noise*. Report No. 534R1231 prepared by Subacoustech Ltd. for the UK Department of Business, Enterprise and Regulatory Reform under Project No. RDCZ/011/0004. www.subacoustech.com/information/downloads/reports/534R1231.pdf.

O'Neill, C., D. Leary, and A. McCrodan. 2010. Sound Source Verification. (Chapter 3) *In* Blees, M.K., K.G. Hartin, D.S. Ireland, and D. Hannay (eds.). *Marine mammal monitoring and mitigation during open water seismic exploration by Statoil USA E&P Inc. in the Chukchi Sea, August-October 2010: 90-day report*. LGL Report P1119. Prepared by LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Applied Sciences Ltd. for Statoil USA E&P Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. 1-34 pp.

Oestman, R., D. Buehler, J. Reyff, and R. Rodkin. 2009. *Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish. Prepared for California Department of Transportation by ICF Jones & Stokes and Illingworth and Rodkin, Inc.* 298 pp. http://www.dot.ca.gov/hq/env/bio/files/Guidance_Manual_2_09.pdf.

Racca, R., A. MacGillivray, and M. Laurinolli. 2007. *NaiKun Meteo Mast Installation: Underwater Sound Level Monitoring of Pile Driving Operations*. Technical report for NaiKun Wind Development by JASCO Research Ltd.

Robinson, S.P., P.D. Theobald, G. Hayman, L.S. Wang, P.A. Lepper, V. Humphrey, and S. Mumford. 2011. *Measurement of Noise Arising from Marine Aggregate Dredging Operations*. MALSF (MEPF Ref no. 09/P108).

Ross, D. 1976. *Mechanics of Underwater Noise*. Pergamon Press, New York. 375 pp.

SMRU, Hemmera, and JASCO. 2014. *Ambient Underwater Noise Study Technical Data Report*. Prepared for Port Metro Vancouver, Vancouver, B.C. http://www.robertsbankterminal2.com/.

SMRU Canada Ltd. 2014. *Roberts Bank Terminal 2 Technical Data Report: Determination of Behavioral Effect Noise Thresholds for Southern Resident Killer Whales*. Prepared for Port Metro Vancouver, Vancouver, B.C. by SMRU Canada Ltd. (on behalf of Hemmera). 44 pp. http://www.robertsbankterminal2.com/.

Southall, B.L., A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Greene, Jr., D. Kastak, D.R. Ketten, J.H. Miller, et al. 2007. Marine mammal noise exposure criteria: Initial scientific recommendations. *Aquatic Mammals* 33(4): 411-521.

Warner, G., C. Erbe, and D. Hannay. 2010. Underwater Sound Measurements. (Chapter 3) *In* Reiser, C.M., D.W. Funk, R. Rodrigues, and D. Hannay (eds.). *Marine Mammal Monitoring and Mitigation during Open Water Shallow Hazards and Site Clearance Surveys by Shell Offshore Inc. in the Alaskan Chukchi Sea, July-October 2009: 90-Day Report*. LGL Report P1112-1. Report by LGL Alaska Research Associates Inc. and JASCO Applied Sciences for Shell Offshore Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. 1-54 pp.

Warner, G., C. O'Neill, A. McCrodan, H. Frouin-Mouy, J. Izett, and A. MacGillivray. 2013. *Underwater Acoustic Measurements in Haro Strait and Strait of Georgia: Transmission Loss, Vessel Source Levels, and Ambient Measurements*. Appendix A in Roberts Bank Terminal 2 technical data report: Ship sound signature analysis study. Prepared for Port Metro Vancouver, Vancouver, B.C. by JASCO Applied Sciences (on behalf of Hemmera). http://www.robertsbankterminal2.com/.

Wright, E.B. and J. Cybulski. 1983. *Low-frequency acoustic source levels of large merchant ships.* Document Number 8677. [NRL] Naval Research Lab, Washington DC. 55 pp. http://www.dtic.mil/dtic/tr/fulltext/u2/a126292.pdf.

Zhang, G., T. Hiraishi, K. Motomatsu, K. Yamamoto, and K. Nashimoto. 1998. Auditory threshold of marbled sole *Pleuronectes yokohamae. Bulletin of the Japanese Society of Scientific Fisheries (Japan)* 64: 211-215.

Zhang, Y. and C. Tindle. 1995. Improved equivalent fluid approximations for a low shear speed ocean bottom. *Journal of the Acoustical Society of America* 98(6): 3391-3396.

Zykov, M., A.O. MacGillivray, M. Austin, O. McHugh, B. Wheeler, and M. Fraker. 2007. *Source Level Study of the Dredge Columbia and Killer Whale Acoustics Impact Report Update.* by Jacques Whitford – AXYS and JASCO Research Ltd. for Vancouver Port Authority.

8.0   STATEMENT OF LIMITATIONS

This report was prepared by JASCO for the sole benefit and exclusive use of Hemmera and Port Metro Vancouver. The material in it reflects JASCO's best judgment in light of the information available to it at the time of preparing this Report. Any use that a third party makes of this Report, or any reliance on or decision made based on it, is the responsibility of such third parties. JASCO accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions taken based on this Report.

JASCO has performed the work as described above and made the findings and conclusions set out in this Report in a manner consistent with the level of care and skill normally exercised by members of the environmental science profession practicing under similar conditions at the time the work was performed.

This Report represents a reasonable review of the information available to JASCO within the established Scope, work schedule, and budgetary constraints. The conclusions and recommendations contained in this Report are based upon applicable legislation existing at the time the Report was drafted. Any changes in the legislation may alter the conclusions and/or recommendations contained in the Report. Regulatory implications discussed in this Report were based on the applicable legislation existing at the time this Report was written.

In preparing this Report, JASCO has relied in good faith on information provided by others as noted in this Report, and has assumed that the information provided by those individuals is both factual and accurate. JASCO accepts no responsibility for any deficiency, misstatement or inaccuracy in this Report resulting from the information provided by those individuals.

APPENDIX A

Figures

Figure A–1 Example Waveform Showing a Continuous Noise Measurement and the Corresponding Root-mean-square (rms) Sound Pressure
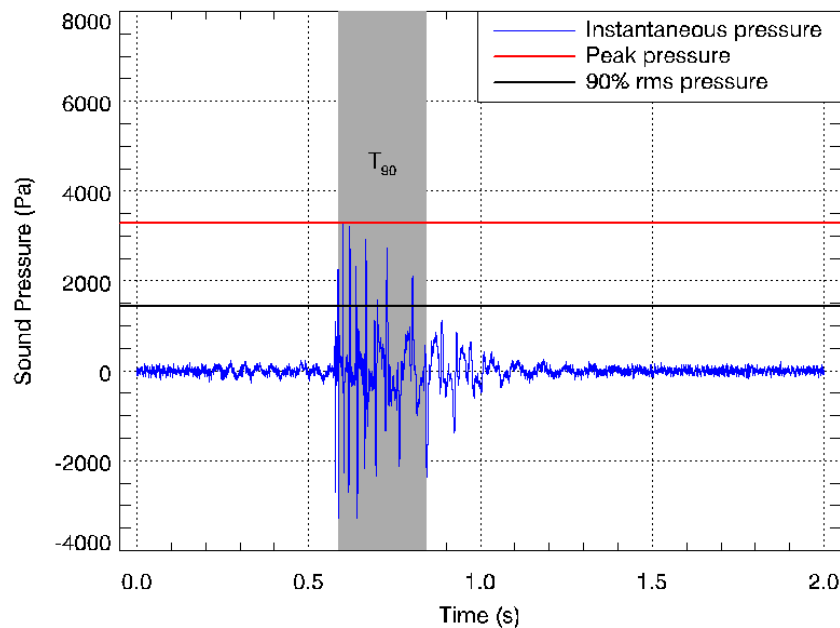
Figure A–2 Example Waveform Showing an Impulsive Noise Measurement (Horizontal lines indicate the peak pressure and 90% rms pressure for this pulse. The grey area indicates the 90% energy time interval (T_{90}) over which the rms pressure is computed.)

Marine Mammal Audiograms
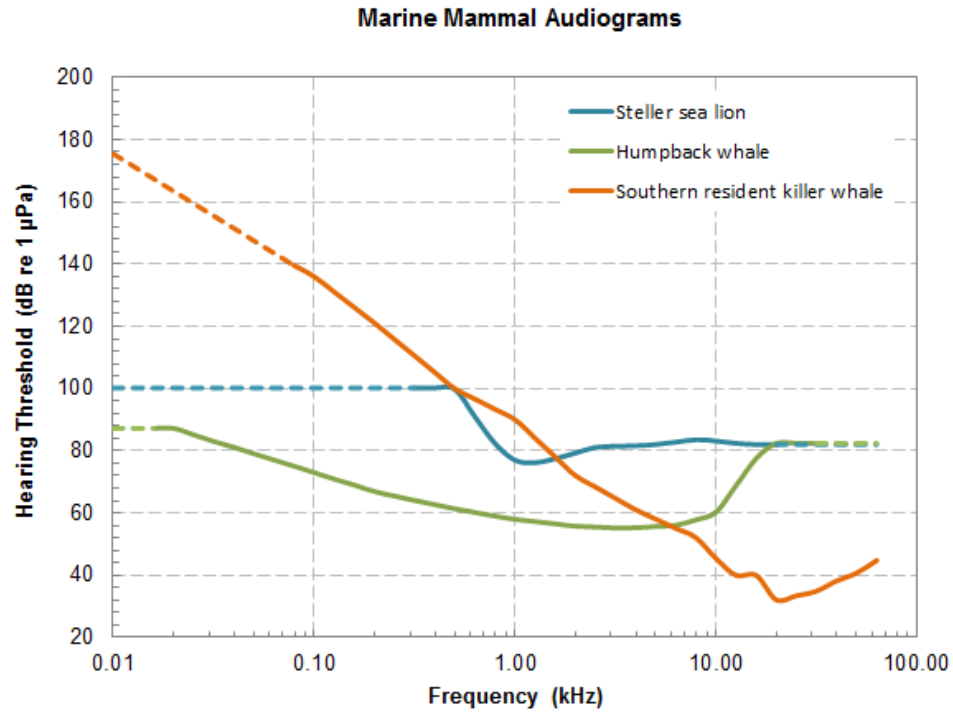
Figure A–3 Audiograms for Steller Sea Lion (Kastelein et al. 2005), Humpback Whale (Erbe 2002), and Southern Resident Killer Whale used in this Study (Yurk and Wood, pers comm.). Dashed lines show extrapolation
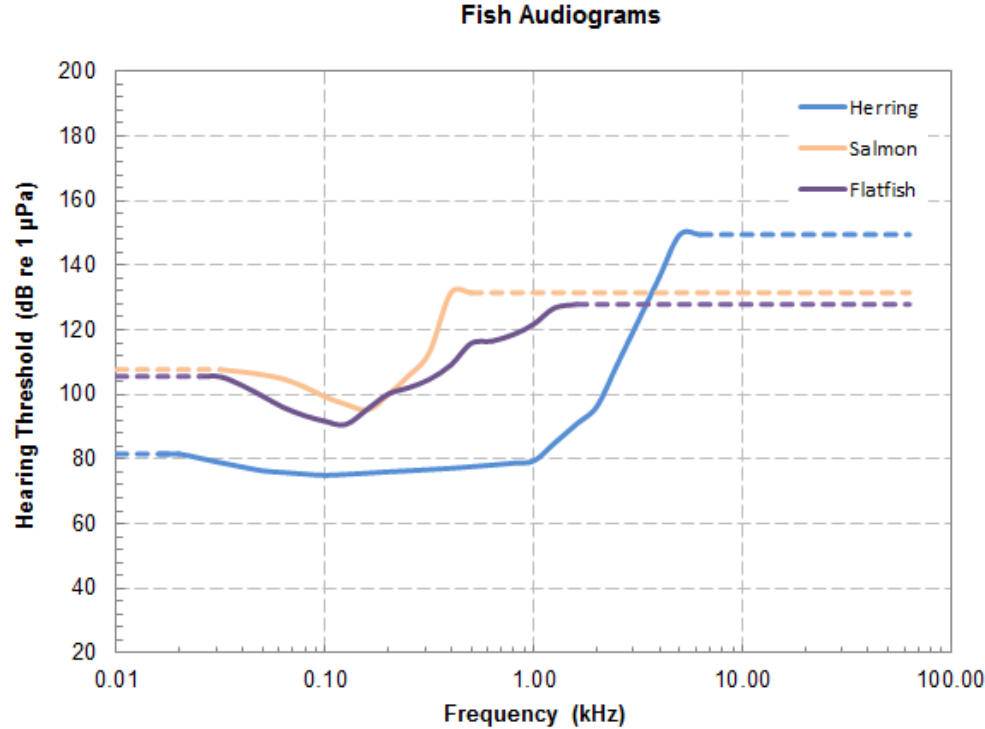
Fish Audiograms

Figure A–4 Audiograms for Herring (Enger 1967), Salmon (Hawkins and Johnstone 1978), and Flatfish Used in this Study (Chapman and Sand 1974, Zhang et al. 1998). Dashed lines show extrapolation
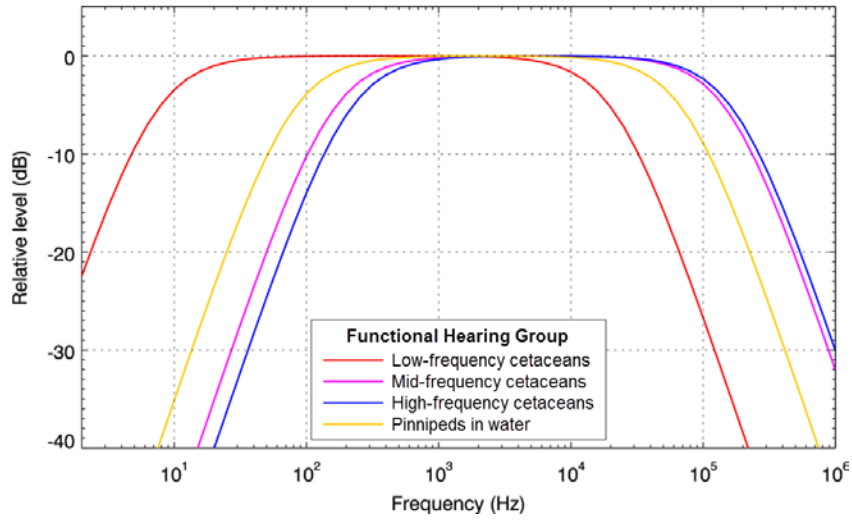
Figure A–5 Standard M-weighting Functions for Low-, Mid-, and High-frequency Cetaceans, and for Pinnipeds in Water
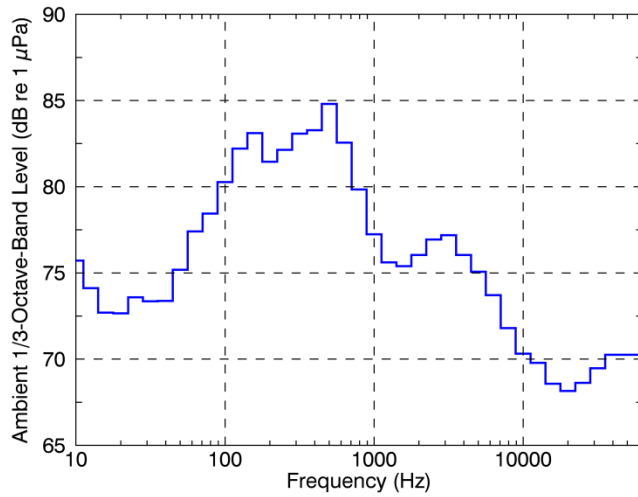
Figure A–6 Ambient Noise 1/3-octave-band SPLs (lowest 5th percentile) for the Study Area

Figure A–7 Aerial View of Roberts Bank Terminals facing North (adapted from http//www.portvancouver.com/the_port/Roberts.html)
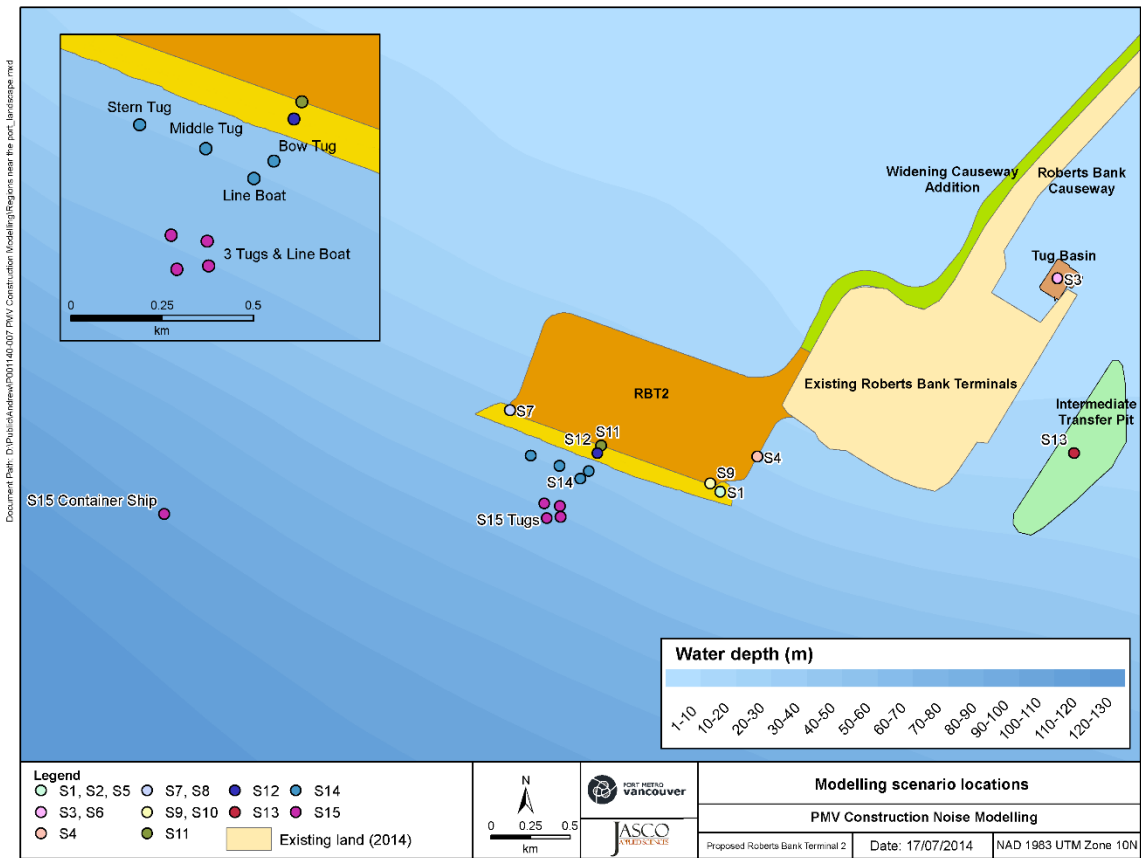
Figure A–8 Map of Modelled Source Locations for all 15 Scenarios investigated (see table B-1 for specification of modelled scenarios S1 to 15). Note: The tug basin design shown is based on preliminary project information and has been updated since the modelling was done, it is expected that the changes would have minimal effects on the modelling results
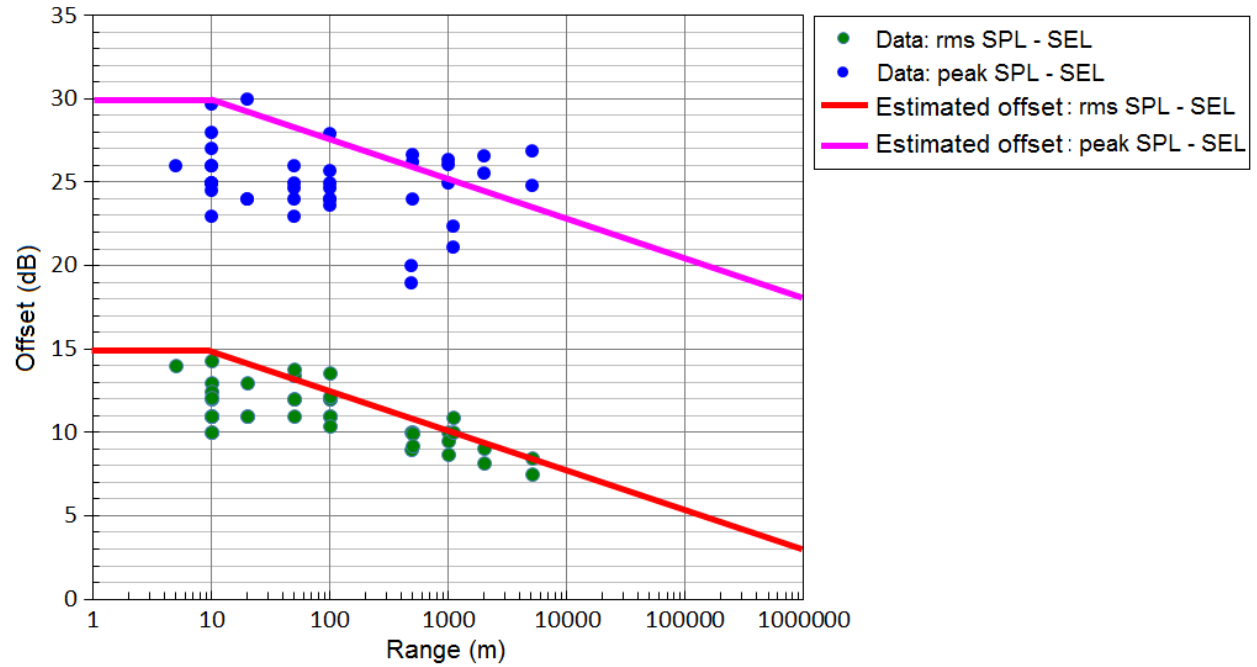
Figure A–9 The rms SPL to Per-pulse SEL and Peak SPL to Per-pulse SEL Offsets of Impact Piling Driving (cylindrical and sheet) Based on Reported Measurements (the red and pink lines are the range-dependent offsets added to the modelled SELs to obtain the rms SPLs and peak SPLs, respectively)
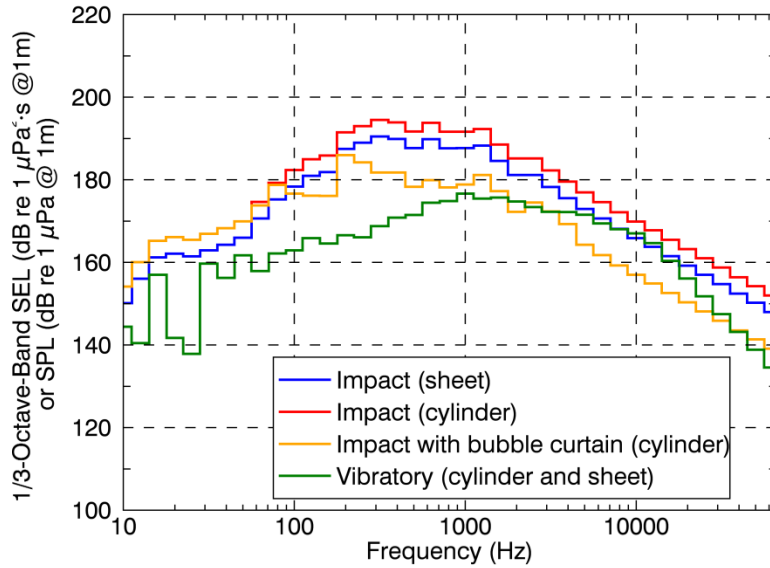
Figure A–10 One-third-octave-band Source Levels for Impact and Vibratory Piling (Impact piling source levels have units of SEL (dB re 1 µPa^{2}s @ 1 m). Vibratory piling source levels have units of SPL (dB re 1 µPa @ 1 m.)
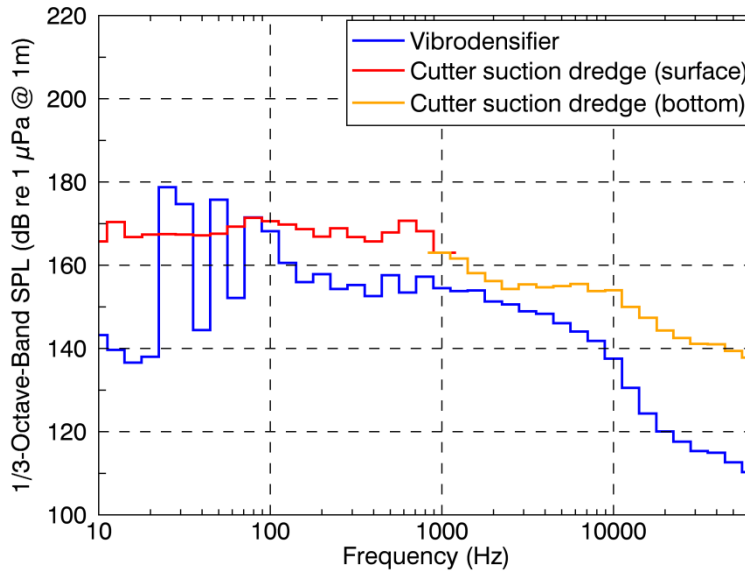
Figure A–11 One-third-octave-band Source Levels for Vibro-densification and Dredging (Dredging source levels below 1,000 Hz are assumed to originate from the dredge's hull near the surface and levels at 1,000 Hz and above are assumed to originate from the cutter head near the seafloor.)
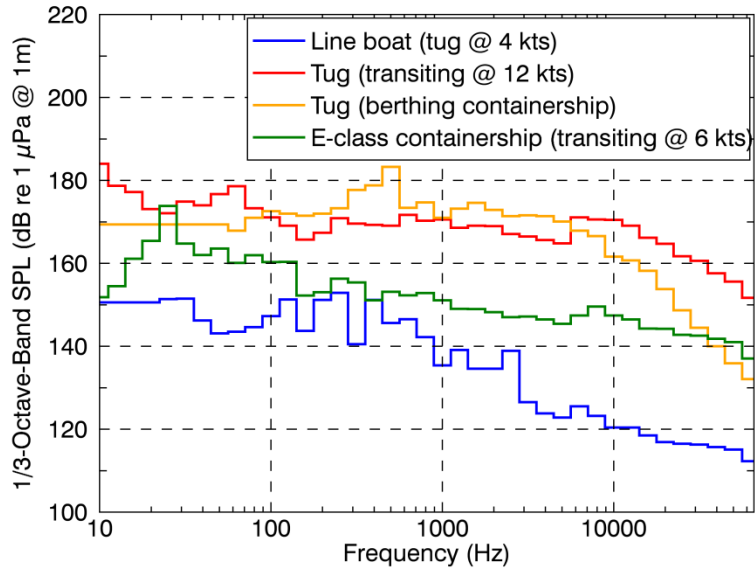
Figure A–12 One-third-octave-band Source Levels for Line Boat, Tugs and an E-class Container Ship Transiting and Tugs Berthing a Container Ship

