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Underwater Acoustic Monitoring Desktop Study: A Collaborative Initiative Between Port of Seattle (PoS) and the National Oceanic and Atmospheric Administration (NOAA)

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National Oceanic and Atmospheric Administration
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Plain Language Summary

Underwater passive acoustics is a method of sensing or monitoring sounds generated in aquatic environments. Traditionally, hydrophones or underwater microphones are used for underwater acoustic monitoring. These passive acoustics approaches are widely used to listen for and detect marine animals who rely on hearing and sound to sense their environment, find food, navigate, and communicate with others in underwater habitats where vision is limited. Researchers use passive acoustic approaches to document the presence and seasonal habitat use of various marine mammals including killer whales, given their vociferous nature. They also use this approach to study sources of underwater noise, natural or otherwise, which are used to characterize acoustic habitats or soundscapes. Passive acoustics approaches can also augment visual sightings of animals and other ocean sound sources, especially in darkness and foul weather.

Since the 1970s, researchers have used passive acoustic approaches to document the presence of locally occurring killer whales in the Salish Sea ecosystem, including endangered Southern Resident killer whales. The Salish Sea consists of the transboundary inland waters of Washington State and southern British Columbia, Canada, and includes several international ports and commercial vessel traffic corridors. Southern Residents rely on sound for finding their fish prey and to communicate among group family members, and have designated critical habitat in the Salish Sea. Given growing concerns about disturbance effects of vessels and noise, several programs have formed that focus on monitoring and mitigating the impacts of maritime vessels operating in Southern Resident habitats.

Following a key recommendation to implement ship monitoring programs and noise-reduction initiatives within Washington State, the Quiet Sound program was formed in 2021. Quiet Sound aims to understand and mitigate the acoustic and physical impacts of large commercial vessels in Washington waters that overlap with Southern Resident critical habitat. Quiet Sound complements similar efforts of the ECHO program led by the Vancouver Fraser Port Authority in British Columbia that launched in 2014. Both programs implement seasonal slowdowns of commercial vessels and support acoustic monitoring programs in Southern Resident habitats.

This report summarizes past and present underwater acoustic monitoring efforts within the geographic area of the Quiet Sound program; identifies spatial and functional gaps in monitoring of Southern Resident killer whales, commercial vessel traffic, and associated noise; and provides recommendations for future acoustic monitoring to evaluate commercial vessel presence and noise and mitigate potential impacts on SRKW, their habitat, and ecosystems more fully.

Links used in this section:

- Passive acoustics: https://passiveacoustics.fisheries.noaa.gov/
- Soundscapes: https://sanctsound.ioos.us/
- Salish Sea ecosystem: https://www.epa.gov/salish-sea/executive-summary-health-salish-sea-report
- Southern Resident killer whales: https://www.fisheries.noaa.gov/west-coast/endangered-species-conservation/southern-resident-killer-whale-orcinus-orca
- Critical habitat: https://www.fisheries.noaa.gov/action/critical-habitat-southern-resident-killer-whale
- Quiet Sound: https://quietsound.org/
- ECHO program: https://www.portvancouver.com/environment/healthy-ecosystem/echo

Executive Summary

This report provides an evaluation of underwater passive acoustic monitoring (PAM) efforts within the geographic scope of the Quiet Sound program in Washington State (Figure 1) and considers those of the Enhancing Cetacean and Habitat Observation (ECHO) program of the Port of Vancouver, British Columbia, Canada. Both programs have overlapping aims, which are to understand and reduce the acoustic and physical impacts of large commercial vessels on endangered Southern Resident killer whales (SRKW) through initiatives such as voluntary seasonal vessel slowdowns.

One of the main objectives of the study was to review past and present underwater PAM efforts to identify gaps in monitoring within the identified geographic area. We conducted literature reviews of and outreach on PAM efforts, covering details on spatial locations, equipment, software and analytical methods, data applications, access of archives, the distribution and spatial understanding of SRKW and commercial vessel use gleaned through PAM, best practices and limiting factors, and the status of PAM projects. We conducted outreach efforts through two online surveys. Past and present efforts have mostly focused on monitoring for Southern Resident and other killer whales and cetaceans using cabled hydrophones (nodes), often with live-streaming capabilities for educational and public interfacing purposes. Most utilized noncalibrated systems for cost and maintenance considerations. PAM efforts to measure noise from large commercial ships, including potential benefits from noise-reduction initiatives, largely involved calibrated hydrophone systems that are either cabled or autonomous to measure underwater noise according to national or international standards. These PAM efforts for measuring vessel noise have considerable costs to implement and maintain in consistent and robust ways, especially for long-term cabled systems, and are thus vulnerable to funding shortages.

We also evaluated the existing PAM network in the context of Quiet Sound noise reduction initiatives, including efforts capable of 1) measuring the effectiveness of commercial vessel slowdowns, especially in SRKW high-use areas, and 2) making real-time detection of SRKWs for dynamic management applications to address whale and vessel interactions. Some cabled nodes in the U.S. waters of Haro Strait have the capability to do both 1) and 2), but cabled nodes in Admiralty Inlet would need to be upgraded with calibrated systems to measure noise benefits of vessel slowdowns where they are currently implemented. We then identified spatial and functional gaps of the existing network gleaned from this evaluation. Spatial gaps largely overlap with those recently identified by the Quiet Sound program and include the Strait of Juan de Fuca, Salish Sea waters north of Admiralty Inlet, and central and south Puget Sound areas. Identified functional gaps were related to cabled systems' ability to make calibrated measurements of commercial vessel noise that follow standards and/or past methods, as well as to monitor in real time while providing detection, classification, and localization of sounds specific to the SRKW population. We thus recommend further investment to develop and implement an SRKW-specific detector–classifier for real-time automation and localization to improve the existing network for dynamic management applications. We also note the importance of data sharing across hydrophone operators and research groups with commercial mariners to maximize information for best conservation practices. We highlight several potential new PAM and complementary technologies that could improve spatial coverage, accuracy, and responsiveness. Our findings inform future acoustic monitoring efforts to assess commercial vessel noise and to mitigate potential impacts on SRKW and their habitats.

Acknowledgments

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Acronyms and Abbreviations

ADCP	acoustic doppler current profiler
A/D	analog-to-digital
AES	available echolocation space
AHB	area habitat biologist
AI	artificial intelligence
AIS	Automatic Identification System
ALS	available listening space
AMAR	autonomous multichannel acoustic recorder
ANSI	American National Standards Institute
ARTEMIA	Acoustic Real-time Exposure Model Incorporating Ambient
AURAL	Autonomous Underwater Recorder for Acoustic Listening
CAB	coastal acoustic buoy
CABOW	coastal acoustic buoy for offshore wind
CRAB	coastal real-time acoustic buoy
CSAS	Canadian Science Advisory Secretariat
CTD	conductivity–temperature–depth
DAS	distributed acoustic sensing
DFO	Department of Fisheries and Oceans Canada
DNR	Department of Natural Resources
EAR	ecological acoustic recorder
ECHO	Enhancing Cetacean and Habitat Observation program
FSVPAD	fisheries survey vessel passive acoustic drifter
GPS	Global Positioning System
HFC	high-frequency component
HPA	hydraulic project approval
Hz	Hertz (cycles per second)
ICES	International Conference on Environmental Systems
ISO	International Standards Organization
JARPA	Joint Aquatic Resource Permit Application
MANTA	making ambient noise trends accessible
MARU	Marine Acoustic Recording Unit
M-weighted	marine mammal weighting function
NARW	North Atlantic right whale

NEMES	Noise Exposure to the Marine Environment from Ships project
NMFS	National Marine Fisheries Service
nmi	nautical mile
NOAA	National Oceanic and Atmospheric Administration
NRT	near real time
NUWC	Naval Undersea Warfare Center
NWIFC	Northwest Indian Fisheries Commission
PAL	passive aquatic listener
PAM	passive acoustic monitoring
PATONS	private aids to navigation
PNNL	Pacific Northwest National Laboratory
PyPAM	Python passive acoustic analysis tool for passive acoustic monitoring
SEPA	State Environmental Policy Act (Washington State)
SMRU	Sea Mammal Research Unit
SoG	speed over ground
SPL	sound pressure level
SRKW	Southern Resident killer whale
TMX	Trans Mountain Expansion project
ULS	underwater listening station
URN	underwater radiated noise
VSR	vessel speed reduction
WDCA	whale detection and collision avoidance
WRAS	Whale Report Alert System

1 Past and Present Underwater Acoustic Monitoring Initiatives Including Spatial Understanding of Acoustic Data Associated with Southern Resident Killer Whales and Large Commercial Vessel Use in the Study Area

1.1 Literature Review

1.1.1 General overview

While killer whales, or orca (*Orcinus orca*), are currently identified as a single, globally distributed species, recent genetic studies support subspecies recognition between resident and transient ecotypes (Morin et al. 2024). Furthermore, many groups form small, reproductively isolated populations that are vulnerable to anthropogenic threats. One such population is the endangered Southern Resident killer whale (SRKW) that inhabits the transboundary waters of the Salish Sea and the Pacific Northwest coasts of the United States and Canada, which also include several international ports and commercial vessel traffic corridors. SRKW rely heavily on sound, using echolocation clicks for foraging, and pulsed calls and whistles for communication. Identified risk factors to their population recovery include prey availability and disturbance from vessels and noise, among other factors. Several studies—many of which are focused on whale-watching and smaller recreational vessels (Holt et al. 2009, Lusseau et al. 2009, Holt et al. 2021a,b, Tennessen et al. 2024)—have documented effects from vessels and noise on SRKW sound use and foraging behavior.

Several programs have formed to monitor and mitigate impacts of large commercial vessels in SRKW habitat, given concerns about increased anthropogenic activities in the marine environment, including maritime shipping and navigation. These include the Canada-based Enhancing Cetacean and Habitat Observation (ECHO) program led by the Vancouver Fraser Port Authority that launched in 2014, and a commitment by the Canadian government to mitigate the impacts of maritime traffic associated with the Trans Mountain Expansion (TMX) project (Robinson and Trounce 2016, DFO 2017). Mitigation strategies proposed or implemented include reducing vessel speed to decrease radiated noise, implementing vessel-quieting technologies, and redirecting commercial vessel traffic away from certain areas (DFO 2017, Trounce et al. 2019). Following a key recommendation to implement ship monitoring programs and noise-reduction initiatives within Washington State (Recommendation 22, SROTF 2019), the United States-based Quiet Sound program was formed in 2021. Quiet Sound aims to understand and mitigate the acoustic and physical impacts of large commercial vessels in Washington waters that overlap with SRKW critical habitat (USOFR 2021, Aronson and O'Morchoe 2023). Quiet Sound complements similar aimed efforts of the ECHO Program. Both programs support acoustic monitoring programs in the Study Area that are reviewed, along with other monitoring efforts, in subsequent sections of this report.

In this section, we review both peer- and non-peer-reviewed written sources about past and present underwater acoustic monitoring initiatives conducted within a specified geographic study area to inform future acoustic monitoring efforts of killer whales and large commercial vessels. The area (hereafter: “Study Area”) fits within the geographic scope of the Quiet Sound program as well as the ECHO program. The Quiet Sound geographic scope, while focused in some specific Washington State waters of the Salish Sea such as Puget Sound, Admiralty Inlet, and the Strait of Juan de Fuca, includes all SRKW critical habitat (USOFR 2021) within Washington waters (within 3 nmi seaward of its coastline). The ECHO program’s geographic scope includes the British Columbia waters of the Salish Sea (Haro Strait, Boundary Pass, Strait of Juan de Fuca), as well as Swiftsure Bank. In this review, we focus on papers and reports specific to underwater acoustic monitoring efforts of killer whales and/or large commercial vessels within these geographic areas.

1.1.2 General distribution of SRKWs in the Study Area

Little was known about the distribution of SRKW prior to the early 1970s, in part due to the inability of observers to distinguish between resident and transient (Bigg’s) killer whales. Early accounts of killer whales in Washington State describe usage of areas similar to those used by SRKW and transients today and movements to areas of high salmon and herring production (Scheffer and Slip 1948, Palo 1972). Since the 1970s, the increase in research, whale watching, and sightings from shore has provided extensive information about the movements and range of SRKW, especially within the Salish Sea. The Whale Museum in Friday Harbor, Washington, maintains the most comprehensive database of sightings from these sources (Olson et al. 2018, Haifley et al. 2022).[1]

Historically, SRKW presence in the Georgia Basin (defined as the Georgia Strait, the San Juan Islands, and the Strait of Juan de Fuca) has been predictable from early spring to early fall, when they are following their preferred prey, Chinook salmon (*Oncorhynchus tshawytscha*), returning to the Fraser River (Hanson et al. 2010). Multiple studies have demonstrated that SRKW concentrate their activity from the south side of San Juan Island northward through Haro Strait and the Gulf Islands to the Fraser River mouth, and to a lesser extent Rosario Strait (Hauser et al. 2007, Thornton et al. 2022, Stredulinsky et al. 2023). During these months, all three pods make short trips to southern Vancouver Island and the outer coast of Washington State. Sightings of SRKW in Puget Sound (south of Admiralty Inlet) increase in the late fall and extend through early winter (Olson et al. 2018), when they are thought to take advantage of chum and Chinook salmon runs (Hanson et al. 2021). SRKW occurrence in the Salish Sea becomes less frequent and predictable in the winter and early spring (Olson et al. 2018, Pilkington et al. 2023).

Winter movements and distribution, especially outside of the Salish Sea, have been identified as data gaps for SRKW (NMFS 2008, Hillborn et al. 2012). SRKWs’ coastal range extends from central California north to the Queen Charlotte Islands (NMFS 2021). Satellite tagging, large vessel surveys, sighting networks, and passive acoustic monitoring (PAM) have shown high usage of the nearshore waters of Washington State between the mouth of the Columbia River and the Strait of Juan de Fuca by SRKW during the later winter and early spring (Hanson et al. 2013, Emmons et al. 2021, Hanson et al. 2021).

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[1] https://whalemuseum.org

In the last few decades, there have been notable changes to these patterns of habitat usage by SRKW. Fall occurrence in Puget Sound has increased since the late 1990s (Olson et al. 2018), while presence in the Salish Sea has declined during spring months since the early 2000s (Shields et al. 2018a, Ettinger et al. 2022). Shields (2023) describes a further decline in spring and summer presence of SRKW from 2018–22, with complete absences from the Salish Sea in some summer months. Proposed reasons for these changes include declining Fraser River Chinook salmon (Shields et al. 2018a) and increased presence of Bigg's killer whales in the Salish Sea (Shields et al. 2018b).

1.1.3 Past and present efforts of acoustic monitoring for killer whales within the Study Area

The first documented hydrophone recordings of Salish Sea killer whales were made in the late 1950s and early 1960s by Canadian and U.S. Navies (Watkins et al. 1998), a few decades prior to more focused acoustic monitoring efforts of resident killer whales in their traditional summer habitat. OrcaLab, based on Hanson Island (B.C., Canada), was founded by Paul Spong in 1970, who spearheaded one of the first shore-based cabled acoustic monitoring programs of resident killer whales in Johnstone Strait, British Columbia (e.g., Gaetz et al. 1993, Deecke et al. 1999). These earlier efforts took advantage of PAM to document the presence and seasonal habitat use of resident killer whales, given their vociferous nature. PAM is also a powerful tool to augment visual detections, especially in darkness and inclement weather. Today, OrcaLab has live-streaming capability and is part of the B.C. Hydrophone Network.[2] By the late 1970s, both boat- and shorebased hydrophone recordings of Southern Residents in the Salish Sea were regularly made by Orca Survey, now the Center for Whale Research (e.g., Foote et al. 2004). In 1983, the Whale Museum also began acoustically monitoring Southern Residents, and in 2000 established the SeaSound Remote Sensing Network that included the cabled hydrophone maintained off of the Lime Kiln Lighthouse on San Juan Island.

In the late 1990s, additional cabled hydrophones were installed to form an array off of the Lime Kiln Lighthouse and, by the early 2000s, Val Veirs installed an additional node off of his San Juan Island home (the Orcasound Lab node) in Haro Strait, which supported many student research projects at Colorado College and through the earlier Beam Reach program, led by his son Scott Veirs. These formidable efforts evolved into Orcasound,[3] which partners with various collaborators to maintain several live-streaming cabled hydrophone locations or nodes within the Salish Sea Hydrophone Network.[4] The number and location of Orcasound nodes has expanded and contracted based on available funding, given the considerable cost to maintain each node. Notably, in 2016, the Whale Museum and SMRU Consulting upgraded the live-streaming hydrophone node at Lime Kiln[5] and provided several datasets for the ECHO Program (e.g., Joy et al. 2019, Malinka et al. 2023b). Another cabled hydrophone was also installed on the west side of Vashon Island and maintained from 2004–13 by the American Cetacean Society (Ann Statler and Joe Olson). The Vashon

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[2] https://orcalab.org/projects/bc-hydrophone-network

[3] https://www.orcasound.net

[4] https://www.eopugetsound.org/articles/salish-sea-hydrophone-network-and-orca-network

[5] https://mcp.stream101.com/start/smrucons/

Hydrophone Project,[6] focused on monitoring Southern Residents in central Puget Sound during the fall and winter, was largely opportunistic in its efforts, and like many other projects vulnerable to funding shortages to maintain operations.

More recently, the Whale Tracking Network of Fisheries and Oceans Canada (DFO) consisted of nine PAM stations located in B.C. waters of the Salish Sea initially deployed by Ocean Sonics in 2017 to detect and track SRKW and to warn about potential threats such as vessel strikes or risk of exposure in case of an oil spill. Details are given in Ocean Sonics (2017) and Yurk et al. (2023). Briefly, each station or node consisted of 1–4 icListen digital hydrophones that recorded continuously and were connected to shore by an underwater ethernet cable. Acoustic files were transmitted via WiFi, and archival acoustic data exists for at least some of the nodes.

In addition to these dedicated cabled systems, several other project-specific efforts have relied on hydrophone recordings to monitor Salish Sea killer whales and/or commercial vessels relevant to the Quiet Sound geographic area. John Ford was one of the first researchers to focus on killer whale acoustics and he described three main categories of sounds produced by Salish Sea killer whales: echolocation clicks, pulsed calls, and whistles. This seminal work led to several publications, including: 1) a description of the acoustic behavior of individually identified Northern and Southern Residents correlated with activity states (Ford 1989), 2) documentation of the vocal tradition with a focus on pulsed call production and classification, defining discrete, aberrant, and variable call types and documenting variation in call production and vocal repertoire among matrilines and pods that form distinct acoustic clans (Ford 1991), and 3) a call catalogue still used today, which describes several discrete (stereotypic) call types that are stable in structure for each of the killer whale populations he encountered in the coastal waters of British Columbia, including the Salish Sea (Ford 1987). This work was foundational in understanding that discrete call production of killer whales in the Salish Sea is identifiable to population and even pods or matrilines, which makes acoustic monitoring of these cetaceans so valuable. Subsequent studies demonstrate that Salish Sea killer whales produce stereotyped whistles that are unique to specific populations, which may be used to diagnose presence through acoustic detections as well (Riesch et al. 2006, Souhaut and Shields 2021).

Other efforts have leveraged the deployment of autonomous acoustic recording systems to monitor killer whales throughout the Study Area. NWFSC has utilized PAM to address the data gap of coastal distribution with the deployment of acoustic moorings from Pt. Reyes, California, to Cape Flattery, Washington (Hanson et al. 2013, Emmons et al. 2019, 2021). DFO has deployed autonomous recorders along the coast of British Columbia to monitor the occurrence of cetaceans, including resident killer whales (Ford et al. 2017, Riera et al. 2019, Thornton et al. 2022), and in the Canadian waters of the Salish Sea to monitor killer whale movements (Pilkington et al. 2023).

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[6] https://acspugetsound.org/VHP/about-VHP.php

1.1.4 Past and present efforts of acoustic monitoring associated with large commercial vessels

At the time of SRKW endangered status listing, disturbance from vessels and/or noise became a research focus for acoustic monitoring efforts using both cabled and autonomous hydrophone systems in the Study Area (Bassett et al. 2012, Veirs et al. 2016). Several studies using Automatic Identification System (AIS) telemetry data have analyzed vessel movements categorized by class and correlated with acoustic measurements to demonstrate that commercial vessel noise is pervasively present in many areas within SRKW critical habitat (Burnham et al. 2021); cargo vessels and tankers are often the largest contributors to noise budgets in the Study Area overall (Bassett et al. 2012, Veirs et al. 2016), with seasonal and subregional variability (Burnham et al. 2021, McWhinnie et al. 2024). Many studies have also reported acoustic measurements that are frequency-specific to SRKW hearing and/or sound production (e.g., Heise et al. 2017), which estimates underwater noise within the Study Area as it is experienced by SRKW (Bassett et al. 2012, MacGillivray et al. 2019, Wilder et al. 2024). This section summarizes the main findings of several relevant studies.

In Bassett et al. (2012), noise measurements were made from a Loggerhead Instruments hydrophone system that recorded on a duty cycle, sampled at 80 kHz; recordings were paired with AIS data to quantify the contribution of large vessel traffic to the underwater soundscape in Admiralty Inlet from May 2010 to May 2011. This site was proposed for tidal energy development, and impacts to protected marine species were under consideration. Noise measurements based on spectra, one-third octave and broadband levels (for details, see Richardson et al. 1995) that were either unweighted or M-weighted depending on the hearing sensitivity of five groups of marine mammals (Southall et al. 2007), were calculated over hourly, daily, and monthly averages and reported in percentile statistics. Over 1,350 unique AIS-vessel transits were logged, with at least one vessel recorded in the study area over 90% of the time. The mean broadband sound pressure level (SPL, based on root mean square pressure in dB re 1 μPa) was 119.2 dB (0.02–30 kHz), and cargo vessels were the largest contributors to the site's noise budget, followed by tugs and passenger ferries.

Williams et al. (2014) report ambient noise statistics for five species-specific bands, including three frequency bands for killer whale communication signals, at 12 sites along the B.C. coast, including two within the Study Area (Haro Strait and Strait of Georgia). SPL noise measurements were made from duty-cycled recordings collected by MARU recording systems (Clark and Clampham 2004) anchored on the seafloor. The investigators computed ambient noise statistics on a daily time scale, reported as daily noisiest (highest) levels, daily median (average) levels, and daily quiet (lowest) levels that were each then averaged as median values across the entire MARU deployment duration for each site. Estimated reduction of communication space was calculated as the relative difference between the median or noisiest levels relative to the quiet levels for the entire deployment duration-averaged measurements. For the killer whale frequency bands, estimated reduction of communication space under the noisiest conditions ranged from 0–97%, with the highest reduction being at the lowest frequency band (1.5–3.5 kHz) and the lowest reduction being at the highest frequency band (18–30 kHz). Exploratory analysis of anthropogenic versus natural contribution sources to these noise levels for the deployment sites illustrated that the dominant broadband noise at Haro Strait was characteristic of shipping traffic.

