

A Dive into Anthropogenic Noise in the Mackenzie Estuary: Using
Qualitative and Quantitative Methods to Investigate Depth-Sounder
Presence in the Tarium Niryutait Marine Protected Area

by

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Abstract

There is a growing use of consumer-grade depth sounders within the Mackenzie Estuary, in the Northwest Territories, Canada, an important summer habitat for Eastern Beaufort Sea beluga whales (*Delphinapterus leucas*) and a region of cultural importance to Inuvialuit communities. It is not well-understood how acoustic signatures from depth sounders travel in this shallow, dynamic estuarine habitat and how they influence beluga. To address this knowledge gap, acoustic propagation measurements and models were incorporated with qualitative interviews of depth sounder users within the region. Propagation experiments provided a basis for informing noise assessments on depth sounders by revealing detectability bounds of the 83 kHz and 200 kHz sonars as well as received levels. Transmission loss of both frequencies varied with environmental conditions, turbidity being most influential. Additionally, the 83 kHz depth sounder propagated further than the 200 kHz with an average source level of 170.45 dB re 1 μ Pa. Interviews with depth sounder users indicated that beluga responses to depth sounders are context-dependent and influenced by ecological and social factors. These results highlighted the importance of integrating Inuvialuit knowledge to understand ecological implications of anthropogenic noise to guide future co-management efforts.

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Contributions of Authors

The following are author contributions for **Chapter 2**:

Cara Rankin (principle author): conceptualization, research design, data collection and processing, data analysis and interpretation, literature review, writing of original drafts.

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This research was implemented in collaboration with Inuvialuit in their traditional homeland within the Inuvialuit Settlement Region. We recognize and honor the Inuvialuit Final Agreement and the deep connection the Inuvialuit have to these lands, waters, and Arctic wildlife.

Positionality Statement

I am a researcher, student, and professional within the quantitative field of underwater acoustics and pursuing this project as a M.Sc. student at the University of Manitoba and Student Researcher at Fisheries and Oceans Canada (DFO). I am a white woman raised in middle class rural Illinois, USA. I recognized being raised with racial and economic privilege, in a culture where diversity was not a priority nor celebrated within the academic and workplace institutions. A desire to experience other environments and walk along the path of ocean and environmental conservation and sciences, I pursued an undergraduate liberal arts education in at Eckerd College, Florida and this opened the curtain of critical thinking skills and acknowledgment of underrepresented voices in society. My B.Sc. focused on marine biology with a minor in psychology, a marriage between traditional scientific method (positivism) training in the natural sciences with less training in social sciences (background in psychology and human experiences).

I was not raised around Indigenous communities and had limited knowledge in Indigenous culture and history in the American public-school system as a product of colonization. However, contradictory to western culture, I was raised on hunting animals for sustenance, not sport, thus taught from a young age to respect wildlife. I came from the philosophy that the land provides for us if we nurture it and show respect. This perspective and upbringing have certainly aided in relationship building with Indigenous partners, despite an absence of Inuvialuit cultural teaching throughout my life into early adulthood.

This M.Sc. research comes from a government and academic position where I have access to countless academic resources and funding opportunities in a Eurocentric society. In the past, these institutions have colonized Indigenous lands and developed a tainted relationship centered on mistrust. It's vital to keep this in mind while conducting every step of this research process.

My goals for this research were: 1) Upkeep and facilitate lasting relationships with the Inuvialuit communities and decision makers and develop a trusting collaboration where I can give back to the community, and 2) Provide an answer to guide solutions for the use of depth sounders and their influence on the local beluga population. I pushed myself out of the Eurocentric box to think critically about the history, present, and future of collaboration with the Inuvialuit and how I can amicably incorporate their work and Inuvialuit Knowledge in every step of the process. I acknowledge that this research is of every bit Inuvialuit work as it is my own.

Chapter One: Introduction

Threats to the Arctic marine ecosystem

The Arctic marine environment is one of the most extreme and rapidly changing ecosystems, influenced by many variables, but most notably defined by sea ice dynamics. Retreating and expanding sea ice cycles influence primary productivity and marine mammal distribution and survival, while also providing barriers from atmospheric heat transfer and coastal erosion (Kovacs et al. 2011; Whalen et al. 2022a; Khopkar et al. 2026). Arctic marine mammals directly rely on sea ice for migration routes and platforms for hunting, resting, predator protection, and birthing (Laidre et al. 2008; Hauser et al. 2017; Halliday et al. 2022; Merkel and Aars 2022; Lindsay et al. 2026). This ecosystem is also changing on a multitude of scales within the twenty-first century as a direct response to an increasingly warmer climate.

One such consequence is sea ice loss, with summer sea ice rapidly declining at a rate of 12.4% per decade (Cavalieri and Parkinson 2012), resulting in more younger and thinner ice in the winter (Schweiger et al. 2019; Druckenmiller et al. 2021). This has caused less dense ice coverage and more ice-free periods, affecting marine mammals in a multitude of ways. One such outcome is increased borealization, impacting prey availability and predator dynamics as warmer water species migrate North (Husson et al. 2024; Wise et al. 2026). For example, southern teleost species, such as capelin, saffron cod, and walleye pollock have increasingly been observed in high latitude habitats, causing geographical dispersion of native polar cod from historical habitats (Hop and Gjøsæter 2013; Wildes et al. 2022; Von Biela et al. 2023).

Another implication is increased human activity as open corridors are exploited for longer periods, primarily allowing increased shipping and industrial activities that lead to anthropogenic

noise pollution (Halliday et al. 2019, 2020a; Berkman 2022). In 2025, Arctic Ship Traffic Data (ASTD) saw a 40% increase in unique vessel traffic entering the Arctic Polar Code area since the start of monitoring efforts in 2013 (PAME 2026). Noise exposure models predicted a 5 dB average increase of underwater noise levels across the Pan-Arctic by 2030 (PAME and Arctic Council 2025).

Acoustic masking is one such phenomena that can be caused by anthropogenic noise and interferes with an individual's ability to perceive other sounds (Fletcher and Munson 1937). The implications of masking can cause cetaceans to cease vocalizations, change the frequency and amplitude of their sound, or increase call redundancy as seen in bottlenose dolphins (*Tursiops truncatus*) (Au and Moore 1984; Buckstaff 2004), killer whales (*Orcinus orca*) (Holt et al. 2011), North Atlantic right-whales (*Eubalaena glacialis*) (Parks et al. 2007), grey whales (*Eschrichtius robustus*) (Dahlheim and Castellote 2016), and beluga whales (*Delphinapterus leucas*) (Au et al. 1985; Lesage et al. 1999). This interrupts their echolocation or communication, leading to stress, beaching, and starvation (Richardson et al. 1995). Other sources of anthropogenic noise can be produced at high dB levels causing hearing loss, while general noise exposure can cause increased stress levels and behavioral changes in marine mammals as seen by seismic airguns (Lucke et al. 2009; Dunlop et al. 2018), acoustic deterrent devices (Götz and Janik 2013), large vessels (L.G.L. et al. 1986; Rolland et al. 2012; Williams et al. 2014), small vessels (i.e., whale-watching boats (Blane and Jaakson 1994; Au and Green 2000) dredging and drilling (Richardson et al. 1991), and pile-driving (Kastelein et al. 2013), just to name a few. Previous research on military grade sonars that function in lower or mid-frequency bandwidths (1-4kHz) were found to temporarily disrupt marine mammal behavior (i.e., short-beaked dolphins and long-beaked dolphins (Casey et al. 2024), beaked whales (Tyack et al. 2011), sperm

whales (Miller et al. 2012), pilot whales (Miller et al. 2012), humpback whales (Sivle et al. 2015), some species showing a higher sensitivity than others (i.e. killer whales (Miller et al. 2012), minke whale (Sivle et al. 2015), and northern bottlenose whale (Sivle et al. 2015). These pressures can exacerbate limitations to a species' ability to rapidly adapt to challenges such as insufficient prey availability, increased predation risk, noise pollution, habitat loss, among other threats (Huntington et al. 2023). However, beluga for example, could be adaptable to such threats given their flexible migration routes and movement patterns suggesting the capacity to alter pathways to avoid vessel traffic and find alternate prey (Halliday et al. 2019; Storrie et al. 2023).

Beluga whales: “Canaries of the sea”

Beluga whales are circum-polar and one of three endemic cetacean species within the Arctic (NOAA Fisheries 2026). Belugas are the only living members of the genus *Delphinapterus* and share the family *Monodontidae* with the narwhal (Perrin et al. 2002). Belugas are physically adapted to the Arctic marine habitat, including white coloration to blend into ice floes, a thick blubber layer for thermoregulation, flexible neck vertebrae to enhance maneuverability beneath ice, and lack of dorsal fin for gliding under ice sheets and accessing small breathing holes in densely packed ice (O’Corry-Crowe 2018). Although confined to Arctic and subarctic marine environments, belugas are eurytopic, meaning they can sustain themselves in diverse environmental conditions. This includes warm, fresh, shallow, and ice-free habitats (Loseto et al. 2006; Hornby et al. 2016) to cold, ice-dense, open ocean habitats (Hauser et al. 2017). Additionally, they are opportunistic and generalist feeders, feeding on benthic, pelagic, and epi-pelagic prey – including fish and invertebrates (Loseto et al. 2009; Quakenbush et al. 2015; Choy et al. 2020). This may be especially advantageous when prey species availability declines, as

shifts in migrating prey are becoming more common in Arctic waters, driven by climate change (Loseto et al. 2018; Bernard et al. 2026). Despite beluga exhibiting strong site fidelity, they can exhibit considerable flexibility in their migration patterns in response to variable ice conditions, including deviations of up to 1,800 km from their typical migration routes during anomalous spring and summer ice conditions (O’Corry-Crowe et al. 2016). These deviations can introduce increased predator abundance and shifts in prey availability, causing ecological implications throughout the marine ecosystem (Hauser et al. 2017; Westdal et al. 2017; McHuron et al. 2023). This highlights the need for belugas to adapt to a changing ecosystem, emphasizing the importance of continued habitat monitoring along their migration route and in key aggregation areas.

As Arctic marine ecosystems continue to change under warming temperatures, beluga continue to rely heavily on acoustic communication. Nicknamed “canaries of the sea” for their extensive vocal repertoire, belugas emit echolocation clicks for navigation and foraging, whistles and pulsed calls for communication, and contact calls for group cohesion and recognition (Au and Hastings 2008; Chmelnitsky and Ferguson 2012; Vergara and Mikus 2019). These contact calls are narrowband (i.e. small frequency range) and tonal, produced between 200 Hz to 20 kHz whereas echolocation clicks are broadband (i.e. large frequency range) signals that can reach frequencies of 120 kHz (Au et al. 1985; Sjøre and Smith 1986). Whistles can be further classified based on the fundamental frequency contour (i.e. flat, U-shaped, upswing, etc.) (Garland et al. 2015). Pulsed calls are also broadband, produced as rapid pulse trains reaching up to 150 kHz. A combined call is composed of two different call types (i.e. narrowband whistle and broadband pulsed call) and can constitute a contact call (i.e. a vocal signature that serves as a unique identifier) (Vergara and Mikus 2019). Specialized whistles called contact calls have shown to

facilitate group cohesion and mother-calf (Vergara and Mikus 2019; Vergara et al. 2021). They can even recognize individual sounds, remember them, and associate them with specific experiences. For example, they can distinguish between the vocalizations of different individuals in their group, and they use this information for social interactions (Morisaka et al. 2013). In addition, novel call types have been found in different geographically isolated beluga subpopulations (Karlsen et al. 2002), potentially indicating either a dialect which has also been observed in sperm whales (Rendell et al. 2003) and killer whales (Deecke et al. 2000), or perhaps evidence of environmental adaptation such as hypothesized with bottlenose dolphins (Luís et al. 2021). Belugas have also been known to mimic sounds by learning a specific sound and committing it to memory for future use, demonstrating the complex ability and utilization of vocalization in this species (Ridgway et al. 2012).

Belugas heavily rely on vocalizing and hearing one another for survival, especially in areas with poor visibility such as the Mackenzie Estuary, NT and Bristol Bay, Alaska (Noel et al. 2022; Song et al. 2023; Lee et al. 2024). Belugas have been observed to change the intensity of echolocation in areas of high turbidity, heavily relying on echolocation to see (Song et al. 2023). The complexity of their repertoire and use of the soundscape is evidence of survival dependency of vocalizing and hearing as a primary sensory modality.

Eastern Beaufort Sea beluga

There are 21 subpopulations or stocks of beluga whales inhabiting the Arctic and subarctic marine environments of North America, Greenland, and Russia (NAMMCO 2018). The Eastern Beaufort Sea (EBS) beluga stock seasonally migrates thousands of kilometers every year. The EBS population was recently estimated at over 38,000 whales, one of the largest in the world (Marcoux et al. 2025). EBS belugas overwinter in the Bering Sea and are limited by advancing

fast ice (Hauser et al. 2017). Here, they frequently make shallow dives, adopting a more generalist diet in a biodiverse habitat rich in benthic invertebrates and pelagic fish (Loseto et al. 2009; Quakenbush et al. 2015; Storrie et al. 2023). During their spring migration, EBS belugas travel along open sea ice leads north of the North Slope Borough and exhibit philopatry, returning to their summering habitats (Richard et al. 2001; O’Corry-Crowe et al. 2018). Following the breakup of the landfast ice bridge, that typically occurs in June and provides access to the warm freshwater Mackenzie Estuary, EBS belugas migrate into the estuary and form one of the largest summer aggregations (Harwood et al. 2014; Hornby et al. 2016; Loseto et al. 2018a). The breakup of the landfast ice has been occurring earlier in the Mackenzie Estuary due to warming temperatures, resulting in belugas entering the estuary earlier than previously documented (Loseto et al. 2018a; Lee et al. 2024). The estuary is covered in landfast ice the rest of the year, resulting in belugas leaving the estuary by September, however observations from locals and passive acoustic monitoring also document prolonged beluga presence as ice formation trend later in the season (Halliday et al. 2020a).

Mackenzie Estuary

The Mackenzie Estuary, hereafter referred to as the estuary, is located in the Northwest Territories, Canada and comprises the largest river basin in Canada and second largest river delta in the Arctic (13,000 km²), defined by 3 main branching river channels: East Channel, Peel Channel, and Middle Channel. The Mackenzie River, which is North America’s largest northward flowing river, outflows about 325 km³/year of freshwater into the Beaufort Sea, contributing about 7% of the freshwater input within the Arctic Ocean (Yang et al. 2015). In addition to the significant freshwater contribution from the river channels, the estuary has characteristically high turbidity as a product of rapid coastal erosion, permafrost melt, and

sediment discharge from river outflows (Carmack and Macdonald 2002; Whalen et al. 2022a; Lee et al. 2024). The bathymetry is relatively featureless, and water depths are very shallow, averaging 2 m across the estuary (Kosarev and Kostianoy 2008; Whalen et al. 2019). The Mackenzie River Delta is a landform composed of deposited sediment from the various river channels that merge into stagnant waters of the Beaufort Sea. The mixture of freshwater river input and salty sea water form the estuary. Waters of the estuary closest to the Mackenzie River Delta are fresh and warm but as distance from the river delta increases, the water column becomes stratified, with warm freshwater layered on top of salty cool water from the Beaufort Sea, creating a freshwater wedge (Lee et al. 2024).

There are different hypotheses as to what drives the large beluga aggregations within the Mackenzie Estuary. Unlike other Arctic populations of belugas (e.g., Cook Inlet (Goetz et al. 2023), prey availability of anadromous fish does not appear to be a main driver for migration from the Beaufort Sea to Mackenzie Estuary, although there are mixed observations (i.e. empty stomachs sampled from harvested beluga but harvesters reporting beluga regurgitating while fleeing) depending on location (Harwood et al. 1996; Quakenbush et al. 2015; Loseto et al. 2018a). Additionally, the shoal sandy bottom composition within the estuary may be favored to facilitate seasonal moulting (Scharffenberg et al. 2019; Whalen et al. 2019; Noel et al. 2022), as hypothesized by observations of belugas rubbing along the bottom (Anderson et al. 2017). Further supporting this hypothesis, belugas have been observed rubbing on the bottom substrate in other Arctic summer habitats including Churchill estuary (Watts et al. 1991), Darnley Bay (Ovitz et al. 2025), and Cunningham Inlet (Smith et al. 1992). Additionally, the warm, shallow waters of the estuary provide an ideal environment for beluga calves by offering refuge from predators and promoting thermoregulation while their blubber develops (Sergeant 1973; Hauser

et al. 2017; Scharffenberg et al. 2019; Noel et al. 2022). Previous aerial surveys revealed that Niaqunnaq Bay (i.e. Shallow Bay) held the highest calf count out of the estuary by 53%, indicating a potential nursery ground for mother-calf pairs (Harwood et al. 2014).

The EBS belugas congregate in groups within the Mackenzie Estuary, preferring habitats with specific environmental conditions, such as habitats with high turbidity, high-water temperatures, and lower wind speeds (Scharffenberg et al. 2019; Noel et al. 2022). These subgroups have been observed shifting into more coastal subregions of the Mackenzie Estuary as environmental conditions vary. Storms from the Beaufort Sea have also been linked with increased presence of belugas into the Mackenzie River Delta in the days following, possibly to escape the cold and windy conditions (Scharffenberg et al. 2021). As previously mentioned, the fresher and warmer waters coupled with the bottom composition may provide optimal conditions for moulting, promoting aggregations in these areas. These environmental parameters could be used as predictors for these aggregations and facilitate habitat monitoring by focusing on areas with the most suitable parameters. Additionally, belugas use of the estuary may vary between sites, as some areas closer to the river mouths have recorded more social calls, indicative of social behaviors, while other more oceanic areas exhibit significantly lower call rates but consistent echolocation clicks, indicative of transient or foraging behaviors (Scharffenberg et al. 2025). These aggregation patterns associated with particular habitats may influence how belugas are exposed to anthropogenic noise via the sound propagation properties that may differ between habitats.

Inuvialuit Knowledge and co-management

The Mackenzie Estuary lies within the Inuvialuit Settlement Region (ISR), native land of Inuvialuit located in the Western Canadian Arctic. The ISR was established through the

Inuvialuit Final Agreement (IFA) in 1984 and was the first land claim agreement within the Canadian Arctic (IFA 1984). The IFA established a framework for protecting and preserving Inuvialuit culture, natural resources, and wildlife co-management while stimulate economic growth. During the summer months (June–August), Inuvialuit communities in Aklavik, Inuvik, and Tuktoyaktuk harvest Eastern Beaufort Sea (EBS) belugas to support food security and sustain cultural traditions (Byers and Roberts 1995; FJMC 2013; Hoover et al. 2013).

Recognizing the ecological and cultural importance of maintaining healthy beluga populations and their habitat, the first Canadian Arctic Marine Protected Area, the Tarniutit Marine Protected Area (TN MPA), was established in 2010 through a co-management partnership between the Inuvialuit and Fisheries and Oceans Canada (DFO) under the Fisheries Joint Management Committee (FJMC) (FJMC 2013). This collaborative management framework brings together Elders, hunters, scientists, and government representatives to weave Indigenous and Western knowledge in support of long-term beluga conservation amid climate change and increasing anthropogenic pressures (e.g. marine shipping, natural resource exploitation, tourism, etc.) (Loseto et al. 2018b; Halliday et al. 2019).

Since 2011, a passive acoustic monitoring program has been conducted throughout the TN MPA to characterize the acoustic environment and monitor beluga presence and behaviour through the integration of Inuvialuit Knowledge (IK) and Western scientific approaches (Simard et al. 2014; Scharffenberg et al. 2025). This program is contingent on continued input and feedback from local Hunters and Trappers Committees. Inuit knowledge mobilisation within underwater noise mitigation efforts is seldomly demonstrated in scientific investigations and reports with few published examples (Carter et al. 2018; Halliday et al. 2020a; Kochanowicz et al. 2021).

However, there is a growing effort to introduce more IK for a comprehensive investigation on noise impacts (Kochanowicz et al. 2021; Yua et al. 2022).

Anthropogenic influences

Passive acoustic monitoring efforts in the area have already highlighted spatio-temporal trends in beluga presence by using vocalization rates across recorder sites, identifying inter-annual variability between hotspots as a result of environmental changes (i.e. higher occurrence in riverine habitats). Despite anthropogenic or environmental pressures, belugas still show high site fidelity within the estuary, emphasizing the importance of this marine protected region. An extensive review of underwater noise and Arctic marine mammals (Halliday et al. 2020a) identified temporary habitat displacement of belugas caused by vessel noise, with potential implications for food security among Inuvialuit harvesters and risks to seasonal migration and aggregation patterns (Scharffenberg et al. 2019, 2021). In recent years, the program has extended its focus to include another anthropogenic noise source: consumer-grade depth sounders, which are becoming a more prevalent boating tool within the communities. These devices enhance harvester safety in shallow waters and support coastal mapping initiatives, as the bathymetry is continuously changing from coastal erosion and permafrost melt (Gao 2009; Whalen et al. 2022a; Aliyeva et al. 2025). However, little is known on how these sonars propagate and what risks they could impose onto belugas.

The reliance on acoustic capabilities has proven extensive in beluga whales, thus may be especially susceptible to anthropogenic noise disturbances that could disrupt hearing or vocalizing. Passive acoustic monitoring within the TN MPA has shown that beluga vocalizations and ship noise were some of the biggest contributors to the soundscape (Halliday et al. 2020b). Vessel noise caused beluga vocalizations to decrease significantly when a vessel was in the close

vicinity of the recorder, suggesting belugas vocalize less or leave the area entirely as a result, and not attributed to acoustic masking (Halliday et al. 2019). On the contrary, the calls of the Cook Inlet beluga population were found to be partially masked by an incoming vessel until the vessel was close, completely masking the calls up to 12 kHz (Brewer et al. 2023). Other vocalization behavior changes have been observed such as an increased source level and frequency range of calls in response to increasing anthropogenic noise within the soundscape, also known as the Lombard vocal response (Scheifele et al. 2005).

In addition, belugas have also been documented to change swimming behavior to avoid approaching vessels up to 79 km away (Martin et al. 2023). Another study observed belugas lose pod integrity and exhibit more shallow dives in the presence of an icebreaker emitting noise at low frequencies (20 -1000 Hz) at 105 dB re 1 μ Pa (Cosens and Dueck 1988). To further highlight this species sensitivity to anthropogenic noise, belugas showed increased levels of stress-related chemicals, catecholamines, for a full 24 hours after exposure to impulsive seismic water guns (Romano et al. 2004). Understanding the behavioral and ecological stressors of belugas caused by increasing anthropogenic sources occurring within the Arctic marine ecosystem is essential to determine the impacts of acoustic masking, avoidance behavior, and noise-induced hearing loss or shifts. This is especially pertinent as corridors within the retreating ice becomes more accessible and utilized by industry activities and vessel traffic.

