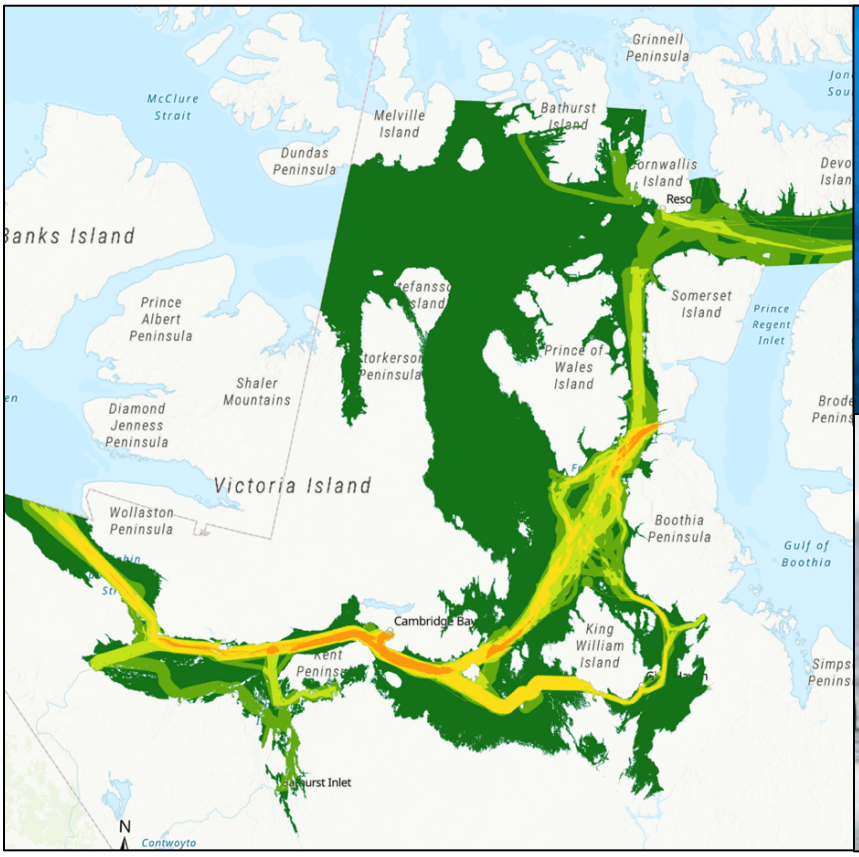
Ship Source Underwater Noise in the Northwest Passage and Culturally Significant Marine Areas



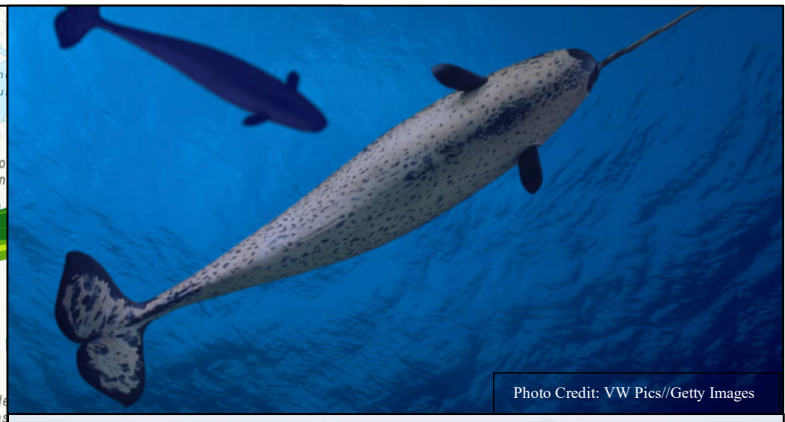


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RESEARCH REPORT

Prepared for the Nunavut General Monitoring Program

July 2026

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NOTICES

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FUNDING PROVIDED BY

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Nunavut General Monitoring Plan
Nunavunmi Tamainni Takuurivangnikkut Parnaiyautaanni
Plan de surveillance générale du Nunavut

EXECUTIVE SUMMARY

Shipping activity in Nunavut has increased significantly since 1990, with the most rapid growth occurring after the mid-2010s and concentrated along key Northwest Passage (NWP) corridors. Results show that ship-source underwater noise is strongly aligned with these corridors, with the highest exposure occurring near Pond Inlet and along southern routes near Cambridge Bay. Noise exposure is not evenly distributed but is concentrated in areas with the greatest vessel activity. Many of these high-noise areas overlap with Culturally Significant Marine Areas (CSMAs). Across all four communities studied, vessel activity within these areas has increased over time. Pond Inlet presently experiences the highest and fastest-growing exposure; while Cambridge Bay and Resolute currently show moderate exposure; and Gjoa Haven experiences lower but consistent levels of underwater noise related to ship traffic. Overall, findings indicate increasing levels of noise overall as well as spatially concentrated noise exposure, and growing overlap between areas with significant shipping activity and ecologically and culturally important marine areas.

Table of Contents

EXECUTIVE SUMMARY 3
List of Figures 5
List of Tables 6
1. Introduction 7
1.1 Historic Growth of Shipping in the Nunavut with focus on the NWP 7
1.2 Sensitivity of Arctic Marine Mammals to Ship Source Underwater Noise 9
1.3 Purpose of This Report 10
2. Study Area 10
3. Methodology 11
3.1 Vessel Traffic Data 11
3.2 Ship-Source Noise Modelling 12
3.3 Culturally Significant Marine Areas 13
3.4 Spatial Analysis 13
4. Results 14
4.1 Shipping Activity Across the Northwest Passage 14
4.2 Community-Level Vessel Activity 15
4.3 Spatial Distribution of Ship Noise 17
4.4 Vessel Activity within Culturally Significant Marine Areas 19
4.5 Overlap with Culturally Significant Marine Areas 23
5. Discussion 27
5.1 Key Patterns of Noise Exposure in the NWP 27
5.2 Implications for Marine Mammals and Inuit Subsistence and Cultural Activities 28
5.3 Limitations 29
6. Recommendations and Conclusions 29
7. References 31
APPENDIX A 33

List of Figures

Figure 1. Total annual sailing distance of vessels operating in Nunavut (1990–2025). 7

Figure 2. Annual sailing distance of vessels operating within the Northwest Passage corridor between 1990 and 2025. 8

Figure 3. Study area within Nunavut, Canada, highlighting the Northwest Passage shipping corridor and the four focal communities examined in this study: Mittimatalik (Pond Inlet), Qausuittuq (Resolute), Uqsuqtuuq (Gjoa Haven), and Iqaluktuuttiaq (Cambridge Bay). 11

Figure 4. Vessel track line density across the Northwest Passage for three time periods: 1990–2005, 2006–2015, and 2016–2025. Values represent cumulative vessel track density (km/km²).15

Figure 5. Annual vessel sailing distance within a 50 km radius of four Nunavut communities along the Northwest Passage from 1990–2025. Panels show trends for (A) Pond Inlet, (B) Gjoa Haven, (C) Resolute, and (D) Cambridge Bay. Dotted lines indicate linear trendlines illustrating long-term changes in vessel activity near each community. 17

Figure 6. Modelled ship-source underwater noise exceedance (RL120) across the Northwest Passage during September 2017. Values represent the number of times the behavioral disturbance threshold was exceeded (120 dB re 1 μPa). 18

Figure 7. Relationship between total sailing distance (km) and RL120 exceedance values across the Northwest Passage. The positive trend indicates that higher vessel activity is associated with increased underwater noise exposure. 19

Figure 8. Culturally Significant Marine Areas (CSMAs) identified by Nunavut communities along the Northwest Passage. Panel (A) shows open-water conditions and Panel (B) shows freeze-up conditions. These areas represent regions of ecological and cultural importance, including key marine mammal habitat, migration routes, and harvesting areas. 20

Figure 9. Annual vessel activity within culturally significant marine areas (CSMAs) associated with four Nunavut communities along the Northwest Passage from 1990–2025. Stacked bars represent the total sailing distance travelled within each CSMA by vessel class. Panel (A) shows vessel activity within the Pond Inlet CSMA, Panel (B) Resolute, Panel (C) Gjoa Haven, and Panel (D) Cambridge Bay. Vessel classes include bulk carriers, fishing vessels, general cargo, government vessels and icebreakers, passenger ships, pleasure craft, tanker ships, tug/barge operations, and other vessel types. 23

Figure 10. Spatial overlap between modelled ship-source underwater noise exceedance (RL120) and Culturally Significant Marine Areas (CSMAs) across the Northwest Passage. Panel (A) shows overlap with open-water CSMAs using September 2017 noise conditions, while panel (B) shows overlap with freeze-up CSMAs using October 2017 noise conditions. 25

List of Tables

Table 1. Summary statistics of vessel activity across three phases of shipping activity in Nunavut waters (1990-2025). % Change is the difference in mean annual distance travelled per vessel between subsequent time periods. 8

Table 2. Spatial extent and ecological characteristics of culturally significant marine areas across four Nunavut communities along the Northwest Passage. 21

Table 3. Seasonal mean of modelled ship-source underwater noise exceedance (RL120) within whale habitat areas associated with Nunavut communities along the Northwest Passage (2015–2018). Values represent the number of times threshold for behavioral disturbances in marine mammals was exceeded (120 dB re 1 u). Cambridge Bay is excluded because there were no areas identified for whales. 26

Table 4. Seasonal mean RL120 noise exceedance within pinnipeds habitat areas associated with Nunavut communities along the Northwest Passage (2015–2018). Values represent the mean number of times the threshold for behavioral disturbance in marine mammals was exceeded (120 dB re 1 u). 26

Table 5. Annual sailing distance (km) within 50 km of selected Nunavut communities along the Northwest Passage (2015–2018). 27

Table 6. Recommendations, rationale and potential actions and policy context. 30

1. Introduction

1.1 Historic Growth of Shipping in the Nunavut with focus on the NWP

Marine transportation in Nunavut is concentrated along a series of navigable corridors shaped by water depth (bathymetry), passage width, and seasonal sea-ice dynamics. These corridors include the eastern gateway to the Northwest Passage through Lancaster Sound and Eclipse Sound; the central Barrow Strait corridor; and the narrow, complex southern route of the Northwest Passage, which includes Queen Maud Gulf, Dease Strait, and Coronation Gulf, leading to the Beaufort Sea.

Historically, navigation and season length within these corridors has been limited by the presence of multi-year sea ice and seasonal ice cover. However, reductions in sea-ice extent, thickness, and seasonal longevity over recent decades has increased accessibility across much of the Canadian Arctic (Kwok, 2018; Dawson et al., 2022). As navigable windows expand, vessel activity within established Arctic shipping corridors has increased (Cook et al., 2024). These environmental changes also contribute to growing interest in Arctic shipping associated with community supply, tourism, government operations, research activities, and commercial transportation.