Veirs et al. (2016) report received and estimated source levels of AIS-transmitting vessels made from continuous recordings of the cabled and calibrated (Reson TC4032) hydrophone off of Lime Kiln Lighthouse in nearshore Haro Strait waters during spring 2011 through fall of 2013. Source levels are SPL measurements of vessel noise referenced to a distance of 1 m and are expressed in dB re 1 µPa (Erbe et al. 2019). Main findings utilizing this acoustic data include that received levels of vessels in the shipping lane (within 3 km of the hydrophone) were detectably above measured ambient levels at lower (< 1 kHz) as well as higher (10–96 kHz) frequencies used by echolocating killer whales. The average broadband (11.5 Hz–40 kHz) received level for the entire dataset of AIS transiting vessels was 110 dB SPL. The vessel source levels reported in this study were lower at the lower frequencies but higher at the higher frequencies relative to other comparison studies, attributed to methodological differences, slower vessel speeds, and shallower water depths of the hydrophone.

Cominelli et al. (2018) modeled SRKW exposure to noise from commercial shipping. They used SRKW kernal density estimation to delineate summer core areas of SRKW in the Salish Sea and the JASCO Applied Sciences cumulative noise model for the Noise Exposure to the Marine Environment from Ships (NEMES) project. The noise model estimated vessel noise in one-third octave bands from 10 Hz to 63.1 kHz using AIS data to define vessel categories, vessel counts, total number of hours of vessels, and vessel speed, to generate monthly cumulative noise distributions in 800 × 800 m grids that were grouped into three subarea zones based on which vessel categories predominate and overlap with SRKW habitat usage by pod. Exposure levels, which factor in duration of vessel noise exposure, were estimated from median cumulative noise values with the following categories showing high levels of exposure in all three subareas: tugboats, vehicle carriers, containers, and bulkers. Ferries and recreational vessels were contributors to high exposure levels in some subareas/grids as well (Cominelli et al. 2018, their Figure 16).

Scientists from Ocean Initiative report on a pilot study to develop an acoustic monitoring program for the Puget Sound Partnership's "Noise in Marine Water" Vital Sign Indicator that involved measuring noise levels at selected sites in Puget Sound tied to a range of vessel traffic intensity from both commercial and recreational vessels (Ashe et al. 2023). They used calibrated SoundTrap (ST600 HF) hydrophones placed at five locations to collect passive acoustic data on a duty cycle to measure noise levels, and supplemented these efforts with spot recordings made both by the scientists using autonomous multichannel acoustic recorders (AMARs) and community science partners with provided Cetacean Research Technology hydrophone (SQ28-06), handheld recording device, data storage, and batteries. Results indicated that 3-minute averaged broadband (20 Hz–150 kHz) SPLs were highest on average for Elliott Bay, Washington, and lowest for Port Townsend, Washington (Ashe et al. 2023).

McWhinnie et al. (2024) gleaned satellite AIS data, sourced from exactEarth Ltd., to provide a description of vessel transits by volume and type in SRKW critical habitat of the Salish Sea (both United States and Canada). Detailed descriptions were also provided for Active Pass and Boundary Pass. Vessel data were analyzed for two "seasons," defined as Winter (Dec–Feb) and Summer (Jun–Aug) over four consecutive years from December 2012 through August 2016. Results include a strong seasonal effect of vessel presence in Active Pass, with an unsurprisingly higher level of ferry traffic in the summer, and an annual increase in cargo, tanker, and ferry presence (in terms of vessel hours) over the study period, especially for cargo ships in Boundary Pass. Summer transits of cargo and passenger vessels were also fastest on average in the beginning of the study, but speed of both types decreased over time.

Understanding how vessel design and operation influence noise emissions of large commercial vessels is paramount for implementing mitigation measures to reduce disturbance to SRKW in the Study Area. Calibrated recordings collected from September 2015 through January 2020 from a combination of cabled hydrophone nodes and bottom-mounted AMARs were used to estimate source levels of 9,880 transits of 3,188 large vessels measured at three locations within the ECHO program (Haro Strait, Boundary Pass, and Strait of Georgia). Correlating these measurements with several statistically tested vessel design and operational variables, MacGillivray et al. (2022) reported that speed through water and actual draft were the strongest operational predictors of measured source levels for all vessel categories represented (cruise ships, container ships, bulk carriers, tankers, tugs, and vehicle carriers). Vessel length was the strongest design predictor of source levels for bulkers, containers, and tankers. Vessel engine revolutions per minute and power, design speed, and age had weaker but significant contributions to source levels and thus radiated noise as well.

While vessel speed is correlated for many categories of large commercial vessels operating in the Study Area, slowing down some vessels does not decrease their patterns of noise emission (Frouin-Mouy et al. 2018). Underwater noise emitted by ships is primarily generated by machinery, turbulence, and cavitations, with cavitation typically being the dominant source of noise emitted by vessels. Vessels outfitted with fixed pitch (FP) propellers have components of radiated noise that depend on speed. However, vessels with controllable pitch (CP) propellers use propeller pitch to control speed; thus, the relationship between speed and noise emitted in these types of vessels is more complicated. A common class of vessel with CP propellers in the Study Area is passenger ferries, which were the focus of an empirical JASCO study on the relationship between ferry operating conditions and underwater noise (McIntyre et al. 2021). In this study, the AMAR G3 hydrophone recording system was used to measure emitted ferry noise during controlled passes at the following tested speeds: Full Away (FA), representing the upper end of practical service speeds; Service Speed (SS), the typical speed for the ferry route; a 2 kn Reduction (r2) and a 4 kn Reduction (r4), 2 and 4 knots slower than typical SS, respectively; and Half Speed (HS), which is half of SS. Five of the eight ferry vessels tested had CP propellers; the other three had FP propellers. Noise emitted by four of eight ferries was anti-correlated with speed in which they all had CP propellers. These four CP-propeller vessels were quietest when operating close to or above their designed SS, suggesting that reducing speed for these vessels is counterproductive (McIntyre et al. 2021).

MacGillivray et al. (2025) used updated datasets and modeling techniques to address several additional questions regarding vessels as ocean noise contributors in SRKW habitat of the Salish Sea. JASCO's Acoustic Real-time Exposure Model Incorporating Ambient (ARTEMIA) was used to compute winter (January) and summer (July) monthly-average sound maps for nine subregions of habitat (Stredulinsky et al. 2023, their Figure 1, based on Thornton et al.'s 2022 report to the Canadian Science Advisory Secretariat, CSAS) for ambient noise and for 15 categories of vessels (Thornton et al. 2022, their Table 2). They used 2022 AIS data for vessel presence/movement and reviewed vessel underwater radiated noise (URN) datasets for source levels of AIS vessels. Investigators used aerial and camera survey data to estimate presence of fishing and recreational vessels, as they typically do not transmit AIS information; they noted that spatial coverage of these supplemental data on non-AIS vessels was limited or absent in some subregions (e.g., Swiftsure Bank), so a scaling factor was added to enhance estimates. Sound maps were modeled for three separate frequency bands: broadband (0.01–50 kHz), SRKW communication (0.5–15 kHz), and SRKW echolocation (15–50 kHz). Total contribution for each category of noise source was ranked relative to its monthly-average SPL. Over the whole region, roll-on/roll-off (ro-ro) ferries were the largest noise contributor to the broadband soundscape, followed by container ships, bulk carriers, anchored cargo vessels, oil tankers, and then tugs in the winter and fishing/recreational vessels in the summer. Tugs and fishing/recreational vessels were higher noise contributors in the two SRKW frequency bands, particularly so for fishing vessels in July. Relative noise contributions by vessel category varied among seasons, subregions, and frequency bands. For Swiftsure Bank and the Strait of Juan de Fuca, for example, container ships and bulk carriers were the largest contributors in winter, while fishing vessels were the largest contributors in the summer. Sonar emitted from fishing vessels with peaks in the 30–50 kHz range, which overlaps with frequencies used by SRKW for biosonar-based foraging, were an important contribution to the noise measurements of this vessel category. Monthly-average SPL from all vessel categories combined exceeded ambient sound by more than 10 dB throughout more than 90% of the Study Area.

1.1.5 Past and present acoustic monitoring efforts associated with speed reduction programs for commercial vessels in the Study Area: The ECHO and Quiet Sound programs

Given that large commercial vessels are the main contributors to anthropogenic noise inputs in SRKW habitat and that slowing vessels down often reduces the resulting underwater noise emitted (McKenna et al. 2013, Simard et al. 2016, MacGillivray et al. 2022), first ECHO and then Quiet Sound have implemented seasonal voluntary slowdown zones for commercial vessels in the Study Area. Several papers and reports highlight efforts and benefits associated with the implementation of the ECHO vessel speed reduction (VSR) program (Joy et al. 2019, MacGillivray et al. 2019, Wilder et al. 2024); they are reviewed in this section.

MacGillivray et al. (2019) report findings of the first seasonal VSR implemented by the ECHO program in 2017 in Haro Strait. The voluntary VSR ran from 7 August–6 October 2017, timed to when SRKW typically had the highest occupancy in the area. JASCO Applied Sciences measured commercial vessel noise using two calibrated AMAR G3 hydrophone units deployed in both the north- and southbound vessel traffic lanes of Haro Strait during the slow period, and another real-time hydrophone node (or underwater listening station) in the Strait of Georgia (ECHO SoG ULS) as vessels operated at normal transit speeds. Received noise levels and various propagation loss assumptions were used to calculate vessel source levels (SLs) in three frequency bands: broadband (0.01–100 kHz), SRKW communication (0.5–15 kHz), and SRKW echolocation (15–100 kHz). The AMARs sampled acoustic data at two sampling rates on a duty cycle (96 kHz for 21 hr/day, 128 kHz for 3 hr/day), while the ECHO SoG ULS sampled acoustic data at 64 kHz. The investigators collected vessel attribute data, including vessel speed, using an AIS receiver station located to the west, and vessels were assigned to three groups based on date and pilot participation logs: 1) control period outside of the slowdown period, 2) non-participant during the slowdown period, and 3) participant during the slowdown period. Mean vessel speed in the participant group was significantly less than in the control or non-participant group, and was the most reduced for container ships. A direct comparison of participating vessels before and after the slowdown period illustrated significant reductions in mean broadband SLs for five commercial vessel categories as follows: container ships (–11.5 dB), cruise vessels (–10.5 dB), vehicle carriers (–9.3 dB), tankers (–6.1 dB), and bulkers (–5.9 dB; MacGillivray et al. 2019). The largest reductions were in the low (< 100 Hz) and high (> 1 kHz) frequency ranges. The correlation between vessel source level and speed also showed frequency dependence; it was greatest above 15 kHz in the SRKW echolocation band and lowest in the SRKW communication band.

Joy et al. (2019) also measured received levels of vessel noise during the 2017 ECHO voluntary VSR using the Lime Kiln (LK) hydrophone node further inshore of the vessel traffic lane in Haro Strait, along with the two AMARs in the vessel traffic lane in Haro Strait and the SoG ULS and AIS receivers used in MacGillivray et al. (2019). Compared to the baseline period, the investigators reported a 1.2 dB reduction in median broadband noise (0.01–100 kHz) at the LK hydrophone location despite longer vessel transit times through Haro Strait during the slowdown period. The median reduction was greater (2.5 dB) when only commercial vessels were within a 6 km radius of LK node during the slowdown. The reductions in vessel noise levels were highest for the lowest frequency band (10–100 Hz, –3.1 dB) and lowest in the 10–100 kHz band (–0.3 dB). The investigators also modeled SRKW exposure as their co-occurrence within the slowdown region using a spatiotemporally explicit approach and converted these exposures to impacts of “lost foraging time.” Model results estimated that vessel slowdowns under the typical participation rate resulted in a 22% reduction in “lost foraging time,” while a 40% reduction in “lost foraging time” would be achieved under a 100% participation rate in which vessels reduce speed to 11 knots.

Wilder et al. (2024) modeled SRKW acoustic space without (“Baseline”) and with (“Slowdown”) VSRs for more recent ECHO slowdown scenarios, as this program has expanded to Boundary Pass and other areas in SRKW habitat.[7] Acoustic space was estimated in frequency bands of sounds to represent 1) available listening space, ALS, for SRKW communication (0.5–15 kHz) and 2) available echolocation space, AES, for SRKW biosonar-based foraging (15–100 kHz). Modeling results relied on JASCO’s ARTEMIA model that combines detailed input from several noise sources—including AIS-based vessel transits, vessel source levels, and environmental data—to predict underwater sound levels. The Haro Strait and Boundary Pass 2023 slowdown areas of the ECHO program were modeled for acoustic space, divided into 200 × 200 m grids, for predicting sound pressure levels in one-minute intervals during the simulation period. Actual participation rates and speeds of vessels over a two-week period (17–30 July) in 2023 were used for both conditions; vessel movements for Baseline were modeled from historic AIS data of the study area. Available acoustic space, x, was defined as the ratio of the reduced volume, $V2$, under shipping noise conditions to the natural volume, $V1$, of the theoretical acoustic space an animal would

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[7] https://www.portvancouver.com/echo

inhabit under natural conditions, with 0 being poor and 1 being excellent conditions. Note that the model makes physics-based assumptions about acoustic space for two biologically defined but broad frequency bands that do not take into consideration specific auditory masking mechanisms (e.g., critical ratios or critical bands of killer whales) to predict listening in noise to compare Baseline and Slowdown conditions (see Holt 2008 for details).

Wilder et al. (2024) qualitatively divided the available acoustic space conditions into six space ranges based on *estimated reductions from maximum available space* under different modeled scenarios (Wilder et al. 2024, their Table 3). These reductions were calculated in the number of median minutes per day for which noise levels resulted in available acoustic space within these defined ranges. For example, if under Baseline conditions, $x \leq 0.1$, the authors defined the available acoustic space as "very poor," and any relative change in minutes that this very unfavorable listening space can be limited under Slowdown conditions is considered beneficial to SRKW. AES effects were spatially more constrained than ALS, especially at the lower available space ranges due to expected frequency-dependent sound propagation losses. However, the Slowdown had beneficial effects on periods of both low and high available AES and ALS. That is, shorter durations of "very poor" conditions and longer durations of "good" or "very good" listening conditions were estimated under Slowdown relative to Baseline (Wilder et al. 2024, their Table 7 and Figure 23). The median amount of quiet time ($x > 0.9$, very good acoustic space) increased during the slowdown by 35.6 and 19.9 minutes/day for AES and ALS, respectively. The median duration of "very bad" listening conditions decreased by 4.4 and 43.9 minutes/day for AES and ALS, respectively. Wilder et al. (2024) then considered the spatial overlap of SRKW occurrence in the area from 1 June–31 October 2023 and assumed similar patterns of acoustic space during the voluntary slowdown period to estimate these qualitative changes in AES and ALS across space and time. For the full five-month period, Slowdown resulted in increased quiet time of 15.6 and 8.6 total hours for AES and ALS, respectively, with a concomitant decrease in "bad" or "very bad" (acoustic space) time of 8.0 and 22.6 total hours for AES and ALS, respectively.

Passive acoustic monitoring of vessel noise in the Quiet Sound area is currently underway as part of a multiyear voluntary VSR program in Admiralty Inlet (Malinka et al. 2023b, Matei et al. 2024). In this VSR program, which conducted its first trial year beginning on 24 October 2022 and lasted through 12 January 2023 (81 days), hydrophone data were sampled prior, during, and/or after a regional slowdown in Admiralty Inlet to evaluate the impact of reduced speed to ambient sound conditions related to vessel movement. When safe to do so, the following transit speeds through water were encouraged through the slowdown area: 14.5 kn or less for vehicle carriers, cruise ships, and container vessels, and 11 kn or less for bulkers and tankers.

SMRU Consulting conducted acoustic monitoring during and after (12 December 2022–9 February 2023) the Quiet Sound slowdown period using an autonomous hydrophone system deployed on a bottom-mounted lander in Admiralty Inlet off of Useless Bay, Washington. The acoustic recording system consisted of a calibrated Reson TC4032 hydrophone connected to an analog-to-digital (A/D) device that sampled data at 250 kHz, but sound measurements were limited to an upper frequency of 50 kHz due to internal noise of an additional device in the electronic housing. A current meter was also installed on the lander to adjust AIS-derived speed over ground to speed through water of vessels transiting the slowdown area. Key findings from the first implemented VSR by Quiet Sound included that over 70% of targeted vessels reported slowdown participation that varied by week and vessel type, with 53% of transits meeting the targeted speed through water. Containers and car carriers slowed down more relative to other vessels given their typically faster operational speed in Admiralty Inlet, resulting in a 2.8 dB reduction in median broadband (10 Hz–50 kHz) sound levels and a 2.3 and 2.1 dB reduction in median sound levels for the SRKW communication (0.5–15 kHz) and echolocation bands (15–50 kHz), respectively, relative to baseline levels after the slowdown (see Malinka et al. 2023b for other details of baseline). SRKW were visually sighted in or south of the slowdown area, indicating movement through the slowdown area, on 36 (of 81) days of the slowdown trial period, with most of the sightings consisting of J pod members, followed by K and then L pods (Aronson and O'Morchoe 2023). During the hydrophone monitoring period, 24 killer whale acoustic detections (18 SRKW and 6 Biggs/transients) across 13 separate days were confirmed as well (Malinka et al. 2023b).

The second Quiet Sound VSR began on 12 October 2023 and lasted through 12 January 2024 (92 days), with the slowdown area (Admiralty Inlet) and the two targeted speeds for the same vessel categories unchanged from the year before (Adams and Aronson 2024). SMRU Consulting conducted acoustic monitoring during and after (20 November 2023–9 February 2024) the slowdown period using the same autonomous hydrophone system deployed off of Useless Bay, with a similar approach to analyze vessel noise and killer whale acoustic detections as in the previous year (Matei et al. 2024). Key findings from the 2023–24 Quiet Sound slowdown are as follows:

- 71% of targeted vessels reported slowdown participation.
- 59% of transits met the targeted speed through water.
- Containers and car carriers again slowed down more relative to other vessels given their typically faster operational speed in Admiralty Inlet.
- There was a 3.0 dB reduction in median broadband (10 Hz–50 kHz) sound levels, a 1.8 dB reduction in median sound levels in the SRKW communication band (0.5–15 kHz), and a 1.9 dB reduction in median sound levels in the SRKW echolocation band (15–50 kHz) relative to baseline levels after the slowdown.
- Slowdowns increased “quiet time” (i.e., broadband sound levels ≤ 110 dB) by 72 minutes/day relative to baseline (see Matei et al. 2024 for other details of baseline).
- A vessel noise budget analysis indicated a lower contribution to overall noise from participating vessels relative to baseline, especially for container vessels, due to reduced source levels as a result of slowing down (Matei et al. 2024).

SRKW were acoustically detected or visually sighted in or south of the slowdown area on 20 (of 92) days of the slowdown trial period, with most of the sightings consisting of J pod members, followed by K and then L pods (Adams and Aronson 2024). During the hydrophone monitoring period, 35 killer whale acoustic detections (31 SRKW and 4 Biggs/transient detections) across 15 separate days were confirmed specifically (Matei et al. 2024).

A third Quiet Sound VSR was implemented from 6 October 2024 through 12 January 2025 in the same slowdown area, but results had not been released by the submission date of this report.

1.2 Outreach on Past and Present Underwater Acoustic Monitoring Initiatives: Survey 1 Results

1.2.1 Survey 1 background

We developed a survey (hereafter: "Survey 1") to conduct outreach covered under Tasks 1 and 2 of Phase 1, as stipulated in the scope of work (Appendix A). The aim of the outreach survey was to cover past and ongoing project details that were not easily available in published or written form. We generated a list of potential participants to take the survey based on our literature review, input from the Quiet Sound program and the Port of Seattle, as well as our general knowledge of passive acoustic monitoring efforts and hydrophone operators in the Study Area. We identified 39 contacts (Appendix B) and invited them to take Survey 1 via an email invitation with the survey link; all invitations but one were successfully received. The survey consisted of 46 questions, formulated according to Phase 1 scope of work (Appendix A), that were a mix of multiple-choice, short answer, and long answer free responses. Only two questions required a response for submission—the first, which asked for a valid email, and the last, which asked whether to opt into a second survey about best practices. Many multiple-choice questions asked respondents to check all boxes that applied, so multiple answers were allowed; thus, many categorical responses often did not equal the number of respondents. We also asked respondents to take the survey as many times as they thought necessary to capture the unique acoustic monitoring projects they lead/led or manage(d) within the study area. We defined those projects coinciding with the geographic scope of the Quiet Sound program, which includes all SRKW critical habitat within Washington waters (within 3 nmi seaward of its coastline), as well as British Columbia waters of the Salish Sea within the ECHO program. We received 20 separate survey responses from 15 different respondents; they are summarized in the next section.

1.2.2 Summary of Survey 1 responses

After requesting contact information for potential follow-ups, we asked respondents about their roles in the project/program(s) involving underwater acoustic monitoring. Most identified their role as a principal investigator, with a handful of responses indicating subject matter expertise/consultation, data analysis, outreach/education, research project management, natural resource management, and/or "other" roles. Most stated that their main funding came from government entities (federal, state, regional), foundations or corporate sponsors, private individual donations, or a combination of these sources.