Marine Mammal noise exposure research methods and frameworks

Noise exposure studies often rely on field measurements and acoustic thresholds to predict potential marine mammal harassment. For example, U.S. National Marine Fisheries Service (NMFS) applies pre-determined behavioral thresholds, which vary between hearing and communication classifications of marine mammal groups (i.e. very high frequency, high

frequency, low frequency, etc.), to evaluate avoidance responses (NMFS 2024). However, behavioral thresholds are limited to rigid categories (i.e. sound type such as impulsive or continuous) using generalized knowledge, rather than species-specific and context-dependant behaviors. There is a growing effort to expand into other methods that use spatial and biological contexts of noise exposure to inform underwater noise management. One such method are range-dependent assessments, which take into account waveform changes (i.e. non-impulsive and impulsive) of the acoustic signal at further distances (Hastie et al. 2019; Darias-O'Hara et al. 2025). Another proposed method incorporates a dichotomous response/no response approach which evaluates biologically meaningful responses to a noise rather than generalized severity of the response (Gomez et al. 2016). And lastly, a case-specific impact assessment which considers species, sound source, ambient conditions, exposure characteristics, and other environmental and biological contexts that can alter the severity of noise exposure (Wright and Moors-Murphy 2022).

Canada lacks a national framework and guidelines for conducting research and evaluating underwater noise impacts. Recently, concrete steps have been taken by introducing Canada's Ocean Noise Strategy (DFO 2024) to promote recommendations and priorities in reducing anthropogenic noise and its impacts on marine fauna. The strategy recognizes the complexity and nuances of mitigating for underwater noise that can be achieved by incorporating other bodies of knowledge such Indigenous Knowledge. As previously stated, Indigenous knowledge is under-utilized in underwater noise studies, thus nuanced information such as individual and pod-level behaviors are not considered or relatively unknown. That leaves scientists and decision-makers to fall back on disturbance thresholds that are broad and not context dependent.

Lastly, regional co-management strategies require the use of Inuvialuit Knowledge (IK) within research processes for habitat monitoring (FJMC 2024). This collaboration between western science methods and IK resulted in the successful monitoring of the health and habitat use of EBS beluga for decades, providing rich insights, including observations of unusual beluga presence, shifts in diet, contaminant exposure, body condition (e.g. fat vs lean individuals), and local environmental changes (FJMC 2013; FJMC 2024; DFO 2026). However, there is currently no established framework for integrating IK into acoustic exposure studies aimed at understanding the effects of anthropogenic noise on beluga within the Mackenzie Estuary, or anywhere else for that matter. Building on existing habitat monitoring initiatives, there remains a need to better characterize anthropogenic noise exposure in key estuarine beluga habitats under highly variable environmental conditions through approaches that integrate both Western science and IK, as prioritized under regional co-management strategies.

Objectives

This study aims to incorporate qualitative and quantitative methods to investigate underwater noise emitted from consumer-grade depth sounders and the potential impacts to EBS belugas in their summering habitat, the Mackenzie Estuary.

The objectives of my first data chapter are to measure the sound propagation properties of consumer-grade depth sounders within the Mackenzie Estuary to quantify and model noise levels relative to background levels in varying environmental conditions. In doing so, we can determine the maximum distance that the depth sounder noise travels across different frequency settings before falling below ambient levels. This in turn informs us how far out belugas would hear the signal, and if the signal intensity could yield a behavioral disturbance response. In addition, we

aim to test which environmental parameters (i.e. salinity, depth, temperature, turbidity, sound speed) influence sound absorption.

The objectives of my second data chapter are to explore observations and perceptions of Tuktoyaktuk harvesters who use consumer-grade depth sounders on their boats through semi-structured interviews. We aim to incorporate Inuvialuit Knowledge through their observations. Participants are asked questions relating to study participants' first-hand experiences with depth sounders around beluga whale habitats, including observations of normal and abnormal beluga behaviours, and their present understanding of beluga hearing capabilities. They are also asked about their perceptions and opinions about the use of the technology, including recommendations for future use.

Finally, the qualitative data collected from the second data chapter will be used in tandem with quantitative propagation models from the first data chapter to inform recommendations for safe sonar use within the region. Ultimately, this work aims to contribute to the local knowledge of the soundscape and how belugas may perceive depth sounders, while also improving marine mammal conservation and our knowledge of acoustic propagation in estuarine environments.

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Chapter Two: Can Belugas Hear Your Sonar? Modeling Depth Sounder Sonar Propagation Within Dynamic Habitats of the Tarium Niryutait Marine Protected Area

Abstract

As stewards of the land, Inuvialuit from Tuktoyaktuk maintain an active role in conducting community-based research in the region and recently initiated a project to use consumer grade sonars (depth sounders) to provide much needed bathymetric maps of their waterways as erosion and permafrost melt is dramatically changing traditional boating routes. These depth sounders have introduced a new sound source to the soundscape of the Tarium Niryutait Marine Protected Area (TN MPA). The TN MPA in the Mackenzie Estuary serves to protect an important summer habitat of the Eastern Beaufort Sea (EBS) beluga whales (*Delphinapterus leucas*). Thus, the objective of this study was to define received level and detectability bounds of depth sounders, relevant for impact assessments. During the summer of 2024 and 2025, depth sounder propagation experiments were completed throughout the TN MPA and Tuktoyaktuk Harbor, NWT, Canada. Recordings were captured of Lowrance HDS9 sonar across eight sites, testing four different frequency settings, to create sound propagation models specific to different habitats and conditions (i.e. water depth, bottom contour, temperature, salinity and turbidity). Transmission loss varied based on daily fluctuations in salinity, temperature, and turbidity, with turbidity having the biggest influence. The 83kHz propagated a longer distance than the 200 kHz, with an average peak source level of 170.45 dB re 1 μ Pa. The dynamic estuarine environment provided an ideal setting to generate novel sound propagation measurements for shallow freshwater systems where anthropogenic noise is present. This work will provide a basis to investigate potential acoustic disturbance in beluga and inform recommendations for depth

sounder use that minimizes noise impact while maintaining the benefits of depth sounders for navigation.

Introduction

Erosion rates largely driven by permafrost melt (Whalen et al. 2022) within the Mackenzie Estuary of the Western Canadian Arctic and the Inuvialuit Settlement Region (ISR), have altered traditional travel routes and drive the need for updated bathymetric maps. In response, the communities of Aklavik, Inuvik, and Tuktoyaktuk started their own bathymetry programs which utilizes boat-mounted depth sounders to update maps in highly transited waterways and traditional harvesting areas for safer navigation (DFO 2026). While this technology provides important benefits, it introduces a novel source of anthropogenic noise into the Tarniutit Marine Protected Area (TN MPA), a critical habitat for the largest summering aggregations of Eastern Beaufort Sea (EBS) beluga whales (*Delphinapterus leucas*) (FJMC 2013). The limited ice-free period within the estuary means motorboat use and beluga presence overlap for the months of June to September (Whalen et al. 2019). Belugas rely heavily on sound for communication, navigation, and foraging (Au and Hastings 2008; Chmelnitsky and Ferguson 2012; Vergara and Mikus 2019), making them potentially vulnerable to additional anthropogenic noise, warranting the need to understand the propagation properties and detectability of depth sounder signals to address growing concern within the communities and management.

Depth sounders emit an impulsive sonar ping in the form of a sound wave that reveals the sea floor beneath the boat (Lowrance 2025). These pings are continuous and range in broadband frequency bandwidths depending on the user's specifications. The devices typically used amongst the communities uses two sonars simultaneously: a side scanner that emits at 600 kHz or higher, and a depth sounder emitting at either 200 kHz or 83 kHz. These depth sounder

frequencies overlap with beluga vocalizations, with narrowband calls produced approximately in the range of 200 Hz to 20 kHz and broadband echolocation clicks reaching maximum frequencies of 120 kHz (Au et al. 1985; Sjö and Smith 1986). Additionally, these active sonars emit broadband signals that overlap within the beluga hearing range (1.2 kHz – 150 kHz), with highest sensitivities between 16 kHz – 120 kHz (Mooney et al. 2018b). Beluga whales have been studied echolocating in shallow water (~2m) with peak spectral energy at 20 kHz to 60 kHz and 80 kHz to 140 kHz (Song et al. 2023).

Increased anthropogenic noise is especially of concern as Arctic marine mammal species may be more sensitive to added ambient noise, given the soundscape is quieter on average than non-Arctic environments (Haver et al. 2017). This is in part because ambient sound levels decrease under solid ice conditions by dampening wind-driven sound and increasing underwater propagation loss (Au and Hastings 2008). Highlighting these concerns, Halliday et al. (Halliday et al. 2019) identified temporary habitat displacement of belugas caused by vessel noise, with potential implications for food security among Inuvialuit harvesters and risks to seasonal migration and aggregation patterns.

Additionally, the dynamic environmental conditions of the Mackenzie Estuary (i.e. turbid, shallow, freshwater) lends to novel scenarios for noise propagation. There is a lack of literature exploring the sound propagation properties of consumer grade depth sounders, despite being one of the most popular tool for boaters (Research and Markets 2025). The few existent studies are done in deep (> 200 m), salty oceanic conditions, focused on other cetacean species (i.e. killer whales (Burnham et al. 2022)) or within environments not inhabited by marine mammals (Deng et al. 2014).

Understanding how these sounds propagate within the soundscape is essential for evaluating exposure within existing noise assessment frameworks. Noise exposure studies often rely on field measurements and acoustic thresholds to predict potential marine mammal harassment. The U.S. National Marine Fisheries (NMFS) uses very generalized behavioral thresholds to evaluate behavioral disturbances by anthropogenic sources (NMFS 2024). Notably, the 120 dB threshold for non-impulsive noise was originally based on studies of gray whale (Malme et al. 1983; Malme et al. 1984). Additionally, generalized thresholds may fail to communicate the extent of exposure for noises that exhibited both impulsive and continuous properties, such as depth sounders, highlighting the need for further investigation. Using thresholds as the sole mitigation strategy neglects key behavioral observations, and the lack of international standards has prompted efforts to move beyond reliance on acoustic thresholds alone (Gomez et al. 2016; Wright and Moors-Murphy 2022).

In this study, we measured propagation characteristics of commercial grade use depth sounders in the TN MPA. We quantified depth sounder signals using metrics applied to both impulsive and continuous sound sources, recognizing that these signals exhibit characteristics of both source types. This research was conducted in tandem with a qualitative study on the observations and perceptions of Tuktoyaktuk harvesters who use depth sounders on their boats (Rankin et al. chpt 3). The propagation data collected will be used with qualitative interview data to inform recommendations for safe depth sounder use, as motivated by questions from the Tuktoyaktuk Hunters and Trappers Committee (THTC).

Methods

Study area

The TN MPA is located within the Mackenzie River Delta and estuary within the coastal regions of the Eastern Beaufort Sea (Figure 1) (FJMC 2013). Established in 2010, the TN MPA is co-managed by Fisheries and Oceans Canada DFO and the Inuvialuit to protect critical beluga habitat, support continued Inuvialuit harvesting, and inform management through research and long-term monitoring. It is divided into three parcels – Niaqunnaq, Okeevik, and Kittigaryuit – spanning the eastern Yukon and into the Northwest Territories, covering approximately 1,750 km² of marine habitat. The cool saltwater influence of the Beaufort Sea and the warmer freshwater influx from the Mackenzie River create an estuary with fluctuating salinity and temperature levels (Lee et al. 2024). Average bottom water temperature levels range across the three parcels (6.03°C – 14.2°C), Niaqunnaq being the coldest by 1.5 -2.6 °C. Average salinity across all parcels are dynamic (0.22 – 23.3 ppt), influenced by river discharge and wind conditions which can push freshwater flow along the eastern coast of the parcel (Carmack and Macdonald 2002). Seasonal land-fast ice contributes to water property dynamics, covering the estuary in the winter months with ice-break up occurring in June and lasting until October (Whalen et al. 2019). Plumes of rich sediment from the Mackenzie outflow and coastal permafrost melt contribute to hot spots of extremely high turbidity zones, the most prominent being within the Shallow Bay, Niaqunnaq parcel (Lee et al. 2024). Depths average < 5 m across the MPA and are relatively featureless throughout with limited bathymetric variability (Whalen et al. 2019). Beluga hotspots have been identified within all three parcels but the two biggest aggregations identified within Shallow Bay and Kugmallit Bay.

The Kittigaryuit parcel lies within the Kugmallit Bay where the Mackenzie River East Channel outflows. The Tuktoyaktuk harbor lies within the eastern coast of the Kugmallit Bay, about 17 km out of the designated TN MPA parcel. The Tuktoyaktuk peninsula also receives sediment

plumes from westerly winds pushing Mackenzie River discharge up along the east coast, reaching several hundred kilometers offshore (Carmack and Macdonald 2002). The depths are also very shallow (< 4 m) with a channel (6 – 25 m depth) running through the middle of the harbor, allowing boat passage. The water is usually below saline conditions unless coastal storms push cold and saline water into the harbor (Scharffenberg et al. 2019).

Project Initiation and Review

This project was motivated by initial inquiries from the THTC with the introduction of the bathymetry mapping program in 2022. This project was presented and discussed with Inuvialuit partners before and during its initiation (Scharffenberg 2025; Scharffenberg and Rankin 2025; Scharffenberg et al. 2026), including periodic check-in meetings with the THTC board.

Data collection

Depth sounder experiments were conducted June – July 2024 and 2025 across seven sites in the TN MPA and Tuktoyaktuk Harbor (Figure 1). The THTC were consulted for selection of depth sounder experiment sites. A passive acoustic mooring was equipped with a high frequency ST300 hydrophone (-176.4 dB/V; Ocean Instruments, New Zealand) which recorded at a sample rate of 576 kHz with 16-bit resolution (Figure 2), an RBR Solo depth sensor, RBR Solo³ turbidity sensor, and three Star Oddi conductivity, temperature, depth (CTD) sensors were also affixed to the mooring. Turbidity was continuously sampling, while the CTD sampled every two minutes, and RBR depth sensor every minute. The mooring was temporarily deployed at the start of each depth sounder experiment and was retrieved after testing concluded.

The test boat was equipped with a Lowrance © HDS9 Pro and the Lowrance Active Imaging 3 in 1 transducer mounted about 0.20 m below the hull (the same model used in the community

bathymetry project). Four frequency settings were tested for each site: 83 kHz, 200 kHz, medium CHIRP (frequency sweep within 85kHz -155 kHz), and high CHIRP (frequency sweep within 140 kHz – 250 kHz) (exception with Kendall Island 77 kHz only) (Table 1). Real-time GPS points were taken with Esri Field Maps in addition to recording depth, date/time, frequency, distance from mooring, and any environmental notes. GPS points were logged every five seconds for the duration of each test (15 – 25 minutes for each frequency). Each experiment began with the hull pointed toward the mooring about 1 m away at idle speed (<4 km/h), then spiraled outward until reaching a maximum distance of 200 m. Some sites had reduced maximum distances due to shallow depths and local bathymetry. At each site, with exceptions of Kugmallit and Kendall Island (which were sampled opportunistically), frequencies were tested once across two separate days and time to capture varying environmental conditions (e.g., storms, tides).

Additionally, a depth sounder test was done in Niaqunnaq with a different design to test how boat speed influences the detectability of the depth sounder, as faster motorboats create more broadband noise (Johansson et al. 2024). The boat circled the temporary mooring at a distance of ~ 20 m while running the 200 kHz sonar for one minute at low (< 8 km/h), medium (13 km/h), and high (20 km/h) speeds. The 83 kHz frequency was not tested due to time constraints; however, based on the 200 kHz results, it was inferred that the sonar signal may have been similarly masked by motor noise, where overlapping frequency and temporal occurrence, combined with the greater amplitude of the motor noise, reduced the detectability of the sonar signal.

Data analysis

Peak received levels (RL) (i.e. the pressure range between zero and the greatest pressure value of a signal) and root mean squared (RMS) (i.e. continuous acoustic energy over a specified time) metrics were measured from the audio files of each experiment. Peak RL were used to define conservative upper-bound detectability distances, while RMS metrics were used for contextual comparison with disturbance guidance. Peak pressures are typically limited to impact assessments of impulsive signals (Faulkner et al. 2018) or to define the amplitude of a signal, while RMS metrics are standard for impact assessments of continuous sounds (Van Geel et al. 2022), however we decided to incorporate both to reflect the ambiguity and subjectiveness of depth sounder signals within the literature (Martin et al. 2020). To measure the loudest portion of individual sonar pings, peak pressure values were measured in each depth sounder test. We considered the distance at which peak pressure dropped below ambient levels to be the maximum theoretical distance of detectability or upper-bound audibility. A band limited energy detector in Raven Pro (version 1.6.5, Cornell University; spectrogram 1024-point resolution, 512-point Hann window) was used to isolate peak ($L_{p,pk}$ or $SPL_{p,pk}$) and RMS ($L_{p,rms}$ or SPL) pressures of each sonar ping based on its target frequency (76 – 78 kHz for Kendall Island, 82 – 84 kHz and 198-202 kHz bandwidths) (Figure 3). The frequency range was built into the detector because peak pressures are not always at the target frequency with depth sounders (i.e. 83 kHz or 200 kHz) (Burnham et al. 2022) so a frequency range was necessary for the detector. The audio files were calibrated using end-to-end system sensitivity of the hydrophone and recorder provided by the manufacturer to convert relative pressure in μPa . Peak and RMS pressures (p) (μPa) were then converted into received sound pressure levels (SPL) or received levels (RL) (dB re 1 μPa) using the following formula:

$$RL = 20 \times \log_{10} \left(\frac{p}{1 \mu Pa} \right)$$

Received levels were averaged per second to reduce variability associated with high ping rates (23-25 pings/second) and to enable comparison with regulatory metrics reported at ≥ 1 s integration times (Erbe et al. 2016). The RL were graphed and the y-intercept of the logarithmic equation of the line was identified as the maximum $L_{p,pk}$ from each test (also described as peak source level below), as well as the $L_{p,rms\ peak}$ of 1 s of sonar pings as a comparison to behavioral thresholds for impulsive signals (160 dB re 1 μ Pa) and non-impulsive signals (120 re 1 μ Pa) (NMFS 2024). Although $L_{p,pk}$ is not used as a standard for behavioral thresholds, but rather for temporary and permanent threshold shifts, it was included to document maximum signal intensity. These thresholds are presented for contextual comparison rather than as indicators of expected behavioral response (Southall et al. 2021). The RL measurements were matched with the depth (d) and range (r) recorded at that time using ArcGIS Pro to measure the distance of each GPS point taken during the experiment from the mooring. GPS accuracy was ± 4 m, though absolute GPS accuracy was less critical than relative distance tracking, which remained consistent within each transect.

The received levels were graphed with distance to visualize the relationship of the intensity of the signal with distance. The logarithmic equation of the line was used to extrapolate to sound intensity at 1 m distance as an estimate of effective source level (SL) for each frequency setting under operating conditions at each site. Effective source levels were averaged across sites to obtain a single value for comparative analysis. Average received sound pressure levels (RMS) of the ambient sound, band-limited (15 kHz – 220 kHz) to filter out small boat engine noise, were also measured across sites and averaged to be included as a below-detectable threshold for broadband measurements. A custom R script was used to measure the band-limited peak SPL of ambient sound per second and average across 15 minutes and included as a below-detectable

threshold for peak received levels. The background noise levels used here covered a variety of ambient conditions ranging from calm to rough water conditions (i.e. BSS 0 – 4).

Depth sounder propagation modeling

Sound speed profiles were input into BELLHOP using MATLAB (version R2025a, MathWorks), a ray tracing model used for sound wave propagation (Porter 2011), using the National Physical Laboratory (NPL) Equation as formulated by Leroy, Robinson and Goldsmith (2008) (Leroy et al. 2008) to calculate sound velocity (m/s) using depth, temperature, salinity, and latitude. We used the NPL equation because its range of validity included colder water temperatures and a wider range in salinity and temperature measurements. Measured transmission loss (TL) of each frequency setting per site were calculated for each distance by the following formula:

$$TL_r = SL_{average} - RL_r$$

r represents range or distance of the depth sounder from the receiver. Theoretical TL models were made using BELLHOP to compare with empirical measurements. BELLHOP models were chosen as the ray trace is well adapted for high frequency sources in less variable shallow habitats (Li et al. 2025). Coherent beams were chosen as it gives the most accurate TL plot (Porter 2011). Ray trace models were also made to compare empirical received levels with the soundwave path as distance increased. Bottom substrate type (i.e. clay, silt, sand) were incorporated by sediment distribution maps (Pelletier 1984; Transport Canada 2016) for bottom loss, with substrate sound speed (m/s), bottom density (g/cm³), and bottom attenuation (dB/λ) retrieved from Jensen et al. (2011). Community members also wanted to know how the depth sounder would travel in deeper channels they regularly transverse in. Using the average

calculated source level and linearly extrapolated sound speeds from empirical measurements for sound-speed profiles, transmission loss was modeled in 10 m depth of water in BELLHOP.

A 1/3 octave analysis was done within the beluga hearing range (1.2 kHz – 150 kHz), frequency weighted based on the beluga audiogram described in Mooney et al. (2018a), using PAMGuide to compare depth sounder noise to background sound levels, better demonstrating the auditory filter bandwidths of beluga (Erbe 2008). Although the depth sounder produces impulsive signals, they are emitted with short inter-pulse intervals, unlike pile driving or blasting, it could be perceived as a continuous noise. Continuous broadband levels were therefore plotted using a bandpass filter above 15 kHz to capture the lower-frequency portion of the depth sounder signal while excluding boat motor noise.

Testing environmental influences

We sought to test the relative influence of how different each environmental parameter on the absorption of sounds emitted by the sonar, given the dynamic environment for a depth sounder propagation study. To do this, we first accounted for expected geometric spreading at distance d , leaving a range-independent loss term (α), or referred to as theoretical absorption, that captured absorption and other distributed attenuation processes. While this term does not represent pure molecular absorption, it provided a comparative metric to broadly evaluate how environmental conditions influence high-frequency transmission loss across sites. Solving for a yielded the following formula:

$$TL_r = \left(\begin{array}{c} \text{Spherical spreading} \\ | \end{array} \right) (20 \times \log_{10} d) + \left(\begin{array}{c} \text{Cylindrical spreading} \\ | \end{array} \right) (10 \times \log_{10}(r - d)) + ar$$

Prior analysis within the study showed that absorption leveled off to a steady constant at a distance > 80 m, so the lowest ten absorption values were averaged at each site to get actual α . This prevented a skewed average absorption closer to the receiver (i.e. < 80 m) where other attenuation influences such as scattering and reflection at the bottom were more dominant given the steep ray angle (Jensen et al. 2011).

We fitted a multiple linear regression (MLR) using the *stats* package in R (R Core Team 2025) to examine relationships between the theoretical sound absorption and environmental predictors (i.e. temperature, salinity, depth, sound speed, and turbidity) for each site and frequency.

Frequency was initially fit as a random variable but we found it did not attribute to variability in the dataset (variance = 0). Each variable was tested for collinearity using a variance inflation factor (VIF). The normality assumption of residuals was evaluated using a histogram and normal Q–Q plot. If a variable was a significant predictor, it was additionally fit in a linear model with a .