Long-term vessel traffic records provide clear evidence of this growing interest . The total annual sailing distance of vessels operating in Nunavut waters between 1990 and 2025 shows a sustained upward trend (Figure 1). Although year-to-year variability occurs, including a temporary decline around 2011 and 2020 (due to the COVID-19 pandemic), the overall distance travelled by vessels has increased substantially since the early 1990s, with the most pronounced growth occurring after the mid-2010s.

Similar trends are observed directly within the Northwest Passage, specifically, the southern route from Lancaster Sound and south of Victoria Island (**Figure 2**). Annual sailing distance within the NWP has also increased over time, with strong growth observed in the period after 2020.

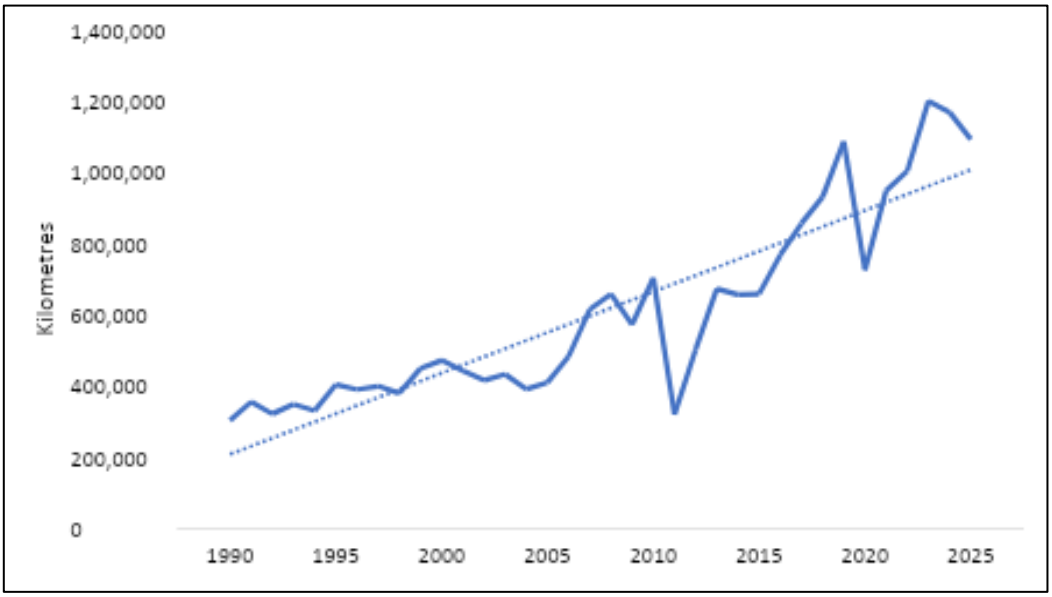


Figure 1. *Total annual sailing distance of vessels operating in Nunavut (1990–2025).*

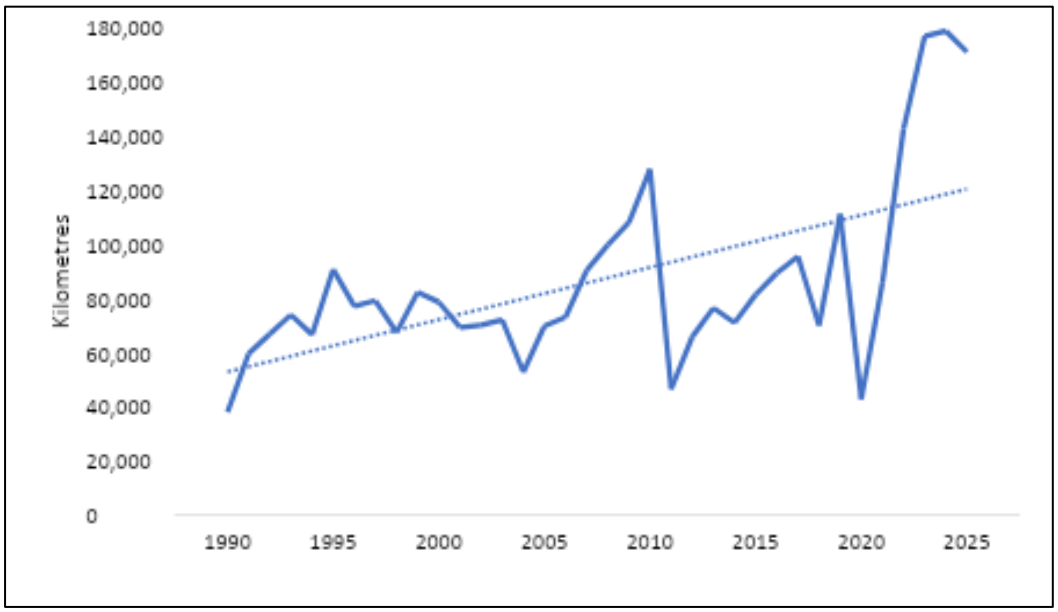


Figure 2. *Annual sailing distance of vessels operating within the Northwest Passage corridor between 1990 and 2025.*

Table 1 further illustrate this growth pattern. Mean annual sailing distance increased from approximately 390,799 km during the 1990–2005 period to 977,603 km during 2016–2025, reflecting a substantial expansion of shipping activity within Nunavut waters. Over the same period, the mean annual number of vessels increased from 68 to 173 (154%), indicating that this growth is primarily driven by an increase in the number of vessels operating in the region. In contrast, the average sailing distance per vessel remains relatively stable, suggesting that increasing traffic volume, rather than longer individual voyages, accounts for most of the observed increase in total sailing distance.

Table 1. *Summary statistics of vessel activity across three phases of shipping activity in Nunavut waters (1990-2025). % Change is the difference in mean annual distance travelled per vessel between subsequent time periods.*

Period	Mean Annual Distance (km)	Mean Annual Vessels	Mean Annual Distance per Vessel (km)	% Change in Mean Annual Distance Per Vessel (Between Periods)
1990–2005	390,799	68	5,752	
2006–2015	584,249	94	6,235	+8%
2016–2025	977,603	173	5,667	-9%

The concentration of vessel movement within these narrow corridors has implications beyond transportation logistics. Many of the primary shipping routes intersect with habitats used by Arctic marine mammals. As vessel traffic increases along the Northwest Passage and surrounding routes, marine mammals inhabiting these areas may experience greater cumulative exposure to ship-source underwater noise.

1.2 Sensitivity of Arctic Marine Mammals to Ship Source Underwater Noise

Many Arctic marine mammals, including narwhals, belugas, bowhead whales, ringed seals, bearded seals, and walrus, rely on specific habitats and migration routes within the Northwest Passage area for activities such as feeding, migration, and seasonal aggregation (Halliday et al., 2017; Huntington et al., 2023). As shipping activity increases in Arctic waters, vessel traffic is increasingly intersecting with these ecologically important areas, raising concerns about potential noise impacts on marine mammals that depend on their acoustic environments for survival.

Underwater sound travels efficiently in marine environments, and vessels generate predominantly low-frequency noise that can propagate over large distances (Halliday et al., 2017; Mannherz et al., 2024). In Arctic ecosystems, many marine mammals rely heavily on sound for communication, navigation, foraging, and predator detection (Middel & Verones, 2017). Vessel noise can be audible to marine mammals over distances exceeding 100km and may cause behavioral disturbance when animals are within several kilometers of vessels (Halliday et al., 2017). Disturbances from increased noise levels can alter movement and migration patterns, mask acoustic signals used in communication, and cause animals to avoid otherwise important habitats.

Behavioral responses to ship source underwater noise are documented in both narwhal and beluga, and include changes in movement patterns, swim speed, and displacement in response to ship traffic, even at distances beyond visual range (Finley et al., 1990; Martin et al., 2022). Other Arctic marine mammals, such as bowhead and beluga whales, depend heavily on acoustic cues for communication and navigation, making them especially vulnerable to increases in anthropogenic underwater noise (Mannherz et al., 2024). Over the past few years there is mounting evidence that these species are being particularly impacted by ship source underwater noise (e.g., Halliday et al., 2019, Ewing et al. 2025). Pinnipeds, such as ringed seals, bearded seals, and walrus, also rely on underwater sound for navigation, communication and other social behavior (Schack & Haapaniemi, 2017). These species produce a range of vocalizations associated with territorial interactions and mating, often within low-frequency ranges that overlap with ship noise (Schack & Haapaniemi, 2017).

Since many Arctic marine mammals rely on sound and use specific migration routes, increases in vessel traffic within specific confined Arctic waterways may lead to repeated acoustic exposure if ship routes overlap with areas that are biologically important for these species (Halliday et al. 2020). Shipping activity in this region occurs primarily during the open-water season and supports a range of activities including community resupply, tourism, research operations, and commercial transportation. Since vessel traffic in the Canadian Arctic is often constrained to narrow channels and predictable routes within the Arctic Archipelago, the result may be noise exposure that is spatially concentrated along specific shipping corridors (Cook et al., 2024).

Beyond their ecological importance, these marine areas an important part Inuit subsistence harvesting systems and vital cultural practices. Many marine mammal species are critical for food security and cultural continuity across Inuit Nunangat, and changes in marine mammal distribution or behavior can affect harvesting opportunities and community well-being more broadly (Panikkar & Lemmond, 2020; Huntington et al., 2023).

1.3 Purpose of This Report

This report examines the potential risks of ship-source underwater noise to marine mammals within the main shipping corridors of Nunavut, including both the Northwest Passage and important community routes. The analysis was conducted as part of research supported by the Nunavut General Monitoring Program (NGMP).

Using ship-source underwater noise modelling outputs, the report evaluates areas where modelled noise levels exceed underwater noise levels of 120 dB re 1 µPa, a threshold commonly used to assess the potential for behavioural disturbance in marine mammals (National Marine Fisheries Service, 2023). These noise exposure patterns were then compared with spatial data representing Community Significant Marine Areas (CSMAs) used by Arctic marine mammals.

By identifying locations where elevated noise levels overlap with ecologically and culturally important marine habitats, this report aims to improve understanding of where ship traffic may create elevated acoustic disturbance risks to marine mammals and the surrounding communities that rely on them.

2. Study Area

The study area for this report included the marine region of Nunavut within the Canadian Arctic Archipelago, with a specific focus on the primary shipping corridors in the region including the Northwest Passage (NWP). The NWP consists of a network of interconnected channels that pass through the Arctic Archipelago, linking the Atlantic and Pacific Oceans. Due to the region's complex geography, vessel traffic is typically constrained to navigable waterways or corridors and create predictable navigation routes throughout the Arctic Archipelago.