Figure A–13 Regions of Construction at Roberts Bank. Note: The tug basin design shown is based on preliminary project information and has been updated since the modelling was done, it is expected that the changes would have minimal effects on the modelling results
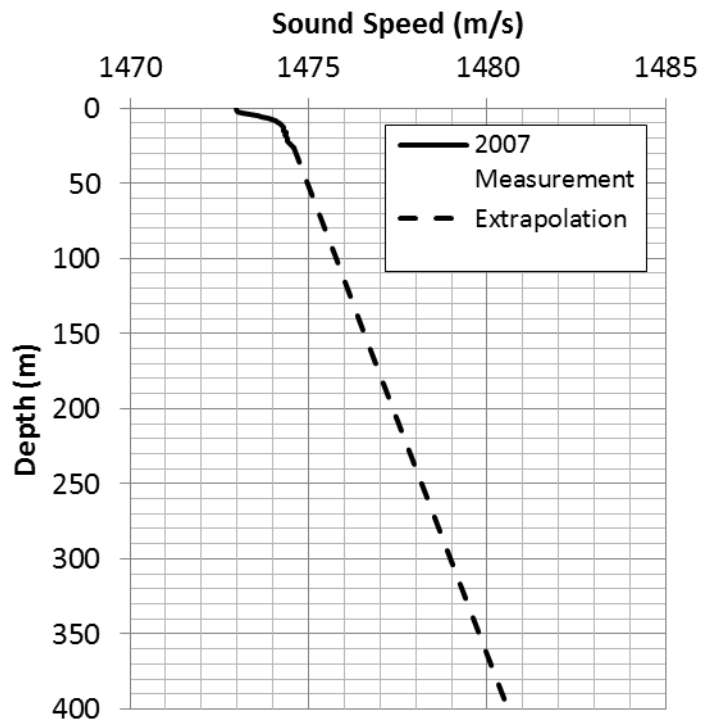
Figure A–14 Sound Speed Profile Extrapolated from a Measurement Near Roberts Bank Terminals (McHugh et al. 2007)
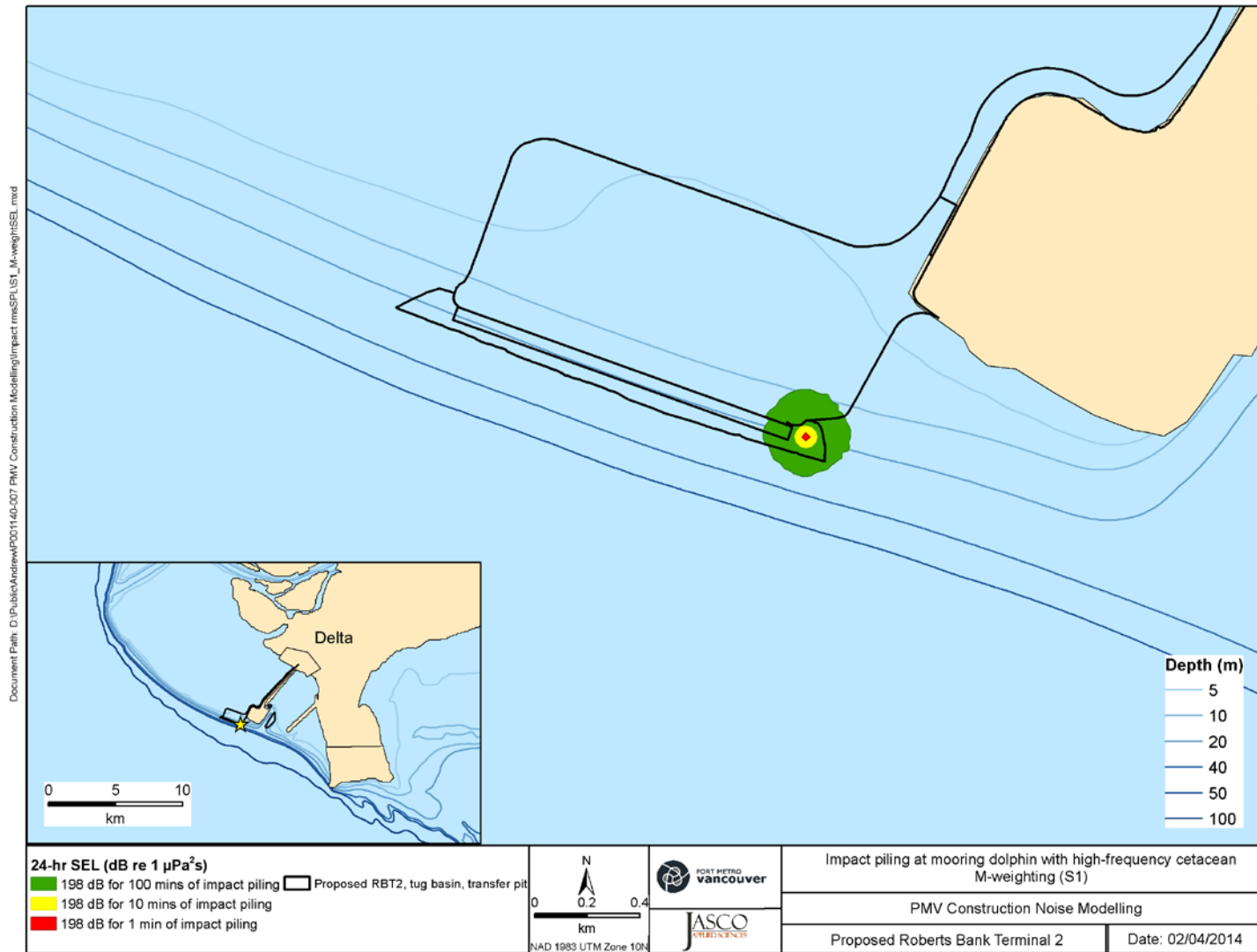
Figure A–15 Isopleth Map of Injury Thresholds for 24-hr Cumulative High-frequency Cetacean M-weighted SEL for Impact Piling at Mooring Dolphin (S1)
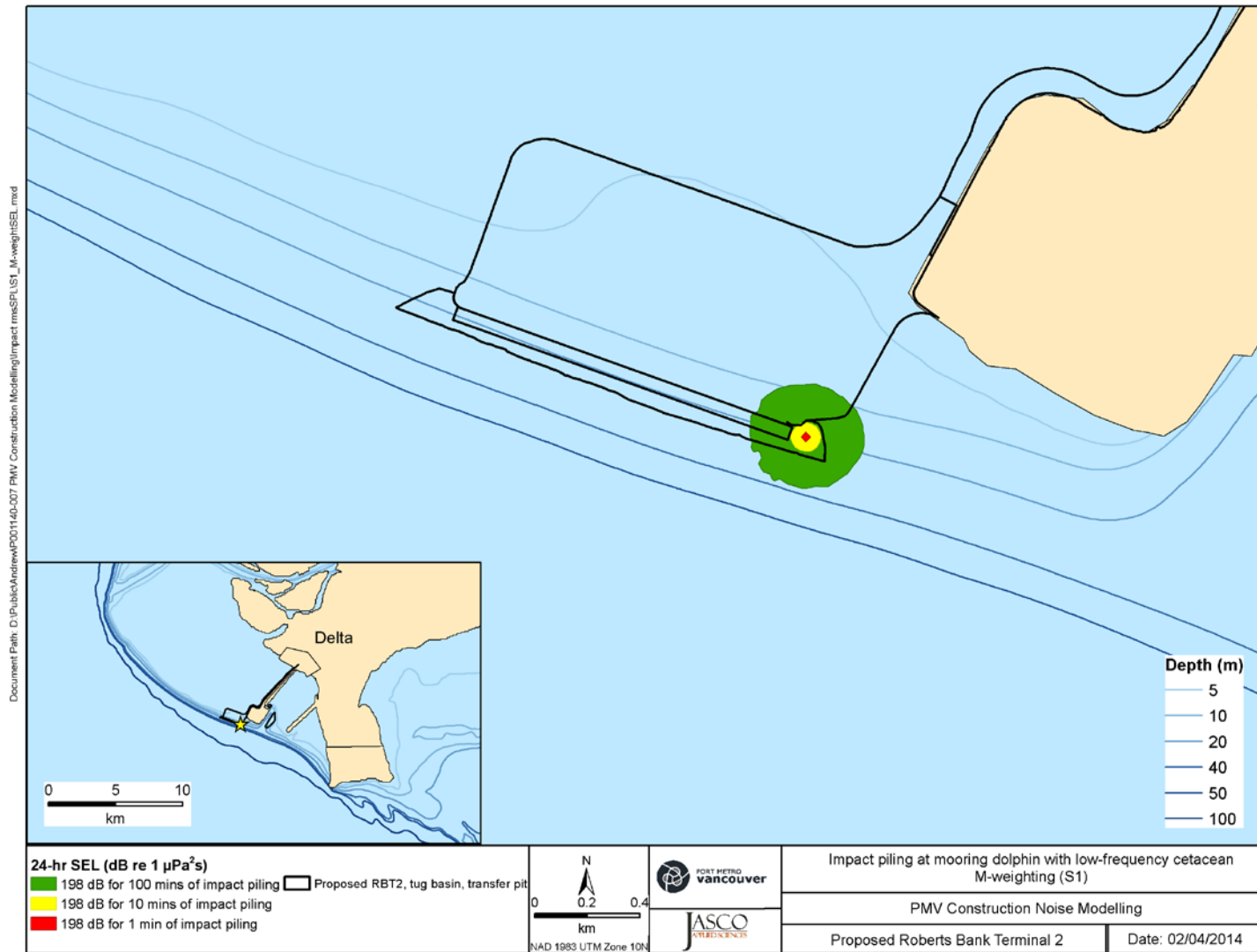
Figure A–16 Isopleth Map of Injury Thresholds for 24-hr Cumulative Low-frequency Cetacean M-weighted SEL for Impact Piling at Mooring Dolphin (S1)
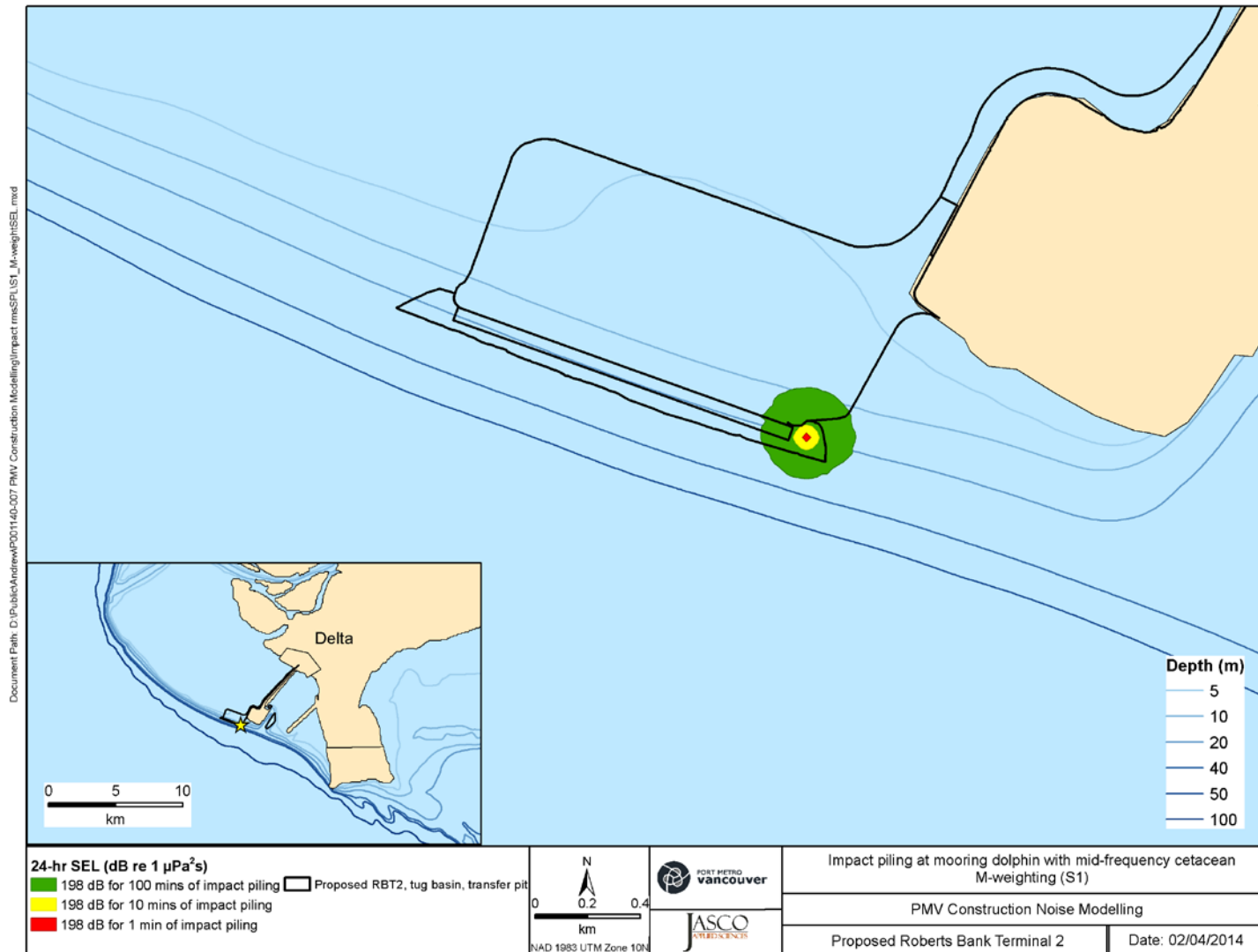
Figure A–17 Isopleth Map of Injury Thresholds for 24-hr Cumulative Mid-frequency Cetacean M-weighted SEL for Impact Piling at Mooring Dolphin (S1)
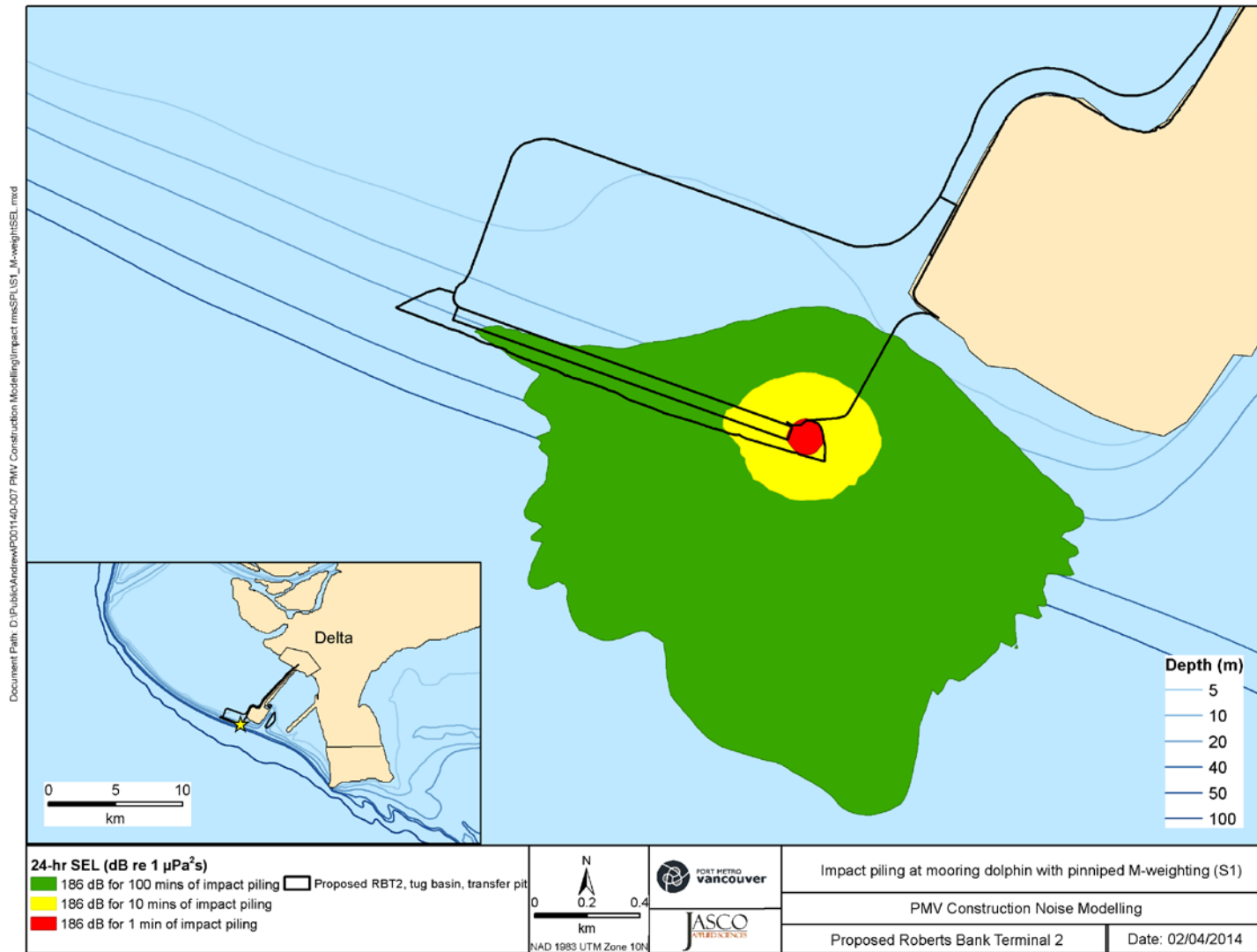
Figure A–18 Isopleth Map of Injury Thresholds for 24-hr Cumulative Pinniped M-weighted SEL for Impact Piling at Mooring Dolphin (S1)
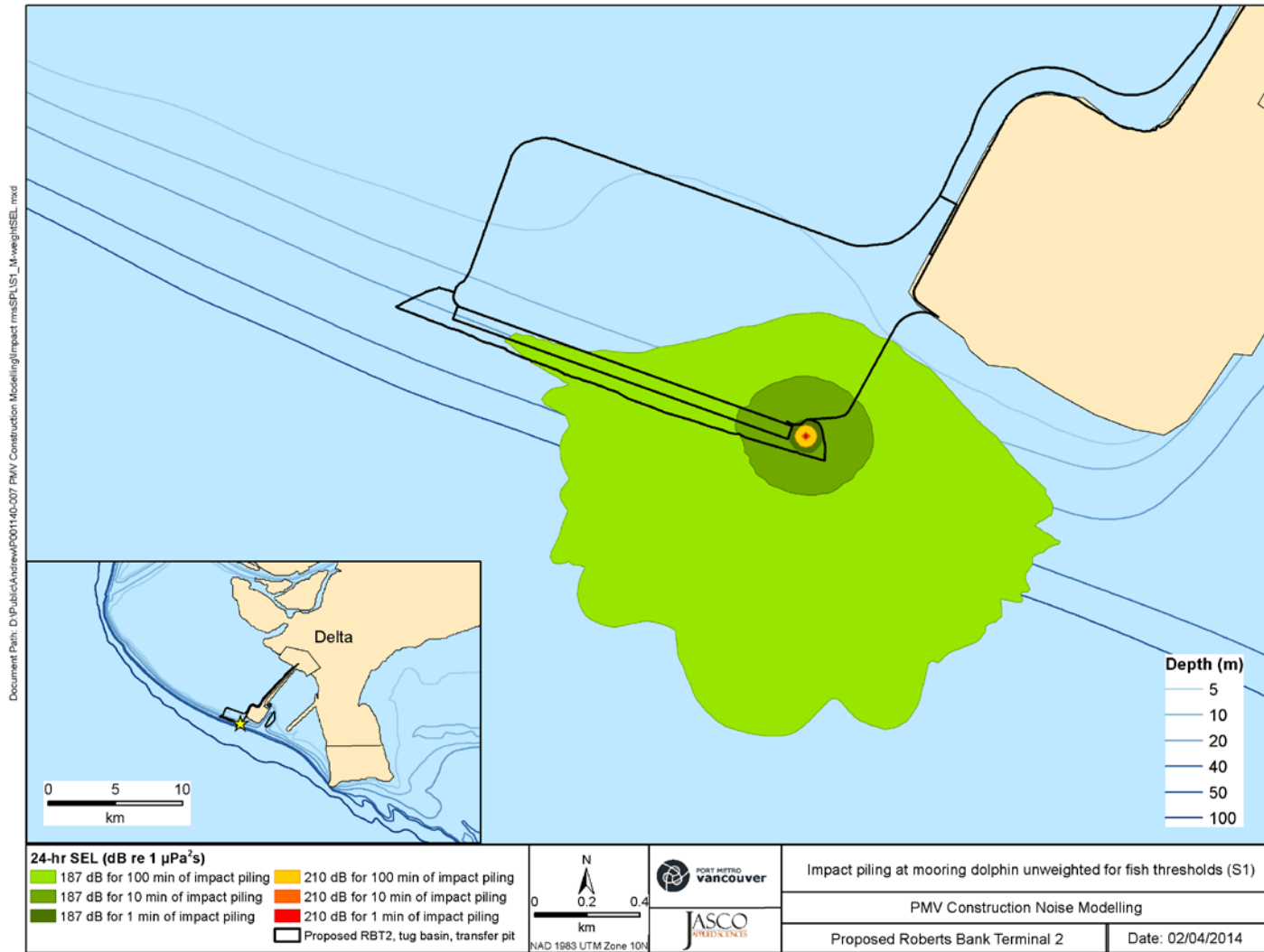
Figure A–19 Isopleth Map for 24-hr Cumulative Unweighted SEL for Impact Piling at Mooring Dolphin (S1) Representing FHWG (2008) and Halvorsen et al. (2011) Fish Injury Thresholds
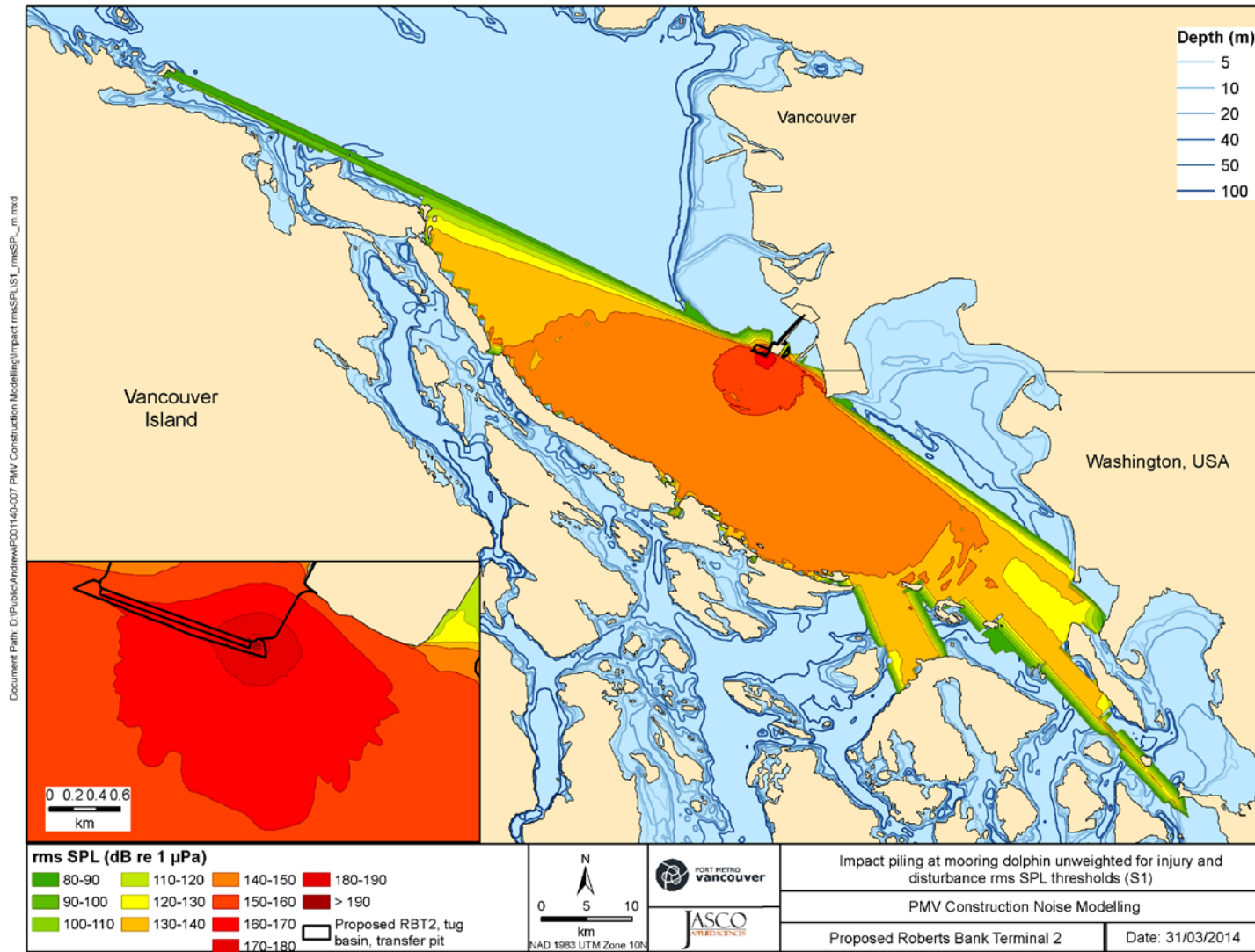
Figure A–20 Isopleth Map of Unweighted rms SPL for Impact Piling at Mooring Dolphin (S1)
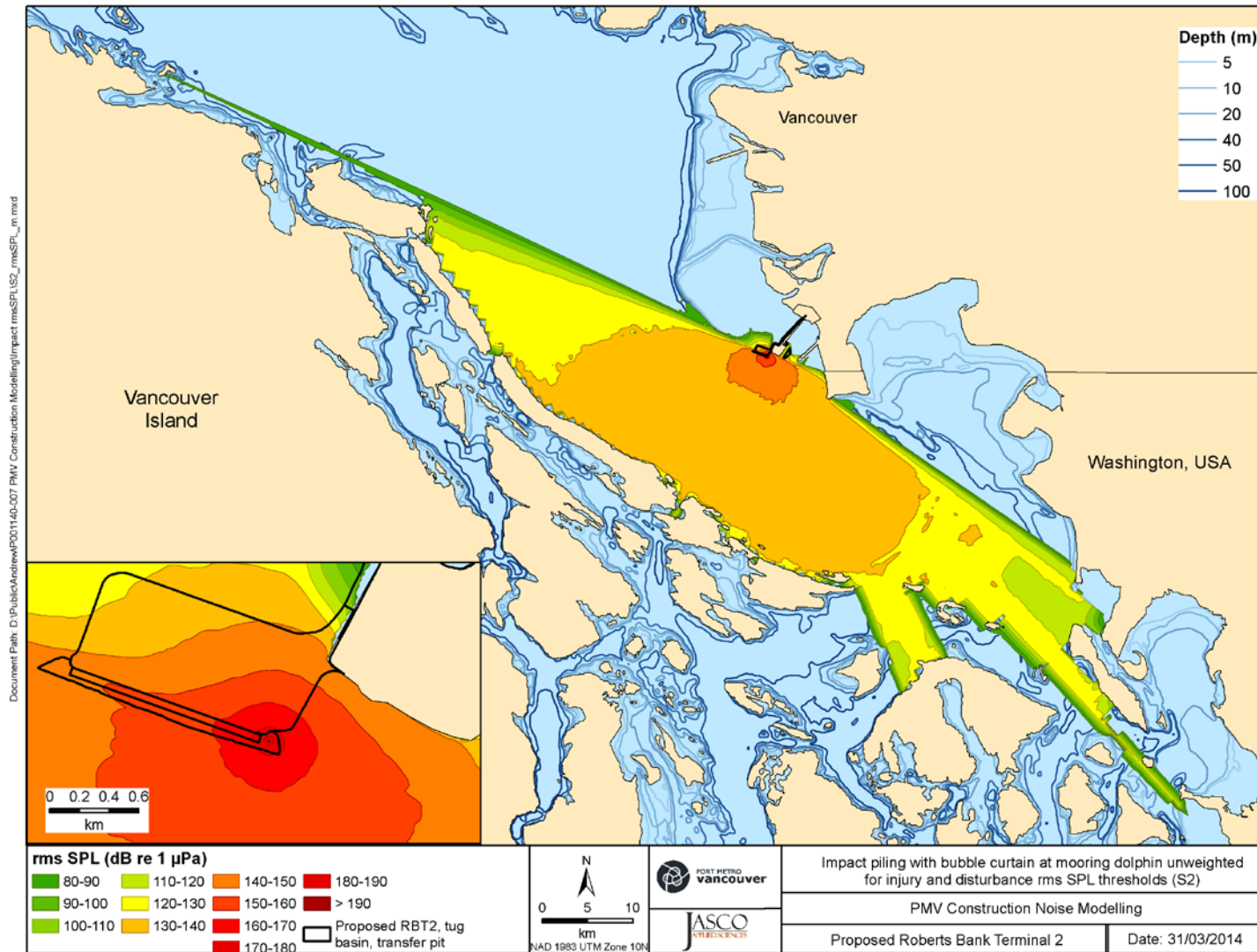
Figure A–21 Isopleth Map of Unweighted rms SPL for Impact Piling with Bubble Curtain at Mooring Dolphin (S2)
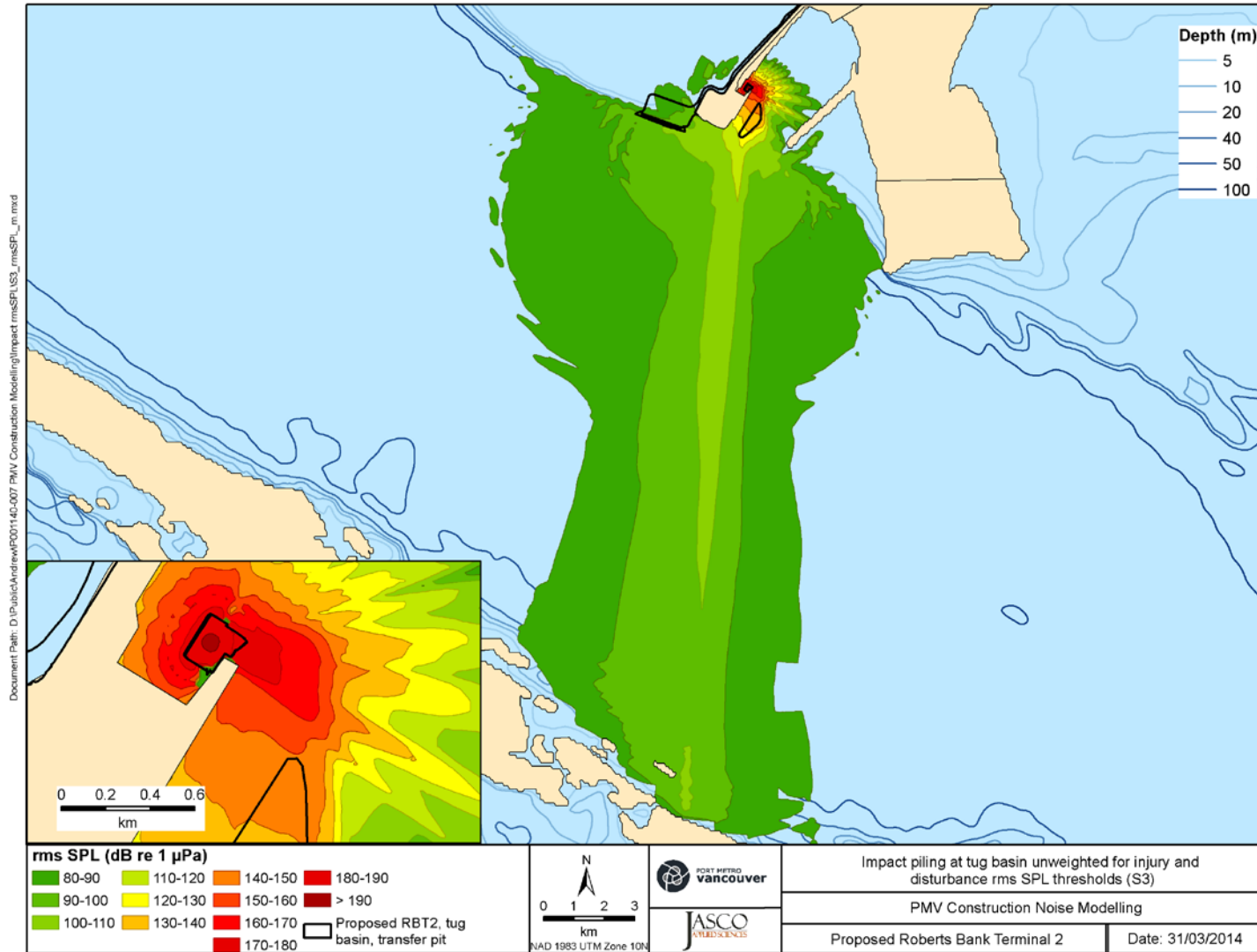
Figure A–22 Isopleth Map of Unweighted rms SPL for Impact Piling at Tug Basin (S3). Note: The tug basin design shown is based on preliminary project information and has been updated since the modelling was done, it is expected that the changes would have minimal effects on the modelling results
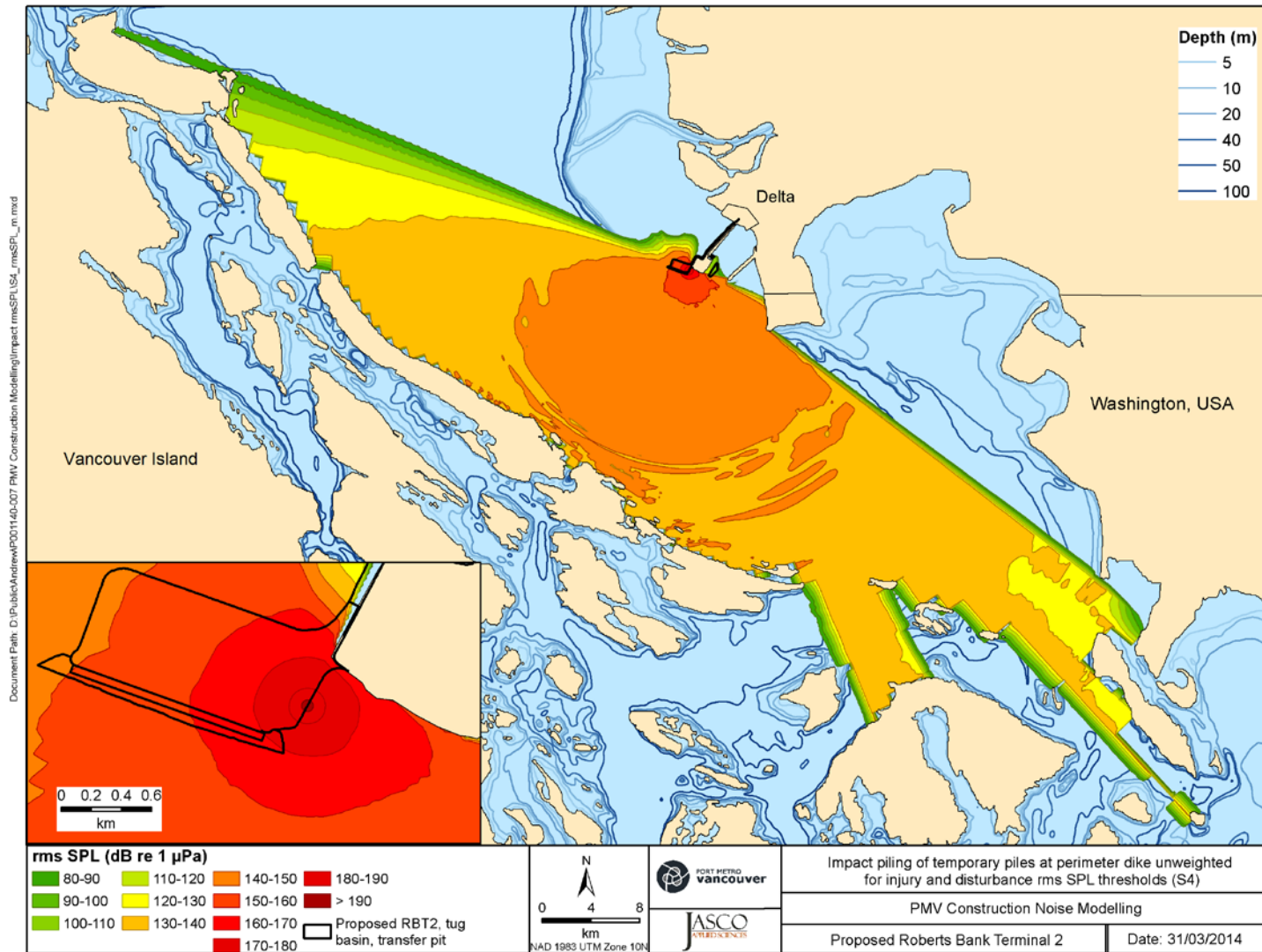
Figure A–23 Isopleth Map of Unweighted rms SPL for Impact Piling of Temporary Piles at Perimeter Dyke (S4)
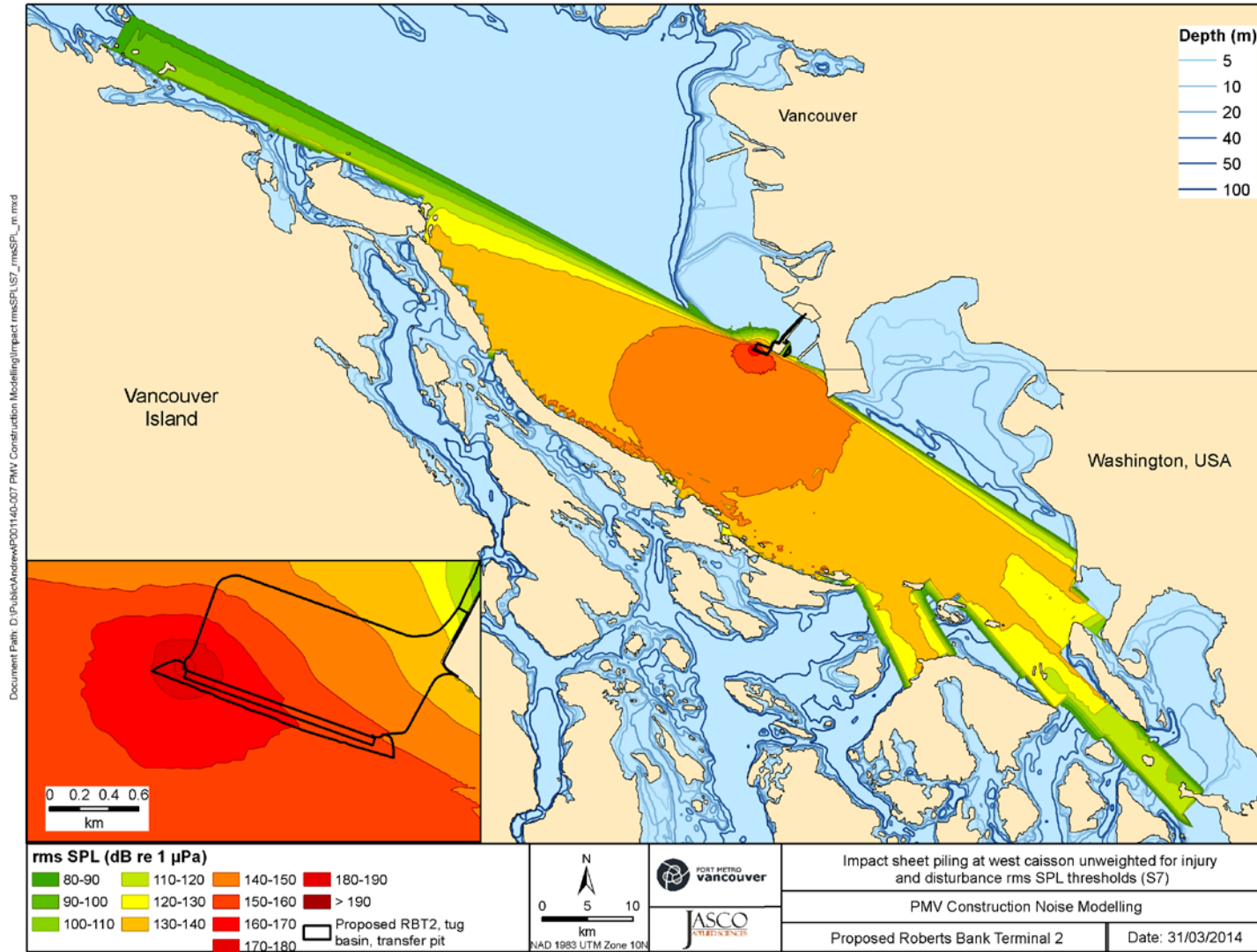
Figure A–24 Isopleth Map of Unweighted rms SPL for Impact Sheet Piling at West end Caisson (S7)
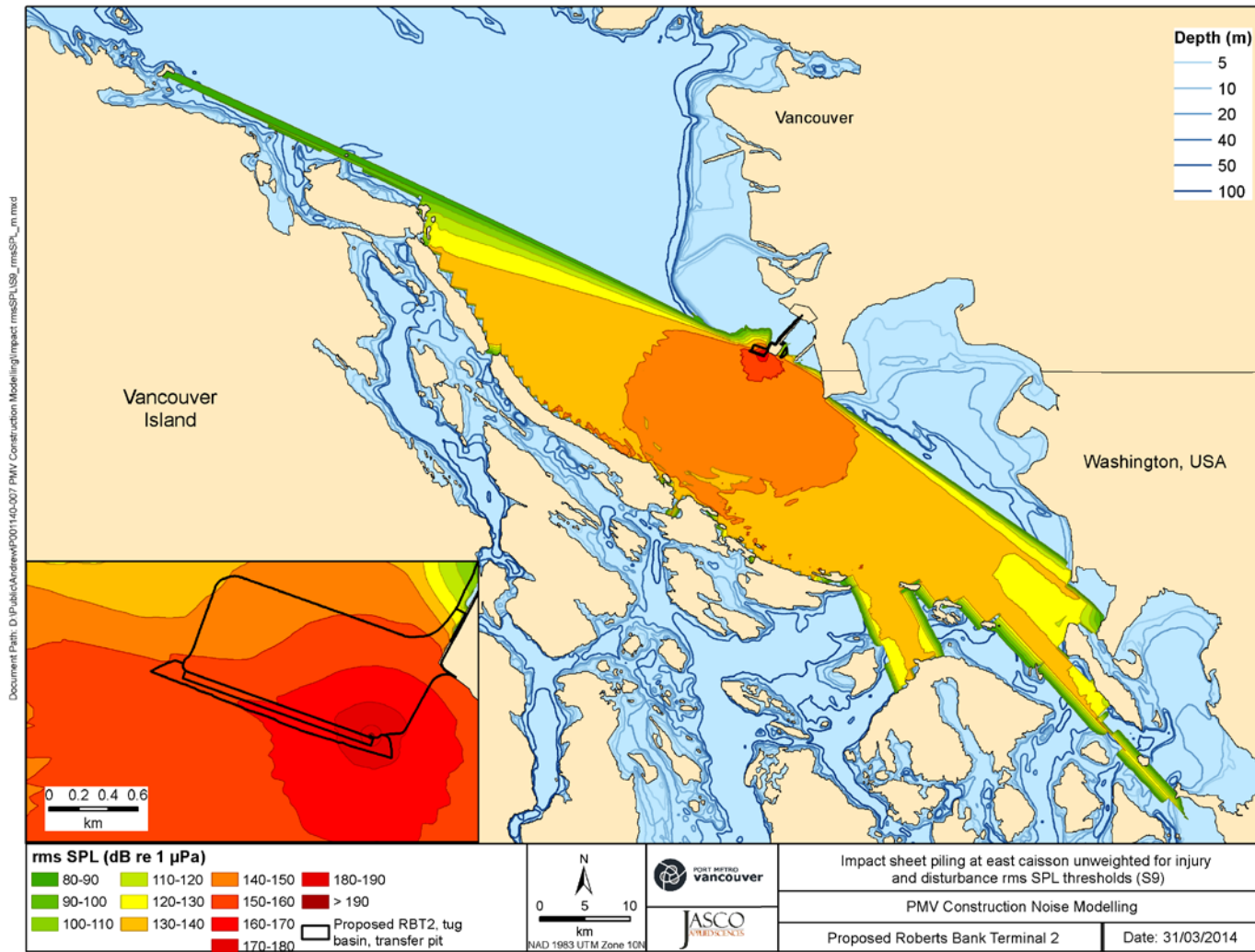
Figure A–25 Isopleth Map of Unweighted rms SPL for Impact Sheet Piling at East End Caisson (S9)
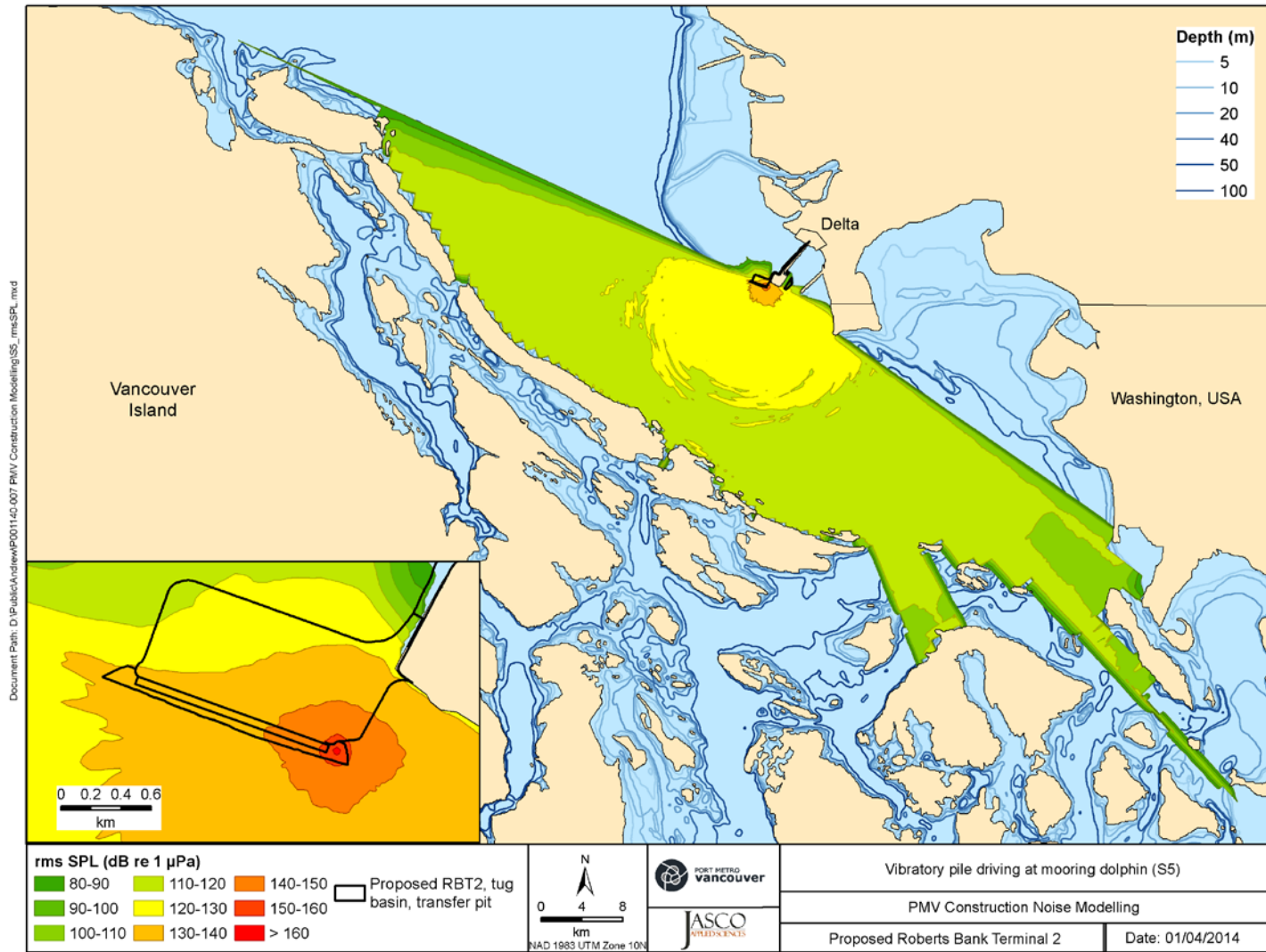
Figure A–26 Broadband Isopleth Map for Vibratory Piling at Mooring Dolphin (S5)
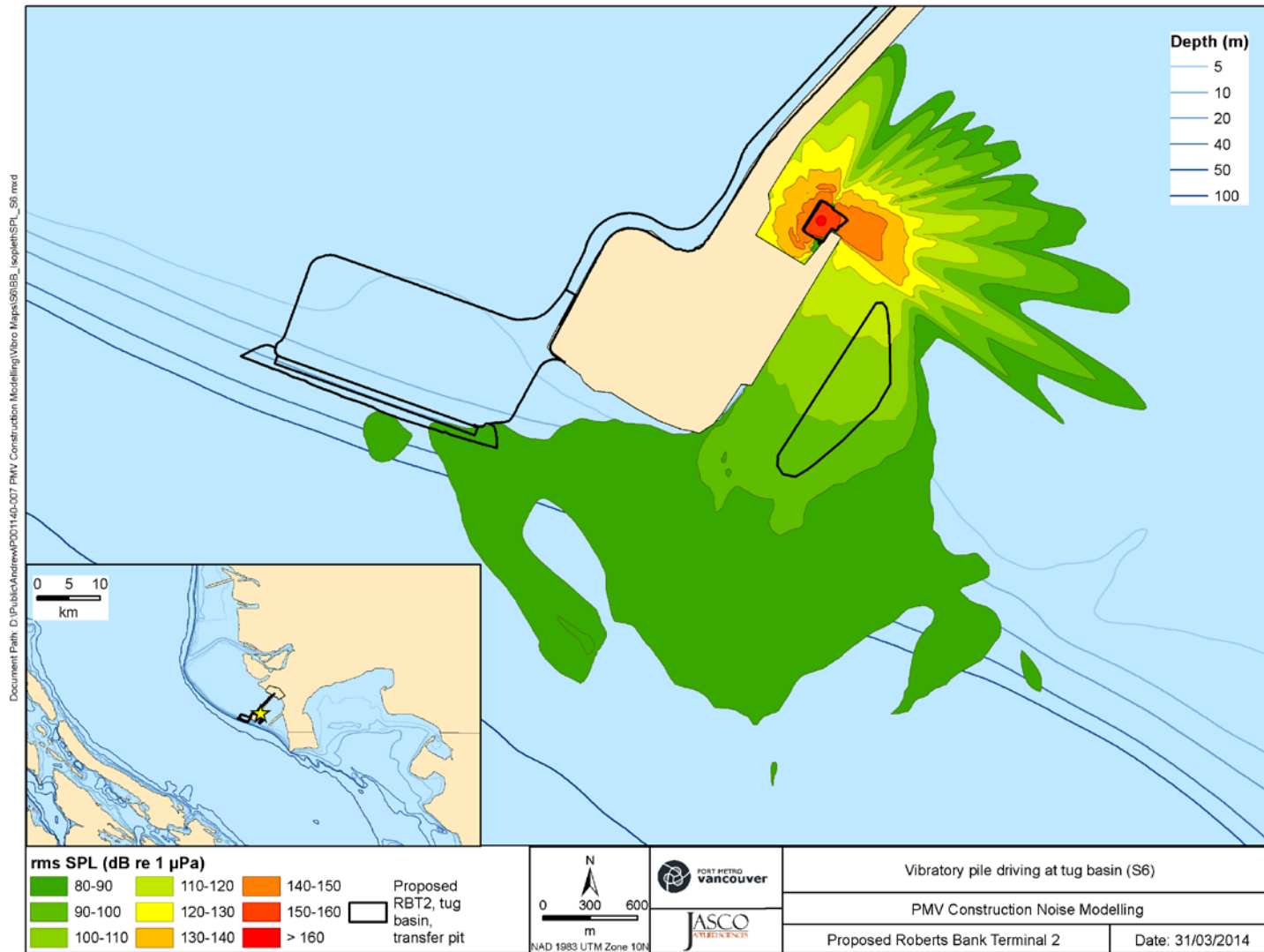
Figure A–27 Broadband Isopleth Map for Vibratory Piling at Tug Basin (S6). Isolated 80-90 dB contours show sound convergence zones.
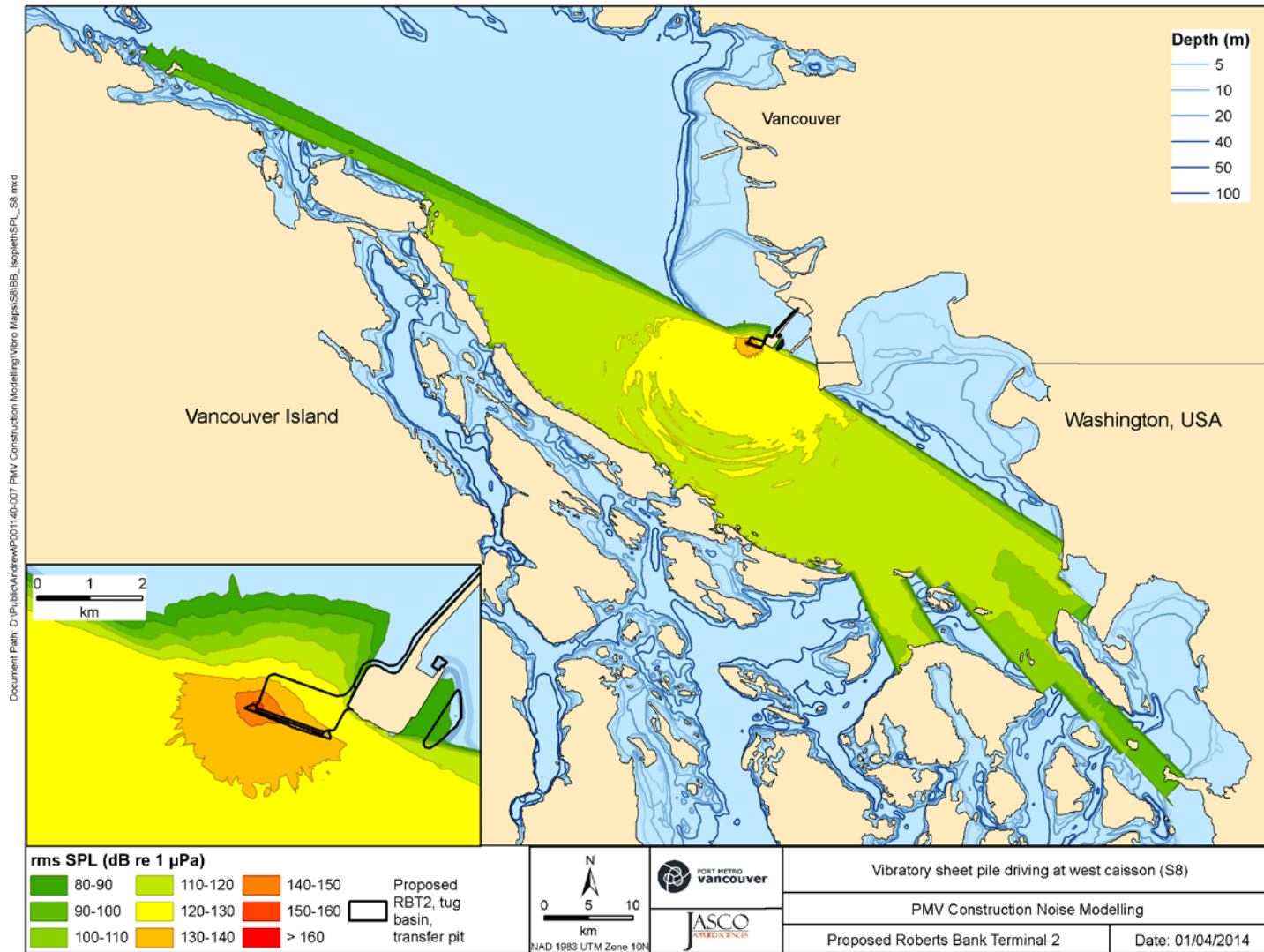
Figure A–28 Broadband Isopleth Map for Vibratory Sheet Piling at West End Caisson (S8)
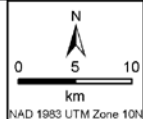
Figure A–29 Broadband Isopleth Map for Vibratory Sheet Piling at East End Caisson (S10)
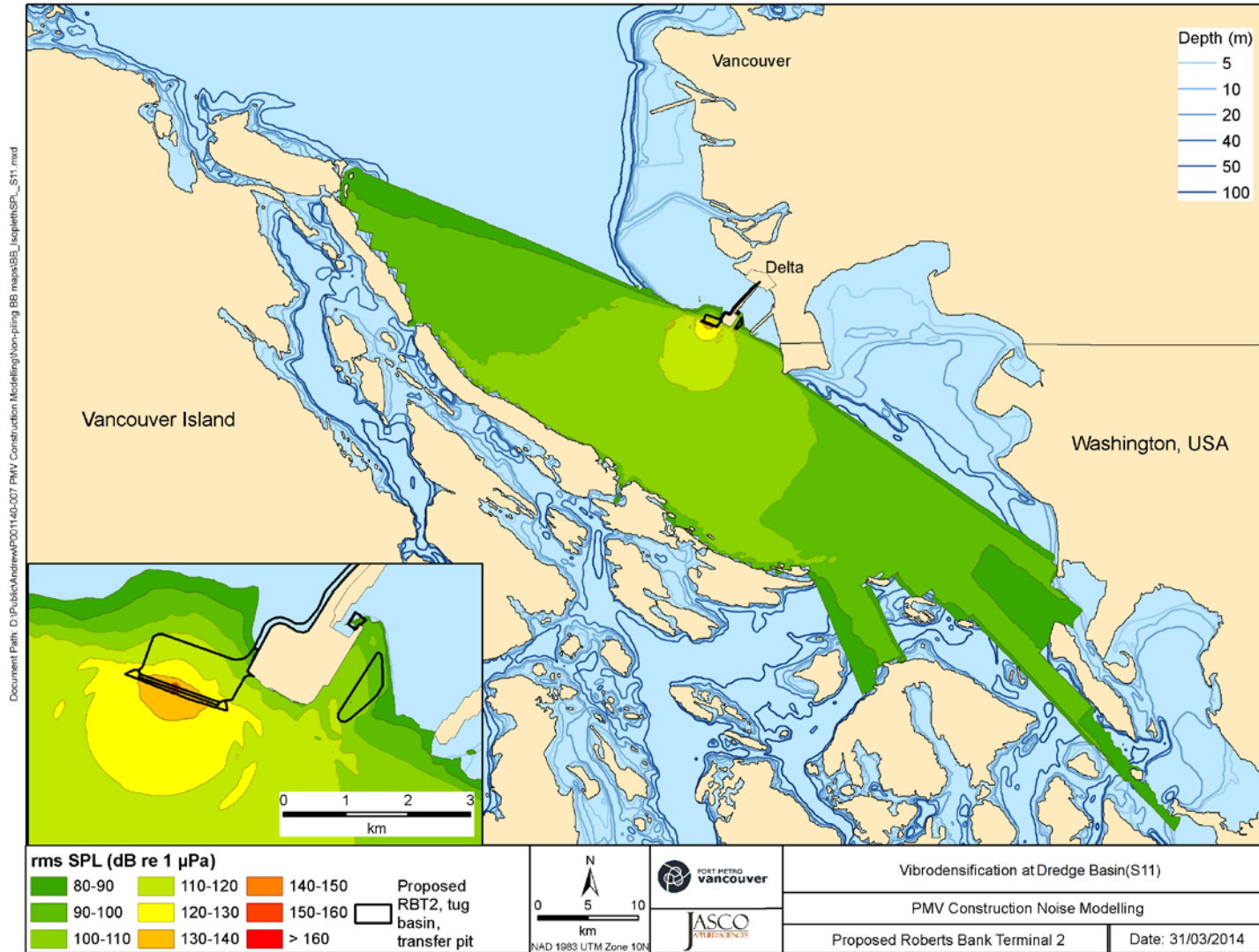