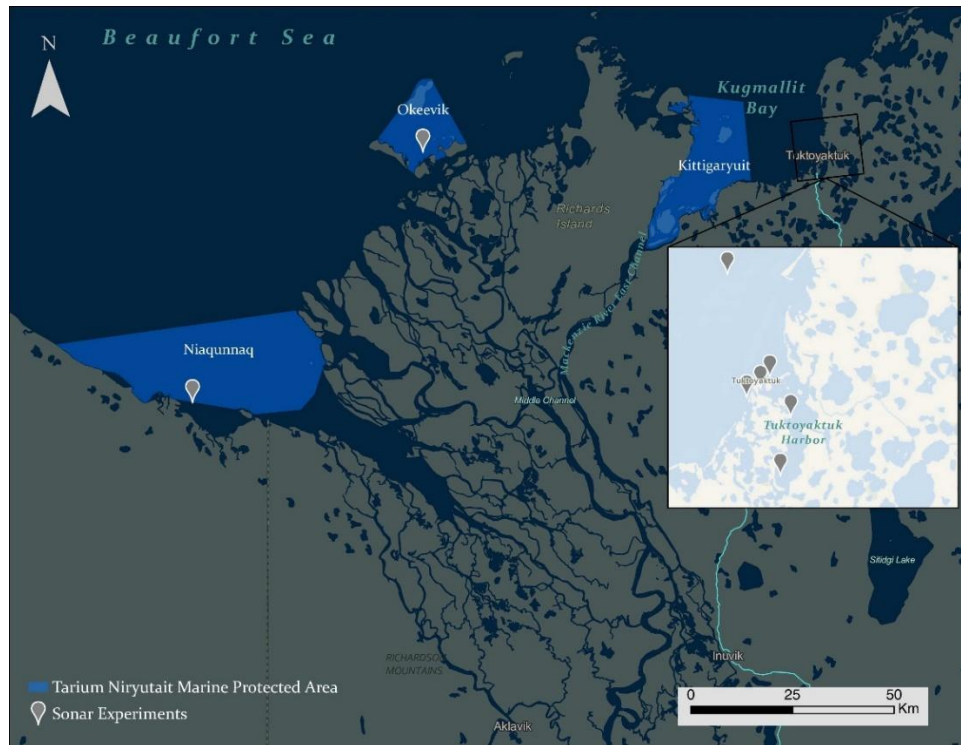


Figure 2.1. Top: Map of depth sounder tests done in proximity to Tuktoyaktuk and TN MPA, June-July 2024 and 2025. Bottom: Satellite image showing the turbid Mackenzie River outflow

into the Beaufort Sea (top). Source: Esri, Vantor, Earthstar Geographics, and the GIS User Community, accessed on February 18, 2025.

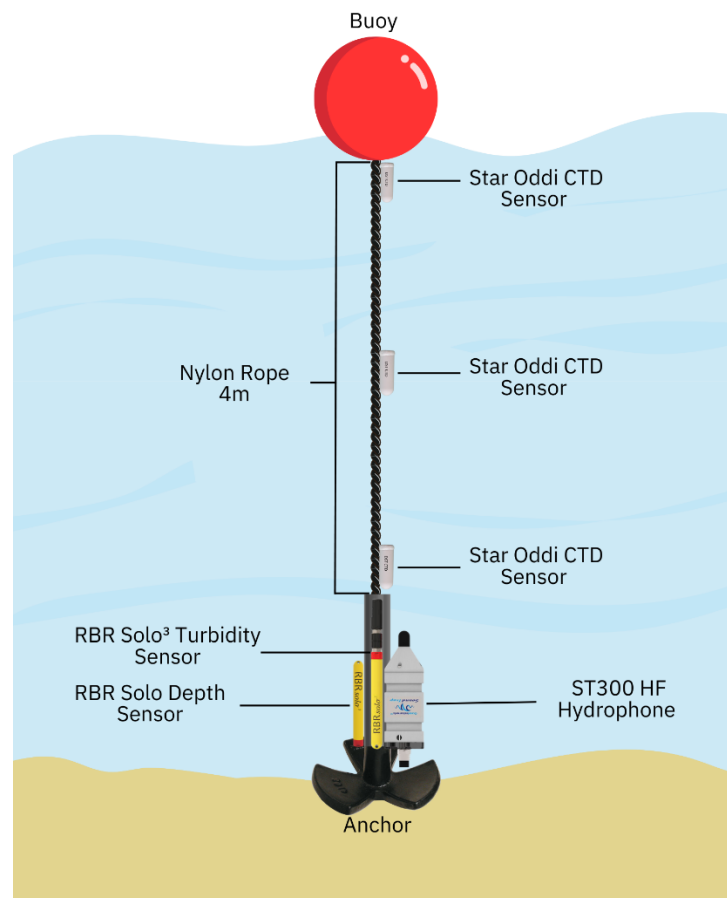


Figure 2.2. Mooring design equipped with ST300 HF hydrophone (-176.4 dB/V), StarOddi CTDs, RBR Solo Depth sensor, and RBR Solo Turbidity sensor.

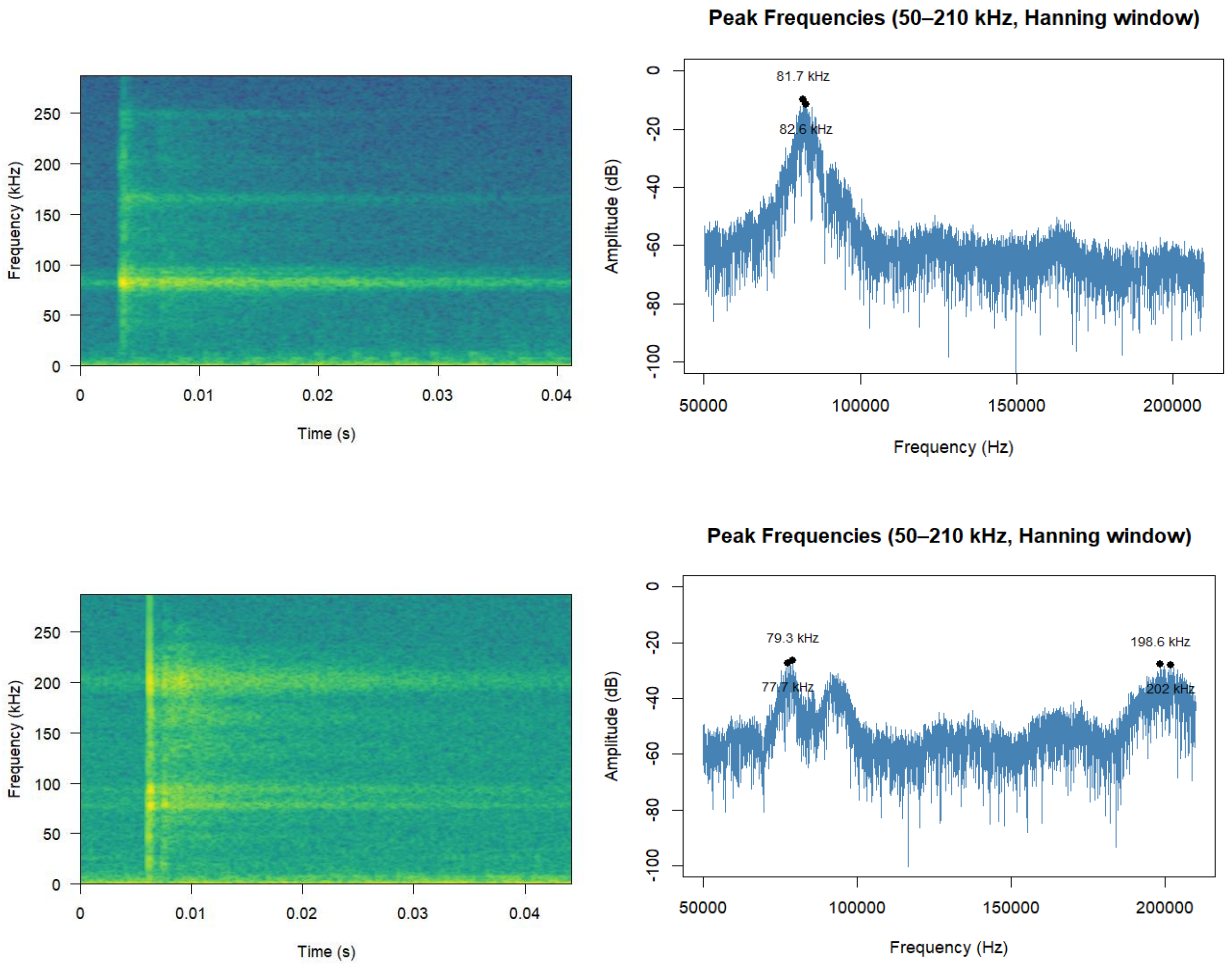


Figure 2.3. Peak frequencies for the (top) 83 kHz sonar and (bottom) 200 kHz sonar.

Results

Measured vs. modeled received sound pressure levels

Received sound pressure levels were measured at seven sites over eight non-consecutive days, encompassing a range of habitat conditions (Table 1). Measurements for CHIRP frequencies were nearly identical to their non-CHIRP counterparts; consequently, CHIRP data were grouped with the corresponding non-CHIRP frequencies for the environmental analysis but excluded from further analysis. The 83 kHz measured higher $L_{p,rms}$ and $L_{p,pk}$ values (with an exception of the West Coast site) than the 200 kHz (Table 2). Ambient sound levels were consistent throughout locations with an average of 98.1 ± 4.34 dB re 1 μ Pa and an average peak pressure of 117.1 ± 5.74 dB re 1 μ Pa. The highest 83 kHz $L_{p,pk}$ (i.e. Reindeer Point) measured 77.44 dB higher than the average peak ambient levels when the depth sounder was at 1 m range. The highest 200 kHz $L_{p,pk}$ (i.e. Tuk Island) had a slightly less intensity difference and measured 58.45 dB higher than average peak ambient levels.

The received levels declined with distance across all tests, following a logarithmic trend as shown in the Figure 4. Source levels varied slightly across frequencies and locations, averaging 170.45 ± 1.18 dB re 1 μ Pa. SPLs were greater for the 83 kHz tests than the 200 kHz across all sites (Table 2). The BELLHOP model best-fit lines for 83 kHz and 200 kHz exhibited little variation from each other, in contrast to the higher variability observed in the measured RL (Figure 4). Model predictions across all sites showed varying degrees of attenuation that did not always correspond closely with the observed variability in measured RL, with degree of agreement between model and measured differing between the 83 kHz and 200 kHz frequency settings at some sites. The 77 kHz BELLHOP model agreed most closely with measured RL at the Kendall Island site, though only one trial was conducted here. The BELLHOP model closely

matched measured RL for both 200 kHz and 83 kHz at the Tuk Island and West Coast sites, whereas Harbor Point, Reindeer Point, and Waterline the model more closely fit the 200 kHz RL. The measured 83 kHz at these sites exhibited less transmission loss than was predicted by the model. Tuk Island showed the least variation in RL between frequencies (± 5 dB), resulting in a consistent agreement with corresponding model predictions. Spikes in received level (RL) were observed at several distances from the receiver in each test, consistent with patterns predicted by the ray trace models within BELLHOP. Models with the sand bottom type (i.e. West Coast) resulted in a less exponential TL than silt or clay as distance increased (see Supplementary Figure S1).

Broadband noise exposure

1/3-octave band levels indicated that depth sounder noise during the tests exceeded ambient levels across multiple frequency bands, with the greatest differences observed between 56 – 112 kHz (Figure 5). 1/3 octave band levels showed frequency weighted RMS levels for the 83 kHz sonar increased by 36 – 50 dB in the 70 – 90 kHz bands, with the largest difference occurring at 79 kHz (130.4 dB re 1 μ Pa). The 200 kHz RMS levels were not as high, due to the peak frequency being outside beluga hearing, however residual spectral power increased RMS levels by 25 – 32 dB in the 70 – 112 bandwidths, also with the largest peak at 79 kHz (112.3 dB re 1 μ Pa) (Figure 5). Broadband SPL levels for the 83 kHz showed peaks above 120 dB re 1 μ Pa within 100 m of the depth sounder, while only within 40 m for the 200 kHz.

Exposure distance and thresholds

The distances at which the 83 kHz and 200 kHz depth sounders dropped below perceivable levels varied by location, as indicated by the leveling off of broadband levels in Figure 6, likely

reflecting varying ambient noise conditions. Consistent across all sites tested, the 83 kHz traveled the furthest, falling below peak ambient sound at the distance of ~ 150 m – 220 m. The 200 kHz sonar was not perceivable above peak ambient sound beyond 80 m – 160 m. The Waterline location had a wide range of depths (5 m – 17 m), and we recorded the furthest propagation of the 200 kHz sonar at least 160 m (the maximum distance that was tested at this site). The shortest propagation distance a signal traveled before dropping below ambient levels occurred at the shallowest site (1.57 m at Kendall Island) where the 77 kHz sonar was not detectable beyond 60 m.

Additionally, we used BELLHOP to model the propagation distances within deeper vessel channels as motivated by questions from community members. The depth sounder within a 10 m deep channel more than doubled the propagation distances, with 200 kHz reaching 400 m and 83 kHz extending to 500 m (see Supplementary Figure S2).

Environmental influences

When evaluating measured TL across sites, the remaining TL after geometrical spreading showed spikes at closer ranges, probably influenced by bottom and surface interactions, but decreased as range from the depth sounder increased. A MLR was used to evaluate the influences of bottom water temperature, salinity, turbidity, depth, and sound velocity on range-independent loss (a). Initial MLR results were significant ($F(5, 10) = 7.188$, $p < 0.05$) and explained 78% of variance in a (adjusted $R^2 = 0.67$, $n = 16$). Only turbidity showed a significant association with a ($t = 3.687$, $p = 0.0042$). Bottom temperature, depth, salinity, and sound speed were not significant predictors. However, salinity (VIF = 26.9) and temperature (VIF = 31.6) showed significant multicollinearity with each other, as predicted, thus influenced the MLR results for those variables. Turbidity had moderate collinearity (VIF = 6.7), however, pairwise

correlations showed only weak relationships between turbidity and other environmental variables. Thus, the significant effect of turbidity in the MLR was unlikely to be driven by strong pairwise collinearity. An additional linear model was fitted to look at the relationship between turbidity and a , and results were significant as turbidity positively predicted a ($n = 16$, $t = 4.98$, $p = 0.0002$). Because turbidity was significantly higher at Kendall Island, it was removed and the linear model was still significant ($n = 15$, $t = 4.43$, $p = 0.0006$) (Figure 7).

Table 2.1. Environmental conditions for each test site. *Site was only used for testing depth sounder presence with boat speed, thus was excluded from environmental analysis. **Site was tested on two different days due to inclement weather. The 83 kHz was tested during storm conditions, and the 200 kHz was post-storm conditions.

Location	Frequency (kHz)	Depth (m)	Bottom Temperature (°C)	Surface Temperature (°C)	Bottom Salinity	Surface Salinity	Turbidity	Bottom Type	Sound Velocity (m/s)	Average Theoretical Absorption
*Shingle Point	200	2.57	8.33	8.026	0	0.11	118.32	-	1440.54	-
Kendall Island	77	1.57	7.297	6.51	0	0.25	211.37	silt	1436.19	0.284
Kugmallit Bay	200	1.95	14.89	15.36	0.01	0.16	42.33	clay	1465.62	0.077
**Harbor Point	83	4.12	12.33	12.35	0.223	0.81	31.19	silt	1456.62	0.108
	200	4.49	9.90	9.66	0.009	0.23	72.92		1446.94	0.112
Tuk Island	83	3.66	10.44	16.30	0.01	0.68	44.43	sand/silt	1449.08	0.105
	200	3.66	10.44	16.30	0.01	0.68	44.43		1449.08	0.123
	High CHIRP	3.45	5.58	17.43	14.12	0.28	31.85		1446.66	0.116
Waterline	83	4.68	10.32	10.21	0.01	0.46	25.53	sand/silt	1448.62	0.045
	200	4.68	10.32	10.21	0.01	0.46	25.53		1448.62	0.020
	Medium CHIRP	4.69	10.96	11.43	0.01	0.84	22.08		1451.12	0.010
	High CHIRP	4.69	10.96	11.43	0.01	0.84	22.08		1451.12	0.046
West Coast	83	3.2	12.13	15.28	0.01	0.16	60.04	sand	1455.58	0.086
	200	3.2	12.13	15.28	0.01	0.16	60.04		1455.58	0.150
	Medium CHIRP	2.9	4.76	19.66	15.16	0.20	33.59		1444.44	0.084
	High CHIRP	2.9	4.76	19.66	15.16	0.20	33.59		1444.44	0.099
Reindeer Point	83	3.2	11.88	17.00	4.20	0.01	11.58	sand/silt	1459.58	0.011
	200	3.2	11.88	17.00	4.20	0.01	11.58		1459.58	0.13

Table 2.2. Noise exposure measurements for 77 kHz, 83 kHz, and 200 kHz. One second window lengths and 0% window overlap. *The 83 kHz for this site exhibited slow ping rates due to technical errors, thus SPL was not possible. $SPL_{p,pk}$ is the maximum received sound levels extrapolated from the logarithmic curve, also recorded as the calculated source level. $L_{p,rms\ peak}$ is the peak RMS measured of 1 s duration of sonar pings closest to the receiver, including idling motor noise for the purpose of comparing to existing behavioral thresholds.

Location	Frequency (kHz)	$SPL_{p,pk}, L_{p,pk}$ (dB re 1 μ Pa)	$SPL, L_{p,rms\ peak}$ (dB re 1 μ Pa)*
Kendall Island	77	167.29	143.4
Harbor Point	*83	179.39	-
	200	160.57	135.2
Tuk Island	83	188.07	143.10
	200	175.51	137.73
Waterline	83	159.67	134.56
	200	156.8	127.45
West Coast	83	162.89	144.98
	200	171.82	141.80
Reindeer Point	83	194.5	145.78
	200	162.5	141.77

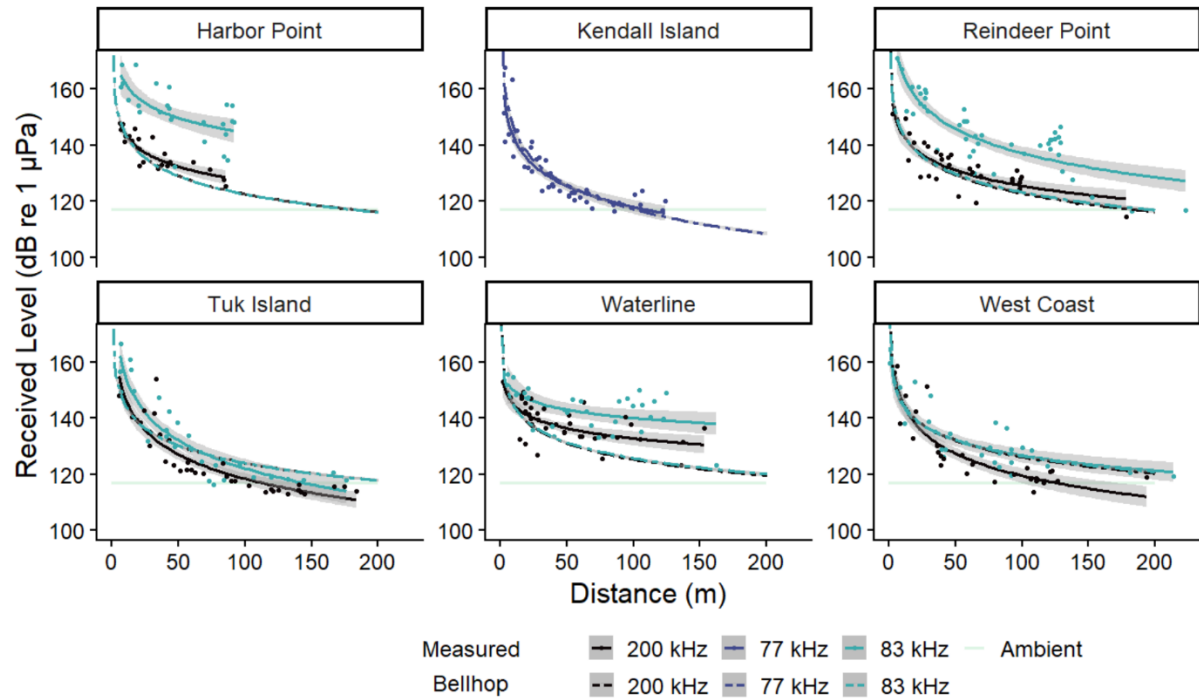


Figure 2.4. Peak received sound pressure levels of three depth sounder frequencies as the sonar traveled away from the receiver. Solid line indicates the logarithmic best-fit line measured received levels taken during field experiments. Dashed line indicates the logarithmic best-fit line BELLHOP modeled received levels. The horizontal line represents average peak ambient levels at 117.06 dB re 1 μ Pa.

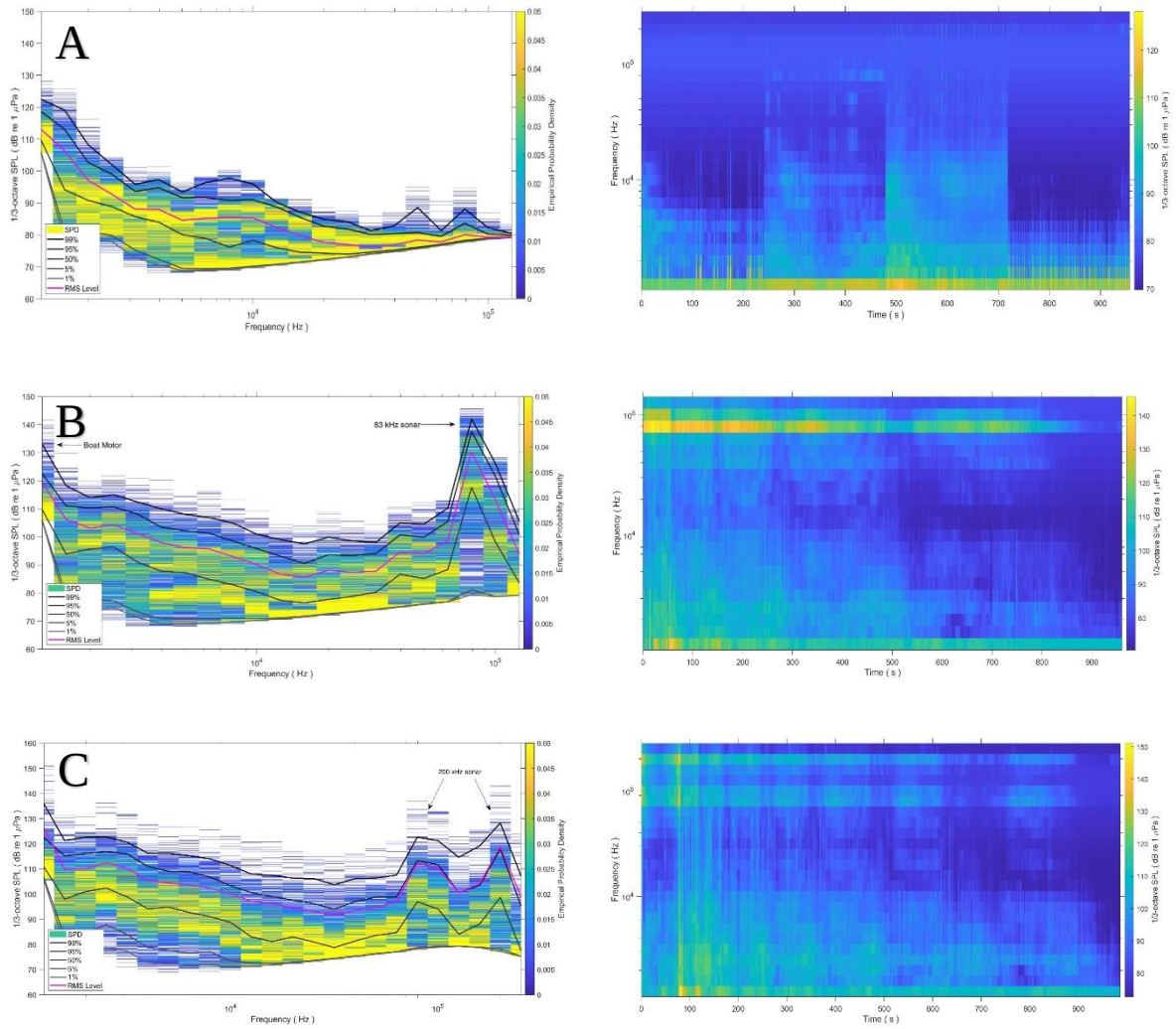


Figure 2.5. 1/3 octave level analysis over a 16-minute time series with A) ambient levels, B) 83 kHz, and C) 200 kHz. Ambient levels were sampled for four minutes across four separate days, including one day of storm conditions.