Since navigation is restricted to specific channels within the archipelago, shipping activity tends to be spatially concentrated along a limited number of primary corridors, including established routes that connect Arctic communities with southern supply hubs and other Arctic areas. These corridors intersect with marine environments used by Arctic marine mammals, including whales, seals, and walrus, creating the potential for interactions between vessels and impacts of vessel activities and sensitive marine habitats and mammals

While the study area includes shipping corridors across Nunavut waters, the analysis specifically focuses on areas surrounding four Nunavut communities located along major segments of the Northwest Passage: Mittimatalik (Pond Inlet), Qausuittuq (Resolute), Uqsuqtuuq (Gjoa Haven), and Iqaluktuuttiaq (Cambridge Bay). These communities are located along important areas where regional shipping routes are used for community resupply and other vessel activity (Dawson et al., 2020) and therefore are useful study areas. Focusing on these four locations allows for a more detailed examination of how ship-source underwater noise may intersect with areas of ecological and community importance.

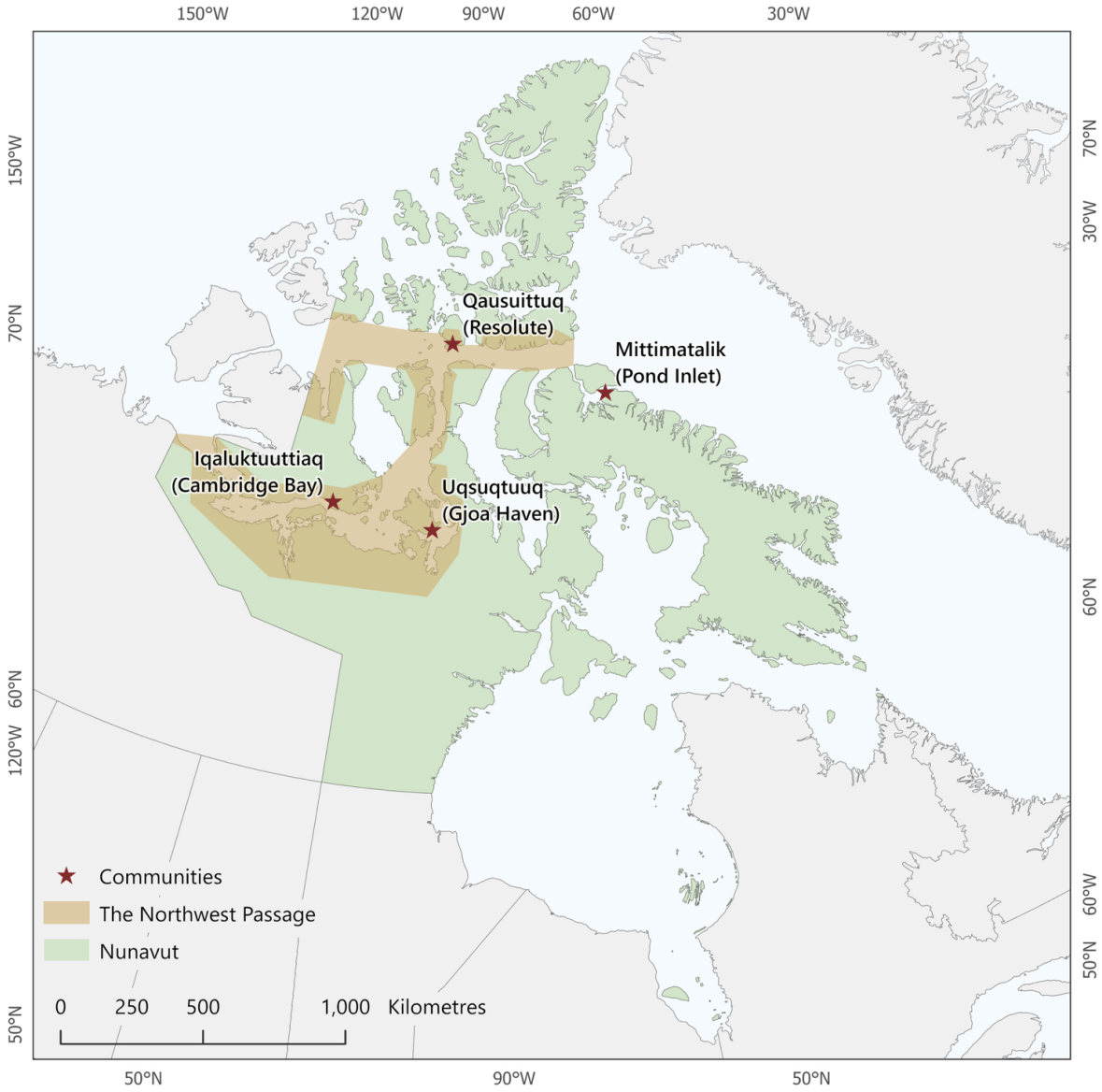


Figure 3. *Study area within Nunavut, Canada, highlighting the Northwest Passage shipping corridor and the four focal communities examined in this study: Mittimatalik (Pond Inlet), Qausuittuq (Resolute), Uqsuqtuuq (Gjoa Haven), and Iqaluktuuttiaq (Cambridge Bay).*

3. Methodology

3.1 Vessel Traffic Data

Shipping activity within the study area has been reconstructed using two complementary datasets covering the period 1990-2025. These datasets combine historical vessel reporting records with more recent satellite-based ship tracking systems to produce a comprehensive representation of vessel traffic across Nunavut.

For the period 1990-2010, vessel tracks reconstructed using historical ship position reports from the Canadian Coast Guard Northern Canada Vessel Traffic Services Zone (NORDREG) archive. These reports provide vessel locations at daily or sub-daily intervals for ships operating within Arctic waters. Since these reports contain discrete position records rather than continuous tracks, vessel routes are reconstructed using Least Cost Path (LCP) modelling to estimate the most plausible navigation route between reported vessel positions.

The LCP modelling approach uses a cost surface that incorporates environmental and navigational constraints affecting vessel movement. For example, the cost surface accounts for sea ice concentration, bathymetry, and distance from land, allowing the model to estimate realistic shipping pathways between known vessel locations.

For the period 2011-2025, vessel tracks were derived from Satellite Automatic Identification System (S-AIS) data. AIS systems transmit real-time vessel information such as vessel identity, geographic position, speed, and course. The AIS dataset used in this analysis was originally procured from exactEarth, followed by Spire Global, and more recently Kepler since 2025.

AIS position messages are processed to reconstruct vessel trajectories across the study region. Records are first sorted by Maritime Mobile Service Identity (MMSI) and timestamp. Quality control procedures are applied to remove erroneous records. Consecutive vessel positions were then connected using linear interpolation to generate continuous vessel track lines that represent ship movement throughout the region. Quality control procedures were applied to ensure that track segments intersecting land were corrected where possible or removed from the dataset.

The use of multiple datasets allows vessel activity to be reconstructed across both the pre-AIS reporting era and the modern satellite-based ship tracking period.

3.2 Ship-Source Noise Modelling

Ship-source underwater noise exposure in this study area is estimated using previously developed noise modelling outputs produced for NGMP. The modelling framework estimated the spatial distribution of underwater noise generated by vessel traffic and identifies areas where sound levels exceed thresholds associated with behavioural disturbance in marine mammals.

The modelling approach consists of three main steps. First, sound propagation across the study region was estimated using the acoustic propagation software dBSea 2.0. Propagation modelling accounted for environmental characteristics such as bathymetry and water depth, which influences how far sound travels through marine environments.

Second, vessel noise footprints are generated for individual ships using satellite AIS vessel track data. Ship tracks were reconstructed from AIS records and used to estimate the spatial extent of underwater noise produced by vessels as they moved through the region by combining the modelled source levels of different vessel classes and the modelled acoustic propagation values for different areas of the study region. Vessel noise footprints were produced for each ship operating within the study area between July and October from 2015 to 2018, representing the open-water season when vessel traffic is most active.

The resulting received sound levels from the vessel noise footprint were then compared against the RL120 behavioural disturbance threshold for marine mammals, as defined by NOAA (National Marine Fisheries Service, 2016). Areas where received sound levels exceeded this threshold were identified as potential zones of behavioural disturbance.

Finally, noise footprints from all vessels operating within each month were combined to estimate cumulative noise exposure. For each grid cell within the study area, the model calculated the number of times that the RL120 threshold was exceeded, representing the potential frequency of exposure to ship-generated underwater noise.

A full technical description of the ship-noise modelling framework was provided in Halliday and Dawson (2021).

3.3 Culturally Significant Marine Areas

Spatial data representing Culturally Significant Marine Areas (CSMAs) were used to identify locations of ecological and cultural importance within the study area. These areas were derived from the Arctic Corridors and Northern Voices project, a community-based research initiative that documents Inuit knowledge of marine environments and concerns around marine shipping across the Canadian Arctic (Carter et al, 2018).

CSMAs represent marine regions identified by Inuit communities as important for marine mammal presence, harvesting activities, travel routes, and other culturally significant uses. The areas are identified through community mapping workshops and participatory research conducted with residents from several Nunavut communities. As a result, these datasets provide spatial representations of marine environments that are both ecologically important for marine species and culturally significant for Inuit communities.

In this study, CSMA spatial polygons were used as indicators of significant marine environments where marine mammals such as whales, seals, and walrus are frequently present and harvested. These areas were used to assess potential overlap between important marine habitats and zones of elevated underwater noise generated by vessel traffic.

3.4 Spatial Analysis

Spatial analyses are conducted using ArcGIS Pro to examine the spatial relationship between ship-source underwater noise and sensitive marine areas within the study region.

Modelled RL120 noise exceedance raster layers, representing the number of times the behavioural disturbance threshold of 120 dB re 1 µPa is exceeded within each grid cell, were used to characterize the spatial distribution of potential ship-noise exposure. These raster datasets were overlaid with CSMA polygons to identify locations where increased underwater noise levels intersect with ecologically and culturally important marine environments.

To further examine potential exposure patterns, spatial analyses were conducted to summarize noise exceedance values within CSMA boundaries. This allows for the identification of areas

where marine mammals and important harvesting locations may experience greater levels of acoustic disturbances from vessel traffic.

These spatial comparisons provide an overview of where ship-source underwater noise overlaps with key marine habitats and community-identified marine areas across the Northwest Passage.

4. Results

4.1 Shipping Activity Across the Northwest Passage

Shipping activity across the NWP has expanded substantially over the past several decades. Track line density maps for three time periods (1990–2005, 2006–2015, and 2016–2025) illustrate how vessel traffic has evolved along these routes, highlighting areas of concentrated vessel activity (Figure 4).