Figure A–30 Broadband Isopleth Map for Vibro-densification at Dredge Basin (S11)
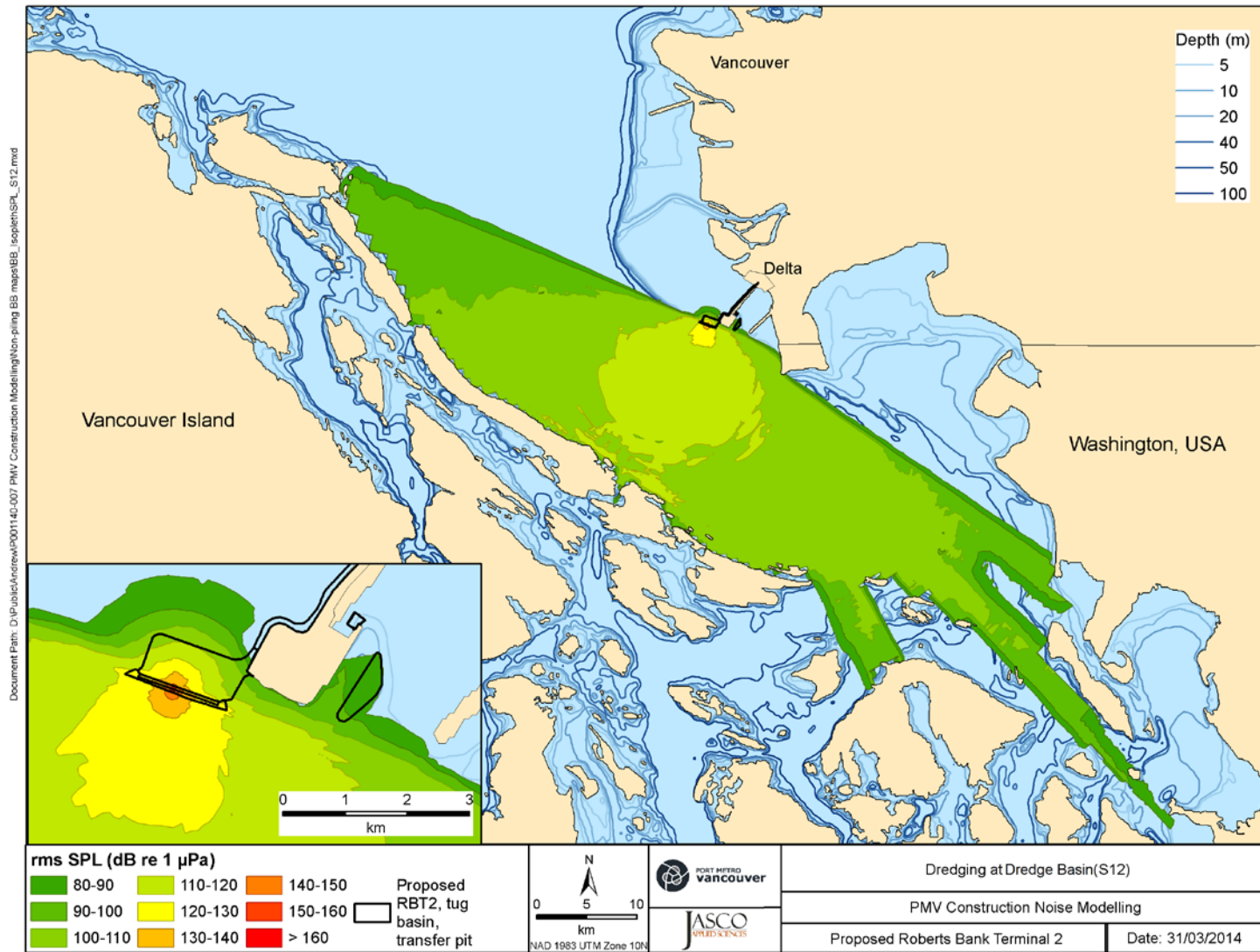
Figure A–31 Broadband Isopleth Map for Dredging at Dredge Basin (S12)
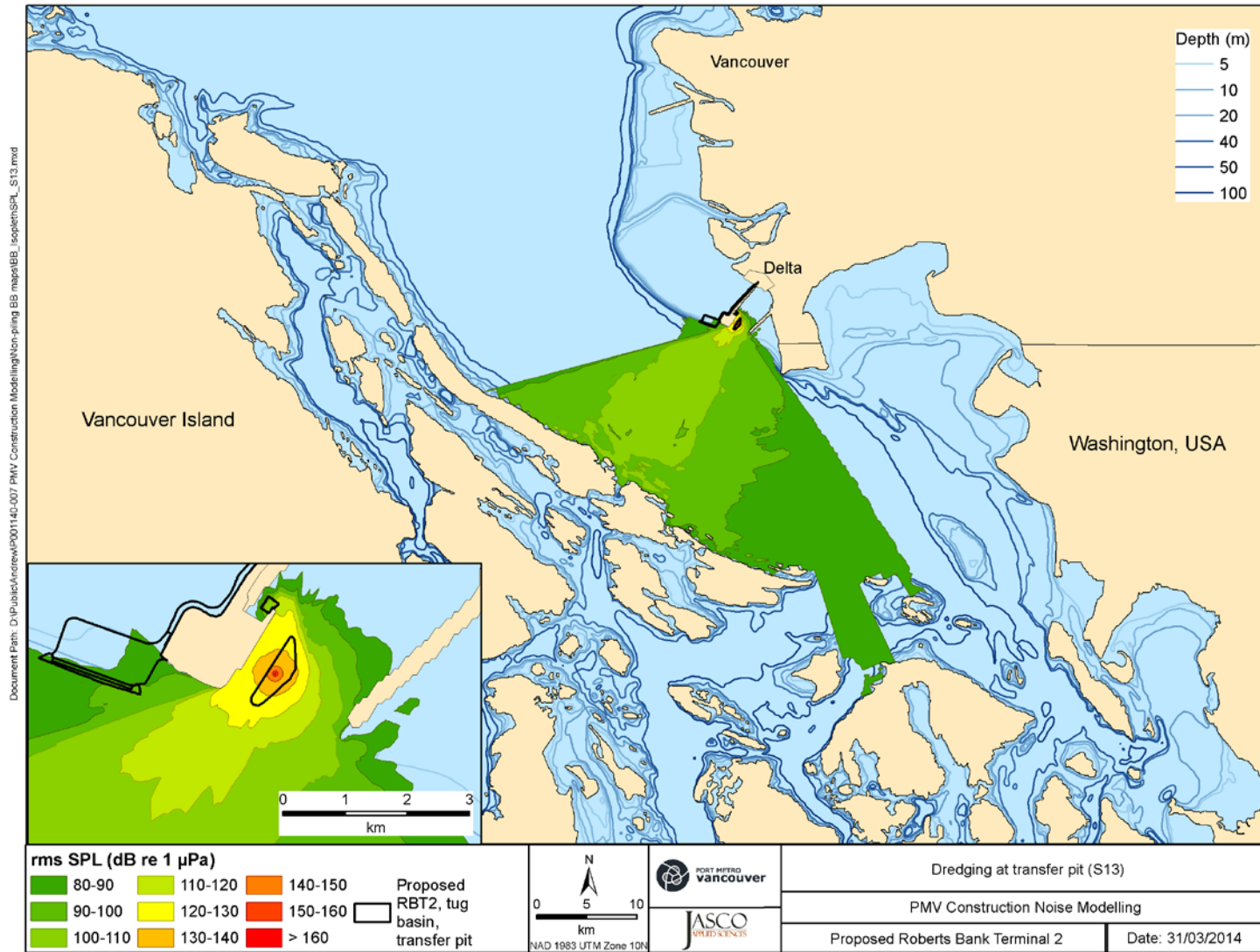
Figure A–32 Broadband Isopleth Map for Dredging at Intermediate Transfer Pit (S13)
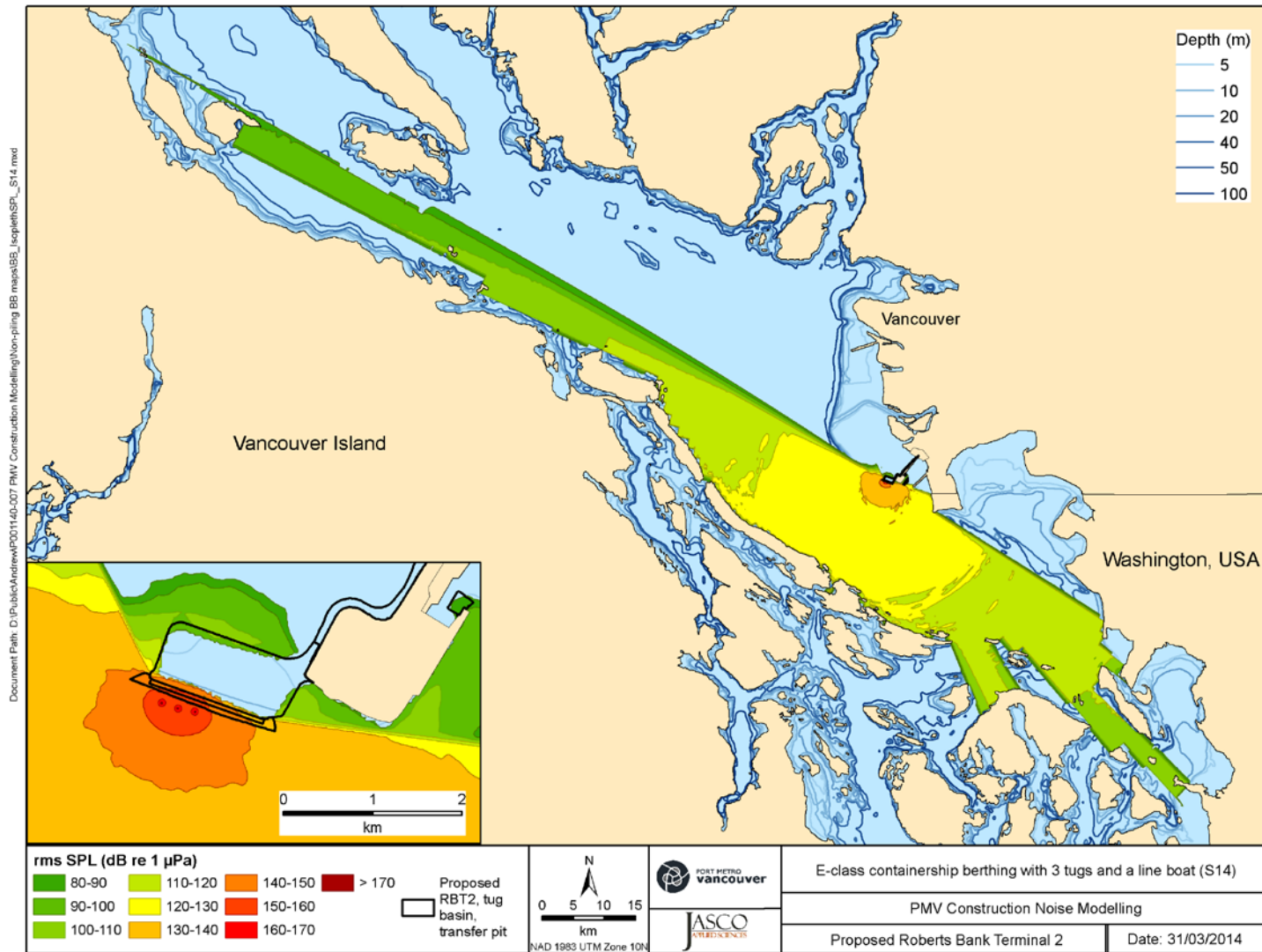
Figure A–33 Broadband Isopleth Map for E-class Container Ship Berthing with Three Tugs and a Line Boat (S14)
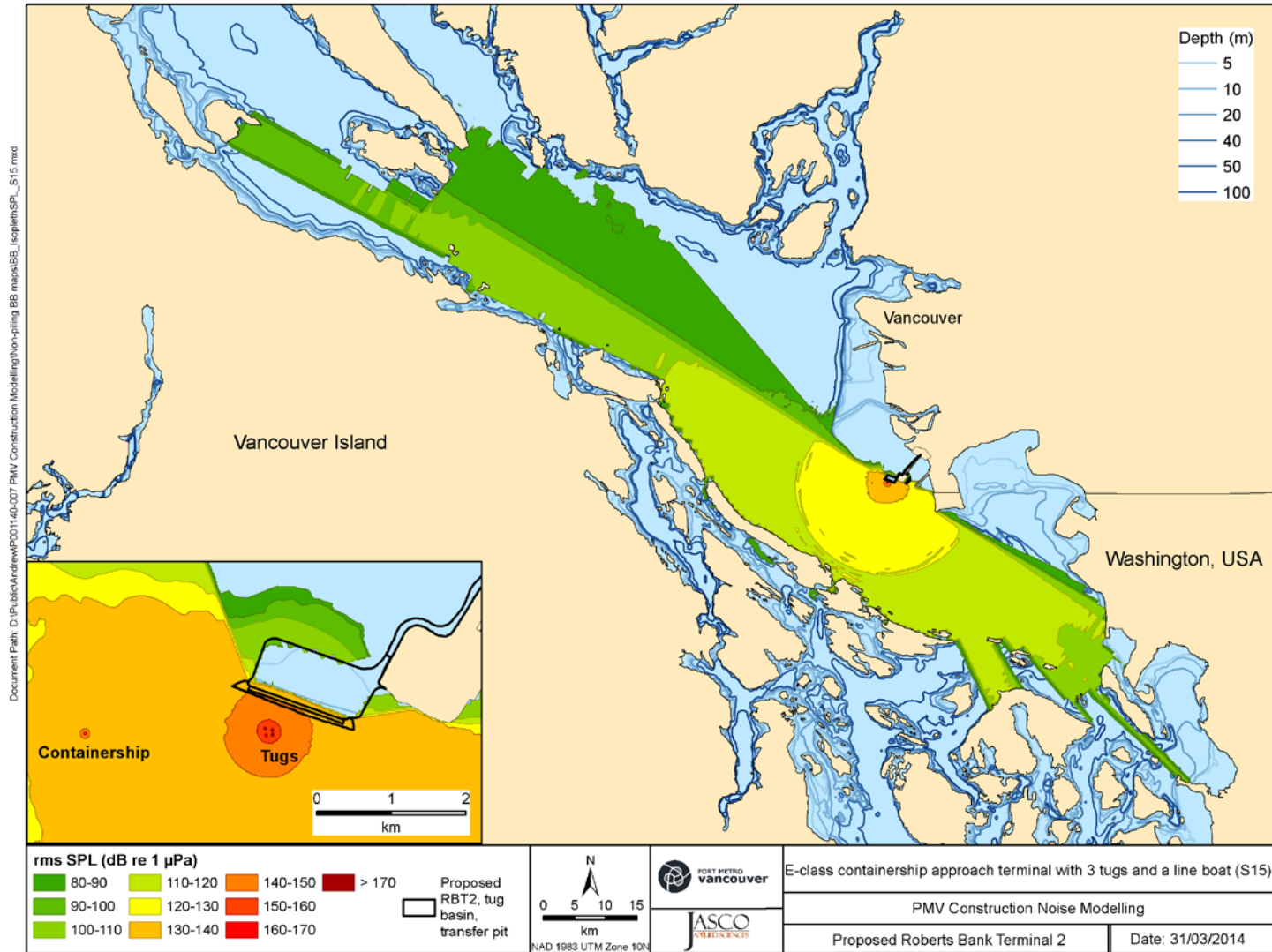
Figure A–34 Broadband Isopleth Map for E-class Container Ship Approaching Terminal (6 kts) with Three Tugs and a Line Boat (12 kts) (S15)
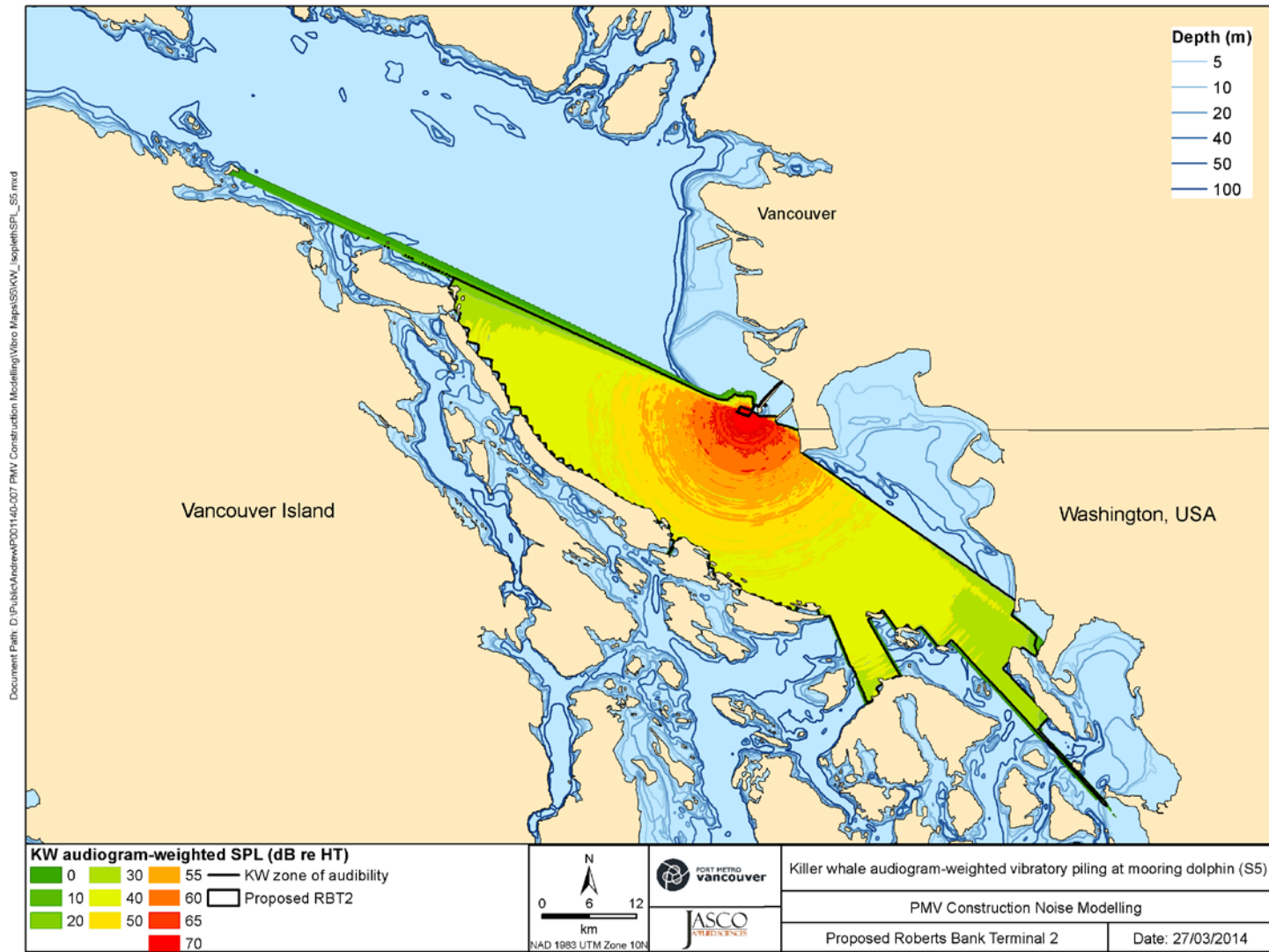
Figure A–35 Killer Whale Audiogram-weighted Map for Vibratory Piling at Mooring Dolphin (S5)
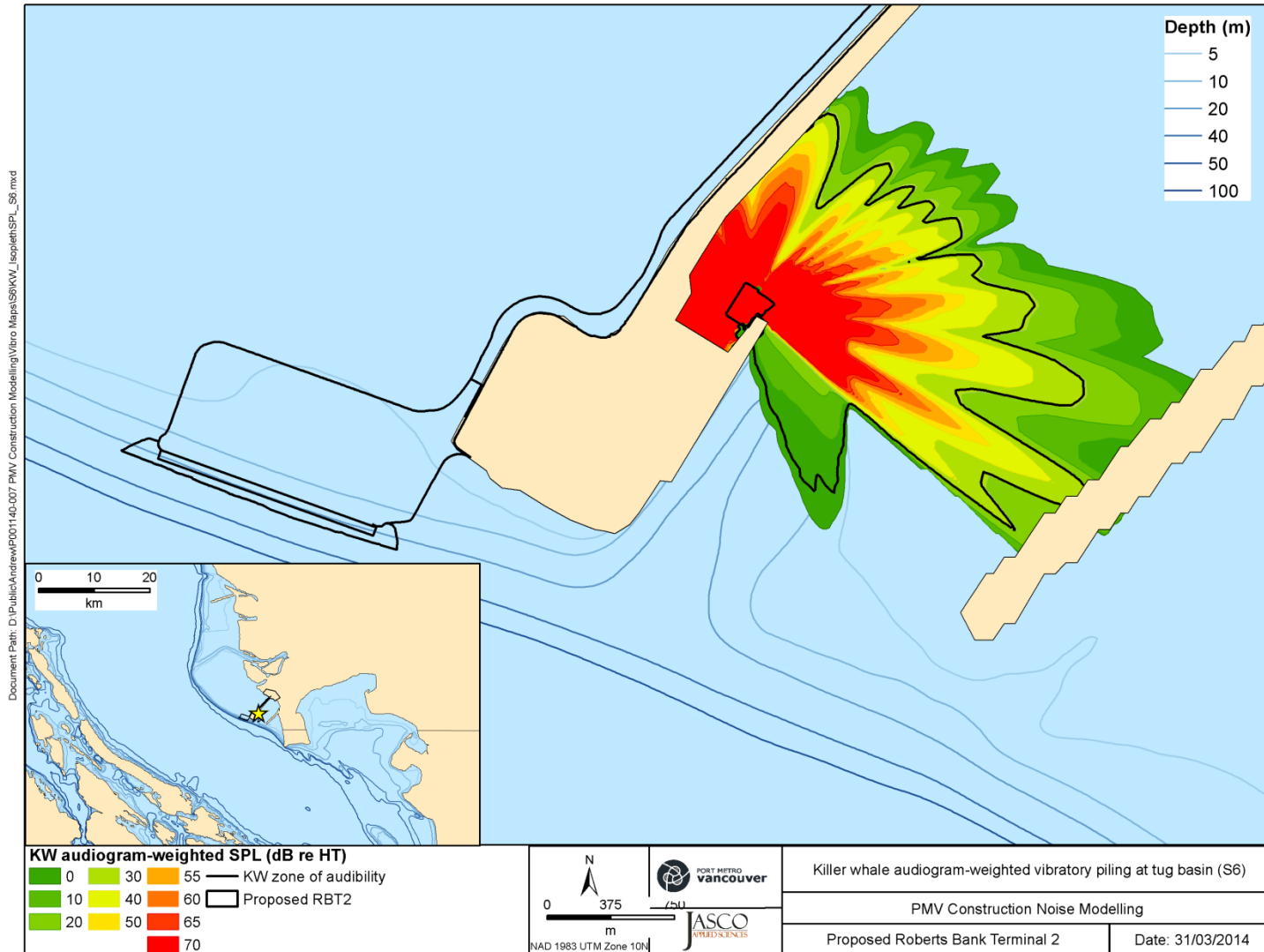
Figure A–36 Killer Whale Audiogram-weighted Map for Vibratory piling at tug basin (S6)
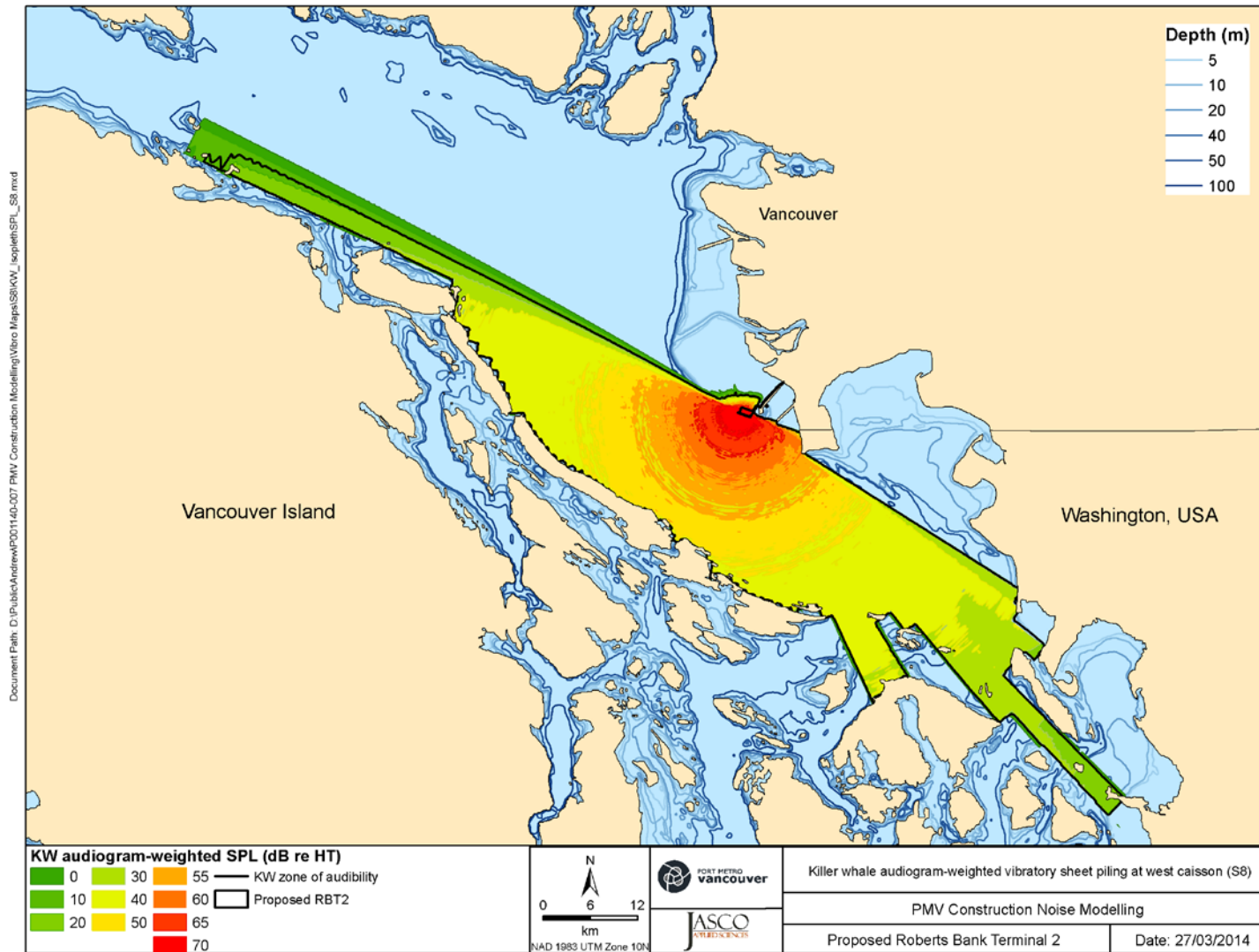
Figure A–37 Killer Whale Audiogram-weighted Map for Vibratory Sheet Piling at West End Caisson (S8)
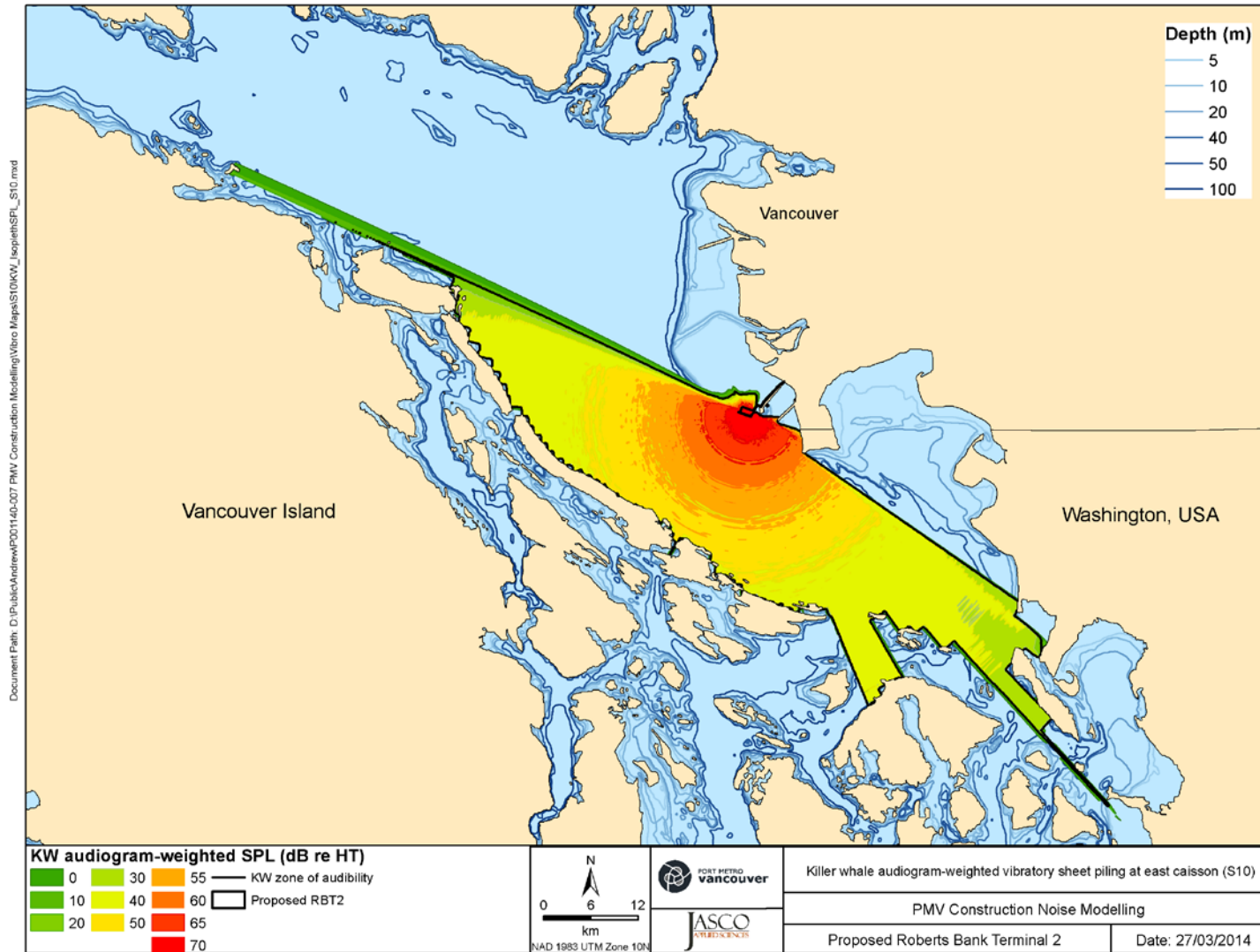
Figure A–38 Killer Whale Audiogram-weighted Map for Vibratory Sheet Piling at East End Caisson (S10)
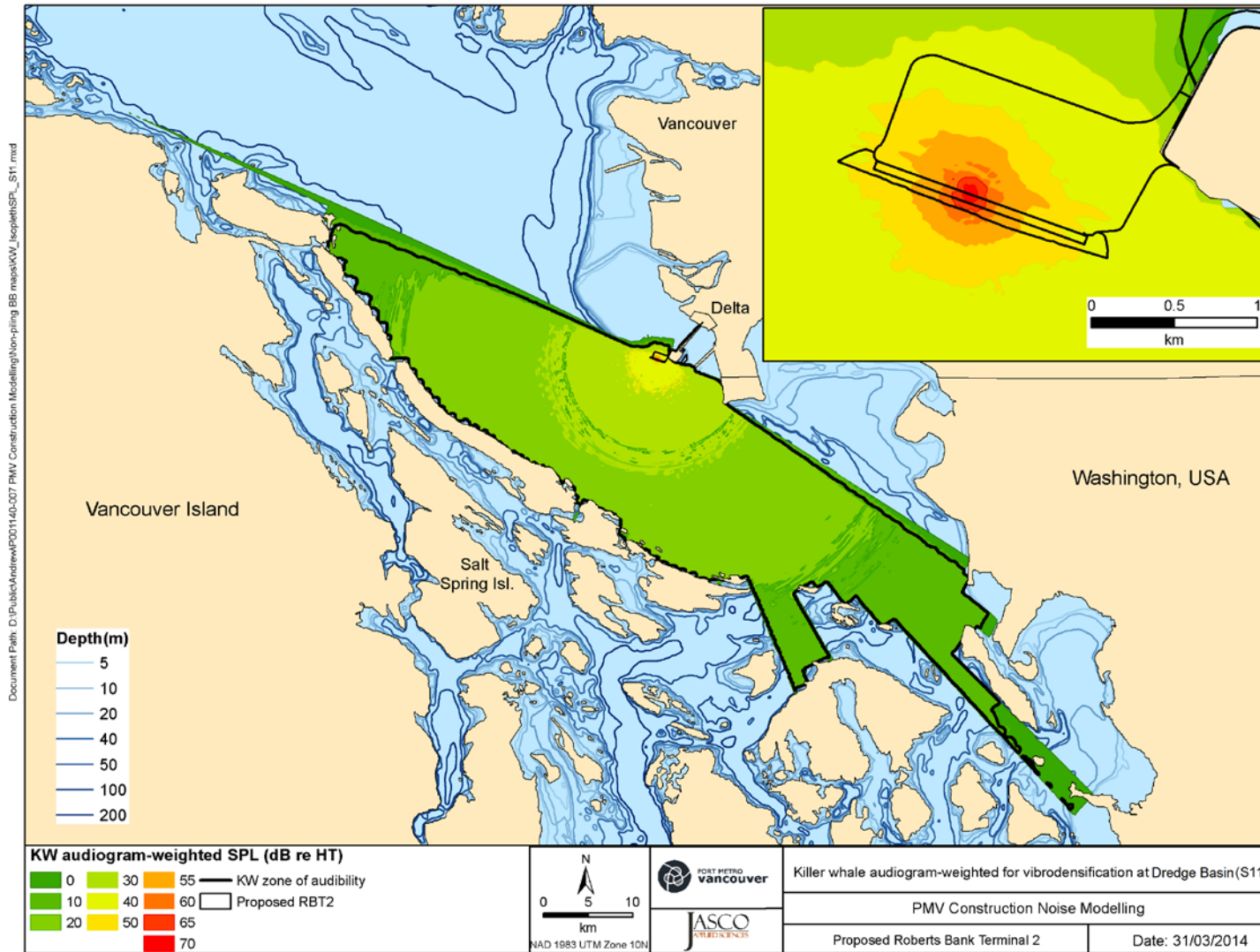
Figure A–39 Killer Whale Audiogram-weighted map for Vibro-densification at Dredge Basin (S11)
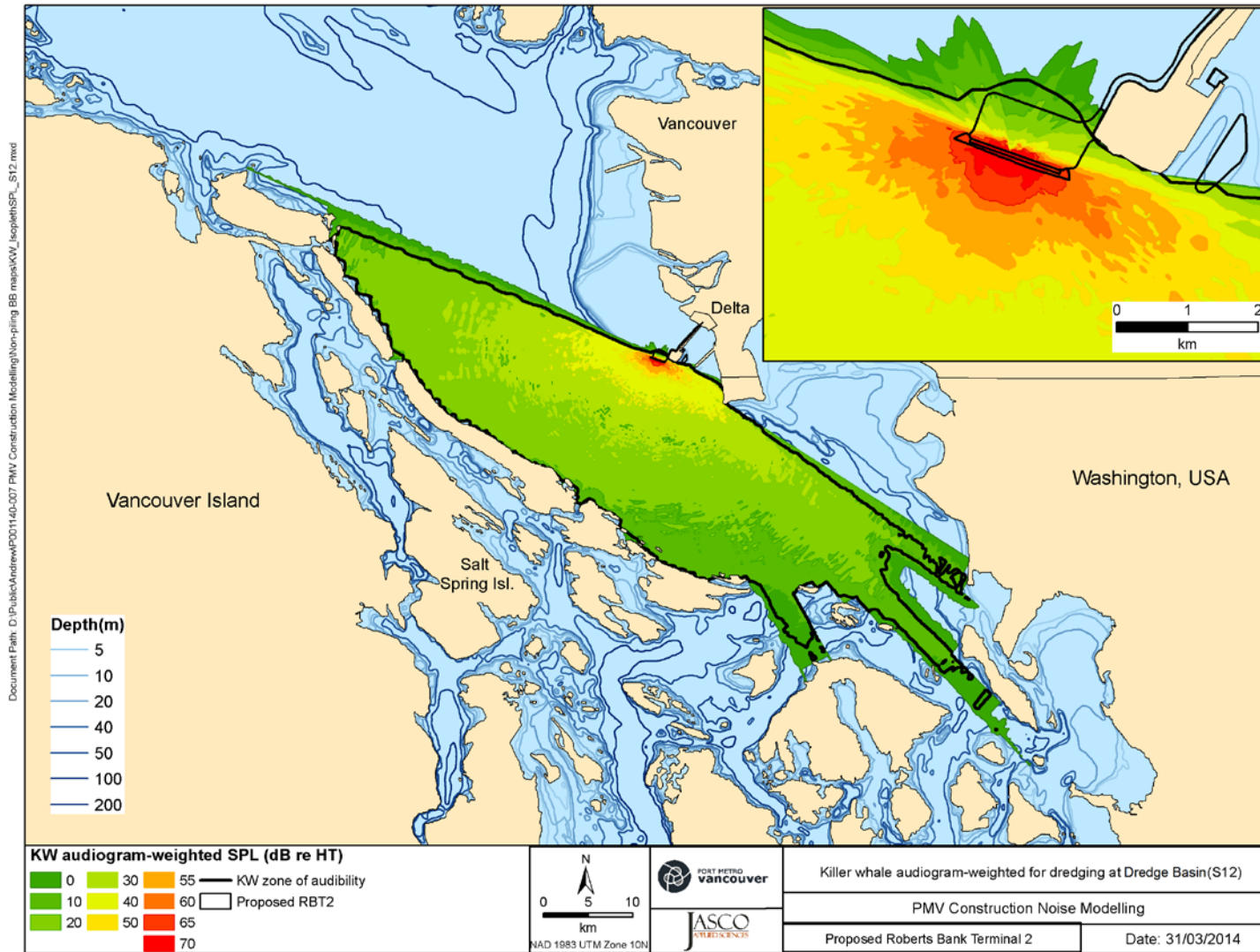
Figure A–40 Killer Whale Audiogram-weighted Map for Dredging at Dredge Basin (S12)
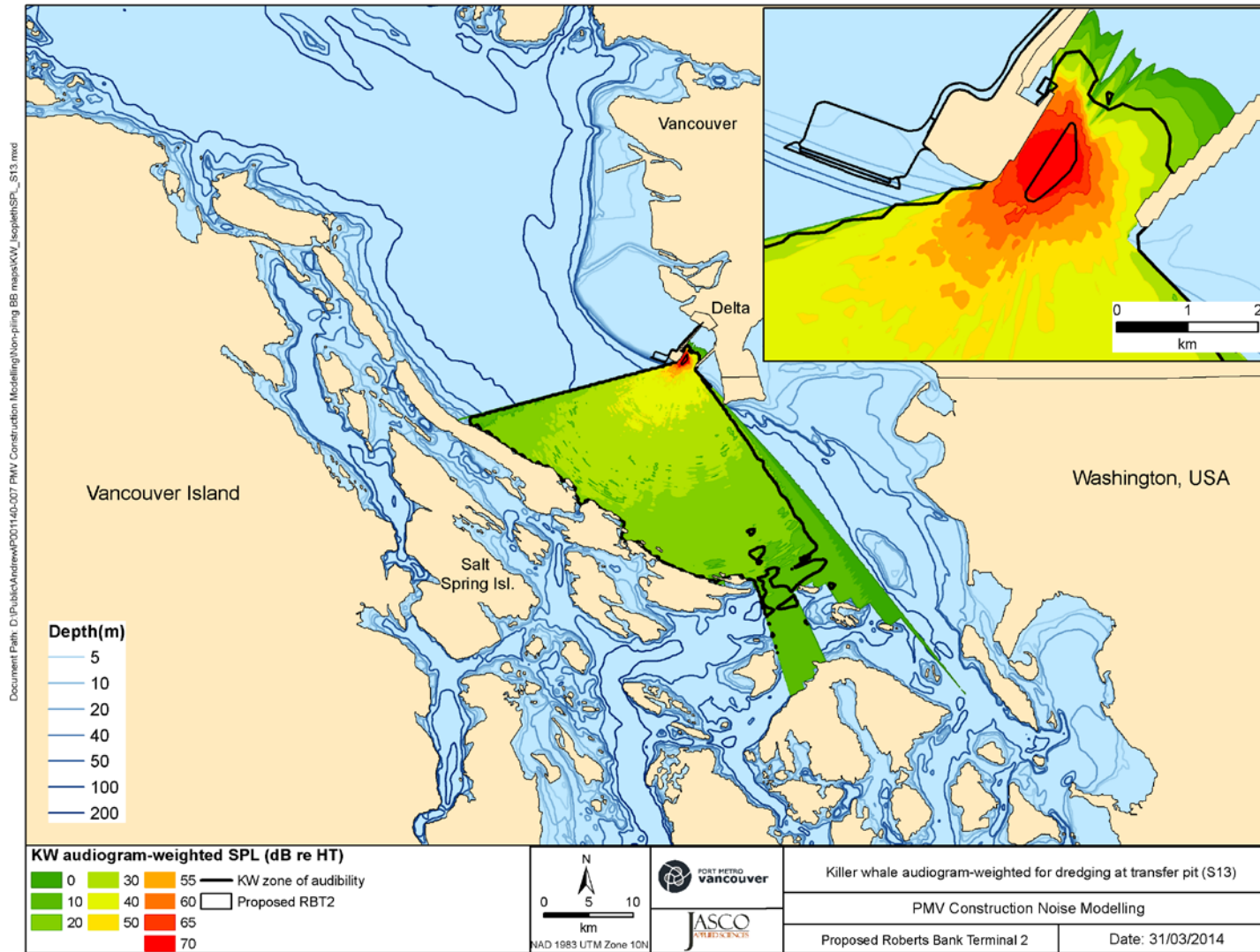
Figure A–41 Killer Whale Audiogram-weighted Map for Dredging at Intermediate Transfer Pit (S13)
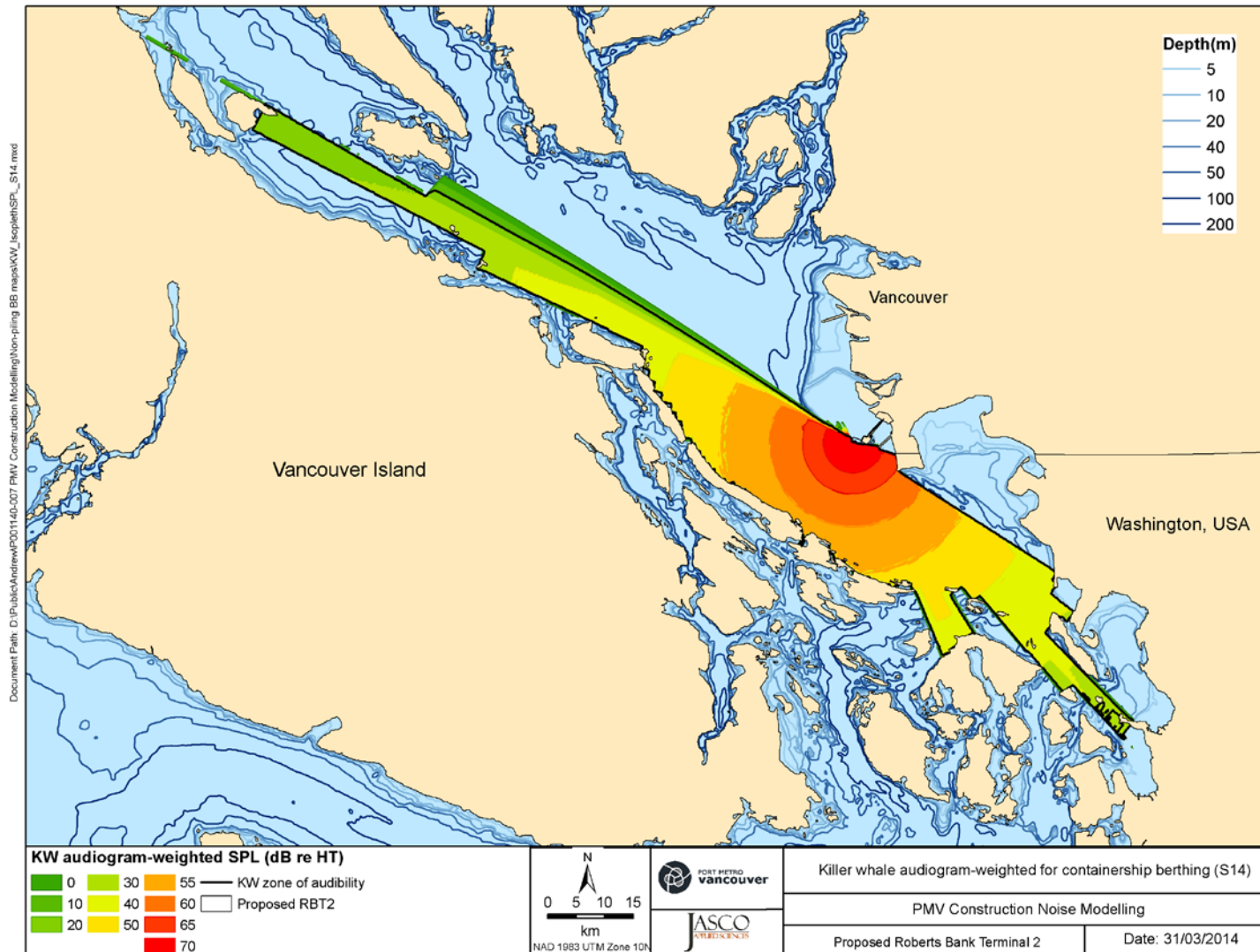
Figure A–42 Killer Whale Audiogram-weighted Map for Container Ship Berthing (S14)
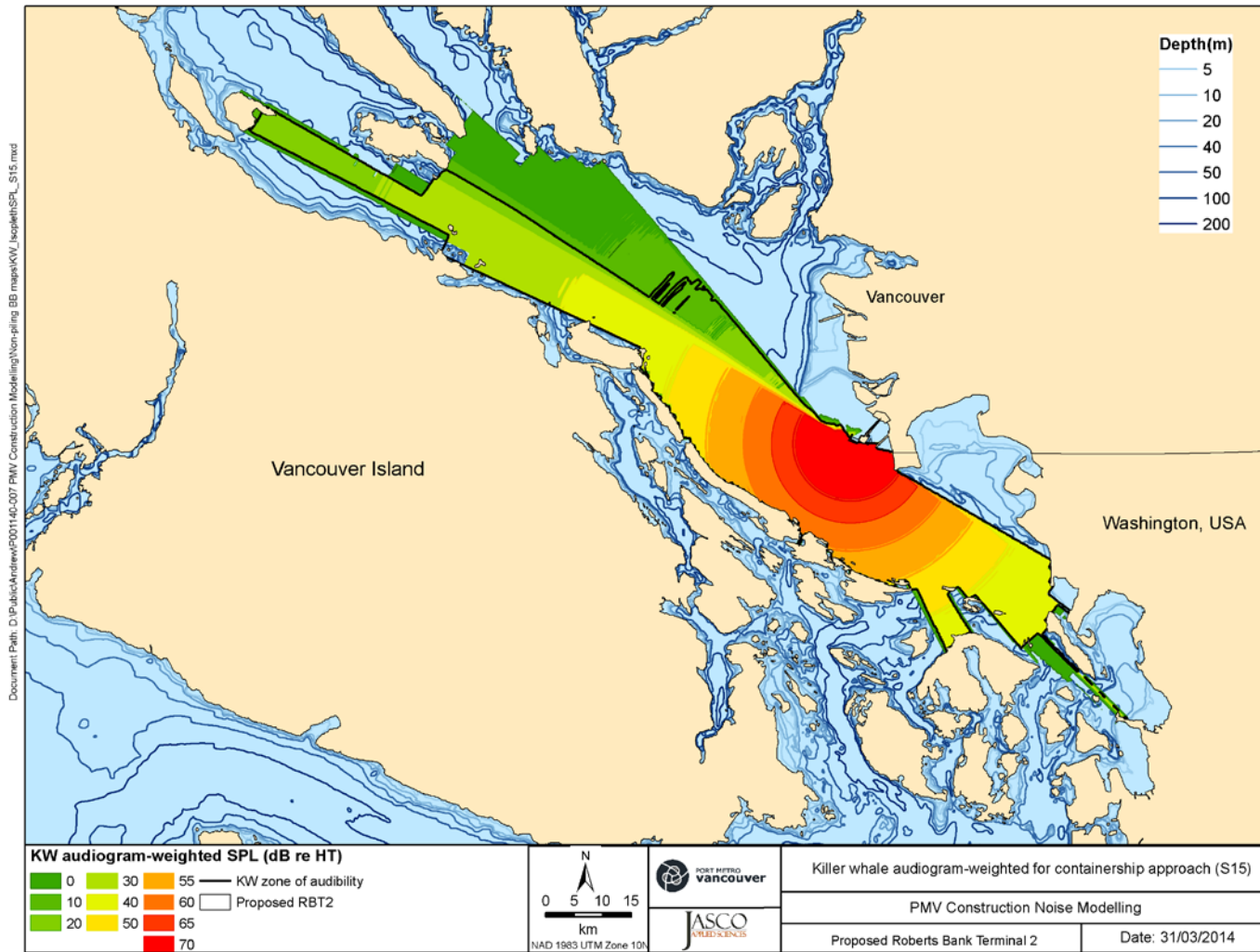
Figure A–43 Killer Whale Audiogram-weighted Map for Container Ship Approaching Terminal (S15)
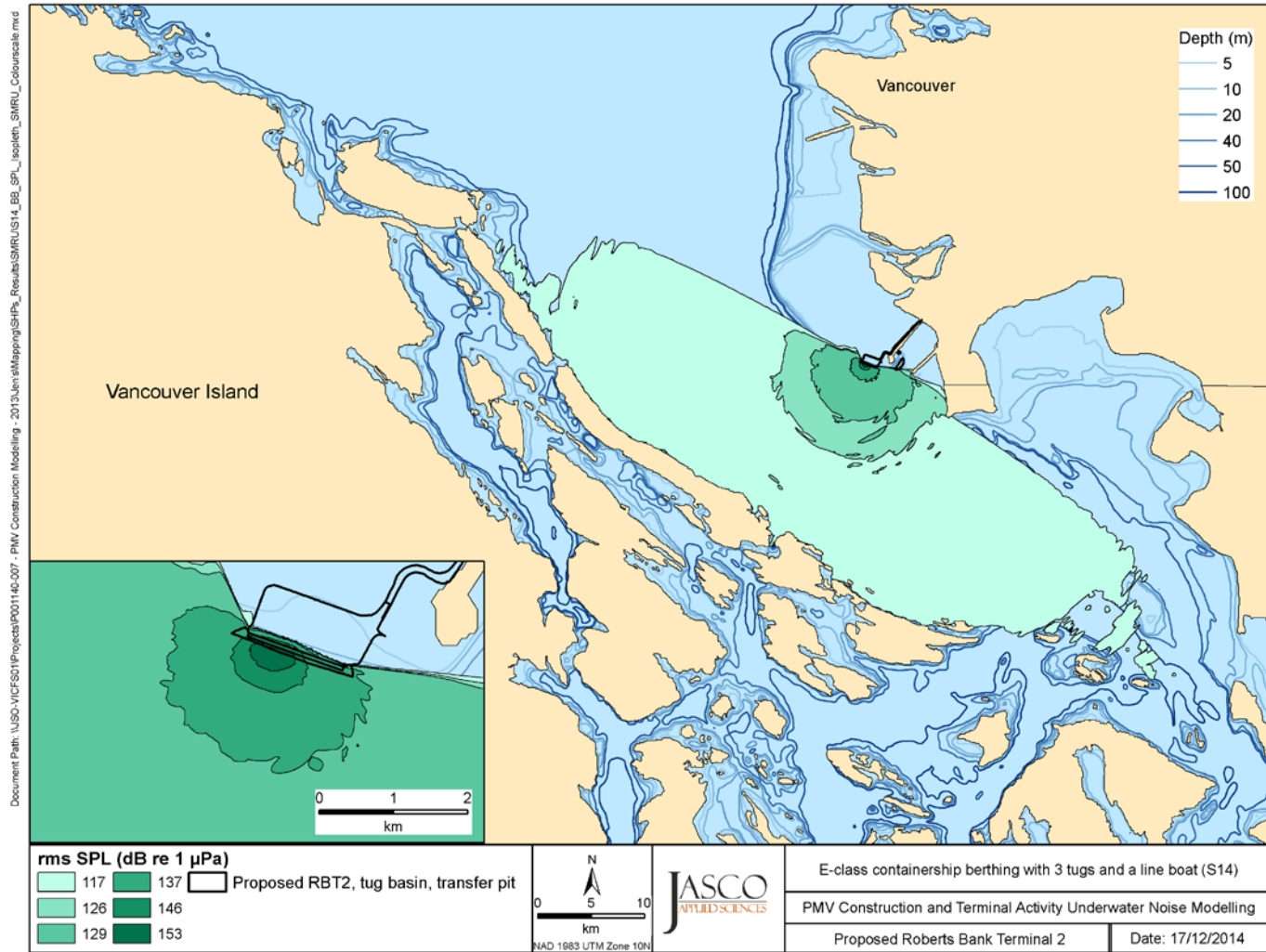
Figure A–44 Map of Killer Whale Behavioural Response Contours for Container Ship Berthing (S14)
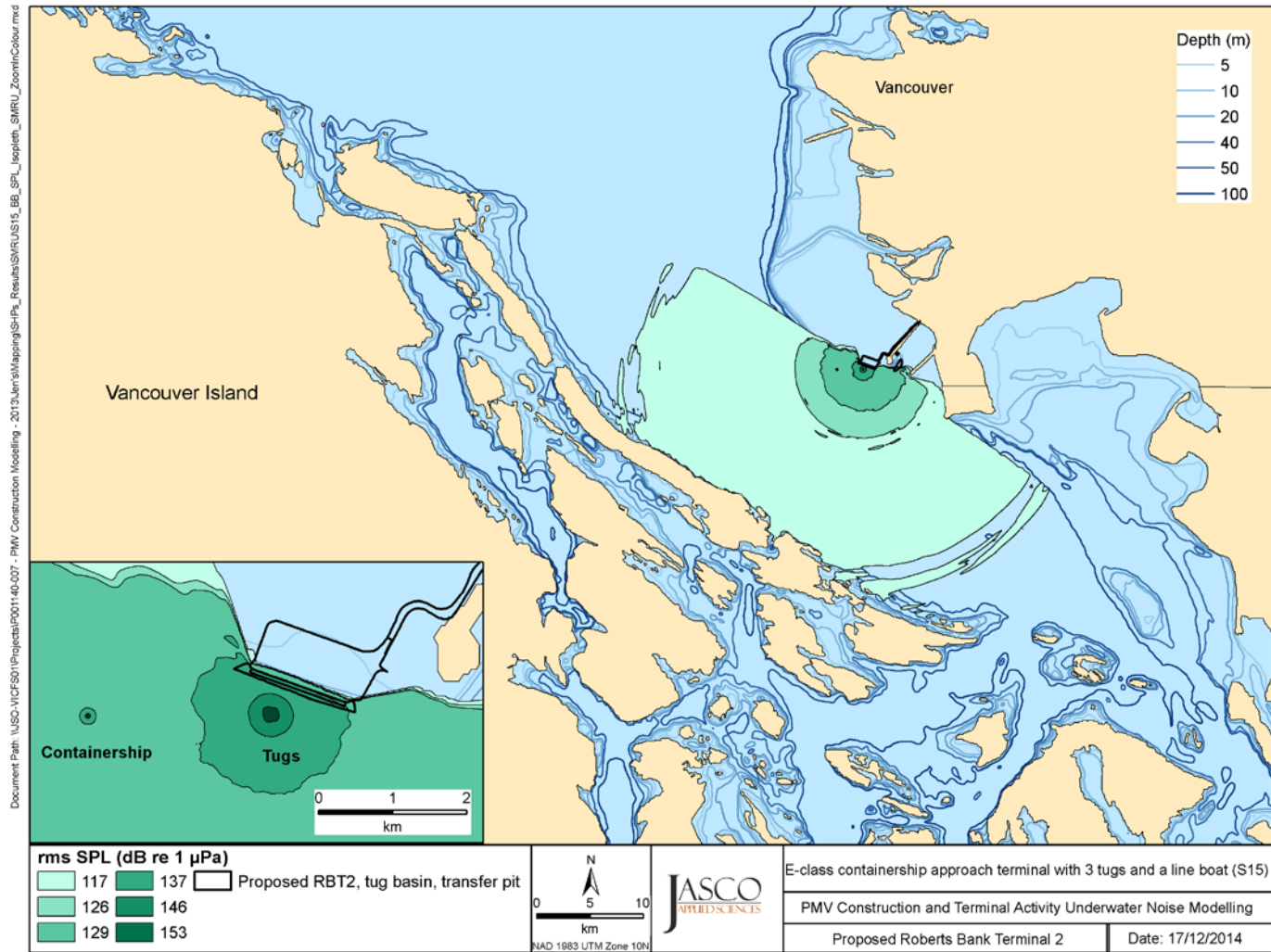
Figure A–45 Map of Killer Whale Behavioural Response Contours for Container Ship Approaching Terminal (S15)
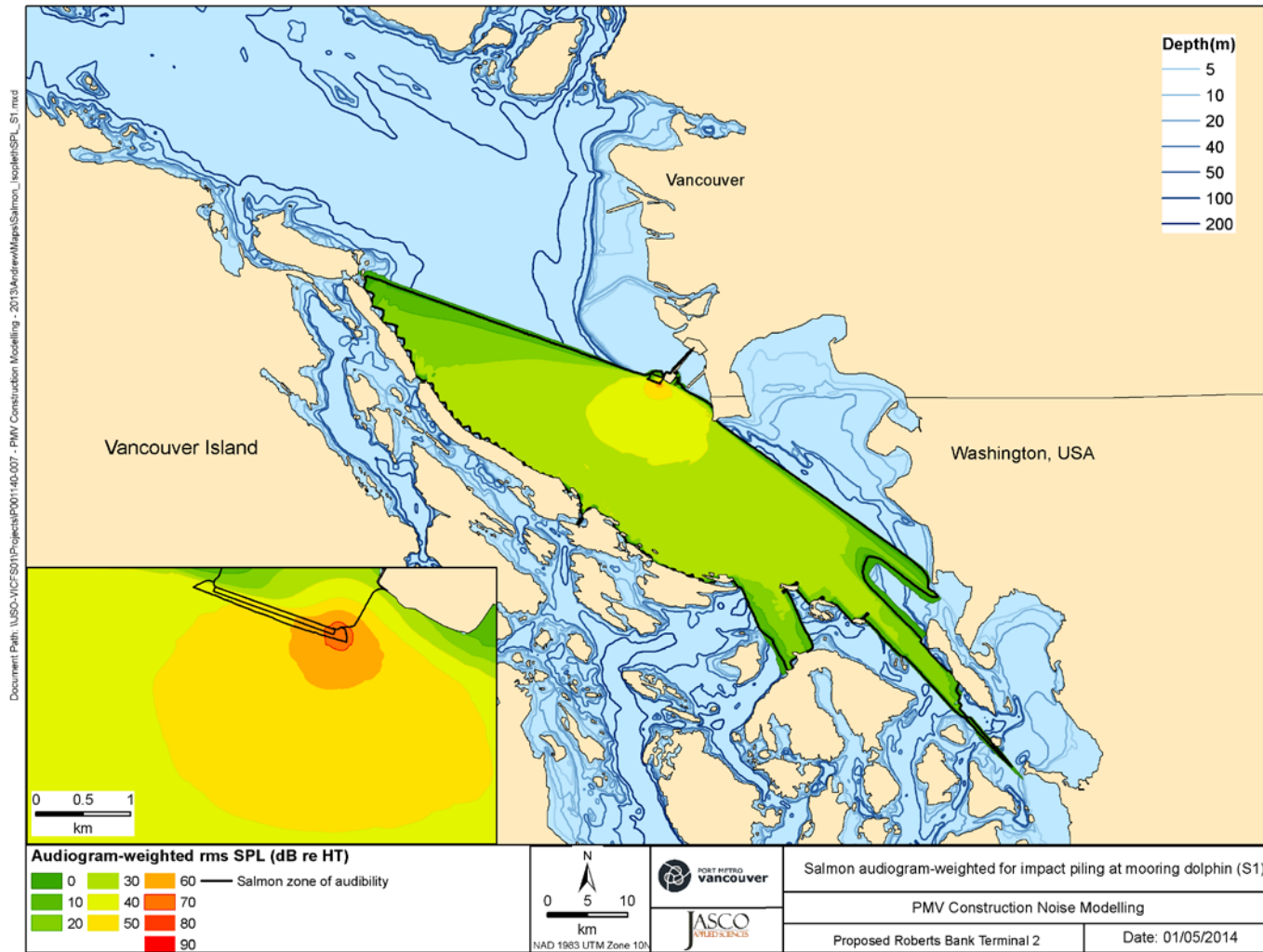
Figure A–46 Salmon Audiogram-weighted Map for Impact Piling at Mooring Dolphin (S1)
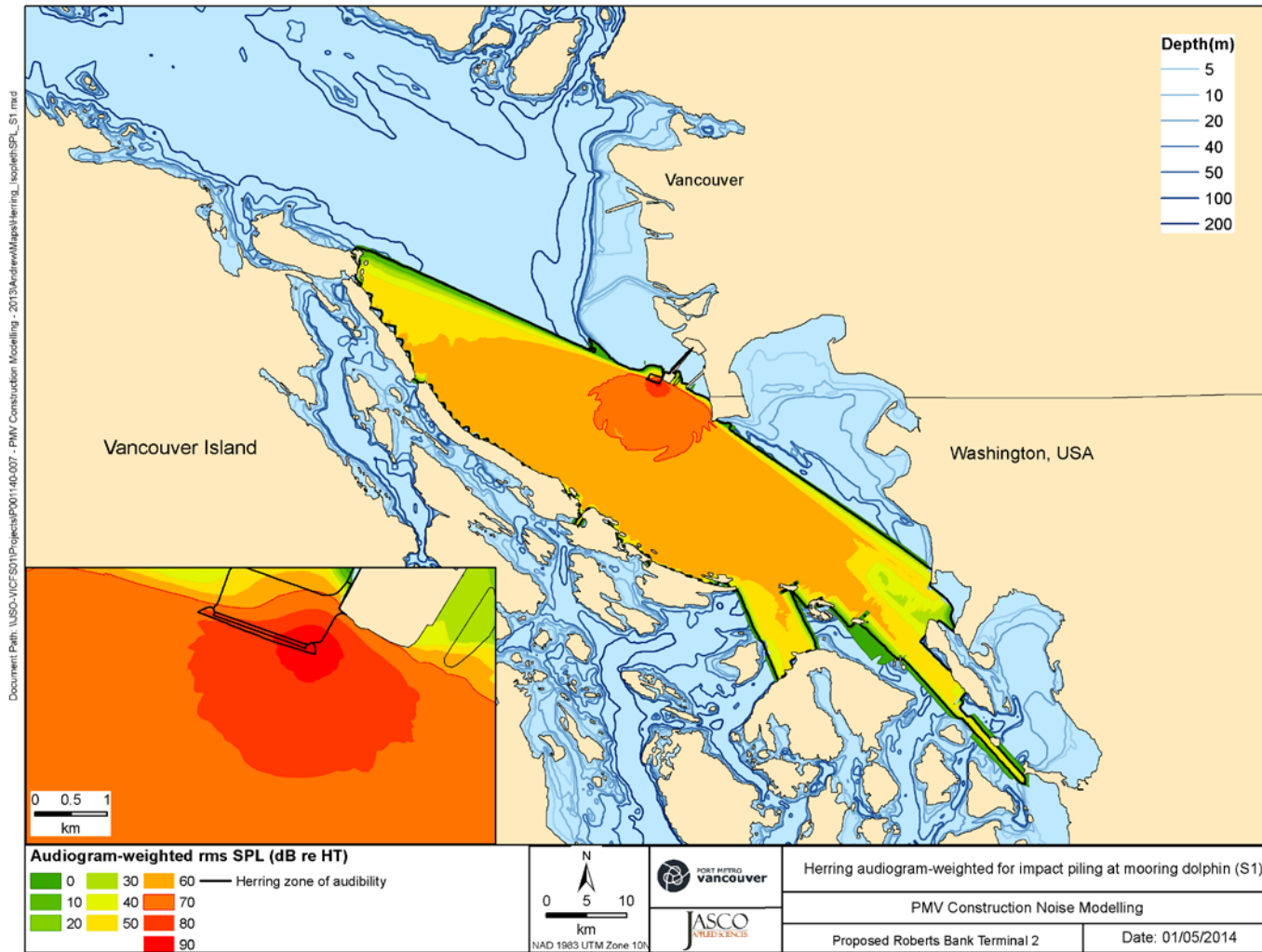
Figure A–47 Herring Audiogram-weighted Map for Impact Piling at Mooring Dolphin (S1).
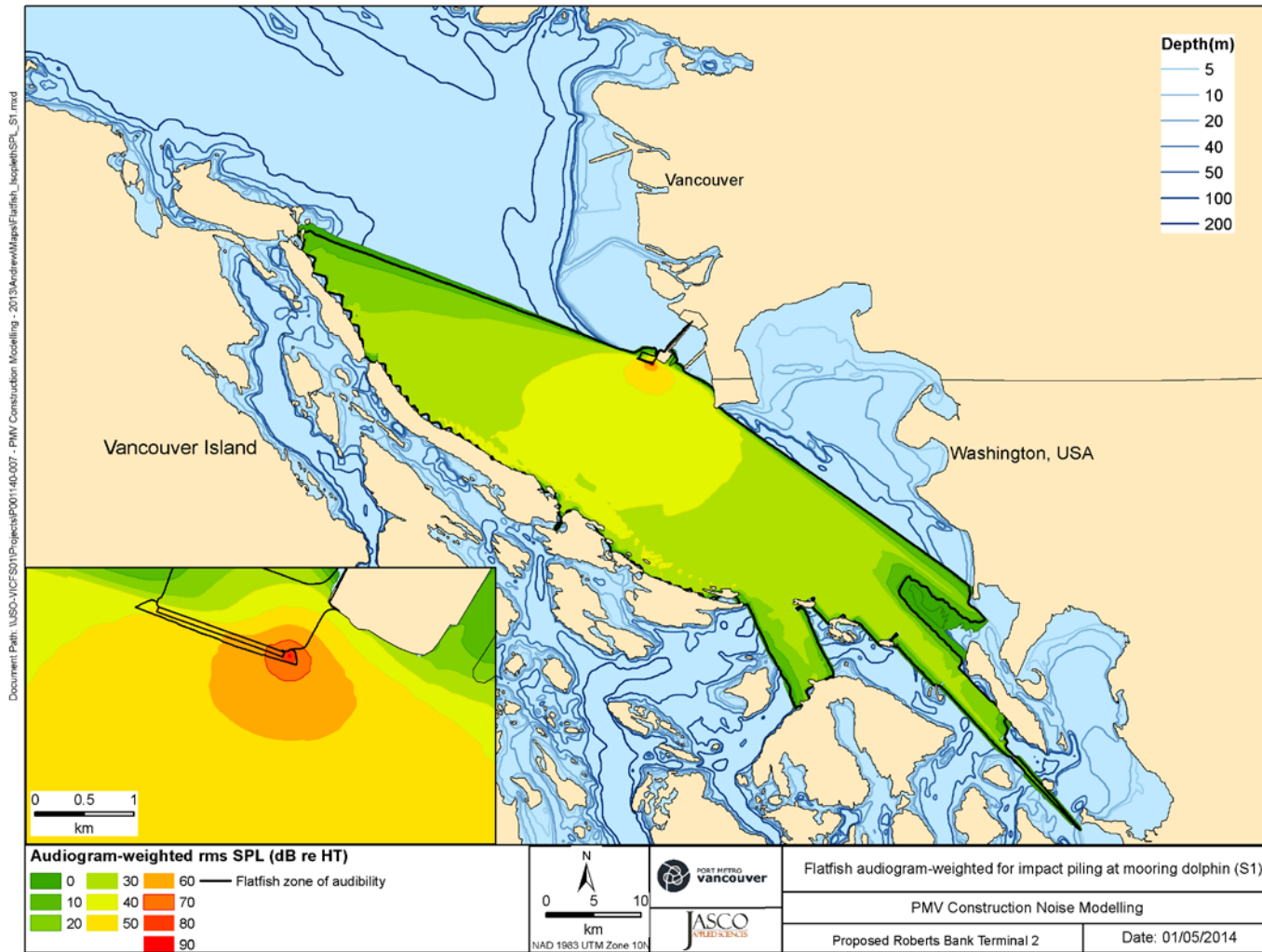
Figure A–48. Flatfish Audiogram-weighted Map for Impact Piling at Mooring Dolphin (S1)
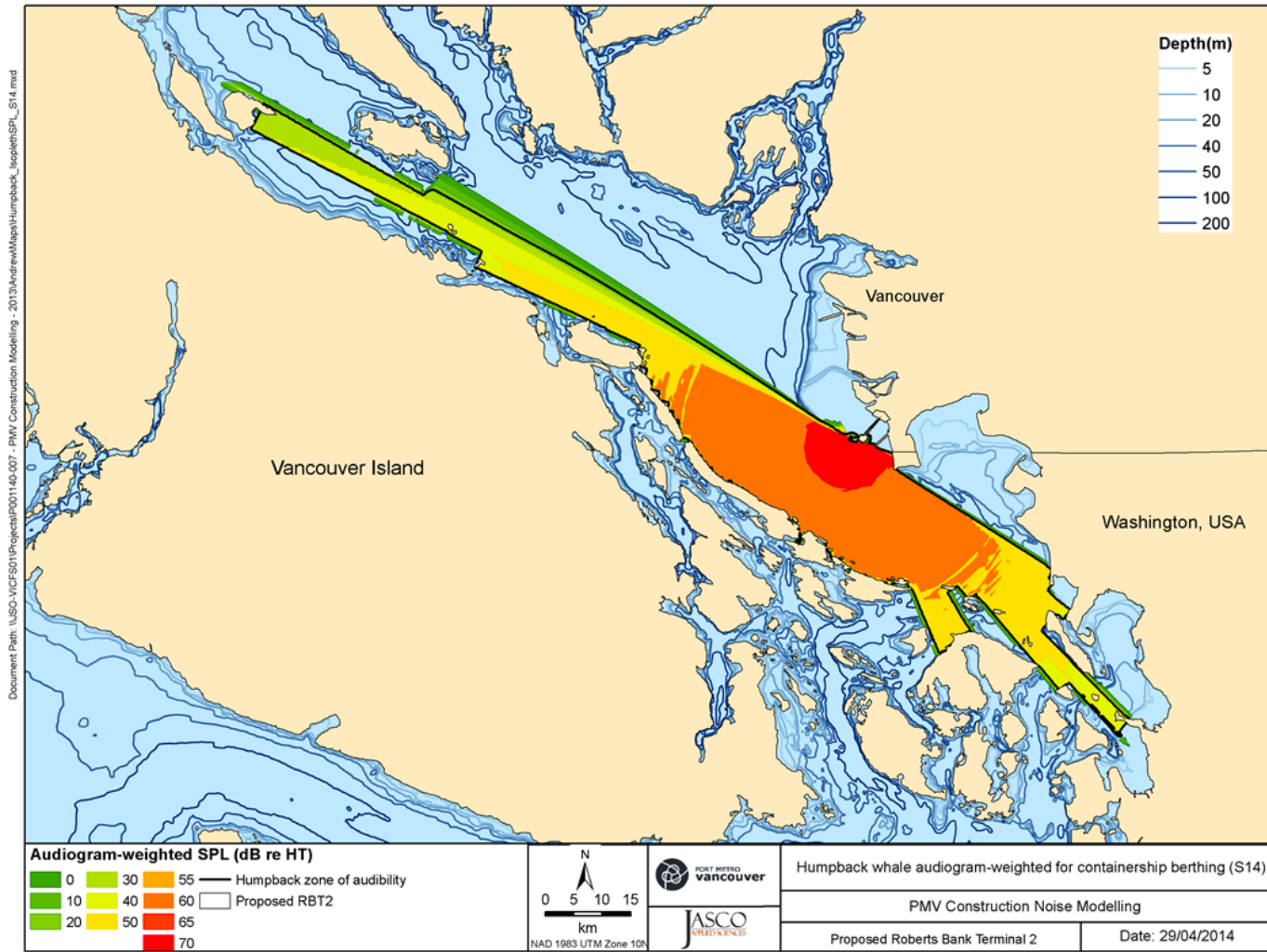
Figure A–49 Humpback Whale Audiogram-weighted Map for Container Ship Berthing (S14)
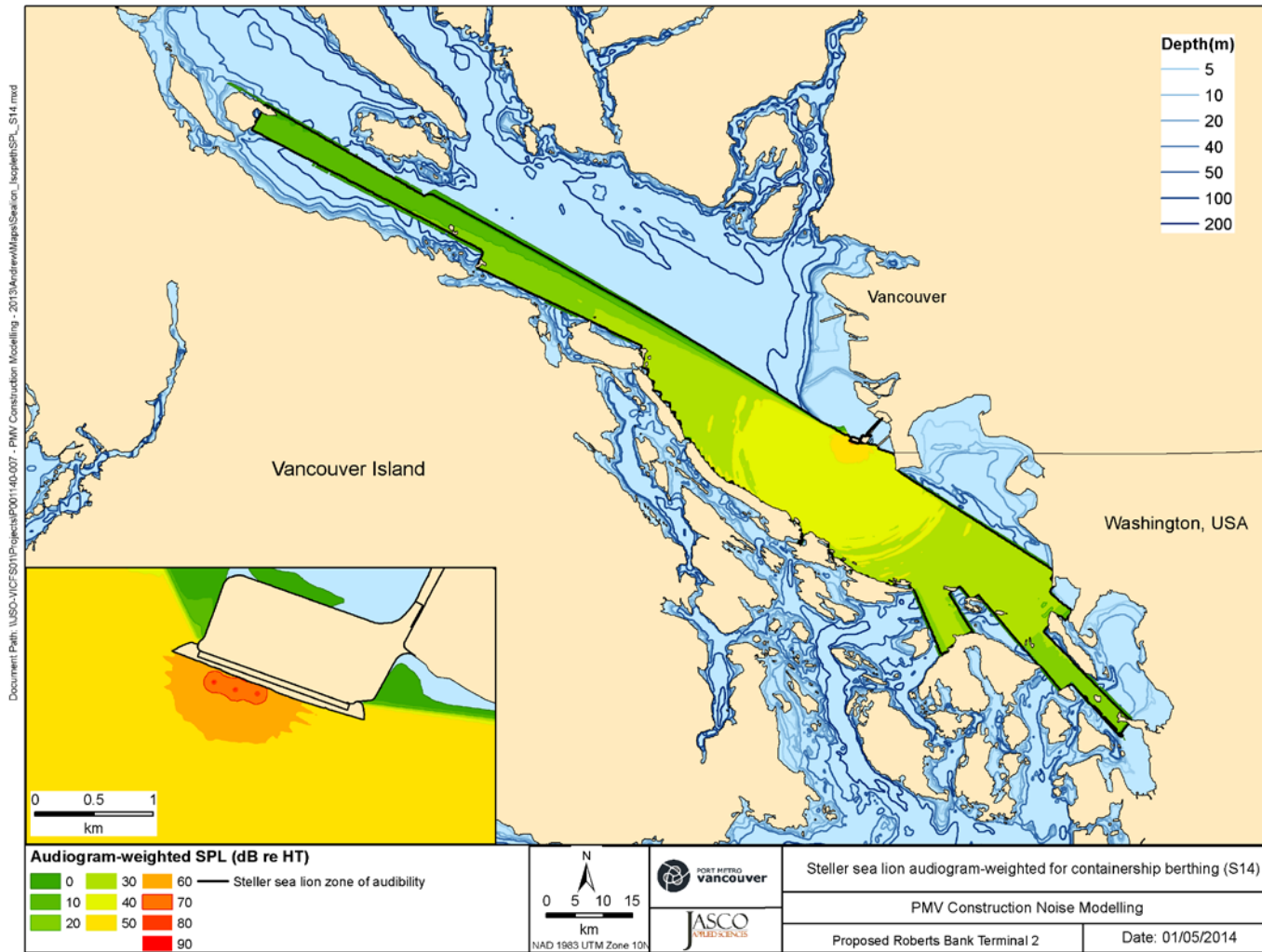
Figure A–50 Steller Sea Lion Audiogram-weighted Map for Container Ship Berthing (S14)
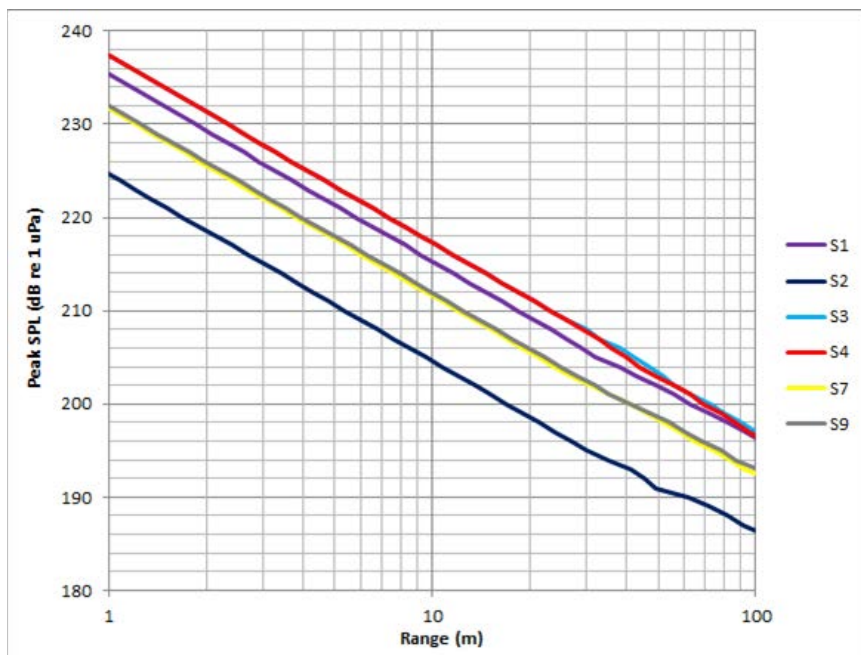
Figure A–51 Peak SPL vs. Range (values < 10 m were extrapolated using spherical spreading)
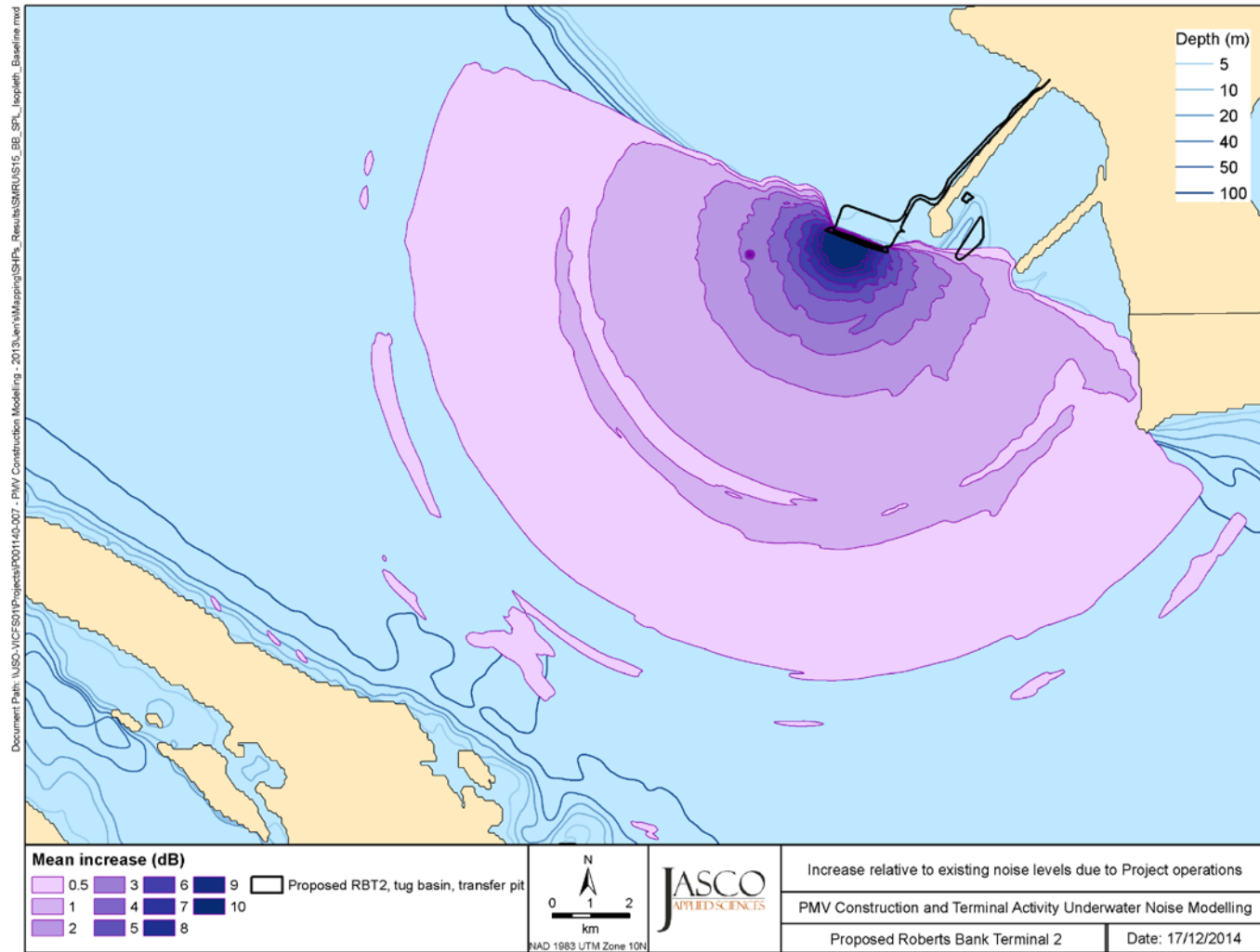
Figure A–52 Contour Map of Change in Existing Noise Level due to Terminal Operations