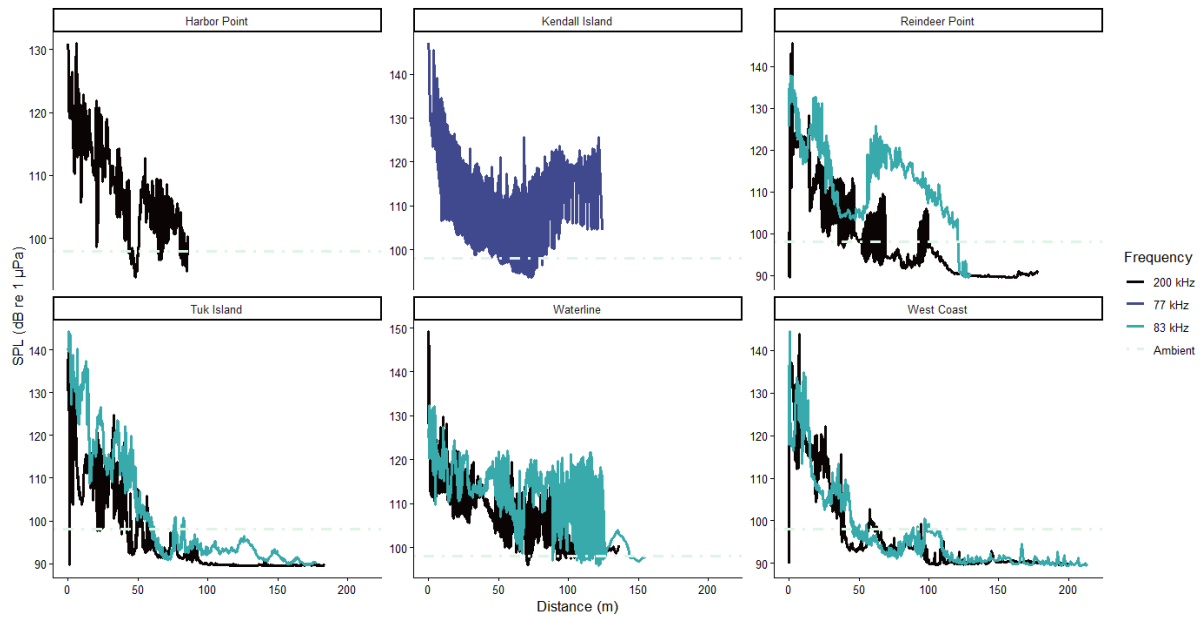


Figure 2.6. Broadband levels of noise exposure at varying distances from the depth sounder.

Modeled in PAMGuide. Note Kendall Island was the first test and transects were ran at cardinal directions instead of a spiral pattern. The mean broadband SPL of 98.1 dB re 1 μ Pa was used for ambient.

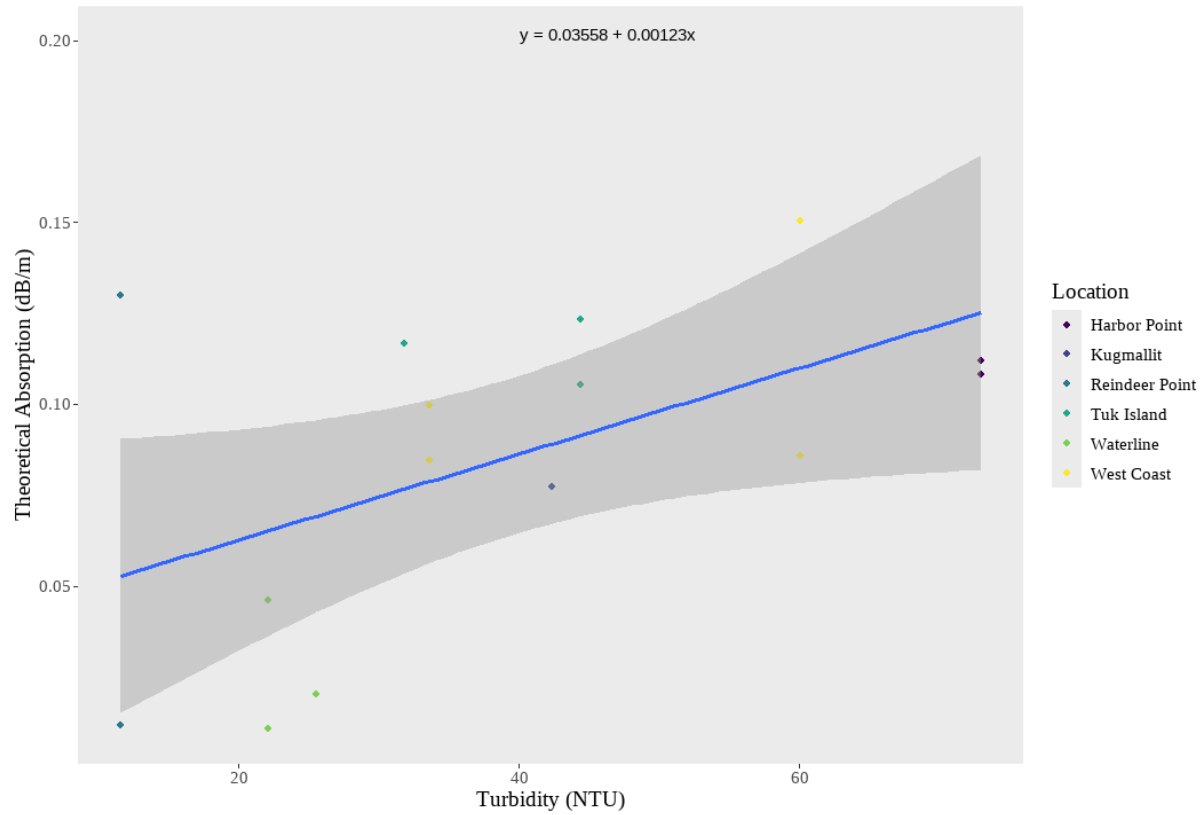


Figure 2.7. Theoretical absorption (dB/m) with varying turbidity values (NTU) across six sites. The shaded area represents standard error. Note that Kendall Island was excluded.

Discussion

We conducted propagation experiments by measuring how pings from a consumer-grade depth sounder propagate through shallow, fresh environments of the Mackenzie Estuary. The 77 kHz, 83 kHz, and 200 kHz active sonar transmitted with a continuous duration within ~ 200 m radius, exceeding peak ambient levels up to 77 dB within the sensitive beluga hearing range (16 kHz – 100 kHz) (Mooney et al. 2018b). Peak SPLs were used to measure maximum distances at which sonar pings at each frequency would be audible above ambient levels, as well as to characterize peak intensity of the impulsive signal. More broadband measurements were also made to characterize the non-impulsive noise exposure over the duration of the test such as SPL and 1/3 octave analysis.

Variability in depth sounder propagation in a shallow estuary

Measurements revealed considerable variation in the propagation range of depth sounder signals across frequencies and environmental conditions. The 83 kHz was detectable about 60 m farther from the source than the 200 kHz at all sites. These maximum distances were similar to those reported by Burnham et al. (2022) when they measured an echo sounder in 5 m of water, though ambient levels were quieter in their testing location, resulting in detectability for their 200 kHz and 83 kHz signals exceeded our own ranges by about 100 m in some transects. Additionally, the depths at some of our testing sites (i.e. West Coast and Kugmallit) were only 2-3 m which likely restricted propagation distances, however these were still biologically relevant depths for beluga presence. The 200 kHz at Harbor Point propagated further than the 160 m maximum distance, likely attributed to the greater depths (3.5 m – 7 m) in this location. Maximum distances for both frequencies more than doubled in models where the depth was set to 10 m with other variable held constant. These detectability ranges can inform us how far out the depth sounder could be

audible to beluga. The depth driven range of noise exposure suggests deeper locations such as boat channels and shipping lanes, like the main channel in Tuktoyaktuk Harbor and coast of Tuktoyaktuk Peninsula, may be locations where belugas could detect signals over greater distances.

RL generally followed a logarithmic regression as the distance between the depth sounder and receiver increased, however we observed spikes in RL over the course of each test, most commonly at shorter distances. Burnham et al. (2022) also observed this in shallow bays, likely explained by a few factors, most notable being rapid attenuation with slight changes in water depth and significant surface and bottom interactions. At certain propagation distances, the receiver may coincide with the peak of the acoustic wave, resulting in localized increases in measured peak sound pressure levels. In our case, the spiral transect design combined with an asymmetrical transducer – which can be caused by an uneven transducer installation or water turbulence from the outboard motor – may have caused unexpected signal strengths.

There are several sources of variability when it comes to measuring and modeling acoustic characteristics in shallow estuarine environments including complex interactions with the surface and bottom (Moore et al. 2007). In our case, transmission loss through bottom attenuation was a large factor because of the steep vertical angle of the depth sounder (Jensen et al. 2011). At cone angles of 20° and 60 ° for the 200 kHz and 83 kHz pings respectively, this will result in most of the soundwaves hitting the seafloor less than the critical angle according to Snell's Law (~ 65° from vertical). Additionally, because of the sediment sound speed (~1600 m/s) being greater than sound speed in the water column (~ 1450 m/s), the soundwaves attenuate into the sediment at close ranges. All surface conditions were relatively calm without notable wave action; thus, surface attenuation was not as significant as bottom attenuation, though this may not always be

the case for boaters. Because of the limited number of study sites, the full range of substrate hardness were not represented, restricting comparisons among bottom habitats. This limited our ability to discern the relative contribution of bottom absorption and attenuation. Ideally empirical bottom measurements should be incorporated for future propagation studies.

In addition to surface and bottom interactions, dynamic freshwater mixing and stratification in estuaries can cause changes in sound speed over time and spatial scales (Reeder 2013), however the speed profiles across sites displayed very little variation with depth. At such shallow depths, the water column was well-mixed from wind and proximity to the river mouth, resulting in a lack of stratification, matching previous trends (Lee et al. 2024). Only three locations (Reindeer Point, Tuk Island, and West Coast) showed one or more tests that exhibited stratification with the warmer freshwater sitting on top of the cooler saltwater, resulting in sound speed profiles where the velocity is greatest at the surface. In a saltwater wedge estuary, pings from a depth sounder emitting at the surface can become reflected and refracted back toward the surface due to the denser water layer underneath (Reeder 2013). At greater depths, this can create shadow zones below the surface layer, however this was not observed at the < 4 m depths in our study, with these sites not differing significantly from received levels than the other non-stratified sites.

Although stratification appeared to have a limited influence on propagation at most sites, other water-column properties were found to broadly affect acoustic transmission. In particular, turbidity was significantly positively correlated with transmission loss. High frequency soundwaves are more susceptible to absorption loss due to the faster oscillations causing more particle collisions (Urick 1983). More suspended particles could lead to increased viscous absorption and thermal absorption as the waves collide with the particles and lose its energy in the acoustic field to heat (Richards et al. 1998). The influence of turbidity on sound absorption

has been tested in laboratory settings (Urick 1948; Brown et al. 1998), however there is absence of in-situ measurements within the literature. Richards & Leighton (2000) found an 80 kHz sonar decreased propagation range by 1/3 when monodispersed particles were suspended within the water column in laboratory conditions. Based on our results, this is a notable variable that should be incorporated in estuarine propagation models. Temperature, salinity, sound speed, and depth were non-significant, most likely due to the lack of variation within the dataset, or the short distances measured (i.e. 100 m – 200 m) over which the study was conducted. Community guidance to avoid interference with subsistence beluga harvesting and limitations of equipment (i.e. larger boat capable of reaching more distant habitats within the delta) prevented testing in additional locations and conditions.

A portion of the discrepancies between modeled and measured transmission loss can likely be attributed to limitations inherent to BELLHOP. While BELLHOP was the chosen model in this study for its accuracy in modeling high frequencies in various environments (Porter 2011; Li et al. 2025), the model is not designed to account for so much surface and bottom interactions. Furthermore, BELLHOP performs better for larger grazing angles from sound sources and on smooth bottom types, while being further limited in implementing reverberation characteristics (Jensen et al. 2011; Porter 2011). This could in part account for inaccuracies in the modeled TL as needed to implement smaller, steep angles associated with depth sounder emission. Similarly, BELLHOP is unable to correctly account for frequency and bottom-dependent ray splitting and ray shifts that influence the reflection coefficient within the model, thus can cause inaccurate absorption and scattering loss that would be more prevalent in the 200 kHz than the 83 kHz (Porter 2011). Discrepancies may also partially be related to site selection and the study design itself. For instance, two sites – Harbor Point and Waterline – whose measurements differed most

dramatically from their perspective models, were limited in sampling distance to around 100 - 150 m because of the shoreline. This did not allow us to situate the receiver outside the area with high surface and bottom interactions, thus did not capture the full scope of transmission loss. Additionally, the Waterline site featured dynamic depth changes (4 m – 17 m) that were too complex to include within the BELLHOP model.

Some of these limitations could be addressed in the future through experimental designs which includes larger sampling distances (>200 m) in more variable bottom types (i.e. soft, medium, and hard substrates) and environmental conditions (i.e. depth, salinity, temperature, turbidity). A dedicated effort to gather acoustic seabed classifications across the Mackenzie Estuary would also improve the propagation models' seabed reflections and absorptions. Additionally, range-dependent cumulative measurements would be valuable in future studies to evaluate the breadth and severity of depth sounders that is more comparable to existing noise exposure studies (Theobald et al. 2009; Hastie et al. 2019). There were limitations to the noise exposure measurements (i.e. RMS SPL) as we did not record the depth sounder emitting at set distance intervals while stationary for a standardized time period. All cumulative measurements were done when the depth sounder continuously traveled further away from the receiver (i.e. 0 m to >200 m), however this was ambiguous for exposure measurements as we observed increased temporal smearing in the waveforms of the sonar pings as the horizontal distance increased, transforming into a non-impulsive signal. A few studies have highlighted the need for range-dependent assessments that look at both peak pressures and RMS pressures (Hastie et al. 2019; Darias-O'Hara et al. 2025), catering to noise that exists in the grey zone of source characterization. For impulsive sound sources, peak pressures are relevant at close-range while

RMS may be appropriate for further distances where temporal smearing takes effect as the signal changes propagation characteristics.

Implications on beluga hearing and behavior

The propagation measurements and models were conducted to ultimately inform beluga whale noise mitigation in the TN MPA. Received levels of the 77 kHz, 83 kHz and 200 kHz depth sounders within the beluga hearing range bandwidth were found to be theoretically detected by beluga within 220 m at 4m depth, and 500 m at 10 m depth. Peak received levels of the depth sounder never approached levels of physiological damage such as permanent hearing shifts as defined under level A harassment (i.e. $L_{p, 0-pk, flat}$ 230 dB for impulsive sounds) (NMFS 2024). NMFS defines level B harassment as “acts that have the potential to disturb (but not injure) a marine mammal or marine mammal stock in the wild by disrupting behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering”. Despite the $L_{p, rms}$ not exceeding the 160 dB re 1 μ Pa impulsive threshold for behavioral disturbance under NMFS, broadband noise levels (SPL) did exceed the 120 dB re 1 μ Pa non-impulsive threshold for behavioral disturbance. With reference to UK thresholds, the $L_{p, rms}$ of some tests does exceed the low-level disturbance threshold of 140 dB (Sinclair et al. 2023). This could be argued that consumer grade sonars be treated as continuous sounds given the rapid ping rate, and absence of noise free periods during exposure, unlike that of pile driving or military sonars (Bailey et al. 2010; Martin et al. 2020). Peaks in amplitude caused by the 83 kHz and 200 kHz sonars increased the noise spectra from ambient levels by 50 dB and 32 dB respectively, in the 79 kHz band (Figure 5). Elevated noise bands overlapped with known sensitive beluga hearing range, where belugas have exhibited the lowest hearing threshold (60.7 dB for 80 kHz)

(Mooney et al. 2018b). Sound intensity of the 83 kHz and 200 kHz sonars far exceeded the lowest hearing threshold by 69.7 dB and 51.3 dB respectively at close ranges.

Within the study area, there have been multiple observations of beluga exhibiting variable behaviors (i.e. ranging from no response to fleeing and aggression) to emitting depth sounders by seasoned beluga harvesters (see Chapter 3). We know beluga can hear the depth sounder and any excess noise within the 16 kHz – 100 kHz bandwidth could elicit a response (Castellote et al. 2014; Mooney et al. 2018b). Beluga hearing sensitivities also vary from location to location as they often parallel ambient levels of their environment (Mooney et al. 2018a). This means a universal behavioral threshold shared amongst species does not adequately inform us if an individual's behavior will be affected and what short-term and long-term consequences may pursue. Beluga are known to have some of the most sensitive hearing and can hear vessels in deep waters up to 50 km away during ice-cover and even longer during open-water season, due to the absence of sea ice surface interactions by acoustic waves (Schack and Haapaniemi 2017). Beluga hearing sensitivities have been found to vary depending on everyday ambient noise, in which the most sensitive hearing thresholds correspond with quieter soundscapes (Mooney et al. 2018a).

Behavioral disturbance thresholds set by NMFS holds limited empirical validity, with more focus on TTS and PTS thresholds (Darias-O'Hara et al. 2025). The few behavioral studies that are used to inform behavioral thresholds were conducted in deeper environments, with one contributing beluga study that was conducted on the Cook Inlet stock in response to pile driving activity (Kendall and Cornick 2016; Southall 2021). The few beluga whale studies are primarily used for informing TTS (Popov et al. 2014). There is a lack of research done on beluga behavioral disturbance thresholds in free-ranging populations. Southall et al. (2021) attempted to

use a severity score whereby behavioral responses to noise are grouped as they relate to the individual's survival, reproduction, and foraging. However, this approach has been criticized for not being specific to species or environment and unsupported correlation between fitness and immediate severity of a response (i.e., many 'severe' behavioral responses are short-term reactions and may not have any long-term effects) (Tougaard et al. 2015).

The novelty of a noise source within an environment should also be considered in our context, as reduced habituation likelihood has been incorporated into impact thresholds for Antarctic marine mammal species where anthropogenic noise has historically been low or absent (Darias-O'Hara et al. 2025b), and a similar rationale could be applied to Arctic species. This is a possibility in this scenario as depth sounders have only become more present within the TN MPA the past couple years (see Chapter 3), which may justify a more conservative threshold or a larger buffer zone being incorporated.

Finally, additional exploration into the acoustic properties of habitats with high beluga concentrations may be warranted. A previous habitat study found beluga preferred shallow sandy shoals within Kugmallit Bay, and coincidentally the hardest bottom type in the estuary (Whalen et al. 2019). We saw this bottom type reflecting more of the sound waves, resulting in longer propagation distances. The highly reflective bottom type could attribute to longer communication ranges between conspecifics, specifically advantageous for mother and calf pairs which are prevalent in the Estuary (Harwood et al. 2014; Vergara and Mikus 2019; Vergara et al. 2021).

Conclusion

To our knowledge, this is the first propagation study assessing depth sounders in a shallow Arctic estuary. Although we did not measure to the direct response of belugas in this chapter, peak and continuous noise measurements and detectability thresholds can inform future noise impact assessments. This is an important first step into investigating the impacts of depth sounders in a unique and dynamic environment that holds cultural and ecological significance in the Western Canadian Arctic. Given the impulsive and continuous characteristics of depth sounders, we found it important to consider both measurements when assessing its spatial and temporal presence. Additionally, we found turbidity to be a significant driver of sound absorption, and worth continued consideration in further noise exposure studies in this region. Although the signal intensities were not sufficient to cause physiological effects, we found that depth sounders emit noise that beluga whales can perceive and that may elicit behavioral responses at close ranges. Understanding the physical properties of depth sounder signals and how they propagate will lend a basis for investigating their presence within beluga whale habitats of the Mackenzie Estuary.