As shown in Figure 4A, during the earliest period (1990–2005), vessel traffic was already focused along the main NWP corridor, near the eastern entrance of the passage through Lancaster Sound and along the southern route connecting the Beaufort Sea with communities in the Kitikmeot region.

Between 2006 and 2015, the overall spatial structure of vessel traffic remained similar, with ships continuing to follow the established NWP navigation routes as shown in Figure 4B. While some variation in track density is visible between the two periods, the primary shipping corridors remain consistent, showing that vessel movement is primarily constrained to a small number of channels within the NWP.

In most recent period (2016–2025) the concentration of vessel traffic along several sections of the passage (Figure 4C) is intensified, showing the spatial structure remains similar and track density increase. Increased track line density is most visible along the eastern entrance of the NWP near Pond Inlet and Lancaster Sound, as well as along parts of the southern NWP route near Cambridge Bay. These patterns suggest that the recent increases in vessel traffic occur mainly within existing navigation corridors rather than expanding into new areas of the passage.

Overall, the results indicate that shipping activity within the Northwest Passage remains very focused within the corridor, with most vessel activity occurring along the eastern entrance and key southern routes of the NWP but with increasing track density over time showing an overall increase in the number of transits.



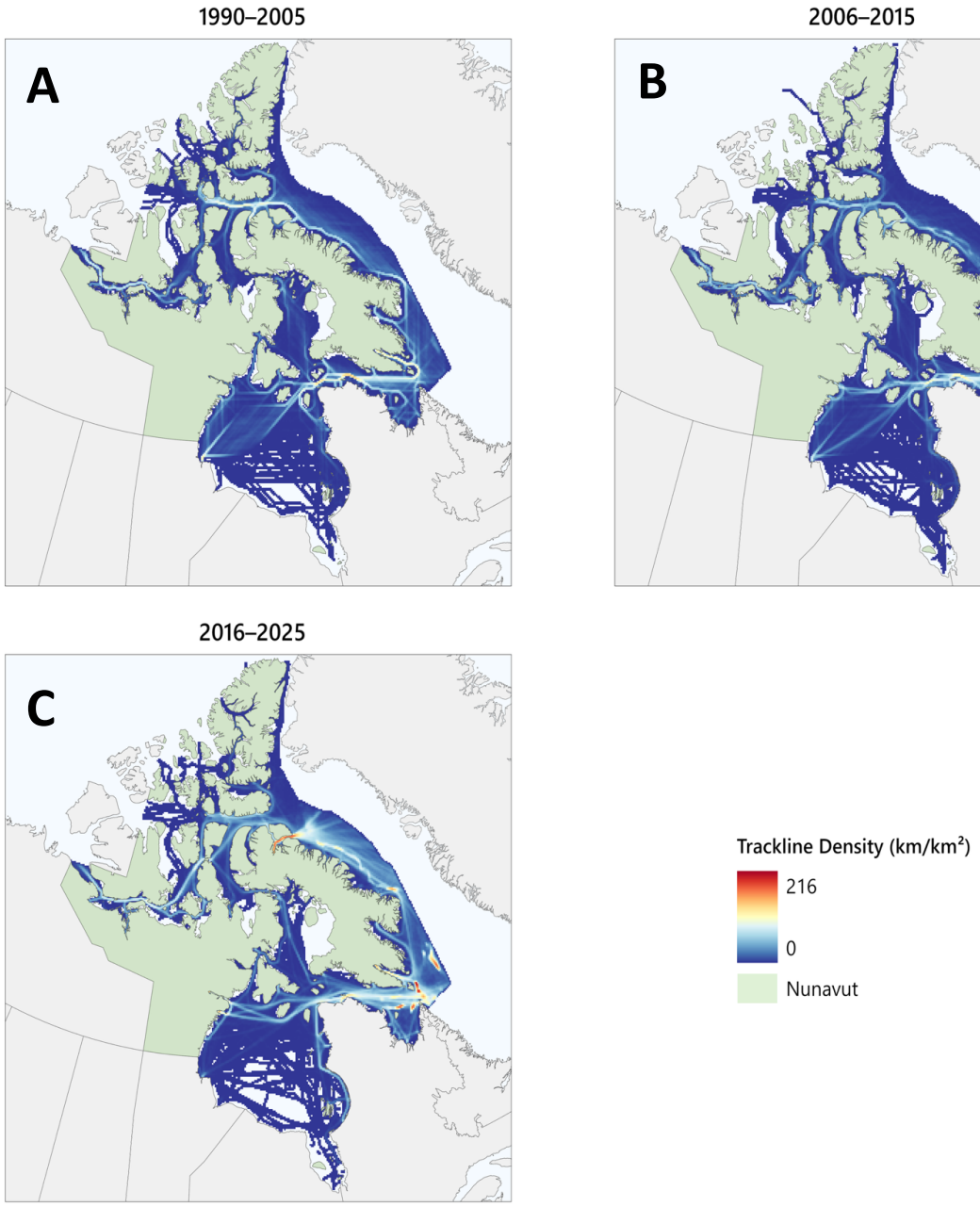


Figure 4. *Vessel track line density across the Northwest Passage for three time periods: 1990–2005, 2006–2015, and 2016–2025. Values represent cumulative vessel track density (km/km²).*

4.2 Community-Level Vessel Activity

To examine how vessel traffic varies near Nunavut communities located along the NWP, annual sailing distance was calculated within a 50 km radius of four communities selected in this study: Pond Inlet, Gjoa Haven, Resolute and Cambridge Bay (Figure 5).

Pond Inlet exhibits the most pronounced increase in vessel activity over the study period (Figure 5A). Vessel travel distances remained relatively low prior to the mid-2010s but increased drastically beginning around 2016, with peak activity taking place between 2017 and 2019 caused by vessels from the Baffinland Mary River Iron Ore Mine, when annual sailing distance exceeds 30,000 km within the community buffer (Baffinland Iron Mines Corporation, 2018).

Gjoa Haven shows a gradual increase in vessel activity over time (Figure 5B). Vessel travel distances remained low prior to the early 2000s but increased starting around 2006 and in subsequent years, reaching approximately 4,000- 4,500 km annually in the 2020s. This increase likely reflects broader changes in Arctic shipping associated with reduced sea ice and increasing commercial, government, and tourism activity in the region (Pizzolato et al., 2016; Carter et al., 2018).

Resolute shows a low and variable vessel activity throughout the study period (Figure 5C). Vessel travel distances fluctuated across years, with slightly higher activity in the 1990s followed by a decline and occasional short-term fluctuations in recent years. This pattern reflects the limited range of vessel traffic in the area, which is largely restricted to community resupply, Canadian Coast Guard and naval vessels, with no cruise activity.

Cambridge Bay shows a long-term increase in vessel activity (Figure 5D). Sailing distance within the community buffer increased gradually beginning in the mid-2000s and continues to increase in recent years, reaching values approaching 10,000 km annually. This trend reflects growing use of the southern Northwest Passage corrido for community resupply and regional marine transportation, as well as increased cruise tourism and transiting vessels using the NWP as a route through the Canadian Arctic.

Overall, vessel activity within the NWP is unevenly distributed across communities, with the most substantial increase occurring near Pond Inlet and a moderate increase around Cambridge Bay, both of which are located along major NWP navigation corridors.



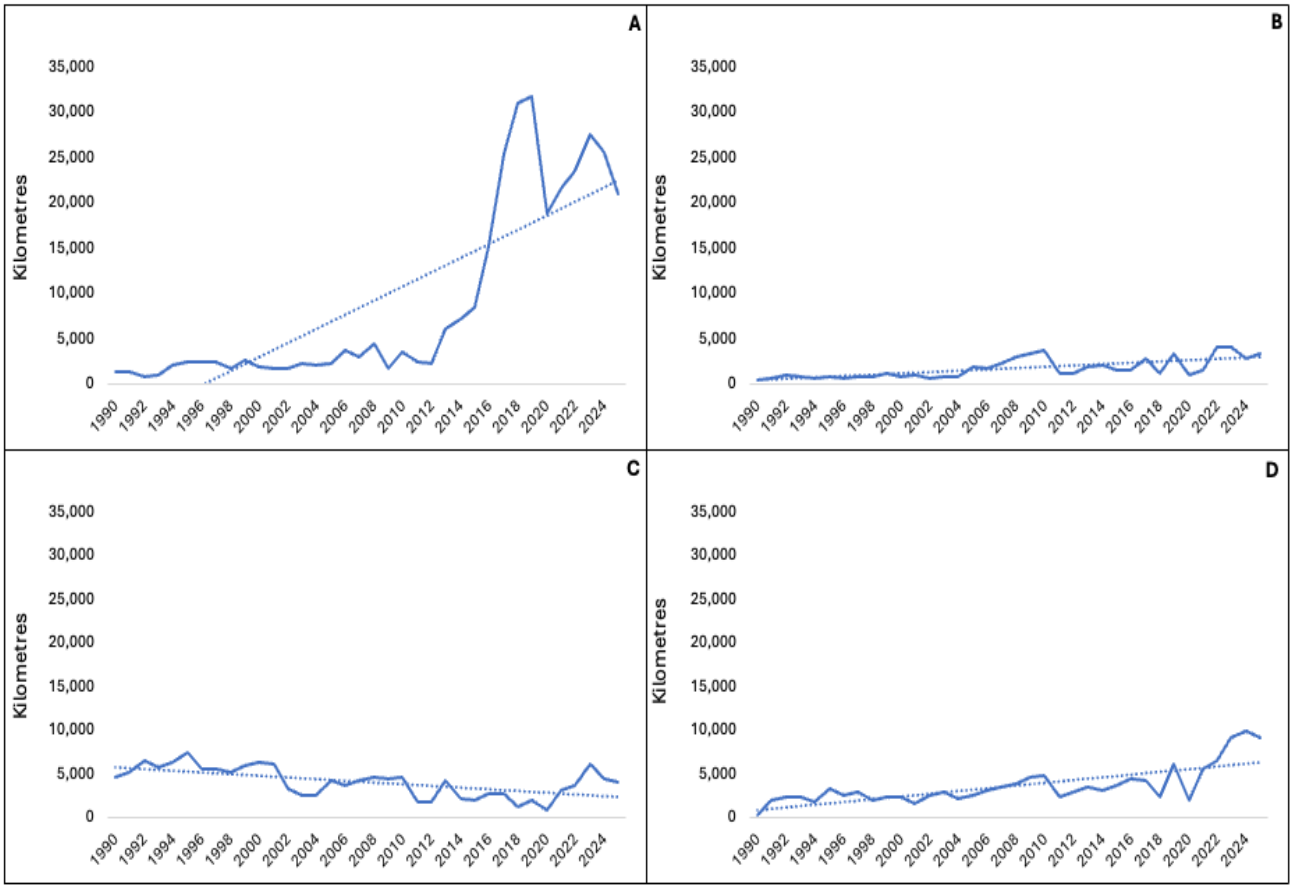


Figure 5. *Annual vessel sailing distance within a 50 km radius of four Nunavut communities along the Northwest Passage from 1990–2025. Panels show trends for (A) Pond Inlet, (B) Gjoa Haven, (C) Resolute, and (D) Cambridge Bay. Dotted lines indicate linear trendlines illustrating long-term changes in vessel activity near each community.*

4.3 Spatial Distribution of Ship Noise

The spatial distribution of modelled ship-source underwater noise across the NWP shows a clear correlation with major vessel navigation corridors. Figure 6 shows RL120 noise exceedance values for September 2017, representing the number of times the behavioral threshold of 120 dB re 1 µPa is exceeded within each grid cell.

