A FRAMEWORK FOR CUMULATIVE RISK ASSESSMENT FOR MARINE SHIPPING: A CASE STUDY IN THE KITIKMEOT REGION

by

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Abstract

The shortening of sea ice in the summer season has caught the attention of the global shipping community due to the potential of the Northwest Passage (NWP) through the Canadian Arctic becoming a shorter and cheaper alternative route to the Panama Canal. This growing utilization of the Arctic ocean could pose increasing risks to the marine animals in this region, such as noise pollution and potential oil spills. Within this context, a framework for cumulative risk assessment (CRA) of shipping stressors to marine receptors has been developed based on an existing algorithm [31]. The framework is composed by spatial, modelling and uncertainty methods and provides a means to combine different stressors-receptors into one single risk equation and presents the results in a simple visualization format using Geographic Information System (GIS) software. Additionally, this study includes an illustrative case study applied to the Kitikmeot region for shipping seasons. The stressors and receptors selected for the case study were based on local communities concerns, as documents by Carter et al. (2018). As the basis for the case study, ship-source oil spills and noise pollution are considered to be two of the shipping stressors of greatest concern among the Northern communities. As for receptors, Beluga, Bowhead and Narwhals were included in the analysis because Inuit communities rely on them for their food security through their traditional subsistence hunting and also their cultural importance to these communities. The results from the case study can be used to determine which sections of the proposed Corridors require more elaborated monitoring and regulating to reduce the impacts from vessels for a long-term safety of these marine mammals and consequently the local communities. It can also help with the allocation of public resources for risk mitigation by identifying which areas of Kitikmeot region are most at risk. Ultimately, this study also shows the benefit of including Traditional Knowledge in scientific decision models in order to gain more meaningful insights on the valuable Arctic marine ecosystem.

Key words: *Canadian Arctic, Risk assessment, shipping, noise pollution, oil spill.*

List of Abbreviations and Symbols Used

AIS Automated Identification System.

AN Ambient Noise.

BC Black carbon.

CCG Canadian Coast Guard.

CCME Canadian Council of Ministers of the Environment.

CDF Cumulative Density Function.

CEA Cumulative Effects Assessment.

CHS Canadian Hydrographic Service.

CRA Cumulative Risk Assessment.

DFO Department of Fisheries and Oceans Canada.

EEZ Exclusive Economic Zone.

EIA Environment Impact Assessment.

GIS Geographic Information System.

HFO Heavy fuel oil.

Hz Hertz.

IMO The international maritime organization.

IRGC International Risk Governance Council.

ITOPF International Tanker Owners Pollution Federation.

MEOPAR Marine Environmental Observation, Prediction and Response.

MSP Marine Spatial Planning.

NMTC The Northern Marine Transportation Corridors.

NOAA National Oceanic and Atmospheric Administration (United States).

NORDREG Northern Canada Vessel Traffic Services Zone.

NSR Northern Sea Route.

NWP Northwest Passage.

PDF Probability Density Function.

PTS Permanent threshold shifts.

RL Received Level.

SEL Sound Exposure Level.

SL Source Level.

TC Transport Canada.

TK Traditional Knowledge.

TL Transmission Loss.

TTS Temporary threshold shifts.

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Chapter 1

Introduction

After 1998, the 10 warmest years since the beginning of systematic measurement have been recorded [68]. As a result of global warming, the area covered by sea ice during summer months in the polar areas has decreased by about 30% over the past few decades [59]. The shortened sea ice seasons has caught the attention of the global shipping community due to the potential of the Northwest Passage through the Canadian Arctic becoming a shorter and cheaper alternative route to Panama Canal [45],[86],[76]. Additionally, there are other factors that can influence in the increase of maritime traffic patterns in the Canadian Arctic, such as exploration for oil and gas, northern communities re-supply, commercial shipping out of Churchill, Manitoba and cruise ship voyages [74]. Pizzolato et al. have studied the spatial relationship between shipping activity and multiyear sea ice concentration within the Canadian Arctic over a 26-year time period (1990 to 2015) and found that the increase of shipping activity in the southern regions of Northwest Passage only occurs when multiyear ice has low concentrations [77]. This growing utilization of the ocean could pose different risks to Arctic marine animals, such as noise pollution, habitat alteration, and potential spill of contaminants, such as crude oil, vessel fuel, chemical discharges and so on [18]. Additionally, local communities would be indirectly affected since they rely heavily on these animals to secure their traditional Inuit food (locally harvested fish and wildlife), which could potentially threaten their food security and the welfare of Inuit communities [93]. Additional to the increase interest on these routes due transportation purposes, there are other reasons behind this phenomenon, such as potential oil and gas development and tourism through cruise vessels in the Arctic waters [29]. However, it is still uncertain if this climate change phenomenon will result in a constant increase of shipping through Arctic waters in the next decade, since the Arctic passages remain difficult routes due to the lack of infrastructure, sea ice in most months of the year, and harsh environmental conditions in the winter [52],

[51], [84].

Therefore, given all the uncertainties and risks associated with the increase of shipping in the Arctic, it is important to develop shipping governance in this region that ensures a safe and sustainable shipping route for all stakeholders involved in this issue, including shipping companies, government and local communities, which protects marine life [12].

The Low Impact Corridors initiative was created as an attempt to fulfill this management gap, an initiative co-led by the Canadian Coast Guard (CCG), the Canadian Hydrographic Service (CHS), and Transport Canada (TC) [12]. However, this Corridor initiative, previously referred as The Northern Marine Transportation Corridors (NMTC), was established at the national level, using historic shipping data, with limited consultation with territorial or Inuit governments [11]. Hence, important areas for marine mammals and fish stocks in the region were not considered, leaving a serious gap regarding the receptors to potential shipping stressors and lack of a more comprehensive risk assessment of marine shipping impacts. Coincidentally, TC has also recently initiated studies on the development of a national Cumulative Effects Assessment (CEA) framework to assess the effects of existing and future vessel movements on coastal ecosystems and the communities that depend on them [10].

In the CEA literature, marine shipping is commonly identified as a single type of anthropogenic stressor [47],[4],[5],[6] & [31]. However, marine shipping activity can, in fact, result in multiple stressors, which consequently produce multiple risks to marine species and coastal communities, as The Department of Fisheries and Oceans Canada (DFO) have already identified in the Shipping pathways of effects project, which includes an extended list of shipping stressors from sub-activities of shipping [54]. Despite the efforts from DFO to identify the shipping stressors, the Shipping pathways of effects project focused restrictively on providing general recommendations, leaving for future researchers the need for development of a framework for cumulative effects assessment (CEA) of shipping stressors. Additionally, CEA also lacks an uncertainty base where probabilities are taken into account instead of just accounting for the stressor intensities. Embedding CEAs in a risk management process can potentially reduce complexity, simplify scientific products, and increases transparency [88].

1.1 Research Problem and scope of study

The lack of a framework for cumulative risk assessment (CRA) to exclusively assess the effects of existing shipping stressors and account for the uncertainties are the main motivators of this present study. The framework for cumulative effects assessment for shipping stressors could support the governance of the Arctic corridors by providing a more comprehensive assessment of the shipping stressors and assisting in the decision-making process of resource allocation. Additionally, recent studies have shown that cumulative effects assessment has become a vital component of risk-based decisions aimed at protecting human populations and environmental ecosystems [32], [61], [64]. Therefore, since this framework is intended to inform decision makers, recognizing and handling uncertainty is important to increase transparency between the scientific and management world. So, towards this scenario, this thesis aims at answering the following research questions: What is a potential framework of a cumulative risk assessment (CRA) for marine shipping stressors? and How would it apply to selected marine receptors and shipping stressors of the Kitikmeot region?

Chapter 2

Literature review

2.1 Shipping in the Canadian Arctic

Due to the effects of climate change in the Arctic environment, for instance, the acceleration of sea ice melting during summer season, the navigability of Arctic waters has considerably increased in the last few years [7],[77] & [76]. This phenomenon has drawn a considerable attention to alternative shipping routes from Suez and Panama Canal, the Northern Sea Route (NSR) and Northwest Passage (NWP) respectively [45], [18].

In order to understand if there is a correlation between sea ice concentration area and shipping activity in the Canadian Arctic, Pizzolato (2014) has investigated relationships between them through dataset of observed vessels, the Vessel Traffic Reporting Arctic Canada Traffic Zone (NORDREG zone) from 1990 to 2012 [76]. During the shipping season, a negative statistical correlation was found between these two variables. Additionally, they have also identified a lengthening of the shipping season in the Canadian Arctic by five days per decade into the shoulder months of early June and November.

Another study conducted by Dawson (2017) about the shipping trends in the Canadian Arctic for the period from 1990 to 2015 by [18], using data provided by the Canadian Coast Guard (CCG) across Nunavut province, has found that the total distance travelled by all vessels doubled within this period, going from 345,567 km (1990) to 793,684 km (2015) with special attention to pleasure crafts, general cargo and tanker vessels. However, the majority of the ships that navigate through the Arctic waters are still being used to support community re-supply (food, fuel, and goods) and local economic activities (tourism, mining, fishing) rather than as a route for long-distance transportation [18],[30],[76] & [105].

Whether these routes will become economically viable for shipping companies in the coming future, it is still uncertain amongst specialists [7],[60]. However, by seeing that this increase of shipping is materializing, it is important to act proactively by addressing stakeholders concerns in face of these changes and understand the shipping risks associated with them.

2.2 Low-Impact Shipping Corridors - NMTC

The Low-Impact Shipping Corridors, initially called NMTC, is a framework for shipping governance, developed under the Government of Canada World-Class Tanker Safety System Initiative (WCTSS) by a collaboration between the DFO, the CCG, the CHS and TC [12].

The main objective of this initiative is to reduce the likelihood of marine incidents in order to enhance the safety of marine navigation through Canadian Arctic water, by providing predictable levels of service to mariners transiting the corridors [12]. However, these corridors were established at the national level, based on current traffic patterns and marine crew safety, with limited consultation with territorial or Inuit governments. Hence, important areas for marine mammals and fish stocks in the region were not initially considered, leaving a serious gap regarding the receptors to potential shipping stressors in the framework [92]. Current studies have addressed these issues by working closely with Inuit communities and creating recommendations for the corridors [11].

Moreover, a more comprehensive risk assessment is needed to fully understand the cumulative effects from the increase of shipping in these corridors. Normally, a shipping impact study covers only one stressor, but it is important for policy makers to appreciate the overall impact of all stressors combined. Therefore, an evidence-based approach for improved shipping governance is needed, including a comprehensive risk-based approach for CRA of shipping stressors to the local receptors in the Nunavut waters.

2.3 Shipping stressors

From all anthropogenic activities on the worlds oceans, marine shipping still rank as a major concern to marine and federal authorities and the reason for that is the exhaustive list of potential environmental issues that can emerge from it [16],[37],[92],[14] &

[97].

Dealing with the effects from shipping stressors can be substantially more challenging in the Arctic due to its remoteness, infrastructural gaps, highly sensitive marine ecosystem and the strong reliance from local communities on the Arctic marine ecosystem for food security, transportation needs and mobility [92]. This section lists some of the known shipping stressors to the Arctic marine ecosystem identified in the literature (see Figure 1), such as ship-source oil spills, discharge of debris and waste, air emission, ship-source noise pollution, introduction of invasive species and ship strikes on marine mammals [16],[37],[14] & [57].