APPENDIX B

Tables

Table B–1 Specifications of the Modelled Scenarios (see Figure A-8 for locations of the modelled scenarios)

Scenario #	Description	Noise Source(s)	Source Coordinates (UTM zone 10)	Source Depth (m)	Bathymetry Dataset #	Hammer Model Proxy
1	Impact piling a 914 mm diameter cylindrical pile at the mooring dolphin	Impact hammer	487018, 5428956	10.2	3	Delmag diesel D36-32
2	Impact piling a 914 mm diametercylindrical pile with confined bubble curtain mitigation at the mooring dolphin	Impact hammer	487018, 5428956	10.2	3	Delmag diesel D36-32
3	Impact piling a 914 mm diameter cylindrical pile at the tug basin	Impact hammer	489151, 5430305	3.8	3	Delmag diesel D36-32
4	Impact piling a 914 mm diameter cylindrical pile at the perimeter dyke	Impact hammer	487251, 5429177	3.4	1	Delmag diesel D36-32
5	Vibratory piling a 914 mm diameter cylindrical pile at the mooring dolphin	Vibratory hammer	487018, 5428956	10.2	3	APE 300/400B
6	Vibratory piling a 914 mm diameter cylindrical pile at the tug basin	Vibratory hammer	489151, 5430305	3.8	3	APE 300/400B
7	Impact piling a sheet pile at the west end caisson	Impact hammer	485685, 5429471	8.8	3	ICE 60S diesel impact
8	Vibratory piling a sheet pile at the west end caisson	Vibratory hammer	485685, 5429471	8.8	3	ICE 60S diesel impact
9	Impact piling a sheet pile at the east end caisson	Impact hammer	486953, 5429008	7.8	3	ICE 60S diesel impact
10	Vibratory piling a sheet pile at the east end caisson	Vibratory hammer	486953, 5429008	7.8	3	ICE 60S diesel impact
11	Vibro-densification at the dredge basin	Vibro-densifier	486263, 5429247	8.4	3	N/A
12	Dredging of the dredge basin	Dredger (vessel)	486241, 5429199	2.14	2	N/A
		Cutter head	486241, 5429199	31		
13	Dredging of the intermediate transfer pit	Dredger (vessel)	489257, 5429198	2.14	3	N/A

Scenario #	Description	Noise Source(s)	Source Coordinates (UTM zone 10)	Source Depth (m)	Bathymetry Dataset #	Hammer Model Proxy
		Cutter head	489257, 5429198	15.6		
14	Berthing of an E-class container ship with three tugs and a line boat at 4 kts	Forward tug	486186, 5429084	3.6	4	N/A
		Mid-ship tug	486000, 5429119	3.6		
		Starboard-quarter tug	485818, 5429184	3.4		
		Line boat	486131, 5429037	3.4		
15	E-class container ship approaching terminal at 6 kts with four tugs approaching container ship at 12 kts	E-class container ship	483496, 5428814	9.3	4	N/A
		Tug 1	485904, 5428881	3.6		
		Tug 2	486002, 5428865	3.4		
		Tug 3	485920, 5428788	3.6		
		Tug 4	486006, 5428797	3.4		

Table B–2 Frequency-dependent Attenuation of Sound in Seawater

Frequency (Hz)	Absorption (dB/km)	Frequency (Hz)	Absorption (dB/km)
10	0.000	1000	0.060
12.5	0.000	1250	0.075
16	0.000	1600	0.093
20	0.000	2000	0.112
25	0.000	2500	0.135
31.5	0.000	3150	0.168
40	0.000	4000	0.218
50	0.000	5000	0.290
63	0.000	6300	0.406
80	0.001	8000	0.594
100	0.001	10000	0.869
125	0.002	12500	1.289
160	0.003	16000	2.011
200	0.005	20000	3.002
250	0.007	25000	4.443
315	0.011	31500	6.551
400	0.016	40000	9.509
500	0.024	50000	13.001
630	0.034	63000	17.233
800	0.046		

Table B–3 Radii ($R_{95\%}$) of 24-hr Cumulative (1 min total piling) SEL M-weighted Contours for Marine Mammals and Fish (unweighted) for Impact Piling Scenarios

SEL (dB re 1 µPa²·s)		S1 Impact Piling at Mooring Dolphin (m)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (m)	S3 Impact Piling at Tug Basin (m)	S4 Impact Piling at Perimeter Dyke (m)	S7 Impact Sheet Piling at West End Caisson (m)	S9 Impact Sheet Piling at East End Caisson (m)
Fish[a]	210 dB	n/r[b]	n/r	n/r	n/r	n/r	n/r
	187 dB	60	n/r	60	70	50	40
HFC (198 dB)		n/r	n/r	n/r	n/r	n/r	n/r
LFC (198 dB)		n/r	n/r	n/r	n/r	n/r	n/r
MFC (198 dB)		n/r	n/r	n/r	n/r	n/r	n/r
Pinniped (186 dB)		60	n/r	80	70	50	50

[a] Fish results were unweighted.

[b] n/r = threshold not reached for the indicated scenario.

Table B–4 Radii ($R_{95\%}$) of 24-hr Cumulative (10 min total piling) SEL M-weighted Contours for Marine Mammals and Fish (unweighted) for Impact Piling Scenarios

SEL (dB re 1 µPa²·s)		S1 Impact Piling at Mooring Dolphin (m)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (m)	S3 Impact Piling at Tug Basin (m)	S4 Impact Piling at Perimeter Dyke (m)	S7 Impact Sheet Piling at West End Caisson (m)	S9 Impact Sheet Piling at East End Caisson (m)
Fish[a]	210 dB	n/r[b]	n/r	n/r	n/r	n/r	n/r
	187 dB	240	50	200	250	160	180
HFC (198 dB)		40	n/r	50	50	30	30
LFC (198 dB)		50	n/r	60	60	30	30
MFC (198 dB)		50	n/r	50	60	30	30
Pinniped (186 dB)		260	60	220	270	180	200

[a] Fish results were unweighted.

[b] n/r = threshold not reached for the indicated scenario.

Table B–5 Radii ($R_{95\%}$) of 24-hr Cumulative (100 min total piling) SEL M-weighted Contours for Marine Mammals and Fish (unweighted) for Impact Piling Scenarios

SEL (dB re 1 µPa²·s)		S1 Impact Piling at Mooring Dolphin (m)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (m)	S3 Impact Piling at Tug Basin (m)	S4 Impact Piling at Perimeter Dyke (m)	S7 Impact Sheet Piling at West End Caisson (m)	S9 Impact Sheet Piling at East End Caisson (m)
Fish[a]	210 dB	40	n/r[b]	50	50	30	30
	187 dB	1,020	220	480	630	590	610
HFC (198 dB)		170	30	140	210	120	130
LFC (198 dB)		200	50	160	220	140	160
MFC (198 dB)		180	30	150	220	130	140
Pinniped (186 dB)		1,170	220	480	680	640	670

[a] Fish results were unweighted.

[b] n/r = threshold not reached for the indicated scenario.

Table B–6 Radii ($R_{95\%}$) to rms SPL Injury and Disturbance Thresholds for Marine Mammals for Impact Piling Scenarios

SPL (dB re 1 µPa)		S1 Impact Piling at Mooring Dolphin (m)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (m)	S3 Impact Piling at Tug Basin (m)	S4 Impact Piling at Perimeter Dyke (m)	S7 Impact Sheet Piling at West End Caisson (m)	S9 Impact Sheet Piling at East End Caisson (m)
Cetacean	180	100	30	110	120	70	70
	160	1,320	330	490	750	690	710
Pinniped	190	30	10	40	40	20	20
	160	1,320	330	490	750	690	710

Table B–7 Radii (R_{max}) to Peak SPL Injury Thresholds for Marine Mammals and Fish for Impact Piling Scenarios

SPL (dB re 1 µPa)	S1 Impact Piling at Mooring Dolphin (m)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (m)	S3 Impact Piling at Tug Basin (m)	S4 Impact Piling at Perimeter Dyke (m)	S7 Impact Sheet Piling at West End Caisson (m)	S9 Impact Sheet Piling at East End Caisson (m)
Cetacean (230)	2[a]	1	2	2	1	1
Pinniped (218)	7	2	9	9	5	5
Fish (206)	29	9	38	36	19	20

[a] Ranges less than 10 m were extrapolated using spherical spreading (source levels were from measurements made at 10 m range).

Table B–8 Radii ($R_{95\%}$) of Unweighted SPL Contours for Vibratory Piling Scenarios

SPL (dB re 1 µPa)	S5 Vibratory piling at Mooring Dolphin (m)	S6 Vibratory Piling at Tug Basin (m)	S8 Vibratory Sheet Piling at West End Caisson (m)	S10 Vibratory Sheet Piling at East End Caisson (m)
120	12,500	640	14,520	14,200
130	1,760	540	1,580	1,860
140	400	390	440	440
150	100	110	110	120
160	20	30	< 20	< 20
170	< 20	n/r[a]	n/r	n/r

[a] n/r = threshold not reached for the indicated scenario.

Table B–9 Radii (R_{max}) of Unweighted SPL Contours for Vibratory Piling Scenarios

SPL (dB re 1 µPa)	S5 Vibratory Piling at Mooring Dolphin (m)	S6 Vibratory Piling at Tug Basin (m)	S8 Vibratory Sheet Piling at West End Caisson (m)	S10 Vibratory Sheet Piling at East End Caisson (m)
120	24,520	890	22,400	23,570
130	2,250	650	1,890	2,400
140	490	440	560	550
150	110	130	140	130
160	20	30	< 20	< 20
170	< 20	n/r[a]	n/r	n/r

[a] n/r = threshold not reached for the indicated scenario.

Table B–10 Radii ($R_{95\%}$) of Unweighted SPL Contours for Continuous Non-piling Scenarios

SPL (dB re 1 µPa)	S11 Vibro-densification at Dredge Basin (m)	S12 Dredging at Dredge Basin (m)	S13 Dredging at Intermediate Transfer Pit (m)	S14 Berthing (m)	S15 Transiting (m)
120	1,740	2,150	960	22,000	14,220
130	550	420	360	4,280	3,560
140	120	150	130	930	570
150	50	40	40	370	160
160	< 20	< 20	< 20	40	20
170	n/r[a]	n/r	n/r	< 20	< 20

[a] n/r = threshold not reached for the indicated scenario.

Table B–11 Radii (R_{max}) of Unweighted SPL Contours for Continuous Non-piling Scenarios

SPL (dB re 1 µPa)	S11 Vibro-densification at Dredge Basin (m)	S12 Dredging at Dredge Basin (m)	S13 Dredging at Intermediate Transfer Pit (m)	S14 Berthing (m)	S15 Transiting (m)
120	2,110	2,460	1,150	33,610	20,320
130	600	460	400	6,770	4,170
140	130	170	130	1,100	620
150	50	40	40	430	180
160	< 20	< 20	< 20	170	80
170	n/r[a]	n/r	n/r	< 20	< 20

[a] n/r = threshold not reached for the indicated scenario.

Table B–12 Killer Whale Zone of Audibility (ZOA) for Vibratory Piling Scenarios

SPL (dB re HT)	S5 Vibratory Piling at Mooring Dolphin (m)	S6 Vibratory Piling at Tug Basin (m)	S8 Vibratory Sheet Piling at West End Caisson (m)	S10 Vibratory Sheet Piling at East End Caisson (m)
ZOA ($R_{95\%}$)	41,570	1,860	58,270	41,840
ZOA (R_{max})	67,520	2,400	75,280	67,310

Table B–13 Areas of Ensonification for Killer Whale Zone of Audibility (ZOA) for Vibratory Piling Scenarios ($R_{95\%}$)

SPL	S5 Vibratory Piling at Mooring Dolphin (ha)	S6 Vibratory Piling at Tug Basin (ha)	S8 Vibratory Sheet Piling at West End Caisson (ha)	S10 Vibratory Sheet Piling at East End Caisson (ha)
ZOA	124,570	290	146,490	125,690

Table B–14 Killer Whale Zone of Audibility (ZOA) for Continuous Non-piling Scenarios

SPL (dB re HT)	S11 Vibro-densification at Dredge Basin (m)	S12 Dredging at Dredge Basin (m)	S13 Dredging at Intermediate Transfer Pit (m)	S14 Berthing (m)	S15 Transiting (m)
ZOA ($R_{95\%}$)	42,030	35,560	24,770	98,340	93,900
ZOA (R_{max})	68,250	56,110	34,400	118,640	118,380

Table B–15 Areas of Ensonification for Killer Whale Zone of Audibility (ZOA) for Continuous Non-piling Scenarios ($R_{95\%}$)

SPL	S11 Vibro-densification at Berth Pocket (ha)	S12 Dredging at Dredge Basin (ha)	S13 Dredging at Intermediate Transfer Pit (ha)	S14 Berthing (ha)	S15 Transiting (ha)
ZOA	120,020	105,980	51,090	190,070	219,420

Table B–16 Radii ($R_{95\%}$) of Unweighted SPL Contours to Killer Whale Behavioural Response Described in SMRU Canada Ltd. (2014) for Vibratory Piling Scenarios

SPL (dB re 1 µPa)	S5 Vibratory Piling at Mooring Dolphin (m)	S6 Vibratory Piling at Tug Basin (m)	S8 Vibratory Sheet Piling at West End Caisson (m)	S10 Vibratory Sheet Piling at East End Caisson (m)
117	21,050	690	22,150	21,310
126	5,420	580	4,390	4,430
129	3,310	550	1,940	2,340
137	2,010	450	630	630
146	1,640	180	200	210
153	1,540	90	80	80

Table B–17 Radii ($R_{95\%}$) of Unweighted SPL Contours to Killer Whale Behavioural Response Described in SMRU Canada Ltd. (2014) for Continuous Non-piling Scenarios

SPL (dB re 1 µPa)	S11 Vibro-densification at Dredge Basin (m)	S12 Dredging at Dredge Basin (m)	S13 Dredging at Intermediate Transfer Pit (m)	S14 Berthing (m)	S15 Transiting (m)
117	2,480	2,860	1,220	29,220	20,290
126	990	680	500	8,430	6,370
129	610	480	400	5,310	4,050
137	170	220	160	1,410	1,010
146	70	70	70	500	290
153	40	< 20	30	300	110

Table B–18. Salmon Zone of Audibility (ZOA) and Range ($R_{95\%}$) to SPLs for Impact Piling Scenarios

SPL (dB re HT)	S1 Impact Piling at Mooring Dolphin (m)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (m)	S3 Impact Piling at Tug Basin (m)	S4 Impact Piling at Perimeter Dyke (m)	S7 Impact Sheet Piling at West End Caisson (m)	S9 Impact Sheet Piling at East End Caisson (m)
ZOA	38,930	37,810	5,550	33,980	38,760	38,010
10	38,720	37,040	2,450	32,130	37,800	37,430
50	2,100	800	440	410	1,110	1,100
90	< 20	< 20	< 20	< 20	n/r[a]	n/r

[a] n/r = threshold not reached for the indicated scenario.

Table B–19 Salmon Zone of Audibility (ZOA) and Range (R_{max}) to SPLs for Impact Piling Scenarios

SPL (dB re HT)	S1 Impact Piling at Mooring Dolphin (m)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (m)	S3 Impact Piling at Tug Basin (m)	S4 Impact Piling at Perimeter Dyke (m)	S7 Impact Sheet Piling at West End Caisson (m)	S9 Impact Sheet Piling at East End Caisson (m)
ZOA	64,830	63,700	6,760	60,730	55,000	63,770
10	64,120	62,030	3,200	54,430	54,860	62,760
50	2,280	880	500	480	1,230	1,190
90	< 20	< 20	< 20	< 20	n/r[a]	n/r

[a] n/r = threshold not reached for the indicated scenario.

Table B–20 Areas of Ensonification for Salmon Zone of Audibility (ZOA) for Impact Piling Scenarios ($R_{95\%}$)

SPL	S1 Impact Piling at Mooring Dolphin (ha)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (ha)	S3 Impact Piling at Tug Basin (ha)	S4 Impact Piling at Perimeter Dyke (ha)	S7 Impact Sheet Piling at West End Caisson (ha)	S9 Impact Sheet Piling at East End Caisson (ha)
ZOA	111,560	107,290	610	79,300	109,560	105,700

Table B–21 Salmon Zone of Audibility (ZOA) and Range ($R_{95\%}$) to SPLs for Vibratory Piling Scenarios

SPL (dB re HT)	S5 Vibratory Piling at Mooring Dolphin (m)	S6 Vibratory Piling at Tug Basin (m)	S8 Vibratory Sheet Piling at West End Caisson (m)	S10 Vibratory Sheet Piling at East End Caisson (m)
ZOA	23,700	875	21,440	20,810
10	9,510	650	8,630	8,290
50	30	30	30	30
90	n/r[a]	n/r	n/r	n/r

[a] n/r = threshold not reached for the indicated scenario.

Table B–22 Salmon Zone of Audibility (ZOA) and Range (R_{max}) to SPLs for Vibratory Piling Scenarios

SPL (dB re HT)	S5 Vibratory Piling at Mooring Dolphin (m)	S6 Vibratory Piling at Tug Basin (m)	S8 Vibratory Sheet Piling at West End Caisson (m)	S10 Vibratory Sheet Piling at East End Caisson (m)
ZOA	30,560	910	26,950	26,130
10	20,470	730	17,570	17,480
50	30	30	30	30
90	n/r[a]	n/r	n/r	n/r

[a] n/r = threshold not reached for the indicated scenario.

Table B–23 Areas of Ensonification for Salmon Zone of Audibility (ZOA) for Vibratory Piling Scenarios ($R_{95\%}$)

SPL	S5 Vibratory Piling at Mooring Dolphin (ha)	S6 Vibratory Piling at Tug Basin (ha)	S8 Vibratory Sheet Piling at West End Caisson (ha)	S10 Vibratory Sheet Piling at East End Caisson (ha)
ZOA	55,440	70	41,210	38,930

Table B–24 Salmon Zone of Audibility (ZOA) and Range ($R_{95\%}$) to SPLs for Continuous Non-piling scenarios

SPL (dB re HT)	S11 Vibro-densification at Dredge Basin (m)	S12 Dredging at Dredge Basin (m)	S13 Dredging at Intermediate Transfer Pit (m)	S14 Berthing (m)	S15 Transiting (m)
ZOA	13,160	12,240	1,630	23,080	12,640
10	4,890	2,950	1,030	10,520	5,650
50	30	30	30	60	100
90	n/r[a]	n/r	n/r	n/r	n/r

[a] n/r = threshold not reached for the indicated scenario.

Table B–25 Salmon Zone of Audibility (ZOA) and Range (R_{max}) to SPLs for Continuous Non-piling Scenarios

SPL (dB re HT)	S11 Vibro-densification at Dredge Basin (m)	S12 Dredging at Dredge Basin (m)	S13 Dredging at Intermediate Transfer Pit (m)	S14 Berthing (m)	S15 Transiting (m)
ZOA	16,440	18,270	1,860	30,440	18,770
10	5,370	3,260	1,200	19,760	6,330
50	30	30	30	70	110
90	n/r[a]	n/r	n/r	n/r	n/r

[a] n/r = threshold not reached for the indicated scenario.

Table B–26 Areas of Ensonification for Salmon Zone of Audibility (ZOA) for Continuous Non-piling Scenarios ($R_{95\%}$)

SPL	S11 Vibro-densification at Berth Pocket (ha)	S12 Dredging at Dredge Basin (ha)	S13 Dredging at Intermediate Transfer Pit (ha)	S14 Berthing (ha)	S15 Transiting (ha)
ZOA	13,480	9,900	330	56,840	17,190

Table B–27 Herring Zone of Audibility (ZOA) and Range ($R_{95\%}$) to SPLs for Impact Piling Scenarios

SPL (dB re HT)	S1 Impact Piling at Mooring Dolphin (m)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (m)	S3 Impact Piling at Tug Basin (m)	S4 Impact Piling at Perimeter Dyke (m)	S7 Impact Sheet Piling at West End Caisson (m)	S9 Impact Sheet Piling at East End Caisson (m)
ZOA	43,450	42,970	22,160	42,060	54,730	43,400
10	44,260	43,610	22,290	42,050	53,890	44,000
50	38,090	30,360	1,410	34,390	37,020	36,850
90	450	140	340	340	280	280

Table B–28 Herring Zone of Audibility (ZOA) and Range (R_{max}) to SPLs for Impact Piling Scenarios

SPL (dB re HT)	S1 Impact Piling at Mooring Dolphin (m)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (m)	S3 Impact Piling at Tug Basin (m)	S4 Impact Piling at Perimeter Dyke (m)	S7 Impact Sheet Piling at West End Caisson (m)	S9 Impact Sheet Piling at East End Caisson (m)
ZOA	67,670	67,800	24,150	61,170	72,070	67,460
10	67,890	67,620	24,230	61,050	71,900	67,920
50	66,970	43,540	1,630	60,850	54,790	60,700
90	520	150	390	370	330	340

Table B–29 Areas of Ensonification for Herring Zone of Audibility (ZOA) for Impact Piling Scenarios ($R_{95\%}$)

SPL	S1 Impact Piling at Mooring Dolphin (m)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (m)	S3 Impact Piling at Tug Basin (m)	S4 Impact Piling at Perimeter Dyke (m)	S7 Impact Sheet Piling at West End Caisson (m)	S9 Impact Sheet Piling at East End Caisson (m)
ZOA	130,510	126,810	12,780	116,830	143,400	127,340

Table B–30 Herring Zone of Audibility (ZOA) and Range ($R_{95\%}$) to SPLs for Vibratory Piling Scenarios

SPL (dB re HT)	S5 Vibratory Piling at Mooring Dolphin (m)	S6 Vibratory Piling at Tug Basin (m)	S8 Vibratory Sheet Piling at West End Caisson (m)	S10 Vibratory Sheet Piling at East End Caisson (m)
ZOA	41,900	2,410	48,580	42,100
10	42,280	1,990	45,380	42,360
50	1,710	510	1,470	1,530
90	< 20	n/r[a]	n/r	n/r

[a] n/r = threshold not reached for the indicated scenario.

Table B–31 Herring Zone of Audibility (ZOA) and Range (R_{max}) to SPLs for Vibratory Piling Scenarios

SPL (dB re HT)	S5 Vibratory Piling at Mooring Dolphin (m)	S6 Vibratory Piling at Tug Basin (m)	S8 Vibratory Sheet Piling at West End Caisson (m)	S10 Vibratory Sheet Piling at East End Caisson (m)
ZOA	67,520	2,550	69,350	67,590
10	67,440	2,280	64,580	67,560
50	1,940	580	1,680	1,800
90	< 20	n/r[a]	n/r	n/r

[a] n/r = threshold not reached for the indicated scenario.

Table B–32 Areas of Ensonification for Herring Zone of Audibility (ZOA) for Vibratory Piling Scenarios ($R_{95\%}$)

SPL	S5 Vibratory Piling at Mooring Dolphin (m)	S6 Vibratory Piling at Tug Basin (m)	S8 Vibratory Sheet Piling at West End Caisson (m)	S10 Vibratory Sheet Piling at East End Caisson (m)
ZOA	121,300	424	133,300	121,020

Table B–33 Flatfish Zone of Audibility (ZOA) and Range ($R_{95\%}$) to SPLs for Impact Piling Scenarios

SPL (dB re HT)	S1 Impact Piling at Mooring Dolphin (m)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (m)	S3 Impact Piling at Tug Basin (m)	S4 Impact Piling at Perimeter Dyke (m)	S7 Impact Sheet Piling at West End Caisson (m)	S9 Impact Sheet Piling at East End Caisson (m)
ZOA	40,170	38,050	6,760	37,030	40,980	39,280
10	39,970	37,710	3,000	35,980	39,560	38,990
50	3,160	1,180	530	700	1,680	1,640
90	20	< 20	30	20	< 20	< 20

Table B–34 Flatfish Zone of Audibility (ZOA) and Range (R_{max}) to SPLs for Impact Piling Scenarios

SPL (dB re HT)	S1 Impact Piling at Mooring Dolphin (m)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (m)	S3 Impact Piling at Tug Basin (m)	S4 Impact Piling at Perimeter Dyke (m)	S7 Impact Sheet Piling at West End Caisson (m)	S9 Impact Sheet Piling at East End Caisson (m)
ZOA	66,950	63,980	8,570	61,010	55,150	66,740
10	66,980	63,000	4,080	60,930	54,900	64,870
50	3,510	1,270	610	830	1,800	1,780
90	20	< 20	30	20	< 20	< 20

Table B–35 Areas of Ensonification for Flatfish Zone of Audibility (ZOA) for Impact Piling Scenarios ($R_{95\%}$)

SPL	S1 Impact Piling at Mooring Dolphin (m)	S2 Impact Piling at Mooring Dolphin with Bubble Curtain (m)	S3 Impact Piling at Tug Basin (m)	S4 Impact Piling at Perimeter Dyke (m)	S7 Impact Sheet Piling at West End Caisson (m)	S9 Impact Sheet Piling at East End Caisson (m)
ZOA	115,840	108,770	1,080	93,120	117,110	111,100

Table B–36 Flatfish Zone of Audibility (ZOA) and Range ($R_{95\%}$) to SPLs for Vibratory Piling Scenarios

SPL (dB re HT)	S5 Vibratory Piling at Mooring Dolphin (m)	S6 Vibratory Piling at Tug Basin (m)	S8 Vibratory Sheet Piling at West End Caisson (m)	S10 Vibratory Sheet Piling at East End Caisson (m)
ZOA	29,580	1,140	24,810	25,100
10	19,960	910	17,850	16,760
50	50	40	60	50
90	n/r[a]	n/r[a]	n/r[a]	n/r[a]

[a] n/r = threshold not reached for the indicated scenario.

Table B–37 Flatfish Zone of Audibility (ZOA) and Range (R_{max}) to SPLs for Vibratory Piling Scenarios

SPL (dB re HT)	S5 Vibratory Piling at Mooring Dolphin (m)	S6 Vibratory Piling at Tug Basin (m)	S8 Vibratory Sheet Piling at West End Caisson (m)	S10 Vibratory Sheet Piling at East End Caisson (m)
ZOA	44,160	1,150	34,620	35,840
10	26,320	990	25,320	25,170
50	60	40	60	50
90	n/r[a]	n/r[a]	n/r[a]	n/r[a]

[a] n/r = threshold not reached for the indicated scenario.

Table B–38 Areas of Ensonification for Flatfish Zone of Audibility (ZOA) for Vibratory Piling Scenarios ($R_{95\%}$)

SPL	S5 Vibratory Piling at Mooring Dolphin (m)	S6 Vibratory Piling at Tug Basin (m)	S8 Vibratory Sheet Piling at West End Caisson (m)	S10 Vibratory Sheet Piling at East End Caisson (m)
ZOA	73,470	120	62,170	62,590

Table B–39 Humpback Whale Zone of Audibility (ZOA) and Range ($R_{95\%}$) to SPLs for Continuous Non-piling Scenarios

SPL (dB re HT)	S14 Berthing (m)	S15 Transiting (m)
ZOA	98,090	94,970
10	101,630	99,440
50	50,060	45,100
90	60	160

Table B–40 Areas of Ensonification for Humpback Whale Zone of Audibility (ZOA) for Continuous Non-piling Scenarios ($R_{95\%}$)

SPL	S14 Berthing (ha)	S15 Transiting (ha)
ZOA	192,150	235,750

Table B–41 Steller Sea Lion Zone of Audibility (ZOA) and Range ($R_{95\%}$) to SPLs for Continuous Non-piling Scenarios

SPL (dB re HT)	S14 Berthing (m)	S15 Transiting (m)
ZOA	98,770	95,910
10	97,710	99,250
50	3,780	2,890
90	< 20	< 20

Table B–42 Areas of Ensonification for Steller Sea Lion Zone of Audibility (ZOA) for Continuous Non-piling Scenarios ($R_{95\%}$)

SPL	S14 Berthing (ha)	S15 Transiting (ha)
ZOA	186,320	225,150

Table B–43 Radii ($R_{95\%}$) and Areas (ha) for Change in Existing Noise Level due to Terminal Operations

Mean Increase (dB)	Distance (m)	Area (ha)
0.5	11,182	21,684
1	7,579	9,260
2	3,862	2,852
3	2,756	1,481
4	2,060	813
5	1,511	468
6	1,246	318
7	1,042	225
8	866	161
9	744	122
10	653	95

APPENDIX 9.8-B
Regional Commercial Vessel
Traffic Underwater Noise Modelling Study
Technical Report

This page is intentionally left blank

ROBERTS BANK TERMINAL 2 TECHNICAL REPORT

Underwater Noise

Regional Commercial Vessel Traffic Underwater Noise Exposure Study

Prepared for:
Port Metro Vancouver
100 The Pointe, 999 Canada Place
Vancouver, BC V6C 3T4

Prepared by:
JASCO Applied Sciences (Canada) Ltd.
2305–4464 Markham Street
Victoria, BC V8Z 7X8 Canada
Tel: +1-250-483-3300
Fax: +1-250-483-3301
www.jasco.com

December 2014

Technical Report/Technical Data Report Disclaimer

The Canadian Environmental Assessment Agency determined the scope of the proposed Roberts Bank Terminal 2 Project (RBT2 or the Project) and the scope of the assessment in the Final Environmental Impact Statement Guidelines (EISG) issued January 7, 2014. The scope of the Project includes the project components and physical activities to be considered in the environmental assessment. The scope of the assessment includes the factors to be considered and the scope of those factors.   The Environmental Impact Statement (EIS) has been prepared in accordance with the scope of the Project and the scope of the assessment specified in the EISG. For each component of the natural or human environment considered in the EIS, the geographic scope of the assessment depends on the extent of potential effects.

At the time supporting technical studies were initiated in 2011, with the objective of ensuring adequate information would be available to inform the environmental assessment of the Project, neither the scope of the Project nor the scope of the assessment had been determined.

Therefore, the scope of supporting studies may include physical activities that are not included in the scope of the Project as determined by the Agency. Similarly, the scope of supporting studies may also include spatial areas that are not expected to be affected by the Project.

This out-of-scope information is included in the Technical Report (TR)/Technical Data Report (TDR) for each study, but may not be considered in the assessment of potential effects of the Project unless relevant for understanding the context of those effects or to assessing potential cumulative effects.

EXECUTIVE SUMMARY

The Roberts Bank Terminal 2 Project (RBT2 or Project) is a proposed new three-berth marine terminal at Roberts Bank in Delta, B.C. that could provide 2.4 million TEUs (twenty-foot equivalent units) of additional container capacity annually. The Project is part of Port Metro Vancouver's Container Capacity Improvement Program, a long-term strategy to deliver projects to meet anticipated growth in demand for container capacity to 2030.

Vessels visiting terminals within PMV jurisdiction use primary commercial traffic routes that pass through important habitat of a number of marine species, including areas of high use for the endangered southern resident killer whale (SRKW) population. Potential cumulative effects of increased commercial vessel traffic noise on marine fauna must be addressed in the Project's environmental assessment, and additional data were required to characterise the existing noise environments and assess relative increases in sound levels due to future vessel traffic.

To address this data gap, a modelling study was undertaken to examine commercial vessel traffic noise near the proposed terminal in PMV jurisdiction and regionally where cumulative effects may occur. A regional-level acoustic model was used to estimate underwater noise due to commercial vessel traffic at monthly and daily scales. Existing noise levels within the study area in 2012 were estimated based on commercial traffic as quantified by real vessel tracking data from the Vessel Traffic Operations and Support System (VTOSS) which compiles different marine traffic tracking methods, primarily radar and Automatic Identification System (AIS). This existing noise was considered in context with forecasts of future commercial vessel traffic noise, representative of the year 2030. Four model scenarios were considered:

- S1: Existing commercial vessel traffic;

- S2: Future commercial vessel traffic with no new projects except RBT2, and future incremental vessel traffic associated with RBT2 (includes existing and expected conditions)[*]

- S3: Future commercial vessel traffic due to certain and foreseeable projects[†] without RBT2, or incremental vessel traffic associated with RBT2 (includes existing and expected conditions); and

- S4: Future commercial vessel traffic due to certain and foreseeable projects, with RBT2, and incremental shipping traffic associated with RBT2 (includes existing and expected conditions).

---

[*] Expected conditions between 2012 and 2030 include no new projects but increases in vessel traffic at Westshore and Deltaport terminals i.e., DTRRIP.

[†] Seven certain and foreseeable projects were included: Fraser Surrey Docks, Richardson Grain Elevator, Neptune Terminals Coal Expansion, Vancouver Airport Fuel Delivery Project, Kinder Morgan Trans-Mountain Pipeline Expansion Project, Gateway Pacific Bulk Terminal, and Pacific Coast Terminals/Other Chemical carrier facilities (HEC 2014).

The three future scenarios were prepared by adding estimates of additional commercial vessel traffic to the existing and expected conditions scenario. Inter-seasonal variations in commercial vessel traffic noise were addressed by considering month-long and day-long periods in both winter (January) and summer (July).

The Regional Commercial Vessel Traffic Underwater Noise Exposure Study had two study areas – the regional study area (RSA) and focused study area (FSA). The regional monthly cumulative noise exposure study was undertaken to predict average commercial vessel traffic noise for the RSA. The purpose of this study area was to characterise the underwater noise levels in the Critical Habitat of southern resident killer whales (SRKW). The focused study area was used to examine commercial vessel traffic noise in key areas of high use by SRKW for one minute intervals over a 24-hour period. The noise outputs from this study area were produced to be used in subsequent models examining potential effects of noise on SRKW (see SMRU 2014a, b). Because of the added complexity of these models and the additional computational requirements for the noise inputs, the spatial extent of the focused model area was smaller than the regional model, but still incorporated most of high-use SRKW critical habitat in Canada and the U.S.

Both studies employed a computational sound propagation model that accounted for location-dependent variation of environmental parameters governing sound propagation, including water sound speed profiles, seabed geoacoustics, and ocean depth. The sound propagation model was previously validated by controlled-source transmission loss measurements at three locations in the study area. Source levels (SLs) for 13 different vessel categories were computed from an extensive commercial vessel traffic noise dataset collected off the Lime Kiln lighthouse in Haro Strait, and were supplemented with SL measurements obtained from past PMV studies and a review of available ship noise literature. Wind-driven ambient noise in the RSA was estimated based on acoustic measurements obtained in Strait of Georgia and Haro Strait from July to September 2012. Cumulative commercial vessel traffic noise was computed on a dense grid covering the study area in 1/3-octave bands over the frequency range 10 to 63,000 Hz. Audiogram weighting was applied to all model results to estimate sound levels above hearing threshold for SRKWs.

For the regional study, winter and summer maps of time-average sound levels (monthly Leq) were produced over a larger (208 × 184 km) study area. Noise levels in this area were based on monthly commercial vessel traffic density data provided by the Marine Activity Risk Investigation Network (MARIN), and provide long-term spatial distributions of commercial vessel traffic noise levels inside the RSA. For the focused daily study, a day of commercial vessel traffic noise was simulated in winter and summer over a smaller (130 × 150 km) area during a 24-hour period. The baseline daily simulations were based on actual VTOSS vessel tracks from two 24-hour periods in January and July. The three future scenarios were prepared by adding simulated vessel tracks to the existing and expected conditions data to represent the passage of new traffic based on future traffic predictions for the three scenarios in HEC 2014 (Appendix 30-A *in* PMV 2015).

A key finding of the present study is that predicted increases in ship traffic are expected to contribute relatively little to overall commercial vessel traffic noise levels in the RSA, due to the high existing vessel traffic density in the study area. In the regional monthly cumulative study, additional incremental traffic associated with RBT2 increased mean existing noise levels by less than 0.1 dB near the international shipping lanes, with maximum localised increases of approximately 0.6 dB at specific locations in Haro Strait and the Strait of Juan de Fuca. Increases in incremental vessel traffic noise associated with RBT2 were predicted to be comparable to those from other planned developments within the study area. When all future projects were considered, the mean existing increase was less than 0.3 dB near the international shipping lanes, with maximum localised increases of approximately 0.9 dB. While the contribution of Project-related traffic to existing and forecasted underwater noise levels is expected to be relatively small, this is primarily because existing commercial vessel traffic noise in the study area is already the dominant contributor to the underwater soundscape.

Modelled noise levels were also weighted according to the hearing abilities of resident killer whales, to investigate whether this would affect the study findings. While average noise levels in the regional study area were well above the resident killer whale hearing threshold (61.3–64.3 dB re HT), the weighted contribution of increased vessel traffic was not appreciably different from the unweighted contribution. Thus the key findings of this study were essentially the same, regardless of whether the hearing abilities of resident killer whales were taken into account.

Another key finding of the study is that seasonal differences in commercial vessel traffic noise levels are driven primarily by seasonal changes in the sound propagation conditions. Despite July having greater ship traffic density, mean noise levels in the study area were predicted to be 4.6 dB higher in January due to strong seasonal temperature variations in the upper water column. Cooling at the sea surface in winter creates a sound duct that focusses vessel noise near the surface and enhances its longer-range propagation. Summer conditions have the opposite effect, with heating at the sea surface creating a down-refracting layer that channels sound toward the seabed. Because this study focused on SRKWs, which are mostly present in the upper water column where the influence of the surface layer is strongest, the importance of this effect is magnified.

TABLE OF CONTENTS

List of Tables

List of Appendices

1.0   INTRODUCTION

1.1   PROJECT BACKGROUND

The Roberts Bank Terminal 2 Project (RBT2 or the Project) is a proposed new multi-berth container terminal intended to provide additional container shipping capacity to Canada's West Coast. The Project is part of the Container Capacity Improvement Program (CCIP), Port Metro Vancouver's (PMVs) long-term strategy to deliver projects to meet anticipated growth and demand for container capacity to 2030.

PMV retained JASCO Applied Sciences, under subcontract to Hemmera, to perform modelling of cumulative underwater noise exposures near the proposed terminal and along international shipping lanes used by commercial vessel traffic. Levels of underwater noise from vessel traffic in winter and summer were assessed for the existing noise environment and for three future scenarios that represent different combinations of new potential commercial vessel traffic. The study has two main sub-components. The first is a regional monthly cumulative noise exposure study, which maps average commercial vessel traffic noise for the RSA. The second is a study of temporal variations of noise levels over one-day periods in winter and summer, which examines noise variability within the high use habitat of southern resident killer whale (SRKW; *Orcinus orca*).