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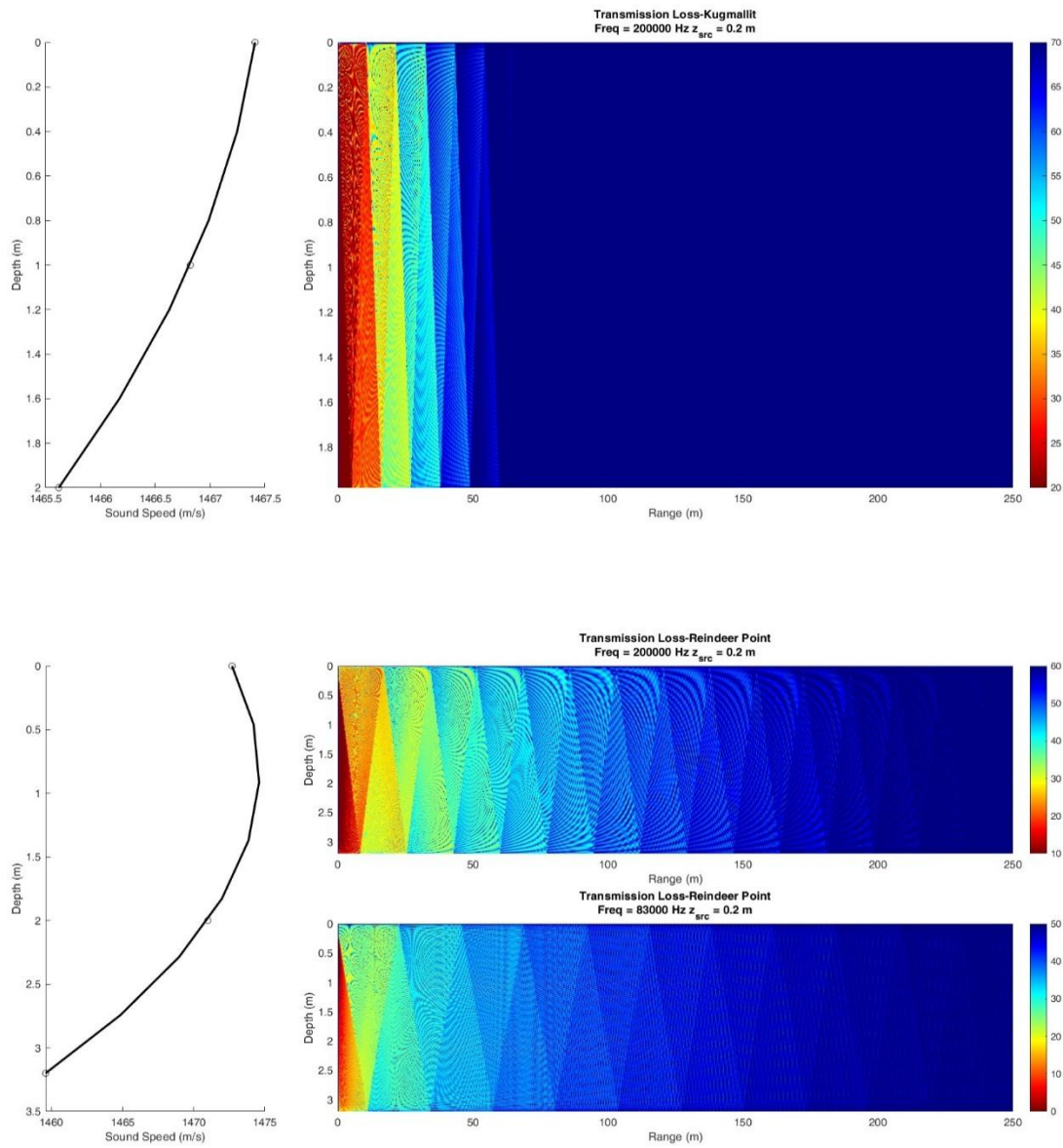
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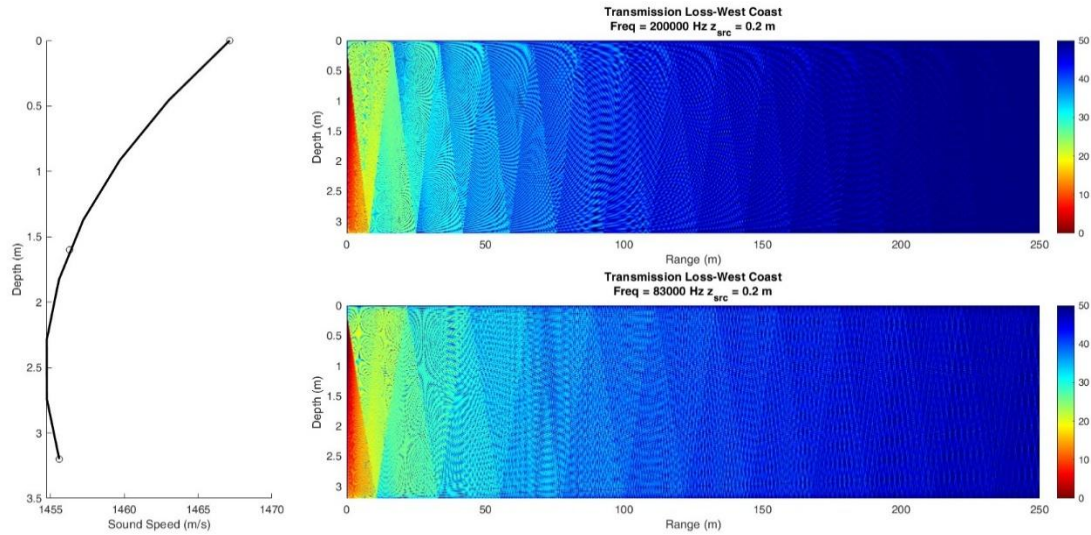
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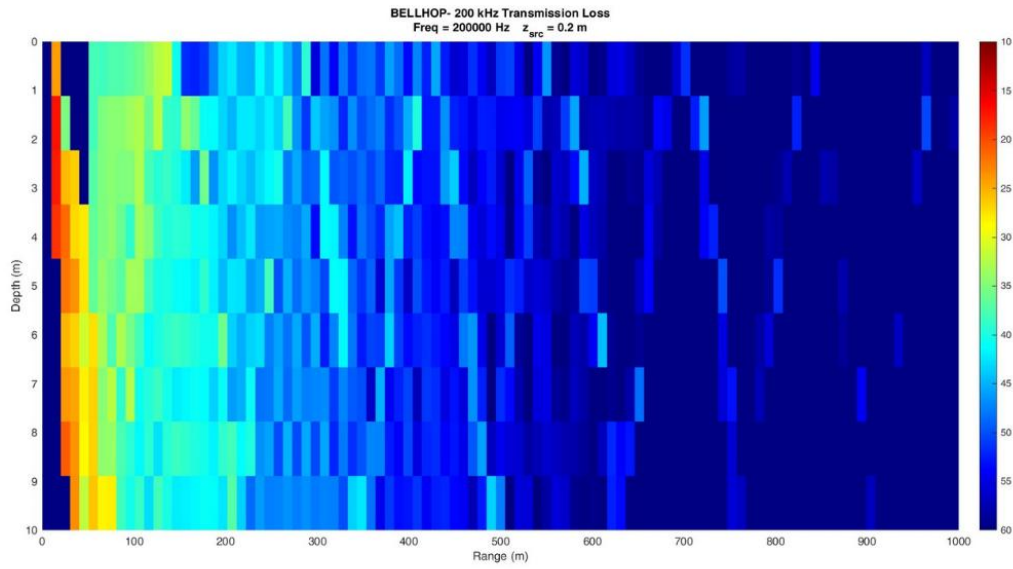
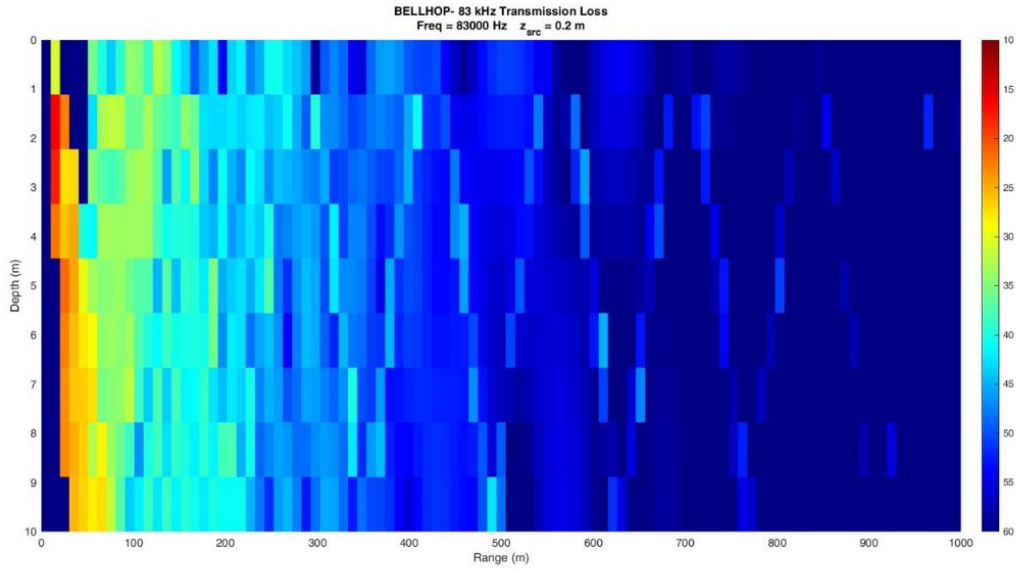
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Supplementary Figures





S2.1. BELLHOP transmission loss models with sound speed profile across different bottom types from soft to hard substrate: (top) clay/silt, (middle) silt/sand, and (bottom) sand. Note the differences in color bar scales. Reindeer Point also exhibited a slight stratification with warm freshwater sitting on top of cooler saltier water.



S2.2. BELLHOP transmission loss models in 10 m depth for the (top) 83 kHz and (bottom) 200 kHz.

**Chapter Three: Local Perspectives on Beluga Behaviour and Depth Sounder Use in the
Tarium Niryutait Marine Protected Area: Informing Place-Based Management Through
Qualitative Interviews**

Abstract

The Tarium Niryutait Marine Protected Area (TN MPA) in the Mackenzie Estuary serves as an important summer habitat for the Eastern Beaufort Sea (EBS) beluga whales (*Delphinapterus leucas*) co-managed by Inuvialuit and the Government of Canada. Recently, co-management partners initiated a project using consumer-grade sonars (depth sounders) to provide detailed bathymetric maps of highly transited and traditional harvesting areas. This community-led initiative promotes harvester safety which is critical given the region's high erosion rates and rapidly changing bathymetry. While sonars have become more common within the community in recent years, uncertainties remain regarding its impacts on beluga whales. To explore the use of sonar technology and how it may affect belugas, we interviewed 10 Tuktoyaktuk residents who are beluga harvesters and depth sounder users. This study was part of a larger beluga acoustic study monitoring and modeling sound propagation that was designed and implemented in collaboration with the Tuktoyaktuk Hunters and Trappers Committee (THTC). Interview transcripts were analyzed in NVivo qualitative analysis software for key themes. Interviews revealed insight on participants' sonar use, their perspectives on the technology, and their knowledge and observation of beluga behavior. Results revealed that beluga responses to depth sounders are context-dependent and influenced by intrinsic and extrinsic factors, while also shaped by participants' own ontological perspectives. Findings highlighted the importance of Inuvialuit knowledge to interpret ecological implications of sonar technology to develop noise

mitigation strategies beyond acoustic disturbance thresholds. Results will compliment related noise propagation modeling experiments and inform recommendations for safe sonar use within the TN MPA.

Introduction

Inuvialuit, the Inuit of Canada's western Arctic, possess extensive environmental knowledge accumulated through first-hand experience on-the-land and intergenerational knowledge transfer (IRC 2013; Fawcett et al. 2018; Ovitz et al. 2023). This place-based knowledge, referred to in the region as *Inuvialuit Knowledge* (IK), has enabled residents to thrive in an extreme environment (Nuligak 1966). This knowledge informs Inuvialuit governance systems who prioritize environmental stewardship to promote community health and support subsistence harvest (IFA 1984). As a result, leaders have voiced concerns about increasing underwater noise pollution in the Canadian Arctic and its potential ecological impacts on harvested species, drawing on first-hand observations and lived experience (ITK 2016; IRC 2020, 2022).

Despite Inuvialuit's extensive environmental knowledge, it's seldomly applied within underwater noise regulatory frameworks or published acoustic literature (Carter et al. 2018; Kochanowicz et al. 2021; Halliday et al. 2022). At the same time, there is a growing recognition of the limits of acoustic thresholds in underwater noise management (Gomez et al. 2016; Wright & Moors-Murphy 2022) and increased interest in incorporating Indigenous knowledge for a comprehensive investigation on noise impacts (Kochanowicz et al. 2021; Yua et al. 2022). Incorporating IK is reflected in Canada's Ocean Noise Strategy as a tool to enhance effective management strategies (DFO 2024). Additionally, in 2023, the International Maritime Organization (IMO), following advocacy from the Inuit Circumpolar Council, issued recommendations to Arctic shipping operators to adopt mitigation guidelines informed by

Indigenous knowledge (IMO 2023). However, these recommendations are entirely voluntary, and lack enforcement, severely limiting the outcome of these initiatives.

Underwater noise concerns are especially important when considering beluga whales (*Delphinapterus leucas* or qilalugaq in Inuvialuktun), a species central to Inuvialuit culture and subsistence. For centuries, Inuvialuit have harvested beluga whales from the Eastern Beaufort Sea (EBS) population as an important food source contributing to food security and cultural continuity (Nuligak 1966; McGhee 1974; Friesen 2004; Friesen and Arnold 1995; Byers and Roberts 1995; FJMC 2024; Hoover et al. 2016). Today, the communities surrounding the Mackenzie Delta (Aklavik, Inuvik, and Tuktoyaktuk) continue to harvest beluga whales between the months of June-August, primarily in the waters of the Tarniur Nirvutait Marine Protected Area (TN MPA) established in 2010 (DFO 2013).

Since the signing of the Inuvialuit Final Agreement in 1984 (IFA 1984), marine resources within the Inuvialuit Settlement Region (ISR) have been co-managed by Inuvialuit and the Government of Canada. This cooperative arrangement brings together local knowledge holders, western scientists, and government officials to implement beluga research, conservation, and management to ensure the health of the EBS beluga population (FJMC 2024). Given increasing anthropogenic activity in the region, one area of emerging concern is underwater anthropogenic noise related to shipping, development, and other activities (Dawson et al. 2018; Loseto et al. 2018; Halliday et al. 2019; Martin et al. 2023). Since 2011, a passive acoustic monitoring program has been underway in the TN MPA to characterize the soundscape and investigate beluga presence and behaviour acoustically (Simard et al. 2014; Scharffenberg et al. 2025). This program, which leverages Inuvialuit knowledge and western science, has recently expanded to include investigation into the impacts of consumer-grade depth sounders on belugas.

Within the ISR, sounds from consumer-grade depth sounders have become more common in recent years as technology has become widely available and adopted (DFO 2022). These devices, often mounted to personal motorized watercrafts used for transit and harvesting, aid boaters in navigating the highly turbid and often shifting channels of the Mackenzie River and coastal waters of the Mackenzie Delta (Rood et al. 2016; Trishchenko et al. 2021). The use of these devices is becoming increasingly important under rapidly changing environmental conditions brought on by climate change (Nielsen et al. 2022; Whalen et al. 2022; Ovitz et al. 2023). For example, the coastal erosion rates in the TN MPA are among the highest in the world, with the most well-known being in the Kittigaryuit parcel, just west of Tuktoyaktuk (Lee et al. 2025). This is further exacerbated by increasingly severe and unpredictable weather, rising air temperatures, and melting permafrost along the coast. These conditions, which further elevate the turbidity of the sediment-rich Mackenzie (Carmack & Macdonald 2002), render boat operators virtually blind to changing water depths.

Under unprecedented rates of change, word of mouth and long-held traditional knowledge about river channels may no longer provide safe passage, requiring reliance on depth sounders for navigation. Considering these navigational challenges and outdated bathymetric data, the communities of Aklavik, Inuvik, and Tuktoyaktuk launched bathymetric mapping projects using consumer-grade depth sounders to map the Mackenzie River and coastal seafloor in commonly used transit and harvesting areas (Figure 1). Some residents have raised concerns about how depth-sounders may impact the environment, and most specifically, beluga whales that inhabit ISR waters during the summer months (Richard et al. 2001; Storrie et al. 2023). Because the area is only accessible to personal watercrafts in the open-water season (typically June-September), bathymetry studies and peak watercraft use coincide with peak beluga presence (Scharffenberg et

al. 2025). Notably, boat operators have reported observing multiple instances of beluga avoidance behaviour in the presence of an active sonar, yielding questions and concerns among community members.

Depth sounders emit an impulsive sonar ping in the form of a sound wave that reveals the depth and features of the sea floor beneath the boat (Lowrance 2025). These pings are continuous and range in frequency bandwidths depending on the user's specifications. The depth sounders used in the community bathymetry project typically emit pulses at two different frequency ranges simultaneously. The side scanner emits a 600 kHz pulse and is designed to record bottom roughness that is linked to a substrate type while the depth sounder (aka fish finder), emits at 200 kHz and 83 kHz. Scientific research on beluga hearing suggests that the 600 kHz side scanner is likely well outside the hearing capabilities of belugas, however, the 200 and 83 kHz depth sounders emit broadband signals, (meaning they cover a much wider frequency spectrum) with much of their energy within the sensitive hearing range of a beluga (1.2 kHz – 120 kHz) (Mooney et al., 2018b). This underscores the importance of these broadband signals as a key focus of investigation.

In this study, we explored observations and perceptions of Tuktoyaktuk harvesters who use depth sounders on their boats through semi-structured interviews. Participants were asked questions relating to study participants' first-hand experiences with depth sounders around beluga whale habitats, including observations of normal and abnormal beluga behaviours, and their present understanding of beluga hearing capabilities. The qualitative data collected in this study will be used in tandem with quantitative propagation models (detailed in a future publication) to inform recommendations for safe sonar use.

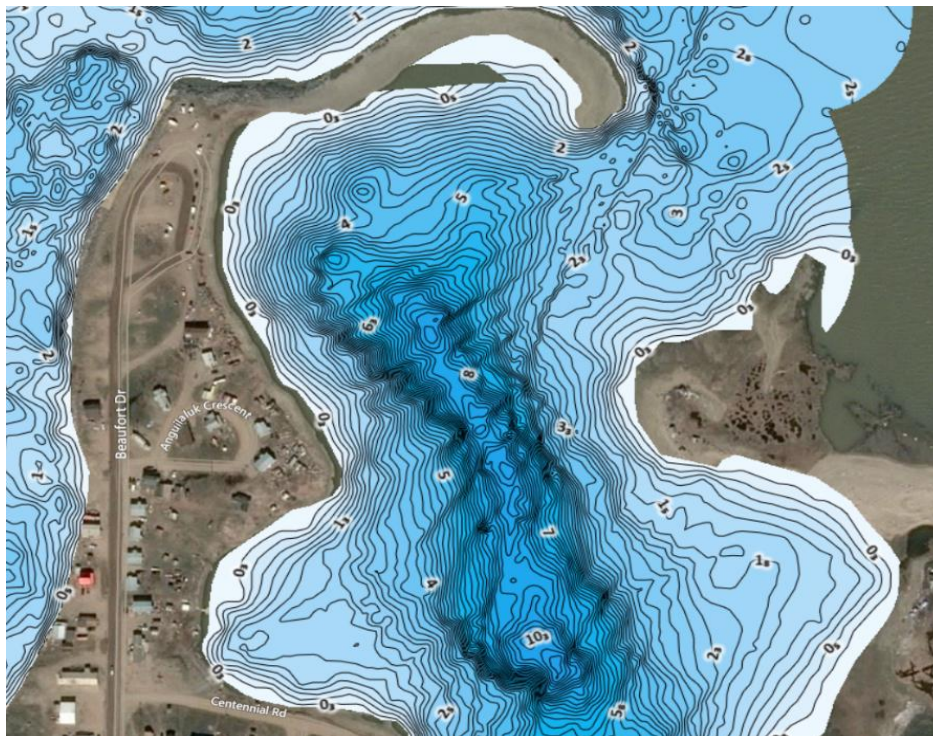


Figure 3.1. Lowrance device functioning with depth sounder and map trails on James Keevik's boat in 2025 (top). Public domain bathymetry data published on C-Map Genesis collected in

Tuktoyaktuk harbor by community boaters showing depth in meters and contour lines (bottom) (DFO 2022).

Methods

This study reflects a partnership between the Tuktoyaktuk Bathymetry Program and the Beluga Habitat Monitoring Program which aims to investigate the environmental impacts of depth sounders as an emerging technology. Research design and implementation was guided by the THTC and the project was led by an interdisciplinary team including THTC board members, government and university researchers, and a master's student specializing in marine acoustics. Interviews complimented quantitative acoustic data by capturing participants' experiences, voices, and observations to inform regional co-management.

Study area

The Inuvialuit Settlement Region, one of the four Inuit Nunangat regions in Canada, spans the Western Canadian Arctic, including the Beaufort Sea (Canadian Geographic n.d) (Figure 2). The TN MPA is located within the coastal regions of the Eastern Beaufort Sea and includes three parcels (i.e., Niaqunnaq, Okeevik, and Kittigaryuit) spanning the eastern Yukon and into the Northwest Territories (FJMC 2024). Tuktoyaktuk (population 1,026), one of six ISR communities, lies on the southeastern coast of Kugmallit Bay, about 17 km east of the Kittigaryuit parcel (GNWT 2025). Coastal waters surrounding the community harbor are influenced by sediment plumes from Mackenzie River outflows driven by westerly winds (Carmack & Macdonald 2002; Lee et al. 2024) (Figure 3). The Beaufort Delta is home to harvesting camps that are accessible from the community either by snowmobile, boat, vehicle (via the Dempster Highway) or ATV (Canadian Geographic n.d).

Project design and approvals

The lead author facilitated communications with the THTC regarding project design and implementation. The initial project proposal and data management protocol were reviewed with the THTC board in February 2025, with updated versions reviewed and approved by the board in March 2025 (see Supplementary Material). Following this, a comprehensive interview protocol was reviewed and approved by the University of Manitoba Human Research Ethics and later, by the Government of Northwest Territories (Licence No. 17732). Routine communications with the THTC board and staff occurred throughout the duration of the project.

Interview design and implementation

THTC staff assisted with participant recruitment and provided a list of individuals that fit the recruitment criteria (i.e., residents with experience using depth sounders in Kugmallit Bay) to inquire about participating. We also employed snowball sampling strategies (Noy 2008) wherein a participant recommended additional residents that fit the criteria to contact. Ultimately, ten beluga harvesters residing in Tuktoyaktuk were interviewed (including three Elders, six adults, and one youth). An Elder is defined as an older member of the community that possesses, preserves, and passes on Inuvialuit Knowledge and culture. Interviews took place between June 27 – July 13, 2025. At the time of the study, boat operations were almost exclusively performed by men, thus no women were interviewed.

Interviews were semi-structured and facilitated by the lead author. Questions were developed in advance and reviewed and approved by the THTC board of directors (see Supplementary Material). Given the semi-structured nature of the interviews, the conversation sometimes deviated to explore additional questions and topics of interest to the participant. The key objectives of the interviews were to: 1) understand the current usage of depth sounders by

Tuktoyaktuk residents (e.g., rate, frequency, standard practices) 2) explore Tuktoyaktuk residents' knowledge and observations of beluga behaviour relating to depth sounder use (e.g., behaviours regarded as normal versus abnormal and potentially indicative of disturbance), and 3) document participants' concerns relating to the use of this technology and their perspectives on best practices for future depth sounder use.

Prior to each interview, consent forms were reviewed and signed by the participant with their preferences for attribution, verification, and data storage recorded. Interview length ranged from 11 to 40 minutes and audio recorded for accurate transcription and data analysis. Interviews were conducted in private settings that were convenient and comfortable for the interviewees (e.g., THTC office and out on the land) and pre-scheduled to not disrupt harvesting practices. Interviewees were compensated for their time in line with standard rates set by the THTC.

Transcript analysis and results sharing

Audio recordings were transcribed using Otter.ai (University of Manitoba ethics approved transcription application) and verified. Participants that requested to stay anonymous were assigned a coded identifier within their transcript. Transcripts were lightly edited to improve clarity and flow to keep vernacular and vocal nuances of participants, including traditional Inuvialuktun terms. Participants had the option to review and verify their transcripts prior to analysis to ensure their involvement in the hermeneutic circle of research interpretation and reinforcing rigour (Hay and Cope 2021).

Transcripts were analyzed using NVivo Qualitative Data Analysis Software (Lumivero, version 15.2). The initial round of coding identified analytical and descriptive codes to highlight reoccurring themes, drawing from manifest (quantified certain phrases or words) and latent (pre-

determined themes) content analysis (Hay and Cope 2021). Codes were refined during a second coding round and organized into thematic tables to compare interviews and summarize findings, following Ovitz et al. (2023).

To evaluate how individual perceptions were formed, participants' perceptions of sonar were subcategorized as knowledge, opinion, or observation based upon the framing of each statement. Statements were classified as knowledge-based when participants explicitly referenced knowledge (e.g., used the term "know"), presented information as factual, described knowledge passed down from others, or indicated a lack of knowledge regarding sonar or its effects on beluga. Statements were classified as opinion-based when participants framed their responses using subjective language (e.g., "I think"), indicating personal belief rather than fact. Statements were classified as observation-based when they were grounded in firsthand experiences, particularly those describing direct encounters with sonar. Participants' perceptions of sonar were also subcategorized under positive, negative, or needed more information. When referring to attributes and opinions of the depth sounder, certain language used to classify phrases included "I like", "I don't like", "I don't know", and other phrases that reflected personal feeling. Preliminary results were presented to the THTC in November 2025 for feedback. A digital copy of the presentation and final draft of this report was shared amongst participants and THTC board of directors to review and provide feedback prior to publication.