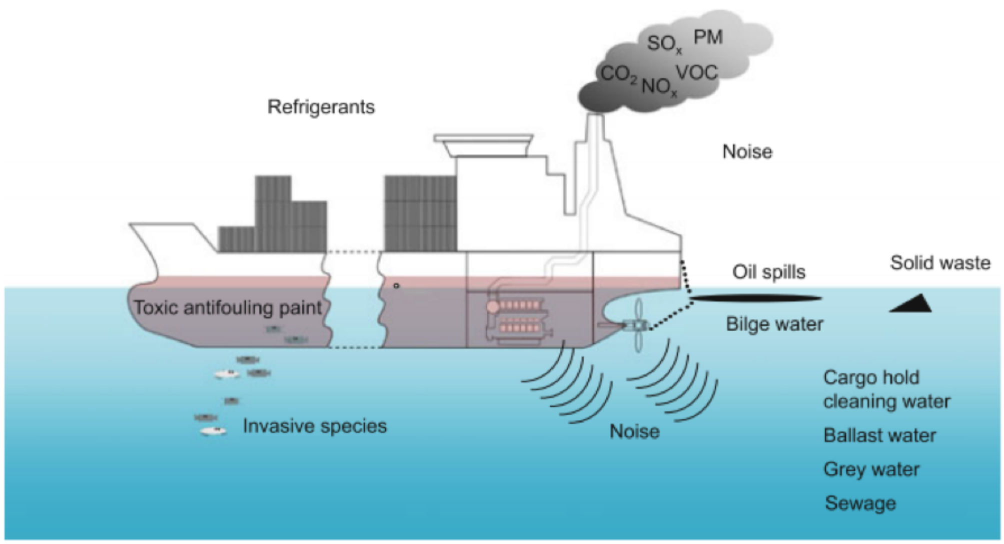

Figure 1: Environmental impacts of marine transportation during the use of a vessel, Source: IMO, 2016.

These stressors differ in nature in a sense where certain stressors are conditional to a sequence of unforeseen events taking place, (e.g. oil spill), while others take place as soon as shipping activity takes place (e.g. noise pollution)[16].

2.3.1 Oil spill

Accidental ship-source spills of oil may result from exceptional events, such as collisions and groundings with vessels carrying liquid cargo, accidental fuel leaking or even a combination of both [79]. Another possible cause for oil spill can be from regular ship operations, also called operational discharges, which is caused by neglect when cleaning of oil tanks, loading and unloading of ships in harbors, etc. [33],[79].

According to [42], collisions and grounding involving tankers are still the most common cause for oil spills in the world, with the first one accounting for 29 % and the second one 32% from all spill cases above 700 tonnes. Another study on the future for Marine transportation in the Canadian Arctic, prepared for TC by [37] also concludes that, spills arising from these two types of incidents are more likely to take place. Another revealing statistic is that the major and more severe oil spills that have occurred in history were resulted from accidents with tankers (see Table 1).

Ship name	**Year**	**Spill size (tonnes)**
Atlantic Empress	1979	287,000
ABT summer	1991	260,000
Castillo de Bellver	1983	252,000
Katina P	1992	67,000
Prestige	2002	63,000
Hebei Spirit	2007	11,000

Table 1: Some of the major oil spills in the world resulted from tanker accidents. Source: [42].

Unfortunately, there have been some drastic oil spills from tanker vessels in the human history (e.g. The Exxon Valdez case in Alaska, releasing 44,000 tonnes of oil into Prince William Sound) that forced marine transportation agencies to get stricter in terms of regulations, which has been reflected in the decline of ship-source oil spills occurrence in the recent years [42]. [42] registered 25 major spills (over 7000 tonnes spilt) in the 1970s, while in the 2000s only 4 large spills have been registered. Even though the worldwide data shows a positive progress toward more rigorous standards and regulations that aimed to prevent ship-source oil spills, oil remains a serious threat for marine ecosystems, especially for highly sensitive areas like the Arctic [16].

Concerns around this shipping stressor in the Canadian Arctic have increased significantly in the past few years due to growing demand for oil products world wide [79] combined with the increase number of shipping traffic through an alternative cheaper and faster shipping route, the NWP, as consequence to climate change [19]. That is because oil spills are the most serious environmental threat to marine life, especially in the fragile ecosystem of the Arctic [16], [37]. Additionally, out-dated nautical charts, limited communications infrastructure for transmitting meteorological and ice chart information, ice navigation systems, and gaps in terrestrial radar and the Automated Identification System (AIS) coverage can increase challenges for mariners navigating in the area, increasing the risk of a ship-source oil spill happens [81]. Another important aspect to be considered is the lack of oil spill preparedness and response planning in the Canadian Arctic, when compared to areas south of the 60th parallel [81],[16].

Empirical data on the effects of oil spill in marine mammals is yet difficult to be collected since researchers could potentially harm these animals when capturing them [91],[67]. Even though data is still sparse, which difficult the assessment of long-term effects, few studies have been done on this topic and some relevant conclusions can be made from them. Below are the most likely effects of oil spill on cetaceans, according to the most recent studies:

1)Mortality by smothering when breathing in an oil slick and inhale volatile hydrocarbons, which can seriously damage the animals respiratory system [34],[79].

2)Ingestion of oil through contaminated prey can lead to mechanical impairment such as animals ability to digest and absorb foods, which can harm various internal organs (e.g., liver, kidney and intestines), leading to reduced health and fitness [70],[34].

3)Reduction in food availability because of possible contamination of invertebrates, fish and plankton. The contamination of marine habitats by toxic chemicals from the oil can compromise the entire food chain due to relationships between organisms and their environment, which can possibly disrupting life within the very foundation of the ocean's food web [79].

Therefore, oil spill can have tragic impacts on the physical and psychological health of marine species; however,the degree of this impact, also referred as sensitivity, is highly variable among them [91].

2.3.2 Dumping of hazardous waste

Different than an accidental discharge of oil spill into the ocean, dumping of garbage, tank washings (oily water), sewage, graywater, ballast water, bilge water, and other hazardous substances may be done intentionally due to the necessity of vessels to remove these wastes generated through normal operations [16],[14] & [37].

These regular discharges are regulated by the IMO through the International

Convention for the Prevention of Pollution from ships (MARPOL, 73/78), which has helped to reduce pollution in the marine environment, however there is still place for improvement [16],[14].

Dumping of untreated graywater, for example, is still lacking international regulations [14], which has raised concerns among marine environmentalists because it can pose serious threats to the marine environment since graywater can contain a series of bacteria, pathogens, oil and grease, detergent and soap residue, metals (e.g. cadmium, chromium, lead, copper, zinc, silver, nickel and mercury), solids, and nutrients that can lead to oxygen reduction, diseases and nutrient enrichment in the marine ecosystem [20].

Similar to oil spill, the contamination from untreated graywater can be spread out throughout the entire food chain, affecting even the human beings that consume marine resources [20],[14].

2.3.3 Air emissions

Another potential stressor generated by shipping activities is the exhaust emissions of long-lived greenhouse gases (i.e. CO_2, SOx and NOx) and short-lived pollutants (i.e. Particular matter (PM), such as black carbon) which contribute significantly to global climate change and can negatively impact human and environmental health [16],[14] & [37].

Shipping activity alone, contributes to 10%-15% of the worlds human-cause SOx and NOx emissions [53]. Besides global impacts, some of these substances can be a particular concern in the local scale, especially in the fragile Arctic environment [14]. For instance, the emissions of SOx and NOx can induce ocean acidification, which can directly affect many local marine organisms by reducing calcification and growth of calcifying species (i.e. mussels, clams, etc.) that strongly rely on equilibrated pH levels to survive[3].

Black Carbon (BC) found in the smoke emitted by ships is also a contributor to global climate change and according to Lack (2016), BC can increase the warming effect in the Arctic by three times [50]. Black carbon (BC) is produced by vessels when oxidation of diesel fuel is not completed and its release in the Arctic can reduce the reflectivity of sea ice and snow, which can consequently accelerate the warming process [16],[14].

Since not all vessel types contribute equivalently to this issue, in order to quantify this stressor and assess the level of impact, the fuel type, engine and engine efficiency should be considered [38]. Some studies have been done on this topic, however more accurate data of gases emissions from shipping activity are necessary to have a better and clear understanding of the environmental impacts that this stressor can cause [14]. Although major ships classes have increased their efficiency from 2013 to 2015, by reducing the CO_2 intensity, its emission from ships has continually increased [71].

This phenomenon is expected to continue increasing, since 90% of the worlds cargo is transported by shipping and the growing demand for additional transportation capacity continues to happen due to globalization, unless changes are made in the following years [37].

2.3.4 Noise pollution

Anthropogenic noise produced by shipping, as an undesirable product from their propellers cavitation and engines operation, can detrimentally affect fish and marine mammals on a global scale [102]. There are other sources of noise pollution in the marine environment (e.g. seismic surveys, offshore activities) but particular attention has been given to this shipping stressor because most of the sound produced by vessels are at low frequencies, typically over a range of 10Hz to 1kHz [9],[36], which is similar to the general hearing sensitivity bandwidths of lager whales [16].

The impacts from noise pollution can be worse if there are multiple loud vessels in the same area (cumulative noise pollution), causing temporary or permanent threshold shifts (TTS,PTS) [101],[30].

In few words, underwater sound alteration caused by low-frequency sources can possibly impact these animals behaviour because they use sound to perform critical biological functions such as communication, social interactions, finding prey, foraging, reproduction and navigation [102]. It becomes a concern when there is an overlap between vessel noise and the frequencies of sound used by marine animals once sound sources can interfere with important biological functions [16].

The noise level (its intensity and frequency), varies among vessel types, which can differ in size, speed, load, condition, age and engine type [2]. Not only the ship characteristics matter to measure the noise intensity received by marine animals, but also oceanographic parameters, such as bathymetry, temperature and pressure of surrounding water column [2].

In the Arctic, due to the recent increase of shipping activities, noise pollution has become an apparent problem, especially because this environment used to experience free anthropogenic noise in the past [14]. Recent studies have reinforced how important is underwater sound for several marine mammals and other acoustically sensitive marine fauna in the Arctic environment [30], [102]. However, this is an area where additional research is still ongoing [16].

2.3.5 Vessel strikes

As consequence of noise pollution caused by shipping, the ability of marine mammals to detect nearing vessels can be blocked, which can increase the probability of vessel striking these animals [14]. The results from these collisions can cost these animals life, massive trauma, hemorrhaging, broken bones and propeller wounds [16],[14] & [37].

The vessel speed can be a determinant factor in the occurrence and damage severity to the cetaceans [95], which justifies the creation of marine regulations that apply speed restrictions in ocean areas where the aggregation of large whales overlaps with intense shipping traffic, in order to mitigate potential risks [16],[14]. A previous study on the correlation between vessel speed and degree of whale injury during strikes have found a significant positive relationship between these two variables and a strong evidence that there is a linear effect of transit speed and strike rates [13].

Even though there have been relatively few known vessels strikes in the Arctic, the increase of shipping in these waters can change the current scenario [16]. Although during periods of ice coverage, certain regions such as the Northeast area of Kitikmeot region in the Canadian Arctic, have both mammals and ships using the same leads and polynyas as preferred routes, increasing the probability of vessel strikes [14].

2.3.6 Introduction of Invasive species

Shipping is a critical vector in the introduction of invasive species in the marine environment, which includes phytoplankton, zooplankton and aquatic pathogens [96].

These aliens can be transported through vessel ballast water or hull fouling [62].

Ballast water works as a replacement for cargo when the vessel is not fully loaded, in order to keep its stability. The vessel discharges the ballast water in the ocean usually when it needs to add cargo again [14].

The possible negative impacts to marine life from this phenomenon include: displacement of native species, alteration in food webs and sedimentation [62]. Even though specialists consider this stressor as the most serious one due to its irreversibility and long-lasting consequences to native biological diversity worldwide [96], there has been made only few assessments of its potential impacts and areas more susceptible for this problem.

In the Arctic, the risk of invasive species causes an ecological and economic disruption, which could rise as the shipping volume increases. In combination with increase of surface water temperature and changes in the salinity level, the environment can become more vulnerable to this stressor [99],[16] & [14]. The prediction of all invasive species that will become permanent residents of the Arctic is still being studied but there are a few species found to be causing issues in the Canadian Arctic environment such as the European green crab [28].

2.4 Potential marine life receptors to shipping stressors in the Arctic

The Arctic is home for ever-present animals such as marine mammals and fishes, and other seasonal animals that can stay over the winter or go south if they decide to escape, including humans [16],[14]. Figure 2 shows the Arctic marine food web and its elements, showing the interconnection among them and humans.