1.2.2.1 Descriptions of past and present underwater acoustic monitoring efforts

We asked what geographic areas were acoustically monitored and, if monitoring occurred within the geographic area of the Quiet Sound program, we asked respondents to reference Washington Department of Fish and Wildlife (WDFW) fishery areas as shown in the map below. We referenced WDFW fishery areas because they are well defined within Washington waters and remain relatively static from year to year. The vast majority (85%)

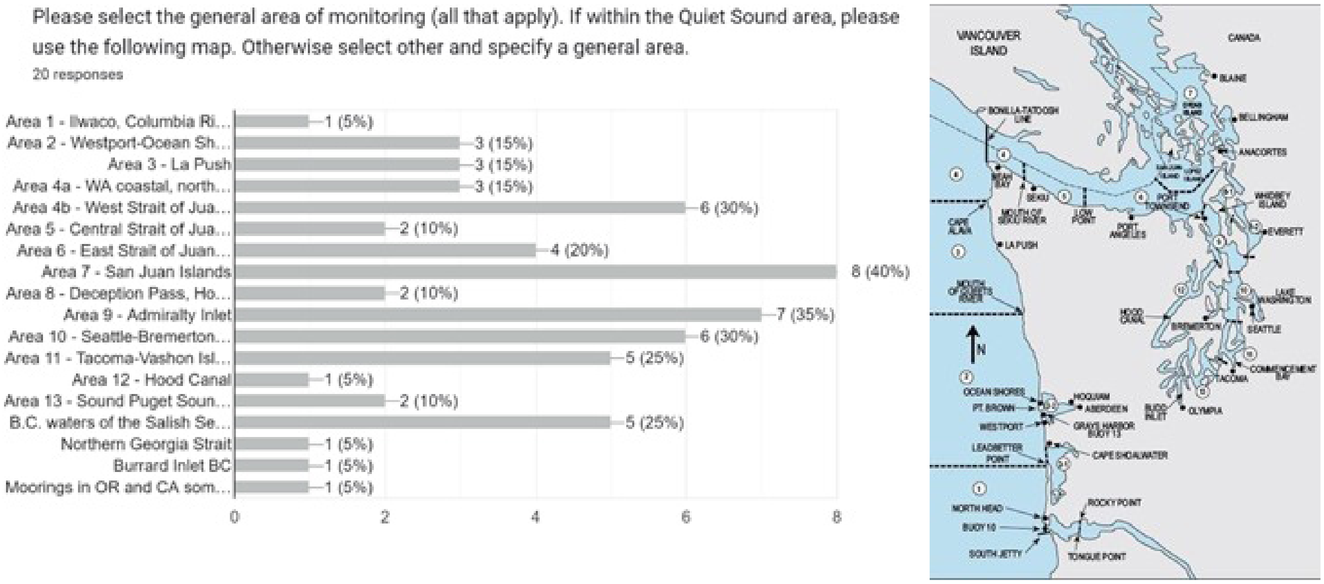

Figure 1. Geographic areas of underwater acoustic monitoring in Washington State, indicated by Survey 1 responses.

of responses included waters that corresponded to the geographic area of the Quiet Sound program. The remaining responses indicated PAM in B.C. waters of the Salish Sea within the ECHO program, the northern Strait of Georgia (B.C.), and along the Oregon and California coastlines. Within Washington waters, the San Juan Islands, Admiralty Inlet, Puget Sound, and the Strait of Juan de Fuca had the most responses, as illustrated in Figure 1.

Half of the responses indicated that monitoring occurred at multiple (5+) locations or nodes that often varied over time, although about a third of the responses indicated that only a single location was monitored for the project/program, with the remainder indicating two or three locations. About half of the responses indicated that fixed autonomous recording systems (e.g., AMARs, Sound Traps), closely followed by fixed cabled systems, best described the hydrophone and monitoring equipment. Two responses indicated near-real-time (NRT) buoy systems, and one response indicated that a mobile cabled system (towed array) best described the equipment.

We then asked respondents to list up to three main objectives for collecting and/or analyzing the passive acoustic data. Table 1 summarizes the results based on our grouping of what respondents reported as free responses.

The survey then asked specific questions about how they obtained their acoustic data. An equal number of responses indicated that they monitored acoustic data in real time and recorded all the incoming data (40%), or used an archival recording system from which data were later retrieved (40%), or a combination of both ways (10%). A few indicated that acoustic data were available in real time, but that only desirable data streams were recorded (10%). In terms of the number of hydrophones deployed per location site, 60% of the responses indicated using one hydrophone (single element), 20% had a variable number of hydrophone(s) that differed among sites or projects, and another 15% had three or more hydrophones deployed. One response indicated using two fiber optic cables which perform

Table 1. Main objectives for collecting and/or analyzing the passive acoustic data.

Objective(s)	**Number of responses**	**% of total responses**
Detection of killer whales, cetaceans, marine mammals, and/or other animals (biophony)	13	24%
Ambient noise	13	24%
Anthropogenic noise, noise pollution, noise impacts	8	15%
Vessel traffic monitoring, including commercial vessels, impacts of vessels, measurements of radiated noise, source level measurements	7	13%
Soundscape characterization	6	11%
"PAM detections"	3	6%
Education and outreach	2	4%
Habitat use	1	2%
Conservation actions	1	2%
Total	**54**	**100%**

like a long array of hydrophones (known as distributed acoustic sensing, DAS). Respondents reported using hydrophones of various makes and models, including: Aquarian Hydrophones, Brüel and Kjær, Cetacean Research Technology, Marine Acoustic Recording Units (MARU; Cornell Lab), GeoSpectrum Technologies, High Tech Inc., International Transducer Corporation, AMAR (JASCO), Labcore, SoundTraps (Ocean Instruments, New Zealand), ecological acoustic recorders (EARs; Ocean Science Institute), Ocean Sonics (icListen), Reson, Turbulent Research, and passive aquatic listeners (PALs; University of Washington Applied Physics Lab).

The vast majority of respondents (80%) reported using calibrated hydrophones. 15% reported that some were calibrated but most were not, and 5% said none were calibrated. Those who reported using calibrated hydrophones indicated they were either manufacturer/factory calibrated, periodically checked with a pistonphone at a single frequency, or cross-calibrated with signals recorded at known SPLs. A handful of responses indicated that hydrophones were calibrated at test facilities (e.g., the Naval Undersea Warfare Center, NUWC, and the Pacific Northwest National Laboratory, PNNL) or "onsite." Sampling rates of the acoustic data varied widely, with 30% reporting using rates above 200 kHz, 25% using rates between 96 and 200 kHz, 30% using variable rates, and the remainder using rates less than or equal to 48 kHz.

In terms of temporal coverage of the recorded acoustic data, 70% reported continuous coverage, while 15% reported using duty-cycled schedules to record data and another 15% reported using both. If duty-cycled data were collected, the schedule varied among the responses: one reported a 50% duty cycle (420 s per 840 s interval), two reported a 15% duty cycle (90 s/600 s interval), and one reported that the duty-cycle schedule varied over the four years of sampling from 1% to 10% depending on the deployment duration and the data storage available as the project progressed.

We also asked respondents to list any other sensors to collect supplementary data and how these data were used along with acoustic data. We received 15 responses to this question, with many listing a combination of supplementary sensors and data streams. For example, seven responses included using an acoustic doppler current profiler (ADCP) or current meter to estimate vessel speed over water and/or to document strong currents to account for covariates (flow/pseudo-noise), seven responses included using conductivity–temperature–depth (CTD) or temperature data for general oceanographic observations or for sound propagation, four mentioned using wave, wind, tide, precipitation, or weather data to understand their contribution to ambient and/or vessel/ship noise levels, four used AIS and three used video, infrared, or radar to track vessel movement and distribution, two used fish tracker or telemetry receivers to track fish presence, and one also mentioned using an ocean-bottom seismometer to understand contribution to ambient noise in the ocean from a variety of environmental sources (beyond geological activity).

When asked to briefly describe how the acoustic data were analyzed, many responses indicated that data were analyzed for: 1) soundscape analytics, noise measurements, or metrics, including source characterization that included ship/vessel contributions, radiated noise for slowdowns, or to calculate ship source levels, and/or 2) cetacean detections or classification and localizations in real time or through post-hoc analyses. One response indicated that processing and analysis were project-specific, but did not provide further details.

The next question asked respondents what the main results of past monitoring efforts were, if applicable, and to list the full citations/links of associated written reports or peer-reviewed publications. We cross-checked subsequent paper citations and links that respondents provided with our existing list of literature for review and added any pertinent papers that were not already included. A handful of respondents provided information about reports associated with the ECHO program that could be requested by email.[8] Responses about the main unpublished noise results not covered by the literature review included:

- Ambient noise in Haro Strait was 90 dB (no mention of reference pressure level or frequency band) in quiet conditions.
- Elliott Bay was the noisiest, a bay near Port Townsend was the quietest, and waters near the Port of Tacoma experienced the widest range of noise conditions among four monitoring sites.
- Vessel (traffic) intensity was positively correlated with noise levels.
- Vessel noise dominated sites in the Strait of Juan de Fuca and Admiralty Inlet.
- Ambient noise statistics have been calculated continuously for more than 5 years and are ongoing in Boundary Pass; the acoustic monitoring system there has measured radiated noise levels and source levels of approximately 65,000 passes of 9,000 different vessels.

With respect to unpublished acoustic detections of cetaceans, respondents reported that:

- Many killer whale and humpback detections were noted at some locations in the Canadian side of the entrance of the Strait of Juan de Fuca.
- The Boundary Pass system has sent hundreds of detections of killer whales to the Whale Report Alert System (WRAS).
- SRKW and other killer whale detections varied by monitoring site among six locations around the San Juan Islands, the Strait of Juan de Fuca, and Puget Sound.

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[8] echo@portvancouver.com

When asked whether the acoustic data were available in an archive, we received 20 responses: 40% yes, 20% no, and 40% maybe. When asked whether the acoustic data were publicly available, we again received 20 responses: 15% yes, 15% yes upon request, 10% yes and no depending on the data, 45% no, and 5% maybe. 65% said that acoustic monitoring effort is ongoing, while the remainder (7/20) said that effort had ended, with the following reasons given for the project ending: effort/project was completed, funding ended, effort was redundant, or equipment was lost due to nature but no funding was available to replace it.

1.2.2.2 Southern Resident killer whales and commercial vessels within the Quiet Sound area

The next section of the survey was about spatial understanding of acoustic data associated with SRKWs and/or commercial vessel use. We asked respondents to answer questions in this section if they had conducted passive acoustic monitoring efforts specifically within the geographic area of the Quiet Sound program. The first question asked whether the acoustic data included killer whale detections and the second question asked whether the acoustic data included SRKW detections. Answers to both questions were the same among all respondents: the vast majority (17/19) said yes, 2 said no, and 1 said maybe (no detectors were run on the archived recordings because the study was about ambient noise). When asked what methods (manual, automated, both, or n/a) were used if the analysis included SRKW acoustic detections, 69% (11/16) said they used automated detections that were then manually validated for SRKW, and 31% said they only used manual detections. In both cases, most stated that manual detections and validations were conducted by bioacousticians with expertise in SRKW call types and/or correlated with visual sightings of SRKW. A subsequent question asked whether visual sightings of SRKW were used; half said yes or sometimes yes (8/16) and half said no or mostly no (8/16). We asked what general patterns emerged from the SRKW acoustic detection analyses in terms of frequency of occurrence, seasonality, and variability. Answers included: 1) peaks in detections were site- and season-dependent, but there was a large amount of interannual variability, 2) patterns generally matched visual detections and about 10% of visually reported sightings were not detected acoustically, while some acoustic detections during the day were not associated with visual detections, and 3) coastal occurrence of SRKW is increasing, especially at the Strait of Juan de Fuca recorders.

With respect to commercial vessel presence and/or movement gleaned from passive acoustic monitoring efforts, 70% (14/20) of the respondents reported that passive acoustic data included details about commercial vessel presence and/or movement within the spatial area of monitoring. The majority (81%) used AIS data either alone or in combination with manual and/or automated acoustic detection methods to document commercial vessel presence and/or movement. Respondents reported obtaining AIS data from the following stated sources: NOAA, NOAA archives, Marine Cadastre National Viewer, AccessAIS, Marine Exchange Puget Sound, online (unspecified source), the U.S. Navy, the Canadian Coast Guard, purchased, collected themselves, or from AIS stations for the project. We then asked what vessel attribute data were included in the AIS data analyses, asking respondents to check all of the following that applied: vessel identification (name/imo/mmsi), vessel location (latitude/longitude), vessel class/type, vessel length, vessel speed, vessel course/direction, vessel hours, n/a, or other (fill in the blank). The bar chart in Figure 2 summarizes the responses we received.

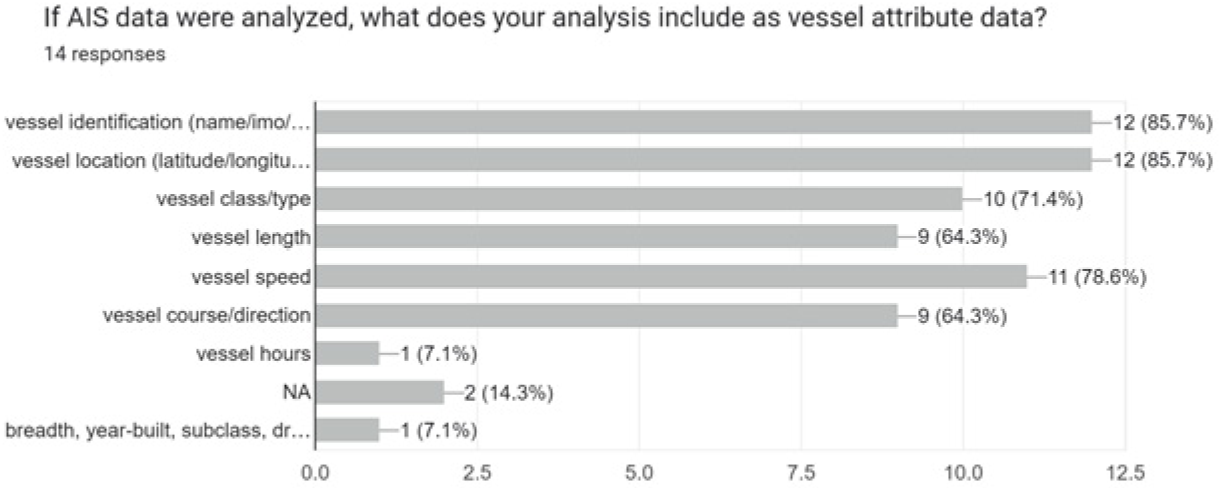

Figure 2. AIS-derived vessel attribute data included in analyses conducted by survey respondents.

We also asked whether respondents analyzed the acoustic data to monitor and/or describe underwater ambient or background noise from the perspective of SRKW (e.g., spatial overlap, in frequency bands relevant to killer whale hearing, communication, echolocation). Approximately 60% of the 18 responses reported yes. Details given about the quantitative measurements were generally associated with acoustic frequency considerations as follows: Coastal Ocean Research Institute (CORI) bands (Heise et al. 2017), marine mammal or killer whale weighted measurements, and/or spectral analysis and noise statistics using PAMlab (JASCO). We then asked what general patterns emerged from the analysis of noise data, if applicable. Responses largely paralleled patterns reported in the literature, which included: 1) vessel noise was detectable in the presence of SRKW very often in Haro Strait, and the Salish Sea is "noisy," 2) vessels dominated ambient noise variability, with daily, weekly, and seasonal trends closely tied to commercial vessel traffic patterns, 3) propeller cavitation was dominant in the vessel noise spectra, and 4) voluntary vessel slowdowns in Boundary Pass and Admiralty Inlet resulted in noise reductions for participating vessel categories. We also asked whether there was an attempt to link noise measurements to SRKW exposure or effects on behavior; 56% reported yes, while 44% (out of 16 total responses) reported no.

1.3 Best Practices, Limiting Factors, and Lessons Learned

This section covers best practices, limiting factors, and lessons learned to acoustically monitor killer whales and commercial vessel noise in the Study Area. Topics included in the following subsections are: selection of hydrophone and recording equipment; appropriate sites to monitor based on bathymetry, substrate, currents/tides, and other human activities that generate noise; appropriate software packages for data acquisition and analysis; data collection and usage consistent with specific existing programs as requested (ECHO, Quiet Sound, DFO, Orcasound); limitations or compatibility issues with these existing programs; cost considerations of hardware, software, data curation, storage, and archiving; and permit and regulatory requirements and/or constraints. We conducted a literature review of available written material and outreach in the form of a second survey to inform the following topical subsections.

1.3.1 Appropriate types of hydrophone equipment and software packages for data collection and analysis

Here we consider appropriate types of hardware and software options for data collection and analysis, including analyses for vessel and ambient noise in the Study Area for monitoring potential impacts to SRKW whale populations. This part of the review also considers appropriate site selection to monitor, based on bathymetry, substrate, currents and tides, and other human activities that generate noise.

1.3.1.1 Hydrophone and hardware considerations

As the standard for passive acoustic soundscape monitoring, calibrated hydrophone data with deployment- and equipment-specific metadata are critical for accurate monitoring of ambient sound conditions. Types of hydrophone and acoustic recording technologies commonly used in passive acoustic research include: stationary (moored) passive acoustic recorders that can be mid-water or bottom-mounted and are often autonomous with data stored on board (archival), or have a surface expressed component for transmitting data in real time (moored surface buoys); cabled systems that connect directly to a recording device and have easier real-time monitoring capabilities; and gliders and animal tags outfitted with hydrophones. Review of technical aspects of underwater acoustic recording equipment, including hydrophone and related hardware, for conducting marine mammal bioacoustic studies is provided by Madsen and Wahlberg (2007). They discuss various selection considerations, including system sensitivity, directivity, self-noise, noise floor and dynamic range, usable frequencies, sampling rates for analog to digital (A/D) conversion and filters, calibration, acoustic localization, and array configurations. While it focuses on recording and analyzing the ultrasonic and highly directional echolocation clicks of toothed whales and dolphins, the general discussion is applicable to acoustic monitoring for killer whale communication calls and vessel noise as well.

An evaluation of shore-cabled hydrophone networks specific to NRT killer whale detection and tracking systems within DFO’s Whale Tracking Network is given by Yurk et al. (2023). The report discusses the pros and cons of cabled versus autonomous acoustic recording systems, power supply considerations (AC vs. batteries), data storage considerations for archival systems, requirements about estimating detection range given signal source level, local ambient noise contributions, and local conditions affecting sound propagation. There is also a discussion of acoustic localization requirements (including frequency-dependent array considerations; Zimmer 2011, 2013) if killer whale movement and tracking is required, especially for NRT systems that are integrated in a whale alert system. Yurk et al. (2023) also discuss automated systems using detector–classifiers, the dependence on specific application of what are acceptable levels of false and missed detections, and the potential requirement of human listener validation for these automation routines.

1.3.1.2 Biofouling

Extensive growth of marine organisms on oceanographic instrumentation, commonly referred to as biofouling, can impact the functionality and maintenance of underwater sensors, especially in shallow-water environments. Biofouling can be caused by a variety of marine life, such as algae, barnacles, mussels, and bacteria. In the case of hydrophones, biofouling can interfere with underwater acoustic recordings if the growth encases the hydrophone sensor element, which will change the impedance contrast between the water and hydrophone and can distort the sound recordings. There are several measures that can be taken to mitigate fouling and prolong the equipment's functional lifespan, including regular maintenance (e.g., divers manually cleaning the instrumentation of organisms) and antifouling coatings.

There are a few key characteristics to consider if a hydrophone operator chooses to use an antifouling agent (e.g., Li et al. 2023). One is efficacy, or how well does the coating prevent biofouling. Another is durability, or how long does the coating last before needing replacement. The potential environmental impact, or whether the coating is toxic to marine life or humans, is also an important consideration, as well as cost (including the initial application and maintenance costs).

1.3.1.3 Considerations for monitoring and measuring ambient noise

Best practices for monitoring and measuring ambient noise generally include following current standards as available from the International Standards Organization (ISO). For example, important upcoming standards for ambient noise analysis are in development. These include standards for measuring ambient noise (ISO 7605) and sound from ships in shallow waters (ISO 17208-3),[9] which were finalized in 2025. Standards for measurements of opportunistic vessel noise observations, including vessel speed reduction, are proposed for development and, when available, will be important for assessing impacts to SRKWs when experimental studies are not possible. Additionally, a working group for bioacoustics terminology standards (ISO 23990) will focus on impacts to aquatic life.

A high-level review of best practices and recommendations to understand and characterize environmental and anthropogenic factors that contribute to ambient noise in Southern Resident critical habitat is given by Eickmeier et al. (2021). Utilizing two years of data from three calibrated and cabled hydrophone stations, including ECHO's Underwater Listening Station (ULS), the paper evaluates hydrophone recordings, vessel traffic, environmental noise, data analysis, and reported metrics. Key findings and recommendations of Eickmeier et al. (2021) include that calibration error and unique system noise floors highlight the need for early and frequent data-quality assessment protocols. In particular, cabled power and auxiliary sensors can inadvertently introduce electronic noise in the acoustic recordings. In addition, weather and tidal influences on noise measurements justify the collection of current and weather-station data spatially proximate to the hydrophone. For example, the Quiet Sound slowdown area in Admiralty Inlet is a highly energetic site due to strong currents that regularly exceed 3.0 m/s from the tidal exchange through the inlet. At this site, both pseudo-noise (flow over the hydrophone) and sediment-generated noise during strong currents significantly

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[9] https://www.iso.org/standard/81321.html

contribute to noise-level measurements, as evident by the correlation of sound levels with current speeds > 0.4 m/s (Bassett et al. 2012, 2013, 2014). Thus, exclusion of hydrophone data for water currents > 0.4 m/s is considered a common best practice for measurements of ambient and vessel noise in this area (Eickmeier et al. 2021, Malinka et al. 2023b, Matei et al. 2024). Vessel traffic is clearly the dominant influence of ambient noise in many locations within the Study Area, and empirical data collection can be augmented with validated noise models (e.g., MacGillivray et al. 2022, 2025). Temporal variability in sound pressure levels is also considerable, making the determination of baseline conditions, trend detection, and evaluatiion of mitigation measures analytically challenging (Eickmeier et al. 2021).

1.3.1.4 Software considerations for passive acoustic data collection, handling, and analysis

Best practices for passive acoustic data handling and analysis include utilizing open-source software packages or custom code that can be published in tandem with datasets. For soundscape analysis, the hybrid millidecade soundscape metric is an increasingly popular standard that minimizes file size while maintaining fine frequency resolution for sound level averaging (Martin et al. 2021). We recommend utilizing either the Making Ambient Noise Trends Accessible (MANTA) package (Miksis-Olds et al. 2021), which by default uses a relatively fine 1 min time resolution, or the Python passive acoustic analysis tool for passive acoustic monitoring (PyPAM, Parcerisas 2023). An open-source wrapper package for PyPAM is recommended for continuous datasets for accurate timekeeping, and can be accessed through GitHub (Rueda et al. 2024). The Triton software package is another user-friendly software created to assist with evaluation of long-duration acoustic recordings (Wiggins et al. 2010). Specialized “remora” packages for Triton are available to facilitate analysis of soundscape conditions and vessel presence (Frasier et al. 2024).

Software for acoustic detection and classification is also useful for this task. A well developed strategy focused on Salish Sea killer whales is Orcasound’s AI for Orcas project,[10] a decades-long open effort to develop the best machine-learning systems for classifying killer whale sounds. Another useful software tool is PAMGuard’s whistle and moan detector, which at the Lime Kiln site has been configured for whistles in the killer whale frequency band. Other efforts for classifying SRKW calls specifically are described in Duc et al. (2024), methods that rely on “frequency ridge” tracing from call spectrograms. This approach was tested among seven SRKW call types, including monophonic and biphonic (that include a high-frequency component, HFC) calls. Classification using this approach was scored as robust for three of the seven call types. Various reasons for poor performance among the other call types included more variability in frequency ridges among exemplars within a call type, less variability in the averaged frequency ridges among confused call types, and the sometimes “incomplete” frequency ridge characterization when the amplitude of the beginning of the HFC of that call was low (Duc et al. 2024). It is important to note that the recording quality of HFCs of killer whale biphonic calls will likely be more variable given that higher frequencies are more directional (dependent on the orientation of the caller, Miller 2002); thus, classification performance of some biphonic calls will inherently have more variability using this method.