Noise exceedance values are highest along primary shipping corridors of the NWP. Elevated noise exposure is visible along the eastern entrance of the NWP near Lancaster Sound and Pond Inlet, where vessel traffic entering and exiting the Canadian Arctic is concentrated. High exceedance values are also evident along the southern NWP route passing through Cambridge Bay and the central Kitikmeot region.

In contrast, much of the surrounding marine environment shows relatively low RL120 exceedance values, indicating limited vessel activity outside of these main corridors. These results highlight

that underwater noise exposure across the NWP is strongly concentrated along established shipping routes rather than evenly distributed throughout the region.

Overall, the spatial distribution of RL120 exceedances closely mirrors observed vessel traffic patterns, with the highest noise exposure occurring in areas where shipping activity is most concentrated.

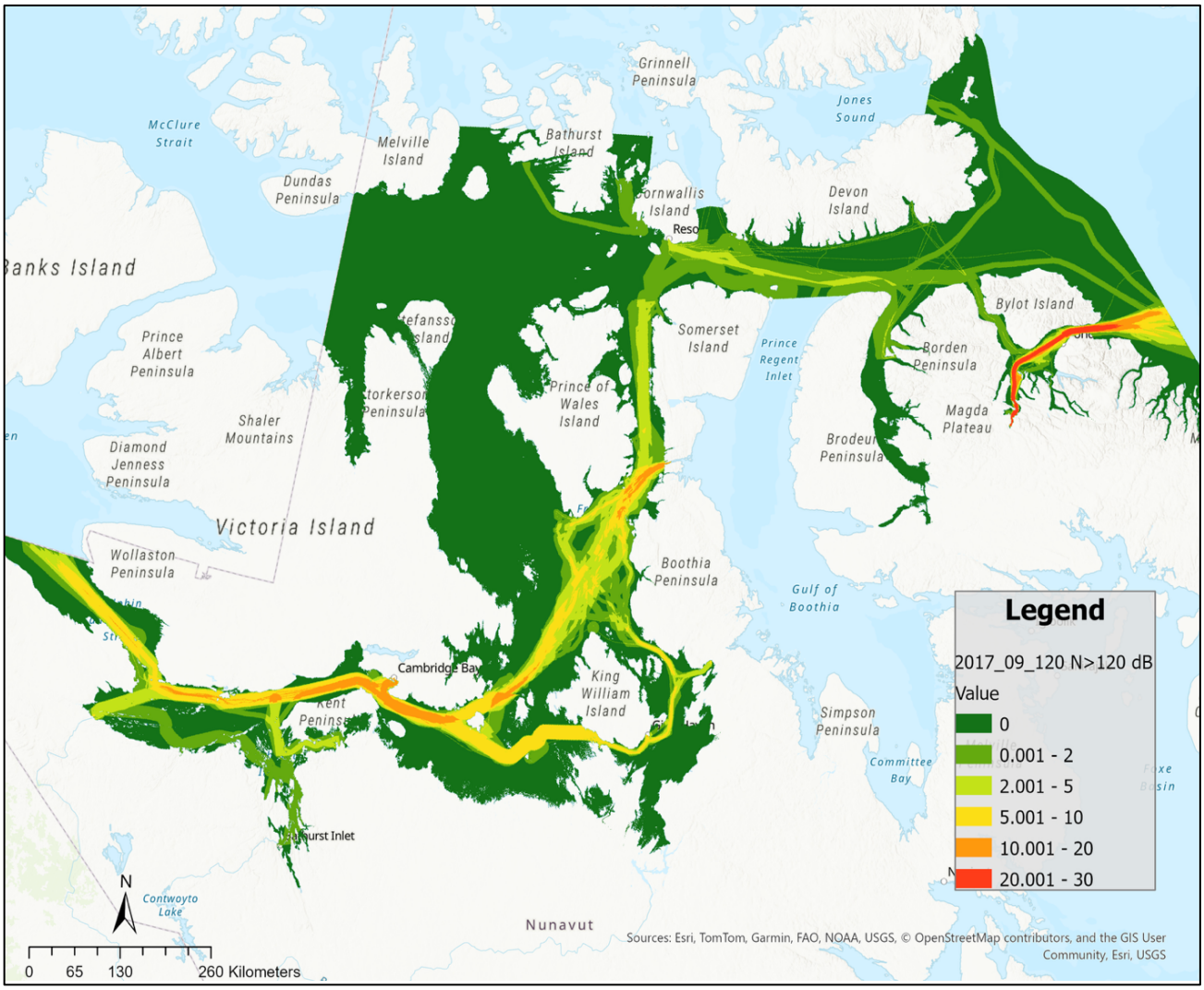


Figure 6. *Modelled ship-source underwater noise exceedance (RL120) across the Northwest Passage during September 2017. Values represent the number of times the behavioral disturbance threshold was exceeded (120 dB re 1 µPa).*

This relationship is further supported by a positive correlation between vessel activity and noise exposure (Figure 7).

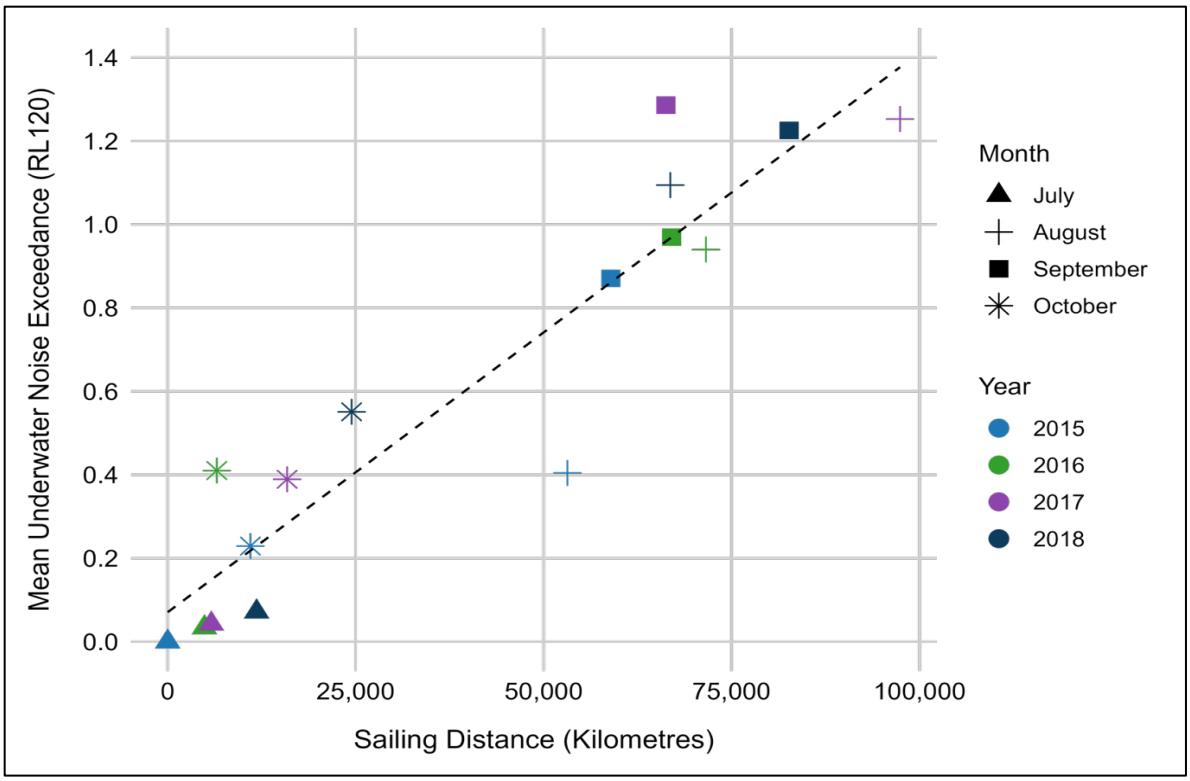


***Figure** 7. Relationship between total sailing distance (km) and RL120 exceedance values across the Northwest Passage. The positive trend indicates that higher vessel activity is associated with increased underwater noise exposure.*

Figure 7 shows a clear positive relationship between vessel activity and underwater noise exposure across the Northwest Passage. As total sailing distance increases, RL120 exceedance values also rise, indicating that areas with more vessel traffic experience more frequent exceedances of the 120 dB re 1 µPa threshold. This relationship is supported by a strong correlation between monthly sailing distance and mean RL120 exceedance during the open-water season (July–October) from 2015 to 2018 (Spearman's $\rho = 0.91$, $p < 0.001$; Pearson's $r = 0.93$, $p < 0.001$). Together, these results confirm that underwater noise is concentrated in areas with higher shipping activity and support the use of vessel activity as a proxy for ship-source noise in periods where modelled noise data are not available. The data used to generate this relationship are provided in Appendix A (Table A1).

4.4 Vessel Activity within Culturally Significant Marine Areas

Vessel activity within CSMAs is assessed to better understand how shipping patterns have changed in regions identified by Nunavut communities as ecologically and culturally important.

Across all four communities, vessel traffic occurs within CSMAs throughout the study period, with overall activity increasing over time. However, the magnitude and timing of vessel presence vary among regions. CSMAs also differ in spatial extent and ecological function across communities and between seasons, reflecting locally identified harvesting areas, travel routes, and important marine mammal habitats and as such have important seasonal variations.