Besides being a harsh and highly fluctuating environment, the Arctic also presents low species richness, if compared to the southern regions of the world, which makes this place unique and its biodiversity more sensitive to potential impacts from anthropogenic stressors and climate change effects [16]. The seasonality of some Arctic animals also makes this particular environment more vulnerable to anthropogenic stressors than other places in the world, that can go in and out of the Arctic for biological purposes. For instance, during spring season, Arctic marine mammals such as whale species Bowhead, Beluga, Narwhal, and seals species such as walrus and others start migrating in large groups to northern areas to feed, mate, give birth or nurture their young in the Arctic summer season [16].

These migration corridors and gathering areas used by marine mammals and birds can overlap with shipping activity, which also gets intensified during the summer seasons, posing significant risk to these vulnerable and sensitive animals [16],[14]. The situation can worsen with global warming and sea ice reduction, allowing shipping season to be extended earlier in the spring and later in the fall, which can increase the vulnerability of these animals to multiple shipping stressors [16]. As part of real life, the relationship between receptors and stressors is very complex and hard to be predicted accurately. Additionally, not all marine receptors will respond to shipping stressors in the same way. The response is highly dependent on the context, including location, season and life history of species [66]. The effects can also vary, which can either be direct, for example, by affecting physical, psychology or behavior traces of an individual animal, or indirectly, by affecting food and habitat availability of other valued components from the ecosystem [66].

Since receptors interact with each other and in some cases, rely on each other (e.g. prey-predator relationship), all these species plays a critical role in their ecosystem, and negative effects could potentially threaten their existence, leading to exponential harm if trends persist [14].

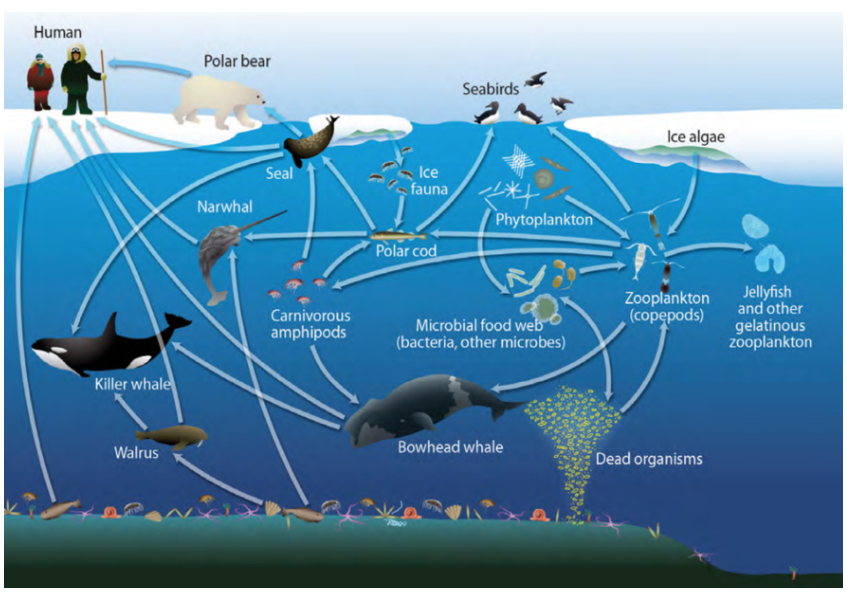

Figure 2: Arctic marine food web. Source: Ocean Conservancy, 2017.

2.5 Cumulative Effects Assessment (CEA)

Cumulative Effects Assessment (CEA), also referred as cumulative impact assessment, is defined by The Canadian Council of Ministers of the Environment (CCME) as the systematic process of identifying, analyzing, and evaluating cumulative effect of anthropogenic activities on valued components. CEA is a comprehensive environmental assessment that describes the link between stressors and receptors through causal pathways and how to properly combine them [43]. CEA is derived from Environment Impact Assessment (EIA), which for years, was failing to represent the extensive influences that multiple human activities have on the environment [65].

CEA involves a series of spatial and analytical methods and can be applied in different contexts, which makes it an interesting, flexible and complex process that requires a clear scoping of the problem and clear management objectives [88]. The methods selection is also highly dependent on data availability and other relevant resources constraints, for example, time [100].

Although CEA can vary in terms of methods and tools, its baseline framework contains the following basic components: Spatial and temporal boundaries, selected stressors, selected receptors and conceptual models of the relationships among stressors and receptors, also referred as pathways in the literature [43].

Regarding its methods, CEA can exclusively use spatial, analytical or modelling method, or even a combination of them [66]. In most cases, the location of stressors and receptors are spatially represented in order to identify potential overlaps [5] and then analytical methods are used to understand the relationship between them followed by a modeling method that allows the prediction of stressors intensity [66].

The result from cumulative stressors effects can also differ from study to study, according to [66], CEA can be composed by: a single action producing a single stressor, over and over again, or a single action producing multiple stressors, or multiple actions producing a single stressor, or multiple actions producing multiple stressors. The stressors interaction can also vary, which resulting effects can be additive (total effect = sum of all effects), synergetic (total effect>sum of all effects) or antagonistic (total effect<sum of all effects) [17].

However, constituting causal relationships between stressors and potential impacts on ecosystems is proven to be highly difficult not only due to the inherent complexity of environmental systems, but also because there are no generally acknowledged and demonstrated methodologies for setting up such connections [1].

In terms of its application, CEA has widely been used in the marine industry, by combining effects from different anthropogenic activities to valuable marine ecosystem components (Table 1).

Reference	Title	Scope	Method
Holon et al. (2015)	Fine-Scale Cartography of Human Impacts along French Mediterranean Coasts: A relevant map for the Management of Marine Ecosystems	This study mapped and quantified the impact of 10 anthropogenic pressures (e.g. boat anchoring, aquaculture, coastine erosion)on 10 habits classes of marine life in a fine resolution of 20x20m. The objective of this study was to identify areas in need of a special management interest.	CEA method developed by Halpern et al. (2007,2008)
Batista et al. (2014)	Assessing of cumulative human pressures on a coastal area: Integrating information for MPA planning and management	This study assessed the cumulative impact from 18 human activities occuring along the mainland Portuguese coastal area in order to assist the creation of Marine Protected Areas (MPAs) and their boundaries.	Adapted the CEA method developed by Halpern et al. (2007,2008)
Micheli et al. (2013)	Cumulative Human Impacts on Mediterranean and BlackSea Marine Ecosystems:Assessing Current Pressures and Opportunities	This study quantified and mapped the cumulative impacts of 22 drivers (e.g. ship traffic, demersal fishing) to 17 marine ecosystems on Mediterranean and Black Sea Marine Ecosystems.	CEA method developed by Halpern et al. (2007,2008)
Korpinen et al. (2012)	Human pressures and their potential impact on the Baltic Sea ecosystem	Measured the cumulative impact index for the entire regional sea, the Baltic Sea, in 5 km × 5 km subareas. The index in each subarea unit consists of the sum of 15 different anthropogenic pressures on 14 ecosystem components. This study used spatial methods and took into account the sensitivity of these ecosystems.	CEA method developed by Halpern et al. (2007,2008)
Moreno et al. (2012)	A method for the spatial analysis of anthropogenic pressures in Spanish marine waters	This study quantified the intensity of 37 human-induced stressors throughout five Spanish marine districts without considering the impacts on specific ecosystem components in order to assist an ecosystem-based management approach used by Spanish authorities.	CEA method developed by Halpern et al. (2007,2008)
Ban et al. (2010)	Cumulative impact mapping:Advances,relevance and limitations to marinemanagement and conservation,using Canada's Pacific waters as a case study	This study analyzed the cumulative impacts of 38 human activities on 12 ecoregions and 14 benthic regions in the Canada's Pacific waters.	CEA method developed by Halpern et al. (2007,2008)

Table 2: List of recent studies where cumulative effects assessment was applied in the marine industry.

The cumulative effects assessment proposed by [32] appears to be the most widely used approach in these recent marine studies. It combines spatial, analytical and modelling techniques. The proposed framework has as its underlining equation, the following cumulative impact score function (Ic):

$$I_c = \sum_{i=1}^{n} (1/m) \sum_{j=1}^{m} D_i * E_j * W_{ij} \quad (1)$$

Where

I_c: cumulative impact scores calculated for each grid cell;

D_i: log-transformed and normalized value of intensity of an anthropogenic driver at location (x,y);

E_j: presence/absence of receptor j;

W_{ij}: impact weight for anthropogenic driver i to ecosystem j, estimated using expert judgment to quantify vulnerability of ecosystems to stressors;

n: number of stressors (i=...n);

m: number of receptors (j=1...m);

1/m: produces an average impact score across stressors-receptors combination.

Equation 1 accounts for the intensity of each anthropogenic activity and the overlap of their impacts on marine components. Despite its widespread use, CEA has not yet been used to combine stressors derived from marine shipping activity solely. This gap in the literature has gained attention among researchers and policy makers, such as Transport Canada, which has recently initiated studies on better methods for cumulative effects of marine shipping through the Oceans Protection Plan, for different coastal environments around Canada including in the Eastern Arctic [10].

By utilizing CEA results, managers and policy makers have a better understanding of the magnitude or degree of impact from the collective effects of anthropogenic activities to receptors, rather than on the individual effect of a singular action, which then helps justifying spatial management of these activities [104].

2.6 Qualitative uncertainty assessment

On one hand, CEA has been proved to be an effective tool used to support science-based Marine Spatial Planning (MSP), in order to understand potential effects of multiple anthropogenic activities on multiple marine environment [26]. On the other hand, the correct interpretation of CEA results can be hampered by the uncertainties that are intrinsically present when modeling complex systems, such as the natural environment [26],[89].

Uncertainty can be found in the stressor data, sensitivity weights, spread of effects from source to receptor, spatial distribution of ecological features, inadequate expert judgments or measurement errors [88]. There are different ways of addressing them. One example is considering the probability of stressor occurrence, instead of just accounting for its intensity [88]. Another alternative is the use of Monte Carlo simulation and sensitivity analyses [89].In fact, there are different ways of recognizing and handling uncertainty in CEA and there is no “one fits all ”solution regarding specific methods.

Recent studies have raised awareness on the importance of uncertainty assessment in CEA [89], [26] & [88]. Stock et al. (2016), for instance, has investigated the effects of model assumptions and data quality on spatial cumulative human impact assessments by quantifying the uncertainties in CEA and associating them to model assumptions and issues with data quality. Gissi et al. (2017) has also attempted to address this model deficiency by proposing a three-level methodology to perform a broad uncertainty analysis of CEA for MSP based on [98] uncertainty matrix. Stelzenmller et al. (2018) has proposed a risk-based approach to CEA, with the goal of increasing transparency of uncertainty treatment by embedding CEA into a ISO standard risk management process.

Essentially, they have all concluded that the accumulation of uncertainties from model assumptions and poor data quality have a significant effect on the CEA results and for that reason it should be included an uncertainty analysis to the model. Another point brought up from these studies is the importance of distinguishing robust from unreliable results to avoid potential misguidance to policy makers. Therefore, there is still a need to strengthen the dialogue between science and policy in order to help bridging the gap between theory and practice in ecosystem based management and this present study was considered that into account.

Additionally, due to the inherent complexity of the marine system and the heterogeneity, dynamism and uncertainty intrinsic in the biophysical process [88], when modelling this type of system, assumptions have to be made throughout the process [32], [47]. For this reason, it is important to execute an uncertainty assessment (UA) in a model-based decision, which can help to build more confidence in the researchers providing policy and decision-making support [98], while serving as a basis for reflection on the model outcomes in the decision-making process [27].

In order to qualitatively assess the uncertainty present in the CEA, a systematic treatment of uncertainty in model-based decision support has been proposed by [98]. He proposed a comprehensive evaluation of three dimensions of uncertainty (see Table 3): location, level and nature by a proposed uncertainty matrix:

(i) The location of uncertainty–where the uncertainty manifests itself within the model complex;

(ii) The level of uncertainty–where the uncertainty manifests itself along the spectrum between deterministic knowledge and total ignorance;

(iii) The nature of uncertainty–whether the uncertainty is due to the imperfection of our knowledge or is due to the inherent variability of the phenomena being described.

Location		**Level**			**Nature**	
		Statistical uncertainty	Scenario uncertainty	Recognized ignorance	Epistemic uncertainty	Variability uncertainty
Context	Natural, technological, economic, social and political, representation					
Model	Model structure					
	Technical model					
Inputs	Driving forces					
	System data					
Parameters						
Model outcomes						

Table 3: Uncertainty Assessment. Source:[98].