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[10] https://www.orcasound.net/portfolio/ai-for-orcas-open-bioacoustic-data-science/

1.3.2 Data collection and usage consistent with ECHO, Quiet Sound, DFO, and Orcasound acoustic monitoring

Collection of acoustic monitoring data and usage that is considered consistent with ECHO, Quiet Sound, and DFO should follow the methods and approaches outlined in the literature reviews provided in the previous sections of this report (ECHO: Joy et al. 2019, MacGillivray et al. 2019; Quiet Sound: Malinka et al. 2023, Matei et al. 2024; DFO: Yurk et al. 2023). Veirs et al. (2016) provides sufficient information to collect passive acoustic data for commercial vessel monitoring consistent with Orcasound. Further details about operational nodes within Orcasound can be found on the Orcasound website.[11]

A highlighted effort for both ECHO and Quiet Sound is the seasonal vessel speed reduction (VSR) program. Proposed community best practices of VSR programs for underwater noise reduction include monitoring both vessel-focused (source-level) and habitat-focused (noise-level) metrics (Hatch et al. 2025). Recommended guidelines for these metrics include adhering to standardized data collection, processing, and metadata documentation, as well as coordinated use of relevant data streams (e.g., AIS). International coordination across participants, coupled with long-term monitoring, will provide information that can be used to understand potential impacts to protected resources and environments and bolster progress toward shipping sustainability goals. Collection of acoustic monitoring data and usage that are considered consistent with monitoring efforts of the seasonal voluntary slowdowns in the Study Area should follow approaches described in Malinka et al. (2023), Matei et al. (2024), and MacGillivray et al. (2019) specifically.

1.3.3 Cost considerations of equipment, installation, operations, data collection, curation, and archiving

In general, costs to maintain calibrated autonomous hydrophone systems are lower relative to comparable shore-cabled hydrophone systems, though the cabled systems more readily provide real-time data. Shore-cabled systems closer inshore are easier to deploy and service compared to those farther from shore (> 100 m) and/or in deeper water, given the higher deployment and maintenance costs. For example, the deeper water Boundary Pass ULS (JASCO-maintained) and the Ocean Networks Canada node in the Strait of Georgia had development and installation costs of several million Canadian dollars, plus operational costs in the hundred-thousand Canadian dollars per year (Yurk et al. 2023). However, the Orcasound project has extensive experience in employing cabled hydrophones at relatively low cost. It is worth noting that the depth of the hydrophone element can limit the quality of the acoustic data collected. For example, shallow shore depths limit the lower frequencies that can be accurately measured and incorporated into noise-level measurements given the physics of sound propagation, which are especially relevant for large commercial vessels.

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[11] https://www.orcasound.net

Measuring source levels of commercial vessels according to standards (ANSI or ISO) can also result in considerable costs in terms of data collection, processing, and analysis. For example, utilizing the two certified naval ranges for ship noise measurements can be time- and effort-intensive. As an alternative, the Fisheries Survey Vessel Passive Acoustic Drifter (FSVPAD) package was designed and created by NOAA to measure the lower levels of noise emitted by the relatively large NOAA Fisheries survey vessels (Bassett et al. 2024). These survey platforms are designed to meet ICES radiated noise recommendations to reduce fish avoidance and interference with active acoustic instruments. The FSVPAD drifter was designed to comply with ANSI (2009) standards for measuring radiated vessel noise at relatively modest costs because it can be deployed under normal marine operational conditions (including under suitable bathymetric, meteorological, and oceanographic circumstances) as an alternative to utilizing the two certified Naval ranges that are more expensive and limited by spatial accessibility. Its core components include three submerged µAURAL hydrophones and a spar buoy for surface drifting. The buoy contains batteries, a GPS, and communications electronics including an antenna assembly to communicate with the vessel at ranges > 1 km. Matlab license-based data acquisition and post-processing scripts are also provided to facilitate the analysis of the FSVPAD data to ensure they comply with ANSI standards.

Results of Survey 2 (see Section 1.4.2.6) also provide experience-based estimates of acoustic monitoring costs to purchase, install, operate, and maintain hydrophone and hardware equipment, and to support data collection, curation, analysis, and archiving. These cost estimates vary widely depending on the goals and objectives of the monitoring efforts and range from $50K to over $1M USD per year per node. It is important to note that cost estimates are subject to inflation, which should be factored into budget planning for multiyear efforts accordingly.

1.3.4 Permitting process for deploying hydrophones in the Study Area

1.3.4.1 Overview

This section provides an outline of the application process to obtain regulatory permissions to deploy underwater sound recording equipment in the Study Area. The permitting process is designed to ensure that hydrophones, along with any associated equipment such as anchors, are properly installed, maintained, and removed without leaving debris behind. The process often involves coordination with multiple agencies to minimize environmental impact, especially with respect to the endangered SRKW population.

1.3.4.2 Completing the Joint Aquatic Resource Permit Application (JARPA)

To simplify the permitting process, several regulatory agencies have come together to create a unified application called the State of Washington Joint Aquatic Resources Permit Application (JARPA). This allows applicants to apply for multiple necessary permits with a single submission. Access to JARPA is available online, and covers permits required at the federal, state, and local levels.[12]

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[12] https://www.oria.wa.gov

At the federal level, the U.S. Army Corps of Engineers issues permits under Section 10 of the Rivers and Harbors Act and Section 404 of the Clean Water Act (CWA), both of which govern activities in U.S. waters. The U.S. Coast Guard also plays a role in regulating Private Aids to Navigation (PATONs) if applicable to the project.

On the state level, the Washington Department of Ecology reviews applications for water quality certification under Section 401 of the Clean Water Act. The Washington Department of Fish and Wildlife issues Hydraulic Project Approval (HPA) for any activity that may affect fish or fish habitat. The Department of Natural Resources (DNR) oversees the use of state-owned aquatic lands and may require an Aquatic Use Authorization for hydrophone monitoring projects.

At the local level, jurisdictions may require permits for shoreline development or construction, such as a Shoreline Substantial Development Permit, Shoreline Conditional Use Permit, or Shoreline Variance. However, note that not all local jurisdictions are part of the JARPA system; some may require separate, local applications, and we include more details below.

1.3.4.3 Best practices for submitting a JARPA application

Before submitting a JARPA application, we recommend having a well defined project plan that clearly outlines the scope and objectives of the hydrophone deployment and includes details about the project descriptions, site maps, diagrams, and any other supporting documents. Contacting the local city or county government corresponding to the area of hydrophone deployment to confirm whether they accept JARPA applications for shoreline permits, if applicable, may save time, as some may require separate, local applications. To streamline this process, it may be helpful to check with local planning departments to ensure the project complies with Critical Areas Ordinances and the National Flood Insurance Program. One key part of the process is collaborating with the local Fish and Wildlife Area Habitat Biologist (AHB). The AHB will help identify any special habitat considerations or guidelines for your project, ensuring that fish and aquatic life are not adversely affected. A directory of AHB contacts is available through WDFW’s website. Depending on the specifics of your project, a State Environmental Policy Act (SEPA) checklist may also be required to evaluate potential environmental impacts.

It is also beneficial to engage with the permitting agencies early. These agencies may request additional information beyond what is required in the JARPA form. By initiating early communication, one can address these potential requirements before they become significant delays or roadblocks.

1.3.4.4 Key coordination

The deployment of hydrophones in the Salish Sea typically involves coordination with several groups during the permitting process. The U.S. Army Corps of Engineers is responsible for issuing permits related to construction activities in U.S. waters, and they approve any underwater structures or obstructions related to hydrophone deployment.

Local tribal leaders and natural resource managers from Washington, Oregon, and California are key rightholders and comanagers in this process. Tribes have a vested interest in ensuring that activities follow treaty rights and do not disrupt traditional fishing areas or negatively impact local ecosystems. Coordination with relevant tribal groups is critical to minimize impact on tribal resources and rights. The Northwest Indian Fisheries Commission (NWIFC) can help identify which specific tribes have interests in the area. It is important to reach out to them to ensure that all tribal interests are addressed in the permitting process.

Additionally, sport fishing associations may also need to be consulted to assess the potential impact of hydrophone deployment on recreational fisheries.

1.3.4.5 Conclusion

Successfully navigating the permitting process for hydrophone deployment in the Salish Sea involves careful planning and coordination with a range of relevant groups and regulatory agencies. By following these best practices and starting the permitting process early, one can ensure compliance with environmental standards and minimize impacts on critical marine habitats. This is especially important for protecting habitats and endangered species such as SRKWs, whose populations are sensitive to changes in underwater noise levels.

1.4 Outreach on Best Practices, Limiting Factors, and Lessons Learned: Survey 2 Results

1.4.1 Background

We developed a second survey (hereafter: “Survey 2”) to conduct outreach covered under Phase 1, Task 3 (“Best practices, limiting factors, and lessons learned for acoustic monitoring of killer whales and large commercial vessel use in Study Area”). The aim of the outreach survey was to cover Task 3 details to supplement information gleaned from published or written sources. We invited 17 contacts to take Survey 2 (Appendix B) via an email invitation with a survey link. Several of these individuals indicated prior willingness to participate in this second survey based on responses during the first survey (see Section 1.2.2). All invitations were successfully received. The survey consisted of 26 questions that were a mix of multiple choice and short- and long-answer free responses. Only the first question, which asked for a valid email address, was a required response for submission. Many multiple-choice questions asked respondents to check all boxes that applied in which multiple answers were allowed, so many categorical responses did not equal the number of respondents. We received seven survey responses from seven different individuals, as summarized below.

1.4.2 Summary of Survey 2 Responses

1.4.2.1 Section 1—Contact information and role(s)

In the first section of Survey 2, after requesting contact information for potential follow-ups, we asked respondents what their role was in the project/program(s) involving underwater acoustic monitoring. Most identified their role(s) as principal investigator and data analysis; a few also indicated research project management, outreach and/or education, or subject matter expertise/consultation.

1.4.2.2 Section 2—Selection of hydrophones, hardware, and software

We then asked a series of questions about what individuals believe are the most important considerations for selecting hydrophone(s) and recording equipment, as well as software packages, for data acquisition and analysis for both killer whale and vessel noise monitoring. We asked specific questions for 1) acoustically detecting killer whales in general, 2) detecting and localizing killer whales, 3) automated detection and/or classification of killer whales including in real time, 4) monitoring and measuring noise emitted by commercial vessels, and 5) monitoring and measuring source levels of commercial vessels.

The following summarizes the Survey 2 responses we received.

1.4.2.3 Hardware and software selection considerations for killer whale acoustic monitoring

When asked what are important considerations for selection of hydrophone(s) and recording equipment for acoustically detecting killer whales in general, we offered the following choices in which respondents could check all that apply:

- Usable frequency range/bandwidth.
- Flat frequency response within usable frequency range (± 3 dB).
- System sensitivity.
- Calibration information.
- Self-noise/noise floor.
- System noise/electrical noise related to power supply, pre-amplifiers, filters, other sensors, etc.
- Hydrophone directivity.
- Number and configuration of hydrophone elements.
- Sampling rate options (on A/D device).
- Anti-aliasing filter.
- Time clock synchronization.
- Other (short free response).

Figure 3 summarizes the responses we received.

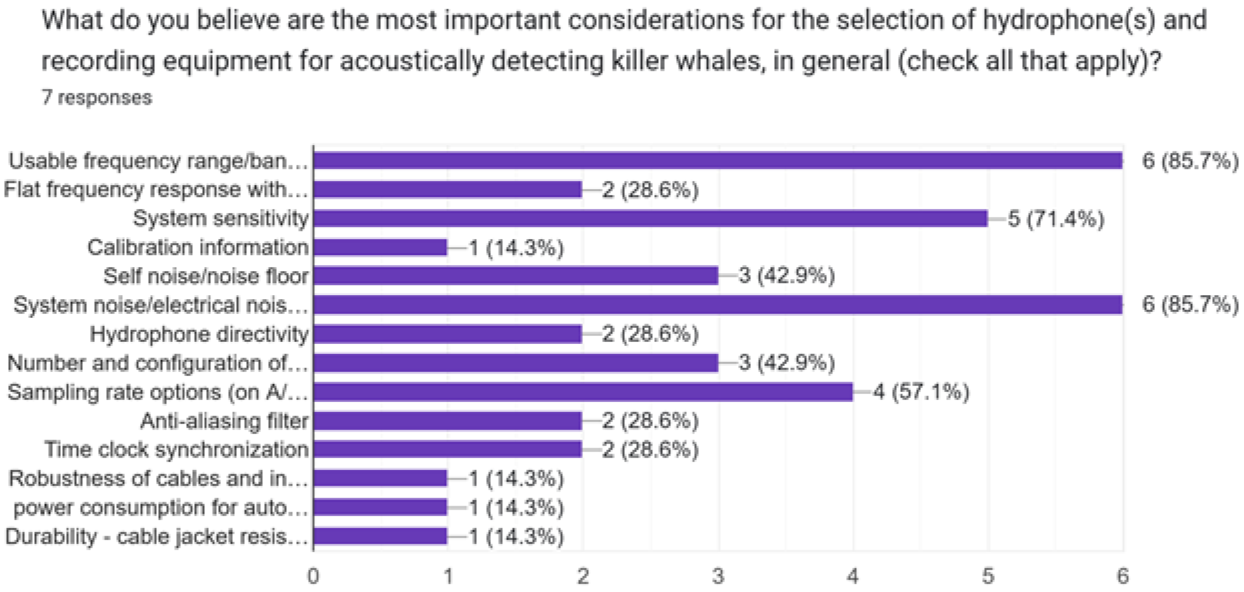

Figure 3. Summary of responses regarding the most important considerations for hydrophone and recording equipment selected to acoustically detect killer whales.

When asked to rank the above considerations for hydrophone and recording equipment selection for acoustically detecting killer whales in general, with 1 being least important and 5 being most important, we received a mixture of responses with the following trends: five responses indicated that usable frequency range/bandwidth was ranked as the most important (score of 5), four responses indicated that system sensitivity was relatively important (score of 4). Other ranked responses are shown below.

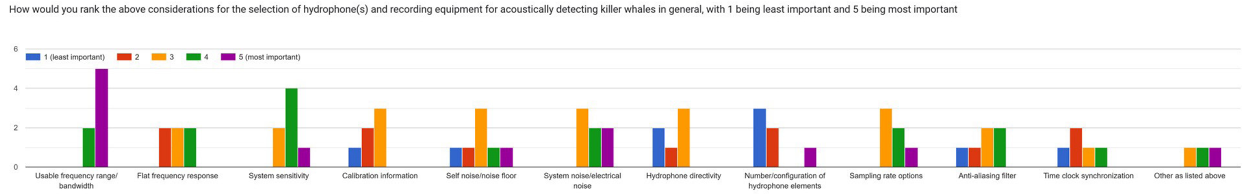

Figure 4. Respondent ranking of the most important considerations for hydrophone and recording equipment selected to acoustically detect killer whales.

When asked what are important considerations for selection of hydrophone(s) and recording equipment for acoustically detecting and localizing killer whales, we offered the same multiple choices in which respondents could check all that apply, and received the responses summarized in Figure 5.

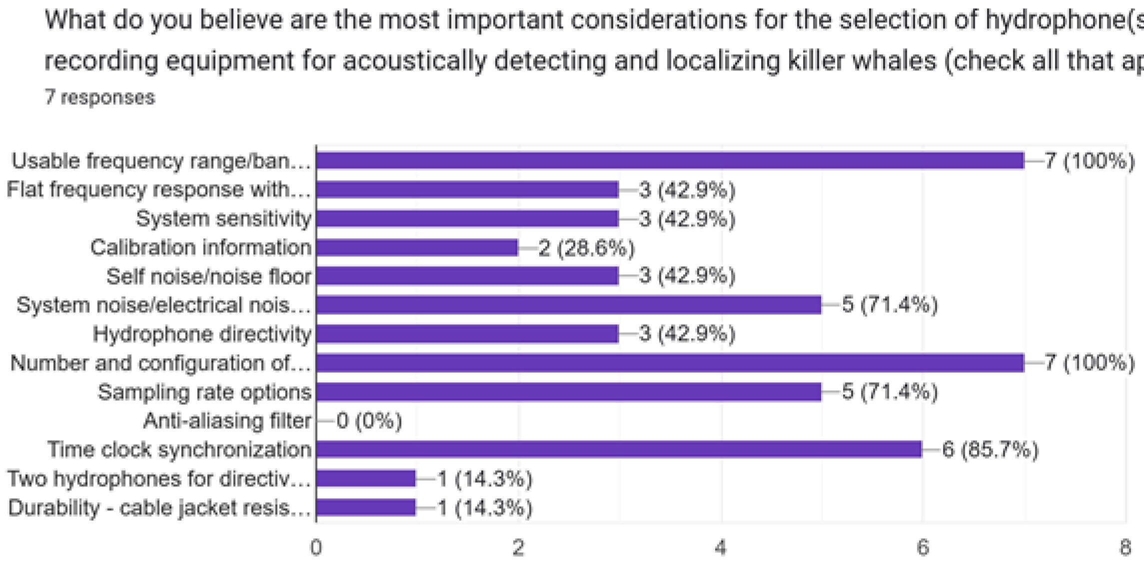

Figure 5. Summary of responses regarding the most important considerations for hydrophone and recording equipment selected to acoustically detect and localize killer whales.

Ranking of the above considerations is shown in the graph below.

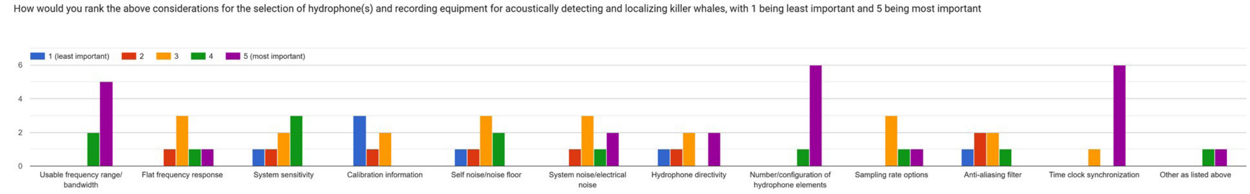

Figure 6. Respondent ranking of the most important considerations for hydrophone and recording equipment selected to acoustically detect and localize killer whales.

Answers in the form of a free response to the question, "If automated detection and/or classification of killer whales were required, how would your selection of hydrophone(s) and recording equipment change from how you answered previously?" were as follows: five out of seven responses effectively said no change, two indicated that relatively low noise floors/system electrical noise suppression becomes more important, and one replied that receiver-operating and precision over recall curves are important for any automated detector–classifier system.

When asked, "If *real-time* detection and/or classification of killer whales were required, how would your selection of hydrophone(s) and recording equipment change from how you answered previously?" All five responses stated no change.

When asked, "If *real-time detection and localization* of killer whales were required, how would your selection of hydrophone(s) and recording equipment change from how you answered previously?" Three out of six responses stated no change, while the other three responses listed the following: all three indicated that the hydrophone array (i.e., multiple hydrophone elements) configuration—such as the number of elements and the overall aperture or volume—was important, with one also indicating that a flat frequency response within the frequency band necessary for localization is more stringent, and that system calibration, along with an understanding of how ambient noise levels affect detection range, is necessary for accurate localization. Another noted that clock synchronization among hydrophone elements within the array is a top priority.

When asked what features are considered important for selecting appropriate software packages for data acquisition and analysis for killer whale acoustic monitoring, responses varied depending on the assumed application. For acquisition and real-time monitoring, time and frequency (spectral/spectrum) domain and spectrogram processing/plotting, along with ease of use, were highlighted. Some indicated they prefer a package with broad flexibility and open-source (without licensing costs) or source code availability (particularly for more complex applications involving localization or detector–classifier automation).

We also asked individuals to list notable limiting factors and lessons learned for hydrophone/hardware and software selection based on any previous experience for acoustic monitoring of killer whales. The following seven responses were submitted:[13]

- *It isn't just about selecting hardware and software. You need skilled team members to do it well consistently. It is even harder if you are doing it in real time an*d/or *with a cabled system.*
- *High quality hydrophones and low noise data acquisition systems, preferably with differential voltage inputs or current loop systems, have better noise performance than single-ended voltage hydrophones.*
- *It is all about cables and any connectors and intertidal protection.*
- *how the hydrophones are deployed can be an important consideration for success. bottom mounted vs moored is very much related to the deployment environment whether that be in a high current, turbulent area, or quiescent water*
- *Most DSP* [digital signal processing] *recording systems do not have a wide flat response curve even if the actual pressure sensor is detecting changes accurately.*
- *Poorly protected and poorly built cables lead to damage and loss of hydrophones. Shore-based power needs to be isolated in order to reduce electrical interference with the hydrophone signal. Electronic connectors need to be robust and not delicate laboratory style connectors.*
- *I don't have anything notable to contribute to this question as I think there is a great deal of readily available equipment that meets general needs with fewer packages available if localization if the target. Given the energetic tides in the region flow noise can be quite impactful and difficult to avoid. While it doesn't impact the frequencies of interest for killer whales, ensuring that packages won't saturate under extreme conditions and high-pass filtering data during strong currents are probably all that is needed to avoid the worst impacts.*

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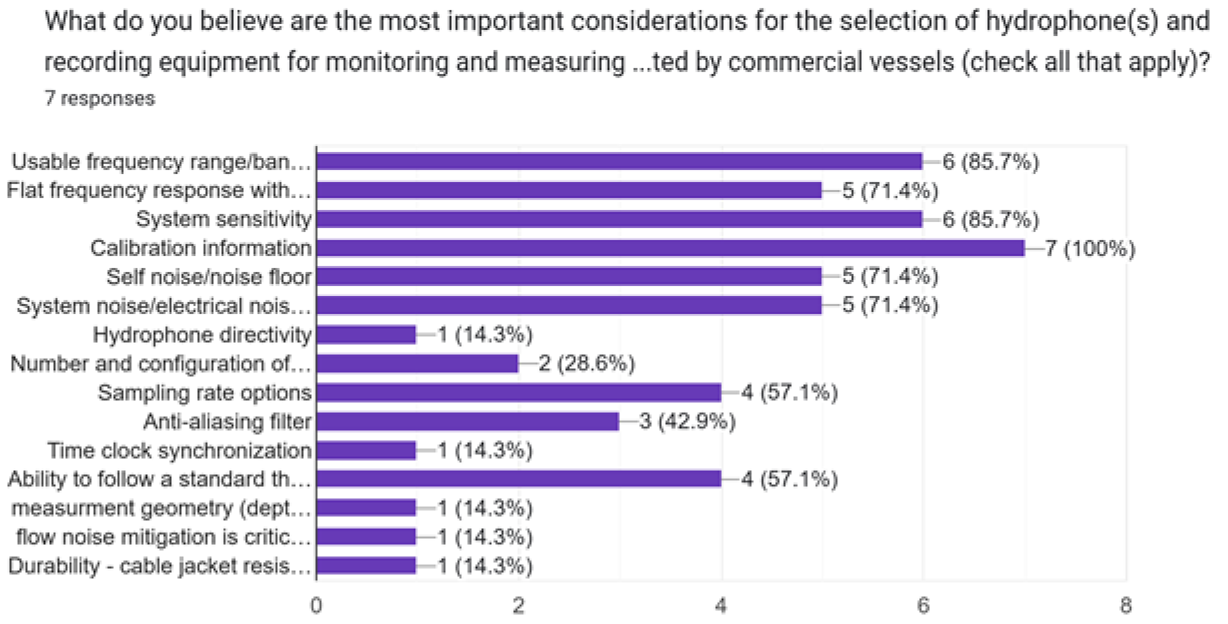
[13] Italics indicate that punctuation, grammar, and spelling (including any typos) have been left as provided by respondents.