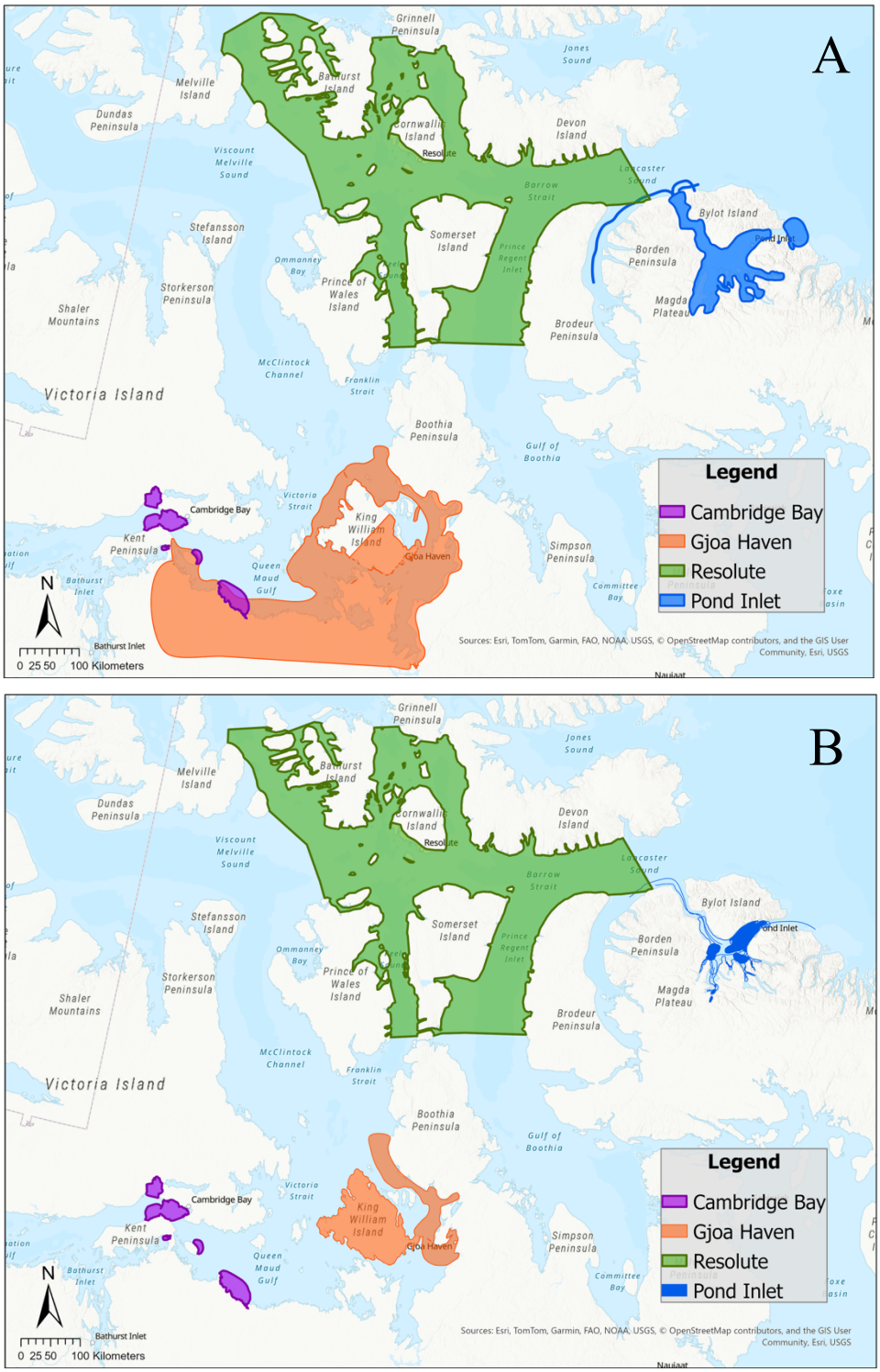


Figure 8. *Culturally Significant Marine Areas (CSMAs) identified by Nunavut communities along the Northwest Passage. Panel (A) shows open-water conditions and Panel (B) shows freeze-up conditions. These areas represent regions of ecological and cultural importance, including key marine mammal habitat, migration routes, and harvesting areas.*

CSMAs associated with Pond Inlet include areas identified as important for narwhal, seal, and walrus. Harvesting of narwhals and seals takes place as well as migration of all three mammals. These areas cover approximately 13,668 km² during open-water conditions and decrease to 4,210.12 km² during freeze-up.

CSMAs near Resolute include extensive areas identified for beluga, and narwhal use, bowhead migration and as well as walrus and seal feeding, pupping and calving habitats. These areas are also associated with harvesting of beluga, narwhal, walrus and seals. The open-water CSMAs cover approximately 119,605 km², with freeze-up areas remaining similarly large at 114,836 km². These areas are substantially larger than those defined for other communities, and as a result, higher levels of vessel activity observed within the Resolute CSMAs may in part reflect their larger spatial extent rather than increased vessel intensity alone.

The CSMAs associated with Gjoa Haven represent important areas for seal harvesting, as well as narwhal migration, and walrus and bowhead whale use. These areas cover approximately 93,422 km² during open-water conditions and decrease to 21,634 km² during freeze-up.

CSMAs near Cambridge Bay are smaller and more localized, representing areas used primarily for seal harvesting. These areas cover approximately 4,234 km² under both open-water and freeze-up conditions.

Table 2. *Spatial extent and ecological characteristics of culturally significant marine areas across four Nunavut communities along the Northwest Passage.*

Community	Open-water area (km2)	Freeze-up area (km2)	Key species and activities
Pond Inlet	13,668	4,210	Narwhal, seals, walrus harvesting; migration
Resolute	119,605	114,836	Beluga, narwhal, walrus, seals, bowhead: feeding, calving, harvesting, and migration
Gjoa Haven	93,422	21,634	Seal, walrus, bowhead, narwhal migration; harvesting
Cambridge Bay	4,234	4,234	Seals; harvesting

Figure 9 presents the total sailing distance travelled by vessels within CSMAs associated with four communities along the Northwest Passage (NWP): Pond Inlet (A), Resolute (B), Gjoa Haven (C), and Cambridge Bay (D). Vessel activity is shown by vessel class for the period 1990–2025.

Within the Pond Inlet CSMA (Figure 9A), vessel activity remains relatively low through the 1990s and early 2000s but increases after approximately 2013, with a sharp increase after 2016. This increase is primarily driven by general cargo vessels, pleasure craft, and passenger vessels. In recent years, total sailing distance within the Pond Inlet CSMA increases substantially, indicating that vessel traffic frequently occurs within this culturally significant area near the eastern entrance of the Northwest Passage.

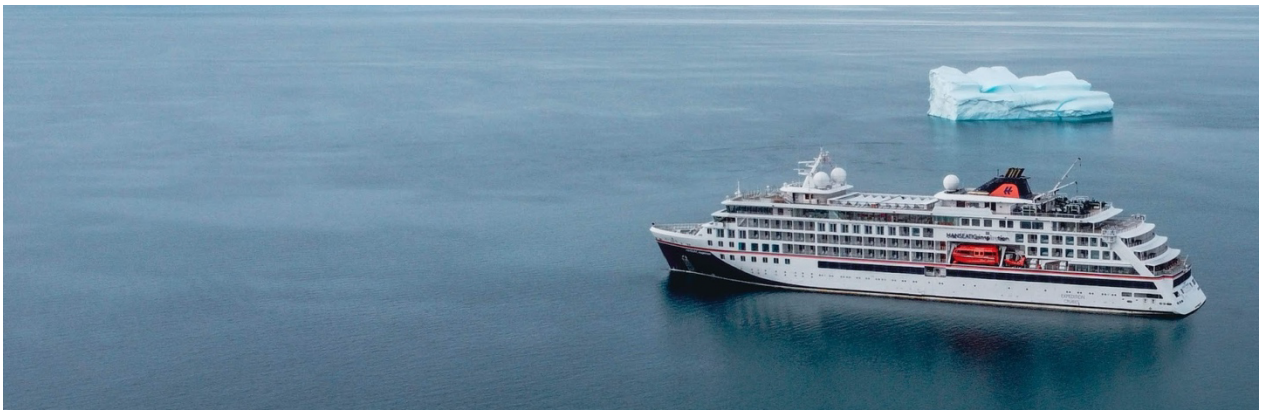
The Resolute CSMA (Figure 9B) shows the highest levels of vessel activity among the four communities and a gradual increase across the study period, with a notable rise after 2020. Vessel presence is observed throughout the 1990s and early 2000s, primarily associated with government vessels and general cargo vessels. In later years, passenger vessels and pleasure craft become more prominent. The relatively high level of activity indicates that vessels regularly travel within the CSMAs located along central Northwest Passage routes.

Within the Gjoa Haven CSMA (Figure 9C), vessel activity is lower than that observed in Pond Inlet and Resolute but remains present throughout the study period. Periodic increases in vessel traffic occur during the late 2000s, around 2015, and again in the early 2020s. Vessel presence within this area is primarily associated with cargo vessels, government vessels, and tug/barge operations, indicating that shipping periodically occurs within the CSMAs.

Vessel activity within the Cambridge Bay CSMA (Figure 9D) shows comparatively low levels of vessel activity across the study period. Vessel traffic in this region is dominated by tug/barge operations, general cargo vessels, and government vessels, with occasional contributions from other vessel classes. Activity gradually increases in the mid-2010s, consistent with broader growth in Arctic shipping along the southern route of the Northwest Passage. However, overall sailing distances within the Cambridge Bay CSMA remain lower than those observed in the other communities.

For all four communities, vessel activity within culturally significant marine areas has generally increased over the past three decades. The highest levels of activity occur in the Resolute CSMA**,** followed by Pond Inlet CSMA, while Gjoa Haven and Cambridge Bay CSMA experience comparatively lower but persistent levels of vessel traffic. These patterns indicate that vessel activity increasingly overlaps with areas identified by Nunavut communities as ecologically and culturally important.

Compared to the 50 km community buffers, these trends reflect differences in how the areas are defined. CSMAs are community-identified and often encompass larger, spatially targeted regions associated with key harvesting areas, travel routes, and marine mammal habitat, whereas the buffers represent fixed-distance zones around communities. As a result, CSMAs more directly capture areas where vessel traffic and ecologically important use overlap, leading to different patterns of observed activity.