2.7 Automatic Identification System (AIS)

The automatic identification system (AIS) is an automatic tracking system used as a tool to increase navigation safety and efficiency as well as vessel traffic management by sending and receiving information from a ship to the other ships and to port authorities [83].

It is an important technology for the scientific community, port authorities and decision makers in the marine industry, that was created in 2004 by the IMO and became mandatory to be aboard of all vessels equal to or greater than 300 gross tonnage (class A transponders) on international voyages, and small vessels that dont need to comply with SOLAS (The international convention for the safety of life at sea) and decide to operate on a voluntary basis (Class B transponders) [83]. It transmits and receives statistical and dynamic vessel information in real time and provides information on vessels characteristics, including their position, speed, course, classification, draught, type of cargo and destination [83].

In terms of its application,[22] reviewed areas where AIS have been used through a vast literature review and identified that there has been a shift in the use of AIS data, which initially used to be viewed as a traditional vessel identification device but more recently has been applied in different fields, including maritime safety and security. Although the ultimate goal is to provide a comprehensive shipping dataset, the AIS data may contain some limitations, for example, vessels operating solely in a domestic domain and government and military vessels are not required to transmit AIS information at all times, which can make the data slightly under-represented [14]. Another limitation is with small boats and pleasure crafts, which are not obligated to have AIS aboard but can still pose several risks to marine life, especially in the Canadian Arctic, where the presence of these vessels has increased in the last few years [22].

Despite its limitations, AIS has proven to be a powerful source of data for marine management and is an important source of input data for cumulative risk assessment (CRA) of shipping stressors.

Chapter 3

Methodology

This research proposed a Cumulative Risk Assessment (CRA) framework for shipping stressors and marine receptors by enhancing an exisisting algorithm proposed by Halpern et al. (2009) [31]. Additionally, it used this framework to assess the cumulative risk of shipping activity on a case study in the Kitikmeot region, where two selected shipping stressors were used: ship-source oil spill and ship-source noise pollution and three selected marine mammals used as receptors: Bowhead, Narwhal and Beluga. This region is an extremely remote area of the Canadian Arctic located in western Nunavut. It is also home to the southern portion of the Northwest Passage, which is becoming increasingly enticing for the global shipping industry as sea ice declines and opens an alternative shipping route to the Panama Canal. This study region was chosen because little research of this nature has been conducted in the Kitikmeot and as shipping trends continue to increase there is a need to better understand the impacts vessel noise could have on marine mammals and fish. This research was conducted through an intensive literature review on Cumulative effects assessment (CEA) and on methods to quantity the stressors oil spill and noise pollution. The CRA equation and framework and its elements will be discussed in the following section.

3.1 CRA framework

3.1.1 Content

For the proposed CRA framework, the determinants of risk includes more than just the probability of adverse effects from stressors on receptors, it also includes the receptors exposure and its sensitivity to stressors [78]. This way, the contribution of each stressor to the overall risk score is taken into account.

Figure 3 shows how the corresponding risk concept is linked with the proposed risk-based cumulative effect assessment framework, as well as the uncertainty assessment.

The CRA follows a stepwise conceptual approach as listed below:

1. Identify relevant problems and policy aims;
2. Identify temporal/spatial boundaries;
3. Identify potential receptors;
4. Identify relevant stressors;
5. CRA model design and parameters;
6. Data collection;
7. CRA implementation and analysis;

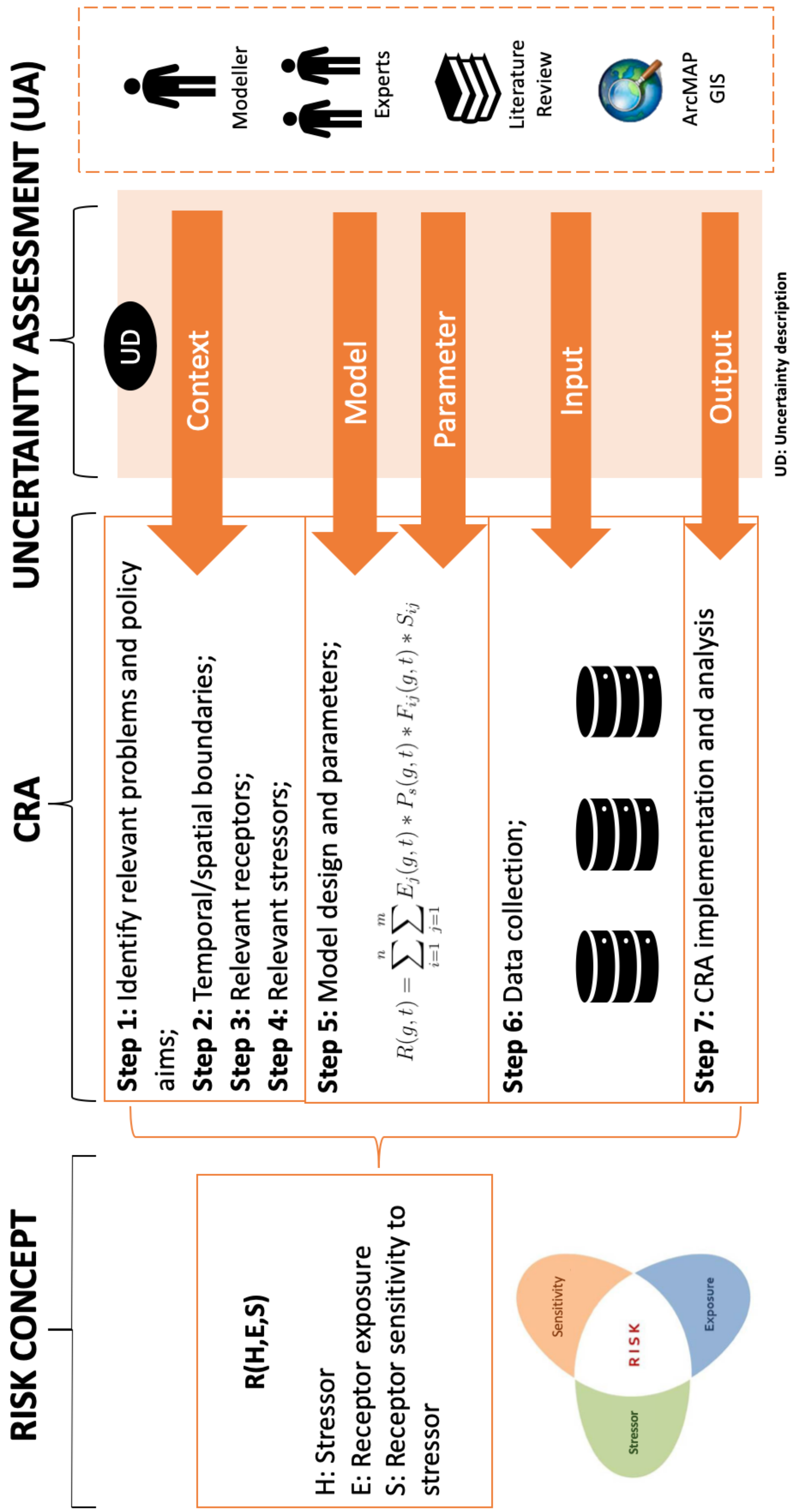

Figure 3: Cumulative Risk Assessment of shipping stressors. Adapted from [26].

3.1.2 Structure

The spatial overlapping of various stressors calls for a multi-risk approach based on existing data and inputs from experts. The CRA framework presented here is an adaptation from the methodology developed by [32]. The basic elements required for a multi-risk assessment were included in the framework: stressor and elements at risk (receptor) [40].

The CRA model uses the simple additive approach, meaning that the total effects resulting from multiple stressors are assumed to be an additive accumulation of impacts associated with single stressors, as in [17].

The proposed equation for the risk-based cumulative effect assessment is:

$$R(g,t) = \sum_{i=1}^{n}\sum_{j=1}^{m} E_j(g,t) * P_s(g,t) * F_{ij}(g,t) * S_{ij} \quad (2)$$

where,

E_j (g,t): receptor exposure, which is the probability of receptor j being at grid cell g during season t;

P_s (g,t): vessel presence, which is the probability of stressor source s being at grid cell g during season t;

F_{ij} (g,t): stressor factor, which is the probability of stressor intensity i exceeding the threshold for receptor j at grid cell g during season t;

S_{ij}: measure of sensitivity, which is the degree to which receptor j responds to stresses resulting from stressor i;

R(g,t): normalized cumulative risk score at grid cell g during season t with upper bound of 1 and lower bound 0;

n: number of stressors (i=...n);

m: number of receptors (j=1...m);

3.1.3 Parameterization

1.Stressor factor (F_{ij}) : any value between 0 and 1;

2.Vessel presence (P_s): any value between 0 and 1;

3.Exposure (E_j) : any value between 0 and 1;

4.Sensitivity index (S_{ij}) : normalized value of sensitivity score (0-1);

The risk index will be higher in the locations where several receptors and several stressors occur together with stressors which are at highest probability of exceeding thresholds, and to which the receptors are more sensitive according to expert judgement.

3.1.4 Qualitative uncertainty assessment

For the CRA proposed here, uncertainty is assessed qualitatively by using the uncertainty matrix proposed by [98], where its location, level and nature are identified. The purpose of this method is to systematically assess the uncertainty perceived by the modeller, who is providing information to the policy makers and therefore, is responsible to disclose the uncertainties present in the model in order to support better decision-making.

Accordingly to Walker et al. (2003), uncertainty can be **located** in the context, model itself, input data, parameters and outcomes [97]. The ”context” refers to the setting in which the temporal and spatial boundaries were set. It also refers to the problem framing and the issues that were decided to be included in the assessment within the spatial and temporal boundaries initially agreed upon. Concisely, context uncertainties consist of all uncertainties related to the external economic scenario as well as environmental, political, social and technological circumstances that shapes the background for the issue being investigated [98].

In terms of uncertainty located in the model itself, there are two types, according to Walker et al. (2003): model structure uncertainty and model technical uncertainty. The first type arises when there is a clear absence or deficiency of comprehension of the system (past, present, or future) that is the matter of the policy analysis. It basically indicates how adequate the proposed model is in terms of representing the real world. The second type refers to uncertainty created by software or hardware errors, for example, possible bugs in the software.

The uncertainties located in the system data refer to the uncertainty present in the input data used for the base system, which in this case is the case study. A good example is the unavoidable uncertainty present in the spatial data (e.g. shapefiles) due to an approximation of real-world phenomena. Finally, there is uncertainty located in the parameters, which are supposedly constants in the model, and in the outcomes of the model, which is the accumulation of uncertainties from all the above elements that directly reflect in the outputs of the model.

The **level** of uncertainty, which is the second dimension of uncertainty according to Walker et al. (2003), ranges in a spectrum that goes from recognized ignorance to statistical uncertainty, with scenario uncertainty in between these two extremes [98]. At one end of the scale, there is the statistical uncertainty, which can be described appropriately in statistical terms, for instance by measuring sampling error [98]. In the sequence, there is the scenario uncertainty which is related to the process of making necessary assumptions throughout the study and to the external environment of a system and its consequences on the system [98].

Lastly, in the other extreme of the spectrum, there is the recognized ignorance which refers to the level of uncertainty where the modeller does not have knowledge about the structure and functional relationships being studied [98]. Recognized ignorance can fall in one of these two categories: reducible ignorance or irreducible ignorance. The first one can be defeated with additional research and the last one describes the uncertainty that can not be reduced by either further research or any sort of advancement [98].

The third and last dimension of uncertainty included in this assessment is the classification of uncertainty based on its **nature**, which can be either epistemic or variability [98]. Epistemic uncertainty refers to the uncertainty caused by imperfection of the modeller's knowledge which can be reduced with additional research [98]. Variability uncertainty, on the other hand, refers to the uncertainty that is inherent to the system and is beyond the modeller's control [98].

3.1.5 Model limitations

For stressor factor (F_{ij}), it only considers the probability of each stressor exceeding thresholds, which were established by previous research in the field; If the stressor factor is equal to 0, it does not necessarily mean that there is no source of stressor (e.g. vessel) present at the grid cell, it means that its intensity does not exceed a minimal threshold to start causing any harm to the receptor. Therefore, this model cannot be used as a representation of stressor source presence.