1.4.2.4 Hardware and software selection considerations for acoustic monitoring of commercial vessels

The next section of the survey asked questions related to acoustic monitoring of commercial vessels. First, we asked what are important considerations for selection of hydrophone(s) and recording equipment for monitoring and measuring noise emitted by commercial vessels, with the following choices in which respondents could check all that apply:

- Usable frequency range/bandwidth.
- Flat frequency response within usable frequency range (± 3 dB).
- System sensitivity.
- Calibration information.
- Self noise/noise floor.
- System noise/electrical noise related to power supply, pre-amplifiers, filters, other sensors, etc.
- Hydrophone directivity.
- Number and configuration of hydrophone elements.
- Sampling rate options.
- Anti-aliasing filter.
- Time clock synchronization.
- Ability to follow a standard through hardware choice (e.g., ANSI, ISO).
- Other (short free response).


What do you believe are the most important considerations for the selection of hydrophone(s) and recording equipment for monitoring and measuring ...ted by commercial vessels (check all that apply)?

7 responses

Figure 7. Summary of responses regarding the most important considerations for hydrophone and recording equipment selected to monitor and measure noise emitted by commercial vessels.

Ranking of the above considerations is shown in the graph below.

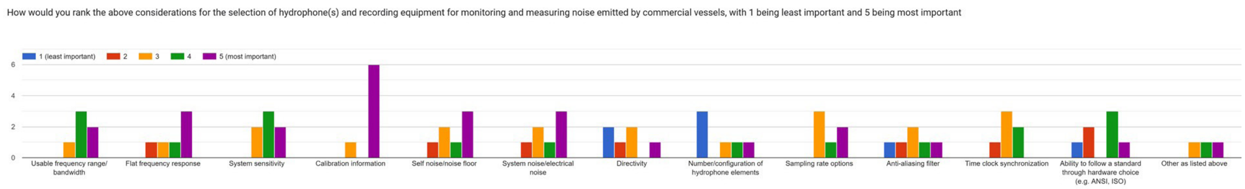


Figure 8. Respondent ranking of the most important considerations for hydrophone and recording equipment selected to monitor and measure noise emitted by commercial vessels.

We then asked what are the most important considerations for the selection of hydrophone(s) and recording equipment for monitoring and measuring source levels of commercial vessels, offering the same multiple choice answers as in the previous question. Figure 9 summarizes the responses we received.

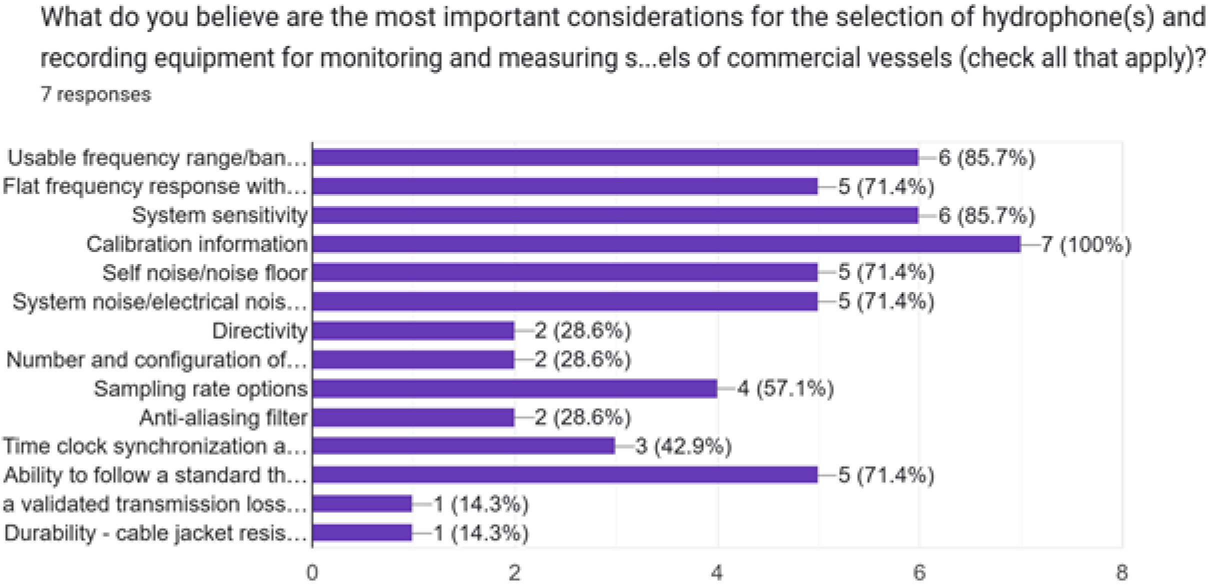


Figure 9. Summary of responses regarding the most important considerations for hydrophone and recording equipment selected to measure source levels of commercial vessels.

Ranking of the above considerations is shown in the graph below.

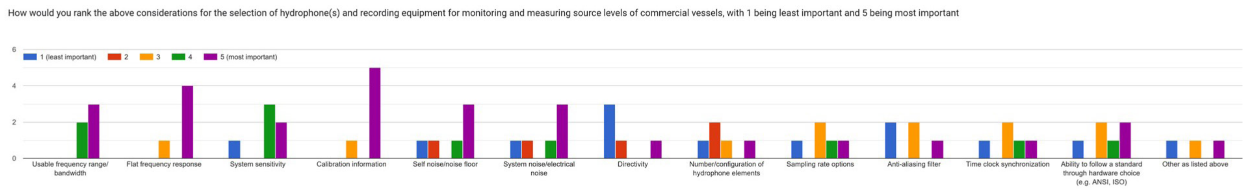


Figure 10. Respondent ranking of the most important considerations for hydrophone and recording equipment selected to monitor and measure source levels of commercial vessels.

When asked what features are considered important for selecting appropriate software packages for data acquisition and analysis for monitoring and measuring sounds of commercial vessels, responses again varied depending on the assumed application, and included the following: team familiarity with the software; flexibility, particularly with high sampling rates (e.g., at least 192 kHz); calibration options, including ability to convert to absolute units according to standards; automation ability for large datasets; and consulting with experts in ship noise measurements if following associated standards (ANSI S12.64 and ISO 17208), given that no off-the-shelf software exists to implement them.

We also asked individuals to list notable limiting factors and lessons learned for hydrophone/hardware and software selection based on any previous experience for acoustic monitoring and measuring sounds of commercial vessels. The following seven responses were submitted:[14]

- *It's not just the hardware and software. It's also the knowledgeable people to use it. Real time and cabled are the hardest to maintain and use.*
- *On our cabled systems we use projectors that produce repeatable frequency sweeps each day to track consistency of hydrophone calibrations. We've found that the most likely failure points are hydrophone and power cables, so choosing high quality cables and connectors, and having professional splicing done, is very important. System redundancy (multiple hydrophones, digitizing systems with separate power supplies) has been useful.*
- *Robustness re salt water and waves*
- *flow noise can be a major challenge contaminating low frequency recordings and making absolute sound level measurements challenging if not impossible in particular environments. there are some hardware and software advances that help with this*
- *System calibration has not been considered important, receiver depth has not been considered important, signal magnitude at different frequencies has not been considered. Flat response is important especially for higher frequency components but is often not considered important*
- *For the hardware: Poorly protected and poorly built cables lead to damage and loss of hydrophones. Shore-based power needs to be isolated in order to reduce electrical interference with the hydrophone signal. Electronic connectors need to be robust and not delicate laboratory style connectors. Non-calibrated signal acquisition instrumentation. For the Software: no way to compute absolute sound pressure levels or measure absolute voltage from input devices. Most bioacoustics software packages don't have logarithmic or octave-band frequency scales and this is very useful for noise analysis.*
- *All decisions are driven by the objective. Less flexibility in processing/implementation is needed and standards provide a good outline of processing decisions. With adequate ancillary measurements autonomous systems rather than real-time (cabled) systems work well. A thoughtfully specified system should be able to broadly address both vessel noise and killer whale concerns.*

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[14] Punctuation, grammar, and spelling (including any typos) as provided by respondents.

1.4.2.5 Section 3—Site selection and spatial considerations

In this section of the survey, we asked what are best practices for site selection and other spatial considerations for deploying hydrophone(s) and other hardware that are essential or necessary to effectively monitor killer whale and/or commercial vessel sounds.

We then asked what are the most important site selection/spatial considerations for acoustic monitoring of killer whales and offered the following multiple-choice options in which individuals could, again, check all that apply:

- Depth of hydrophone(s) in the water.
- Hydrophone(s) placement that adequately covers the study area spatially.
- Proximity to where killer whales are known to travel and forage.
- Proximity to where killer whales enter/exit specific portions of their Salish Sea habitat.
- Physical/environmental features that affect sound propagation (bathymetry, substrate, etc.).
- Factors that introduce extraneous noise (wind, currents, tides, anthropogenic, etc.).
- Permitting and regulatory requirements/constraints.
- Other (short free response).

Figure 11 summarizes the responses we received.

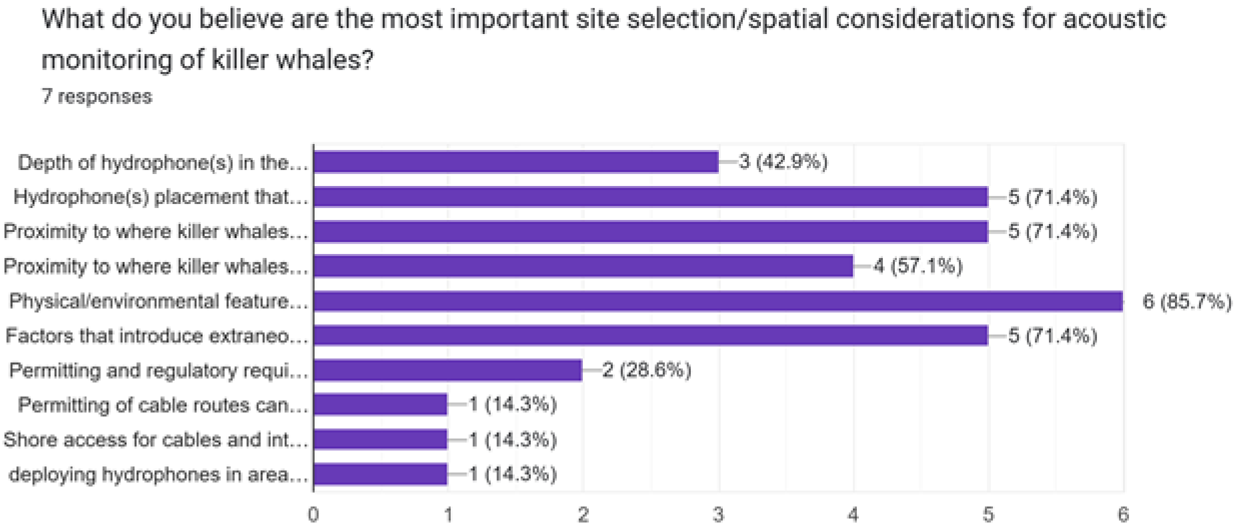

Figure 11. Summary of responses regarding the most important site selection and/or spatial considerations to acoustically monitor killer whales.

Ranking of the above considerations is shown in the graph below:

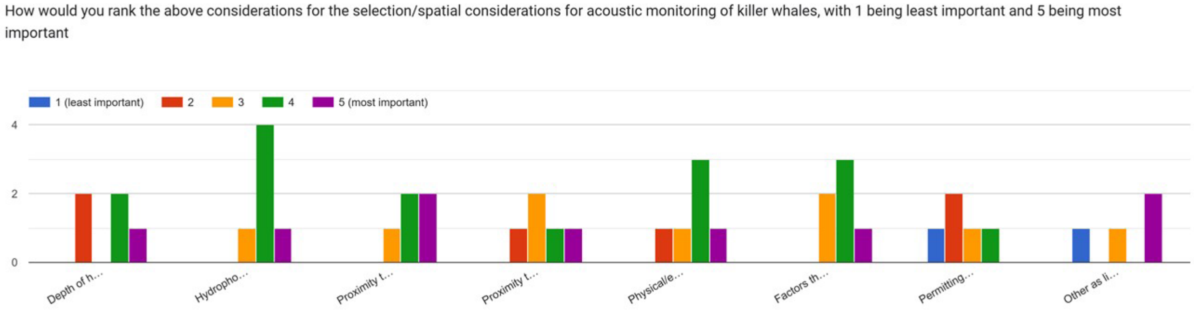

Figure 12. Respondent ranking of the most important site selection and/or spatial considerations to acoustically monitor killer whales.

Likewise, we asked what are the most important site selection/spatial considerations for acoustic monitoring of commercial vessels, including differentiating commercial vessel noise from other noise inputs (both environmental and anthropogenic) in the Quiet Sound area as defined in Section 1, and offered the following choices:

- Depth of hydrophones.
- Hydrophone(s) placement that adequately covers the Study Area spatially.
- Proximity to commercial shipping lanes.
- Ability to obtain information about individual vessels through AIS or other means.
- Ability to follow a standard (e.g. ANSI, ISO).
- Physical/environmental features that affect sound propagation (bathymetry, substrate, etc.).
- Factors that introduce extraneous noise (wind, currents, tides, anthropogenic, etc.).
- Proximity to weather stations.
- Permitting and regulatory requirements/constraints.
- Other (short free response).

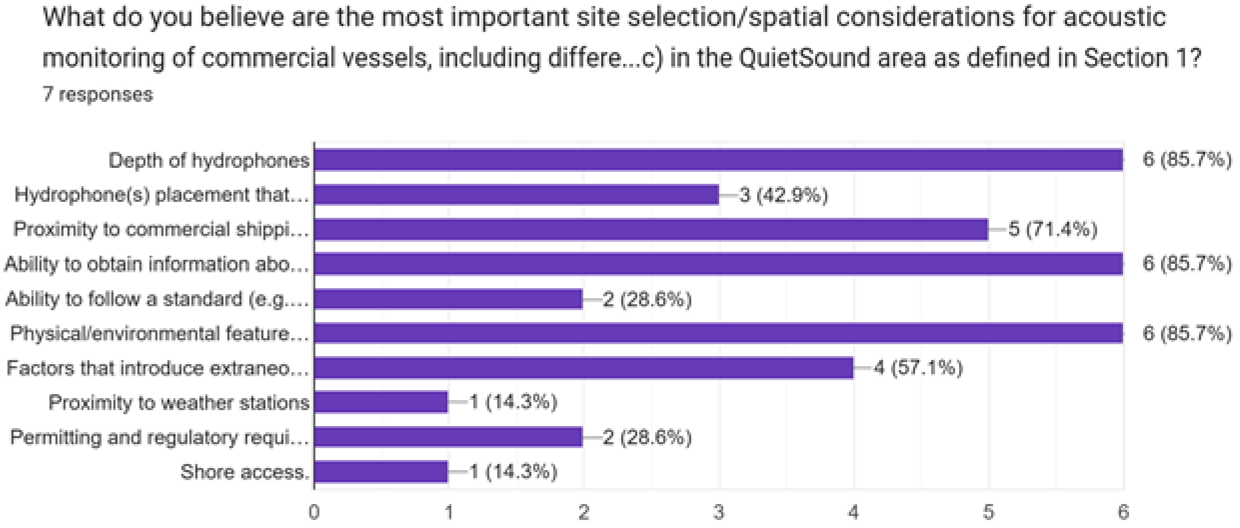

Figure 13. Summary of responses regarding the most important site selection and/or spatial considerations to acoustically monitor commercial vessels.

Ranking of the above considerations is shown in the graph below.

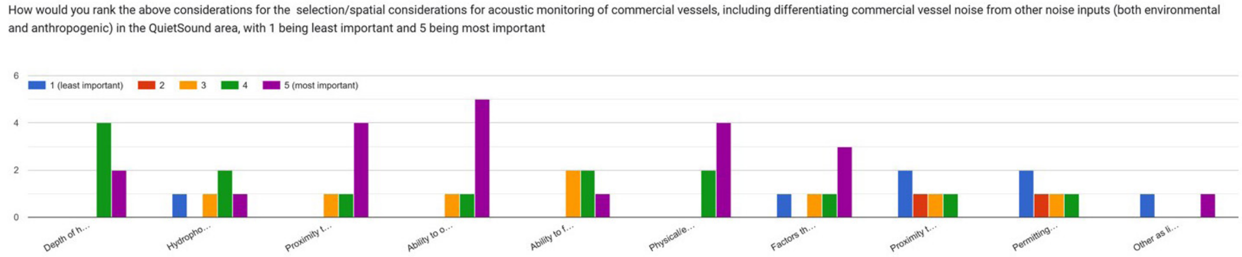

Figure 14. Respondent ranking of the most important site selection and/or spatial considerations to acoustically monitor commercial vessels.

1.4.2.6 Section 4—Costs of acoustic monitoring and best practices with existing programs

In this section we asked, based on experience, what is the likely cost to purchase and install hydrophone and hardware equipment, operate and maintain the equipment, and support data collection, curation, and archiving? The following seven responses were submitted:[15]

- *$100k per year per location*
- *Roughly, the annual cost for the above items can range from $100k/year for a simple near-shore recording station or autonomous system, to $2.5M/year for a deep water cabled array system with automatic detection and ship noise measurement systems and related equipment (e.g. ADCP, CTD), and real-time data processing and management portal.*
- *$5,000 per year*
- *per station: $80K*
- *That depends on the study goal and whether noise/soundscape needs to be accurately assessed. A system that is primarily used for whale detection can be much cheaper than a system that is used to assess noise. And a system that is meant to be used to localize whales is likely the most expensive system. Prices can range from between 2–3k to over 100k.*
- *That's a very difficult question. It will depend on the deployment location, how much cable is needed, how long the system will be maintained, etc. I would expect to pay between $5k and $100k for the hardware and software (depending on features and how many hydrophone elements you want), between $1k and $5k to deploy the system, and about the same to maintain it for one year. I don't know the costs of labor for data collection, curation and archiving.*
- *Costs don't scale linearly and are highly dependent on environment/supporting infrastructure so I will do my best. Assume here the system is autonomous and a single unit (for cabled systems the math is too dependent on circumstances and permitting to better constrain things but added costs easily enter the 100k range). I would expect hardware and supporting equipment to fall into the 50 to 100 k range. Operations and maintaince would be relatively cheap for a cabled system but could easily cost 100–200k/yr if supporting autonomous equipment that requires vessel support and staff time. Data curation is the challenging part. Initial expenses would be high as methods are development to improve the process and reduce costs. As a starting point 100–200k*

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[15] Punctuation, grammar, and spelling (including any typos) as provided by respondents.

but scaling down with time (although this same cost would could easily be shared across multiple points in a network). Thinking more broadly, a multi-year effort with a broad network of sensors and a real effort to development methods to archive data and reduce costs is easily a multi-million dollar effort. These costs, however, would decrease significantly with time as methods are development and OandM costs become dominant. I would be more than happy to discuss estimates for this but would need to better understand the targets to produce a more constrained budget.

We also asked what are important requirements for acoustic data collection and usage consistent with existing programs in the Salish Sea (e.g., ECHO, Quiet Sound, DFO). The following five responses were submitted:[16]

- *Following published best practices.*
- *Abilities to: track noise levels, detect and localize marine mammals including SRKW, measure noise from commercial and recreational vessels, automatically detect and warn approaching vessels of animal presence.*
- *Development of a Salish Sea acoustic model for ambient levels (max thru min) and 3D transmission loss simulations with existing models from the shipping lanes would be very informative for strategic placement of hydrophone stations to validate model results and inform future areas important for acoustic monitoring.*
- *Calibrated system with sensor location choice and depth based on both acoustic propagation models and empiric assessments. Variations soundscapes are relevant and need to be assessed accordingly. Assessments for a short period of time and models only considering a few scenarios, e.g. sound speed variation in only two seasons, is not adequate.*
- *That's outside of my area of expertise. The only thing I know from my own data collection is that it's important to have multiple redundant backups of the original non-compressed data.*

Finally, we asked if there is anything else to mention or provide as feedback regarding best practices, limiting factors, or lessons learned for acoustic monitoring of killer whales and/or commercial vessel noise. The following four responses were submitted:[17]

- *People often think installing hydrophone systems are a once-off bit of work. Keeping them running at high quality takes a lot of ongoing effort and funding.*
- *There are some amazing underwater listening systems now operating (e.g., Lime Kiln monitoring station and Boundary Pass underwater listening station). These real-time systems collect high quality real-time data that could be more generally shared between government organizations or at least better collaborations could be established.*
- *Understand the limits of your data well before making them public and make the limitations also public.*
- *If you can afford to put in two 4-element arrays like I built for the Whale Museum in 2000, then please do it. The use of such an array for detecting and recording vocalizations of individual animals would be incredibly useful.*

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[16] Punctuation, grammar, and spelling (including any typos) as provided by respondents.

[17] Punctuation, grammar, and spelling (including any typos) as provided by respondents.