Below, interview results are presented by topic, first on our objectives, followed by additional topics that organically emerged during the interviews. Participants reported their use of consumer-grade marine electronics units equipped with integrated depth sounder (aka sonar) and GPS functions. In this manuscript we describe device operation as categorized: (1) *active sonar use* - in which the depth sounder and transducer were enabled and acoustic signals emitted, or (2)

GPS-only use - in which the depth sounder was disabled and the unit was used solely for navigation, mapping, and track logging. Note that participants often used the terms sonar and depth sounder interchangeably to refer to different functions and this language occasionally appears in quotes.

Any interview content beyond the scope of this study (i.e., feedback on specific programs) was omitted from this report but shared with the THTC and program leads as relevant. Participants are identified (by name or a confidential descriptor) as indicated on their consent form.

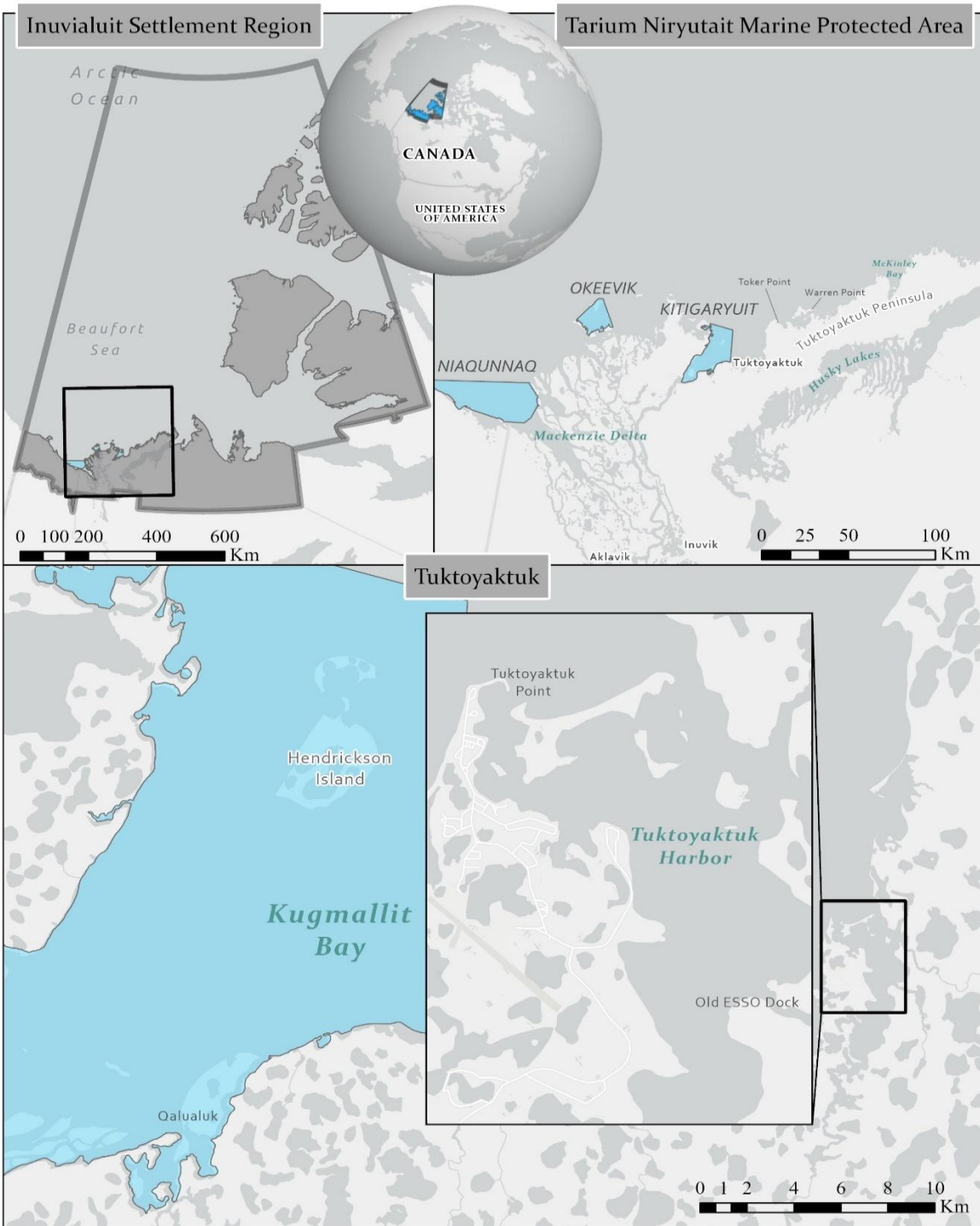


Figure 3.2. Map of the Inuvialuit Settlement Region (top left), Turiut Niryutait Marine Protected Area (top right), and the town of Tuktoyaktuk in Kugmallit Bay (bottom). Place names

described in the interviews were included for reference. Map created using ArcGIS® software (Esri Canada 2026) and geospatial data from the Government of Canada (2106a, 2016b, 2017)

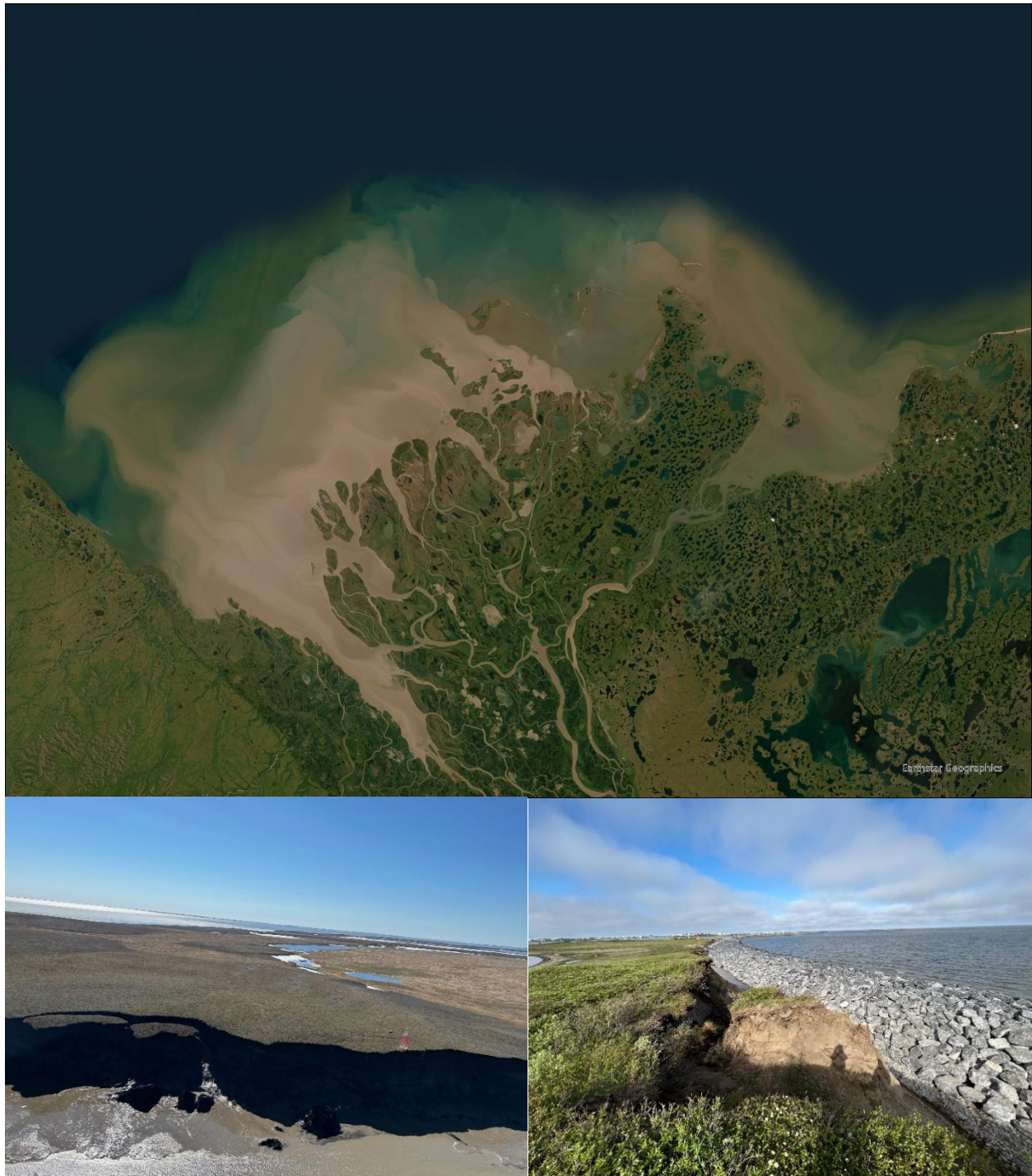


Figure 3.3. Satellite image showing the turbid Mackenzie River outflow into the Beaufort Sea (top). Source: Esri, Vantor, Earthstar Geographics, and the GIS User Community, accessed on February 18, 2025. Coastal erosion and slumping along Pelly Island, located in the Okeevik TN

MPA parcel in 2024 (bottom left) and land sloughing off Tuktoyaktuk Island, with the town visible in the distance in 2025 (bottom right).

Results

Depth sounder usage in Tuktoyaktuk

To understand the breadth of device utilization, participants were asked questions about their sonar usage and device specifications, including the device model, years of device use, and frequency of use (Table A2). All ten participants used Lowrance © depth sounder models on their boats purchased through the community-based bathymetry mapping program, with at least three participants owning more than one device. At the time of the interview, nine participants had the depth sounder installed while one participant had it installed in previous years. Four participants' depth sounders were not operational at the time of the interview (i.e., unplugged or the transducer unhooked) to prolong battery life or in anticipation of being replaced with a newer model. The duration of usage varied; six people had the device since the start of the program in 2022, and four for a longer timeframe (5 to 21 years) (Table A2).

With regards to frequency of depth sounder use (i.e., light, medium, or heavy use), seven participants identified as light or non-frequent users while the other three identified as heavy or frequent users (Table A3). A Tuktoyaktuk Elder, Chucky Gruben, explained that he primarily used the marine electronic unit's GPS and map feature, stating, "I don't use [a depth sounder] often, most of the time, I'll just use it for my direction, navigation, to see where I am... it's got a nice big map on it... so if I'm not working, it's sitting there like an ornament." In contrast, James Keevik, who identified as a frequent sonar user, said that he powers it on every time he uses his boat and has become accustomed to it and enjoys seeing what's beneath the boat. Most participants highlighted the rising popularity of the tool within the Tuktoyaktuk community ever since the start of the bathymetry program. Tuktoyaktuk Elder Jim Elias further elaborated on this:

“In the last eight years, it's pretty widespread now. (...) It's a very good tool to use. That way we don't get lost, or you don't have to get search and rescue or anything like that. So, we're promoting that. This is for our safety of our harvesters and we know where [they're] going out, and if they're using this technology, the person will eventually come back home.”

All participants emphasized the reliability and safety this technology provides harvesters, when navigating shallow waterways, dense fog, darkness, or in unfamiliar areas. James emphasizes this and even mounted a sonar on his 19 year old son's boat for his safety. He recognizes these benefits, reflecting:

“you're traveling at night, [a sonar] can't stop you from hitting a log you can't see, but it shows you a route you've been on, the waters depth, that you know you're in safe waters every time you're following a track. So that's the comfort of that, it gives you the opportunity to travel through fog or darkness, it just boosts up the comfort of the captain because it's a tool he needs.”

While some participants rely heavily on their depth sounder, others only turn it on in unfamiliar areas. For example, Chucky noted, “I don't put it on in the [Tuktoyaktuk] Harbor here. I travel North of here, to McKinley Bay area, as soon as I get into the deeper water, or maybe 30 miles out North, I'll put it on.” John Noksana echoed this sentiment: “...that's the only time [I use it], really, is when I'm not too sure or haven't been there before, I turn my sonar on so I don't bottom out.”

In addition to using the marine electronic unit for navigation and safety in transit, some participants identified using their device while subsistence harvesting, and while working or supporting research endeavors, including bathymetry mapping and wildlife tagging (Table A3). Notably, these activities were either active sonar use or GPS-only use (i.e., for recording or following previously recorded travel routes). With the conversational interview approach, participants were not uniformly asked about sonar use during harvesting, though the topic arose naturally in some interviews. (Table A3). Davy Krengnektak explained that Tuktoyaktuk harvesters know the depths and shallow spots of the beluga harvesting area in Kugmallit Bay through traditional knowledge and upbringing, thus active sonar is not necessarily needed in harvesting areas. However, Davy said that he may not bother to turn off the transducer when coming across a whale if he is prioritizing the tracking and harvesting of the whale.

Lastly, to gauge the potential confounding effect of motor noise on beluga behaviour, participants were asked about specific contexts within which active sonar was used, particularly if they ever use it while the motor is idling or motor is off. Five participants reported using sonar while the motor was off or idling, while the other participants would turn everything off. Some participants expressed that whether they left the sonar on or off was often situational, depending on factors such as battery life, the amount of time idling, and whether the activity required sonar.

Knowledge and observations of beluga behaviour

A key objective was to document participants' knowledge and observations of beluga behaviour to define normal (undisturbed) and abnormal (disturbed) behaviours. "Normal" behaviours were defined to be exhibited by beluga under natural circumstances, absent of anthropogenic disturbance, while "abnormal" behaviours were observable responses to anthropogenic activity or influences. All participants self-identified as beluga harvesters with extensive experience

observing belugas from land and boat while harvesting, traveling to and from camps, working, and participating in research. Observations were limited to the open-water season (June – September) when belugas are present in Kugmallit Bay. Seven participants reported encountering beluga most, if not all, of the time while on the water, and all had encountered beluga at some point, most commonly from Hendrickson Island or traveling to harvesting sites. Examples of normal, undisturbed beluga behaviour included directional travel by individuals or groups, floating at the surface without directionality, feeding on fish, spyhopping (where a beluga is positioned vertically in the water column with its head above the water's surface), rubbing in shallow and rocky areas, mothers nursing calves, playing between conspecifics, and resting (in bays or Tuktoyaktuk Harbor). According to Elder Charles Pokiak, belugas behave normally when, “They're just all together in a pod, traveling. Some are resting in bays, across Hendrickson [and] *Qalualuk*.” Conversely, Jim described how a beluga's normal behaviour is variable when he observes them from Hendrickson Island, saying, “Every year you see something a little bit different. Like last year, the whales were right near the shore, just bobbing up like buoys and putting on a show because they're looking at us” (see example in Figure 4). He frequently observed belugas in diverse water conditions including calm and rough waters. In contrast, examples of abnormal or disturbed behaviour included fleeing (i.e., swimming away), increasing swimming speed, diving and sinking below the boat, diving towards deeper waters, charging the boat (aggressive behaviour), and altering their travel path. For example, Charles recalled observing aggressive behaviour from a male beluga that charged his boat: “That one bit my fin, you know, that hydrofoil, he bit a piece of it off. Pissed off. It could get really aggressive, those males.”

Participants reported a shift in beluga behaviour to avoid approaching boats depending on the type, intensity, and patterns of the approaching noise with at least four participants noting that beluga distinguish between harvesting and non-harvesting boats (e.g., traveling or observing). This was not a prompted question in the interview, yet there were shared experiences with this belief. Most described getting in proximity to belugas while just observing in a non-hunting context, with beluga appearing curious by approaching the boat if the engine and sonar is turned off. Charles described this behavior: “When you're after them, they know too. You're not after them, they're tame as ever. Yeah, they'll come right up just like caribou. When you're not hunting them, you come right up to them. And they sense it.” Similarly, Jim noted that beluga often traveled alongside passing boats without disturbance when harvesting was not occurring. Chucky echoed similar experiences, noting that beluga remained near loud generators because they know they aren't being hunted. Charles believed the pattern of the boat noise triggers an avoidance response, an indicator of active harvesting, by saying, “Just like [beluga] whale, when you're after them, they'll know. They know the difference. You picture the engine just from the noise when you're speeding up and stopping.” He went on to report observing beluga reacting to passing aircrafts by diving into deeper waters, even with calves, and noted that the THTC will contact airlines to mitigate further noise disturbances. John described how a whale's behaviour instantly changes once being pursued, stating, “They know we're after them. When you start chasing them, the smart ones, they'll just stop and drop to the bottom and let you drive around like this (circling motions with finger).”

Participant accounts suggest that individual characteristics (e.g., age, experience, sex) may play a role in how belugas respond to disturbance stimuli, for example, larger males may react more aggressively towards a pursuing boat. Additionally, participants interpreted some behaviors

observed during harvesting as learned behaviours from previous pursuits. Participants commonly reported that older belugas previously pursued by harvesters develop learned evasive behaviours, such as sinking below boats to avoid harpooning and waiting for harvesters to leave before swimming away. James Jr., a youth in the community, elaborated on this learned behavior and recalled, “When they've been disturbed, they're pretty smart and they kind of know how to escape the trouble.” In contrast, young beluga who have not been pursued have not learned these evasion maneuvers and can be less cautious around boat noises and thus more easily approached. Additionally, harvesters reported changes in beluga behaviour over the course of the hunting season. James elaborated on this, “At the start of the years... If you're one of the first ones to the island [Hendrickson], and you're commuting to go to a harvest, the whales don't even know you're gonna harvest.” Jim echoed similar observations of beluga becoming more cautious as the season progresses:

“When you look at pods, some pods are more inclined to be right there, and then some of them are street smart, basically. When they go out harvesting a whale, we'll know which whales was already followed because [of] the way they react. When they first come up here, and ones that's not bothered by the harvester, you could follow them very easily and harpoon them. But the ones that's been followed before, they'll attempt to turn around every time the boat gets close to them.”

Interpretations of beluga hearing sensitivities

Our third objective was to explore participants understanding and interpretations of beluga auditory sensitivity and potential disturbance thresholds. Participants recounted a range of

observations, resulting in different perceptions and opinions across hunting and non-hunting contexts. Five participants described belugas as having sensitive hearing, with two of them emphasizing that virtually any noise could cause disturbance. For example, Chucky articulated that beluga will rapidly flee from the boat motor and added that “any sound, even before they see you, they’re gonna be gone. Any kind of noise, it disturbs the beluga.” He further detailed his experience with belugas fleeing just from the sound of him walking on gravel along the shoreline: “My cousins got a cabin [...] and there’s about a 10-foot-deep channel right offshore there [...] and they’re just hanging around close to the edge. But they can hear us walking along the gravel and they all take off.”

Three participants believed beluga hearing sensitivity depended on the situational contexts. For example, one sonar user explained how environmental parameters influence how far sound will travel. He stated, “It depends on where you see them. The depth of the water has stuff to do with it, the wave action, all that plays a part, right? It’s like yelling in the wind, it can only go so far.” Similarly, Jim highlighted how belugas react differently, even curious depending on the noise: “I know back in the day, we could go out there, shut off our motors and that, and then you bang your boat up with a paddle, and then they’d [belugas] come. They’re curious... So it depends on what kind of noise you’re talking about.”

In contrast, two participants citing their regular encounters with beluga pods believed beluga hearing may be less sensitive, or they could become behaviourally habituated to noise. For instance, a Tuktoyaktuk harvester detailed observing beluga frequently around loud generators in Tuktoyaktuk Harbor: “Couple years ago, I was working at the ESSO [barge] and had the generators on. You know, they’re loud. They come right up to the barge. It doesn’t bother [them]. They even grab fish over there, right beside the barge.” James detailed similar experiences in the

harbor, "...we've seen whales in October, and they're sticking around in the back bay there where the industry has some big tugs. They're taxing barges around during the day and they're not running away from that area."

Participants repeatedly described belugas inhabiting Tuktoyaktuk Harbor despite large vessels and personal watercrafts regularly entering the area. Participants described a resident beluga frequently seen near boats and generators within the harbor, apparently unbothered by human activity. John shared his encounters along with stories he's heard of this beluga: "Yeah, he's usually there, July right until August somewhere. You know, he'll enjoy the NT [NTCL] dock and the old ESSO dock. The people who would work on the ESSO stayed on the ship; they'd see [that same whale] everyday swimming by." James shared a similar encounter he had with a beluga sleeping by the barge, however it was unclear if it was the same lone beluga that John talked about. He said, "They are so used to those barges by now, they just sleep next to them. (...) Because one time I thought that was a white tarp in the water, and I was going by the barge and it was a sleeping whale!" Some participants suggested this tolerance is context-dependant while two participants theorized that the abundance of fish and deeper water (less suitable for beluga harvesting) may explain why beluga choose to remain near boats and people. "The risk must be worth the reward" John said.

Participants also underlined how Inuvialuit harvesters have always recognized anthropogenic noise as a potential disturbance to beluga. To illustrate, Charles shared a historical account of when harvesters used to hunt whales from kayaks, emphasizing how silence was strictly enforced while harvesting to avoid alerting beluga (Figure 5):

"They used to hunt with kayak in Kittigaryuit Bay... They harvested a lot of whales there. When a young guy is joining the

hunt, it could be his first year, he had to be very quiet with his kayak and with his paddle, not to make any noise, no splashing, nothing. And if he made too much noise with his paddle, a splash, he's banned from hunting for a while, for a couple of years, really to, teach him a lesson. You're waiting for the whales to go in and to the shallower water where you could get them to drive them in with kayaks. Everybody's a team...Not [paddle] too fast [and] you stay behind until they get into the shallows. Then you're after them with your harpoons and spears. There were so much people that time. They counted over 200 kayaks.”

Despite observing tolerance towards boat noise in some contexts, several participants reported that boat motor noise commonly elicits avoidance behaviour. As Davy explained: “A sound like an outboard makes a lot of noise. I think soon as they hear that, they veer off. I've never encountered a beluga where it just stayed there by the boat.”

Beluga and depth sounder interactions

Next, we sought to document participants’ experiences using depth sounders around belugas and the behavioural responses they observed. There were multifaceted views among participants’ over whether beluga are disturbed by depth sounders, with a wide range of observations and opinions provided to corroborate their answers (Figure 6). Some participants confirmed seeing beluga reacting to the sonar, with one sonar user reported seeing this on many occasions while the motor was turned off, reporting “...the whales stayed away from the boat. (...) Not so much fleeing, but it’s not coming anywhere close to the boat.” Charles detailed an aggressive encounter when a beluga knocked his transducer off, sharing, “Last time I went out whaling, one

big male I got. (...) I left my sonar on and forgot to turn it off. Sometimes I do and that's the second time that happened. Then he knocked it [transducer] right off. After I harpooned it, it turned back around and charged the sonar.” He emphasizes that beluga will flee around Hendrickson Island from hearing the sonar on its own: “I know when you have it [sonar] on heading to the island, the whales get spooked right away. They sense the noise from it.” He also confirmed in these instances the beluga are reacting to the sonar and not the motor. One participant, however, described curious behaviour from beluga when the sonar was on and off, and suggested the response may be based on the individual rather than differences in sonar and motor noise.