For receptor presence (E_j), although in the real-world receptors have a high mobility, they are treated as static receptors in this model; However, temporal dynamism is taken into account by considering their variation in terms of geographic location throughout the shipping seasons.

For sensitivity score (S_{ij}), although season and type of habitat might influence how sensitive the receptor is to the stressor, this model does not include these two aspects for sensitivity.

The uncertainty assessment included in the CRA framework had as a goal to identify the location, level and nature of the uncertainty in the model. However, an analysis of the magnitude of these uncertainties and their implications are outside of the scope of this study

3.2 Methods and data

The CRA framework combines spatial and modelling methods, along with other supporting methods, such as Traditional Knowledge (TK) and Expert survey. In the sequence, an illustrative case study was conducted in the Kitikmeot region, which is an administrative region of Nunavut province that has been experiencing an increase in ship traffic since 1990 [18]. The selected shipping stressors and receptors for the case study were identified based on Nunavut communities concerns and will be presented in the results section (Chapter 4) [11].

Spatial methods were used to map location and assign characteristics of the stressors and receptors through ArcGIS tools. For the case study, ArcMAP Version 10.5 software was used due to its free availability for Dalhousie researchers. In terms of projection, The Canada Lambert Conformal Conic projection was chosen because of its suitability for maps at small scale and its wide use to represent the northernmost areas of Canada. Due to lack of empirical data, Traditional Knowledge (TK) on the receptors' geographical location was collected through participatory mapping with local communities [18]. The outputs from this consultation were used to calculate the receptor exposure (E_j). This approach introduces a significant amount of uncertainty to the assessment; However, it was the only source of receptor data currently available. Additionally, the shipping traffic spatial dataset (AIS) for the period of 2011 to 2018 was used to compute the stressor factor (F_{ij}) through existing submodels of acoustic modelling and event tree modelling, which will be explained in the following section.

3.3 Case study specific methods

The following flowchart illustrates the submodels necessary to calculate each element of the CRA Equation (2). This submodel, its operations and rationale, are explained in section 3.3.1 to 3.3.4.

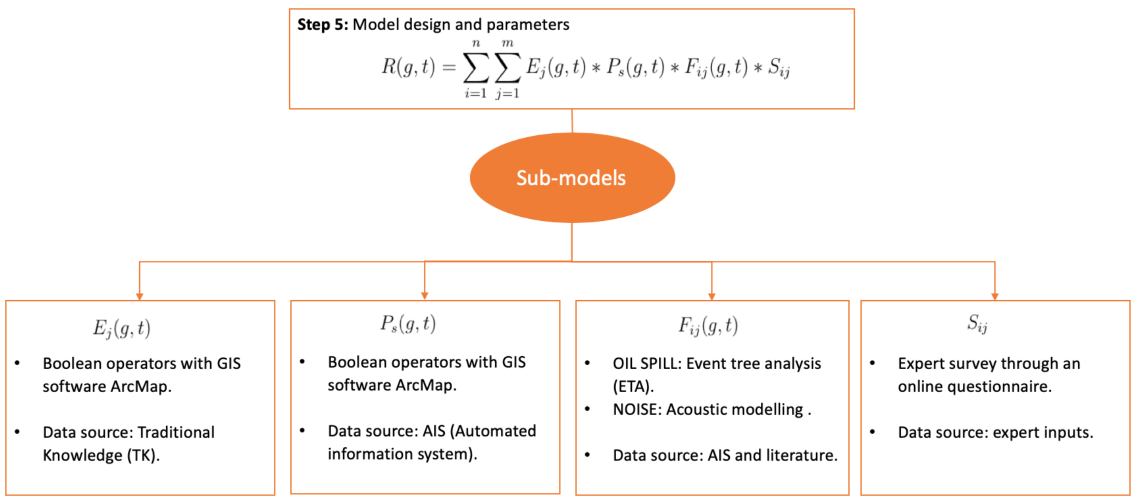

Figure 4: Diagrammatic representation of submodels for each element of CRA equation

3.3.1 Receptor Exposure (E_j)

From a previous study, Traditional Knowledge (TK) on marine local areas was gathered through participatory mapping and focus group discussions with Cambridge Bay community members who were identified by the Ekaluktutiak Hunters and Trappers Organization as key knowledge holders ([11]). This includes maps of the geographical location of local marine species and based on these maps, a uniform probability distribution for each receptor was calculated (E_j) per shipping season by counting how many grid cells (size 25km^2) each original receptor polygon intersects from [11], and then assigned uniform probability of 1/(total number of grid cells) for each grid cell. These probabilities were calculated per shipping season t and grid cell g.

3.3.2 Vessel presence (P_s)

From AIS the overall traffic volumes were extracted over the 8-year data-span, 2011-2018. Then, the probability of vessel presence was calculated by dividing the amount of time (in seconds) all vessels spent per grid cell by the total amount of time all vessels (in seconds) spent throughout the entire area of Kitikmeot. These probabilities were calculated per shipping season t and grid cell g.

3.3.3 Stressor factor (F_{ij})

For the case study, existing submodels were used to calculate the stressor factors (F_{ij}) for each stressor(i) and receptor(j) combination.

Noise pollution was modelled through acoustic modelling based on the sonar equation in section 3.3.4 [94]. A MATLAB algorithm was developed and is presented in more detail in the Appendix D of this thesis. Figure 5 shows a flowchart of the macro steps of the MATLAB code developed for acoustic modelling.

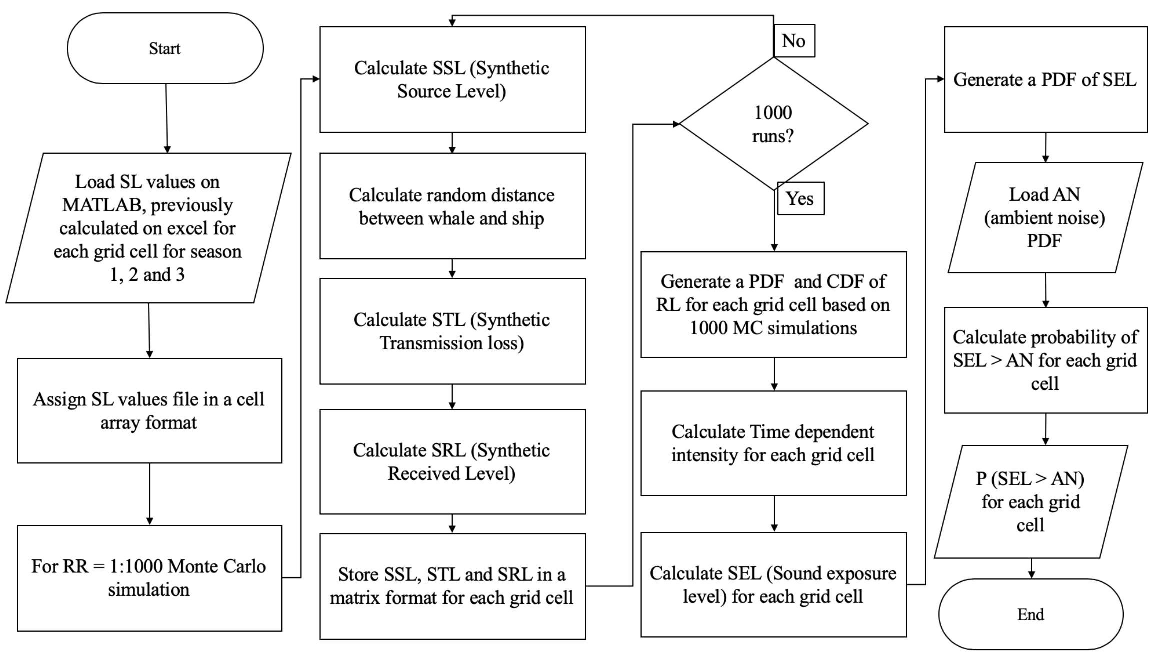

Figure 5: Flowchart of the MATLAB code for acoustic modelling.

The threshold considered was the ambient noise (AN). Ambient noise refers to all noise present in a given environment, with the exclusion of the primary sound, which in this case is shipping noise.

Oil spill was modelled through Event tree analysis (ETA), in section 3.3.5, for the two most common sources of ship-source oil spill: collision and grounding. The quantity threshold for oil spill has not yet been defined in the literature [44]; therefore, it was assumed that the incidence of an oil spill itself can potentially cause serious impacts to these receptors.

3.3.4 Acoustic Modelling ($\mathbf{F_{11}}$,$\mathbf{F_{12}}$,$\mathbf{F_{13}}$)

The following acoustic modelling was used to calculate the stressor factors (F_{11},F_{12},F_{13}) from ship-source noise pollution (stressor 1) to Narwhal (receptor 1), Beluga (receptor 2) and Bowhead (receptor 3). These values will be used in Equation 2. The stressor factor computed here for noise is understood as the the probability of each of these receptors being exposed to ship-source noise levels above Ambient Noise (AN) threshold over a certain amount of time.

In order to estimate what is the probability of a whale (receptor) being exposed to ship-source noise above a specified threshold over a certain amount of time [87], the following equation needs to be solved:

$$P(SEL > threshold) = P((RL + Tref) > threshold) \tag{3}$$

Where

SEL = sound exposure level;

RL = received level;

Tref = time dependent intensity, which accounts for an exposure time;

The baseline equation used to calculate instantaneous values of received level (RL) is a simplified sonar equation:

$$RL = SL - TL \tag{4}$$

Received level (RL) is the sound intensity (in dB) received by the receiver, which in this case is referred as receptor. Since RL is a measurement of the received level at one instant, and in reality, the receptor will be exposed to a certain level of sound over a certain amount of time, it is necessary to estimate the sound exposure level (SEL), which is the duration of time the receiver is exposed to the sound in a given area [85]. As equation 4 shows, RL can be obtained by subtracting the transmission loss (TL) from the source level (SL). SL (also in dB) is the sound energy that flows steadily away from a source, which in this case is a vessel, and TL is the loss of intensity and energy of a sound wave when travelling from source to receiver [94]. After calculating RL, a time dependent intensity level (TdB) has to be calculated by using calculated transit time per grid cell, which will then be added with RL to generate SEL. Also, since uncertainty has to be considered and accounted for as part of the CRA framework (Figure 3), a probabilistic model was developed for each term in the sonar equation (equation 4) through the Monte-Carlo (MC) approach as equation 5 below presents. The MC simulation was run and equation 5 was calculated for each grid cell.

It was decided to use this approach because this is a commonly used method to account for uncertainties in physical simulation problems [25]. A Monte-Carlo simulation is a process that involves generating random variables of inputs in order to simulate stochastic processes in proportion to their joint probability density function. It requires a large number of simulations to provide a reliable distribution of the response and for that reason it was decided to run 1000 MC simulations for the present model.

$$P(RL) = P(SL) - P(TL) \tag{5}$$

The 1000 samples were generated for each shipping season at 1 kHz frequency (this will be justified in subsection 3.2.1.2) to compute SL, TL and RL probability density functions (PDF).

Initially, a probability density function (PDF) of source level (SL) was calculated for each grid cell by using vessel average speed (v) and vessel length (ls) data as variables for the following frequency-dependent source level (SL) equation developed by Ross (1987) and adapted by [85]. These data were obtained from AIS data source.

$$SL(f, v, ls) = SL0(f) + 60 * log10(v/12) + 20 * log10(ls/300) + df * dl + 3 \tag{6}$$

where

$$df = \begin{cases} 8.1 & \text{if } 0 < f <= 28.4 \\ 22.3 - 9.77 * log10(f) & \text{if } 28.4 <= f < 191.6 \\ 0 & \text{if } f > 191.6 \end{cases}$$

$$dl = ls^{1.15}/3643 \tag{7}$$

and for f $\leq$ 500Hz

$$SL0(f) = -10 * log10(10^{-1.06*log10(f)-14/34} + 10^{3.32*log10(f)-21.425}) \tag{8}$$

and for f>500Hz

$$SL0(f) = 173.2 - 18 * log10(f) \tag{9}$$

3.3.4.1 Frequency for acoustic modelling

The decision on which frequency should be used for SL calculations was based on the recently updated scientific recommendations for residual hearing effects [87] where they have estimated new audiograms, weighting functions, and underwater noise exposure criteria for temporary and permanent auditory impacts effects for all marine mammal species based on recent scientific findings. An audiogram is basically a graph that shows the audible threshold by frequencies derived from either direct measurement (empirical data) or estimates based on assumptions and extrapolations [87].