1.5 Section 1 Conclusions

In this section of the report, we completed a literature review of and conducted outreach on past and present underwater acoustic monitoring initiatives conducted within the Study Area, including spatial understanding of acoustic data associated with SRKW and large commercial vessel use. We summarized the various types of hydrophone and acoustic recording equipment, software and analytical methods used, main results, data access, and present status of various acoustic monitoring projects, if known. Past and present efforts have focused on monitoring for SRKW and other killer whales and cetaceans using cabled hydrophones (nodes), often with live-streaming capabilities for educational and public interfacing purposes, but mostly using relatively inexpensive noncalibrated systems. We also included spatial information on AIS-derived commercial vessel movement by type among other variables, the general distribution of SRKW, and patterns of underwater noise experienced by SRKW in the Study Area. There are several seasonal SRKW high-use areas that overlap with commercial shipping lanes within the Study Area, including Haro Strait and Admiralty Inlet.

Finally, we reviewed literature and conducted outreach on best practices and limiting factors regarding hydrophone/recording equipment and software packages appropriate for acoustically monitoring killer whales and commercial vessels, including associated noise. These include cost considerations for selection of hydrophone recording equipment—including installation, operations, data curation, and archiving—as well as best practices for selection of spatial areas to monitor (given bathymetry, currents, and permitting requirements, among other considerations). In general, costs to maintain calibrated autonomous hydrophone systems are lower relative to comparable shore-cabled hydrophone systems capable of providing both real-time monitoring data and calibrated measurements.

The next sections include the following content as described in Phase 2 of the Scope of Work (Appendix A): evaluation of the hydrophone network in the context of Quiet Sound noise reduction initiatives, and recommendations for type and location of additional hydrophones and minimum standards.

2 Evaluation of Hydrophone Network in Context of Quiet Sound Noise Reduction Initiatives

In this section, we evaluate the hydrophone network in the Study Area based on previous sections of Phase 1 of this report and specifically in the context of Quiet Sound noise reduction initiatives. This evaluation includes considerations for measuring the effectiveness of commercial vessel slowdowns and other potential noise reduction initiatives, especially in SRKW high-use areas. Here, we also evaluate the hydrophone network for making real-time detection of SRKW sounds for dynamic management applications of whale and vessel interactions, such as alerting mariners when to slow down to reduce noise or disturbance.

2.1 Evaluation of PAM Systems Capable of Measuring Slowdown Effectiveness and/or Real-Time Killer Whale Detections

Several passive acoustic monitoring systems that can measure the effectiveness of commercial vessel slowdowns and other potential noise reduction initiatives within the Study Area are summarized in the literature review sections of this report. Here, we evaluate existing hydrophone nodes within the Study Area that monitor in SRKW high-use zones and follow best practices for making robust, reliable, and reproducible empirical measurements (see Section 1.3).

The cabled node at the lighthouse at Lime Kiln Point State Park, Washington, installed and maintained by SMRU Consulting North America in partnership with the Whale Museum's SeaSound Remote Sensing Network, currently consists of two systems that serve distinct purposes. One is for a public-interfacing live-stream feed,[18] and the other is a calibrated, single-element hydrophone system designed to make empirical measurements of ambient noise and noise emitted by commercial vessels, including those participating in ECHO program slowdowns in Haro Strait (Joy et al. 2019, Trounce et al. 2019, Malinka et al. 2023a). The system's capability also includes automated real-time killer whale detections that are entered into Ocean Wise's Whale Report application, which pushes them to the Whale Report Alert System (WRAS).[19] WRAS then sends real-time notifications to commercial mariners within the Study Area. Hydrophone detections are automated using the PAMGuard whistle and moan binary detector, and classified as a killer whale event based on the detection rate in a 20 min listening window. Through ECHO program funding, SMRU Consulting is working to reduce false positive rates related to non-killer whale cetacean detections to improve automation precision. Currently, the node does not have localization capability given the single-element hydrophone (Zimmer 2011, 2013). SMRU Consulting also has capability to monitor and measure the effectiveness of commercial vessel slowdowns using the autonomous hydrophone system previously deployed in Admiralty Inlet during the 2022–23, 2023–24, and 2024–25 Quiet Sound slowdown periods (Malinka et al. 2023b, Matei et al. 2024). We described this autonomous hydrophone system in the literature review of Phase 1 (Section 1.1.5*).* Measurements of noise emitted by vessels participating in future Quiet Sound slowdown periods by the same or similarly specified hydrophone systems would allow the most consistent and comparable measurements of effectiveness of noise reduction initiatives relative to past years.

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[18] https://www.smruconsulting.com/lime-kiln-live-hydrophone

[19] https://ocean.org/whales/wras/. For other details, see Section 2.2.2.3.6.

Orcasound currently has several live-streaming hydrophone nodes capable of making real-time killer whale detections in SRKW high-use locations within the Study Area, including those at Sunset Bay, Bush Point, Port Townsend, and Orcasound Lab, Washington (Figure 15). In the past, some nodes have included hydrophone systems capable of making calibrated ambient and vessel noise measurements, but funding to replace damaged or failed components has been limited. A few nodes have also had two hydrophones deployed for stereo (binaural) live-streaming to aid humans in determining the direction where sources (SRKW sounds or vessels) might be coming from relative to the node. Humans listening to the live-streaming hydrophone feeds can report "whale," "vessel," or "other sounds" acoustically detected at Orcasound nodes through the live-streaming web-based application, and live reports are logged and can be viewed in an online table.[20]

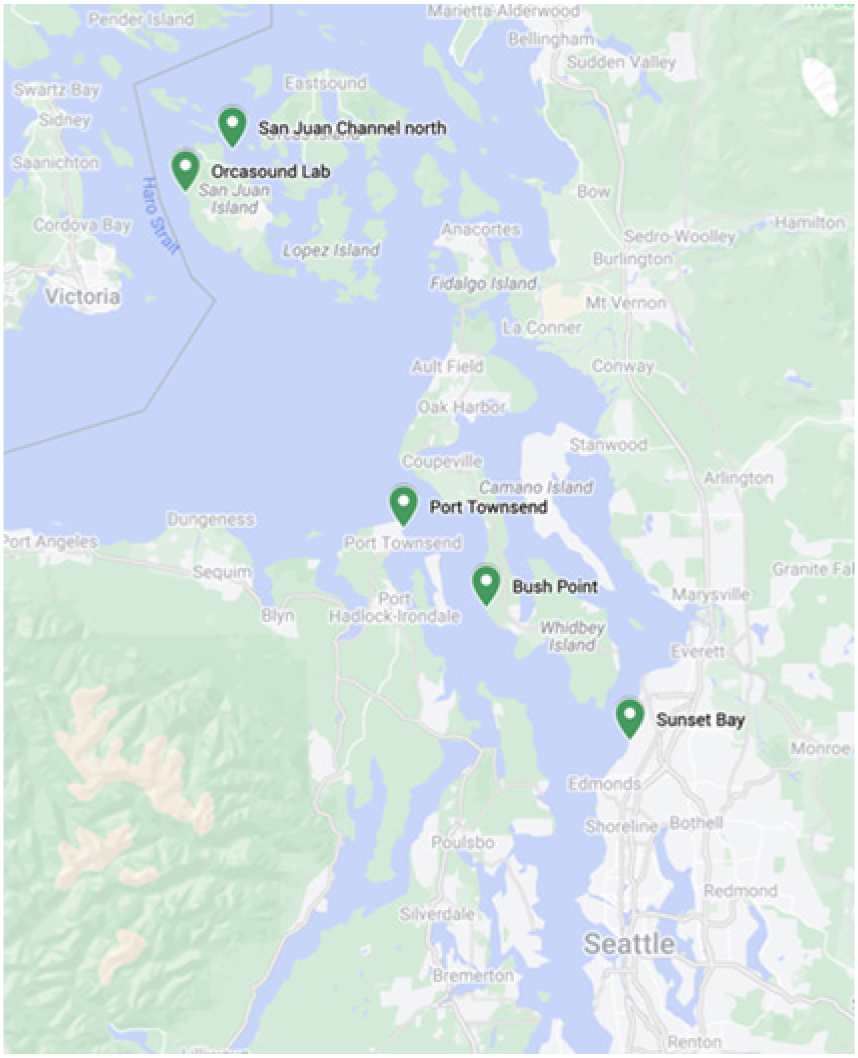

Figure 15. Map of Orcasound live-streaming hydrophone nodes (source: Orcasound).

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[20] Live-streaming web-based application: https://live.orcasound.net/
Online table: https://live.orcasound.net/reports

Labeled or annotated detections of killer whales are also used for training and modeling for the "AI for Orcas" initiative involving Orcasound, Orca Conservancy, and collaborators at Microsoft. The initiative includes the development of an open-source, SRKW-specific binary classifier, called OrcaHello. The OrcaHello project ultimately aims to provide a real-time AI-assisted notification system in which live-streaming audio data are analyzed using the SRKW binary classifier, detections are passed to human experts for annotation and validation, and confirmed SRKW calls are sent as notifications to subscribers from various sectors. Orcasound scientists have also recently partnered with Protected Seas to deploy the Marine Monitor (M2) system, a real-time visual (optical) camera and radar system to track vessels, especially non-AIS vessels. Orcasound scientists have installed the M2 system at Orcasound Lab to capture images of vessels, which are then labeled and used to build an AI model to classify vessels by type. Eventually, they aim to combine this vessel information with hydrophone data to associate noise with vessel class, track, and/or speed.

Passive acoustic approaches for SRKW detections and dynamic management are not foolproof. For example, whales need to be vocalizing within the detection range of the hydrophones, and the received sounds need to be quickly identified as SRKW sounds to implement an NRT action. Several complementary approaches, in conjunction with passive acoustic monitoring, are quite valuable to address these PAM limitations. For example, researchers and the public can report visual sightings of killer whales to various Salish Sea networks, such as Orcanetwork or WRAS, for timely alerts. At the Point Wilson lighthouse near Port Townsend, Quiet Sound has installed a thermal camera imaging system with WhaleSpotter's software to automatically identify the heat signatures of whales as they swim through Admiralty Inlet.[21] The thermal camera can address limitations of real-time whale detections using other methods, for example, when whales are quiet or in low-visibility conditions. This report further covers complementary (non-PAM) technologies in the next section. The stability of the current network may be vulnerable to gaps in funding, since it is maintained through volunteers, crowdfunding, and short-term grants. For example, Orcasound is a cooperative network in which members—mostly local nonprofit organizations—"establish network node(s) consisting of hydrophone(s), computers and software, power, and an Internet connection, and/or related educational outreach infrastructure."[22]

2.2 Recommendations for Type(s) and Location(s) of Additional Hydrophones and Minimum Standards

This section includes recommendations for type(s) and location(s) of additional hydrophones/nodes, based on gaps in acoustic monitoring of vessels and SRKW within the Study Area. It also covers recommendations that would improve hydrophone network interoperability and data sharing among operators, to meet acoustic monitoring needs and minimum standards. Minimum standards are largely covered in Section 1.3 and are briefly summarized here as well. This section also discusses opportunities for new acoustic technologies, reconfiguration of existing equipment, and potential complementary (non-passive acoustic) technologies to meet monitoring needs within the Study Area.

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[21] https://quietsound.org/thermal-imaging-camera

[22] https://www.orcasound.net/join/

2.2.1 Gaps in the hydrophone network in the Study Area

Here we identify gaps in the Study Area's hydrophone network, focusing on spatial and functional gaps to monitor commercial vessel noise and SRKW sounds (Figure 16). Spatial gaps in the Salish Sea portion of the Study Area include the U.S. side of the Strait of Juan de Fuca leading both north to San Juan Island (including Middle and Hein Banks) and south to the entrance of Admiralty Inlet; Rosario Strait; Saratoga Passage; and central and south Puget Sound (sound of Edmonds, Washington). We identify Saratoga Passage, between Whidbey and Camano Islands, as another important waterway corridor that SRKW may travel through (from Deception Pass south through Possession Sound) to reach Puget Sound. Additionally, Quiet Sound, through a desktop study, has recently identified a handful of areas that are being considered to spatially expand their slowdown zone for most commercial vessels, or for select categories that evaluated the overlap between high vessel-traffic density and SRKW seasonal presence. Locations considered were Rosario Strait, north to south between Vancouver Island and Port Angeles, the southwest side of San Juan Island, and east to west between Port Angeles and the entrance of Admiralty Inlet. These Quiet Sound-identified areas considerably

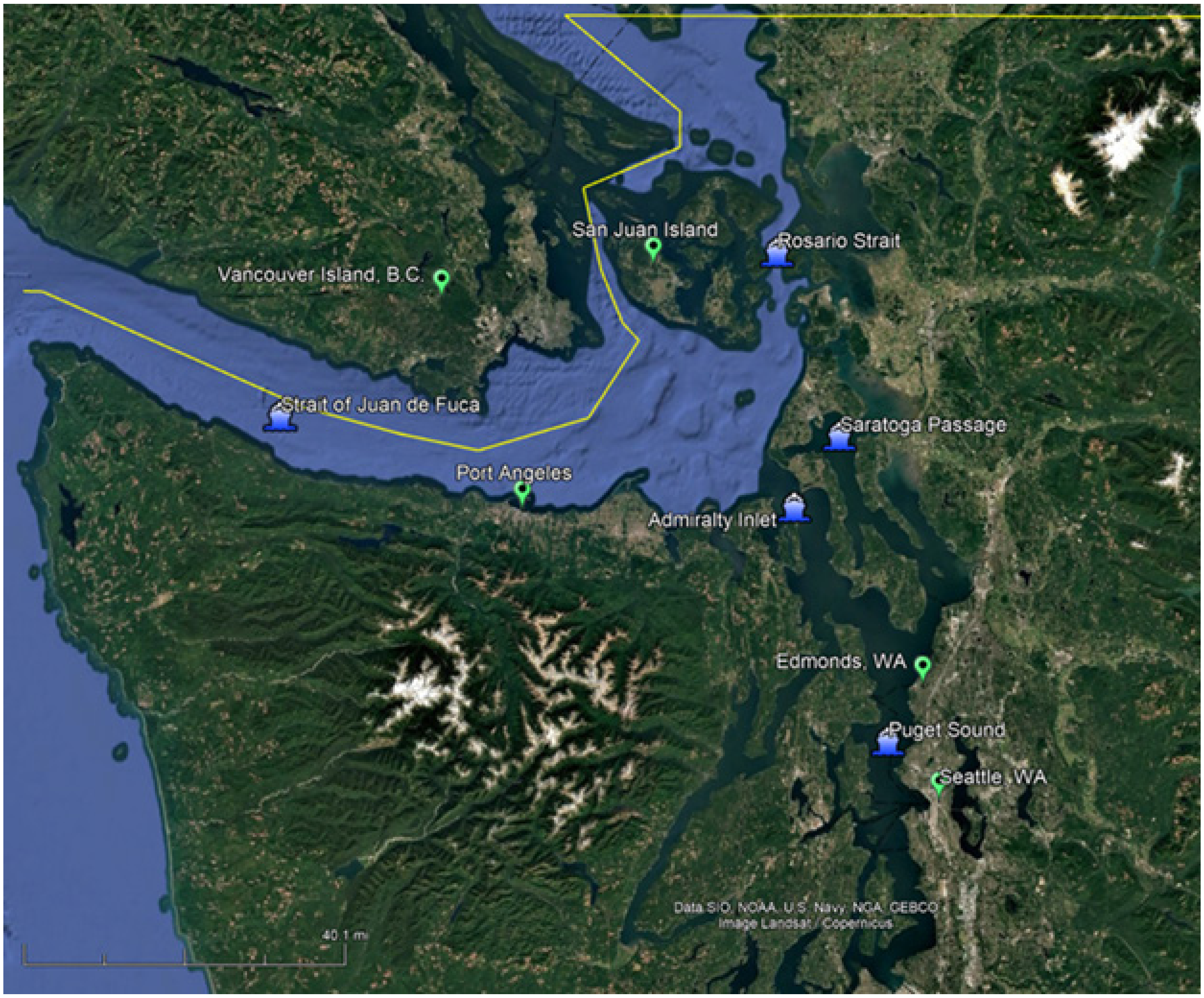

Figure 16. Map of locations referenced in hydrophone monitoring gaps.

overlap with spatial gaps we have identified. Notably, the remaining Washington State coastline (Cape Flattery to the mouth of the Columbia River) is also a sizable portion of SRKW habitat that represents a spatial gap in the network. It is important to note that SRKW typically split off into groups as they travel and forage within their critical habitat, and habitat usage within the Study Area varies by SRKW pod (Hauser et al. 2007). So, real-time detection of SRKW based on a group or pod in one area does not rule out the possibility that another SRKW pod or subpod is concurrently in another area of their critical habitat.

Functional gaps in the hydrophone network are generally related to cabled systems and the ability to make calibrated noise measurements of commercial vessels that follow standards and/or past methods for comparability. Functional network gaps are also related to the ability to monitor in real time and provide reliable detection, classification, and localization of killer whale sounds specific to the SRKW population and the pod/subpod level.

2.2.2 Recommended improvements to network to meet acoustic monitoring needs

2.2.2.1 Hydrophone network interoperability

Within the current network, we refer to interoperability as the ability of the system to function reliably as intended among operators. There are at least two components to consider for dynamic management applications: 1) the detection and identification component, and 2) what to do with the information, or specifically how to reach the intended recipient for management purposes.

Killer whales in the Study Area inhabit noisy environments, and discriminating SRKW sounds from other killer whales and cetacean species and among other acoustic signals can be challenging. PAM systems themselves can also generate both internal and external noise that are confounds or artifacts in acoustic recordings and can affect the performance of automation (Oswald et al. 2022). Thus, PAM in real time by expert human observers would likely result in the most accurate and precise detections and classifications of SRKW as distinct from other killer whales and cetaceans in the Study Area. However, commercial vessels transit the Study Area during both day and night periods, and manually monitoring real-time hydrophone feeds continuously over a 24 hr cycle would be labor-intensive and result in considerable costs. At the time of the report, citizen scientists contribute most of the manual detection as they listen to live-streaming feeds (e.g., Orcasound).

The Lime Kiln hydrophone data stream, which employs a simple automated detection protocol, automatically feeds real-time detections directly into WRAS, which can alert mariners accordingly—although operators acknowledge the high false-positive rate with the detection automation process and are working to improve it. In the absence of an unlimited budget, we currently recommend a two-step automation process that involves humans in the loop for real-time or near-real-time monitoring of SRKW for dynamic management applications. Step 1 would involve the application of detector–classifier automation that reasonably minimizes misses (false negatives), while Step 2 would involve manual validation by experts, assuming that too many false positives would be costly (e.g., slowing down commercial vessels when automation reports SRKW presence when, in fact, SRKW are not there). Similar strategies are implemented for mitigating risk of commercial vessel traffic or offshore wind construction to North Atlantic right whales (NARW; Van Parijs et al. 2009, Palmer et al. 2022). We recommend developing a SRKW-specific detector–classifier that improves automation of real-time PAM for dynamic management applications in the Study Area. Another recommendation is to add automated localization capability to nodes to provide better SRKW location data for dynamic management applications.

2.2.2.2 Data sharing across existing hydrophone equipment operators

Data sharing across hydrophone operators and research groups maximizes information for best conservation practices. In the case of vessel slowdowns or other noise reduction initiatives, we recommend ensuring that the real-time information of SRKW presence within the Study Area can easily and effectively reach commercial vessel operators through the most effective channels, especially for dynamic management. Whether that be WRAS or another alert system, in order to be most effective, it should be consistently used and agreed upon by hydrophone and vessel operators alike, considering costs and ease of implementation and operation. Recommended best practices for data sharing include publishing both real-time streaming data and archival recordings via publicly accessible archives. Archiving options include customized project-hosted websites, open-access data repositories (e.g., Dryad), as well as larger data archiving projects such as the National Centers for Environmental Information's (NCEI) passive acoustic data archive.[23] While this NOAA data archive requires strict metadata and methods for archiving, the extra effort needed to comply with these standards increases the likelihood that archived data will be accessed and used by other researchers for complementary projects. Data sampled by calibrated systems are especially valuable to share broadly, as the information can be used for environmental monitoring over time and comparison to other areas.

Data products, such as species-specific detections, are also important to distribute. Within the boundaries of Quiet Sound, several established programs exist to report on whale sightings and acoustic detections. For example, WRAS, described above, is specifically targeted to update commercial mariners in real-time about whale presence, and some of the data streams that supply information to WRAS are also publicly accessible via an online dashboard. In addition, some research groups are actively engaged in publicizing results, and even include citizen scientists in research activities. For example, the Orcasound project maintains an online dashboard of code for various analytical objectives related to acoustic monitoring of SRKWs.[24] Many collaborative partnerships contribute to the Orcasound project, including a library of calls.[25] These and other analytical tools enable hydrophone operators to provide efficient and accurate information on species presence. However, it is also important to distribute results and archive information for research needs beyond real-time (or near-real-time) detection. NMFS is actively expanding its Passive Acoustic Cetacean Map (PACM) project to archive species detection data provided

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[23] https://www.ncei.noaa.gov/products/passive-acoustic-data
[24] https://github.com/orcasound
[25] https://orca.research.sfu.ca/call-library/

by NOAA researchers and collaborators.[26] The NCEI passive acoustic data archive also hosts detection data for acoustic monitoring projects. These federal data archives are examples of data sharing in addition to efforts already underway in the Quiet Sound region. However, as detection data are distributed, minimum best practices include adhering to metadata standards established by current projects to maximize comparability. Future projects and funding requests should consider requiring the inclusion of a data disposition or sharing plan for data and data products in initial research planning or proposals. It is increasingly common for journals and publishers to require data be made publicly accessible, so it is likely researchers are already considering options to meet this demand.

2.2.2.3 Opportunities for new equipment or reconfiguration of existing PAM equipment

The existing network of passive acoustic recorders (hydrophones) deployed throughout the Study Area, while comprehensive, exhibits previously noted spatial and functional gaps, limiting the network's ability to thoroughly monitor commercial vessel noise and SRKW vocal presence. Theriault et al. (2020) provide a review of existing or emerging technologies that are options to provide information on the presence and location of NARW and SRKW in near-real time for Canada's Whale Detection and Collision Avoidance (WDCA) initiative. They consider and review PAM and sonar systems as underwater sensing systems, in addition to radar, basic light cameras, thermal/infrared cameras, satellite, and other above-water sensing technologies. Of these, visual sensing and PAM systems are noted as the most operational in terms of their ability to detect and classify whales in general, and NARWs and SRKWs specifically. Furthermore, the authors review PAM systems that include detector–classifier and localization capabilities and respective performance considerations, including relevant physical and biological signals of interest, sensor sensitivity, probability of detection, and recall and precision of automation (Theriault et al. 2020).

To improve coverage, accuracy, and responsiveness of acoustic monitoring, the following PAM technologies should be considered.