Additionally, some participants reported the absence of belugas from areas where they are typically observed when multiple boats were conducting bathymetry transects, suggesting the whales were avoiding those locations. However, participants also expressed a degree of uncertainty regarding whale’s behaviour or presence noting that observations were often limited by reduced visibility in turbid waters (Figure 4). Chucky explained, “We can't actually see them till they come up versus the clear water, I can see them from a long way. So, when you're out here, you know, all the time you don't even know how many you're on because the water's so muddy. You can imagine how many there is by the waves because they're pushing the water.” They also noted that during harvesting, their focus on harpooning can make it difficult to recall specific behaviours.

Conversely, some participants never witnessed beluga react to sonar and believed beluga do not react to it. James Jr. explained how beluga react to the boat motor but never saw a difference in behaviour when the sonar was on vs. off. Other participants, such as Jim, were uncertain whether beluga responded to the sonar, or other factors like the motor noise, citing conflicting

observations over the years. Reflecting on seven years of using the sonar, Jim shared: “I sometimes just test it out. I turn it off and put it on. [One time] leaving the Tuktoyaktuk Harbor here, I didn't see a whale right off the [Tuktoyaktuk] Point, and all of a sudden this whale was just taking off. It could either be the sonar or it got jumped and got skittish and just took off. Because when I had this [sonar] on around in different areas, and I'm traveling, we'll see the whales.” He also voiced the need for more information on sonars before he could make an informed stance on the matter.

One sonar user observed more reactive behaviors from beluga to the motor than the sonar. He stated, “The motor is a lot louder than the sonar, so I don't think the sonar has as big an impact as the motor does. (...) I see far more disturbance with the noise of the motor in the water...” It was also emphasized by participants how difficult it can be to distinguish reactive behaviours to specific noise sources, whether it be from the motor, sonar, or other factors.

Among participants who had observed a reaction, estimates of the distance at which this could occur varied. Three participants claimed that belugas will come right up to the boat provided that the sonar and engine is turned off, with Chucky stating “The only time I'm able to get really [close], is when I'm drifting around with no motor on. Even if you hit the paddle on the water when it's quiet, they're gonna [fleeing motion with hands]. I think what they mostly do is flee away from the sound.” Four participants reported observing beluga within 200 m while sonar was on, whereas another said whales became “shy” at roughly 500 m during transit, and one could not estimate a distance. Participants acknowledged that distance estimates can be challenging in murky or rough waters, where white caps can be mistaken for beluga. Many participants also expressed that they do not regularly get close to beluga in non-hunting contexts to avoid scaring them or splitting up pods, especially mother-calf pairs. Jim emphasized the

importance of this within the community by stating, “We try our hardest not to harass our animals. If we aren't gonna harvest it, look at them and be on our merry way.”

Participants also reflected on the on-going bathymetry surveys, which involves multiple boats emitting sonar near one another (see Figure 7). John described a typical bathymetry survey: “Three hours a day, three days, five boats, and we're [spaced apart] 100 - 115 yards. (...) [We are] idling up to 12 knots or seven miles an hour. Everybody goes the same speed, and we just reach, and we turn around. We all traveled in a straight line, pretty slow.” Four participants noted that they had never seen a beluga while conducting these surveys, which one participant noted as strange; however, it was acknowledged that surveyors are too occupied with the transects to watch out for beluga and so it's possible they were missed.

Similarly, Jim reported not encountering any whales near the Tuktoyaktuk Peninsula during a year when multiple sonars were active in deeper waters, despite the area being known for feeding aggregations. He goes on to theorize that depth changes may influence what noise beluga hear or respond to: “Maybe because of the sonars and the water, when you get farther away from Tuk, like from Warren Point going northeast, the water is very, very deep. And so maybe that sonar would travel a lot farther under deeper water.”

On the topic of context specific reactions, Jim and James acknowledged seeing belugas in the Tuktoyaktuk Peninsula area with sonars on in other years. James encountered beluga in this area swimming in the wash of their boats, even with the sonar on. He suggested that it being a non-traditional harvesting area is why the beluga don't react to the sonar here. He remarked: “They're going back into the same area after we go through, so they're not getting scared away. The area I'm talking about is from Toker Point to Warren Point. That's [an area] where they're really tame, like, nobody hunts them in that area, that's why. Not for a 100 or more years.” Drawing on his

past experience with a pinger program (a program designed to use acoustic pingers to deter beluga from entering narrow channels of the lakes) implemented in Husky Lakes (roughly 25 km southwest of Tuktoyaktuk) Jim noted that some beluga were sensitive to the pinger noise while others were unaffected. He highlighted pod variability by stating, “Maybe a certain type of whale are scared of that..., and some of them just didn't really care about the pingers and just kept on their merry way. I think there's some different reactions between the pods.”

Knowledge of noise effects on marine species

Although not a primary focus of the interviews, some participants discussed their thoughts and observations of noise impacts on other marine species such as seals, bowheads, and fish. This provided valuable insight to the complexity and severity of anthropogenic noise in the Arctic soundscape. The impact of sonars on bowhead whales was mentioned across interviews. Charles recalled first using sonars while tagging bowhead whales along the Tuktoyaktuk Peninsula starting in 2004 where he observed both beluga and bowhead reacting to the sonar while in the middle of a feeding aggregation near Toqa (Toker) Point. When he turned the sonar on, he recounted seeing bowheads become more ‘skittish’. James shared a similar account from bowhead whale tagging, and hypothesized it was due to the presence of vessel noise in a traditional harvesting area which the whales associated with hunting:

“I've even used my sonar when we were bowhead tagging to see the depth. It was around 50 to 100 feet of water. But we weren't recording, but they were still pinging noise to get to the bottom. The bowheads were hearing that. You can see them in advance [when] we would get to the reservoir... he [referring to another boat captain] knew about bowhead tagging. He'd done it before. He

said, turn your sonars off. They must be hearing that. So, we did that. I think they still ran a bit because they're hearing the motors. But that's what bowheads would usually do. They'd still turn from you because they're in the Arctic waters. They know they can be hunted here, because I think they're so smart anyway, bowheads. They know they're in harvesting waters when they're in the high Arctic.”

These observations with bowheads sparked advocacy for bowheads to be included in future noise investigations. Jim stated he heard conflicting accounts about the impacts of sonar on bowheads: “...and then with the sonar, it's telling us that it affects the toothed whale, but not the ones with the baleen. But we don't know that yet too. (...) We got two different stories there, so it would be good if they could do some research on the whale.” Participants also recommended further research on sonar and seals, noting they are more abundant during freeze-up and have been observed approaching boats when people bang on the hull, appearing curious and inquisitive. In addition to sonar, interviews also touched on other noise-emitting activities that may affect country foods and the broader environment. Chucky shared his father’s stories about seismic blasting (a method of terrain mapping and resource exploration which relies on loud low-frequency soundwaves; EPA 2026) in Husky Lakes, an ecologically and traditionally important area to Inuvialuit:

“You know this sonar stuff brings me back to seismic blasting. I always wonder how many fish and whales they killed, eh? Probably about 50 years ago, in the 60s, when they first started doing that, they were doing it on the Southeast of Husky Lake. My

dad was a young man. They used to blast. Fish that used to come up, far as you could see with your eyes, dead fish float to the top. That was just from one blast. There's nothing for us to fall back on to protect what resources we rely on for our food, for our life, for our culture.”

Although seismic blasting is no longer conducted in this area, the historical impacts on country food continue to inform and shape personal perspectives on the potential risks of anthropogenic noise, including sonar.

Perceptions of depth sounder use

Participants had mixed perceptions on depth sounders within the community. Every participant acknowledged the importance of sonar for safety, especially when navigating in low visibility, while negative views centered on the potential for noise disturbance. Overall, there were more positive perceptions of depth sounders, while negative and uncertain comments occurred in roughly equal proportions (Table A4). Participants perspectives on depth sounders were shaped primarily through knowledge and observation from being on the land and water, with a smaller proportion of statements being based solely on opinion (Table A5). Participants also ranked their concern about depth sounder impacts on belugas as low, medium, or high, relative to other threats, with responses evenly distributed and dominant perceptions aligned with rankings (e.g. those expressing more negative views corresponded to higher concern) (Figure 6).

Three participants expressed predominantly negative views and emphasized precautionary use, arguing to restrict depth sounder use to when it's necessary and avoid critical beluga habitat. On this matter, John shared, “I think we have a lot of understanding here that they're not good for marine life... The bottom line is, don't use it unless you really need it. Disrupting the marine life,

right, or anything for that matter. I mean, the boat is loud enough as it is.” Chucky was also concerned and advocated for restricting the use of sonars in beluga habitat zones: “I don't approve of sonars being used in this [Tuktoyaktuk] Harbor, anywhere beluga zones are. I don't support sonar in that way. We know it's going to affect the beluga. There is no doubt about it.” Charles echoed this perspective but added that it's ultimately up to the individual: “I can't stop it, but I wouldn't mind that when you're after your whale, harvesting - beluga or bowhead - that they turn off their sonar. You know, we didn't need it in the past.”

In contrast, three participants expressed low concern with depth sounder effects on beluga relative to other threats. These individuals stated that belugas did not appear to respond to sonar and/or that motor noise posed a greater issue, while emphasizing the benefits—including improved navigation, safety, and opportunities for travel and knowledge transfer. One sonar user cited uncertainty about the effects of sonar exposure on beluga compared to motor noise and stressed the benefits for travel: “The sonars have been great for our community members. They're another form of navigation for us because it saves our tracks. So, you can come home in complete darkness. You don't have to know where you are. You just follow your line back. You know that's the same navigation route.”

Some also emphasized how this tool can be used to teach the youth as a form of knowledge transfer and complement to traditional word of mouth. Jim passionately illustrated this point, “I always travel, and I use my own upbringing traveling. But now with our future leaders and our own children, we want them to go towards this technology, because it's for our safety of our harvesters.” A younger beluga harvester emphasized how bathymetry mapping enabled him to travel and explore new areas. Additionally, a Tuktoyaktuk harvester noted how the tool could help people from Inuvik and Aklavik reconnect with ancestral sites in Tuktoyaktuk: “Our

Inuvialuit would have that opportunity, not only to come from Inuvik, but to come from Aklavik, you know, go see their ancestors long ago, ruins. Because lot of those people from Aklavik and Inuvik used to live here, and they've moved away because their selected parents have stopped harvesting.”

The remaining participants expressed uncertainty about the effects of sonar, requesting more information about the technology such as how far the sound travels and with different depths and bathymetric features, it's signal intensity, how it compares to boat motor noise, and evidence of beluga disturbance. Participants advocated for more information and community-engaged data collection to guide decision making. For example, Jim stated, “We hear a lot of different discrepancy between a sonar scaring away [belugas] or sonar not doing anything. [We need to] get more information on that from a neutral person.”, while James urged that it would be “good to know about the sonars before the bigger ships come and the noise action. (...) Good to get some data before industry comes along.” Additionally, Davy advocated precaution while information remains limited, suggesting sonar be turned off near belugas, including during bathymetry surveys.

Recommendations for safe sonar use

Lastly, participants communicated ways to improve responsibility and safety with depth sounder use that can benefit both the community and beluga whales. The most common suggestion was to manually turn off active sonar or disconnect the transducer when entering critical beluga habitats or when it is not required for reading depth. It was also suggested to create sonar restriction zones within traditional beluga harvesting areas and limit bathymetry surveys in these regions. Participants further recommended employing a designated wildlife monitor on at least one bathymetric survey boat to watch for marine mammals and relay disturbances to captains.

They also proposed hiring a designated sonar technician within the community to educate and aid other users and troubleshoot user and technology errors. This included hosting community workshops to teach device specifications and educate new users. Increased education and knowledge around the technology will enforce responsible and safe sonar use.



Figure 3.4. Three beluga whales interacting in Kugmallit Bay, along the coast of Hendrickson Island in 2025, illustrating the low visibility of beluga in turbid waters (top). A beluga whale spyhopping, observed from the shoreline of Hendrickson Island in 2025 (bottom).



Figure 3.5. Two Inuit men in their 16-foot-long seal skin kayaks. Photo by C.W. Mathers, 1901.

Source: NWT Archives/C. W. Mathers fonds/N-1979-058: 0001.

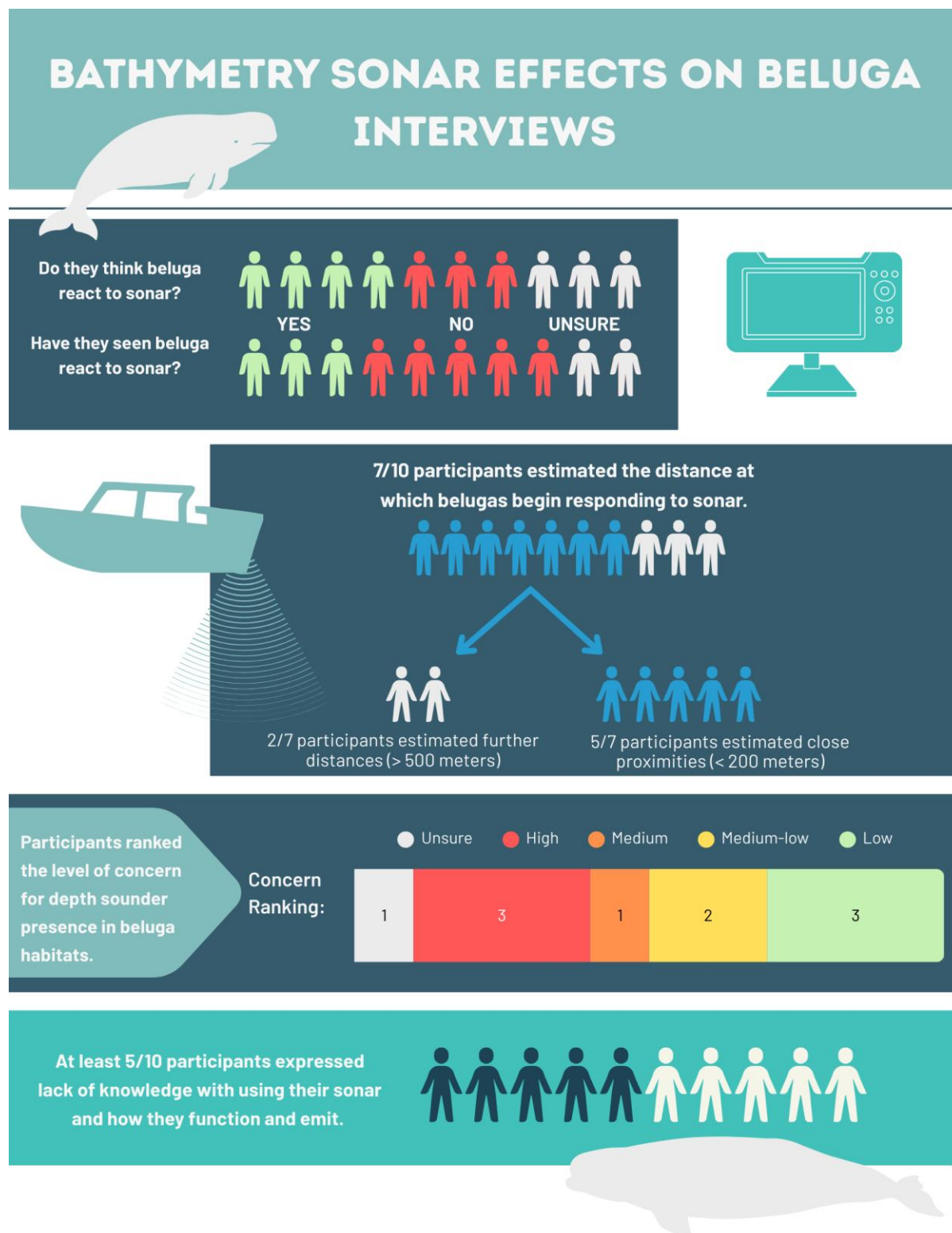


Figure 3.6. Quantifying key results that highlights the diverse perceptions and observations of sonars. Figure made in Canva Pro.

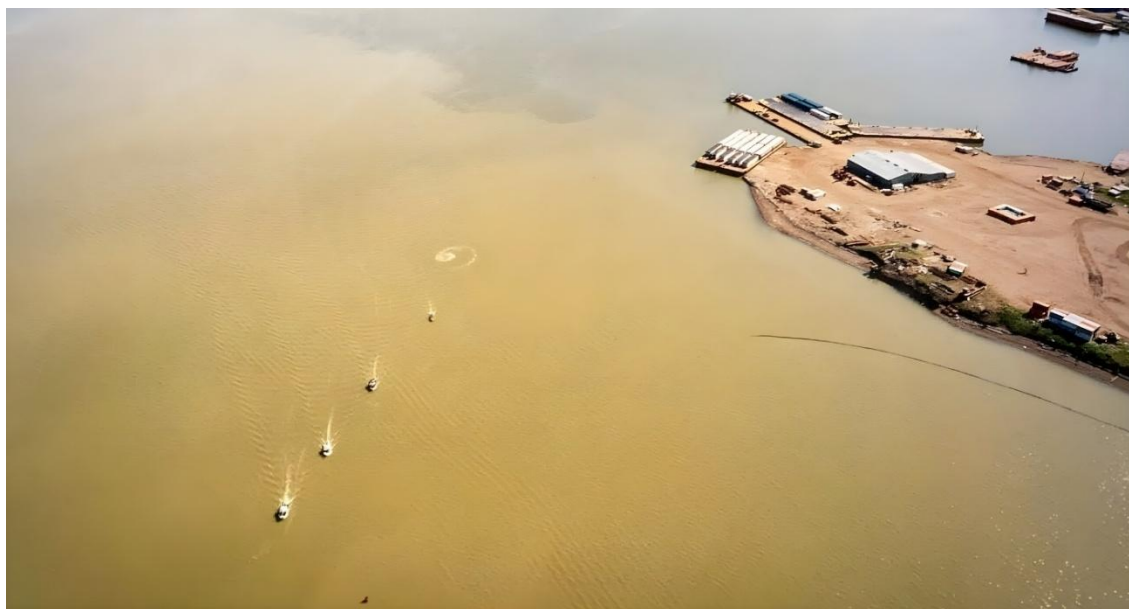


Figure 3.7. Aerial image of four boats doing a bathymetry survey in the Tuktoyaktuk Harbor in 2024 (top) (credit: Natalya Saprunova). Five boats spaced out doing bathymetry transects in Kugmallit Bay (bottom) (credit: Hester Inuaslurak).

Discussion

In this study we sought to understand the current depth sounder usage by Tuktoyaktuk residents, explore their knowledge and observations of beluga behavior relating to depth sounder use, and document their perceptions of the technology and recommendations for future use. Participant reflections demonstrated how generations of Inuvialuit Knowledge about belugas and the underwater soundscape can be applied to understand the ecological implications of depth sounder use in the Arctic marine environment, despite limited understanding of its mechanisms. Across interviews, the integration of sonar technology within Inuvialuit knowledge was valued to promote boater safety and facilitate climate change adaptation, however, questions and concerns about the potential impacts on beluga persisted. Below, these findings are discussed in relation to the literature, focusing on, 1) beluga hearing sensitivities may and the role of environment variables; 2) factors influencing beluga behaviour in response to depth sounders; and 3) using Inuvialuit knowledge to inform in underwater noise mitigation; and 4) recommendations for next steps.

Beluga hearing and signal detection in dynamic environments

Behavioral responses to acoustic stimuli can depend on hearing sensitivities, influenced by physiological variables (e.g., age, hearing loss, etc.) (NMFS 2024; Houser 2025), and their temporary ability to discern signals affected by environmental factors including ambient sound levels and physical and oceanographic characteristics (e.g., depth, bathymetry, temperature, salinity, etc.) (Mooney et al. 2018a, 2018b). All these factors can influence beluga hearing and ultimately, behavioral responses.

It is widely supported across literature that beluga whales have sensitive hearing (Awbrey et al. 1988; Mooney et al. 2008; Mooney et al. 2016). For example, beluga whales can detect

echolocation return signals when they are 1 dB above ambient noise levels (Au et al. 1987). However, individuals can have varying tolerance for noise, ranging from extreme sensitivity to complete tolerance and can result in changes in movement direction, swimming speed, diving and breathing patterns, and vocal behaviour (Richardson et al. 1995). Additionally, lower hearing sensitivities could be attributed to biological attributes such as age. Older odontocetes have been observed with high frequency hearing loss associated with degradation, or rather known as Presbycusis (Brill et al. 2001; Finneran et al. 2005; Houser 2025), thus older beluga may not receive high frequency depth sounders the same way that younger beluga might. Finally, individual hearing variability has been demonstrated (Mooney et al. 2018a). Because the 83 kHz signal falls within the sensitive hearing range, whereas 200 kHz does not, these frequencies may be perceived differently by individuals.

Alongside biological attributes, study participants emphasized how environmental conditions—such as water depth, wave action, and wind—affect how sound travels and is likely perceived by beluga whales. This is well supported by propagation theory which demonstrates that water depth, temperature, bathymetric features, bottom type, and wave action can scatter and distort sound waves (Jensen et al. 2011). A beluga's ability to discern signals varies depending on background noise levels, in which the most sensitive hearing thresholds correspond with quieter soundscapes (Mooney et al. 2018a, 2018b). While higher hearing sensitivities can be advantageous in detecting predators and communicating at lower amplitudes, high levels of background noise can limit detection of acoustic signals (Clark et al. 2009). Given that the TN MPA soundscape is partially dominated by wind and waves, with variability between sites and days (Halliday et al. 2020), the fluctuating intensity of ambient levels could change the detection of sonar across time.

Beluga behaviour and response to noise

Observed behavioural responses to depth sounders varied across interviews, including an absence of response (i.e., no observed abnormal behaviours), curiosity (i.e., approaching a boat), avoidance (e.g., changing direction, diving, swimming away), temporary displacement, and aggression (e.g., charging the boat's transducer). These observations align with literature which suggests that responses to acoustic stimuli differ on the pod and individual levels, shaped by intrinsic (e.g., age, sex, pod dynamics, learned behaviors) and extrinsic (e.g., seasonality, location, harvesting experience) factors (Stewart et al. 1982; Finley et al. 1990; Blane and Jaakson 1994; Ausen et al. 2022). Below we explore how these factors may influence the behaviours described within the context of the interviews.

A beluga's intrinsic behaviour may be influenced by external environmental variables and pressures such as its location and past experiences within that area. Evidence suggests that beluga whale responses to boats can be learned and context-dependent. For instance, in Alaska, belugas feeding in rivers fled from outboard motors but not fishing boats, likely due to local habituation (Stewart et al. 1982), and in Hudson Bay where belugas tolerate tourist vessels but avoid motorboats in traditional harvesting areas (Tyrrell 2007; Malcolm and Penner 2011; Ausen et al. 2022). This may be why participants' observe different behaviors near Hendrickson Island (a traditional harvesting area), where beluga may associate the location with danger, compared to belugas along the Tuktoyaktuk Peninsula, an area where they are never harvested and thus deem safer. Additionally, in Kugmallit Bay, the overlap between the beluga presence and open-water season ensures constant interaction between hunters and whales throughout the summer. In an area such as Kugmallit Bay, where hunting is common, belugas may learn to evade any boat noise because they associate it with danger. It's important to consider locational factors when

predicting noise disturbance, especially in areas with a long history of co-habitation with humans with an existing dynamic.