They can be used to identify at which frequencies an animal has sensitive hearing (lower thresholds), and therefore, will tend to be more susceptible to auditory effects of noise exposure (i.e. TTS). Southall (2019) estimated the audiograms for 6 different marine mammal hearing groups, where Belugas and Narwhal are classified as High-frequency cetaceans (HF) and Bowhead as Low-frequency (LF). The following graphs (Figure 6) show the results for the estimated audiograms for LF and HF groups:

Knowing that vessels can produce noise at low frequency, typically over a range of 10Hz to 1kHz [9] and that at frequency of 1 kHz, both groups (HF & LF) present a low hearing threshold (approximately 58 dB re 1 uPa for LF and 95 dB re 1 uPa for HF), the frequency used to calculate the source levels for this model is 1 kHz.

3.3.4.2 Source level (SL)

For computation purposes, a probability density function (PDF) of SL was generated for each grid cell and stored in a matrix format, where each column represents a grid cell. A random number (between 0 and 1) was then generated and matched to the bin value of the cumulative density function (CDF) of SL (equation 6). This number

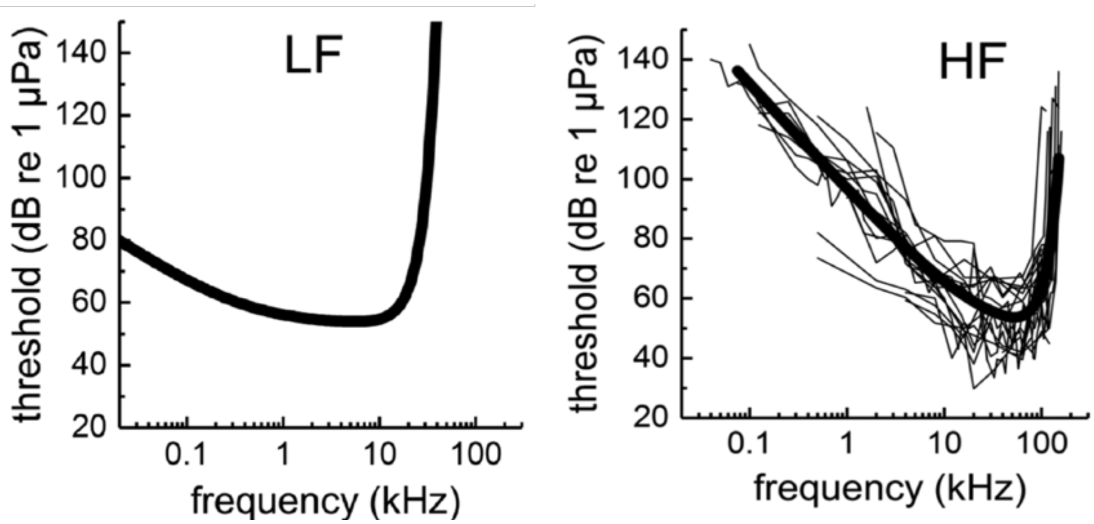

Figure 6: Estimated group audiogram based on original behavioral threshold for Low-frequency (LF) & High-frequency (HF) cetaceans. Source: [87].

was then used as the synthetic source level (SSL), which varied depending on the random number generated during each run of the Monte Carlo simulation.

3.3.4.3 Transmission Loss (TL)

With P(SL) calculated, the next element from the sonar equation (equation 4) to be calculated is the transmission loss (TL). Therefore, a PDF of transmission loss (TL) between the source (vessel) and the receptor (whale) was calculated per grid cell, using the following assumptions:

1. Whales are uniformly distributed in (x,y,z) in the cell;
2. Ships are uniformly distributed in (x,y) in the cell;
3. The amount of noise that propagates from one cell to the next is negligible;
4. Assume constant bathymetry accross the entire region.

To compute P(TL), we need to consider all possible instantaneous interactions between a ship and whale within the grid cell. Since whales and ships are distributed with uniform probability, the distance between them can be calculated by convolving the PDF of Dx and Dy [75]. The probability density of the distance between two random points in a box can be calculated through the following equation [75]:

$$P(d) = 2d(-4d/a^3 + \pi/a^2 + d^2/a^4) \tag{10}$$

Where

a = length of the side of the grid cell, which is 25 km;

d = random distance between source and receptor.

After computing P(d), another random number was generated (between 0 and 1) and matched to the bin value of the CDF of P(d). This synthetic distance (ds) was then used to calculate TL analytically using a closed form expression. For convenience and to reduce complexity, TL was estimated by using simple spreading laws of the form (equation 11) for a range independently of the shallow water wave guide, where ds represents the distance from the noise source [94].

$$TL = 10 * log10(ds) \tag{11}$$

However, due to its simplistic nature, this approach does not account for complexities in the environment, this can only produce reasonable predictions [103].

3.3.4.4 Received level (RL) and Sound exposure level (SEL)

Next, a PDF and CDF of TL were calculated based on 1000 MC samples and another random number (between 0 and 1) was generated and matched to the bin value of CDF of TL, for each grid cell. This synthetic TL (STL) was then used to calculate the received level (RL), which was computed directly using numerical methods through the sonar equation (equation 5).

With the PDF and CDF of instantaneous values of RL calculated, another random number was generated (between 0 and 1) and matched to the bin value of the CDF of RLs. This number was then used as the synthetic received level (SRL) to estimate the sound exposure level (SEL), which is the duration of time the receiver is exposed to the sound in a given area [85]. The SEL can be estimated through the following equation [85]:

$$SEL = RL + TdB \tag{12}$$

where TdB is the time dependent intensity level, which can be obtained through the following equation:

$$TdB = 10 * log10(T) \tag{13}$$

and T is the average transit time within a grid cell, which can be calculated by the following equation:

$$T = D/v \tag{14}$$

For each grid cell, the average vessel speed (v) was calculated among all vessels through 25 kilometers (D), resulting in different values of average transit time (T).

3.3.4.5 Stressor factor for noise pollution ($\mathbf{F_{11}}$,$\mathbf{F_{12}}$,$\mathbf{F_{13}}$)

After calculating the PDF of 1000 samples of SEL, the final step in the acoustic modelling was to determine the probability of SEL being above, measured ambient noise (AN) levels (equation 3). Ambient noise was the threshold considered for this model because when SEL >AN, whales are able to hear the ship noise, which can cause them behavioral disturbance and/or overlap with their social interactions [9].

Due to lack of ambient noise data for the Kitikmeot region, ambient levels from months between August 29th and October 14th were collected from the Barrow Straight, which is also a shipping waterway in the Northern Canadian territory of Nunavut. It was not possible to collect the AN data for the entire shipping period (June 1st to October 14th) since the operating sensor between those dates had an upper frequency limit of approximately 800Hz. The PDF of AN was then combined with the PDF of SEL and the integral of P(SEL>AN) was calculated on MATLAB [58] through *trapz* function.

3.3.5 Oil Spill Modelling ($\mathbf{F_{21}}$,$\mathbf{F_{22}}$,$\mathbf{F_{23}}$)

The following oil spill modelling was used to calculate the stressor factor ((F_{21},F_{22},F_{23}) from ship-source oil spill (stressor 2) to Narwhal (receptor 1), Beluga (receptor 2) and Bowhead (receptor 3). These values will be used in Equation 2.

Since adequate historical data on ship-source oil spill for the study region do not exist, an event scenario model was built with input shipping frequencies calculated based on AIS data or estimated based on previous studies when necessary, similarly to [80].

Since ship-source oil spills result from a sequence of events according to Boolean logic, event trees for each accident scenario, collision and grounding, are built for this case study. A scenario of each accident is composed of a sequence of events starting with a perturbation from the normal course of events, typically called the initiating event, until the final event, which in this case is an oil spill [80].

For an oil spill stressor, the literature has not yet defined a threshold that if exceeded could cause damage to marine mammals, therefore just the likelihood of an oil spill event itself will be assumed to cause stress in the present case study. This is a conservative assumption. Both models, collision and grounding, present the following limitations: Weathering processes and the forecasting of the fate of oil once it is spilled are not being considered due to their complexity and environmental characteristics, such as wind, weather conditions and water temperature, that would influence an oil spill.

3.3.5.1 Collision model

"Collision events consist of scenarios where two vessels accidentally come into contact with each other"[80]. The present collision model considers as a critical situation (initiating event) when two vessels cross within half a nautical mile of each other. Figure 7 illustrates how the initiating event for collision was considered in the grid cell. This approach is the same as that used by the Marine Accident Risk Calculation System (MARCS) during the SAFECO project [23]. Apart from this condition, these two vessels' tracking data have to overlap in time, and both must have different Maritime Mobile Service Identity (MMSI). It should be noted that the present model considers a pairwise vessel encounter, with one being a tanker. This assumption may underestimate collision frequencies in densely trafficked areas compared to some models of ship collisions but since traffic is still low in Kitikmeot waters, this approach suits well for the purpose.

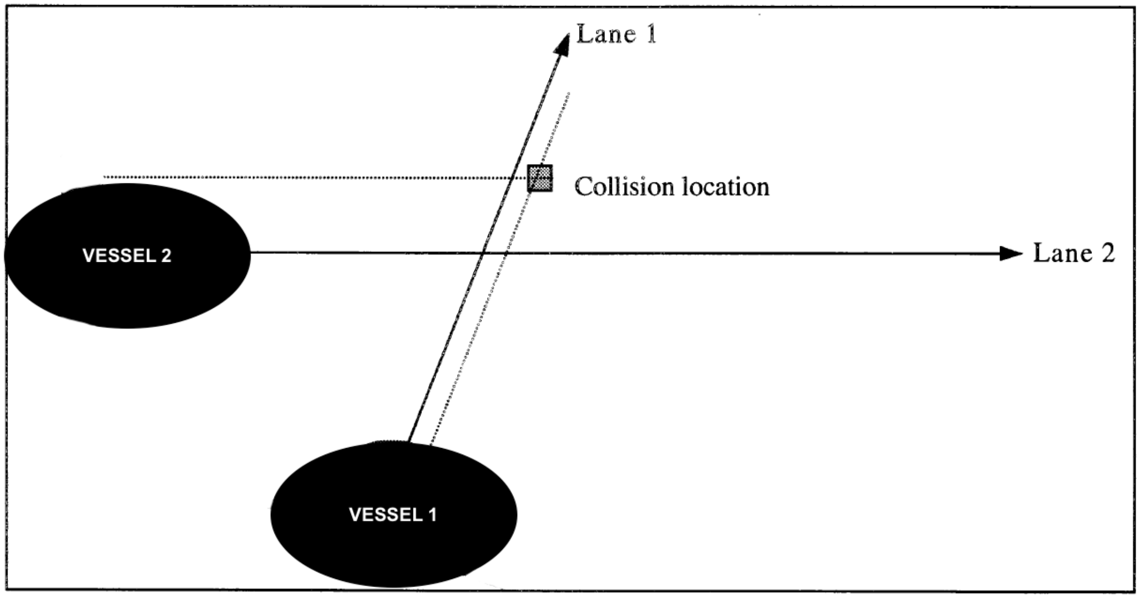

Figure 7: Initiating event for collision. Adapted from [23].

Another important consideration is that where multiple vessels were within the distance of 1/2 nautical mile of a tanker at once, they were treated as additive. This has came up as critical because the probabilities are time based, and how this is factored in will impact how to treat the temporal aspect. For instance, when considering a transit (line) of tanker travel which is within 1/2 nautical mile of a vessel for only half of its length, it was assumed that half of its time is encounter and the other half not. If, on the other hand, it is near 3 vessels during this time, the encounter is multiplied by three times (3x).