2.2.2.3.1 Coastal acoustic buoys

There are several bottom-mounted, moored systems with surface buoys capable of transmitting real-time acoustic data to shore, enabling immediate detection of cetacean presence and/or ambient noise. These systems include RAOS (Real-Time Acoustic Observing System), CRAB (Coastal Real-Time Acoustic Buoys), CAB (Coastal Acoustic Buoy), and CABOW (Coastal Acoustic Buoy for Offshore Wind). NOAA's Pacific Marine Environmental Laboratory (PMEL), along with partners, developed the RAOS—a prototype system for real-time monitoring that relies on an Iridium satellite connection to relay acoustic detections of killer whale calls in remote areas; details on performance and accuracy are provided in Matsumoto et al. (2016). CRAB, CAB, and CABOW are well suited for areas with more consistent connectivity, as they can integrate with existing marine monitoring networks. PMEL, along with partners, also developed the CRAB system for transmitting ambient noise levels via local cell networks off the Oregon coast (Dziak et al. 2023). SMRU Consulting, along

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[26] https://passiveacoustics.fisheries.noaa.gov/pacm/

with various partners, developed the CAB (Guardian or Sentinel) and CABOW systems.[27] Details about the components of CABOW and system performance for detecting and providing accurate bearings of NARW upcalls relative to an offshore wind development exclusion zone are provided in Palmer et al. (2022). We note that these coastal acoustic buoys are battery-powered, with current configurations allowing two weeks to several months of operational life depending on configurations, and may not be ideal for long-term monitoring applications without regular servicing (Palmer et al. 2022). However, buoy systems often provide a more cost-effective and flexible solution for passive acoustic monitoring, particularly in areas where cable laying is not feasible or permits are difficult to obtain.

2.2.2.3.2 Boundary Pass Underwater Listening Station

While not in the Study Area, the Boundary Pass ULS is a hydrophone array system operated by JASCO Applied Science and the Port of Vancouver and sponsored by Transport Canada.[28] Since 2020, the system monitors sound in relatively deep water (190 m) in the major commercial shipping lane and represents a high-end cabled option. It consists of two time-synchronized pyramidal-shaped hydrophone arrays for localization, video cameras, CTD sensors (salinity, current, and temperature for sound propagation modeling), and other self-monitoring sensors. The arrays sit 300 m apart from each other on the seafloor and each house eight hydrophones, with four operational at any given time for localization and tracking in three dimensions (the other four are backups). Hydrophones are calibrated daily using on-board reference sounds. Fiber-optic cables transmit data to shore, enabling immediate reporting of marine mammal detections and PAM data analysis. Nearly all vessels transiting to and from the Port of Vancouver are measured following international standards, allowing measures of effectiveness of vessel slowdowns and other quieting measures and technologies. Real-time acoustic detections and localizations of cetaceans, including SRKW, in Boundary Pass support dynamic management of whale and vessel interactions. Ambient and vessel noise measurements also provide long-term empirical records about the acoustic environment (i.e., soundscape) of SRKW habitat.

2.2.2.3.3 Distributed acoustic sensing (DAS)

This emerging technology converts fiber optic cables into large-scale arrays of acoustic sensors, significantly increasing the coverage area with high spatial resolution. DAS is particularly promising for monitoring marine traffic noise and detecting low-frequency vocalizations over relatively shallow, near-coastal regions. University of Washington (Bothell campus) and Orcasound scientists are currently collaborating on a project to add DAS devices to existing fiber optic cables in the Study Area to test this new approach for monitoring vessel traffic and explore ways to record the higher-frequency sounds of killer whale signals.

2.2.2.3.4 Directional hydrophones

Unlike standard omnidirectional sensors, directional hydrophones can localize the source of an underwater sound. Directional hydrophones are ideal for locating vocalizing SRKWs and could be used in arrays to triangulate the position and movement of individuals or pods with greater precision.

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[27] https://www.smruconsulting.com/cabgrd

[28] https://www.jasco.com/boundary-pass-uls

2.2.2.3.5 *Drifting buoys with AI-enabled hydrophones*

These mobile platforms combine acoustic sensors with onboard artificial intelligence (AI) for real-time detection, classification, and localization of marine mammal vocalizations. Their mobility allows for flexible coverage of dynamic, high-traffic areas, such as shipping lanes and/or near SRKW critical habitat across the Salish Sea.

2.2.2.3.6 *Potential complementary (non-PAM) technologies*

In addition to PAM, other technologies have been developed to detect cetaceans for mitigation purposes. As previously highlighted, these technologies have been used both in isolation and to complement acoustic monitoring. They include visual sighting networks, unmanned aerial systems or drones, thermal and infrared imaging, sonar and radar detection systems, movement models, and ultra-high-resolution satellite imagery. Efficiency of the monitoring methods will depend on the target species, animal behavior, acceptance of false positives, and environmental conditions; however, using a combination of complementary systems generally improves the overall performance (Verfuss et al. 2018, Smith et al. 2020).

In the 1970s, the Whale Museum in Friday Harbor began operating a sighting network for cetaceans, specifically SRKW (Olson et al. 2018). Since then, the number of regional, shorebased sighting networks, such as Orca Network, has increased, resulting in extensive coverage of the Salish Sea. New technologies such as phone apps have provided a mechanism to integrate, modernize, and streamline these regional sighting networks. As part of the ECHO program, there has been investment in the WhaleReport Alert System (WRAS). The WRAS framework has four components: 1) developing networks of dedicated volunteer reporters, 2) applying smartphone technology to streamline cetacean data collection, 3) developing a system to deliver alerts to commercial mariners, and 4) disseminating information back to citizen scientists to facilitate long-term engagement in marine conservation (Scott et al. 2019). Similar apps have been developed to mitigate ship strikes in the northeastern United States and California.[29] The Whale Alert app is being adapted for use by recreational boaters in SRKW habitat.

Advancements in imaging technologies have increased their utility for marine mammal mitigation. Imaging can be done from shorebased stations, vessels, unmanned aerial systems, and high-resolution satellites. The use of satellite imagery for cetacean detection is in its infancy, and is not currently being used in real time (Cubaynes et al. 2019, Höschle et al. 2021). Vessel-based thermal imaging systems have been effective in detecting large whale blows, regardless of daylight, with a uniform, omnidirectional probability out to 5 km (Zitterbart et al. 2013). Imaging systems have the challenges of higher transmission effort and the generation of large quantities of data, but machine learning and AI have proven effective in detecting and tracking target features (Harasyn et al. 2022, Rodofili et al. 2022).

Richter et al. (2023) used land-based thermal imaging to detect killer whales at Boundary and Active Passes in the Salish Sea. Similar to the thermal imaging system now deployed by Quiet Sound partners at Point Wilson, detections of killer whales are based on the body, as opposed to the blow as in large whales. While Richter et al. (2023) were able to detect killer whales, it

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[29] E.g., https://www.whalealert.org/ and https://whalesafe.com/whale-safe-tool/.

was not possible to identify the ecotype (Theriault et al. 2020). The addition of color cameras may increase the possibility of ecotype identification.[30] More frequent detections may indicate a larger group size, but that is not a reliable indicator of ecotype. Their results also indicate that choice of lens and the resulting field of view is a tradeoff between coverage and resolution.

Radar is often used to detect and track vessels on the surface of the water (Kemsley and Pukini 2021), but there is a lack of empirical evidence that it is useful for detecting marine mammals. Radar cannot distinguish between species and can be impacted by weather conditions (Verfuss et al. 2018). Sonar systems have been used to detect and track marine mammals near tidal turbines (Hastie et al. 2019), but the range of these systems is limited, especially when sea conditions are not optimal (Verfuss et al. 2018).

Predictive movement models are currently being developed for SRKW (Randon et al. 2022). These models use real-time location data and a stochastic movement model to provide short-term forecasts of whale movement. The authors report prediction success of J pod movements with 2.5 hour advance notice and with < 5 km of prediction error. With further refinement, these predictive models may be able to forecast SRKW movements with increasing accuracy.

2.3 Section 2 Conclusion

In this section of the report, we evaluated hydrophones and PAM systems within the Study Area that can measure Quiet Sound noise reduction initiatives, particularly in SRKW high-use areas, as well as those systems capable of making real-time killer whale detections for dynamic management. The node currently at the Lime Kiln Lighthouse has both the capability to make calibrated noise measurements to evaluate vessel slowdown effectiveness, and real-time detections in Haro Strait. Several nodes within the Orcasound hydrophone network are also capable of making real-time detections in Admiralty Inlet, where Quiet Sound is conducting seasonal slowdowns. However, we identified spatial gaps in the PAM network, including the areas directly to the north and sound of the Admiralty Inlet slowdown zone. Functional gaps are generally related to the ability to make calibrated noise measurements that follow standards and/or past methodological approaches for comparability and/or the ability to monitor in real time that provide reliable detections, classifications, and localizations of SRKW-specific sounds. Based on these gaps, we recommended improvements to the existing network, including further development and implementation of an SRKW-specific detector–classifier for real-time automation and localization for dynamic management applications. We also noted the importance of data sharing across hydrophone operators and research groups to maximize information for best conservation practices. Lastly, we summarized new equipment or reconfiguration of existing PAM equipment or complementary technologies that could improve spatial coverage, accuracy, and responsiveness in the Study Area.

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[30] https://www.whalespotter.com/

References

Adams, S., and R. Aronson. 2024. Results of the 2023–2024 Voluntary Commercial Shipping Slowdown in Washington Waters for the Protection of Southern Resident Killer Whales. Washington Maritime Blue, Seattle.

ANSI (American National Standards Institute). 2009. American National Standard: Quantities and Procedures for Description and Measurement of Underwater Sound from Ships Part 1: General Requirements. American National Standards Institute, New York.

Aronson, R., and C. O'Morchoe. 2023. Results of the 2022–2023 Voluntary Commercial Shipping Slowdown Trial in Washington Waters for the Protection of Southern Resident Killer Whales. Washington Maritime Blue, Seattle.

Ashe, E., M. S. Collins, K. Nielsen, R. Reiss, K. Wold, and R. Williams. 2023. Develop foundation to monitor noise in marine water vital sign indicator. Contract Report 2022-37. Puget Sound Partnership and the Puget Sound Ecosystem Monitoring Program, Seattle.

Bassett, C., A. De Robertis, and M. Gallagher. 2024. A passive acoustic drifter for radiated noise measurements of NOAA Fisheries survey vessels. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC-490.

Bassett, C., B. Polagye, M. Holt and J. Thomson. 2012. A vessel noise budget for Admiralty Inlet, Puget Sound, Washington (USA). The Journal of the Acoustical Society of America 132(6):3706–3719.

Bassett, C., J. Thomson, P. H. Dahl, and B. Polagye. 2014. Flow-noise and turbulence in two tidal channels. The Journal of the Acoustical Society of America 135(4):1764–1774.

Bassett, C., J. Thomson, and B. Polagye. 2013. Sediment-generated noise and bed stress in a tidal channel. Journal of Geophysical Research: Oceans 118(4):2249–2265.

Burnham, R. E., S. Vagle, C. O'Neill, and K. Trounce. 2021. The efficacy of management measures to reduce vessel noise in critical habitat of Southern Resident killer whales in the Salish Sea. Frontiers in Marine Science 8:664–691.

Clark, C. W., and P. J. Clapham. 2004. Acoustic monitoring on a humpback whale (*Megaptera novaeangliae*) feeding ground shows continual singing into late spring. Proceedings of the Royal Society of London Series B: Biological Sciences 271(1543):1051–1057.

Cominelli, S., R. Devillers, H. Yurk, A. MacGillivray, L. McWhinnie, and R. Canessa. 2018. Noise exposure from commercial shipping for the Southern Resident killer whale population. Marine Pollution Bulletin 136:177–200.

Cubaynes, H. C., P. T. Fretwell, C. Bamford, L. Gerrish, and J. A. Jackson. 2019. Whales from space: Four mysticete species described using new VHR satellite imagery. Marine Mammal Science 35(2):466–491.

CWA (Clean Water Act). 1972. Federal Water Pollution Control Act of 1972. Clean Water Act of 1977. U.S. Code, title 33, sections 1251–1387.

Deecke, V. B., J. K. Ford, and P. Spong. 1999. Quantifying complex patterns of bioacoustic variation: Use of a neural network to compare killer whale (*Orcinus orca*) dialects. The Journal of the Acoustical Society of America 105(4):2499–2507.

DFO (Fisheries and Oceans Canada). 2017. Evaluation of the Scientific Evidence to Inform the Probability of Effectiveness of Mitigation Measures in Reducing Shipping-Related Noise Levels Received by Southern Resident Killer Whales. Fisheries and Oceans Canada, Ottawa, Ontario, Canada. Available: https://www.dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2017/2017_041-eng.html (April 2026).

Duc, P. N. H., D. A. Campbell, M. Dowd, and R. Joy. 2024. Functional data analysis to describe and classify Southern Resident killer whale calls. Ecological Informatics 83:102841.

Dziak, R. P., H. Matsumoto, S. M. Haver, D. K. Mellinger, L. Roche, J. H. Haxel, S. Stalin, C. Meinig, K. Kohlman, A. Sremba, and 3 coauthors. 2023. PMEL Passive Acoustics Research: Quantifying the Ocean Soundscape from Whales to Wave Energy. Oceanography 36(2/3):196–205.

Eickmeier, J., D. Tollit, K. Trounce, G. Warner, J. Wood, A. MacGillivray, and Z. Li. 2021. Salish Sea Ambient Noise Study: Best Practices. Vancouver Fraser Port Authority, Vancouver, British Columbia, Canada.

Emmons, C. K., M. B. Hanson, and M. O. Lammers. 2019. Monitoring the occurrence of Southern Resident killer whales, other marine mammals, and anthropogenic sound in the Pacific Northwest. Northwest Fisheries Science Center, Seattle.

Emmons, C. K., M. B. Hanson, and M. O. Lammers. 2021. Passive acoustic monitoring reveals spatiotemporal segregation of two fish-eating killer whale *Orcinus orca* populations in proposed critical habitat. Endangered Species Research 44:253–261.

Erbe, C., S. A. Marley, R. P. Schoeman, J. N. Smith, L. E. Trigg, and C. B. Embling. 2019. The effects of ship noise on marine mammals—A review. Frontiers in Marine Science 6:606.

Ettinger, A. K., C. J. Harvey, C. Emmons, M. B. Hanson, E. J. Ward, J. K. Olson, and J. F. Samhouri. 2022. Shifting phenology of an endangered apex predator mirrors changes in its favored prey. Endangered Species Research 48:211–223.

Foote, A. D., R. W. Osborne, and A. R. Hoelzel. 2004. Whale-call response to masking boat noise. Nature 428(6986):910.

Ford, J. K. 1987. A catalogue of underwater calls produced by killer whales (*Orcinus orca)* in British Columbia. Canadian Aquatic Science Data Report 633. Fisheries and Oceans Canada, Nanaimo, British Columbia, Canada.

Ford, J. K. 1989. Acoustic behaviour of Resident killer whales (*Orcinus orca)* off Vancouver Island, British Columbia. Canadian Journal of Zoology 67(3):727–745.

Ford, J. K. 1991. Vocal traditions among Resident killer whales (*Orcinus orca)* in coastal waters of British Columbia. Canadian Journal of Zoology 69(6):1454–1483.

Ford, J. K., J. F. Pilkington, A. Reira, M. Otsuki, B. Gisborne, R. M. Abernethy, E. H. Stredulinsky, J. R. Towers, and G. M. Ellis. 2017. Habitats of Special Importance to Resident Killer Whales (*Orcinus orca)* off the West Coast of Canada. Fisheries and Oceans Canada, Ottawa, Ontario, Canada.

Frasier, K., S. Fregosi, M. Ziegenhorn, A. Solsona, S. Baumann-Pickering, M. Roche, M. Rafter, J. Hildebrand, C. Schoenbeck, and R. Cohen. 2024. MarineBioAcousticsRC/Triton: Remora update early 2024. Zenodo, Geneva, Switzerland. DOI: 10.5281/zenodo.10963175

Frouin-Mouy, H. 2018. BC Ferries Vessel Underwater Radiated Noise Measurements in Swanson Channel: Vessel Noise Analysis. JASCO Applied Sciences Ltd., Victoria, British Columbia, Canada.

Gaetz, W., K. Jantzen, H. Weinberg, P. Spong, and H. Symonds. 1993. A neural network method for recognition of individual *Orcinus orca* based on their acoustic behaviour: Phase 1. Pages I455–I457 in Proceedings of OCEANS ’93. Institute of Electrical and Electronics Engineers, Piscataway, New Jersey.

Haifley, A., S. T. Abdel-Raheem, J. K Olson., J. Wood, and R. W. Osborne. 2022. Southern Resident Killer Whale Sighting Compilation – Historical Database 1948–2022. Northwest Fisheries Science Center, Seattle.

Hanson, M. B., R. W. Baird, J. K. Ford, J. Hempelmann-Halos, D. M. Van Doornik, J. R. Candy, C. K. Emmons, G. S. Schorr, B. Gisborne, and K. L. Ayres. 2010. Species and stock identification of prey consumed by endangered Southern Resident killer whales in their summer range. Endangered Species Research 11:69–82.

Hanson, M. B., C. K. Emmons, M. J. Ford, M. Everett, K. Parsons, L. K. Park, J. Hempelmann, D. M. Van Doornik, G. S. Schorr, and J. K. Jacobsen. 2021. Endangered predators and endangered prey: Seasonal diet of Southern Resident killer whales. PLOS ONE 16(3):e0247031.

Hanson, M. B., C. K. Emmons, E. J. Ward, J. A. Nystuen, and M. O. Lammers. 2013. Assessing the coastal occurrence of endangered killer whales using autonomous passive acoustic recorders. The Journal of the Acoustical Society of America 134(5):3486–3495.

Harasyn, M. L., W. S. Chan, E. L. Ausen, and D. G. Barber. 2022. Detection and tracking of belugas, kayaks and motorized boats in drone video using deep learning. Drone Systems and Applications 10(1):77–96.

Hastie, G. D., G.-M. Wu, S. Moss, P. Jepp, J. MacAulay, A. Lee, C. E. Sparling, C. Evers, and D. Gillespie. 2019. Automated detection and tracking of marine mammals: A novel sonar tool for monitoring effects of marine industry. Aquatic Conservation: Marine and Freshwater Ecosystems 29:119–130.

Hatch, L. T., M. McKenna, R. Burnham, K. E. Fraiser, C. Gabriele, S. Hastings, S. Haver, A. Kunz, A. MacGillivray, C. Malinka, and 6 coauthors. 2025. A call for comparable measurements of underwater radiated noise related to vessel speed reduction programs. The Journal of the Acoustic Society of America Express Letters 5(8):087201.

Hauser, D. D., M. G. Logsdon, E. E. Holmes, G. R. VanBlaricom, and R. W. Osborne. 2007. Summer distribution patterns of Southern Resident killer whales *Orcinus orca:* Core areas and spatial segregation of social groups. Marine Ecology Progress Series 351:301–310.

Heise, K. A., L. G. Barrett-Lennard, N. R. Chapman, D. T. Dakin, C. Erbe, D. E. Hannay, N. D. Merchant, J. S. Pilkington, S. J. Thornton, and D. J. Tollit. 2017. Proposed metrics for the management of underwater noise for Southern Resident killer whales. Coastal Ocean Report Series 2:30.

Hilborn, R., S. P. Cox, F. M. D. Gulland, D. G. Hankin, N. T. Hobbs, D. E. Schindler, and A. W. Trites. 2012. The Effects of Salmon Fisheries on Southern Resident Killer Whales: Final Report of the Independent Science Panel. ESSA Technologies Ltd., Vancouver, British Columbia, Canada.

Holt, M. M. 2008. Sound exposure and Southern Resident killer whales (*Orcinus orca)*: A review of current knowledge and data gaps. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-89.

Holt, M. M., D. P. Noren, V. Veirs, C. K. Emmons, and S. Veirs. 2009. Speaking up: Killer whales (*Orcinus orca)* increase their call amplitude in response to vessel noise. The Journal of the Acoustical Society of America 125(1):EL27–EL32.

Holt, M. M., J. B. Tennessen, E. J. Ward, M. B. Hanson, C. K. Emmons, D. A. Giles, and J. T. Hogan. 2021a. Effects of vessel distance and sex on the behavior of endangered killer whales. Frontiers in Marine Science 7:582182.

Holt, M. M., J. B. Tennessen, M. B. Hanson, C. K. Emmons, D. A. Giles, J. T. Hogan, and M. J. Ford. 2021b. Vessels and their sounds reduce prey capture effort by endangered killer whales (*Orcinus orca)*. Marine Environmental Research 170:105429.

Höschle, C., H. C. Cubaynes, P. J. Clarke, G. Humphries, and A. Borowicz. 2021. The Potential of Satellite Imagery for Surveying Whales. Sensors 21(3):963.

Joy, R., D. Tollit, J. Wood, A. MacGillivray, Z. Li, K. Trounce, and O. Robinson. 2019. Potential Benefits of Vessel Slowdowns on Endangered Southern Resident Killer Whales. Frontiers in Marine Science 6:344.

Kemsley, A., and C. Pukini. 2021. Marine Protected Area Watch and Marine Monitor (M2) RADAR Technology: Case Studies in Anthropogenic Use Monitoring in California's Marine Protected Areas. Institute of Electrical and Electronics Engineers, Piscataway, New Jersey.

Li, Z., P. Liu, S. Chen, X. Liu, Y. Yu, T. Li, Y. Wan, N. Tang, Y. Liu, and Y. Gu. 2023. Bioinspired marine antifouling coatings: Antifouling mechanisms, design strategies and application feasibility studies. European Polymer Journal 190:111997.

Lusseau, D., D. E. Bain, R. Williams, and J. C. Smith. 2009. Vessel traffic disrupts the foraging behavior of Southern Resident killer whales *Orcinus orca.* Endangered Species Research 6(3):211–221.

MacGillivray, A. O., L. M. Ainsworth, J. Zhao, J. N. Dolman, D. E. Hannay, H. Frouin-Mouy, K. B. Trounce, and D. A. White. 2022. A functional regression analysis of vessel source level measurements from the Enhancing Cetacean Habitat and Observation (ECHO) database. The Journal of the Acoustical Society of America 152(3):1547–1563.

MacGillivray, A. O., Z. Li, D. E. Hannay, K. B. Trounce, and O. M. Robinson. 2019. Slowing deep-sea commercial vessels reduces underwater radiated noise. The Journal of the Acoustical Society of America 146(1):340–351

MacGillivray, A. O., F. M. C. Stothart, C. H. Grooms, Z. Li, and M. M. Zykov. 2025. Ocean noise contributors in Southern Resident killer whale habitat. Marine Pollution Bulletin 215:117859.