Previous studies have investigated vessel acoustic source emissions and sound transmission characteristics (JASCO 2014a). Source levels (SL) of three representative container ships were measured at different transit speeds, with each container ship measured at two locations. Acoustic transmission loss (TL) rates were also characterised at Roberts Bank, Haro Strait, and the Strait of Juan de Fuca. Noise emissions of a large number of merchant, passenger, and fishing vessels were measured at an acoustic monitoring station near Lime Kiln lighthouse on San Juan Island (Hemmera et al. 2014). TL measurements were used with the Lime Kiln measurements to derive SLs that feed directly into the models used in the present study to calculate noise energy accumulation from all large-vessel traffic.

1.2   STUDY OVERVIEW

Commercial vessel traffic will generate increased levels of underwater noise near the terminal in PMV jurisdiction and as vessel traffic move through international shipping lanes within the Straits of Georgia and Juan de Fuca, and Haro Strait. The potential effects of increased commercial vessel noise on marine fauna must be addressed in the Project's effects assessment, but currently there are insufficient data available to characterise the existing noise environments or to assess the relative increases in sound levels due to future vessel traffic. The primary commercial shipping routes leading to RBT2 pass through important habitat of a number of marine species, including areas of high use by SRKW. This study provides noise levels which are based on measurements and computer model predictions.

1.2.1   Regional Monthly Cumulative Noise Exposure Study

A regional monthly study of cumulative sound energy from commercial vessel traffic was performed to generate maps of monthly time-average noise levels, in winter and summer, inside the RSA. The Maritime Activity and Risk Investigation Network (MARIN) analysed historical ship track data from the Vessel Traffic Operations and Support System (VTOSS) and forecasts of future commercial vessel traffic activity from HEC (2014) to generate monthly databases of traffic density and speed for 13 unique vessel categories. These traffic density databases were included in an acoustic model to compute the total sound energy emitted by commercial vessel traffic for January and July. The resulting noise maps show the long-term spatial distribution of sound energy from commercial vessel traffic inside the RSA for the existing conditions scenario and three future scenarios. Furthermore, the noise maps can be overlaid on marine mammal distributions to estimate cumulative noise effects due to the combination of existing and future commercial vessel traffic.

1.2.2   Focused Daily Temporal Noise Exposure Study

A focused daily study of the temporal variations of sound levels in areas of high use by SRKW overlapping with international shipping lanes was performed over two 24-hour periods in winter and summer, to investigate specific exposures to SRKW. The focused daily study used an approach similar to that of the regional monthly study, but individual vessel positions were based on actual vessel tracks through selected one-day periods. Noise levels over the focused study area were computed in 1-minute time steps to examine the variability in sound levels to which individual animals or groups of animals would be exposed.

1.2.3   Objectives of the Acoustic Modelling Studies

The objectives of the two primary study components and brief overviews of each are provided in **Table 1-1**.

Table 1-1   Cumulative Commercial Vessel Traffic Underwater Noise Study Components and Major Objectives

Component	Major Objective	Brief Overview
1) Regional Monthly Cumulative Noise Exposure Study	Create maps of underwater commercial vessel traffic noise in the RSA for January and July, based on a cumulative sound energy model. An existing conditions scenario (2012) and three future scenarios (2030) are considered as follows: 1. S1: Existing commercial vessel traffic; 2. S2: Future commercial vessel traffic with no new projects except RBT2, and future incremental vessel traffic associated with RBT2 (includes existing and expected conditions); 3. S3: Future commercial vessel traffic due to certain and foreseeable projects without RBT2, or incremental vessel traffic associated with RBT2 (includes existing and expected conditions); and 4. S4: Future commercial vessel traffic due to certain and foreseeable projects, with RBT2, and incremental shipping traffic associated with RBT2 (includes existing and expected conditions). The three future scenarios were produced by adding commercial vessel traffic density forecasts for reasonably certain and foreseeable projects to the existing conditions scenario.	Area-wide cumulative monthly sound levels are calculated for all vessel traffic as identified by the VTOSS ship tracking dataset, adjusted to 2012 activity levels (existing vessel traffic scenario; S1). The three additional future scenarios were simulated based on commercial vessel traffic density forecasts for reasonably certain and foreseeable projects. Results are intended to assess changes in sound levels due to incremental vessel traffic associated with RBT2 and reasonably certain and foreseeable projects.
2) Focused Daily Temporal Noise Exposure Study	Create a temporal model of underwater commercial vessel traffic sound pressure levels in areas of high use by SRKW in 1-minute steps over two 24-hour periods (one day in January and one day in July) to inform assessment of SRKW exposure to noise. One existing conditions scenario (S1) and three future scenarios are considered (S2 to S4) as above. The three future scenarios are prepared by adding simulated vessel tracks to the existing conditions scenario to represent commercial vessel traffic density forecasts for reasonably certain and foreseeable projects.	Sound pressure levels, and temporal variations thereof, are calculated on a dense grid covering high use SRKW habitat for two 24-hour windows from the VTOSS dataset (existing conditions scenario). Vessel tracks for three additional future scenarios are added to the VTOSS data based on a probabilistic simulation of per-route vessel increases.

[1]Expected conditions between 2012 and 2030 include no new projects but increases in vessel traffic at Westshore and Deltaport terminals i.e., DTRRIP.

2.0   REGIONAL MONTHLY CUMULATIVE NOISE EXPOSURE STUDY

2.1   METHODS

2.1.1   Overview and Scenarios

This study applied computer acoustic models to calculate cumulative sound levels produced by commercial vessel traffic activities over a large area covering the international shipping lanes and areas relevant to marine fauna most susceptible to noise disturbance. The analysis compared existing conditions with future-case scenarios based on three forecasts of commercial vessel traffic for reasonably certain and foreseeable projects.

The primary purpose of the analysis was to consider potential cumulative effects of additional noise exposure from expanded commercial vessel traffic on marine fauna. Four vessel traffic scenarios (S1, S2, S3, S4) were considered (see HEC 2014):

1. S1: Existing commercial vessel traffic in 2012;

2. S2: Future commercial vessel traffic in 2030 with no new projects except RBT2, and future incremental vessel traffic associated with RBT2 (includes existing and expected conditions)[*];

3. S3: Future commercial vessel traffic in 2030 due to certain and foreseeable projects[†] without RBT2, or incremental vessel traffic associated with RBT2 (includes existing and expected conditions);

4. S4: Future commercial vessel traffic in 2030 due to certain and foreseeable projects, with RBT2, and incremental shipping traffic associated with RBT2 (includes existing and expected conditions).

For each scenario, received level (RL) grid maps showing monthly time average sound levels (Leq) for January and July, representing winter and summer conditions respectively, were produced. Leq is the equivalent continuous sound level, equal to the mean SPL over a specified time period (i.e., one month).

Underwater sound transmission was predicted using a computational acoustic model that accounted for sound speed profiles, seabed geoacoustics, and bathymetry for the study area over multiple geographic zones. Noise energy from vessels in 13 categories was computed from gridded vessel density and speed data covering the entire study area. Vessel source levels (SLs) were computed from an extensive commercial vessel traffic noise dataset collected at Lime Kiln (see Hemmera et al. 2014), supplemented

---

[*] Expected conditions between 2012 and 2030 include no new projects but increases in vessel traffic at Westshore and Deltaport terminals i.e., DTRRIP.

[†] Seven certain and foreseeable projects were included: Fraser Surrey Docks, Richardson Grain Elevator, Neptune Terminals Coal Expansion, Vancouver Airport Fuel Delivery Project, Kinder Morgan Trans-Mountain Pipeline Expansion Project, Gateway Pacific Bulk Terminal, and Pacific Coast Terminals/Other Chemical carrier facilities (HEC 2014).

by acoustic measurements obtained from previous PMV studies and available ship noise literature. Wind-driven ambient noise conditions in the study area were estimated based on measurements obtained in Georgia Strait and Haro Strait from July through September 2012 (see SMRU et al. 2014c). Audiogram weighting was applied to the model outputs to estimate sound levels above the hearing threshold for SRKWs. Mean monthly sound levels were computed on an 800 × 800 m grid covering the study area. These results will be used for evaluating long-term acoustic habitat exposure for all four vessel traffic scenarios considered in the present study.

2.1.2   Study Area

The study area (i.e., 208 × 184 km) includes the Strait of Juan de Fuca from its western entrance, around the south end of Vancouver Island, and north through the Strait of Georgia to approximately 124° 20′ N, as shown in **Figure A-1**. The study area boundaries were chosen to encompass the international shipping lanes and regions that could be ensonified above ambient sound levels by commercial vessel traffic, and to help quantify exposure in areas of high use by SRKW.

2.1.3   Temporal Scope

Sound exposure levels (SEL) were computed over one-month periods in January (winter cases) and July (summer cases) for each scenario. The existing conditions case was calculated from 2010 vessel density and speed records from those months, with a correction for container and coal ships using 2012 activity levels from HEC (2014). The three future scenarios were based on traffic projections for 2030 for RBT2 and other terminals in the study area, and accounted for expected changes in vessel traffic densities for each scenario (see HEC 2014).

2.1.4   Vessel Source Levels

The cumulative noise model used representative SLs for 13 vessel categories to represent sound emissions from commercial vessel traffic inside the study area. Vessel SLs were compiled from several resources, including a large collection of SL measurements accrued over many years by The Whale Museum and Beam Reach (TWMBR) (Hemmera et al. 2014). SLs were compiled in 1/3-octave bands with band centre frequencies from 10 Hz to 63,100 Hz, covering the frequency range where vessel sound energy emissions overlap the hearing sensitivity of marine mammals and fish inside the study area.

Propeller cavitation and hull-borne machine vibration are the predominant sources of underwater noise from vessels. Different types of vessels have characteristic SL spectra (i.e., variations of sound emission levels with sound frequency) because of their specific design and operating conditions. For the purpose of modelling noise from hundreds of vessels over large spatial scales and long time periods, representative SLs for different vessel categories were used (NRC 2003). In this study, SLs were derived for the 13 vessel categories defined by the MARIN vessel density dataset (**Table 2-1**).

Table 2-1   Vessel Categories. LOA is an Abbreviation for Length Overall.

Vessel Category	VTOSS Category	Minimum LOA (m)	Maximum LOA (m)
1	Container ships	320	367
2	Container ships	250	320
3	Container ships	139	250
4	Oil tankers	182	287
5	Tugs	5	59
6	Ferries	20	167
7	Other merchant/Tankers	252	306
8	Other merchant/Tankers	100	250
9	All other vessels by size	100	294
10	All other vessels by size	50	100
11	All other vessels by size	25	50
12	All other vessels by size	10	25
13	All other vessels by size	5	10

SLs for vessel categories 1 to 5, 7 to 9, and 11 were based primarily on the TWMBR dataset, which contains SL statistics for 2,187 unique vessels in 11 different categories (Hemmera et al. 2014). Because the TWMBR data lacked results for 1/3-octave bands below 50 Hz, it was necessary to supplement SLs for these categories with low-frequency data from published literature (**Table 2-2**). Where TWMBR data were supplemented with literature data, mean SLs were computed by weighting each data point by the reported number of measurements. A correction was also applied to the TWMBR dataset above 8 kHz to deal with possible background noise contamination suspected due to the dataset's inconsistent trend in higher-frequency spectral variation relative to the expected spectral slope associated with cavitation (Ross 1976); therefore, 1/3-octave band SLs above 8 kHz were extrapolated using the shipping source spectrum model of (Breeding et al. 1994).

Table 2-2   Vessel Source Level Data Sources by Vessel Category. Modelled Source Depth is the Nominal Acoustic Source Depth for Use with the Acoustic Transmission Loss Model

Vessel Category	Modelled Source Depth (m)	Data Sources
1	6	Hemmera et al. (2014), McKenna et al. (2012), JASCO (2014b)
2	6	Hemmera et al. (2014), McKenna et al. (2012), JASCO (2014b)
3	6	Hemmera et al. (2014), McKenna et al. (2012), JASCO (2014b)
4	6	Hemmera et al. (2014), Cybulski (1977), McKenna et al. (2012)
5	2	Hemmera et al. (2014), JASCO (2014b)
6	2	JASCO (2012)

Vessel Category	Modelled Source Depth (m)	Data Sources
7	6	Hemmera et al. (2014), Arveson and Vendittis (2000), MCR International (2011), McKenna et al. (2012)
8	6	
9	6	Hemmera et al. (2014), NAVSEA Warfare Center Carderock Division (2004a), NAVSEA Warfare Centers Carderock Division (2004b)
10	2	Austin et al. (2013)
11	2	Hemmera et al. (2014)
12	2	Kipple and Gabriele (2003), Zykov et al. (2008)
13	2	

The same SLs were applied for all three container ship categories (1 to 3) because TWMBR SLs for these categories are nearly identical and published measurements indicate that SLs for merchant ships correlate more strongly with ship category than with vessel size (Scrimger and Heitmeyer 1991); however, a 1.67 dB adjustment was applied to category 1 SLs for future scenarios S2 and S4 as a conservative assumption to account for anticipated increases in the size of container ships calling on RBT2 (approximately 21% greater LOA; Equation 1 below).

SLs for ferries (category 6) were calculated from acoustic measurements of two B.C. Ferries vessels taken at Roberts Bank (JASCO 2012). SLs in 1/3-octave bands from 10 Hz to 50 kHz were computed from calibrated acoustic recordings and AIS position logs of M/V *Queen of Alberni* and M/V *Coastal Inspiration*, following the methodology described in JASCO (2014b). SLs from these two vessels were averaged to obtain a representative SL for ferry traffic transiting in the study area.

Low-frequency SLs for vessels with LOA 25 to 50 m (category 11) could not be obtained from the published literature; therefore, SLs below 50 Hz for this category were taken to be the average value of the TWMBR 1/3-octave band SLs from 50 Hz to 100 Hz.

SLs for vessels smaller than 10 m LOA (category 13) were obtained from two studies of small watercrafts at: 1) Glacier Bay National Park and Preserve (Kipple and Gabriele 2003); and 2) and Alaskan Beaufort Sea (Zykov et al. 2008). An extensive literature review did not identify any SL measurements for vessels 10 to 25 m LOA (category 12); therefore, SLs for this category were calculated from the category 13 SLs by adding a 7.5 dB length correction factor, based on an assumed second-power law dependence of radiated sound power on ship length (Ross 1976):

$$SL_{12} = SL_{13} + 20 \times \log_{10}(l_{12}/l_{13}) \qquad (1)$$

In this equation, l_{12} was the effective length of category 12 vessel (i.e., equal to 18.5 m), and l_{13} was the effective length of category 13 vessels (i.e., equal to 7.8 m. The effective lengths were calculated from the minimum and maximum reported vessel lengths (**Table 2-1**), where more weight was given to larger vessels, which have higher SLs.

SLs for all vessel categories were adjusted to a common reference speed v_{ref} of 10 knots (**Figure A-2**) according to an assumed sixth-power law dependence of radiated sound power on ship speed (Ross 1976):

$$SL_{ref} = SL_{\bar{v}} + 60 \times \log_{10} v_{ref} / \bar{v} \tag{2}$$

In this equation, the reference source levels SL_{ref} were determined from the mean source levels $SL_{\bar{v}}$ according to the mean speed $\bar{v}$ of the underlying measurements. Given the reference SLs for each vessel category, the sixth-power law of Equation 2 was then used to compute SLs of vessels in the model according to their transit speed (**Section 2.1.7**). For modelling TL (**Section 2.1.8**), the source depth for ship categories with LOA greater than 100 m was assumed to be 6 m and the source depth for other ship categories was 2 m.

2.1.5   Environmental Parameters

Seasonal changes of water temperature and salinity profiles with depth influence the corresponding sound speed profile. The nature of the sound speed profile can have a large effect on TL in the ocean. Water column sound speed profiles for the study area for January and July were computed from historical temperature and salinity data obtained from Fisheries and Oceans Canada (DFO) Institute of Ocean Sciences (Patricia Bay) Ocean Sciences Division. Monthly average sound speed profiles were computed from approximately 120 historical temperature-salinity casts for January and July, collected from 2006 to 2010 (**Figure A-3**). 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):

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

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, whereas wind-driven mixing in winter combined with atmospheric cooling 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.

The geoacoustic properties of the seabed strongly influence TL 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 TL measurements (JASCO 2014b) and a review of the scientific literature (Hamilton 1980, Erbe et al. 2012). To account for geographic variation inside the study area, the study area was divided into four geoacoustic regions based on bottom type: Strait of Georgia, Haro Strait, East Strait of Juan de Fuca, and West Strait of Juan de Fuca (**Figure A-4**). A different set of geoacoustic properties was used to represent each region (**Table 2-3**).

Table 2-3   Seabed Geoacoustic Profiles for the Four Geoacoustic Regions

Depth (mbsf)	Sediment Type	Compressional Speed (m/s)	Density (g/cm^3)	Compressional Attenuation (dB/λ)	Shear Speed (m/s)	Shear Attenuation (dB/λ)
Strait of Georgia						
0-100	clayey-silt	1,502-1,602	1.54	0.61	125.0	2.2
> 100	bedrock	2,275	1.90	0.10		
Haro Strait and Rosario Strait						
0-50	sand-silt-clay	1,541-1,591	1.80	0.72	250	1.2
> 50	bedrock	2,275	1.90	0.10		
East Strait of Juan de Fuca						
0-50	silt	1,558-1,608	1.64	0.83	250	3.4
> 50	bedrock	2,275	1.90	0.10		
West Strait of Juan de Fuca						
0-50	sand	1,713-1,763	1.94	0.90	500	3.4
> 50	bedrock	2,275	2.20	0.10		

Bathymetry inside the study-area was modelled on a 20 m resolution BC Albers grid (**Figure A-5**), and compiled from the following three sources:

1. Data south of latitude 49⁰N were obtained from the NOAA digital elevation model (NGDC 2013);

2. Data north of latitude 49⁰N were data obtained from a Canadian Hydrographic Service (CHS) digital elevation map from Nautical Data International Inc. (NDI); and

3. High-resolution (10 m) bathymetry data within several kilometres of the Roberts Bank terminals were provided to JASCO by Hemmera.

2.1.6   Ambient Noise

Ambient noise in shallow water, in the absence of vessel traffic, is dominated by wind-driven surface noise at all frequencies (Urick 1984). The spectrum of wind-generated ambient noise in the study area was estimated from measurements collected by JASCO in the Strait of Georgia and Haro Strait from July

through September 2012 (JASCO 2014b). 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 to obtain a representative spectrum for wind-generated noise for the study area (**Figure A-6**). To investigate the seasonal dependence of wind-generated noise, historical wind speed data in the study area were analysed from marine weather buoys in the Strait of Georgia (Station 46146–Halibut Bank, Environment Canada) and the Strait of Juan de Fuca (Station 46088–New Dungeness, NOAA). Average monthly wind speeds in the study area for January and July from 2009 through 2013 were 5.4 m/s and 5.0 m/s, respectively. Given the small difference (8%) between the mean wind speeds in January and July, mean measured spectrum was assumed sufficient to represent wind-generated ambient noise in the model for both months.

2.1.7   Vessel Density and Speed Data

Monthly maps of vessel traffic density were computed by MARIN, based the VTOSS dataset for January and July 2010. Monthly data for all 13 vessel categories were provided on a 424,053 km^2 grid in BC Albers projection. Each 200 × 200 m grid cell in the traffic density maps included the following information:

- Cumulative time occupied by vessels in a specific category;
- Average speed of vessels in a specific category; and
- Total number of vessel movements in a specific category.

The grids of cumulative time and average speed for January and July were rebinned to 800 m resolution inside the modelling boundary for input to the cumulative noise exposure model.

The four modelled vessel traffic scenarios (S1, S2, S3, S4) were simulated by overlaying additional traffic on the VTOSS 2010 dataset based on future traffic predictions in HEC (2014). For each scenario, MARIN provided maps containing the yearly number of additional vessel movements per cell (positive or negative) for each vessel category. To obtain the additional yearly traffic density for each scenario, grids of cumulative time (D) and speed (V) were computed from the number of movements (NT) in VTOSS. The overlay grids for the model scenarios were computed according to the following procedure:

1. If the number of VTOSS movements for a given cell was greater than zero ($NT_{VTOSS} > 0$) then,

    i.   The additional vessel time was set equal to the ratio of the additional number of movements to the number of VTOSS movements in the same cell ($D_S = D_{VTOSS} \times NT_S / NT_{VTOSS}$).

    ii. The vessel speed was set equal to the VTOSS speed in the same cell ($V_S = V_{VTOSS}$); and

2. If the number of VTOSS movements for a given cell was equal to zero ($NT_{VTOSS} = 0$) then,

    i.   An adjacent VTOSS cell was selected according to the median speed of the 50 closest nonempty cells.

    ii. The additional vessel time and vessel speed were computed from the selected VTOSS cell according to the procedure above.

Yearly cumulative vessel time per cell was divided by 12 to yield monthly average values. The monthly overlay cell grids for each scenario were then rebinned to 800 m resolution and combined with the VTOSS grids to yield cumulative time (**Figure A-7**) and average speed (**Figure A-8**) for input to the cumulative noise exposure model.

Because the VTOSS database was compiled from multiple data sources (i.e., AIS, radar, manual position reports, and dead reckoning) with heterogeneous spatial and temporal coverage, vessel tracking data from VTOSS contain temporal gaps, some inconsistent ship tracks, and outlier values. Special filtering was applied to the VTOSS data to remove artefacts (e.g., outlier speed values and misclassified vessels) that would negatively affect the accuracy of the cumulative model predictions.

For the future scenarios (S2 to S4), a special layer was added to the vessel density data specifically to account for the noise contribution of berthing operations at RBT2. For each additional category 1 container ship berthing at RBT2, 30 minutes of activity from three berthing tugs and a line boat was added to the model (including 5 minute ramp-up and 5 minute decay) at a fixed point directly offshore from the RBT2 berth face. For each additional category 2 or 3 container ship berthing at RBT2, 30 minutes of activity from two berthing tugs was added to the model. SLs for berthing tugs were identical to those used in JASCO (2014a).

2.1.8 Transmission Loss Model

Acoustic TL represents the reduction of sound level as sounds propagate from a source to a receiver. TL was calculated using JASCO's Marine Operations Noise Model (MONM). MONM computes acoustic propagation via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for elastic seabed properties (Zhang and Tindle 1995). The **parabolic equation method** has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). MONM incorporates the following site-specific environmental properties: a bathymetric grid of the modelled area; underwater sound speed as a function of depth; and a geoacoustic profile based on the overall stratified composition of the seafloor. Past measurements obtained during a dedicated TL study (JASCO 2014b) were used to validate MONM predictions for the study area.

The study area was divided into 20 zones (**Figure A-9**) based on four unique geoacoustic regions (**Table 2-3**) and five water depth ranges (**Table 2-4**). 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 75 km from the source (**Figure A-10**). TL for each zone was modelled assuming uniform bathymetry (i.e., range-independent water depth) for a receiver depth of 10 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 (see **Section 2.1.5**), and two source depths, representing the nominal acoustic emission centres of small and large draft vessels (see **Table 2-1**).

Table 2-4   Description of Zone Numbers and Corresponding Geoacoustics and Water Depths. Geoacoustic Properties of Each Region are Listed in Table 2-3.

Zone Number	Water Depth Range (m)	Modelled Water Depth (m)	Geoacoustic Region
1	0-50	25	Strait of Georgia
2	0-50	25	Haro Strait and Rosario Strait
3	0-50	25	East Strait of Juan de Fuca
4	0-50	25	West Strait of Juan de Fuca
5	50-100	75	Strait of Georgia
6	50-100	75	Haro Strait and Rosario Strait
7	50-100	75	East Strait of Juan de Fuca
8	50-100	75	West Strait of Juan de Fuca
9	100-150	125	Strait of Georgia
10	100-150	125	Haro Strait and Rosario Strait
11	100-150	125	East Strait of Juan de Fuca
12	100-150	125	West Strait of Juan de Fuca
13	150-200	175	Strait of Georgia
14	150-200	175	Haro Strait and Rosario Strait
15	150-200	175	East Strait of Juan de Fuca
16	150-200	175	West Strait of Juan de Fuca
17	> 200	225	Strait of Georgia
18	> 200	225	Haro Strait and Rosario Strait
19	> 200	225	East Strait of Juan de Fuca
20	> 200	225	West Strait of Juan de Fuca

2.1.9   Noise Model

Maps of monthly commercial vessel traffic noise were modelled for four vessel traffic scenarios (S1, S2, S3, S4), based on the vessel density data (**Section 2.1.7**), the vessel SL data (**Section 2.1.4**), the tabulated TL versus range curves (**Section 2.1.8**), and the wind-driven ambient noise curves (**Section 2.1.6**). The study area was represented on a 208 × 184 km BC Albers grid, where acoustic sources and receivers were assumed to be at the centre of each 800 × 800 m grid cell. The 1/3-octave band SEL in each map cell was computed as the total vessel 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 received at some location over a specific time duration, and 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 category 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:

$$TL_{ij} = -10\log_{10}\sum_{n}10^{-TL^{(n)}(r_{ij})/10} \times d_{n}/r_{ij}$$

(4)

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

$$TL_{ii} = 10\log_{10}(4\pi/D^2) = 20\log_{10}D - 11$$

(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 categories and adjusted for vessel speed and cumulative vessel category time in each source cell:

$$E_{ij} = \sum_k 10^{(SL_k - TL_{ij})/10} \times \left(\frac{v_k}{v_{ref}}\right)^6 \times T_k$$

(6)

In the above equation, the SL for each vessel category *k* is computed by adjusting the reference source level SL_k for speed v_k according to the sixth-power law (see Equation 2). The source energy is then computed by multiplying the source power by the cumulative time T_k that vessels from category *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:

$$SEL_j = 10\log_{10}\left[T_{mon} \times 10^{AN/10} + \sum_j E_j\right]$$

(7)

In the above equation, T_{mon} is the number of seconds in the month and *AN* is the SPL of the wind-driven ambient noise. The mean monthly 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., Leq = SEL - 10 × $\log_{10}(T_{mon})$).

2.1.10 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 (i.e., 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 likely inaudible to those animals. Higher dB re HT values represent greater auditory sensation levels (i.e., greater perceived loudness). While specific dB re HT thresholds are not related to behavioral or injury effects in this study, audiogram-weighted levels can be used to compare different sounds in terms of species-specific hearing ability.

In this study, audiogram weighting was applied for resident killer whales (**Figure A-11**) 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. Modelled dB re HT values from this study provide a quantitative measure of where and when sound levels are highest, relative to the hearing ability of resident killer whales.

2.2   RESULTS OF CUMULATIVE UNDERWATER NOISE EXPOSURE STUDY

Eight maps of cumulative commercial vessel traffic noise were produced for the study area (**Figure A-12 to Figure A-19**), based on January and July vessel traffic density data for each of the four model scenarios (S1, S2, S3, S4). An additional eight audiogram-weighted commercial vessel traffic noise maps were produced (**Figure A-20 to Figure A-27**), showing the corresponding sound levels above the resident killer whale hearing threshold. The linear mean and interquartile range (IQR) sound levels were computed over the entire cumulative study area and within 4 km of the inbound and outbound Roberts Bank transit routes (from Roberts Bank in the international shipping lanes to the entrance of Strait of Juan de Fuca) (**Table 2-5**).

Table 2-5   Linear Mean and Interquartile Range (IQR) of Shipping Noise Levels over the Entire Cumulative Noise Study Area and within 4 km of Roberts Bank Transit Routes (from Roberts Bank in the international shipping lanes to the entrance of Strait of Juan de Fuca)

Scenario	Monthly Leq (dB re 1 μPa)				Audiogram-weighted Leq (dB re HT(KW))			
	January		July		January		July	
	Mean	IQR	Mean	IQR	Mean	IQR	Mean	IQR
Entire cumulative noise study area								
S1	122.14	11.41	117.54	19.04	64.22	13.67	61.40	12.08
S2	122.17	11.40	117.56	19.07	64.23	13.74	61.41	12.14
S3	122.20	11.47	117.59	19.14	64.25	13.80	61.43	12.22
S4	122.22	11.45	117.60	19.17	64.26	13.84	61.44	12.24
Within 4 km of Roberts Bank transit routes								
S1	121.75	2.31	119.32	4.18	62.25	4.13	61.26	5.66
S2	121.85	2.27	119.39	4.17	62.38	4.12	61.32	5.67
S3	121.91	2.27	119.42	4.16	62.42	4.15	61.35	5.69
S4	122.00	2.25	119.48	4.18	62.53	4.16	61.40	5.72

Brightly-coloured regions on the noise maps generally correspond to locations with high densities of commercial vessel traffic, such as shipping lanes and ferry routes. Ferry routes (category 6) are the most prominent features on the cumulative noise maps, due to the large number of vessel movements concentrated in relatively small areas. Shipping lanes are also clearly visible in the noise maps along corridors where commercial vessel traffic (categories 1 to 4, 7 to 8) is concentrated. On the audiogram-weighted maps, commercial vessel traffic noise decays more rapidly around ferry routes and shipping lanes 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 (**Figure A-10**). Nonetheless, increases in audiogram-weighted sound levels due to increased vessel traffic are similar to increases in unweighted levels.

2.3   SUMMARY OF CUMULATIVE UNDERWATER NOISE EXPOSURE STUDY

The noise maps show the modelled spatial distribution of underwater noise originating from commercial vessel traffic throughout the study area. While VTOSS provides the best-available data on vessel traffic density in the RSA, coverage of small vessels is incomplete because they are not required to report to Marine Communications and Traffic Services. Because SLs of smaller boats are lower than those of larger vessels, errors introduced by neglecting smaller vessels from the model estimates are expected to be spatially isolated to areas where small vessels congregate.

Differences between the monthly noise maps in January and July are much greater than differences between the four considered scenarios. Except along seasonal ferry routes, sound levels are generally higher in January than in July (**Figure A-28**), which is attributed mainly to differences in the sound speed profiles of the water column between these months (**Figure A-3**), rather than to changes in vessel traffic density. In winter, the temperature gradient in the thermocline layer (i.e., less than 50 m depth) has a very strong effect on sound transmission. In January, low water temperatures near the sea surface create a surface duct that concentrates sound energy in the thermocline, whereas in July, higher temperatures create a down-refracting 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 combine with the down-refracting sound speed profile in July to increase the rate of TL relative to January conditions. As a result, commercial vessel traffic 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 (i.e., the seasonal change in TL is expected to be smaller for deeper receiver depths, below the thermocline). Many marine mammals spend substantial time at depths less than 10 m; therefore, differences in sound levels in the near-surface waters between summer and winter can be important.

For all future-case scenarios, the overall increase in cumulative commercial vessel traffic noise levels from future developments is small (< 2 dB) relative to existing conditions (**Figure A-28**), which is due to the large amount of pre-existing vessel traffic in the study area. In the future scenarios, higher noise levels are concentrated primarily along main shipping routes, with increases predicted to be slightly greater in winter than in summer due to seasonal sound propagation effects discussed above. Even along the international shipping lanes, the greatest increase in existing noise levels is predicted to be 0.25 dB in winter and 0.16 dB in summer for S4 (**Table 2-6**). The contribution of Project-related traffic to existing and forecasted underwater noise levels is expected to be relatively small, primarily because existing commercial vessel traffic noise in the study area is already quite high, as other studies have established (Erbe et al. 2012).

Table 2-6   Increase above Existing (S1) of Monthly Mean Cumulative Commercial Vessel Traffic Noise Levels for Future Scenarios (S2, S3, S4)

Scenario	Monthly mean Leq Increase above Existing Conditions (dB)	
	January	July
Entire cumulative noise study area		
S2	0.03	0.02
S3	0.06	0.05
S4	0.08	0.06
Within 4 km of Roberts Bank transit routes		
S2	0.10	0.07
S3	0.16	0.10
S4	0.25	0.16

3.0   FOCUSED DAILY TEMPORAL NOISE EXPOSURE STUDY

3.1   METHODS

3.1.1   Overview and Scenarios

The SRKW population uses habitat near the primary shipping routes of vessels that visit the Project area. The results of the cumulative study, given in previous sections of this report, are useful for evaluating the long-term sound emissions from vessel traffic that accumulate in key areas, but they do not provide detailed characterisation of the instantaneous sound levels and variation in sound levels that occur due to transit by individual and multiple vessels. The focused study was designed to complement the cumulative study by producing higher-resolution sound fields on a finer temporal scale. Specifically, the additional outputs of this study were as follows:

- Temporal snapshots of sound pressure levels (SPL) in 1-minute steps through an actual day based on individual vessel tracks recorded by the VTOSS system; and

- Higher spatial resolution (200 x 200 m cells) over a reduced area (**Figure A-1**) that covers areas of high use by SRKW that overlap with international shipping lanes.

As with the cumulative study, this focused study examined four scenarios (see **Section 2.1.1**). The existing conditions scenario was developed from actual VTOSS vessel tracks from two 24-hour periods in January and July 2010, adjusted for 2012 traffic levels. The three future scenarios were prepared by adding simulated vessel tracks to the existing conditions case data to represent the passage of additional traffic. Sound levels for each 1-minute snapshot were predicted using the same gridded vessel noise propagation model used for the cumulative study, but on a finer spatial scale.

3.1.2   Modelling Approach

The focused model computed broadband SPL (10 Hz to 63 kHz) and resident killer whale audiogram-weighted SPLs (**Section 2.1.10**) of vessels for each minute over two 24-hour periods: one in January; one in July. The modelled area was represented on a 130 × 150 km BC Albers grid, where acoustic sources and receivers were assumed to be at the centre of each 200 × 200 m grid cell. SLs were assigned to each vessel according to procedure described in **Section 2.1.4**, with a speed-based correction applied based on the sixth-power law of Equation 2 (Ross 1976). Vessels were assigned to grid cells based on their time-interpolated coordinates from the track data. For every minute of the simulation, sound propagation between all source and receiver cells was computed according to the same method used for the cumulative model (see **Section 2.1.9**). Aggregate SPL in all grid cells was computed from the superimposed sound field of all vessels in the simulation. The output of the model was the time-dependent 1/3-octave band SPL, computed at 10 m receiver depth for every point on the model grid, for each 1-minute interval.

3.1.3   Existing Conditions VTOSS Track Data

Existing conditions vessel tracks for the 24-hour simulations were selected from 22 days of raw track data extracted from the VTOSS database (**Table 3-1**) provided by the MARIN. The raw VTOSS tracks were collected from January 10 to 20, 2010 and July 10 to 20, 2010. To ensure the existing conditions scenario was conservative, two dates were selected from the raw tracks according to the following criteria:

- The selected days contain a large number of vessels from a variety of vessel categories;

- The selected days have minimum missing data; and

- The selected days fall on a typical working day (Monday to Friday).

The two dates selected were Tuesday 19 Jan 2010 and Friday 16 July 2010 (**Figure A-29**).

The 24-hour track data from the selected dates were extracted from the database. Vessel positions were sampled for every 1-minute interval along the tracks. Any single track with a gap greater than 10 minutes was split into two separate tracks. Because a detailed review of the raw track data showed that many tracks had inconsistent position reports, where vessels jumped over unrealistically long distances or even over land, some position reports were manually removed. An anomalous oscillation was also found in the raw vessel speeds with a period of 11 minutes and an approximate magnitude of ± 1 m/s. The source of this artifact in the VTOSS data is unknown, but was assumed to be artificial. To remove this artifact, an 11-point median filter was applied to all vessel speeds exceeding 2 m/s. Several U.S. ferries were also misclassified in the raw data and were manually reassigned to category 6. Application of these post-processing steps to the VTOSS data removed most of the critical artefacts; however, missing track segments in the raw data could not be recovered, so several broken and incomplete tracks remained in the baseline data. These missing segments are an intrinsic limitation of the VTOSS dataset.

The 2010 VTOSS data were adjusted to 2012 traffic levels by comparing total calls between these two years. The total number of coal carrier calls at Westshore Terminals increased in 2012; therefore, one additional category 7 vessel was added to the July simulation. The additional coal carrier was added to the existing conditions by duplicating an existing category 7 track at Westshore Terminals from January in the July data. No additional adjustments were deemed necessary to bring the selected VTOSS data up to 2012 traffic levels.

Table 3-1   Summary of Raw Daily 2010 VTOSS Vessel Track Data (midnight to midnight, local time). Coloured Rows Indicate Days Selected for the Focused Model Baseline.

Date	Number of Position Reports	Vessel Categories Present	Percent Unclassified	Approximate Missing Data (minutes)
January				
10	13,285	1-11	0	none
11	13,285	2-12	0	none
12	24,239	2-13	0.01	45
13	31,632	1-13	0.85	60
14	24,562	2-13	0	100
15	27,058	1-12	0	250
16	28,829	2-12	0.52	15
17	23,861	1-12	1.45	120
18	27,375	2-13	0.79	10
19	30,108	2-13	0.07	15
20	34,546	2-12	0.38	60
July				
10	33,604	2-12	0	none
11	32,291	1-12	0	none
12	38,721	1-12	0.03	none
13	42,162	1-12	0.21	none
14	36,560	1-12	0.27	none
15	39,724	2-12	0.36	none
16	43,707	1-12	0.62	none
17	38,100	1-12	0.04	90
18	36,524	1-13	0.21	90
19	27,923	1-12	0.34%	180
20	36,945	1-12	0.97	none

3.1.4   Simulation of Future Scenario Vessel Tracks

For the future scenarios considered in this study, numerous combinations of vessels and routes are possible in any 24-hour period. The objective of the current study was to base the 24-hour simulations on combinations of vessels that represented a conservative level of noise emissions. To accomplish this goal, possible combinations of vessels movements were analysed in terms of their overall sound emissions, which depends on the number of vessels from different categories transiting through the study area. To derive a conservative estimate, a combination of vessels representing the 90th percentile of additional commercial vessel traffic noise emissions was selected to represent each future scenario.

Probabilistic simulations were used to generate the combinations of new vessel movements for the future scenarios. The MARIN vessel traffic projections for 2030 were used to estimate the mean time between calls for each route and vessel category, averaged over a year. The daily number of additional vessel movements, assumed equal to twice the number of calls, was then simulated as a Poisson process. To obtain a large sample, which would increase the accuracy of resultant statistics, 1,000 days were randomly simulated for each scenario (S2, S3, S4). Each simulated day was ranked according to the total noise power emitted by all transiting vessels (i.e., the weighting was equal to the total SL of all vessels) (**Figure A-30**). Routes with negative numbers of movements, representing a reduction in vessel traffic, were assigned a negative SL weighting. Cherry Point traffic (S3 and S4 only) was treated as a special case because there are two possible routes available. Cherry Point traffic was always simulated with three movements per day, with each trip having a 5% probability of transiting through Haro Strait. Because the two routes were not independent, only the Haro Strait movements from Cherry Point, which transit through areas of high use by SRKW, were included in the rankings. The number of movements in the simulations did not strictly increase with ranking because different ship types in the simulation have different SLs (e.g., a large container ship can radiate more noise than several smaller vessels) (**Figure A-31**). Nonetheless, the overall trend was to add about 1.7 vessels per quartile in the probabilistic simulation.

The 90th percentile from the probabilistic simulations was used to represent 24 hours of new traffic for each of the future scenarios (**Table 3-2**). Additional movements for the future scenarios were simulated by adding synthetic vessel tracks to the existing conditions data along the routes specified by the MARIN (**Figure A-32**). Vessel speeds along the routes were sampled from the vessel density database (**Section 2.1.7**) by taking the median speed of the nearest 50 cells for the corresponding vessel category. The sampled speeds were then manually adjusted so that the simulated vessels moved with constant speed along the different route segments. Start times for the synthetic vessel tracks were randomised, and movements were evenly split between inbound and outbound routes. Thirty minutes of activity for three berthing tugs and a line boat was also added to inbound category 1 movements for scenarios S2 and S4 to account for the noise contribution of berthing operations at RBT2. SPLs for the additional vessels were modelled separately and, afterwards, superimposed on top of the existing conditions simulations to generate results for the future scenarios.

Table 3-2   Additional Vessel Movements Added to the Existing Conditions (S1) Track Data Representing the 90th Percentile of Commercial Vessel Traffic Noise Emissions for the Future Scenarios (S2, S3, S4)

Category	Routes	S2	S3	S4
1	Inbound and outbound from Roberts Bank to the Strait of Juan de Fuca in the international shipping lanes	2‡	1	2‡
2	Inbound and outbound from Roberts Bank to the entrance of Strait of Juan de Fuca in the international shipping lanes	1	0	1
3	Inbound and outbound from Roberts Bank to the Strait of Juan de Fuca in the international shipping lanes	0	0	0
7	Inbound and outbound from Roberts Bank to the Strait of Juan de Fuca in the international shipping lanes	0	0	0
8	Inbound and outbound from Roberts Bank to the Strait of Juan de Fuca in the international shipping lanes	2	3	3
4	Asia to Vancouver, then back towards Asia or up the West Coast of U.S.A. to Vancouver, then back down the West Coast of U.S.A.	0	3	3
7	Asia to Vancouver, then back towards Asia or up the West Coast of U.S.A. to Vancouver, then back down the West Coast of U.S.A.	0	1	0
8	Asia to Vancouver, then back towards Asia or up the West Coast of U.S.A. to Vancouver, then back down the West Coast of U.S.A.	1	1	1
7	Asia to Gateway Pacific Terminal, then back to Asia	0	2	2
7	Asia to Gateway Pacific Terminal, then back to Asia	0	0	0
8	Asia to the Fraser River, then back towards Asia or up the West Coast of U.S.A to the Fraser River, then back down the West Coast of U.S.A	0	0	0
1	Asia to Seattle or Tacoma, then to Vancouver, then back towards Asia	0	0	0
3	Asia to Seattle or Tacoma, then to Vancouver, then back towards Asia	0	0	0
1	Asia to Vancouver, then to Seattle or Tacoma, then back towards Asia or up the West Coast of U.S.A. to Vancouver, then to Seattle or Tacoma, then back down the West Coast of U.S.A	0	0	0
3	Asia to Vancouver, then to Seattle or Tacoma, then back towards Asia or up the West Coast to Vancouver, then to Seattle or Tacoma, then back down the West Coast of U.S.A	0	0	0
7	Asia to Texada Island, then back towards Asia	0	0	0
5	Mouth of the Fraser River to Texada Island (for towed coal barges)	0	3	3
	Total additional movements	**6**	**14**	**15**

---

‡   Category 1 source levels for S2 and S4 were adjusted by 1.67 dB to account for increased size of container ships using RBT2. Noise from berthing tugs was added for 30 minutes to the inbound movements, to simulate berthing of the container ships at RBT2.

3.2 RESULTS OF FOCUSED DAILY NOISE EXPOSURE STUDY

Eight sets of 24-hour SPL grids were generated using the focused daily model (January and July for four scenarios), which represented 1-minute snapshots of vessel traffic noise in 1/3-octave bands over a single day. The snapshots of broadband SPLs and resident killer whale audiogram-weighted levels from the focused model simulations were rendered as animations to show the time evolution of the commercial vessel traffic noise field in the study area (example frames shown in **Figure A-33** and **Figure A-34**). Digital files of broadband and 1/3-octave band SPLs from the focused model were used in further modelling of potential effects on SRKW (see SMRU 2014a and b).

Four receiver locations were selected inside the focused daily study area for detailed analysis of 24-hour simulation data (**Figure A-35**). Received levels versus time were plotted for these four receiver locations, in terms of broadband SPL (**Figure A-36** and **Figure A-37**) and resident killer whale audiogram-weighted SPL (**Figure A-38 and Figure A-39**). Note that the gap near 00:45 UTC in the January baseline data is due to approximately 15 minutes of missing data in the VTOSS tracks. Peaks in the received level plots correspond to individual vessel passes in the data. The plateau at location 1 shortly after 18:00 UTC originates from berthing operations at the terminal. Because all four scenarios are based on the same existing conditions ship track data, differences between scenarios are exclusively due to additional vessels in the simulations.

Histogram plots, generated from the 1-minute data at the four receiver locations, show the distribution of received levels in terms of broadband SPL (**Figure A-40** and **Figure A-41**) and audiogram-weighted SPL (**Figure A-42** and **Figure A-43**). Mean received levels (i.e., 24-hour Leq) were also computed at each location (**Table 3-3**). The data show that the greatest overall noise level increase above existing conditions (~4.5 dB) is at Roberts Bank (location 1) for S2 and S4, which is primarily attributable to noise from container ship berthing. Noise levels for all the future scenarios increased to a lesser degree in Haro Strait (location 2) and Boundary Pass (location 3), along the main traffic routes. There is little change between scenarios at Active Pass (location 4) due to the predominance of ferry traffic noise at this location over all other noise sources.

Table 3-3   Mean SPL (24-hour Leq) at Four Receiver Locations in the Focused Daily Study Area for January and July

Scenario	Mean SPL (dB re 1 µPa)							
	Location 1 Roberts Bank		Location 2 Haro Strait		Location 3 Boundary Pass		Location 4 Active Pass	
	Jan	Jul	Jan	Jul	Jan	Jul	Jan	Jul
S1	125.69	117.14	118.54	120.08	122.61	125.92	127.29	123.49
S2	130.13	123.98	119.49	120.35	123.36	126.13	127.35	123.49
S3	125.70	117.14	119.16	120.20	123.06	126.03	127.27	123.49
S4	130.15	123.98	119.70	120.39	123.55	126.16	127.37	123.49

3.3   SUMMARY OF FOCUSED DAILY NOISE EXPOSURE STUDY

The results of the focused daily model are intended to evaluate time-dependent disturbance and masking effects of commercial vessel traffic noise on marine mammals. Because the SPL grids were generated in 1/3-octave bands over a very wide frequency range, they can be used to investigate effects of commercial vessel traffic noise on different species of marine mammals and fish. For example, while audiogram-weighted levels are applicable specifically to SRKWs, unweighted received levels are more appropriate for assessing commercial vessel traffic noise effects on baleen whales due to their sensitivity to most of the range of sound frequencies produced by vessels.

The VTOSS database includes no classification type for commercial whale watching boats. Furthermore, while VTOSS provides the best-available data on vessel movements in the RSA, small boat traffic is underrepresented in the study area. Therefore certain kinds of exposures that may be important to mammals, like commercial whale-watching boats, may be incompletely captured in the focused daily model results. However, even with inclusion of these small vessels, the relative difference in underwater noise levels between scenarios would remain the same.

The focused model predictions exhibit a strong seasonal effect, where vessel noise propagates considerably farther in January than in July, due to the winter surface duct in the study area. This is consistent with the findings of the cumulative monthly study (**Section 2.3**). Seasonal effects are more difficult to assess in the focused daily model than in the cumulative monthly model, because long-term trends in commercial vessel traffic patterns are not averaged over the 24-hour simulation period. The limited time sampling of the focused daily model, which is necessary for achieving high temporal and spatial fidelity in the simulations, is important to consider when interpreting the results of this study.

4.0   KEY FINDINGS

This section discusses the major results arising from the Regional Commercial Vessel Traffic Underwater Noise Exposure Study and data gaps.

4.1   DISCUSSION OF KEY FINDINGS

Commercial vessel traffic noise inside the regional study area (RSA) was characterised over long-term (monthly) and short-term (daily) scales inside high use SRKW habitat areas, using sophisticated acoustic models in combination with historical ship traffic data. The high spatial and temporal fidelity of the models permits habitat-level assessment of commercial vessel traffic noise effects on marine organisms throughout the study area. The study captured seasonal variations in vessel traffic and sound propagation conditions by considering winter (January) and summer (July) months separately. Three detailed future scenarios were considered to assess changes in underwater noise from RBT2, incremental vessel traffic associated with RBT2, and other certain and foreseeable projects, relative to existing conditions within the study area. Because S2 included future incremental vessel traffic in 2030 associated not only with RBT2 but also with Deltaport Terminal, Road, and Rail Improvement Project (DTRRIP) vessel activity, and other predicted changes in vessel traffic from 2012 to 2030 without any other new projects, for a total of 363 additional vessels (see HEC 2014) - it can be considered a conservative assessment of the changes in underwater noise associated with RBT2 which contributes an additional 260 ship movements.

A key finding of the present study is that foreseen increases in ship traffic are expected to make a relatively small contribution to overall commercial vessel traffic noise levels in the RSA, due to the high density of pre-existing traffic in the study area. In the regional monthly cumulative study, additional traffic in S2 increased mean existing noise levels by less than 0.1 dB near the international shipping lanes, with a maximum localised increase of approximately 0.6 dB within 800 m x 800 m grid cells at specific locations in Haro Strait and the Strait of Juan de Fuca. Increases in commercial vessel traffic noise associated with RBT2 were predicted to be comparable to those from other planned developments within the study area (S3). When all future certain and foreseeable projects (S4) were considered, the mean increase from existing conditions was less than 0.3 dB within 4 km of the shipping routes, with maximum localised increases of approximately 0.9 dB. The relatively small contribution of future developments relative to existing noise levels does not imply that their effects are benign. Under scenario S4, over 1,300 large merchant ship calls will be added to the study area on a yearly basis. The prediction that these additional ship calls will increase existing noise levels by a small amount reflects the high density of existing vessel traffic within the study area and the already-dominant contribution of ship noise to the underwater soundscape.

Modelled noise levels were weighted according to the resident killer whale audiogram, to see whether this would affect the study findings. While average noise levels in the regional study area were well above the resident killer whale hearing threshold (61.3–64.3 dB re HT), the audiogram-weighted contribution of increased vessel traffic was not appreciably different (i.e., less than 0.3 dB overall) from the unweighted contribution. Thus the key findings of this study were essentially the same, regardless of whether the hearing abilities of resident killer whales were taken into account.

Another key finding is that seasonal differences in commercial vessel traffic noise levels in the study area are driven primarily by seasonally-variable sound propagation conditions rather than by vessel traffic. Mean noise levels over the entire study area were predicted to be 4.6 dB higher in January, despite greater traffic density in the study area in July, due to seasonal sound propagation effects. The seasonal propagation effect was less pronounced at locations close to high traffic density, since the surface duct has less influence on short-range sound propagation (i.e., within 4 km of shipping routes, average January noise levels were predicted to be only 2.5 dB higher than in July). It is important to note that the seasonal propagation effect is expected to be more prominent at the 10 m receiver depth considered in this study than at deeper depths. That receiver depth was chosen to represent a common exposure depth for SRKWs that spend much of their time near the surface. Animals below the thermocline (i.e., at depths greater than approximately 50 m) would likely experience a much smaller difference between seasonal sound levels.

4.2 DATA GAPS AND LIMITATIONS

The historical VTOSS database contains gaps that may underestimate ship density and consequently noise at some locations inside the study area. Small vessels (i.e., typically less than 20 to 30 m LOA), which are not required to check in with MCTS or transmit on AIS, were sparsely represented in VTOSS and, as a result, were incompletely captured in the vessel tracking database used in this study. SLs of small boats are relatively low, so errors introduced by neglecting their contribution to underwater noise is expected to be geographically limited to specific areas with high concentrations of small boats. As discussed in **Section 3.3**, omitting small craft noise, other than from whale watch vessels, likely does not result in an underestimation of the exposures of SRKW. Detailed examination of the raw track records from VTOSS also revealed other issues including time gaps, incomplete tracks, and misclassified vessels. Because errors of this kind tend to average out over time, these issues would have greater influence on the focused model results, which represent a single day of activity, than on the cumulative model results, which represent a monthly average.

This study considered only sound contributions from vessels and wind-driven ambient noise. Other potential sources of underwater noise such as biological sources, sonars, seismic activity, terminal operations, and aircraft were not included. These omissions are not expected to be important for the study purposes since commercial vessel traffic noise dominates over the entire study area (JASCO 2012, 2014b).

Accurate SL estimates are necessary for modelling commercial vessel traffic noise from large numbers of vessels. SLs for most types of vessels were captured in the TWMBR dataset from Lime Kiln, although gaps remained for certain vessel categories (6, 10, 11, and 13) and for certain frequency ranges (below 50 Hz and above 8 kHz). Data from past PMV studies were combined with best-available literature sources to supplement gaps in this dataset; however, some of the MARIN categories (notably 9 to 13) were very broad and available measurements were limited. In particular, category 10 (50 to 100 m LOA), was not covered by the TWMBR dataset and encompassed many different kinds of ships, including coast guard vessels, military vessels, roll-on-roll-off (RORO) ships, research ships, and fishing vessels, for which there are few available measurements. For this study, SLs of category 10 were derived principally from measurements of ocean-going support vessels 50 to 100 m LOA; however, it is unknown whether they broadly represent other category 10 vessels in the study area. Very few published measurements exist for vessels smaller than 25 m (categories 12 and 13), although VTOSS tracking data for those categories are limited. No SL data were identified for extremely large container ships (e.g., Maersk E-class and Triple-E-class, approximately 400 m LOA) that are capable of calling at RBT2. SLs for this category were estimated by adjusting levels from somewhat smaller container ships (up to 335 m). Consequently, category 1 SLs used in the current study may not accurately represent that traffic at RBT2.