Based on these conditions and assumptions, 'overall tanker time (presence)' (in seconds) and the overall encounter time (in seconds) was calculated per grid cell. These are used to generate the probabilities of critical situations for collision, by dividing encounter time by presence, over the 8-year period (2011-2018). This probability brings the spatial element to the collision event tree (see Figure 8), in the initiating event stage. These values, per grid cell, will be presented in chapter 4 (results). The subsequent events were obtained from previous studies ([73], [48], [39]) and added to the following collision event tree in Figure 8 in order to calculate the frequency of collision for each grid cell, per shipping season.

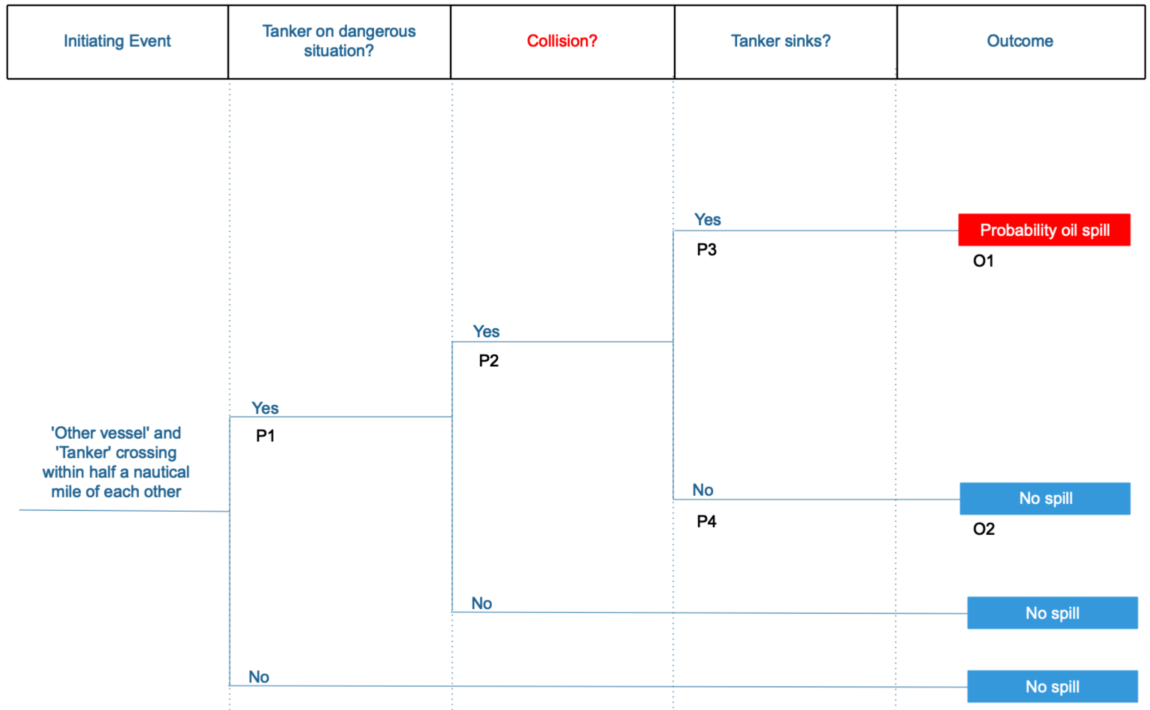

Figure 8: Event tree for Collisions.

3.3.5.2 Grounding model

"Grounding events consist of scenarios where the vessel accidentally comes into contact with the sea bed or shore, for which causes can be either navigation failure (powered grounding) or steering failure (drift grounding)" [80]. A drift grounding model would require more sophisticated environmental data (wind/current) to calculate its probabilities and, when compared to powered grounding, its likelihood of happening is almost 5 times lower and the consequences 2 times lower as investigated by [80], and for those reasons it was decided to leave drift grounding out of the scope of this case study.

The initiating event (critical situation) considered for powered grounding event tree (see Figure 10) is an adaptation from the approach used by MARCS for the SAFECO project, where they considered a critical situation when the tanker track results in a way-point within 20 min from landfall, such that if a course change is not made the tanker can potentially ground [23]. However, instead of representing it as an instantaneous event as [23] considered, the time interval when a tanker has its course change within or less than 20 min from landfall was calculated. In other words, the probability of the initiating event for powered grounding was calculated as the amount of time the tanker has spent making a course change within or less than 20 min from landfall.

Different than the noise modelling, it was decide to use the vessel segment as a representation to calculate the source levels for sonar equation, the powered grounding model used vessel track points as the representation, which was found to be more suitable for the probability calculations. The first step after extracting the data from AIS was to verify the criticality requirement through ArcMap, which is shown in Figure 9. Figure 9 portrays an illustrative example of how the model works and it is important to note that the course represented in this figure does not intend to accurately represent the cardinal direction in which the tanker is to be steered.

In the following steps, the distance (Ln) between the tanker (Pn) and landfall (Sn) was calculated and checked whether it is less or equal to 20 min, then time (Tn) was stored in an Excel table format to be used for the time intervals computation. This verification is then replicated for the next points following the vessel path until the criticality requirement is no longer applied (see Figure 9 for the criticality requirement step-by-step). Lastly, the time interval between the initial and final points was used to compute the 'overall way-point time" (in seconds). Based on these values and the 'overall tanker time" (in seconds), the probability of tanker track results in a way-point within (or less) than 20 minutes of a landfall was calculated, per grid cell and shipping season. These probabilities bring the spatial element to the event tree (see Figure 10).

After having probabilities computed per grid cell and shipping season, these were used as input for the powered grounding event tree. The probability for the subsequent events were obtained from previous studies [73], [48] & [39] and added to the powered grounding event tree in order to calculate the frequency of grounding for each grid cell, per shipping season. These probabilities will be presented in chapter 4 (Results).

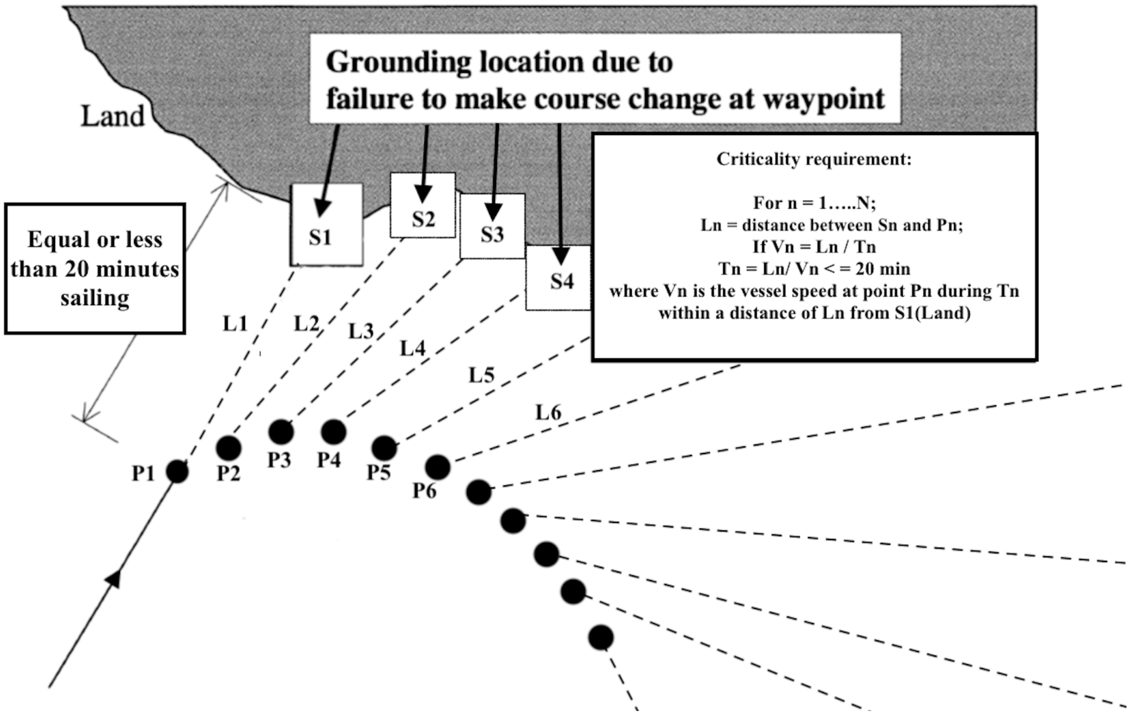

Figure 9: Initiating event for powered grounding. Adapted from [23].

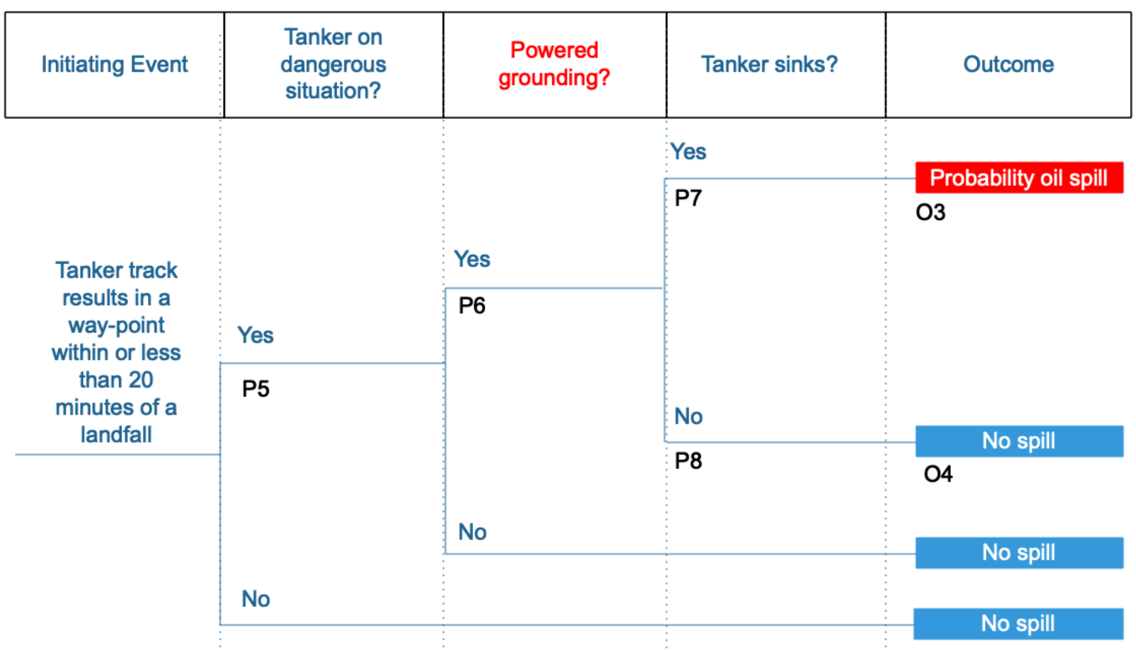

Figure 10: Event tree for Powered Grounding.

3.3.6 Sensitivity (S_{ij})

Given that multiple stressors do not affect the receptors equally, it is necessary to assess the sensitivity of each receptor to each stressor, based on stressor-specific sub-factors (Figure 11). In order to do that, a measure of sensitivity from each receptor to each stressor is incorporated (S_{ij}) in equation 2.

Due to ethical research limitations, data on sensitivity of marine life receptors to shipping stressors are not always available in the literature or able to be collected empirically [67]. Therefore, due to lack of comprehensive empirical information on receptor–stressor interactions, expert inputs are needed to make existing research directly useful to policy makers. Ecological sensitivity is an inherently complex concept, hence, structuring the collection of expert knowledge on sensitivity into these sub-factors creates more consistency and transparency to the use of expert opinion. Additionally, previous studies on expert bias asserted that eliciting through more than one factor results in better calibrated expert assessment than eliciting the target index directly [67].

The sub-factors for each stressor are identified based on literature review [67], [91],[101],[21] and consultation with experts in the field and, will be presented on Chapter 4 (Results). After identifying the key sub-factors, a pilot test was run with lay people in order to check whether the questionnaire was clear and concise. Then, the final version of this questionnaire was sent to a selected list of experts. Figure 11 presents the graphical representation of the generic sensitivity assessment. The sub-factors, their description and the results from this expert survey are presented in the results (Chapter 4).