In addition, extrinsic situational factors across temporal scales, such as potential habituation to repeated noise, may also play a role in how belugas respond to noise. For instance, belugas with little prior exposure to ship noise early in the season showed behavioural responses to icebreakers and ships at distances of up to 50 km (Finley et al. 1990; Cosens and Dueck 1993) attributed to a lack of habituation resulting from limited previous exposure to vessel noise (LGL and Greeneridge 1986). Whales later returned to the areas where noise levels were higher suggesting habituation of context dependent responses (Finley et al. 1990). This aligns with observations of some belugas within our study region becoming less reactive as the season progresses.

Behavioral differences among beluga by sex and size class may reflect learned responses shaped by experience, as older individuals have been shown to be more reactive to vessels (Blane and Jaakson 1994). In Tuktoyaktuk, where harvesters typically target larger males, this subset of whales may become more cautious over time and develop stronger avoidance behaviour. On the contrary, some participants also observed whales becoming more cautious as the season progresses, influenced by an extrinsic variable of seasonality and harvesting experience.

Participants also noted seasonal changes, with whales appearing less avoidant upon first entering Kugmallit Bay and more cautious as the season progresses. Together, these observations suggest that both short-term exposure within a season and longer-term learning across years influence beluga responses to noise. Accordingly, factors such as age, sex, harvesting selectivity, and seasonality should be considered when predicting behavioural disturbance.

Lastly, vessel activity patterns (e.g., whether it is moving or stationary, speed, and directionality) may also be influential factor. Supported by several participants who said beluga would more likely approach their boat if stationary. This is consistent with a previous study done in the area that found beluga to react less to stationary dredge boat than a moving one, despite the sound exposure levels being the same (Fraker 1977). Likewise, participants highlighted how belugas in Kugmallit Bay know when a boat is hunting or not, likely due to the way the vessel is being maneuvered including frequent speed and heading changes. This further supports the idea that factors other than sound exposure could influence elicited responses.

Incorporation of IK into acoustic propagation models, risk assessments and mitigation practices

Indigenous knowledge is a knowledge-practice-belief system embedded into management systems and social institutions, and if viewed through an epistemological lens, includes a holistic dimension between people and wildlife enriched by place-based intergenerational oral knowledge (Johnson et al. 2016; Berkes 2018). This study primarily focused on documenting practical observational knowledge including where and when belugas are observed and what constitutes disturbance behavior under different circumstances. However, perceptions were also shaped by intergenerational knowledge transfer such as teachings on the importance of silence to achieve a successful whale hunt, distrust in anthropogenic noise sources that could affect country food, and responsibility to respect beluga outside of harvesting contexts. This illustrates the ontological nuances of IK beyond empirical observations, bringing a multifaceted understanding of relationships between people and wildlife. Incorporating dimensions of IK into noise disturbance mitigation strategies is imperative for future research.

There are many confounding factors that challenge the development of standardized behavior assessment to noise exposure. In this study, many contextual covariates were identified as a crucial component to understanding beluga behavioural responses to noise. This has been observed across other noise exposure studies where behavioural responses to noise vary contextually (e.g., Southall et al. 2007, 2019, 2021; Ellison et al. 2012); and higher received noise levels do not always result in more severe behavioral responses (Gomez et al. 2016). These observations highlight the limitations of fixed all-or-nothing acoustic thresholds that are historically and currently used by many government agencies to mitigate underwater noise (e.g., NMFS 2024). While acoustic thresholds offer a tangible target for mitigation, they can incorrectly imply that negative outcomes will occur only if/when thresholds are exceeded. Researchers are increasingly calling for more nuanced mitigation strategies that better predict the likelihood of behavioral disturbances (i.e., behavior probability functions as described in Southall et al. 2021). Additionally, behavioral responses to military sonar have been reviewed across different cetaceans and were not predictable by the received SPL, and other variables such as situational contexts like previous behavioral state influenced reaction probabilities (Southall et al. 2016). Frequency weighted thresholds specific to a species hearing curve could provide more tailored and conservative estimates when considering targeted conservation efforts (Tougaard et al. 2015). In our context, this would likely result in a lower SPL threshold at the frequency of interest for beluga based on their sensitive hearing range. Considering thresholds as a fixed dB increment relevant to ambient levels (i.e. SNR) could also account for varying environmental conditions. In contrast to the adoption of acoustic thresholds, probability functions are much more conducive to the inclusion of traditional knowledge, local observations, and other

qualitatively derived metrics. Shifting towards a more species and context-specific approach, which could be achieved with the inclusion of IK, would improve noise mitigation frameworks.

We sought to implement this qualitative work in conjunction with empirical noise measurements and acoustic modeling aimed at noise exposure of depth sounders and the ecological implications for beluga. Where applicable, future acoustic modelling and risk mitigation efforts should be informed by Indigenous knowledge to improve ecological relevance and predictive accuracy. However, care must be taken to avoid reducing IK to simplified model inputs and to retain its relational, contextual, and place-based meaning. Rather than being treated as data, IK should inform how models are designed, interpreted, and applied. Collaborative approaches should involve Indigenous partners' input throughout every step of the research process to ensure accuracy and relevancy of products and maintain its contextual place-based knowledge. The importance of this was seen in this study where place-based contexts informed behavioral variability, which could not be achieved by quantitative methods alone.

IK is currently underrepresented in noise exposure studies and mitigation frameworks, however, local observations through IK can improve co-management mitigation practices in areas such as assessing responses and behaviours in tandem with empirical noise measurements to provide a cohesive analysis that can enhance our understanding. For example, a study conducted in Lancaster Sound, Nunavut, also mobilized Inuit knowledge to identify critical marine mammal habitats, paired with propagation models, revealing areas where vessel traffic intersects with ecologically important regions (Kochanowicz et al. 2021). Similarly, a study in Pond Inlet interviewed Inuit community members potentially affected by increased vessel traffic to provide alternate strategies for low impact shipping corridors (Carter et al. 2018). The information from either study would not have been possible without sustained, long-term monitoring if IK had not

been incorporated, also improving the accuracy and efficiency of science advice for mitigation. To address participant's requests for community-engaged data collection to guide decision making, field measurements and propagation modeling are also being used to fill information gaps regarding how far the sonar travels, signal intensity, and how these change in varying conditions. This demonstrates how qualitative and quantitative methods used together enhance the entire picture.

Limitations and further steps

This study revealed uncertainties and limitations that are important to highlight here. For instance, participants noted that simultaneous motor and sonar noise made it difficult to isolate which source caused observed changes in beluga behaviour. Half of the participants reported keeping their sonar on while idling or while the motor was off and a few participants observed belugas avoiding their boat under these conditions, suggesting motor noise is a key factor in these interactions. Preliminary research in the area suggests sonar is only detectable above engine noise at speeds under 15 km/h; at higher speeds, motor noise masks most of the sonar energy, likely contributing to the varied behavioral responses reported by participants (see Chapter 2). This masking effect highlights the need for mindfulness when using sonar at low speeds.

Lastly, we elected to rely solely on boaters' observations to provide details on belugas response to sonar, rather than conducting potentially disruptive playback experiments. However, some participants noted it would be beneficial to perform such experiments to generate detailed observations of beluga behaviour before, during, and after exposure to a motorboat and sonar separately. This could be a future avenue to help distinguish reactions from motor noise vs depth

sounders; such a study would need to be implemented in close collaboration with the Tuktoyaktuk community who can dictate ethical considerations and priorities.

Conclusion

To our knowledge, this is the first study to investigate the effects of consumer-grade depth sounders on belugas in the ISR, and the first to do so with qualitative methods. Study findings ultimately suggest that beluga responses to sonar are highly context-dependent and variable, based on intrinsic and extrinsic factors on the individual and pod levels such as age, sex, habituation, learned behaviors, environmental variables, harvesting contexts, location, and seasonality. There was a shared perspective that sonars can benefit the community as a safety and navigation tool but should be used in a way that minimizes impacts on wildlife. The observations and feedback from the interviews will inform propagation models and contribute to recommendations for safer sonar use that minimizes risk within and around the TN MPA. This framework is in support of regional mandates to consider IK and western science together (IFA 1984) and is in alignment with recommendations under Canada's Ocean Noise Strategy (DFO 2024). Because the TN MPA is co-managed across knowledge systems, decisions about technologies such as sonar should integrate scientific evidence and Inuvialuit knowledge in tandem. Expanding the use of qualitative data within quantitative noise exposure studies could improve context-specific management strategies.

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Appendix A:

Table A3.1. List of codes used within NVivo analysis.

Code Name	Number of References
Age	10
Bathymetry Program	23
Beluga Encounters	36
Beluga Encounter Frequency	11
Beluga Harvesting	34
Beluga Hearing	21
Beluga Sonar Interactions	32
Bowheads	6
Change	17
Concern Ranking	10
Concerns	27
Dredging	2
Fish	8
Harbor Beluga	5
Lack of Sonar Knowledge	14
Land Use and Experience	15
Motor Noise	22
Multiple Boats	5
Natural Beluga Behaviour	25
Occupation	10
Oral Knowledge	11
People and Beluga Interactions	41
Pingers	2
Recommendations and Feedback	34
Seals	2

Seismic Blasting	1
Sonar Basics	17
Sonar Distance	7
Sonar Frequency	27
Sonar Usage	45
Thoughts on Sonar	52
Negatives	11
Positives	31
Need More Information	10
Tuktoyaktuk Residency	9
Unnatural Beluga Behaviour	22
Vessel Presence	7
Water and Land Observations	16

Table A3.2. User specifications for individual sonar use. N/A denotes the column is not applicable to that interview participant. ‘Not specified’ indicates there was no clear answer during the interview.

Sonar installed?	If not currently installed, was it in the past?	Sonar currently operational?	What model?	Own more than one?	How many years have you had it?	Is the sonar currently unhooked/transducer taken off?
Yes	N/A	Yes	Lowrance	No	3	Not
Yes	N/A	No	Lowrance	No	3	Yes
Yes	N/A	No	Lowrance	Yes	3	Yes
Yes	N/A	Yes	Lowrance	Not	3	No
Yes	N/A	No	Lowrance	No	21	Yes
No	Yes	No	Lowrance	No	Not specified	Yes
Yes	N/A	Yes	Lowrance	Yes	3	No
Yes	N/A	Yes	Lowrance	No	3	No
Yes	N/A	Yes	Lowrance	Yes	7	No
Yes	N/A	Yes	Lowrance	No	5	No

Table A3.3. Sonar usage of each interview participant. *Navigation includes reading depth, following tracks, and recording tracks.

Participant Identifier	Navigation (reading depth, following tracks, recording tracks)	Bathymetry work	Harvesting	Fishing	Other (specify)	Sonar Frequency (Heavy/medium/light sonar user?)	Is sonar on while motor is off/idling?
INTV-01	yes	yes	no answer	no answer		Heavy	yes
INTV-02	yes	yes	sometimes	no answer		Light	yes
INTV-03	yes	no	no	no		Light	yes
INTV-04	yes	yes	no	no		Heavy	no
INTV-05	yes	no	no	no answer	Tagging bowhead whales	Light	no
INTV-06	yes	yes	no answer	no answer		Heavy	no
INTV-07	yes	yes	no answer	yes		Heavy	yes
INTV-08	yes	yes	no answer	yes		Heavy	yes
INTV-09	yes	yes	sometimes	no		Heavy	no
INTV-10	yes	yes	no answer	no		Heavy	sometimes

Table A3.4. Participants' perceptions of sonar were categorized based on the tone and content of their statements as negative, positive, or expressing a need for additional information.

Participant Identifier	Negative	Positive	Need more information	Concern Ranking
INTV-01	0	2	1	low
INTV-02	2	1	0	high
INTV-03	2	1	0	high
INTV-04	0	1	1	low
INTV-05	2	1	0	high
INTV-06	1	2	3	medium
INTV-07	0	6	2	low-medium
INTV-08	0	4	0	low-medium
INTV-09	1	2	2	unsure
INTV-10	0	2	0	low
Totals:	8	22	9	

Table A3.5. Thoughts or perceptions of sonar that arose during interviews and were formulated by either knowledge, opinion, or observation. Criteria for categorization are as follows; A thought is based on knowledge about sonar that had included the word 'know', or stated something as a fact, presented information passed down, or if they acknowledged their lack of knowledge surrounding sonar and beluga effects. An opinion was categorized if it included the phrase 'I think'. Observation based thoughts were formulated based on experiences they have had with using the sonar.

Participant Identifier	Knowledge (or lack of)	Opinion	Observation
INTV-01	1	1	1
INTV-02	1	1	1
INTV-03	1	1	1
INTV-04	1	0	1
INTV-05	1	0	2
INTV-06	4	0	2
INTV-07	3	2	3
INTV-08	1	1	2
INTV-09	3	1	1
INTV-10	0	1	1
Totals:	16	8	15

Chapter Four: Synthesis and Conclusion

Understanding how depth sounder signals travel through the shallow, dynamic conditions of the Mackenzie Estuary is critical in investigating the variability of exposure within critical beluga habitats and informing recommendations for future use of this technology. Integrating empirical propagation measurements with local Inuvialuit Knowledge enabled a more nuanced interpretation of ecological implications that can be used to inform noise exposure assessments in addition to acoustic thresholds.

Summary

Chapter 2 results highlighted novel, empirical propagation measurements of depth sounders within a shallow estuarine environment. Both impulsive and continuous measurements were relevant for investigating propagation characteristics of depth sounders as it exhibited a range-dependent shift in signal characterization which supports previous literature that highlighted the limitations of using RMS SPL in noise exposure assessments (Madsen 2005). Using impulsive peak measurements, we found that the acoustic spread of the 83 kHz and 200 kHz were spatially limited within 500 m in shallow depths less than 10 m. Furthermore, RMS noise levels of both the 200 kHz and 83 kHz at close ranges exceed NMFS non-impulsive threshold for behavioral disturbance in marine mammals but did not exceed thresholds for physiological effects (NMFS 2024). This could be further exacerbated in less turbid conditions as sound absorption decreases, which have been previously observed in laboratory experiments (Richards & Leighton 2000). Field measurements were integrated with BELLHOP acoustic propagation models to develop noise exposure diagrams that can inform depth sounder users of potential acoustic exposure (Figure 1).

Chapter 2 defined bounds of detectability and received levels to support future impact assessments of depth sounders in the region while providing novel measurements in shallow estuarine habitats. Although Chapter 2 did not introduce measurements that can be indicative of a beluga's behavioral or physiological response (i.e. stress levels, call rates, movement behaviors, etc.), the propagation measurements contribute baseline knowledge in assessment factors such as range of detectability, noise intensity thresholds, and habitat variability in spatial spread and detections. This work also begins to highlight the limitations of acoustic thresholds for noise impact assessments by the ambiguity of impulsive and non-impulsive categorizations for depth sounders. Even though the propagation properties of depth sounder will change among marine environments, the findings of this study provide a reference for others evaluating the use of depth sounders within their region. The limitations to acoustic thresholds were further unpacked in Chapter 3, as well as investigations of beluga behavior that could not be concluded by propagation models alone.

Chapter 3 revealed that beluga behavior was highly variable and heavily context specific, influenced by intrinsic and extrinsic factors. This was supported by interview participants who observed variable behavioral responses from beluga to depth sounders including curiosity, avoidance, temporary displacement, aggression, and no response. This aligned with Southall et al. (2016) that also did not see a correlation between SPL levels and behavioral responses across cetaceans exposed to military sonar, but instead found other factors better predicted reaction probabilities such as previous behavioral states, individual and group contexts, and situational nuances. Observations of beluga behavior in these contexts provided additional information that could not be attained from propagation measurements alone, emphasizing the importance of integrating Indigenous Knowledge when assessing underwater noise exposure.

Interviews lent a better understanding on how this technology is used within the region, providing additional nuanced information to improve recommendations. Participants shared the perspective that depth sounders can provide safe navigation for boaters while minimizing risk to wildlife. Their views were also shaped by their own place-based intergenerational knowledge, providing a multifaceted outlook on human and wildlife interactions and relationships that can benefit noise mitigation frameworks and noise exposure research methods. The implications of this study will contribute to informing the co-management of the TN MPA while additionally supporting ISR mandates and National recommendations to incorporate IK with western science (IFA 1984; DFO 2024). Participants provided rich observations, although it could not be determined if the beluga were directly responding to the noise of the depth sounder. While we opted to not conduct a playback study to gather information of beluga behavior and responses, it was noted that future experiments in close collaboration with the THTC could provide clarity in what noise component of the boat (i.e. sonar or motor) individuals are responding to.

Recommendations

A main outcome of this study was the production of a plain-language infographic that can inform depth sounder users in the Mackenzie Estuary region and be circulated among communities and science partners (Figure 1). These recommendations were developed from the results of Chapter 2 and 3, synthesizing the most important takeaways from both studies. Information presented directly addresses questions frequently asked by community members throughout the duration of both studies. This includes information on beluga hearing range, if side-scan sonars and depth sounders are audible to beluga, how may beluga respond to noise, if the sonar is audible over boat motor noise, and how far out can beluga hear the sonar. The six recommendations inform depth sounder users on how to safely use their depth sounders such as changing specific device

settings, ensuring the sonar is off when not in use, restricting the use of sonar in traditional harvesting areas, designating a wildlife monitor during bathymetry surveys, and lastly, delegating a sonar knowledge holder within the community to educate and help other depth sounder users. Although the recommendations only apply to the Mackenzie Estuary region, the broader implications include providing a framework for future noise exposure studies to incorporate more qualitative methodologies.

Future Work

The short timeframe (2 years) of this study limited the scope and thoroughness that should be applied to noise impact assessments. Although we attempted to measure propagation characteristics in variable habitat conditions, data gaps could be further addressed by more access to variable habitat sites, as well as a longer time frame for repeated experimentation. Such data gaps include covering deeper sites, varying and repeated bottom sediment types, higher variability in turbidity, and more dramatic fluctuations in temperature and salinity profiles that could be achieved by changing sampling distance from the river mouth. Experimentations were also limited outside of traditional harvesting areas where beluga are most abundant. Future work would expand to include these variables, and with approvals from local HTC's, be done in beluga hot spot areas while beluga are not present and harvesting has ceased (likely right before ice formation). Moreover, more biological and physiological assessments partitioned by before, during, and after depth sounder exposure, as discussed previously, could provide more context to the effects of noise exposure.

Limited time also restrained the results of Chapter 3. More time and resources would have allowed us to expand interviews to other communities outside of Tuktoyaktuk to compare depth sounder usage results across parcels of the TN MPA, not just within Kugmallit Bay. It's worth

mentioning that depth sounder propagation and interview results were also shared in real-time with the Inuvik HTC for questions and feedback. In terms of continuity, it would be beneficial to keep exploring this topic with interview participants and re-visit the same questions to record any new or changing observations and opinions that developed over the last year. This will become more pertinent as depth sounder use continues to become more accessible within the ISR.

The TN MPA is co-managed by different knowledge systems, thus regulation of technologies like active sonar depends equally on measured levels of disturbance and Inuvialuit perspectives on disturbance. We elected to rely on harvester observations to provide details on belugas behavioral response to depth sounders, rather than conducting potentially disruptive playback experiments. Acoustic thresholds are not always reliable predictors for behavioral responses that could be elicited from sound exposure. Thus, interviews became essential for attempting to fill in those data gaps and prompting context-specific evaluations. These nuanced observations can be incorporated into probability functions as proposed by Southall et al. (2021) to get likelihood percentages of beluga reacting to noise exposure.

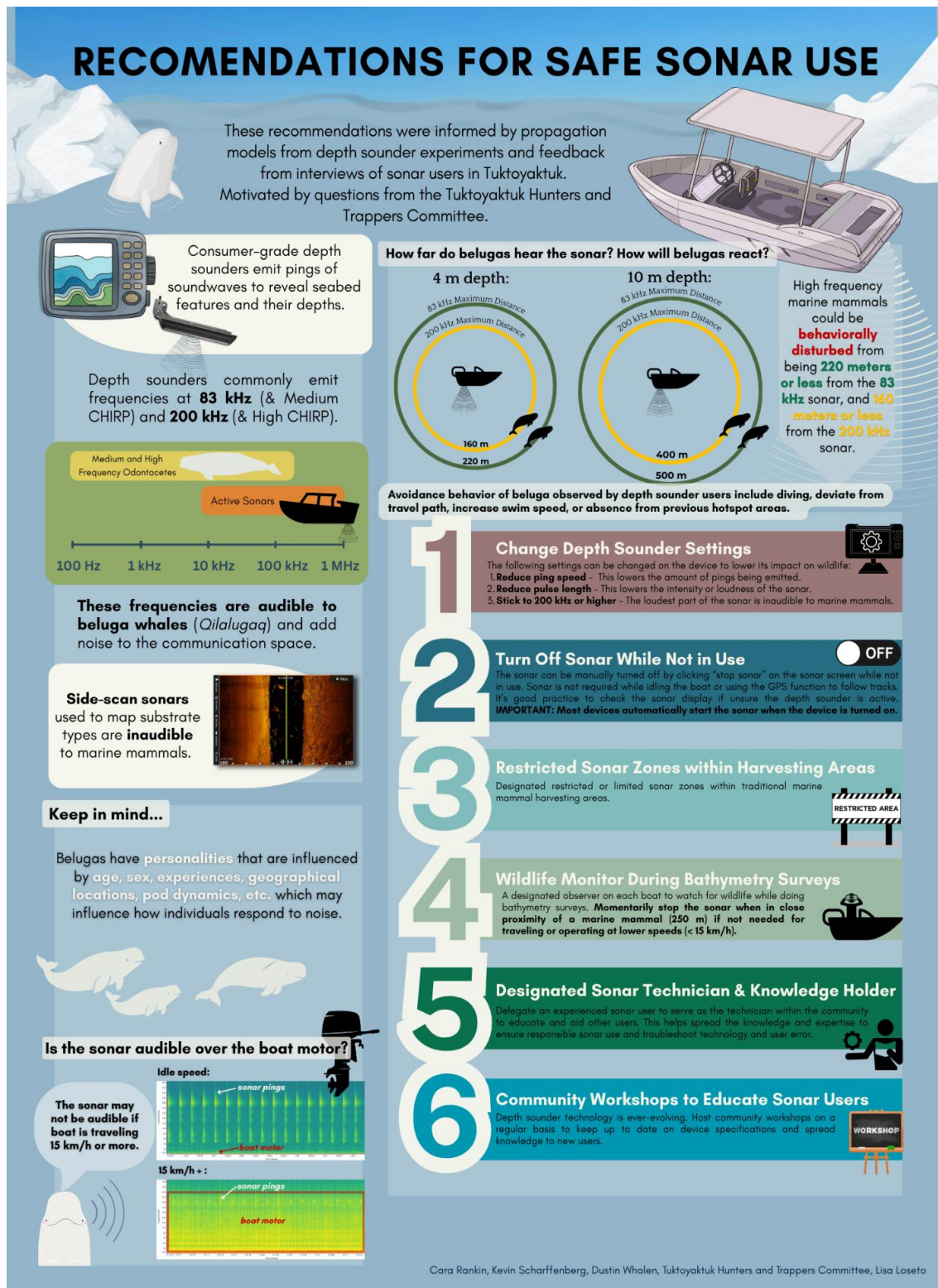


Figure 4.2. Infographic detailing recommendations for safe depth sounder use and outcomes from this study and complimentary community interviews.

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