Accurate model predictions of underwater sound propagation (characterised as TL) are necessary for estimating commercial vessel traffic noise on the spatial scales considered in the present study; therefore, considerable effort was made to validate the numerical acoustic models with ground-truth data (JASCO 2014b). The current study used numerical TL models capable of generating highly accurate predictions (Jensen et al. 2010), although their capabilities are limited by the fidelity of the environmental input data (i.e., bathymetry, water sound speed, and geoacoustics). High-resolution bathymetry data and good-quality historical sound speed profile data were available through most of the study area; however, seabed geoacoustics were more sparsely sampled. Geoacoustic profiles were derived primarily by inverting TL data acquired specifically for that purpose at three locations inside the study area (i.e., Roberts Bank, Haro Strait, and East Strait of Juan de Fuca). TL predictions are expected to be reliable close to the locations where TL measurements were taken, but the spatial extent of the study area is very large, so variability in seabed geoacoustics over regional scales may be poorly characterised. Nonetheless, a wide variety of seabed types were included in the model (i.e., silty clay to coarse sand) and broad-scale TL predictions are expected to represent the range of conditions that would be encountered in the study area.

5.0   CLOSURE

Major authors and reviewers of this technical data report are listed below, along with their signatures.

Report prepared by:
JASCO Applied Sciences

Alexander MacGillivray, M.Sc., Project Lead

Zizheng Li, M.Sc., Project Scientist

Graham Warner, B.Sc., Project Scientist

Caitlin O'Neill, B.Sc., Project Scientist

Report peer reviewed by:
Hemmera

Sonya Meier, M.Sc., R.P. Bio.,
Senior Biologist

6.0   REFERENCES

Arveson, P.T. and D.J. Vendittis. 2000. Radiated noise characteristics of a modern cargo ship. *Journal of the Acoustical Society of America* 107(1): 118-129.

Austin, M., A. McCrodan, C. O'Neill, Z. Li, and A. MacGillivray. 2013. Marine mammal monitoring and mitigation during exploratory drilling by Shell in the Alaskan Chukchi and Beaufort seas, July– November 2012: 90-Day Report. (Chapter 3) *In* Funk, D.W., C.M. Reiser, and W.R. Koski (eds.). *Underwater Sound Measurements.* LGL Rep. P1272D–1. Report from LGL Alaska Research Associates Inc., and JASCO Applied Sciences, for Shell Offshore Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. 266 pp, plus appendices.

Breeding, J.E., L.A. Pflug, M. Bradley, M. Herbert, and M. Wooten. 1994. *RANDI 3.1 User's Guide: Naval Research Laboratory*.

Clay, C.S. and H. Medwin. 1977. *Acoustical Oceanography*. John Wiley & Sons, New York. 576 pp.

Collins, M.D. 1993. A split-step Padé solution for the parabolic equation method. *Journal of the Acoustical Society of America* 93: 1736-1742.

Collins, M.D., R.J. Cederberg, D.B. King, and S. Chin-Bing. 1996. Comparison of algorithms for solving parabolic wave equations. *Journal of the Acoustical Society of America* 100(1): 178-182.

Cybulski, J. 1977. *Probable origin of measured supertanker radiated noise spectra. OCEANS'77 Conference*, 17-19 Oct 1977. IEEE, pp. 184-191.

Erbe, C., A. MacGillivray, and R. Williams. 2012. Mapping cumulative noise from shipping to inform marine spatial planning. *Journal of the Acoustical Society of America* 132(5): EL423-EL428.

François, R.E. and G.R. Garrison. 1982a. Sound absorption based on ocean measurements: Part II: Boric acid contribution and equation for total absorption. *Journal of the Acoustical Society of America* 72(6): 1879-1890.

François, R.E. and G.R. Garrison. 1982b. Sound absorption based on ocean measurements: Part I: Pure water and magnesium sulfate contributions. *Journal of the Acoustical Society of America* 72(3): 896-907.

Hamilton, E.L. 1980. Geoacoustic modeling of the sea floor. *Journal of the Acoustical Society of America* 68: 1313-1340.

HEC (Herbert Engineering Corp. and Environmental Research Consulting). 2014. *Roberts Bank Terminal 2 technical report: Marine vessel incidence prediction inputs to the quantitative risk assessment*. Prepared for Port Metro Vancouver, Vancouver, B.C. Appendix 30-A *in* Port Metro Vancouver (PMV). 2015. *Roberts Bank Terminal 2 Environmental impact statement: Volume 5. Environmental Assessment by Review Panel*. Submitted to Canadian Environmental Assessment Agency.

Hemmera, SMRU, and JASCO. 2014. *Roberts Bank Terminal 2 technical data report: Ship sound signature analysis study*. Prepared for Port Metro Vancouver, Vancouver, B.C. Available at: http://www.robertsbankterminal2.com/.

JASCO. 2012. *Ambient Noise and Killer Whale Monitoring near Port Metro Vancouver's Proposed Terminal 2 Expansion Site: July–September 2012*. Prepared for Port Metro Vancouver, Vancouver, B.C.

JASCO. 2014*a*. *Roberts Bank Terminal 2 technical report: Construction activities and terminal vessel operations noise modelling study*. Prepared for Port Metro Vancouver, Vancouver, B.C. in Port Metro Vancouver (PMV). 2015. *Roberts Bank Terminal 2 Environmental impact statement: Volume 2. Environmental Assessment by Review Panel*. Submitted to Canadian Environmental Assessment Agency.

JASCO. 2014b. *Underwater Acoustic Measurements in Haro Strait and Strait of Georgia: Transmission Loss, Vessel Source Levels, and Ambient Measurements. Appendix A in Hemmera SMRU and JASCO. Roberts Bank Terminal 2 Technical Data Report: Ship Sound Signature Analysis Study*. Prepared for Port Metro Vancouver, Vancouver, B.C.

Kipple, B. and C. Gabriele. 2003. *Glacier Bay Watercraft Noise*. NSWCCD-71-TR-2003/522. Prepared by Naval Surface Warfare Center – Carderock Division for Glacier Bay National Park and Preserve.

Marquardt, T., J. Hensel, D. Mrowinski, and G. Scholz. 2007. Low-frequency characteristics of human and guinea pig cochleae. *Journal of the Acoustical Society of America* 121(6): 3628-3638.

McKenna, M.F., D. Ross, S.M. Wiggins, and J.A. Hildebrand. 2012. Underwater radiated noise from modern commercial ships. *Journal of the Acoustical Society of America* 131(1): 92-103.

MCR International. 2011. *Final Report Describing Measurements of Ship Noise Taken from R/V Song of the Whale in the English Channel and the Hebrides in June and August 2011*. 23 pp. http://www.marineconservationresearch.co.uk/wp-content/Downloads/Final%20Report%20Describing%20Measurements%20of%20Ship%20Noise%20Taken%20from%20RV%20Song%20of%20the%20Whale%20in%20the%20English%20Channel%20and%20the%20Hebrides%20in%20June%20and%20August%202011.pdf.

NAVSEA Warfare Center Carderock Division. 2004a. *Volendam Underwater Acoustic Levels*. Technical Report prepared by Naval Surface Warfare Center – Detachment Bremerton for Holland America Line and Glacier Bay National Park and Preserve.

NAVSEA Warfare Centers Carderock Division. 2004b. *Coral Princess Underwater Acoustic Levels*. Technical Report prepared by Naval Surface Warfare Center – Detachment Bremerton for Princess Cruises and Glacier Bay National Park and Preserve.

Nedwell, J.R. and A.W. Turnpenny. 1998. The use of a generic frequency weighting scale in estimating environmental effect. *Workshop on Seismics and Marine Mammals*. 23–25th June, London, U.K.

Nedwell, J.R., A.W.H. Turnpenny, J. Lovell, S.J. Parvin, R. Workman, and J.A.L. Spinks. 2007. *A validation of the dB_{ht} as a measure of the behavioural and auditory effects of underwater noise*. Report No. 534R1231 prepared by Subacoustech Ltd. for the UK Department of Business, Enterprise and Regulatory Reform under Project No. RDCZ/011/0004. www.subacoustech.com/information/downloads/reports/534R1231.pdf.

NGDC (National Geophysical Data Center). 2013. High resolution NOAA digital elevation model. *U.S. Coastal Relief Model (CRM)*. National Oceanic and Atmospheric Administration, U.S. Department of Commerce. http://www.ngdc.noaa.gov/dem/squareCellGrid/download/655.

NRC (National Research Council). 2003. *Ocean Noise and Marine Mammals*. National Research Council (U.S.), Ocean Studies Board, Committee on Potential Impacts of Ambient Noise in the Ocean on Marine Mammals. The National Academies Press, Washington, DC. 192 pp.Port Metro Vancouver (PMV). 2015. *Roberts Bank Terminal 2 Environmental impact statement: Volume 2. Environmental Assessment by Review Panel*. Submitted to Canadian Environmental Assessment Agency.

Ross, D. 1976. *Mechanics of Underwater Noise*. Pergamon Press, New York. 375 pp.

Scrimger, P. and R.M. Heitmeyer. 1991. Acoustic source-level measurements for a variety of merchant ships. *Journal of the Acoustical Society of America* 89(2): 691-699.

SMRU, Hemmera and JASCO. 2014. *Roberts Bank Terminal 2 technical data report: Ambient underwater noise measurements*. Prepared for Port Metro Vancouver, Vancouver, B.C. Available at: http://www.robertsbankterminal2.com/.

SMRU. 2014a. *Roberts Bank Terminal 2 technical report: Southern Resident Killer Whale Underwater Noise Exposure and Acoustic Masking Study*. Prepared for Port Metro Vancouver, Vancouver, B.C. Available at: http://www.robertsbankterminal2.com/.

SMRU. 2014b. *Roberts Bank Terminal 2 technical report: Southern Resident Killer Whale Population Consequences of Disturbance.* Prepared for Port Metro Vancouver, Vancouver, B.C. Available at: http://www.robertsbankterminal2.com/.

Urick, R.J. 1983. *Principles of Underwater Sound.* 3rd edition. McGraw-Hill, New York, London. 423.

Urick, R.J. 1984. *Ambient noise in the sea.* 20362. No. 20070117128. Naval sea systems command Department of the Navy Washington, D.C.

Zhang, Z.Y. and C.T. Tindle. 1995. Improved equivalent fluid approximations for a low shear speed ocean bottom. *Journal of the Acoustical Society of America* 98(6): 3391-3396.

Zykov, M., D. Hannay, A.O. MacGillivray, M. Austin, and G. Warner. 2008. *Oooguruk Island Acoustic Measurements, 2006: Vessel and Construction Equipment Source Levels.* JASCO Report presented to Pioneer Natural Resources Alaska, Inc. and FEX LP. 76 pp.

7.0 GLOSSARY

Term	Definition
1/3-octave bands	Standard, non-overlapping frequency bands approximately one-third of an octave wide (where an octave is a doubling of frequency). Standard 1/3-octave band centre frequencies (f_c) are given by the formula $f_c = 10^{n/10}$ where n is an integer. Measured in the unit Hz.
Ambient noise	An all-encompassing sound at a given place, usually a composite of sounds from many sources near and far (ANSI S1.1-1994 R2004). Underwater sources of ambient noise include distant shipping, seismic activity, precipitation, sea ice movement, wave action, and biological activity.
Audiogram	A curve of hearing threshold (SPL) as a function of frequency that describes the hearing sensitivity of an animal over its normal 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). Measured in units of dB re HT.
Broadband	An acoustic term that indicates that the amplitude measurements were made over a large frequency range.
Ensonified	Exposed to sound.
Parabolic equation (PE) method	A computationally-efficient solution to the acoustic wave equation that is used to model transmission loss (TL). The PE method omits effects of backscattered sound, which simplifies computing TL. The effect of backscattered sound is negligible for most ocean-acoustic propagation problems.
Received Level (RL)	Acoustic term indicating the amplitude of a sound measured or modelled at some distance greater than 1 m from the source of the sound. Often reported in units of dB re 1µPa.
Ship	Large (i.e. usually 20 m or greater in length) commercial vessels that include tugs, cruise ship, bulk carriers, container carriers, etc., but not commercial whale-watch vessels.
Sound exposure level (SEL)	A measure of the total sound energy received over a specified period. Measured in units of dB re 1 $\mu Pa^2 \cdot s$.
Sound speed profile	The speed of sound in the water column as a function of depth below the water surface. The sound speed profile in the ocean strongly influences long-range acoustic propagation by refracting and trapping sound energy in the water column. Speed of sound in seawater is a function of temperature, salinity, and depth.
Source Level (SL)	Acoustic term indicating the amplitude of a sound measured or modelled at a standardised 1 m from the source of the sound. Usually reported in units of dB re 1µPa at 1 m.
Thermocline	A layer in a body of water with a steep vertical temperature gradient
Time-average sound level (Leq)	A time-average sound level during a specified period. Equal to the corresponding sound exposure level according to Leq = SEL − 10 log(T) where T is the time period in seconds; measured in units of dB re 1 µPa.
Transmission loss (TL)	The decibel reduction in sound level that results from propagation away from an acoustic source subject to the influence of the surrounding environment. Also referred to as propagation loss. Measured in units dB re 1 m.
Vessels	Generic term that includes ships, boats and commercial whale-watch vessels.

8.0 STATEMENT OF LIMITATIONS

This report was prepared by JASCO, based on fieldwork conducted by JASCO, for the sole benefit and exclusive use of Port Metro Vancouver. The material in it reflects JASCO's best judgment in light of the information available to it at the time of preparing this Report. Any use that a third party makes of this Report, or any reliance on or decision made based on it, is the responsibility of such third parties. JASCO accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions taken based on this Report.

JASCO has performed the work as described above and made the findings and conclusions set out in this Report in a manner consistent with the level of care and skill normally exercised by members of the environmental science profession practicing under similar conditions at the time the work was performed.

This Report represents a reasonable review of the information available to JASCO within the established Scope, work schedule and budgetary constraints. The conclusions and recommendations contained in this Report are based upon applicable legislation existing at the time the Report was drafted. Any changes in the legislation may alter the conclusions and/or recommendations contained in the Report. Regulatory implications discussed in this Report were based on the applicable legislation existing at the time this Report was written.

In preparing this Report, JASCO has relied in good faith on information provided by others as noted in this Report, and has assumed that the information provided by those individuals is both factual and accurate. JASCO accepts no responsibility for any deficiency, misstatement or inaccuracy in this Report resulting from the information provided by those individuals.