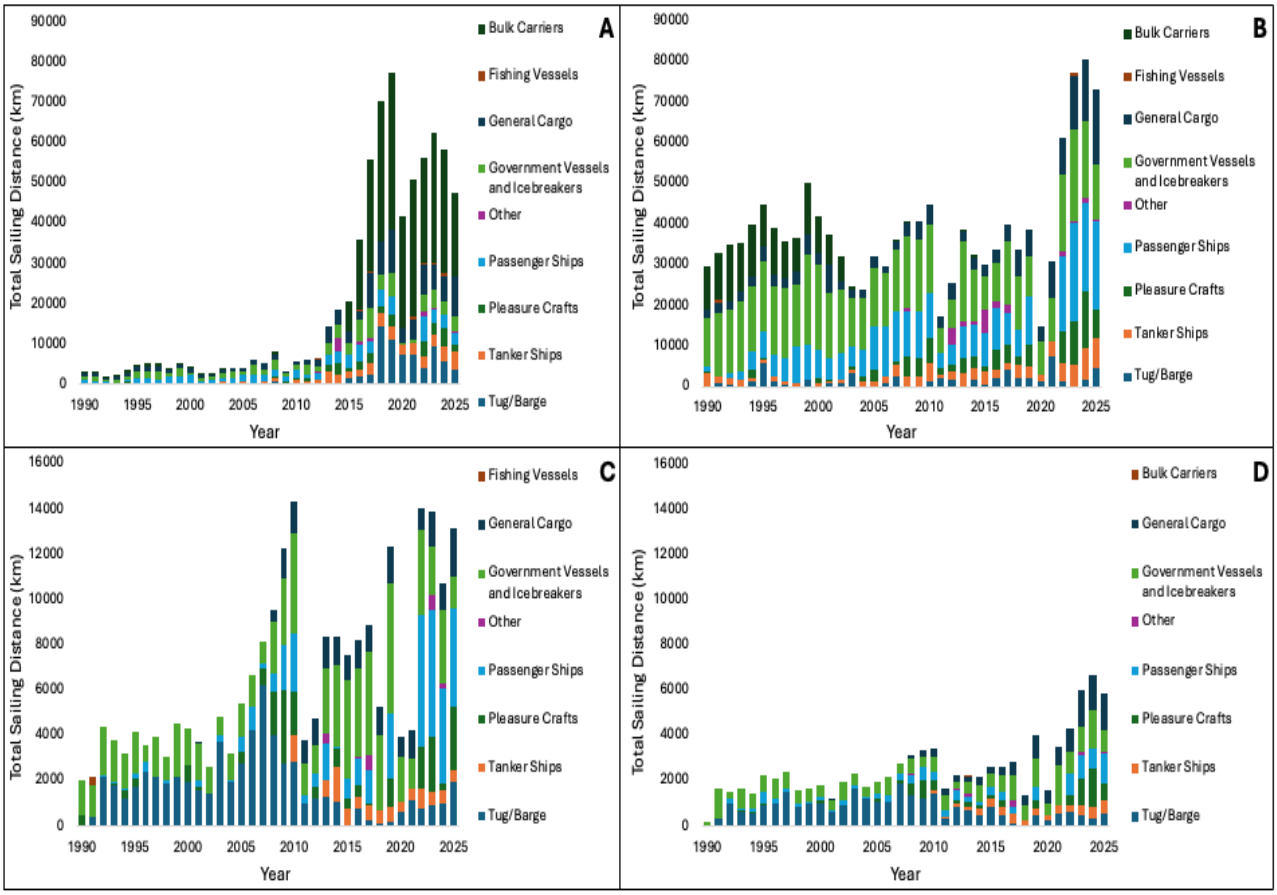


Figure 9. *Annual vessel activity within culturally significant marine areas (CSMAs) associated with four Nunavut communities along the Northwest Passage from 1990–2025. Stacked bars represent the total sailing distance travelled within each CSMA by vessel class. Panel (A) shows vessel activity within the Pond Inlet CSMA, Panel (B) Resolute, Panel (C) Gjoa Haven, and Panel (D) Cambridge Bay. Vessel classes include bulk carriers, fishing vessels, general cargo, government vessels and icebreakers, passenger ships, pleasure craft, tanker ships, tug/barge operations, and other vessel types.*

4.5 Overlap with Culturally Significant Marine Areas

Modelled ship-source underwater noise is compared with CSMAs identified by Nunavut communities to assess potential exposure of sensitive marine environments to vessel-generated noise. These areas represent locations of ecological and cultural importance, including regions used by marine mammals such as whales and pinnipeds.

Figure 10 shows the spatial overlap between RL120 noise exceedance and CSMAs across the NWP. Panel (A) shows overlap with open-water CSMAs using September 2017 noise conditions, while panel (B) shows overlap with freeze-up CSMAs using October 2017 conditions.

Under open-water conditions, several CSMAs intersect with major shipping corridors of the NWP. Notable areas of overlap occur near Pond Inlet and Lancaster Sound, where vessel traffic entering the eastern gateway of the NWP produces elevated RL120 exceedance values. Additional areas of overlap are visible along the southern NWP route near Cambridge Bay and within passages surrounding King William Island, showing that vessel traffic regularly passes through or close to CSMAs.

During freeze-up conditions, the spatial extent of RL120 exceedance decreases slightly as vessel activity becomes more limited. However, several CSMAs continue to experience noise exposure along established navigation corridors, particularly near Pond Inlet and slightly southwest of Cambridge Bay.



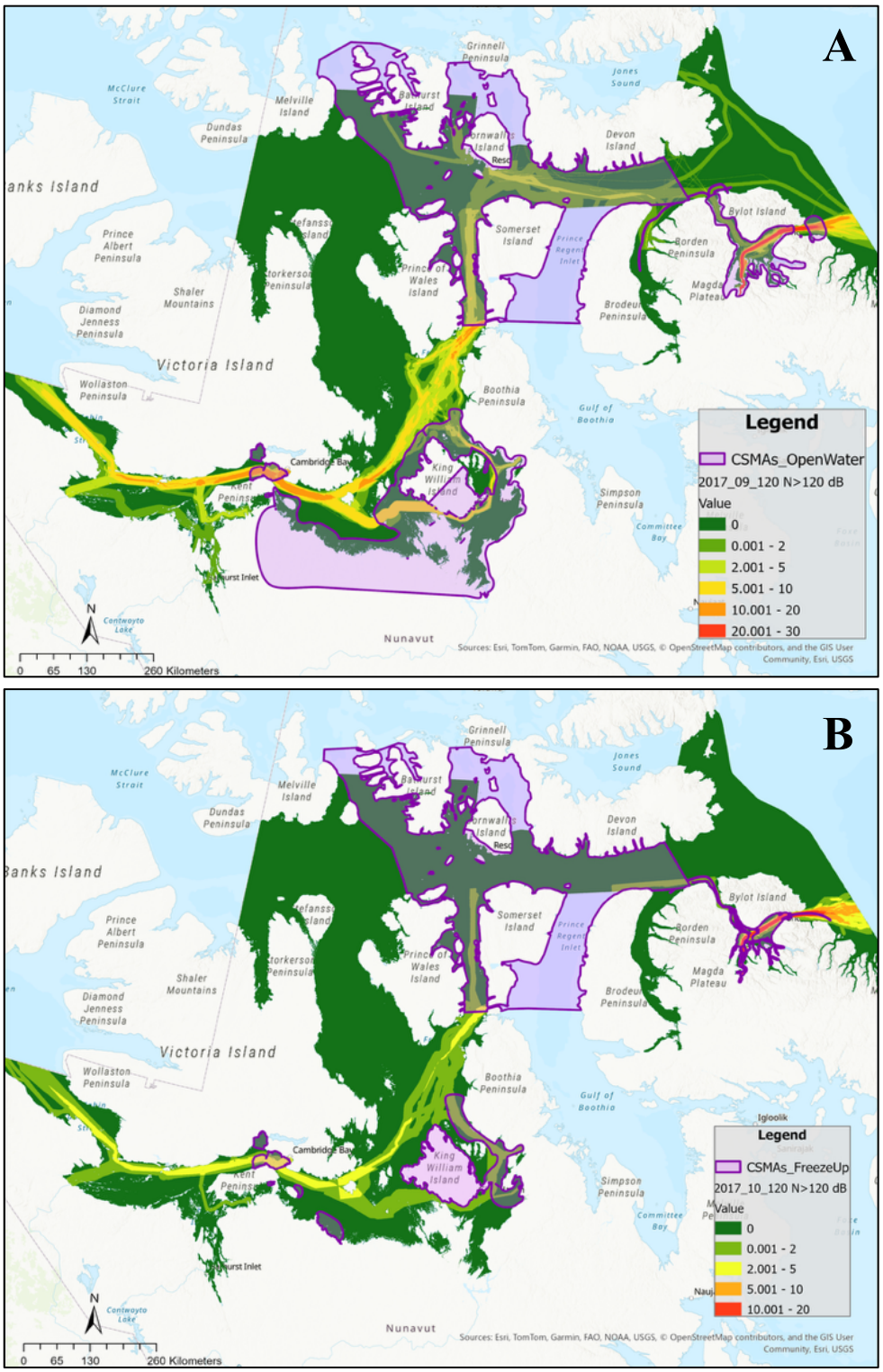


Figure 10. *Spatial overlap between modelled ship-source underwater noise exceedance (RL120) and Culturally Significant Marine Areas (CSMAs) across the Northwest Passage. Panel (A) shows overlap with open-water CSMAs using September 2017 noise conditions, while panel (B) shows overlap with freeze-up CSMAs using October 2017 noise conditions.*

Seasonal mean exposure values within mammal habitat areas associated with these CSMAs further show differences in noise exposure among communities (Table 3). The highest exposure levels occur near Pond Inlet, where mean RL120 exceedance values increase from 1.65 in 2015 to 6.10 in 2018 for whales, and from 1.70 to 6.28 for pinnipeds. In contrast, communities located farther from the eastern entrance of the Northwest Passage, including Resolute and Gjoa Haven, exhibit consistently low exposure levels throughout the study period, generally remaining below 0.5 RL120 exceedances. However, Cambridge Bay shows moderate exposure values where mean exceedance values range between 0.79 and 1.3. These results indicate that marine mammal habitat areas near Pond Inlet and Cambridge Bay experience greater noise exposure than the other regions in the study area.

Table 3. *Seasonal mean of modelled ship-source underwater noise exceedance (RL120) within whale habitat areas associated with Nunavut communities along the Northwest Passage (2015–2018). Values represent the number of times threshold for behavioral disturbances in marine mammals was exceeded (120 dB re 1 u). Cambridge Bay is excluded because there were no areas identified for whales.*

Community	2015 (mean)	2016 (mean)	2017 (mean)	2018 (mean)	Std. Dev.
Pond Inlet	1.65	3.36	5.66	6.10	2.08
Resolute	0.18	0.40	0.33	0.27	0.09
Gjoa Haven	0.20	0.24	0.33	0.23	0.06

Table 4. *Seasonal mean RL120 noise exceedance within pinnipeds habitat areas associated with Nunavut communities along the Northwest Passage (2015–2018). Values represent the mean number of times the threshold for behavioral disturbance in marine mammals was exceeded (120 dB re 1 u).*

Community	2015 (mean)	2016 (mean)	2017 (mean)	2018 (mean)	Std. Dev.
Pond Inlet	1.70	2.97	5.31	6.28	2.05
Resolute	0.21	0.38	0.36	0.31	0.08
Gjoa Haven	0.26	0.34	0.34	0.27	0.04
Cambridge Bay	1.15	1.28	1.32	0.79	0.25

These results show that marine mammal habitat areas near Pond Inlet and Cambridge Bay experience greater exposure to vessel-generated underwater noise, while communities located farther from major shipping corridors experience comparatively lower levels of exposure.