Madsen, P. T., and M. Wahlberg. 2007. Recording and quantification of ultrasonic echolocation clicks from free-ranging toothed whales. Deep Sea Research I 54:1421–1444.

Malinka, C. E., D. J. Tollit, K. Trounce, and J. D. Wood. 2023a. Evaluating the Benefits of Noise Reduction Mitigation: The ECHO Program. Pages 1–21 in A. N. Popper, J. Sisneros, A. Hawkins, and F. Thomsen, editors. The Effects of Noise on Aquatic Life: Principles and Practical Considerations. Springer International Publishing, Cham, Switzerland.

Malinka, C., M. Quinn, M. Matei, S. Tabbutt, R. Charish, and J. Wood. 2023b. Quiet Sound Trial Slowdown 2022. SMRU Consulting, Vancouver, British Columbia, Canada.

Martin, S. B., B. J. Gaudet, H. Klinck, P. J. Dugan, J. L. Miksis-Olds, D. K. Mellinger, D. A. Mann, O. Boebel, C. C. Wilson, D. W. Ponirakis, and 1 coauthor. 2021. Hybrid millidecade spectra: A practical format for exchange of long-term ambient sound data. JASA Express Letters 1(1):011203.

Matei, M., R. Charish, M. Quinn, F. Wilder, S. Tabbutt, and J. Wood. 2024. Quiet Sound Vessel Slowdown 2023. SMRU Consulting, Fife, United Kingdom.

Matsumoto, H., A. Turpin, J. Haxel, C. Meinig, M. Craig, D. Tagawa, H. Klinck, and B. Hanson. 2016. A Real-time Acoustic Observing System (RAOS) for killer whales. Marine Technology Society/Institute of Electrical and Electronics Engineers, Monterey, California.

McIntyre, D., W. Lee, H. Frouin-Mouy, D. Hannay, and P. Oshkai. 2021. Influence of propellers and operating conditions on underwater radiated noise from coastal ferry vessels. Ocean Engineering 232:109075.

McKenna, M. F., S. M. Wiggins, and J. A. Hildebrand. 2013. Relationship between container ship underwater noise levels and ship design, operational and oceanographic conditions. Scientific Reports 3(1):1760.

McWhinnie, L. H., P. D. O'Hara, C. Hilliard, N. Le Baron, L. Smallshaw, R. Pelot, and R. Canessa. 2021. Assessing vessel traffic in the Salish Sea using satellite AIS: An important contribution for planning, management and conservation in Southern Resident killer whale critical habitat. Ocean & Coastal Management 200:105479.

Miksis-Olds, J. L., P. J. Dugan, S. B. Martin, H. Klinck, D. K. Mellinger, D. A. Mann, D. W. Ponirakis, and O. Boebel. 2021. Ocean Sound Analysis Software for Making Ambient Noise Trends Accessible (MANTA). Frontiers in Marine Science 8:703650.

Miller, P. J. O. 2002. Mixed-directionality of killer whale stereotyped calls: A direction of movement cue? Behavioral Ecology and Sociobiology 52(3):262–270.

Morin, P. A., M. L. McCarthy, C. W. Fung, J. W. Durban, K. M. Parsons, W. F. Perrin, B. L. Taylor, T. A. Jefferson, and F. I. Archer. 2024. Revised taxonomy of eastern North Pacific killer whales (*Orcinus orca)*: Bigg's and Resident ecotypes deserve species status. Royal Society Open Science 11(3):231368.

NMFS (National Marine Fisheries Service). 2008. Recovery Plan for Southern Resident Killer Whales (*Orcinus orca)*. National Marine Fisheries Service, Seattle.

NMFS (National Marine Fisheries Service). 2021. Revision of the Critical Habitat Designation for Southern Resident Killer Whales: Final Biological Report (to accompany the Final Rule). National Marine Fisheries Service, Portland, Oregon. Available: repository.library.noaa.gov/view/noaa/31587 (January 2026).

Ocean Sonics 2017. Whale Tracking Network: Final report. Ocean Sonics, Ltd., Truro Heights, Nova Scotia, Canada.

Olson, J., J. Wood, R. Osborne, L. Barrett-Lennard, and S. Larson. 2018. Sightings of Southern Resident killer whales in the Salish Sea, 1976–2014: The importance of a long-term opportunistic dataset. Endangered Species Research 37:105–118.

Oswald, J. N., C. Erbe, W. L. Gannon, S. Madhusudhana, and J. A. Thomas. 2022. Detection and Classification Methods for Animal Sounds. Pages 269–317 in C. Erbe and J. A. Thomas, editors. Exploring Animal Behavior Through Sound, volume 1: Methods. Springer International Publishing, Cham, Switzerland.

Palmer, K. J., S. Tabbutt, D. Gillespie, J. Turner, P. King, D. Tollit, J. Thompson, and J. Wood. 2022. Evaluation of a coastal acoustic buoy for cetacean detections, bearing accuracy and exclusion zone monitoring. Methods in Ecology and Evolution 13(11):2491–2502.

Palo, G. J. 1972. Notes on the natural history of the killer whale *Orcinus orca* in Washington State. The Murrelet 53(2): 22–24.

Parcerisas, C. 2023. PyPAM: A package to process long-term underwater acoustics data in chunks. Zenodo, Geneva, Switzerland. DOI: 10.5281/zenodo.10037826

Pilkington, J. F., E. H. Stredulinsky, K. Gavrilchuk, S. J. Thornton, J. K. B. Ford, and T. Doniol-Valcroze. 2023. Patterns of winter occurrence of three sympatric killer whale populations off eastern Vancouver Island, Canada, based on passive acoustic monitoring. Frontiers in Marine Science 10:1204908.

Randon, M., M. Dowd, and R. Joy. 2022. A real-time data assimilative forecasting system for animal tracking. Ecology 103(8):e3718.

RHA (Rivers and Harbors Act). 1899. U.S. Code, title 33, section 401–467.

Richardson, W. J., C. R. Greene, Jr., C. I. Malme, and D. H. Thomson. 1995. Marine Mammals and Noise. Academic Press, San Diego, California.

Richter, S., H. Yurk, A. Winterl, E. Chmelnitsky, N. Serra, P. D. O'Hara, and D. Zitterbart. 2023. Coastal Marine Mammal conservation using thermal imaging-based detection systems. bioRxiv, Davis, California. DOI: 10.1101/2023.08.25.554754

Riera, A., J. Pilkington, J. Ford, E. Stredulinsky, and N. Chapman. 2019. Passive acoustic monitoring off Vancouver Island reveals extensive use by at-risk Resident killer whale (*Orcinus orca)* populations. Endangered Species Research 39:221–234.

Riesch, R., J. K. B. Ford, and F. Thomsen. 2006. Stability and group specificity of stereotyped whistles in Resident killer whales, *Orcinus orca,* off British Columbia. Animal Behaviour 71(1):79–91.

Robinson, O., and K. Trounce. 2016. The Enhancing Cetacean Habitat and Observation (ECHO) Program: Collaborating to manage potential cumulative threats to at-risk whales from commercial vessels. Salish Sea Ecosystem Conference, Vancouver, British Columbia, Canada.

Rodofili, E. N., V. Lecours, and M. LaRue. 2022. Remote sensing techniques for automated marine mammals detection: A review of methods and current challenges. PeerJ 10:e13540.

Rueda, Carlos, D. Cline, and J. P. Ryan. 2024. PBP – PyPAM-Based Processing. Python. Available: github.com/mbari-org/pbp (January 2026).

Scheffer, V. B., and J. W. Slipp, J. W. 1948. The whales and dolphins of Washington State with a key to the cetaceans of the west coast of North America. The American Midland Naturalist 39(2):257–337.

Scott, J. L., C. Birdsall, C. V. Robinson, L. Dares, K. Dracott, K. Jones, A. Purdy, and L. Barrett-Lennard. 2024. The WhaleReport Alert System: Mitigating threats to whales with citizen science. Biological Conservation 289:110422.

Shields, M. W. 2023. 2018–2022 Southern Resident killer whale presence in the Salish Sea: Continued shifts in habitat usage. PeerJ 11:e15635.

Shields, M. W., J. Lindell, and J. Woodruff. 2018a. Declining spring usage of core habitat by endangered fish-eating killer whales reflects decreased availability of their primary prey. Pacific Conservation Biology 24(2):189.

Shields, M. W., S. Hysong-Shimazu, J. C. Shields, and J. Woodruff. 2018b. Increased presence of mammal-eating killer whales in the Salish Sea with implications for predator–prey dynamics. PeerJ 6:e6062.

Simard, Y., N. Roy, C. Gervaise, and S. Giard. 2016. Analysis and modeling of 255 source levels of merchant ships from an acoustic observatory along St. Lawrence Seaway. The Journal of the Acoustical Society of America 140(3):2002–2018.

Smith, H. R., D. P. Zitterbart, T. F. Norris, M. Flau, E. L. Ferguson, C. G. Jones, O. Boebel, and V. D. Moulton. 2020. A field comparison of marine mammal detections via visual, acoustic, and infrared (IR) imaging methods offshore Atlantic Canada. Marine Pollution Bulletin 154:111026.

Souhaut, M., and M. W. Shields. 2021. Stereotyped whistles in Southern Resident killer whales. PeerJ 9:e12085.

Southall, B. L., A. E. Bowles, W. T. Ellison, J. J. Finneran, R. L. Gentry, C. R. Greene, D. Kastak, D. R. Ketten, J. H. Miller, P. E. Nachtigall, and 3 coauthors. 2008. Marine mammal noise-exposure criteria: Initial scientific recommendations. Bioacoustics 17(1–3):273–275.

SROTF (Southern Resident Orca Task Force). 2019. Southern Resident Orca Task Force final report and recommendations. Cascadia Consulting Group, Seattle. Available: www.orca.wa.gov/wp-content/uploads/TaskForceFinalReport-2019.pdf (January 2026).

Stredulinsky, E. H., S. Toews, J. Watson, D. P. Noren, M. M. Holt, and S. J. Thornton. 2023. Delineating important killer whale foraging areas using a spatiotemporal logistic model. Global Ecology and Conservation 48:e02726.

Tennessen, J. B., M. M. Holt, B. M. Wright, M. B. Hanson, C. K. Emmons, D. A. Giles, J. T. Hogan, S. J. Thornton, and V. B. Deecke. 2024. Males miss and females forgo: Auditory masking from vessel noise impairs foraging efficiency and success in killer whales. Global Change Biology 30(9):e17490.

Theriault, J. A., H. Yurk, and H. B. Moors-Murphy. 2020. Workshop report: Review of near-real time whale detection technologies. Canadian Technical Report Fisheries and Aquatic Sciences 3410:1–37.

Thornton, S. J., S. Toews, E. Stredulinsky, K. Gavrilchuk, C. Konrad, R. Burnham, D. P. Noren, M. M. Holt, and S. Vagle. 2022. Southern Resident Killer Whale (*Orcinus orca)* summer distribution and habitat use in the southern Salish Sea and the Swiftsure Bank area (2009 to 2020). Fisheries and Oceans Canada, Ottawa, Ontario, Canada.

Trounce, K., O. Robinson, A. MacGillivray, D. Hannay, J. Wood, D. Tollit, and R. Joy. 2019. The effects of vessel slowdowns on foraging habitat of the Southern Resident killer whales. Proceedings of Meetings on Acoustics 37:070009.

USOFR (U.S. Office of the Federal Register). 2021. Endangered and Threatened Wildlife and Plants; Revision of Critical Habitat for the Southern Resident Killer Whale Distinct Population Segment, final rule. Federal Register 86:145(2 August 2021):41668–41698.

Van Parijs, S., C. Clark, R. Sousa-Lima, S. Parks, S. Rankin, D. Risch, and I. Van Opzeeland. 2009. Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales. Marine Ecology Progress Series 395:21–36.

Veirs, S., V. Veirs, and J. D. Wood. 2016. Ship noise extends to frequencies used for echolocation by endangered killer whales. PeerJ 4:e1657.

Verfuss, U. K., D. Gillespie, J. Gordon, T. A. Marques, B. Miller, R. Plunkett, J. A. Theriault, D. J. Tollit, D. P. Zitterbart, P. Hubert, and 1 coauthor. 2018. Comparing methods suitable for monitoring marine mammals in low visibility conditions during seismic surveys. Marine Pollution Bulletin 126:1–18.

Watkins, W. A., M. A. Daher, N. A. DiMarzio, and G. Reppucci. 1998. Distinctions in sound patterns of calls by killer whales (*Orcinus orca)* from analysis of computed sound features. Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

Wiggins, S. M., M. A. Roch, and J. A. Hildebrand. 2010. TRITON software package: Analyzing large passive acoustic monitoring data sets using MATLAB. The Journal of the Acoustical Society of America 128(4_Supplement):2299.

Wilder, F., Z. Li, A. O. MacGillivray, and D. J. Tollit. 2024. ECHO Program 2023 Voluntary Vessel Slowdown Hydroacoustic Studies: Chapter 2, SRKW Acoustic Space Modelling. JASCO Applied Sciences and SMRU Consulting, Vancouver, British Columbia, Canada.

Williams, R., C. W. Clark, D. Ponirakis, and E. Ashe. 2014. Acoustic quality of critical habitats for three threatened whale populations: Acoustic quality of critical whale habitats. Animal Conservation 17(2):174–185.

Yurk, H., L. Quayle, R. Burnham, S. MacConnachie, and T. LeBlond. 2023. Evaluating the effectiveness of shore cabled hydrophone networks as near real-time killer whale detection and tracking systems with special reference to DFO's Whale Tracking Network (WTN). Canadian Technical Report Fisheries and Aquatic Sciences 3543:1–69.

Zimmer, W. M. 2011. Passive acoustic monitoring of cetaceans. Cambridge University Press, Cambridge, United Kingdom.

Zimmer, W. M. X. 2013. Range estimation of cetaceans with compact volumetric arrays. The Journal of the Acoustical Society of America 134(3):2610–2618.

Zitterbart, D. P., L. Kindermann, E. Burkhardt, and O. Boebel. 2013. Automatic round-the-clock detection of whales for mitigation from underwater noise impacts. PLOS ONE 8(8):e71217.

Appendix A

Scope of Work (from Attachment A to Agreement ILA-2023-001)

Underwater Acoustic Monitoring Desktop Study
Collaborative Initiative Between Port of Seattle and Northwest Fisheries Science Center

July 27, 2023

Background

Port of Seattle is contributing funds towards a study of the hydrophone network in the Study Area (defined below). The funding is a requirement of a legal settlement agreement with the Center for Biological Diversity.

Study Area

The Study Area includes those portions of Puget Sound, Admiralty Inlet, Strait of Juan de Fuca and the Salish Sea which are in the geographic scope of the Quiet Sound program. To the extent that information gathered may be relevant to the project, the Study Area may also include British Columbia waters in the Salish Sea which are within the geographic scope of the ECHO program.

Objective

Characterize the existing underwater acoustic monitoring network in the Study Area to inform future underwater noise monitoring efforts.

Phase 1

1. *Past and present underwater acoustic monitoring initiatives.* Complete literature review and outreach to determine:
   a. Project sponsor and objectives (if known);
   b. Equipment, software, and analysis methods, including any associated limitations/shortcomings (generally);
   c. Summary of results;
   d. Data application, compatibility, access, and location of archives; and,
   e. Present status of project or initiative.
2. *Spatial understanding of acoustic data associated with SRKWs and large commercial vessel use in Study Area.* Complete outreach and literature review to describe:
   a. Vessel movement data by class of vessel (e.g., tug vs. tanker vs. bulker) using AIS data available (e.g., from Marine Exchange) within the Study Area;
   b. General distribution of SRKWs in the Study Area;

    c. Known patterns of underwater noise within the Study Area as it is experienced by SRKWs; and,
    d. Location of past and present initiatives gathering acoustic information from within Study Area.
3. *Best practices and limiting factors for hydrophone deployment.* Complete outreach and literature review to describe:
    a. Types of hydrophone equipment and software packages that are appropriate for measuring whale and vessel noise (including limitations and constraints, compatibility issues, etc.);
    b. Cost of equipment, installation, operations, data curation and archiving (rough order of magnitude);
    c. Best practices and equipment selection criteria considering bathymetry, substrate, currents, tides, cost, etc.;
    d. Permitting and regulatory requirements/constraints and data collection and usage consistency with Quiet Sound, ECHO DFO, OrcaSound, etc.

Phase 2

1. *Evaluate network in context of Quiet Sound noise reduction initiatives, including dynamic management based on real-time detection of SRKW signals.* On the basis of Phase 1 information, evaluate:
    a. Hydrophone network in the Study Area with respect to measuring effectiveness of proposed vessel slow-downs and other potential noise reduction initiatives in SRKW high use areas.
2. *Recommendations for type/location of additional hydrophones and minimum standards.* Identify:
    a. Gaps in the hydrophone network in the Study Area with respect to acoustic monitoring of vessels and SRKWs;
    b. Improvements to network interoperability and data sharing across existing hydrophone equipment operators to meet acoustic monitoring needs;
    c. Opportunities for new equipment or reconfiguration of existing equipment to meet acoustic monitoring needs in the Study Area. Note: There are different standards for a hydrophone capable of making calibrated noise measurements and a hydrophone capable of detecting SRKW calls, whistles, and/or clicks. And,
    d. Potential complementary (other) technologies such as aerial drones, infrared cameras, and visual sighting networks.

Deliverables

1. Progress report of Phase 1 within 10 full months of signed agreement. While this is a collaborative study between the Port of Seattle, NOAA Northwest Fisheries Science Center (NWFSC), and NOAA Sandpoint Pacific Marine Environmental Lab (PMEL), a separate scope of work states roles and responsibilities of NOAA PMEL.
2. Summary report describing the findings of Phase 1 and 2, all tasks within 18 full months of signed agreement (target date: March 31, 2025).

Appendix B

Table B-1. Contact list for Survey 1 and Survey 2 outreach.

Affiliation	Sector	Country	Response	Survey 1	Survey 2	Comments
Cetacean Research Technology	Consulting	USA	Yes	Yes	Yes	
Department of Fisheries and Oceans Canada	Gov't.	Canada	Yes	Yes	Yes	
ECHO, Vancouver Fraser Port Authority	Gov't.	Canada	Yes	No	No	Captured by other respondents
JASCO Applied Sciences	Consulting	Canada	Yes	Yes	Yes	
Makah	Tribal	USA	Yes	No	No	Partners responded
Noise Control Engineering, LLC.	Consulting	USA	Yes	Yes	Yes	
Northwest Indian Fisheries Commission	Tribal	USA	Yes	No	No	
Ocean Wise	Consulting	Canada	No	No	No	
Oceans Initiative	Consulting	Canada	Yes	Yes	No	
Olympic Coast National Marine Sanctuary	Gov't.	USA	Yes	Yes	No	
Orca Conservancy	Nonprofit	USA	Yes	Yes	No	
Orca Network	Nonprofit	USA	No	No	No	
OrcaLab	Research	Canada	No	No	No	
OrcaSound	Research	USA	Yes	Yes	No	
Pacific Northwest National Laboratory	Consulting	USA	Yes	Yes	Yes	
QENTOL, YEN/W̱SÁNEĆ Marine Guardians	Tribal	Canada	Yes	No	No	
Raincoast Conservation Foundation	Nonprofit	Canada	No	No	No	
Sea to Shore Systems, Ltd.	Consulting	Canada	Yes	Yes	No	
SLR Consulting	Consulting	USA	Yes	Yes	No	
SMRU Consulting	Consulting	USA Canada	Yes	Yes	No	
Suquamish Tribe	Tribal	USA	No	No	No	
The Whale Museum	Nonprofit	USA	No	No	No	
U.S. Navy	Gov't.	USA	No	No	No	
University of California, San Diego	Research	USA	No	No	No	
University of Victoria	Research	Canada	No	No	No	
University of Washington	Research	USA	Yes	Yes	No	
Applied Physics Laboratory (UW)	Research	USA	Yes	Yes	Yes	
Washington State Ferries, WSDOT	Gov't.	USA	Yes	No	No	Provided report
WAVE Consulting	Consulting	USA	No	No	No	

Recently published by the Northwest Fisheries Science Center

NOAA Technical Memorandum NMFS-NWFSC-

206 **Somers, K. A., K. E. Richerson, and V. J. Tuttle. 2026.** Estimated Discard and Catch of Groundfish Species in the 2024 U.S. West Coast Fisheries. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-206. https://doi.org/10.25923/c8cz-tk83

205 **Keller, A. A., V. H. Simon, D. L. Draper, A. C. Chappell, K. L. Bosley, J. C. Buchanan, P. H. Frey, J. H. Harms, and M. A. Head. 2026.** The 2019 U.S. West Coast Bottom Trawl Survey of Groundfish Resources off Washington, Oregon, and California: Estimates of Distribution, Abundance, and Length Composition. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-205. https://doi.org/10.25923/w111-ja31

204 **Gaydos, J. K., H. H. Nollens, C. F. Lo, M. B. Hanson, K. Haman, M. Weiss, D. Giles, S. J. Thornton, T. R. Robeck, and C. Dold. 2026.** Remotely Sensed Metrics for Evaluating Wild Killer Whale Health. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-204. https://doi.org/10.25923/jftd-d217

203 **Somers, K. A., K. E. Richerson, and V. J. Tuttle. 2025.** Fishing Effort in the 2002–23 U.S. Pacific Coast Groundfish Fisheries. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-203. https://doi.org/10.25923/1rck-7159

202 **Sol, S. Y., P. M. Nicklason, B. F. Anulacion, and R. B. Johnson. 2025.** Use of Non-Native Columbia River American Shad (*Alosa sapidissima*) as an Alternative Fishmeal Source for Juvenile Sablefish (*Anoplopoma fimbria*). U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-202. https://doi.org/10.25923/8dcv-5t90

201 **WC Chinook Salmon Status Review Team. 2025.** Biological Status of the Washington Coast Chinook Salmon Evolutionarily Significant Unit: Report of the Status Review Team. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-201. https://doi.org/10.25923/1713-1129

200 **Steiner, E., A. Phillips, and A. Chen. 2025.** Economic Status of the Pacific Hake Fishery, 2009–23. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-200. https://doi.org/10.25923/gcr3-ph80

199 **Somers, K. A., K. E. Richerson, V. J. Tuttle, and J. T. McVeigh. 2024.** Estimated Discard and Catch of Groundfish Species in the 2023 U.S. West Coast Fisheries. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-199. https://doi.org/10.25923/mxc3-9934

198 **OP Steelhead Status Review Team. 2024.** Biological Status of the Olympic Peninsula Steelhead Distinct Population Segment. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-198. https://doi.org/10.25923/tnxh-7j96

NOAA Technical Memorandums NMFS-NWFSC are available from the NOAA Institutional Repository, https://repository.library.noaa.gov.

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