APPENDIX A
Figures

Figure A-1 Boundaries of Regional Monthly Cumulative Noise Exposure Study (purple) and Focused Daily Temporal Noise Exposure Study (green) Shown on Shaded Bathymetry Map
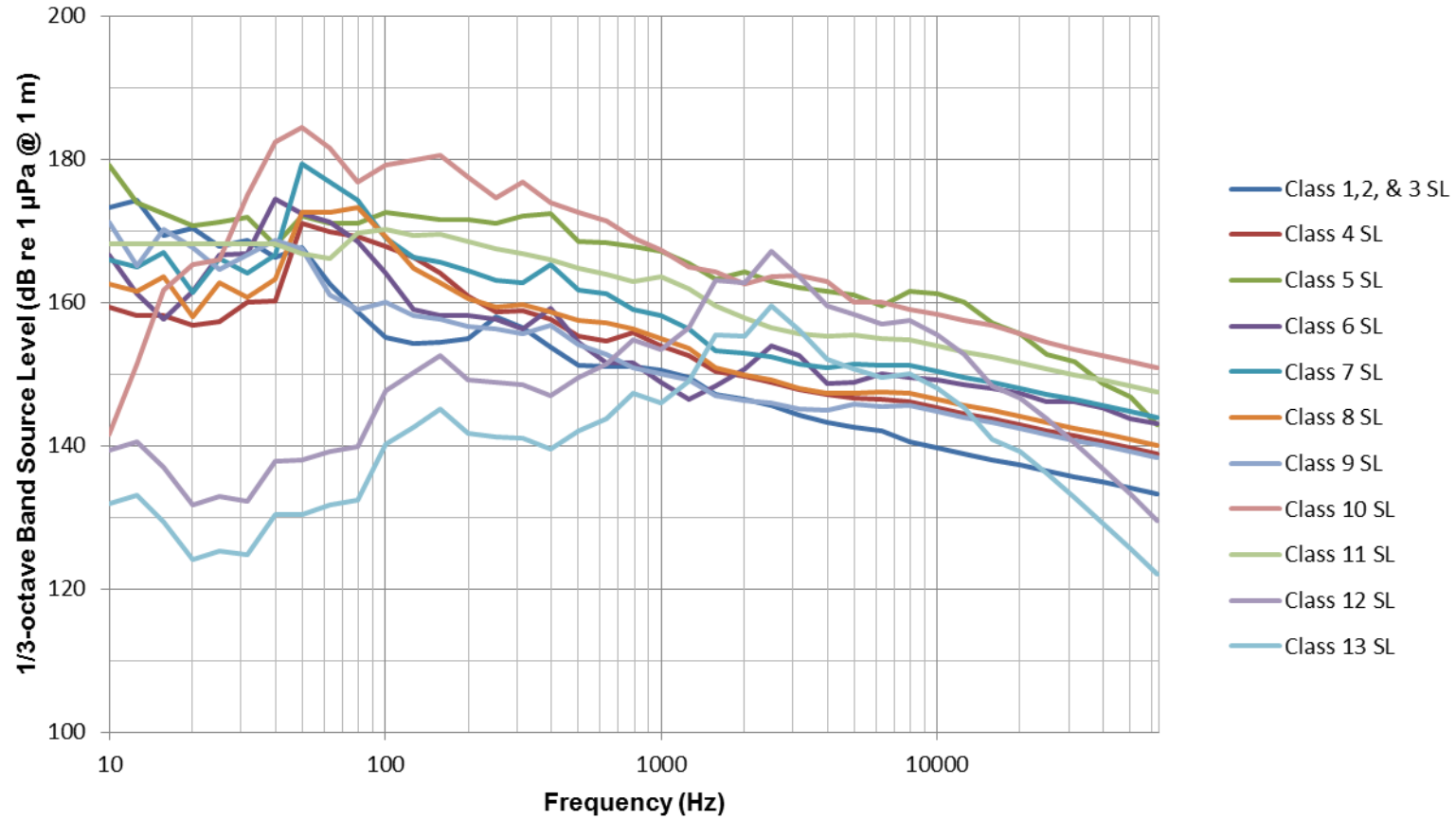
Figure A-2 Modelled 1/3-octave Band Source Levels for Vessel Categories 1 to 13, Adjusted to 10 Knot Reference Speed
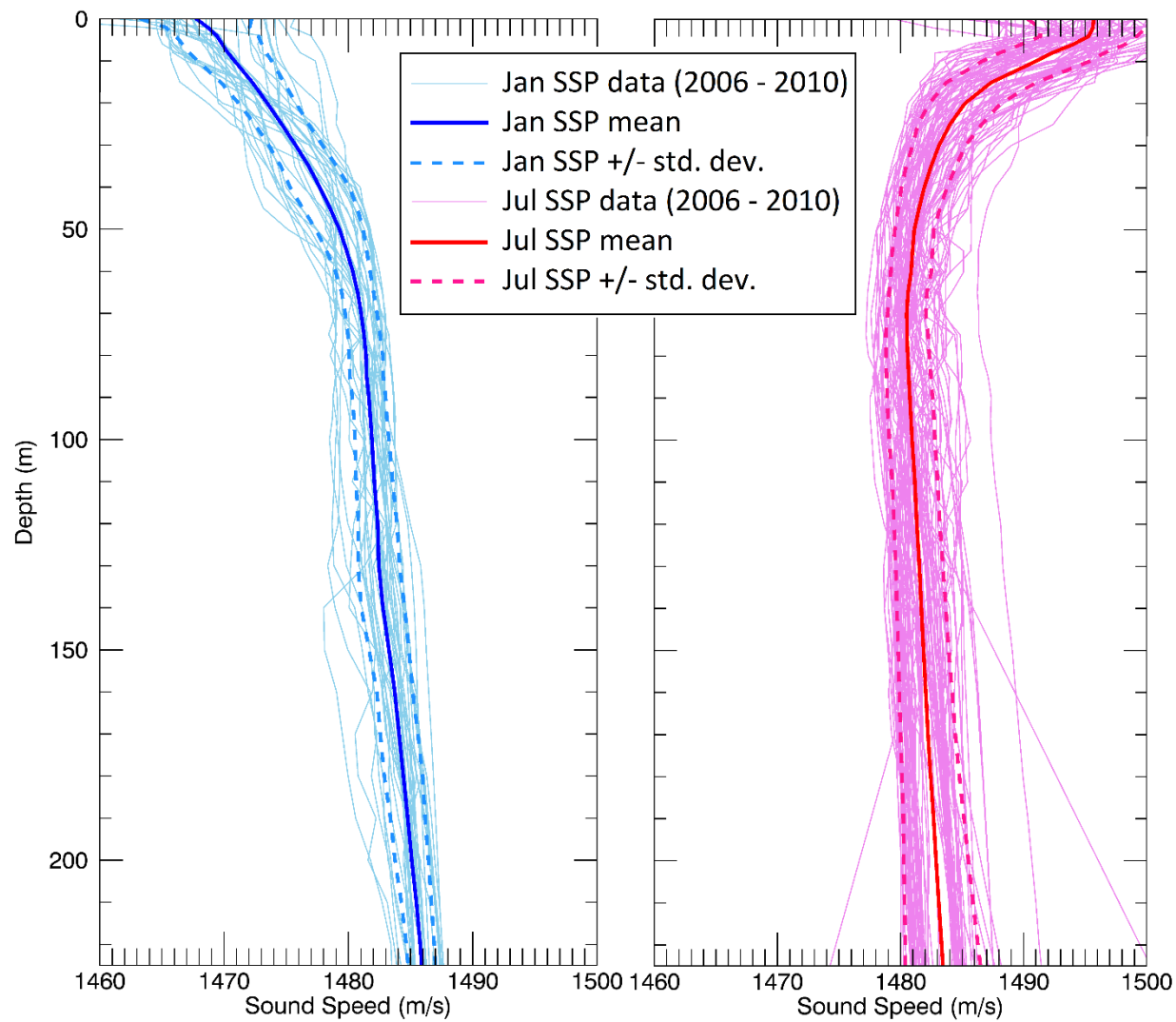
Figure A-3 January (left) and July (right) Sound Speed Profile Data for the Study Area (profiles collected by Fisheries and Oceans Canada (DFO) Institute of Ocean Sciences from 2006 to 2010)
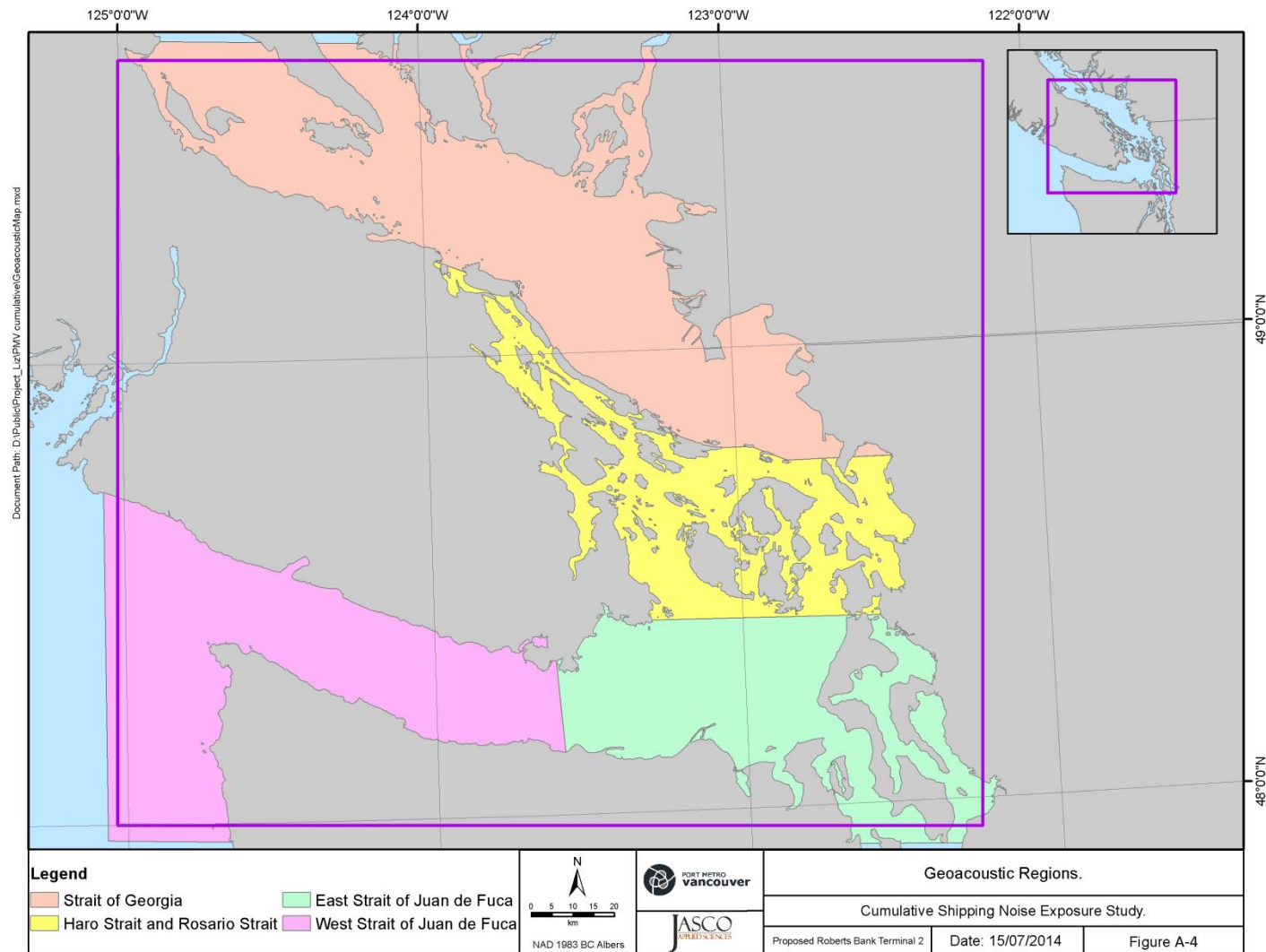
Figure A-4 Map of Geoacoustic Regions Used for Modelling Seabed Acoustic Properties in the Study Area
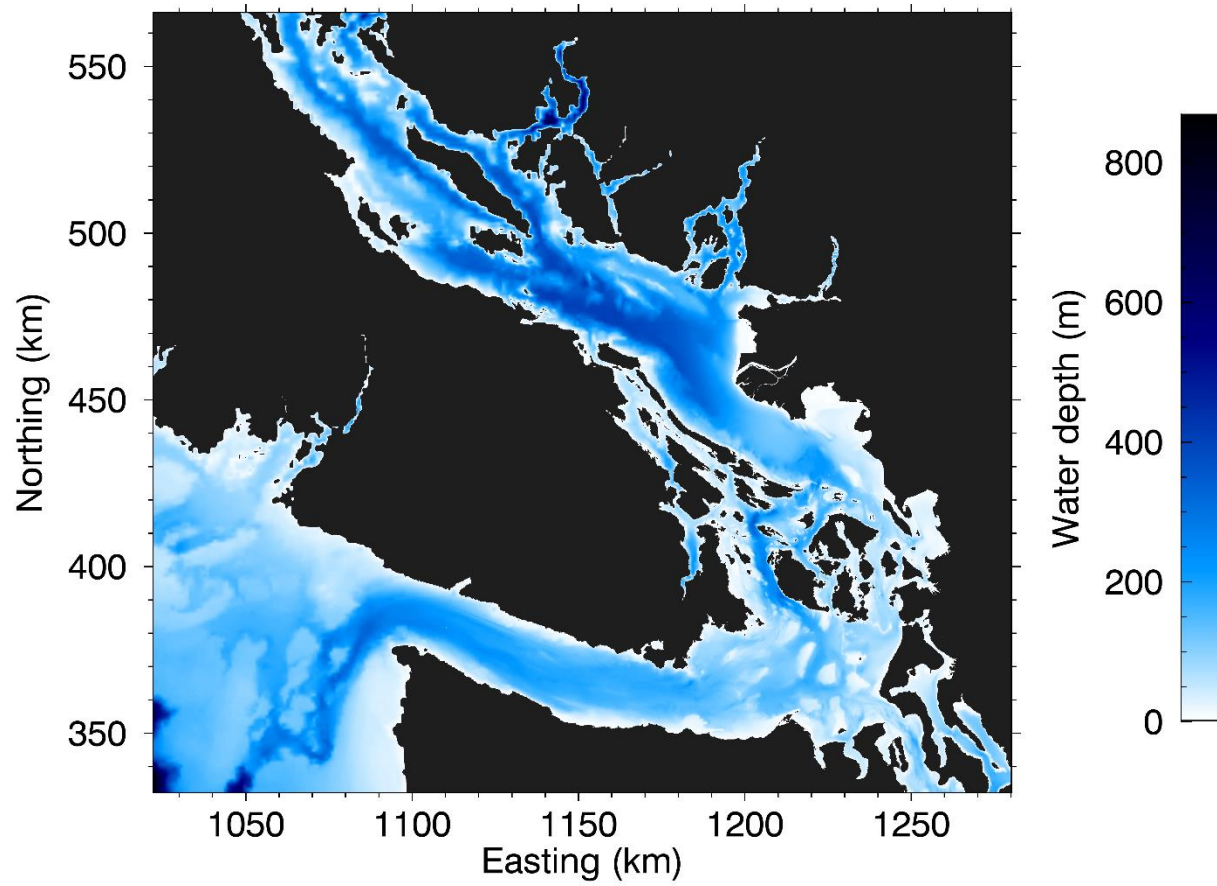
Figure A-5 Gridded High-resolution (20 m) Bathymetry Data for the Study Area
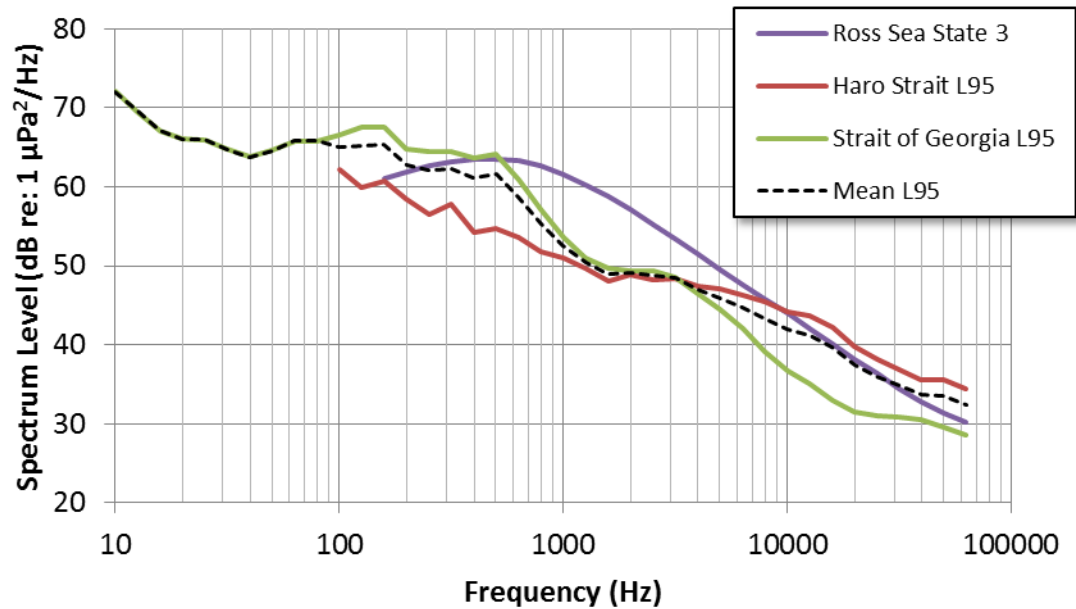
Figure A-6 Modelled Wind-generated Ambient Noise Spectrum in the Study Area (dashed line), as Estimated from the Mean L_{95} Spectrum Level Measured from July to September 2013 in Haro Strait (red line) and the Strait of Georgia (green line). Ross (1976) Wind-generated Noise Spectrum for Sea State 3 (purple line) is Shown for Comparison.
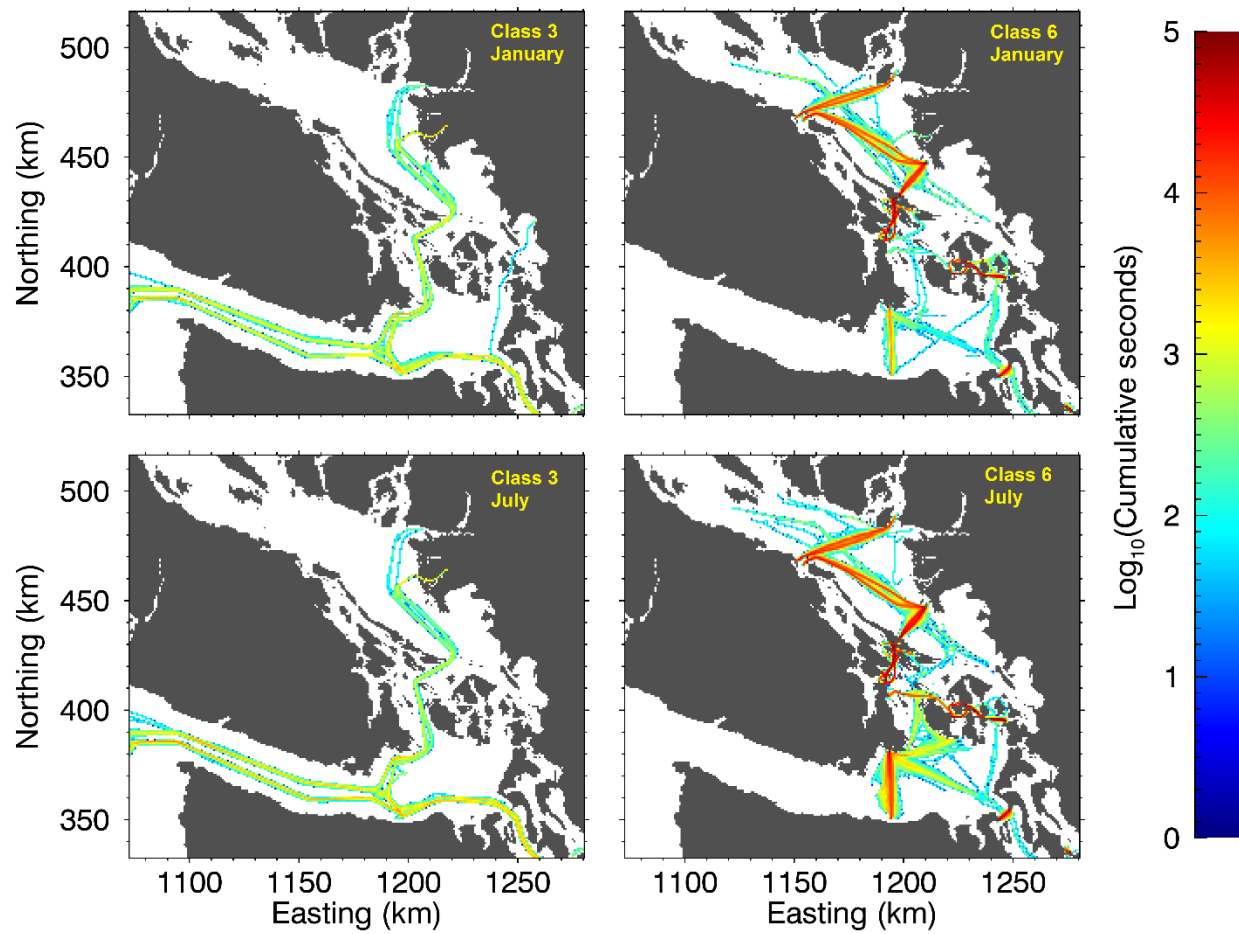
Figure A-7 Example of S1 Cumulative Vessel Time Data for January and July for Category 3 (container ships) and Category 6 (ferries)
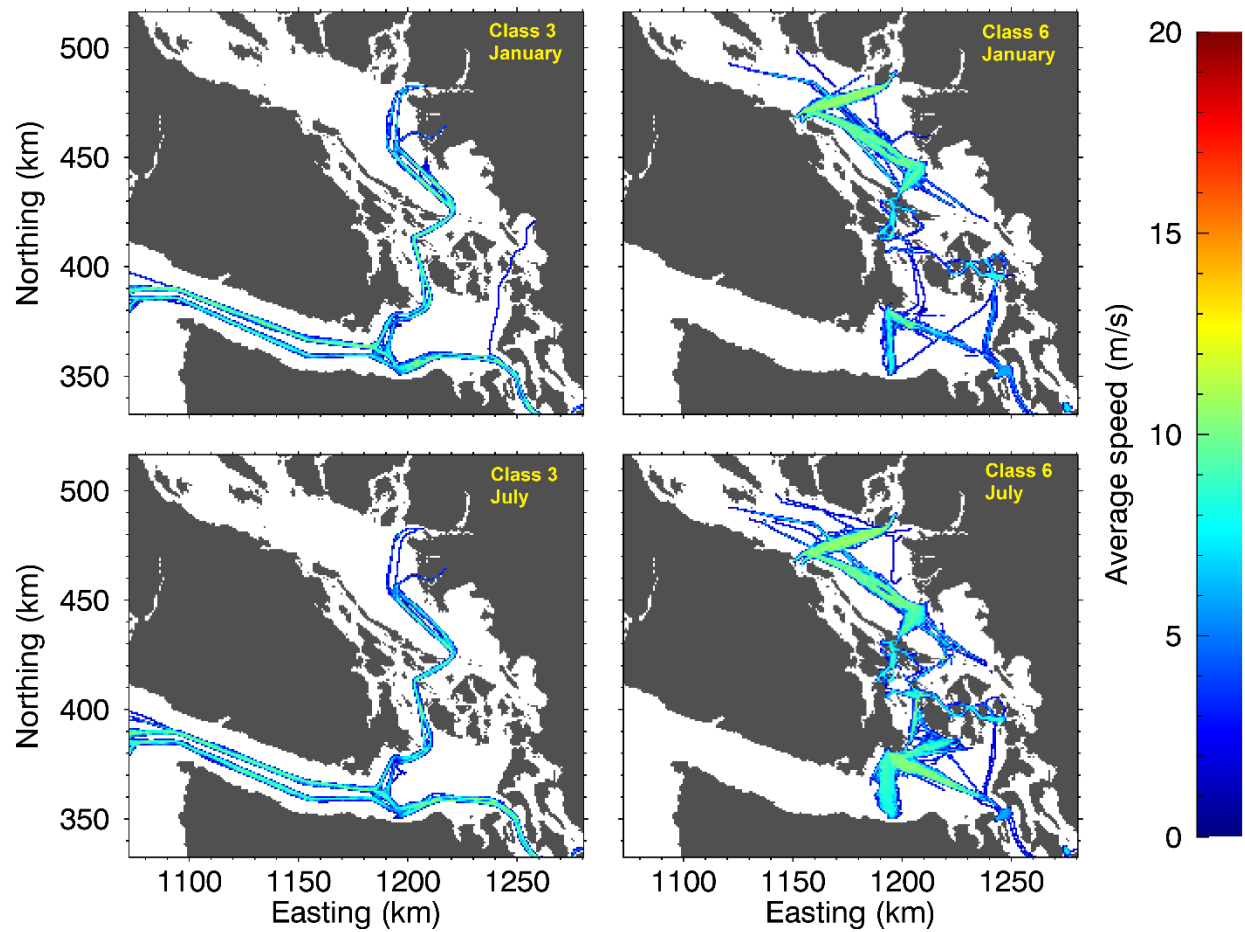
Figure A-8 Example of S1 Mean Vessel Speed Data for January and July for Category 3 (container ships) and Category 6 (ferries)
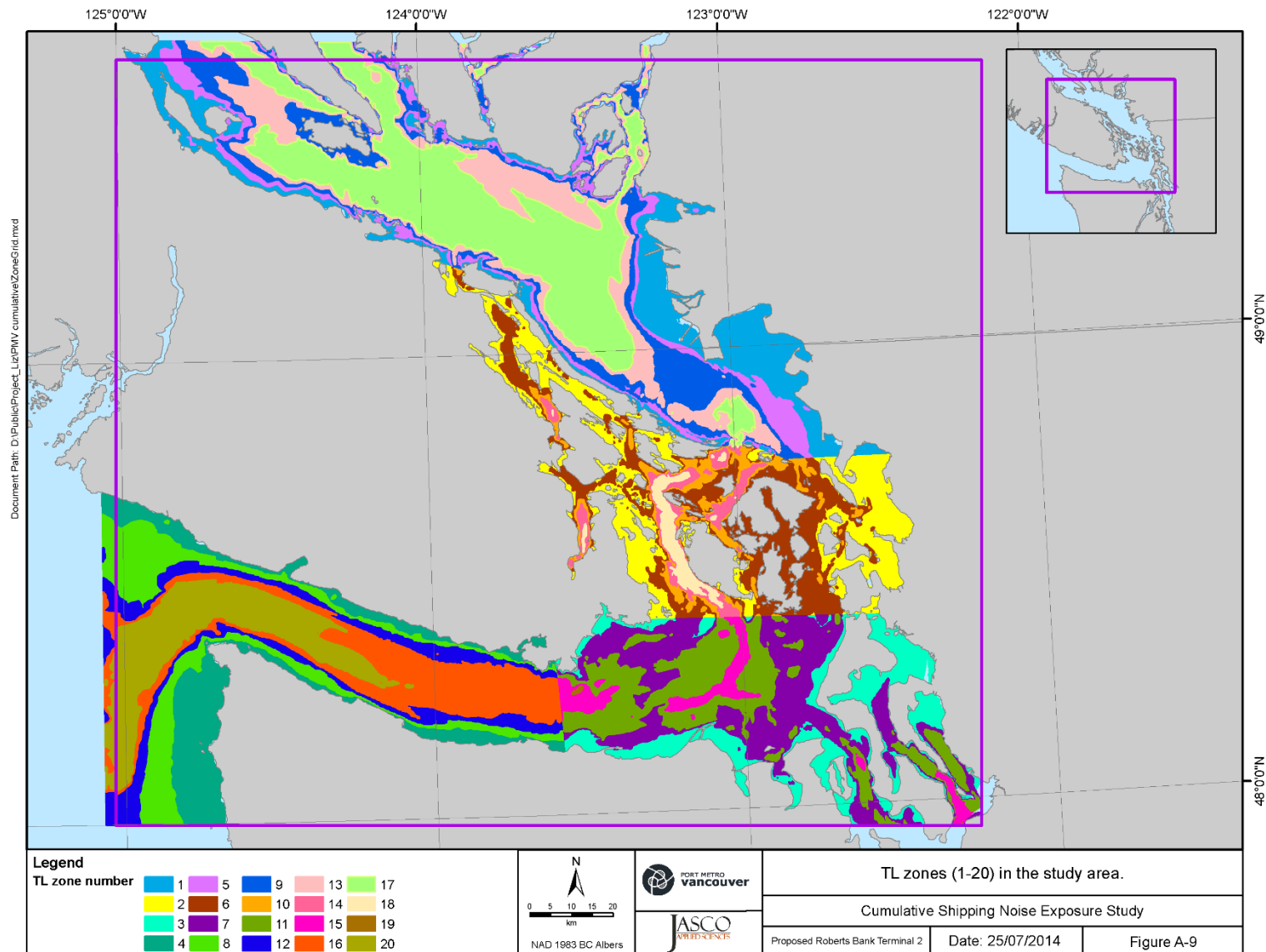
Figure A-9 Map of TL zones (1-20) Used for Modelling Sound Propagation in the Study Area
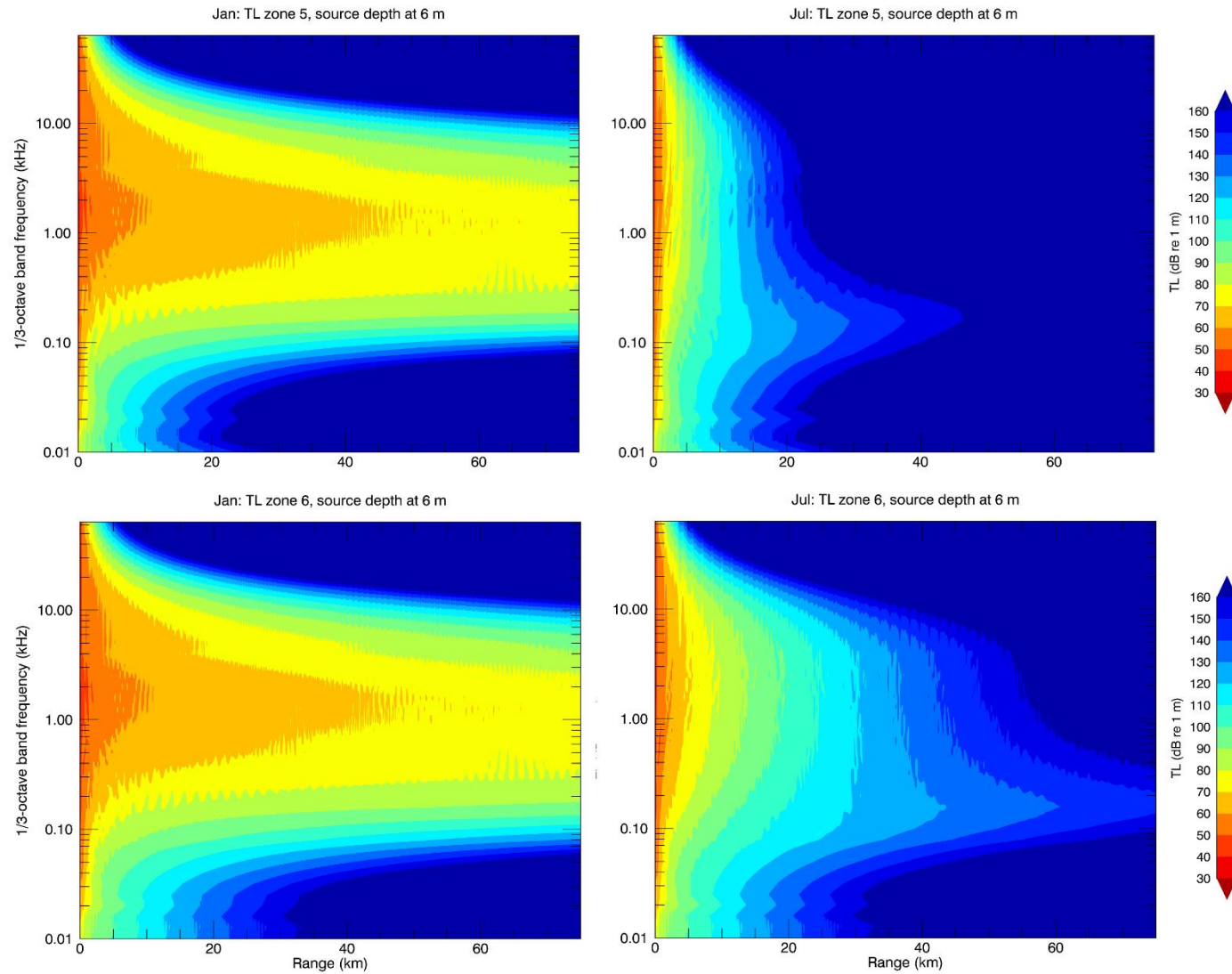
Figure A-10 Example Plots of Modelled TL vs. Range and 1/3-octave Band Frequency for Zone 5 (top) and Zone 6 (bottom) for January (left) and July (right). Source Depth is 6 m and Receiver Depth is 10 m.
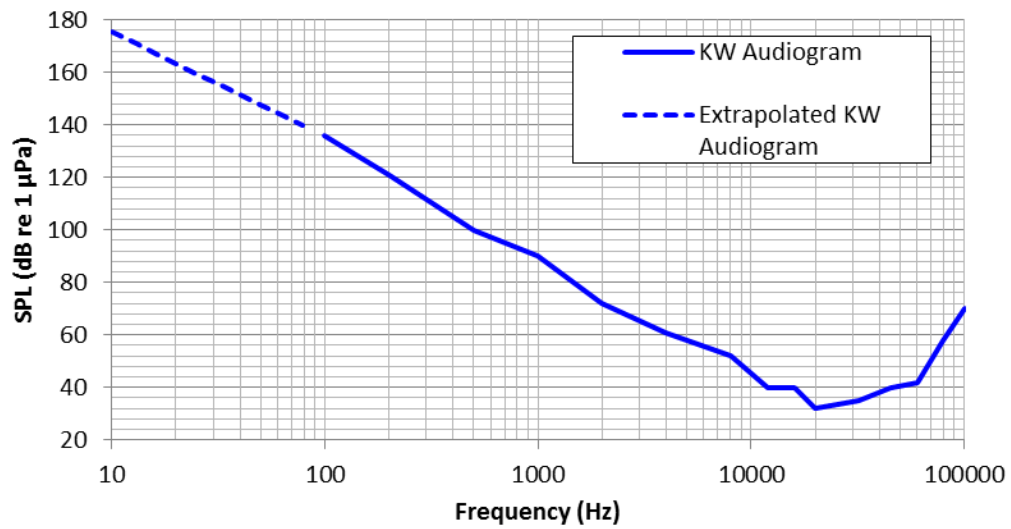
Figure A-11 Resident Killer Whale (*Orcinus orca*) Audiogram Used for this Study (adapted from Yurk, pers. comm, January 2014). Dashed Curve is Extrapolated Low-frequency Threshold.
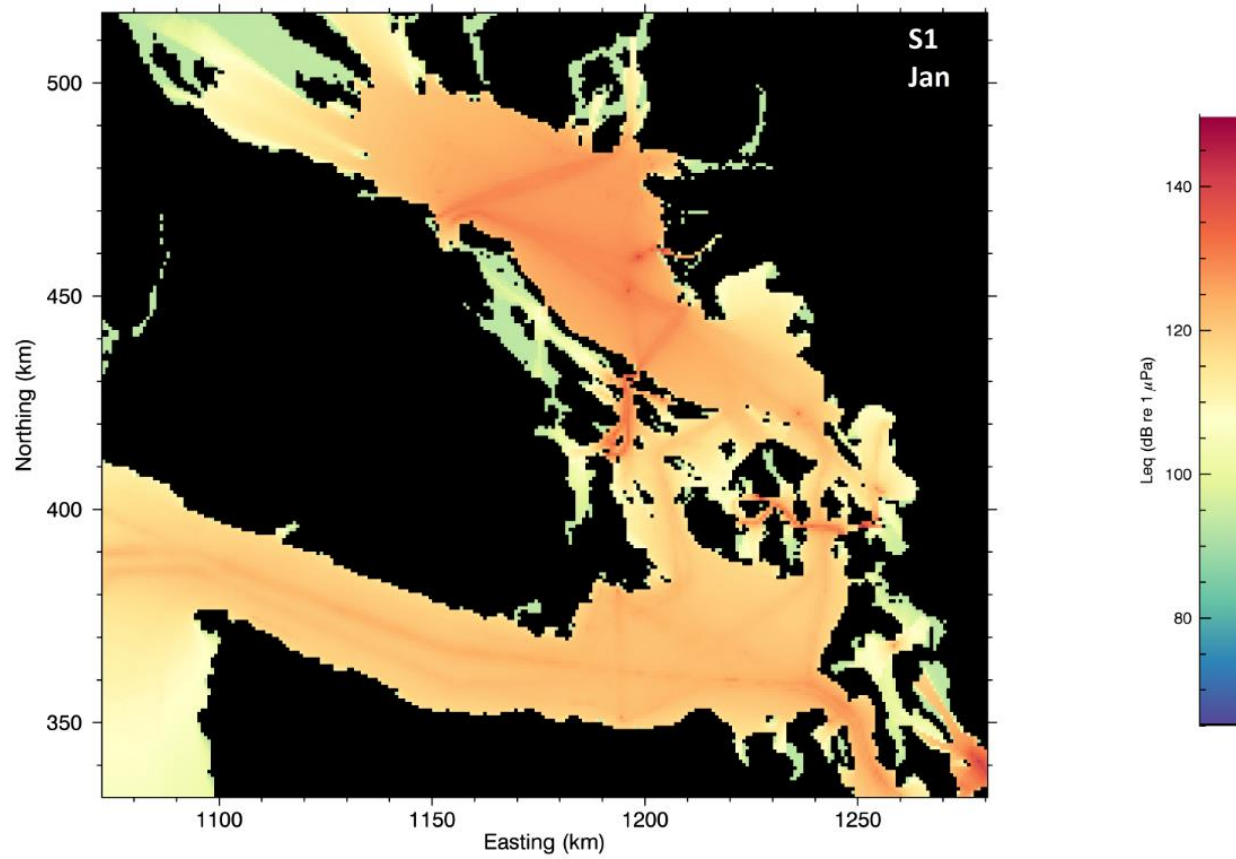
Figure A-12 Scenario S1: Unweighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for January. Grid Coordinates are BC Albers (NAD83).
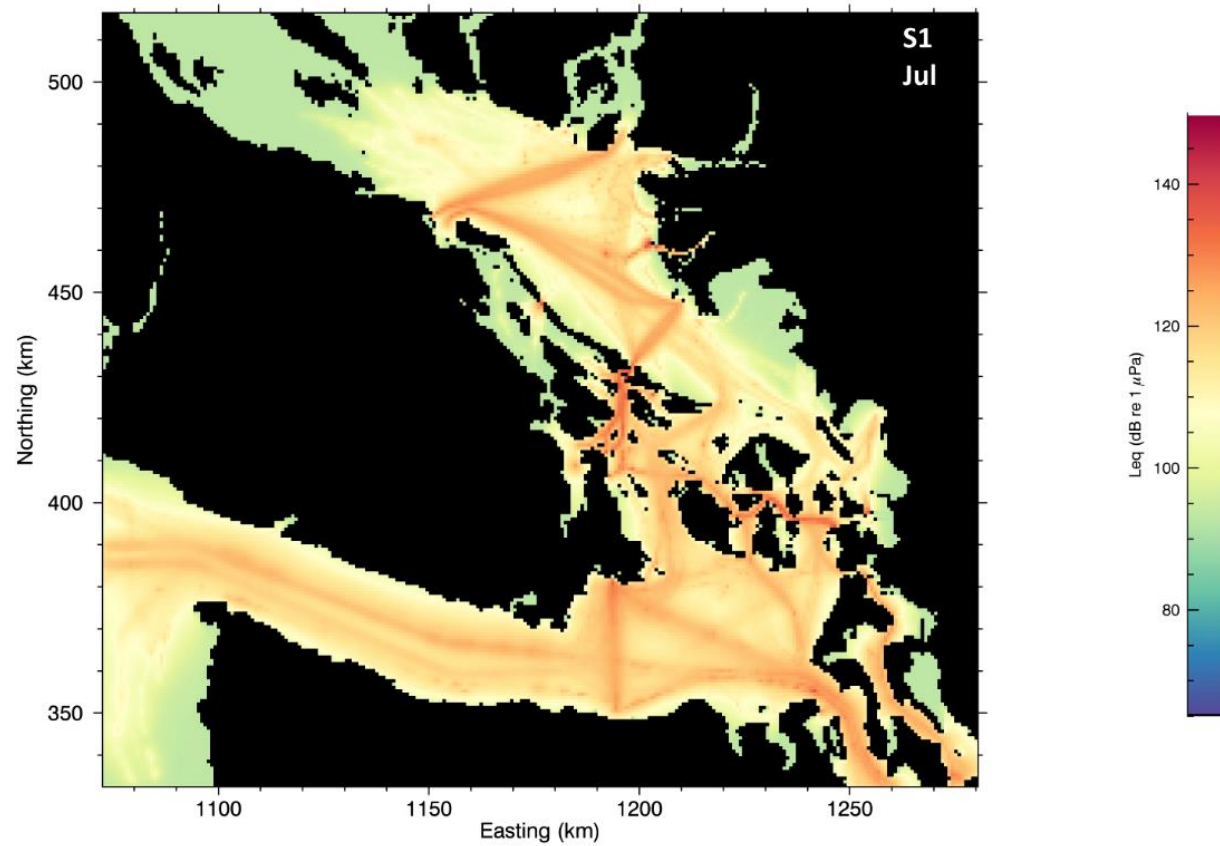
Figure A-13 Scenario S1: Unweighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for July. Grid Coordinates are BC Albers (NAD83).
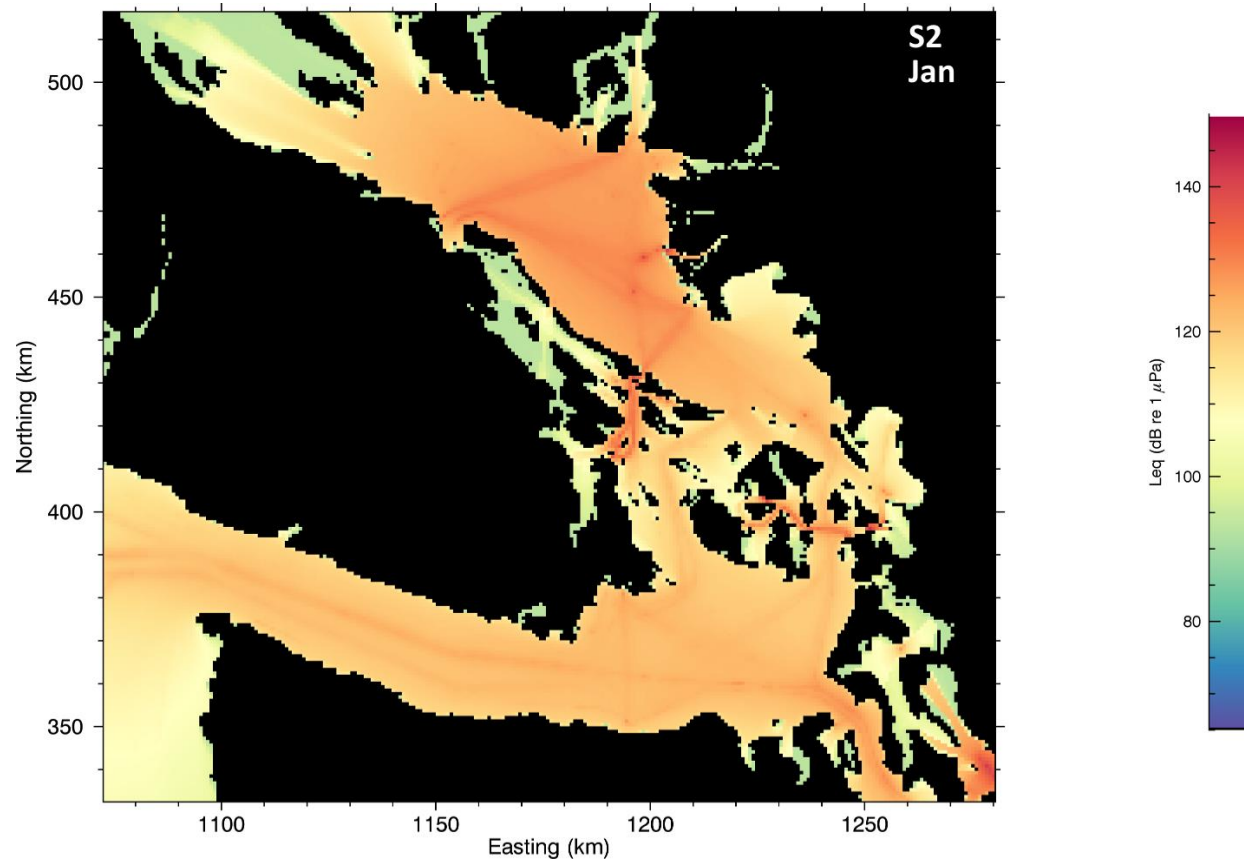
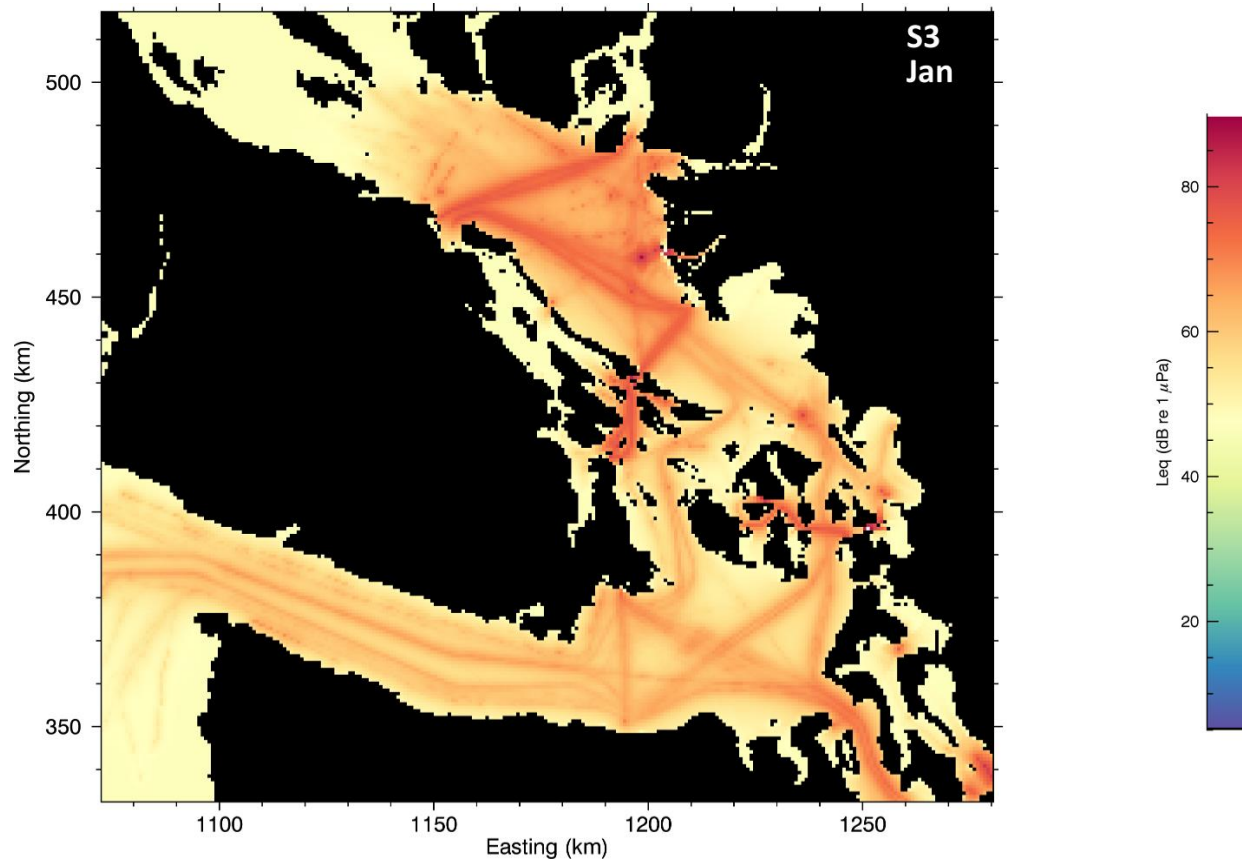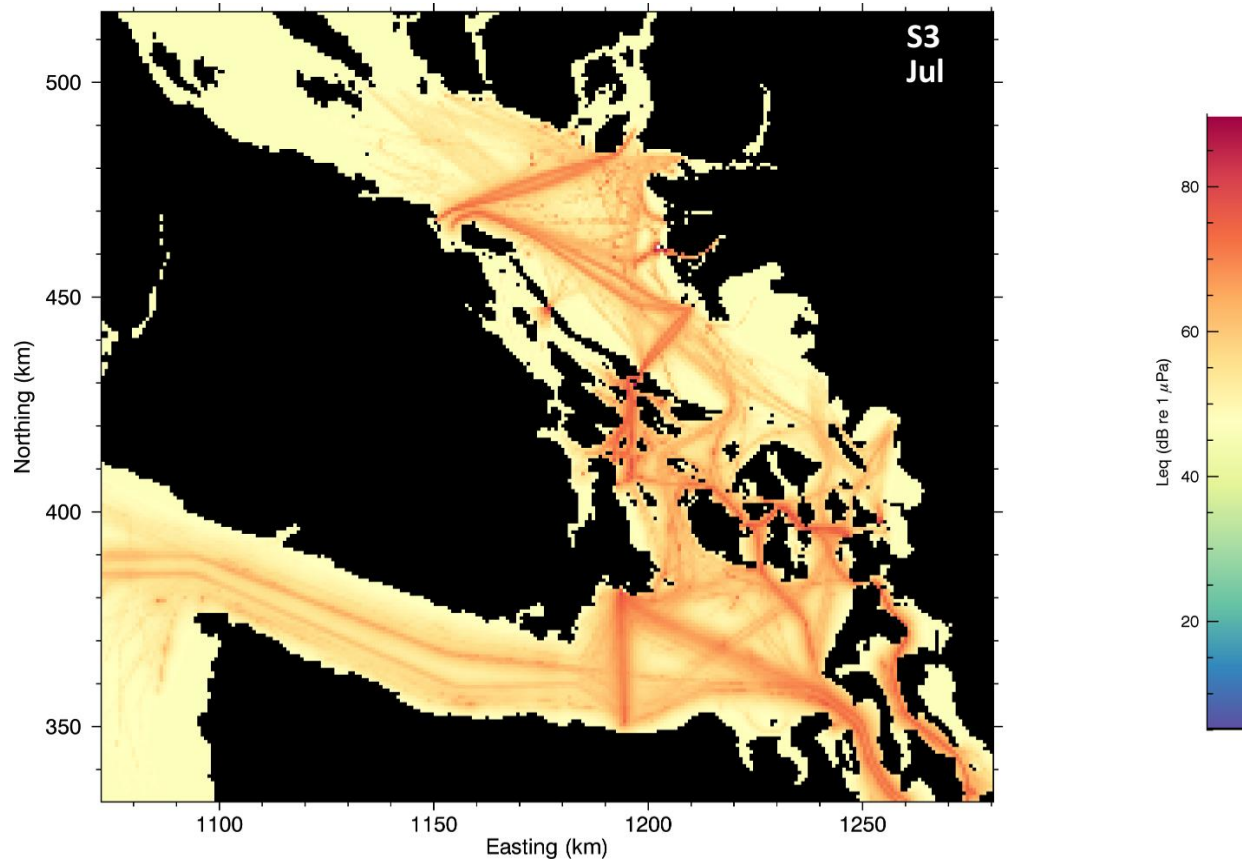**Figure A-14 Scenario S2: Unweighted Monthly Mean Shipping Commercial Vessel Traffic SPL Noise Levels for January. Grid Coordinates are BC Albers (NAD83).**
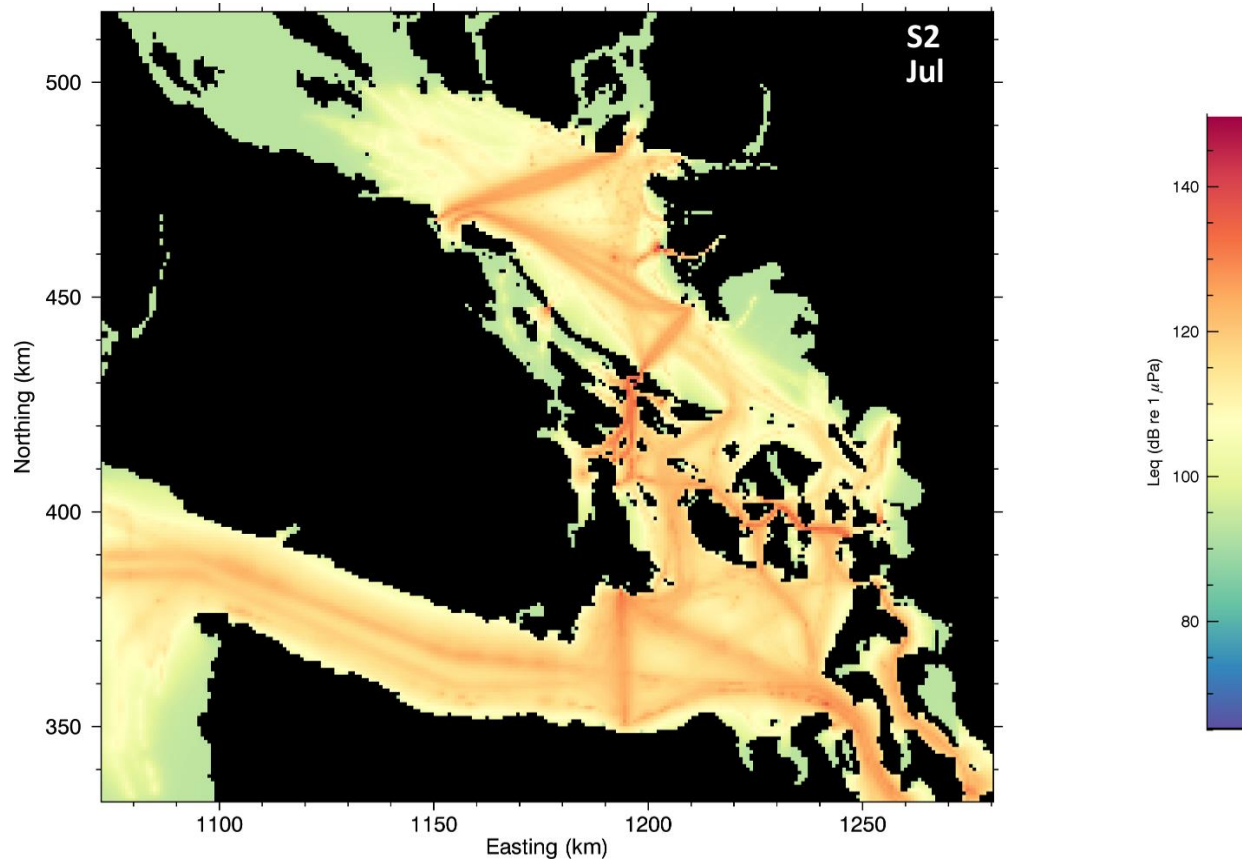
Figure A-15 Scenario S2: Unweighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for July. Grid Coordinates are BC Albers (NAD83).
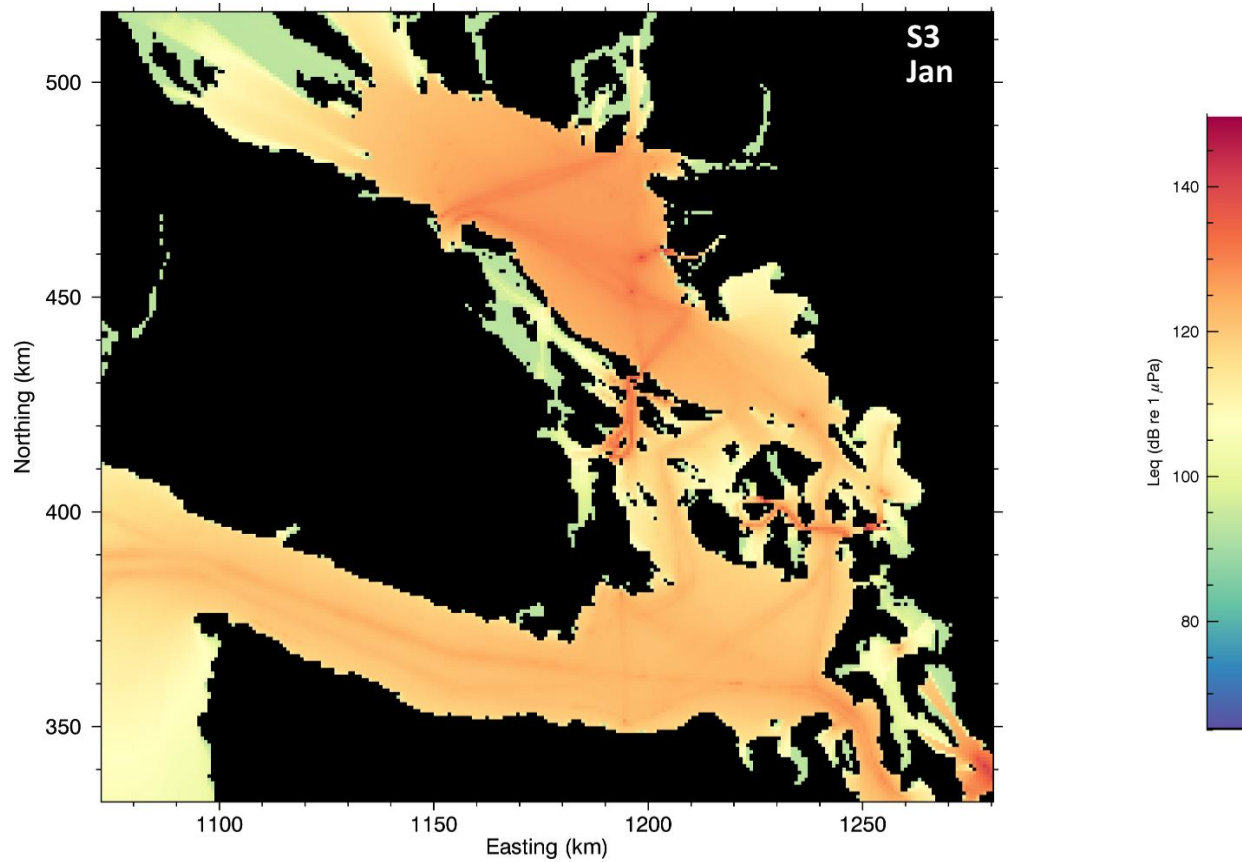
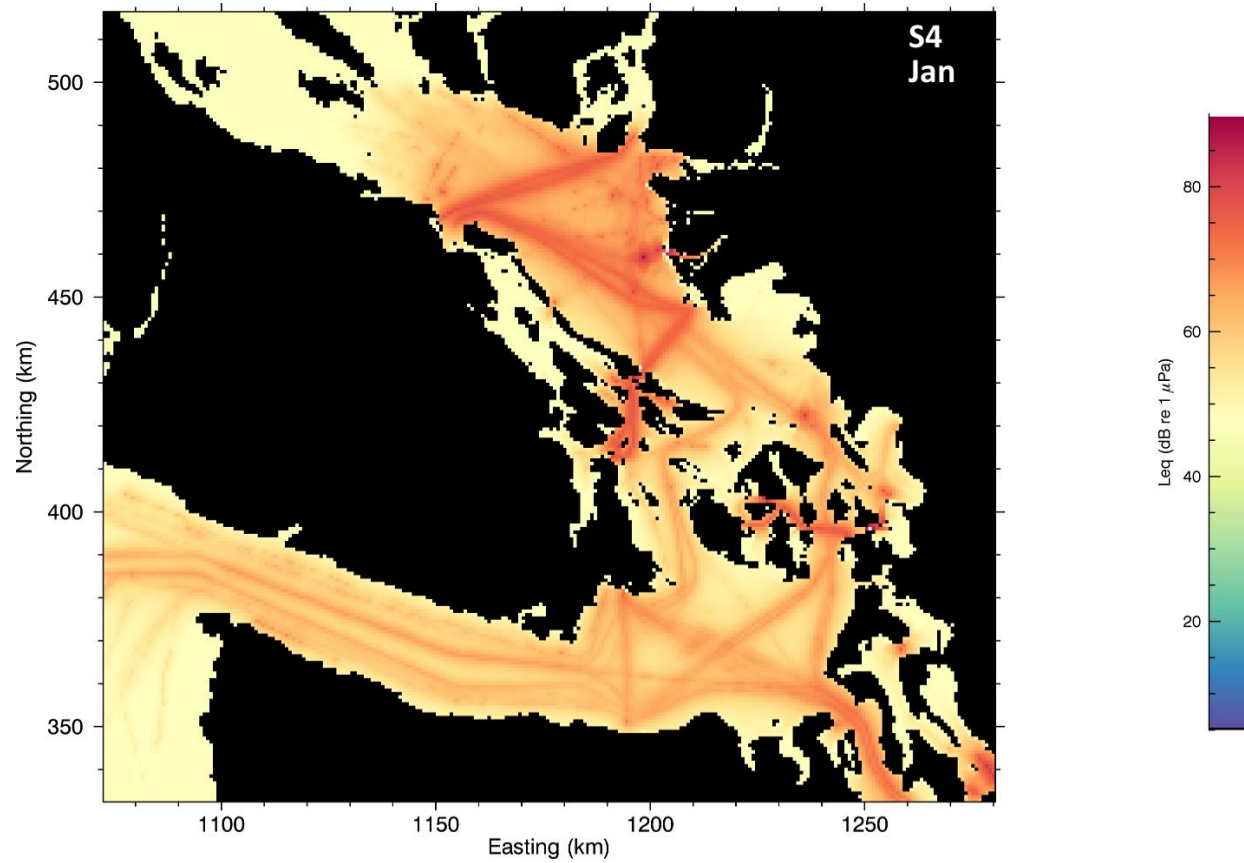**Figure A-16 Scenario S3: Unweighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for January. Grid Coordinates are BC Albers (NAD83).**
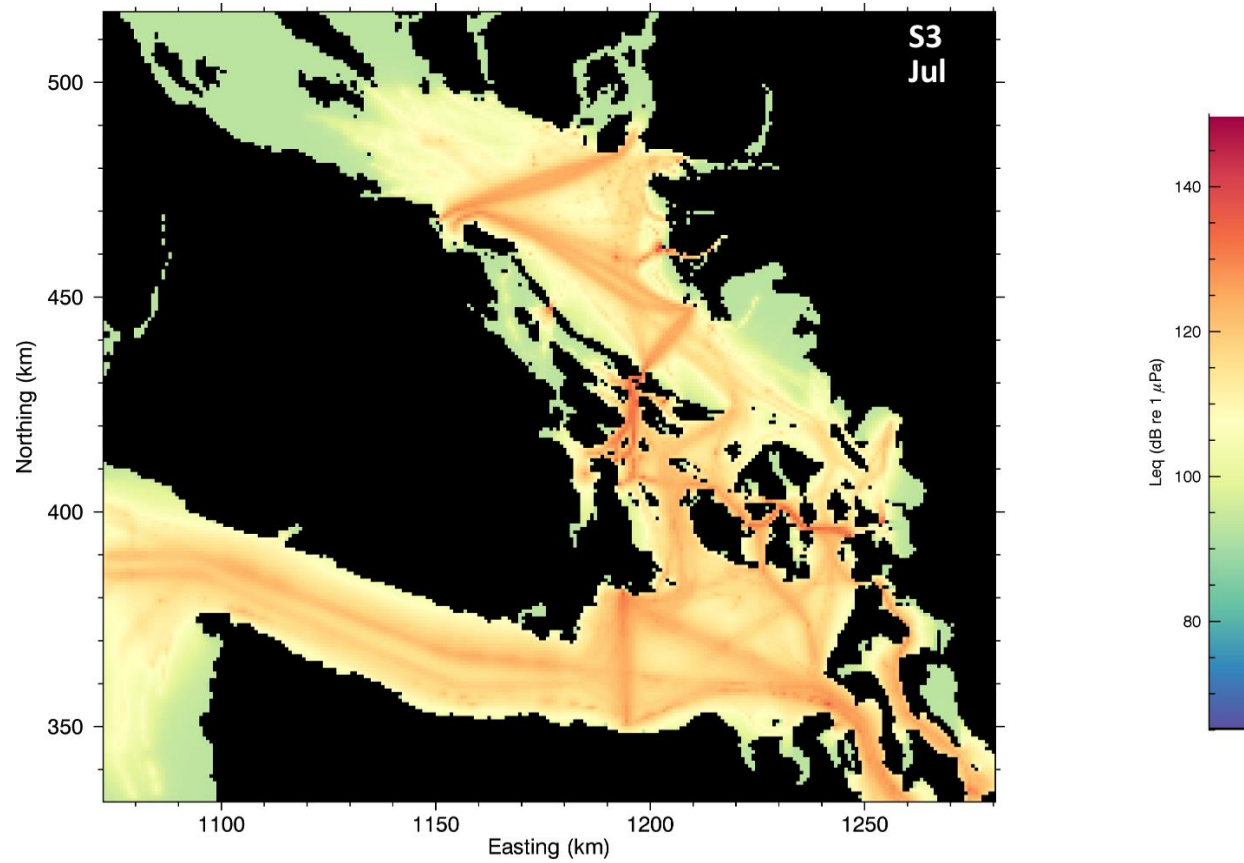
Figure A-17 Scenario S3: Unweighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for July. Grid Coordinates are BC Albers (NAD83).
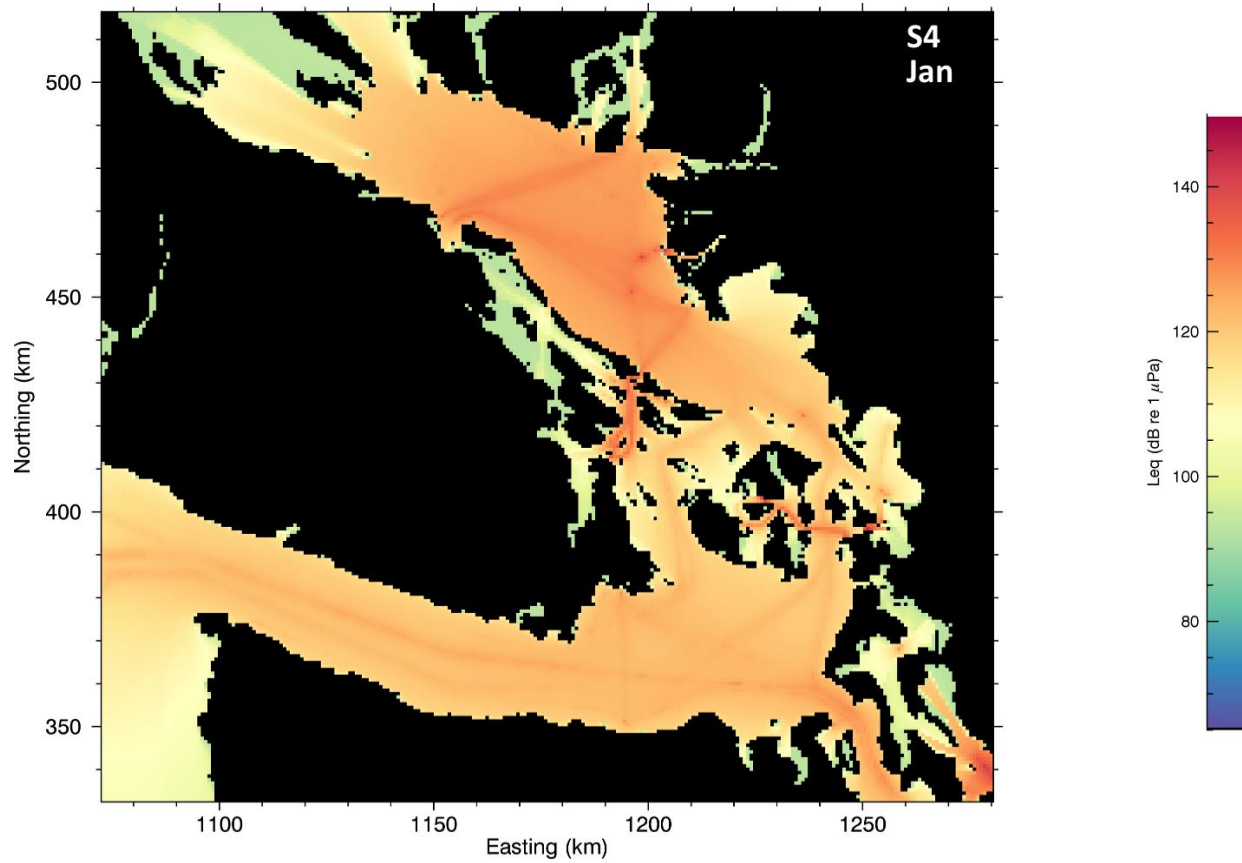
Figure A-18 Scenario S4: Unweighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for January. Grid Coordinates are BC Albers (NAD83).
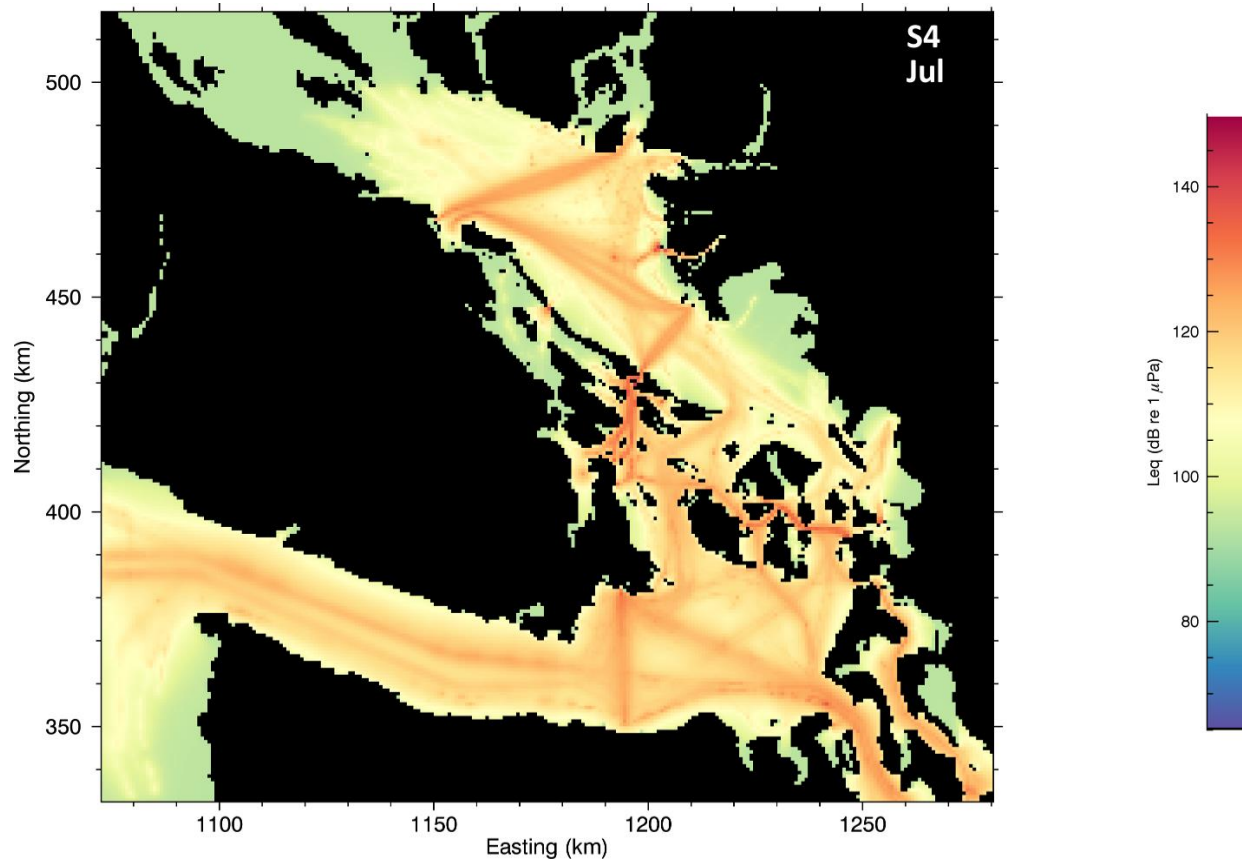
Figure A-19 Scenario S4: Unweighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for July. Grid Coordinates are BC Albers (NAD83).
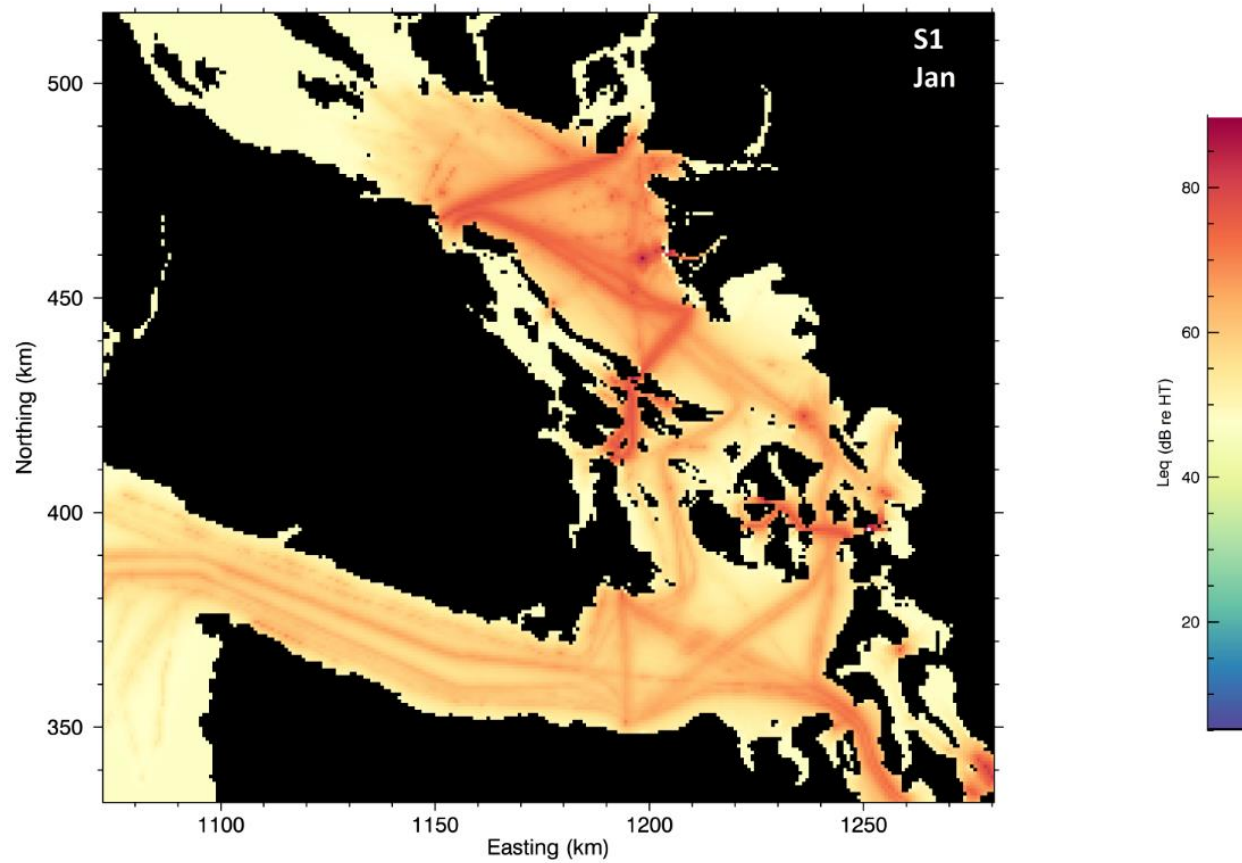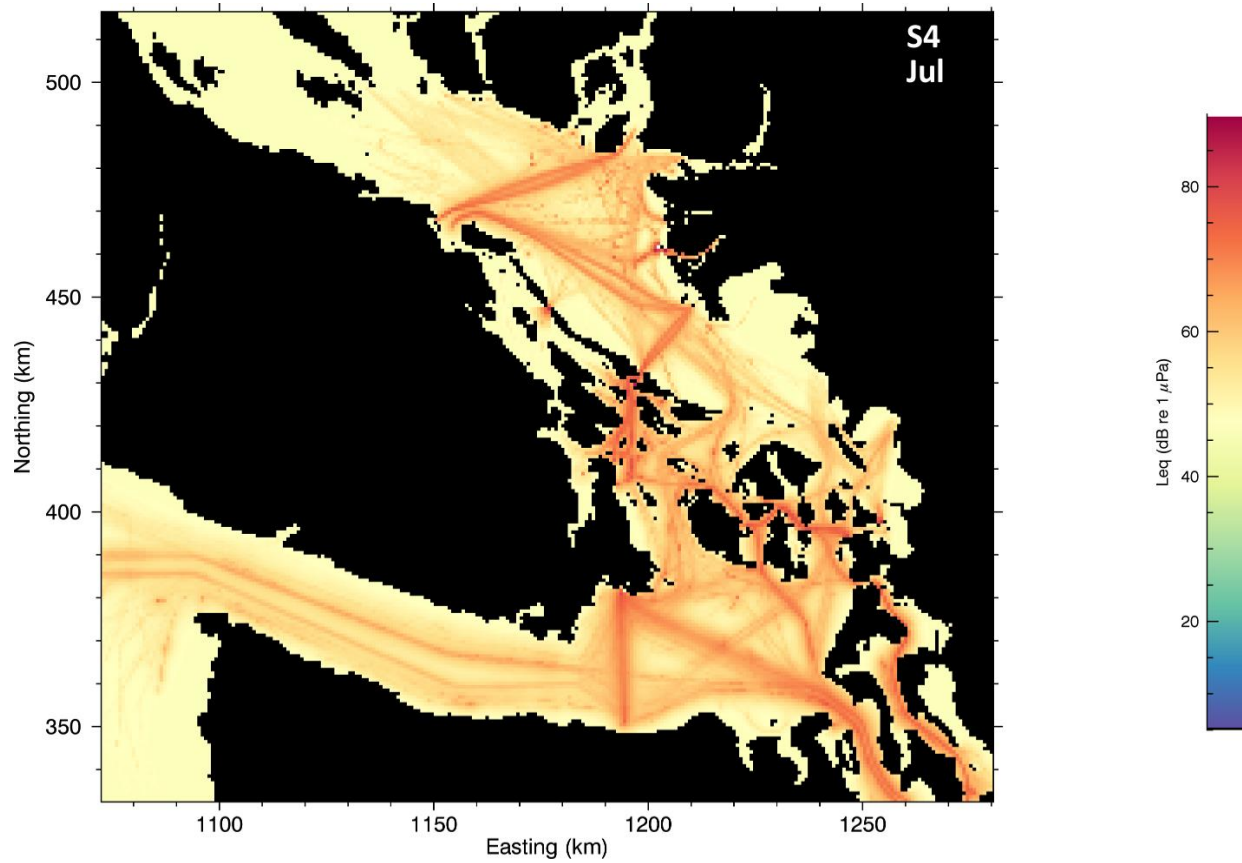
Figure A-20 Scenario S1: Resident Killer Whale Audiogram-weighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for January. Grid Coordinates are BC Albers (NAD83).
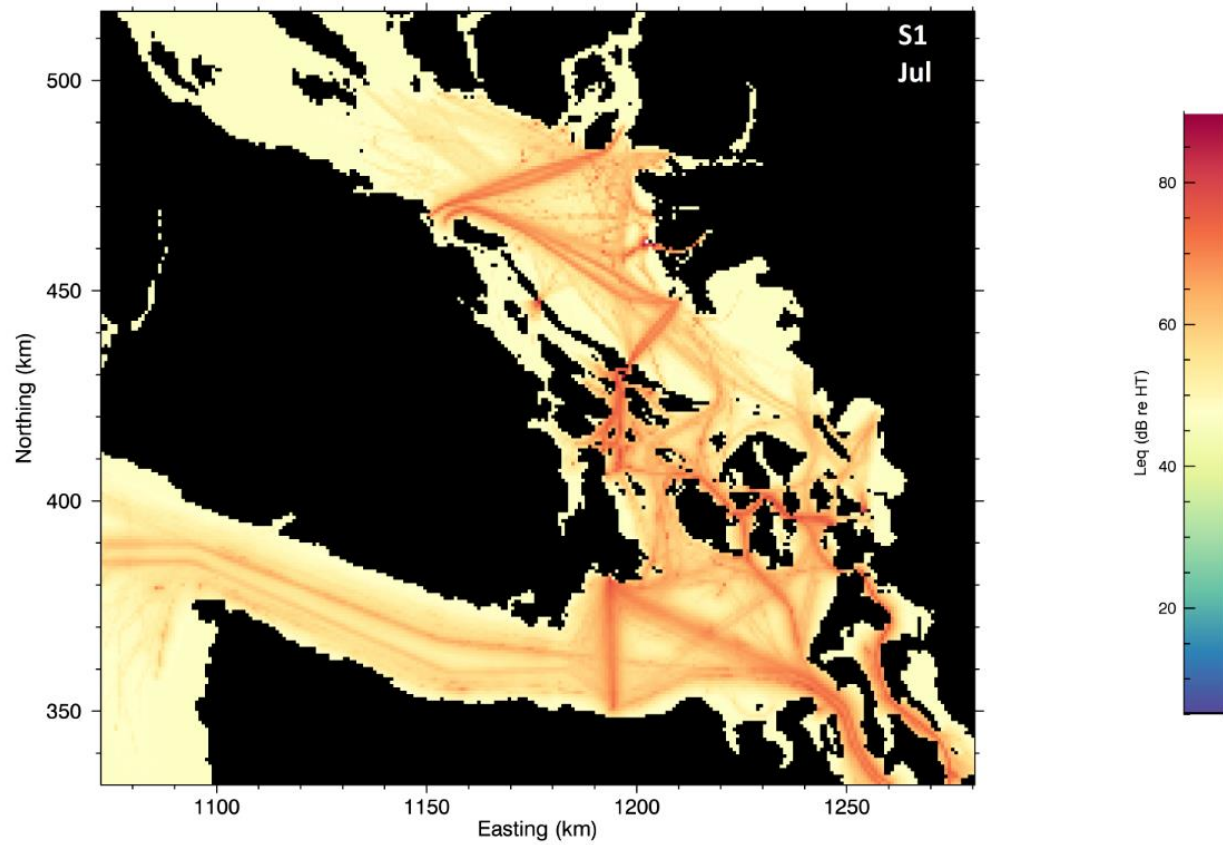
Figure A-21 Scenario S1: Resident Killer Whale Audiogram-weighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for July. Grid Coordinates are BC Albers (NAD83).
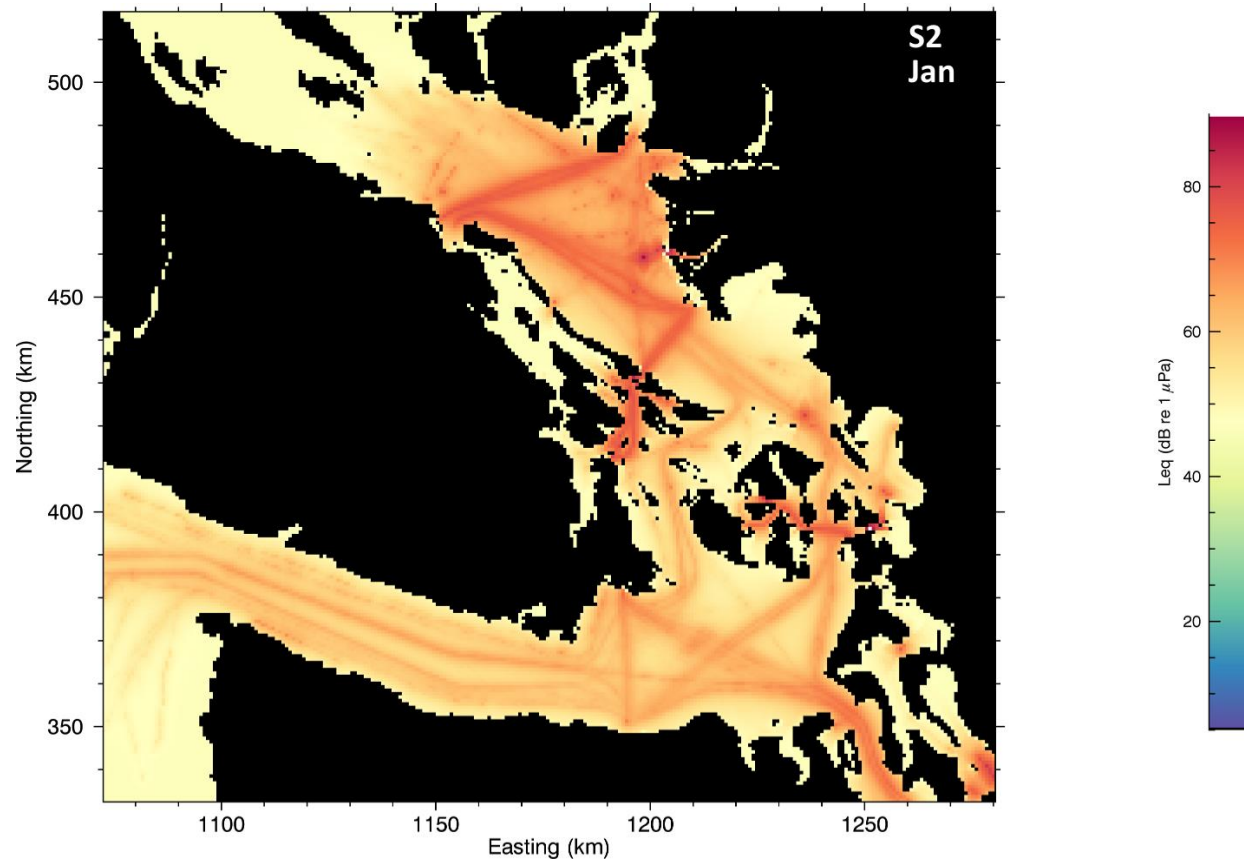
Figure A-22 Scenario S2: Resident Killer Whale Audiogram-weighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for January. Grid Coordinates are BC Albers (NAD83).
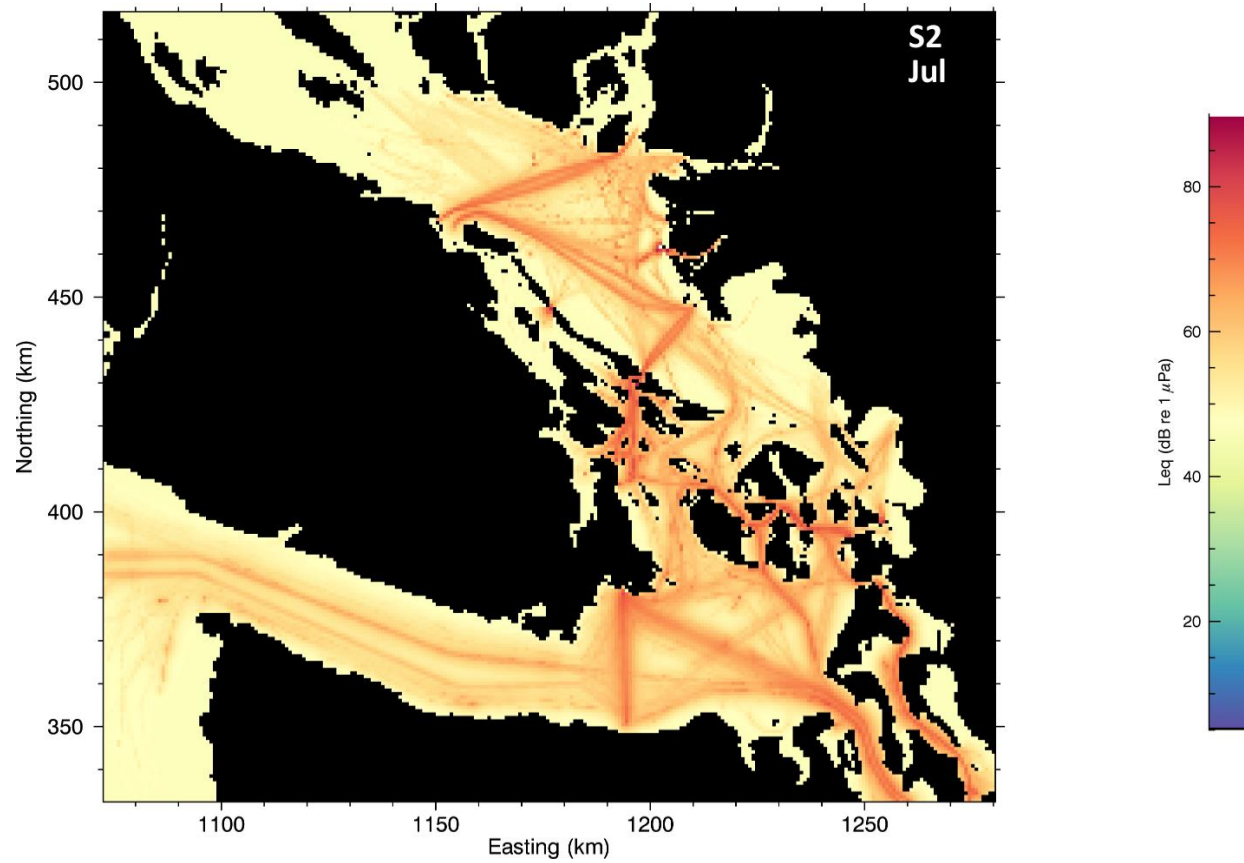
Figure A-23 Scenario S2: Resident Killer Whale Audiogram-weighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for July. Grid Coordinates are BC Albers (NAD83).