To account for differences in the size and spatial extent of CSMAs, a standardized 50 km buffer is also used to assess noise exposure around each community. This allows for more direct comparison of noise levels across regions.

Table 5. *Annual sailing distance (km) within 50 km of selected Nunavut communities along the Northwest Passage (2015–2018).*

Community	2015 (km)	2016 (km)	2017 (km)	2018 (km)	Std. Dev.
Pond Inlet	8524	15260	25324	31011	10062
Resolute	2062	2663	2723	1230	694
Gjoa Haven	1596	1531	2902	1225	743
Cambridge Bay	3740	4384	4233	2371	916

Vessel activity within 50 km of Nunavut communities shows clear spatial and temporal variation between 2015 and 2018, with patterns that align closely with observed underwater noise exposure (Table 5). Pond Inlet experiences the highest and most rapidly increasing sailing distances, rising from 8,524 km in 2015 to over 31,000 km by 2018, and shows the greatest variability (Std. Dev. = 10,062 km). This corresponds with the elevated RL120 exceedance values identified in this region, indicating that higher vessel activity is associated with increased underwater noise exposure. In contrast, Resolute and Gjoa Haven exhibit comparatively low and more variable levels of vessel activity, consistent with the lower noise exceedance values observed in these areas. Cambridge Bay shows moderate activity with some interannual variability, reflecting intermediate noise exposure. Overall, these results reinforce that differences in vessel traffic intensity are a key driver of spatial patterns in underwater noise across the Northwest Passage.

5. Discussion

5.1 Key Patterns of Noise Exposure in the NWP

The results of this study show a clear increase in ship-source underwater noise exposure across the Northwest Passage (NWP), which is consistent with the long-term growth in vessel activity observed across Nunavut waters. As shown in Figure 1 and Figure 2, total sailing distance has increased substantially since the 1990s, with the most pronounced growth occurring after the mid-2010s. This trend is consistent with previous studies linking increased Arctic shipping to declining sea ice and expanding navigation opportunities (Kwok, 2018; Dawson et al., 2022; Pizzolato et al., 2016).

Noise exposure across the NWP is not evenly distributed, but instead closely matches the structure of major shipping corridors. As shown in Figure 6, the highest RL120 exceedance values occur along primary navigation routes, particularly near the eastern entrance of the NWP around Pond Inlet and Lancaster Sound, as well as along southern routes near Cambridge Bay and through the Kitikmeot region. This corridor-focused pattern reflects the physical constraints of Arctic navigation through narrow channels within the archipelago (Dawson et al., 2018; Carter et al., 2018).

Community-level results further highlight how noise exposure varies spatially across the NWP and its overlap with culturally significant marine areas (CSMAs). The most substantial increases in vessel activity are observed near Pond Inlet, where sailing distance rises sharply after approximately 2016 and reaches the highest levels among the four communities (Figure 5A). This

increase is reflected in nearby marine mammal habitat areas, where mean RL120 exceedance values increase steadily from 2015 to 2018 for both whales and pinnipeds (Tables 3 and 4). Gjoa Haven exhibits lower and more variable levels of activity, while Cambridge Bay shows moderate increases over time consistent with growing use of the southern NWP route. These patterns suggest that exposure is becoming increasingly concentrated in key community-adjacent regions.

Across all four communities, vessel activity within CSMAs increases over time, demonstrating a growing spatial overlap between shipping corridors and areas identified as ecologically and culturally important. Spatial overlap analysis further shows that several CSMAs intersect with areas of elevated RL120 exceedance (Figure 10).

Together, these findings show that ship-source underwater noise exposure in the NWP is characterized by three main patterns:

(1) increasing exposure over time linked to growth in vessel activity,
(2) strong spatial concentration along established shipping corridors, and
(3) increasing overlap with culturally significant marine areas.

These patterns confirm that noise exposure is not uniform across the region but is instead concentrated in specific locations where vessel traffic and sensitive marine environments intersect.

5.2 Implications for Marine Mammals and Inuit Subsistence and Cultural Activities

Ship-source underwater noise has the potential to affect marine mammals in the NWP by altering their behaviour where vessel activity overlaps with important habitats. Results from this study show that noise exposure is concentrated along major shipping corridors and within culturally significant marine areas (CSMAs), indicating that marine mammals in these regions may experience repeated exposure to vessel-generated noise.

Arctic marine mammals are highly sensitive to underwater noise, and vessel-generated sound can interfere with communication and behaviour due to its overlap with biologically important frequencies (Halliday et al., 2017). Behavioural responses to vessel noise are documented across Arctic species. Beluga whales, for example, exhibit strong avoidance responses to icebreaking vessels at distances of tens of kilometres, while narwhals may respond by reducing movement and vocalisations (Lancaster et al., 2021). Bowhead whales have also demonstrated avoidance and displacement responses at distances of several kilometres, even at relatively low noise levels (Lancaster et al., 2021). Together, these findings indicate that vessel noise can lead to behavioural disturbance across multiple species.

Pinnipeds, including seals and walrus, respond to vessel activity and associated underwater noise through a range of behavioral changes. These responses include flushing from haul-out sites, increased alertness, and head-raising behaviours in the presence of vessels, as well as alterations in diving behaviour when exposed to underwater noise (Erbe et al., 2019). Studies also show that vessel noise can overlap with pinniped vocalizations and may lead to changes in vocal behavior or movement away from noisy areas, indicating potential avoidance responses (Erbe et al., 2019). In some cases, pinnipeds spend less time in areas with higher vessel activity, suggesting that repeated exposure to noise may influence spatial distribution patterns (Erbe et al., 2019).

When considered alongside the results of this study, these findings suggest that areas experiencing repeated RL120 exceedance, particularly near Pond Inlet and along key NWP corridors, may correspond to locations where marine mammals are more likely to experience disturbance. Since these areas overlap with important habitat and migration routes, repeated exposure to vessel noise leads to displacement from key areas, changes in movement patterns, and reduced foraging efficiency.

These ecological impacts also have important implications for Inuit subsistence harvesting. Marine mammals such as whales, seals, and walrus are critical to food security and cultural practices across Nunavut. Changes in marine mammal distribution, behaviour, or migration timing may affect the availability and predictability of species used for harvesting (Huntington et al., 2016), which is a legal right for Inuit as outlined in Article 5 in the Nunavut land claim agreement (Nunavut Tungavik 1993). Given that many areas experiencing increased vessel activity and noise exposure are located near communities and within CSMAs, vessel traffic may influence harvesting conditions, particularly if animals avoid areas that are traditionally used for hunting.

Overall, increasing vessel activity in the NWP, combined with the high sensitivity of Arctic marine mammals to underwater noise, suggests a growing risk of acoustic disturbance in areas that are both ecologically and culturally important.

5.3 Limitations

This analysis is subject to several limitations related to data and modelling assumptions. Ship-noise exposure was assessed using modelled RL120 exceedance, which represents a generalized behavioral disturbance threshold and does not account for species-specific sensitivity or context-dependent responses. Vessel traffic data were reconstructed from multiple sources, including historical NORDREG records and AIS data, which may introduce inconsistencies in spatial and temporal coverage across the study period. In addition, culturally significant marine areas (CSMAs) represent important locations identified through community knowledge but may not capture all areas used by marine mammals or all spatial and temporal variations in habitat use. As a result, the findings presented here provide a broader scale assessment of potential exposure rather than precise estimates of behavioral impact.

6. Recommendations and Conclusions

Results from this study show that ship-source underwater noise in the Northwest Passage is increasing over time and is strongly concentrated along key shipping corridors, with growing overlap in culturally significant marine areas. These patterns highlight a potential for increasing acoustic disturbance in regions that are both ecologically important for marine mammals and central to Inuit subsistence practices. The recommendations outlined above provide practical pathways to better manage these risks by aligning monitoring, policy, and community knowledge. As Arctic shipping continues to expand, integrated and adaptive approaches will be essential to reduce impacts on marine ecosystems and northern communities (Table 6).

Table 6. *Recommendations, rationale and potential actions and policy context.*

Recommendation	Rationale	Potential Actions & Policy Context
Prioritize management for high-exposure areas	Noise exposure and vessel activity are concentrated along key corridors, particularly near Pond Inlet and along central and southern NWP routes, with increasing overlap in CSMAs.	Align management with emerging federal initiatives, including Canada's Ocean Noise Strategy and Transport Canada's Proactive Vessel Management initiative, by identifying high-risk zones for targeted mitigation and surveillance.
Incorporate seasonal patterns into management approaches	Noise exposure is concentrated during peak navigation periods, increasing the likelihood of repeated disturbance in sensitive areas.	Explore seasonal management measures (voluntary slowdowns, areas to be avoided, corridors, timing restrictions, etc) consistent with International Maritime Organization underwater noise mitigation guidance.
Promote vessel-based noise reduction strategies	Vessel noise is the primary driver of observed exposure patterns, particularly along major corridors.	Adoption of quieter vessel technologies and design improvements.
Expand research and monitoring of ship-noise impacts	Current analysis identifies spatial exposure patterns but does not capture species-specific responses or long-term cumulative effects.	Support continued monitoring through various programs and Arctic Council initiatives to inform future updates to Arctic shipping policy, including the Polar Code (International Code for Ships Operating in Polar Waters)

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APPENDIX A

Below is the data used to generate Figure 7 (vessel activity and RL120 relationship)

Table A1. Monthly sailing distance (km) and mean RL120 exceedance across the Northwest Passage during the open-water season (July–October), 2015–2018. These values were used to generate the correlation shown in Figure 7.

Year	Month	Sailing Distance (km)	Mean RL120
2015	July	20.89057	0
2015	August	53,167	0.404
2015	September	58,949	0.871
2015	October	11,022	0.229
2016	July	4,913	0.034
2016	August	71,593	0.940
2016	September	67,033	0.970
2016	October	6,548	0.410
2017	July	5,825	0.043
2017	August	97,402	1.253
2017	September	66,268	1.286
2017	October	15,900	0.389
2018	July	11,845	0.072
2018	August	66,851	1.094
2018	September	82,655	1.225
2018	October	24,478	0.551