Figure A-24 Scenario S3: Resident Killer Whale Audiogram-weighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for January. Grid Coordinates are BC Albers (NAD83).

Figure A-25 Scenario S3: Resident Killer Whale Audiogram-weighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for July. Grid Coordinates are BC Albers (NAD83).

Figure A-26 Scenario S4: Resident Killer Whale Audiogram-weighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for January. Grid Coordinates are BC Albers (NAD83).

Figure A-27 Scenario S4: Resident Killer Whale Audiogram-weighted Monthly Mean Commercial Vessel Traffic SPL Noise Levels for July. Grid Coordinates are BC Albers (NAD83).
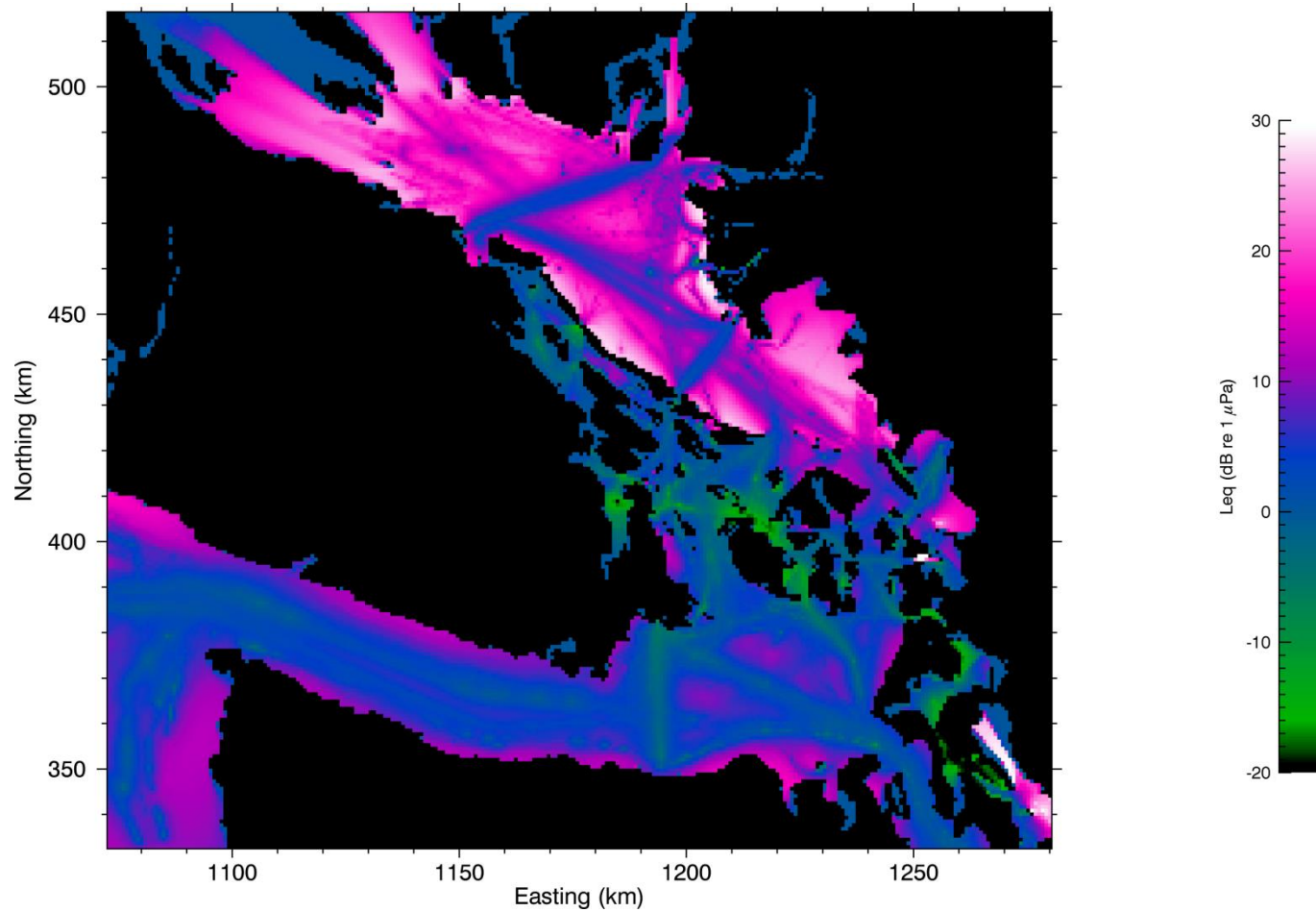
Figure A-28 Differences in Mean Monthly Commercial Vessel Traffic SPL Noise Levels between January and July for Scenario S1. Grid Coordinates are BC Albers (NAD83).
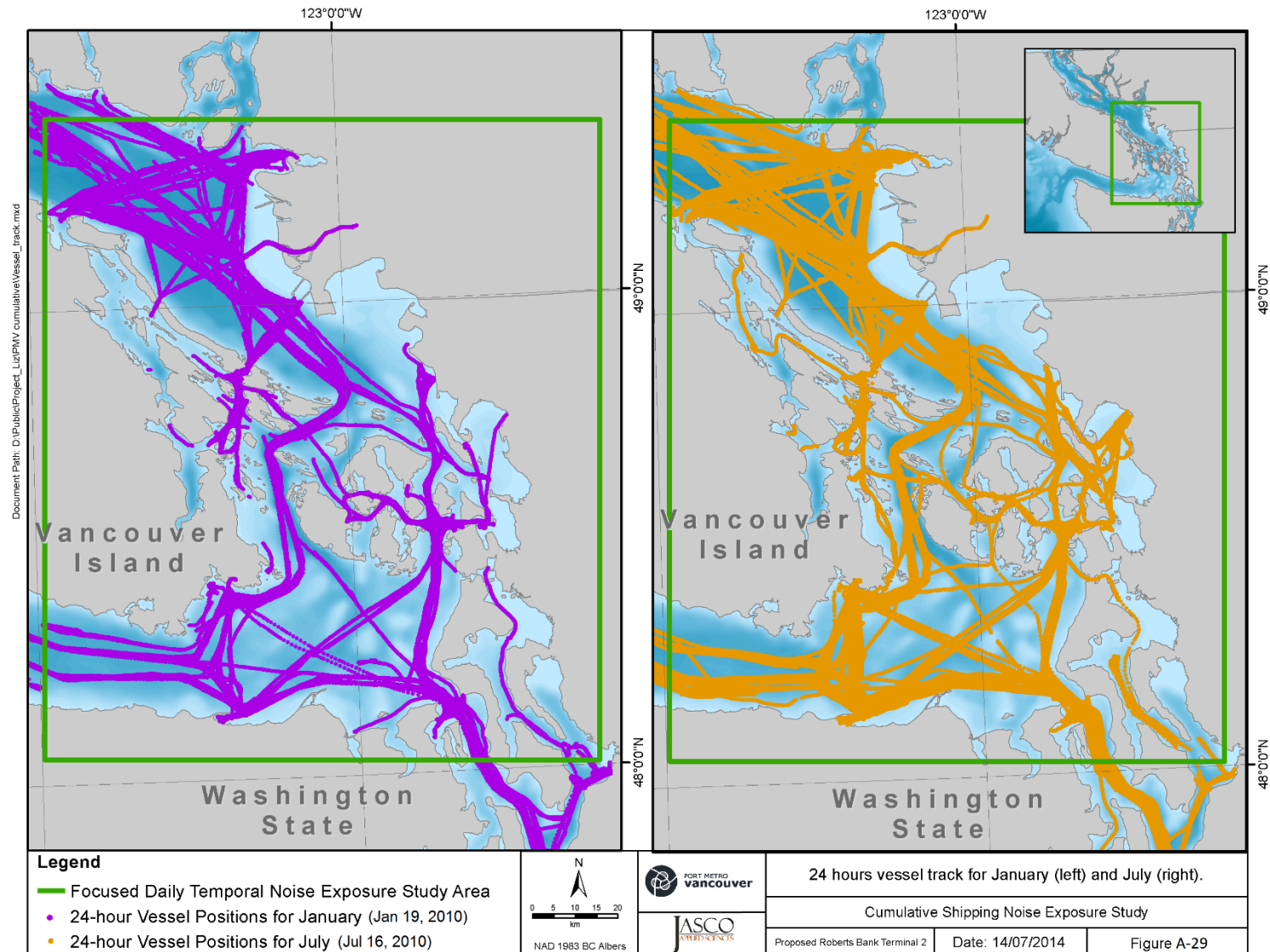
Figure A-29 Map of 24-hour Vessel Position Reports from VTOSS for 19 January (left) and 16 July (right) 2010
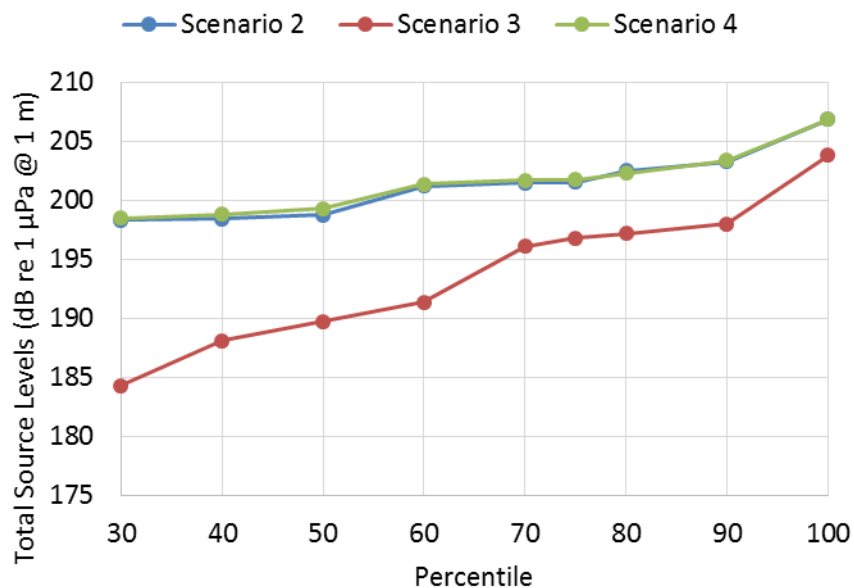
Figure A-30 Ranking of Different Combinations of New Vessels Present in the Study Area over a 24-hour Period from Probabilistic Future Scenario Simulations, in Terms of Total Source Level
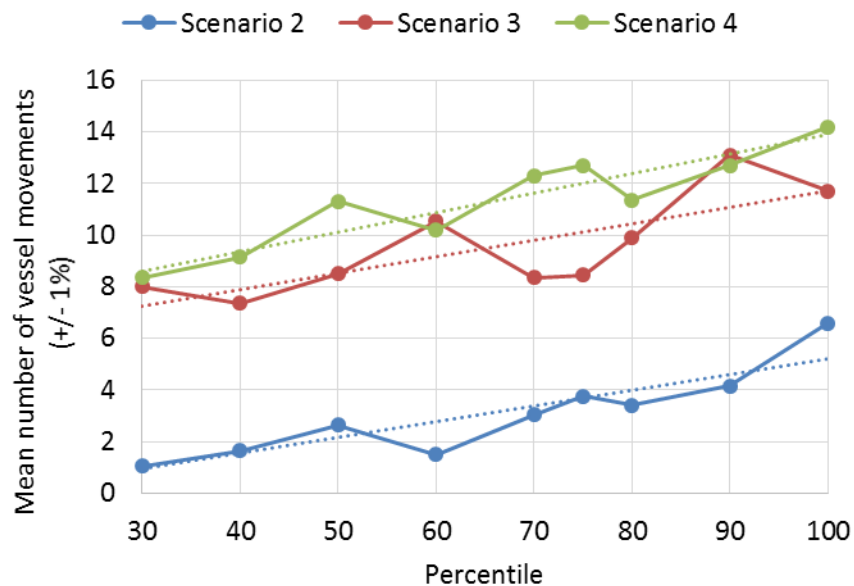
Figure A-31 Number of Vessel Movements versus Ranking for Probabilistic Future Scenario Simulations
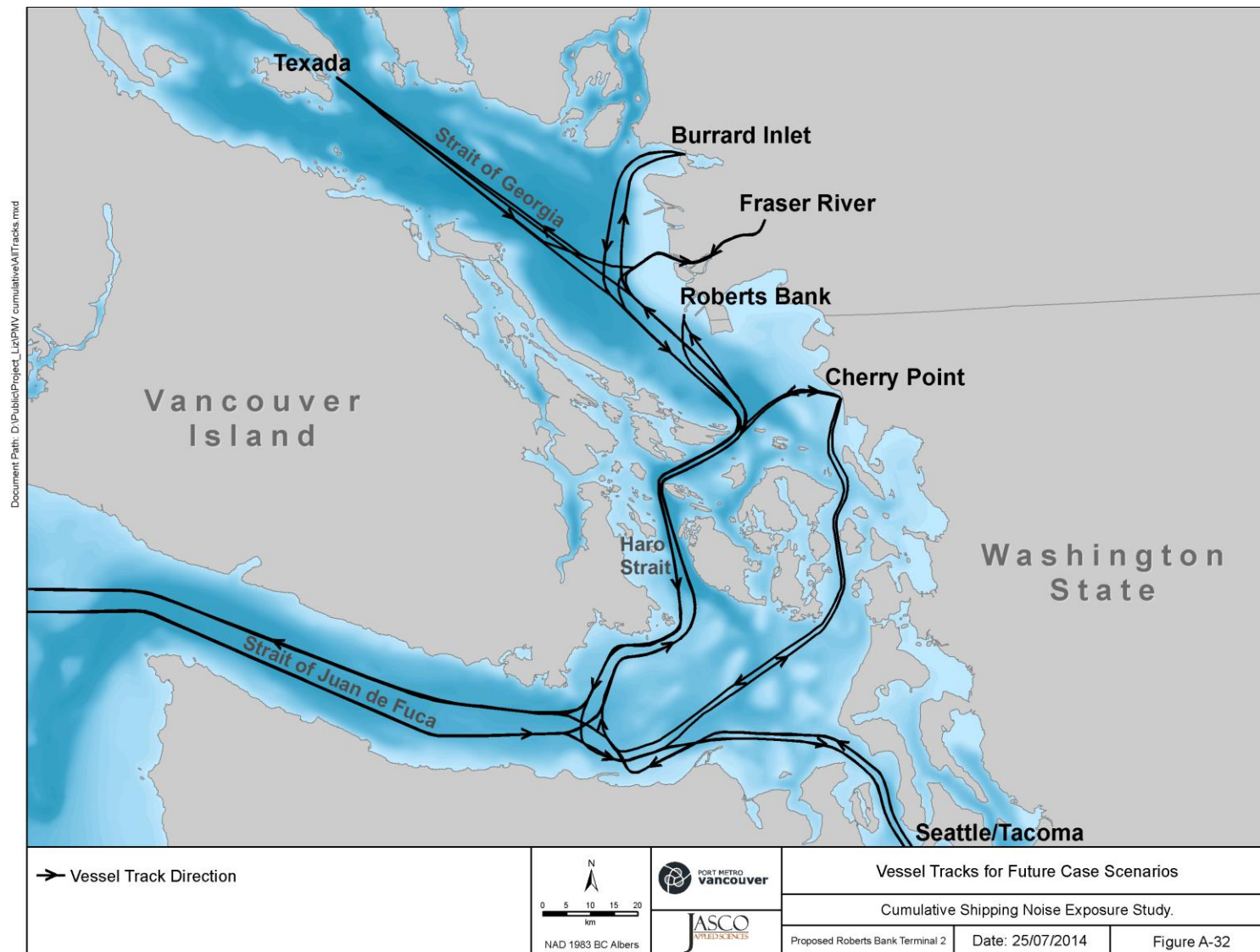
Figure A-32 Map of Vessel Traffic Routes Used for the Future Scenario Simulations
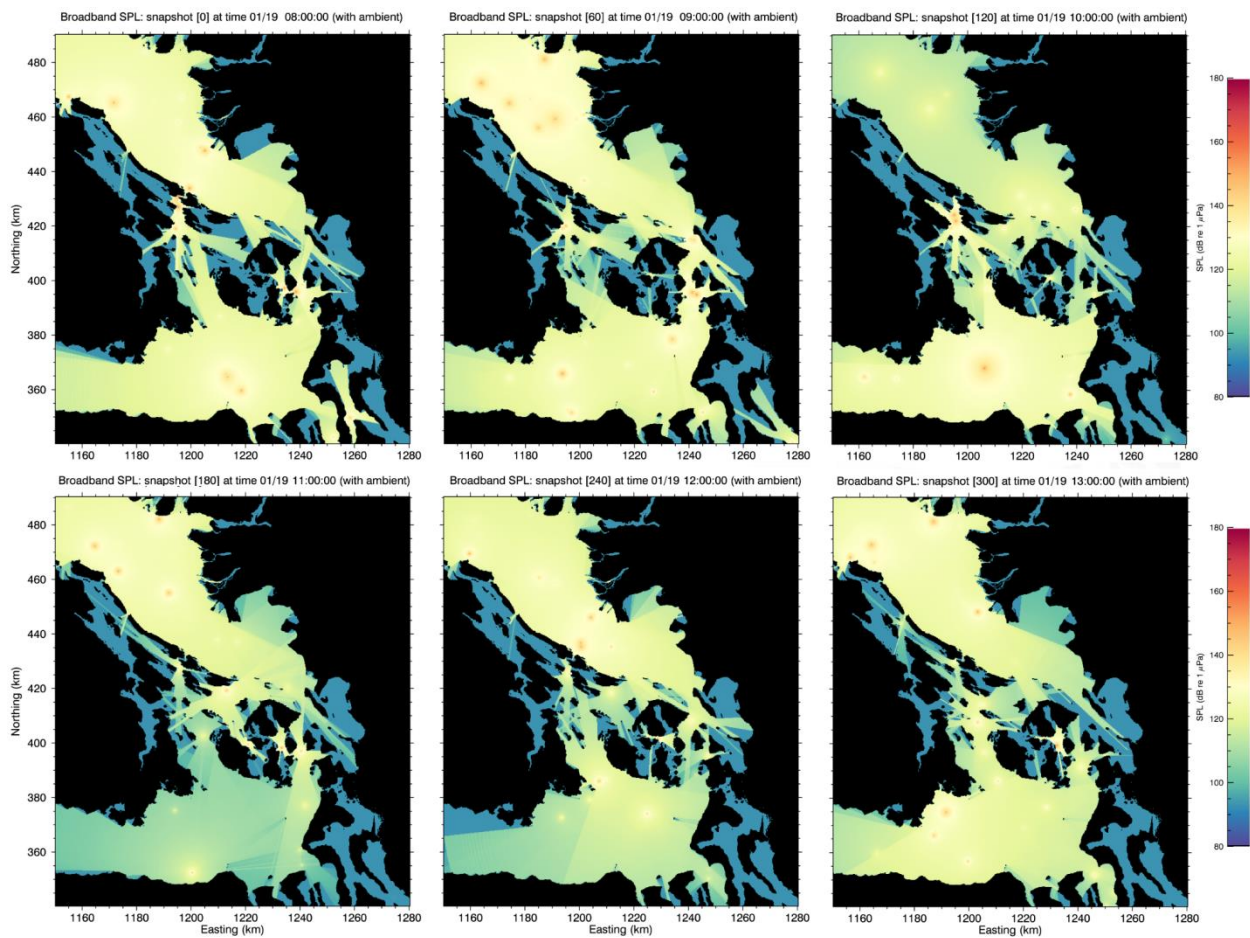
Figure A-33 Scenario S1: Example Time Snapshots of Unweighted SPLs for January. Time Step is 1 hour between Successive Snapshots. Grid Coordinates are BC Albers (NAD 83).
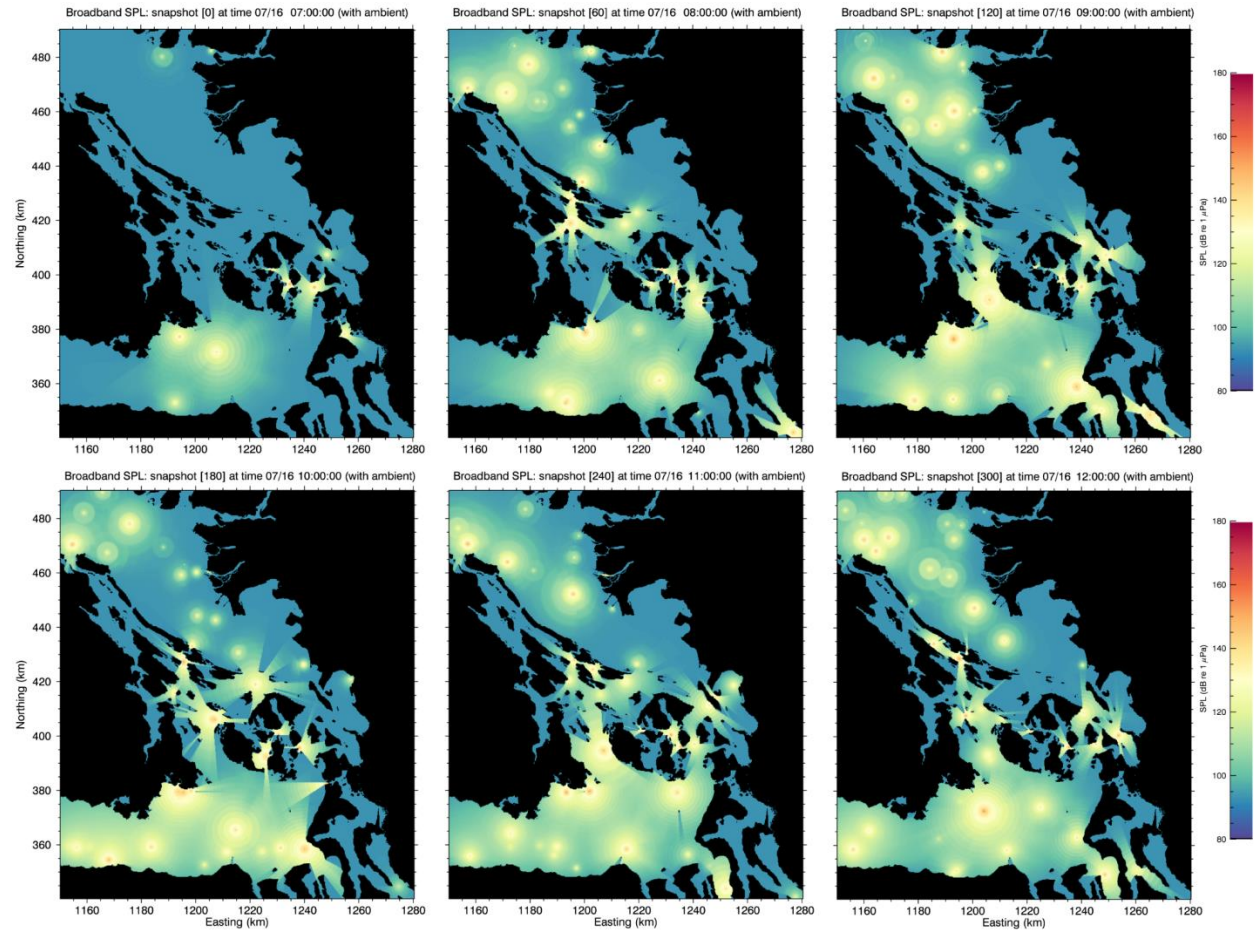
Figure A-34 Scenario S1: Example Time Snapshots of Unweighted SPL for July. Time Step is 1 hour between Successive Snapshots. Grid Coordinates are BC Albers (NAD 83).
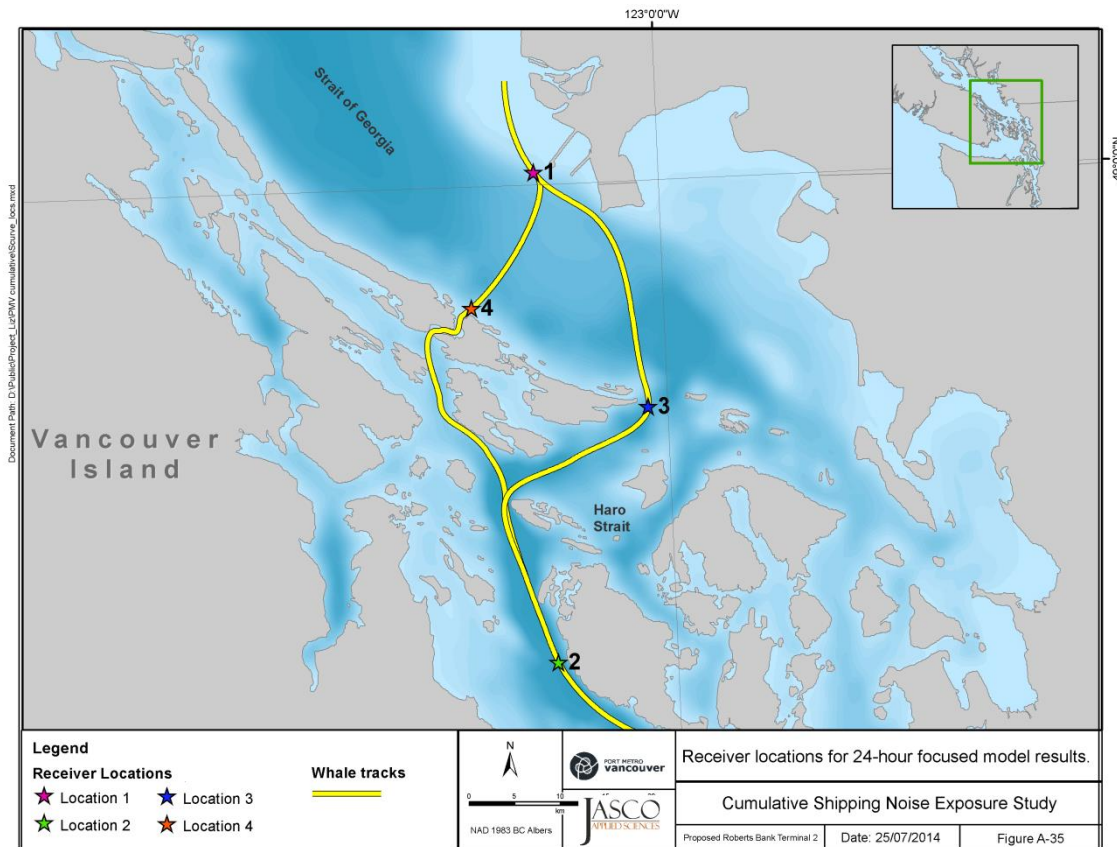
Figure A-35 Receiver Locations for Detailed Analysis of 24-hour Focused Model Results. Grid Coordinates are BC Albers.
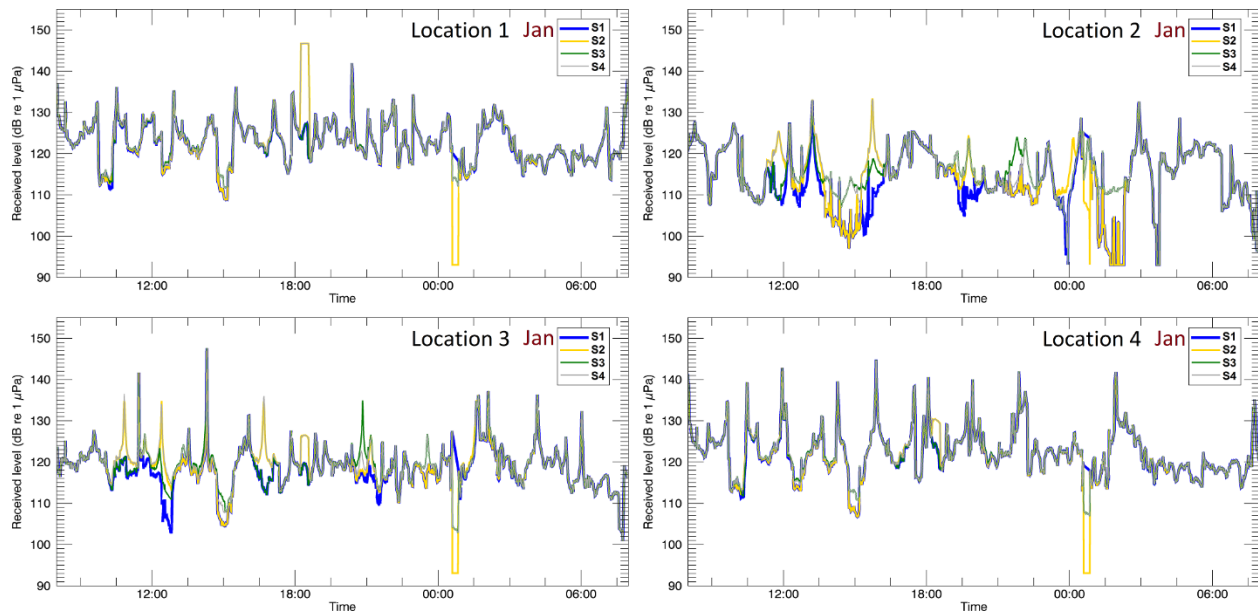
Figure A-36 Plot of Unweighted Received Levels versus UTC Time at Locations 1 to 4 from the 24-hour Focused Model for January
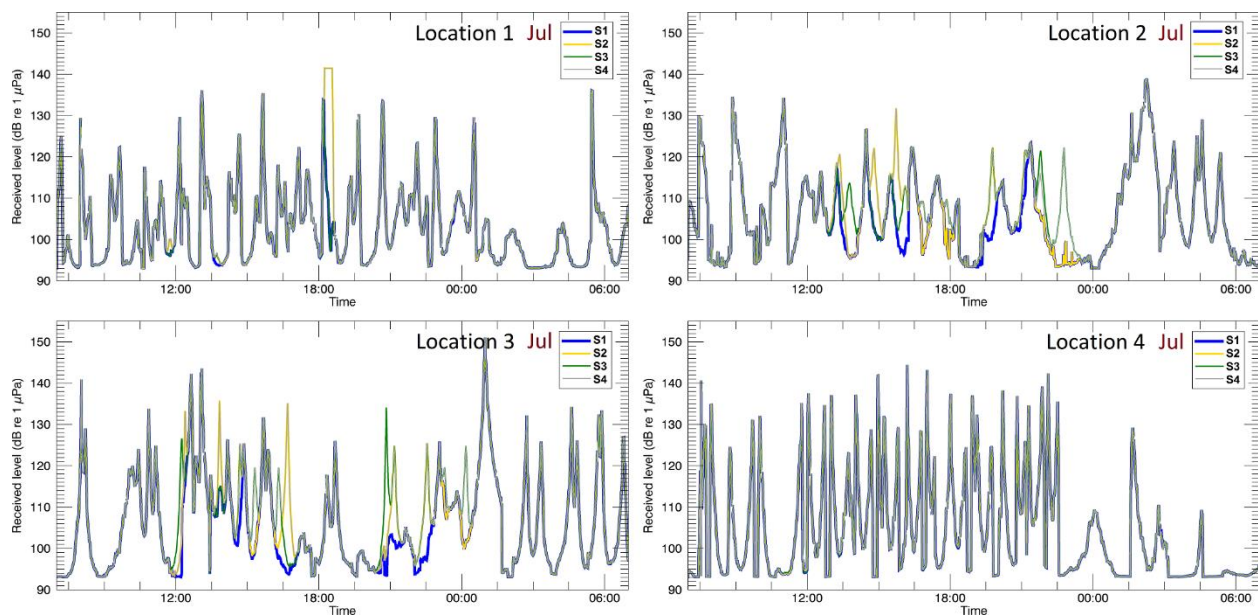

Figure A-37 Plot of Unweighted Received Levels versus UTC Time at Locations 1 to 4 from the 24-hour Focused Model for July
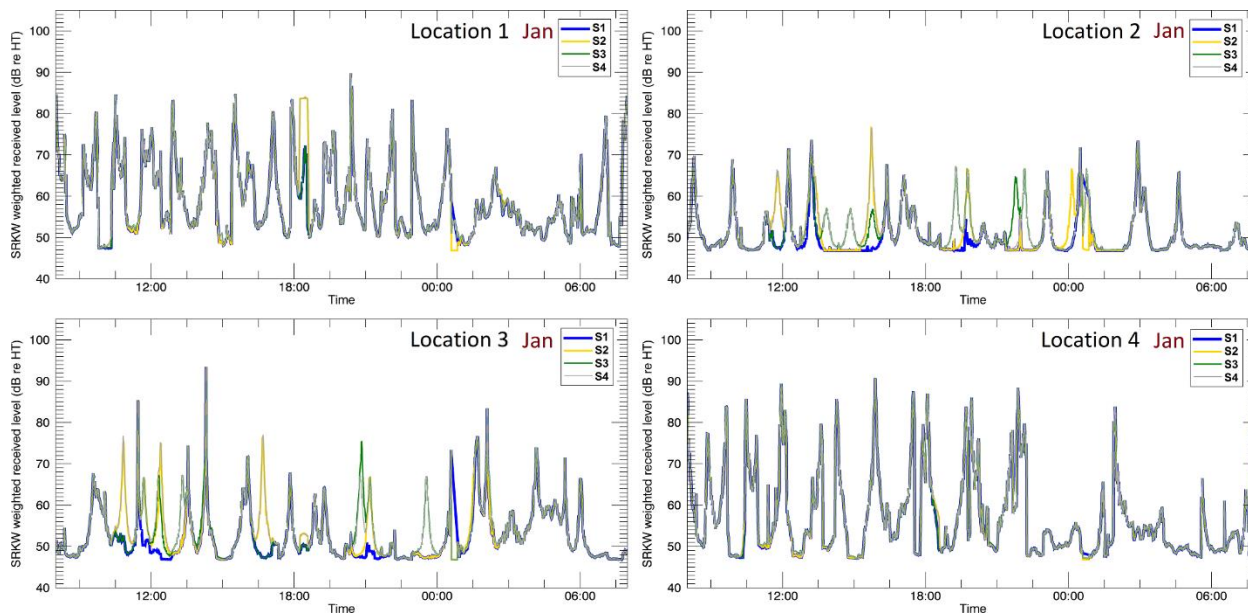
Figure A-38 Plot of Resident Killer Whale Audiogram-weighted Received Levels versus UTC Time at Locations 1 to 4 from the 24-hour Focused Model for January
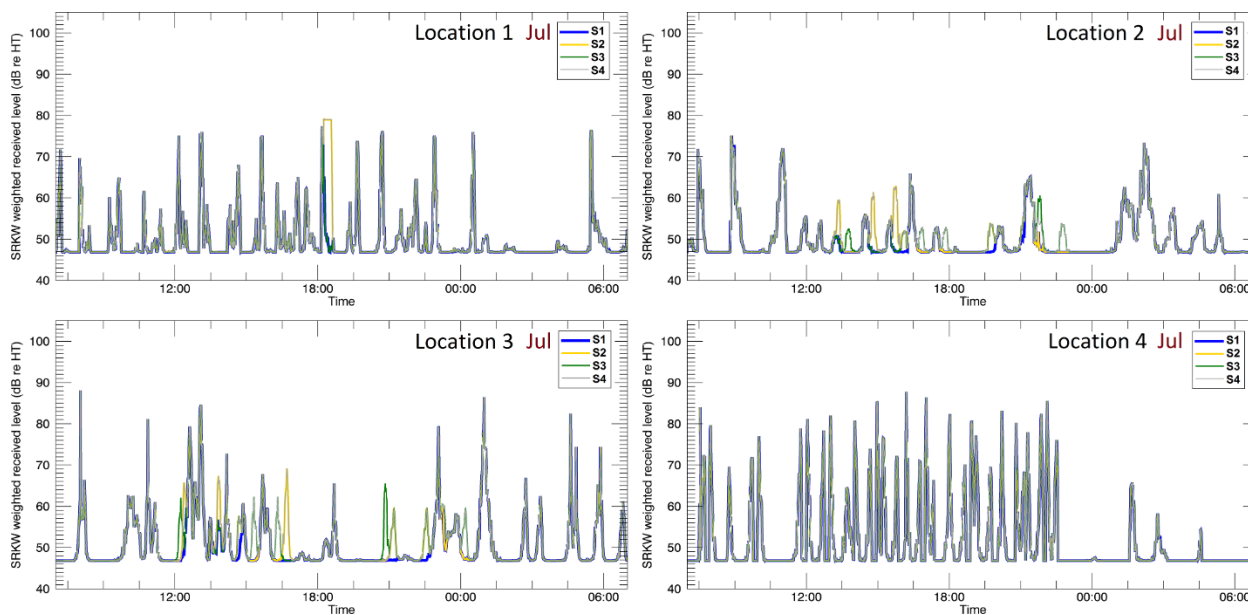

Figure A-39 Plot of Resident Killer Whale Audiogram-weighted Received Levels versus UTC Time at Locations 1 to 4 from the 24-hour Focused Model for July
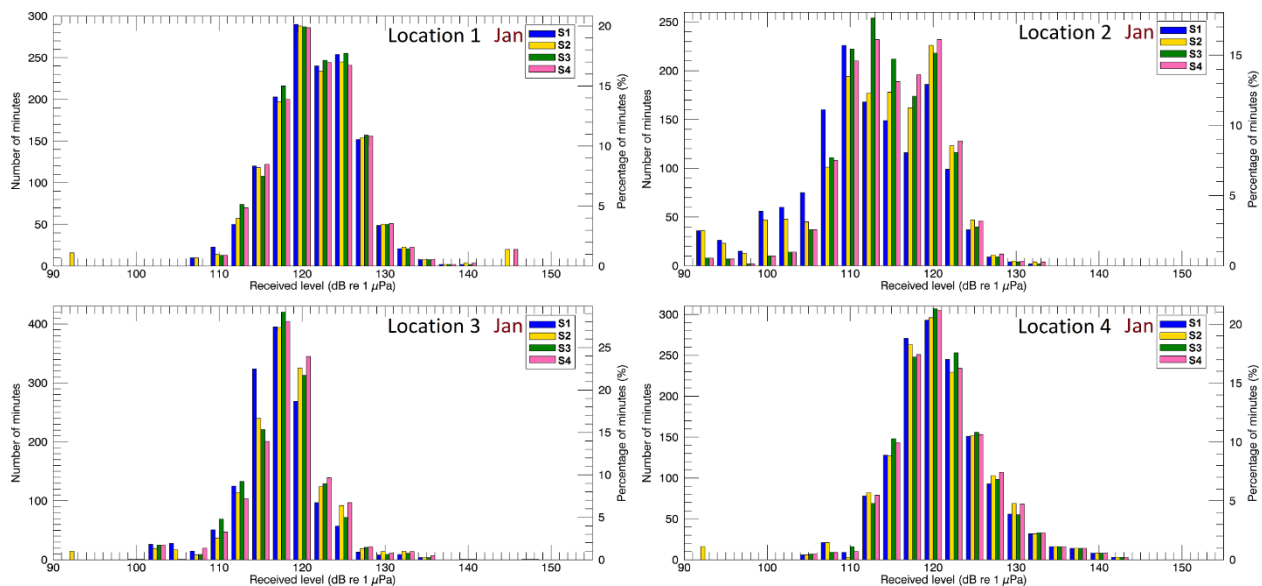
Figure A-40 Histogram of Unweighted Received Levels at Locations 1 to 4 from the 24-hour Focused Model for January
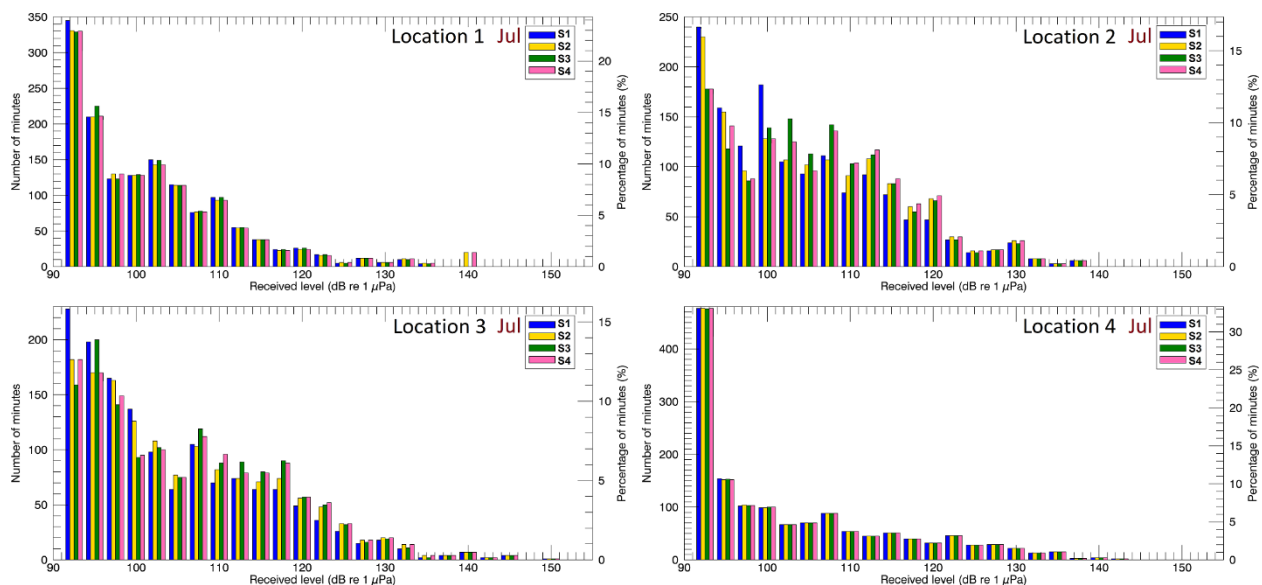

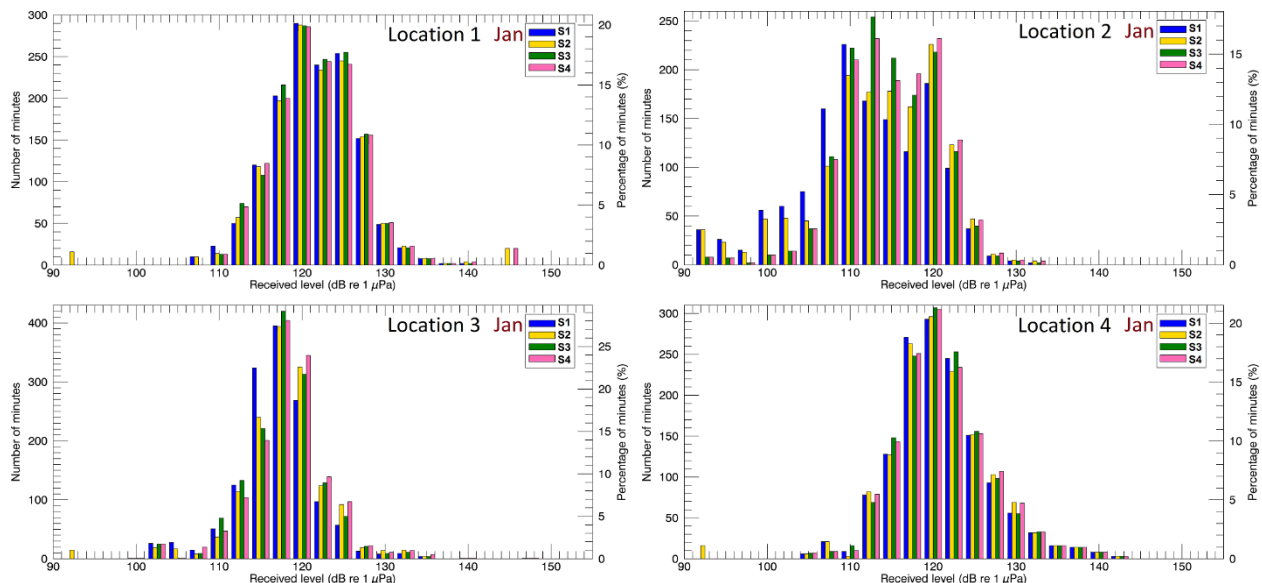**Figure A-41 Histogram of Unweighted Received Levels at Locations 1 to 4 from the 24-hour Focused Model for July**

Figure A-42 Histogram of Resident Killer Whale Audiogram-weighted Received Levels at Locations 1 to 4 from the 24-hour Focused Model for January
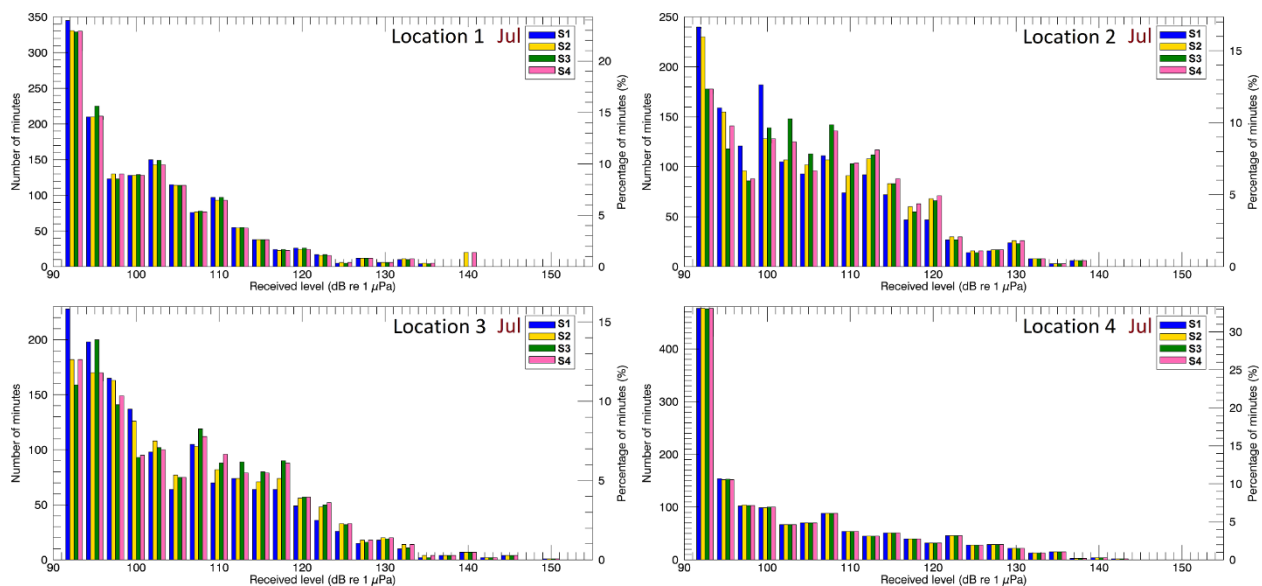

Figure A-43 Histogram of Resident Killer Whale Audiogram-weighted Received Levels at Locations 1 to 4 from the 24-hour Focused Model for July

APPENDIX 9.8-C

Rationale for Inclusion / Exclusion of Other Certain and Reasonably Foreseeable Projects and Activities in the Underwater Noise Assessment of Cumulative Change

This page is intentionally left blank

Appendix 9.8-C Rationale for Inclusion / Exclusion of Other Certain and Reasonably Foreseeable Projects and Activities in the Underwater Noise Assessment of Cumulative Change

The assessment included consideration of the potential for an interaction between potential Project-related changes to underwater noise and the changes resulting from other certain and reasonably foreseeable projects and activities on underwater noise. The rationale for inclusion or exclusion of each certain and reasonably foreseeable project and activity identified in **Table 8-8 Project and Activity Inclusion List** for the assessment of cumulative change for this IC is presented in **Table 9.8-C**.

Table 9.8-C   Rationale for Inclusion/Exclusion of Other Certain and Reasonably Foreseeable Projects and Activities in the Underwater Noise Assessment of Cumulative Change

Other Certain and Reasonably Foreseeable Project /Activity	Included (I) /Excluded (E)	Rationale for Inclusion / Exclusion
Projects		
BURNCO Aggregate Project, Gibsons, B.C.	E	No potential for cumulative interaction due to distant location from Roberts Bank.
Centerm Terminal Expansion, Vancouver, B.C.	E	Potential for cumulative interaction with RBT2 as the project will contribute to underwater noise from vessel traffic within the Strait of Georgia; however, the number of vessels is anticipated to be small compared to overall traffic (**Table 8-8**), and any cumulative change would not be measurable.
Fraser Surrey Docks Direct Coal Transfer Facility, Surrey, B.C.	I	Potential for cumulative interaction with RBT2 as underwater noise is anticipated from barge and vessel traffic.
Gateway Pacific Terminal at Cherry Point and associated BNSF Railway Company Rail Facilities Project, Blaine, Washington	I	Potential for cumulative interaction with RBT2 as underwater noise is anticipated from barge and bulk carrier traffic.
Gateway Program - North Fraser Perimeter Road Project, Coquitlam, B.C.	E	Not relevant to this IC assessment due to land-based nature of project.
George Massey Tunnel Replacement Project, Richmond and Delta, B.C.	E	No potential for cumulative interaction due to Project location upstream on Fraser River.
Kinder Morgan Pipeline Expansion Project, Strathcona County, Alberta to Burnaby, B.C.	I	Potential for cumulative interaction with RBT2 as the project is anticipated to contribute to underwater noise from tanker traffic within the Strait of Georgia.
Lehigh Hanson Aggregate Facility, Richmond, B.C.	E	No potential for cumulative interaction anticipated with RBT2 as project is expected to have a negligible contribution to future underwater noise levels.

Other Certain and Reasonably Foreseeable Project /Activity	Included (I) /Excluded (E)	Rationale for Inclusion / Exclusion
Lions Gate Wastewater Treatment Plant Project, District of North Vancouver, B.C.	E	No potential for cumulative interaction due to land-based project; noise generated from discharges to Burrard Inlet anticipated to be negligible.
North Shore Trade Area Project – Western Lower Level Route Extension, West Vancouver, B.C.	E	Not relevant to underwater noise assessment due to land-based nature of project.
Pattullo Bridge Replacement Project, New Westminster and Surrey, B.C.	E	Not relevant to underwater noise assessment due to land-based nature of project and inland location.
Southlands Development, Delta, B.C.	E	Not relevant to underwater noise assessment due to land-based nature of project.
Vancouver Airport Fuel Delivery Project, Richmond, B.C.	I	Potential for cumulative interaction with RBT2 as the project will contribute to underwater noise from tanker and barge traffic within the Strait of Georgia.
Woodfibre LNG Project, Squamish, B.C.	E	No potential for cumulative interaction with RBT2 due to distant location from Roberts Bank.
Activities		
Incremental Road Traffic Associated with RBT2	E	Not relevant to this underwater noise assessment due to land-based nature of activity.
Incremental Train Traffic Associated with RBT2	E	Not relevant to this underwater noise assessment due to land-based nature of activity.
Incremental Marine Vessel Traffic Associated with RBT2	I	Potential for cumulative interaction with RBT2 as the activity will contribute to underwater noise from container vessel traffic within the Strait of Georgia.