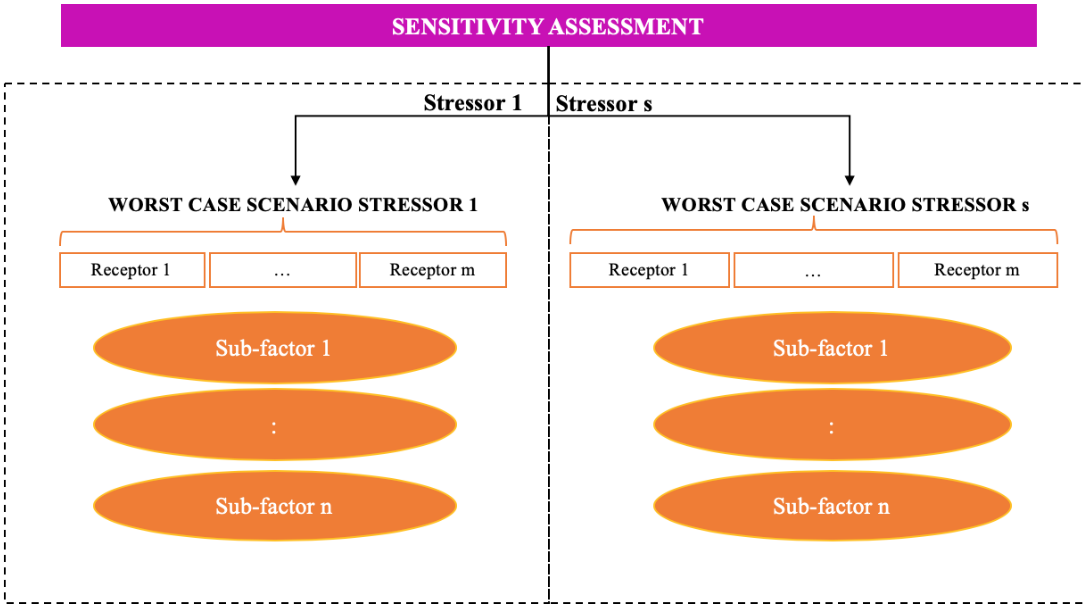

Figure 11: Generic sensitivity assessment framework and its subfactors.

Through the online questionnaire, the experts were asked to score each sensitivity sub-factor qualitatively, which was then converted to a qualitative-quantitative scale following the scheme below:

Sub-factor score	Level of impact
1	Low impact
2	Medium impact
3	High impact

Table 4: Subfactor score and its respective level of impact.

For Sensitivity (S_{ij}), judgments from experts are based on given baseline scenarios that are intended to frame the worst case scenario for each stressor; therefore, this framework does not intend to cover all possible stressor-receptor scenarios. Additionally, sub-factors are equally weighted, which means that each sub-factor has the same importance for the overall sensitivity score.

The proposed sensitivity framework uses a simple mathematical approach to combine all sub-factors into one final single score (addition). Since sensitivity is expected to be monotonic (i.e. higher values derived greater impacts), it can be reasonably approximated by a simple linear model with the assumption that factors are equally weighted [90]. The maximum value of the sensitivity score is 9 according to Table 4.

$$S_{\text{ij}} = \sum_{k=1}^{k} (subfactor) \tag{15}$$

where k is the number of sub-factors.

3.4 Case study limitations

Due to restrictions related to data and resource availability, not all the stressors identified from shipping activity are included in the presented case study. Additionally, the analysis only considers stressors from shipping activity, without considering other stressors possibly affecting the marine mammals in the study region (i.e. climate change effects). Pollution sources are limited to ship-source spills (oil tankers); therefore, offshore and onshore oil and gas development (offshore installations, exploration rigs and pipelines) are outside of the scope of this study as is fuel leaking.

Weather data (such as temperature, wind, etc.) and iceberg presence are outside of the scope of this study, including omission of drift/weathering from an oil spill event. Additionally, due to time and data constraints, ship-source oil spill refers to any spills that could occur from products transported by tankers as refined cargo carriers, not considering the oil spills from transferring oil between a vessel and an oil handling facility (OHF), nor oil spill from fuel leaking used for vessel propulsion. The main reason for that is because of the current discussions between the Canadian government with The international maritime organization (IMO) to ban the use of Heavy fuel oil (HFO) as a bunkering fuel for shippping in the Arctic [35]. Although it has not been implemented yet, there is high chances of this mitigation strategy to materializing, since HFO has already been banned in the Antarctic.

For the causation probability (Pc) found from the literature for collision and powered grounding, assumptions had to be made seeing that the study region for this case study is a VTS zone Northern Canada Vessel Traffic Services Zone (NORDREG) but there is insufficient evidence about environmental conditions or human performance issues; therefore, it is difficult to pick a single value from literature findings. For that reason, it was decided to use 1×10^{-4} as causation probability for both, collision and grounding. Consequently, in order to get the probabilities of a tanker sinking given collision and powered grounding occurrences from SAFEDOR project [80], an open sea type was assumed operational state, and the worst case scenario where the tanker is the struck vessel, loaded and breach of both hulls occurs (inner and outer).

Different than the ARA methodology developed by Dillon Consulting (2015), the oil spill assessment incorporated in this case study is limited only to the screening-level risk assessment, which is intended to identify specific locations within Kitikmeot boundaries that are more vulnerable to ship-source oil spills, excluding a more detailed oil spill risk assessment.

In terms of the receptors selected for this case study, it is important to highlight that Bowhead, Beluga and Narwhal do not represent all the marine life in the Kitikmeot region, nor does it include spatial planning areas such as Ecologically or Biologically Significant Marine Areas (EBSAs) and Marine Protected Areas (MPAs). However, these three receptors are highly important to local communities in the Arctic, for cultural and survival reasons. Additionally, this framework can be used as an example for more comprehensive future applications.

Another limitation is related to the sensitivity assessment performed in the case study. The main goal of the sensitivity assessment was to focus on the generalised impacts from initial stages of large ship-based spill for an oil spill stressor and from a consistent ship-source noise pollution where the animal is assumed to be very close to the source for a reasonable amount of time. Therefore, this study excludes other scenarios that are different than the baseline scenario set for the sensitivity assessment.

Finally, this assessment is strictly informative, hence no control measures for the stressors nor the receptors are included/recommended in the study.

Chapter 4

Results

4.1 Case study

For the case study, the geographic area selected is the Kitikmeot region (see Figure 12), which is home to numerous endemic Arctic marine species [16]. Two shipping stressors in the case study, ship-source oil spill and ship-source noise pollution were included and three species that are highly important Arctic whales to Inuit communities as the direct receptors to the shipping stressors, Narwhal, Beluga and Bowhead. This study focuses on the shipping season only, which extends from Upingaaq (June 1 — August 14), Aujaq (August 15 — September 14) to Ukiaksaaq (September 15 — October 14) [18] for years 2011 to 2018 inclusive (see Table 5).

This period was chosen due to minimal shipping activity identified in the remaining period of the year (from October 15 to May 31). From the AIS ship positions falling within the Kitikmeot grid boundaries, there were 2,490,531 noted to fall between 2011 and 2018. Of these, 2,457,441 were in the study time period between June 1 and October 14, inclusive; the remaining 33,090 records that fell outside the study time period. These numbers represent 98.7% and 1.3% of the total respectively. Therefore, seasons of Ukiak (October 15 to February 15), Ukiuq (February 16 to March 31) and Upingaksaaq (September 15 to October 14) were excluded from this case study. It is important to note that during this shipping period sea ice is largely melted in the study area; therefore, it was not necessary to simulate ice-covered waters in the case study.

Ideally, a CRA assessment of the full extent of the NMTC should be done; However, by considering the time, financial and data challenges that exist in examining the full extent of NMTC, which extends across the entire Canadian Arctic, only the segment that crosses Kitikmeot region was assessed in the case study.

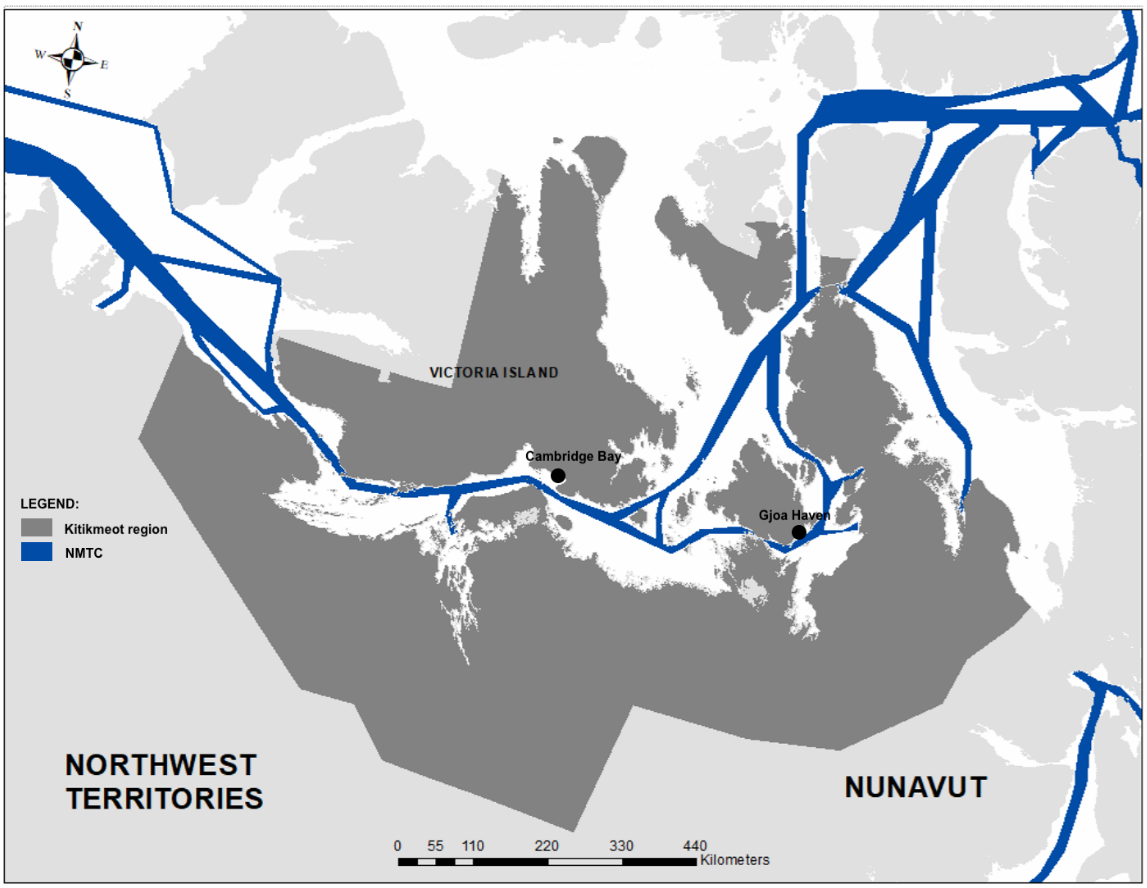

Figure 12: The Kitikmeot region of Nunavut and the The Northern Marine Transportation Corridors (NMTC). Source: adapted from [12]

T	Season	Months
1	Upingaaq	June 1 – August 14
2	Aujaq	August 15 – September 14
3	Ukiaqsaaq	September 15 – October 14

Table 5: Shipping seasons in Kitikmeot region, Source:[18]

4.2 Shipping in the Kitikmeot region

AIS from 2011 to 2018 identified a total of 157 unique vessels entering the Kitikmeot boundaries during the shipping season which goes from June 1st to October 14^{th}. The two-digit information contained in the AIS-transmitted message can be used to deduce the vessel type. The first digit represents the general category of the subject vessel and the second digit provides additional information regarding the subject vessel's type of cargo [83]. Figure 14 shows the breakdown of vessel classes from the total unique vessels, which are represented by 10 different industries. The majority of unique vessels were pleasure craft (36%), followed by cargo vessels (12%). However, when it comes to total distance travelled within the study period, Search & Rescue (30%) and Passenger vessels (16%) seemed to be dominating the region (see Figure 15). Between 1990 and 2000 the region used to be dominated by government vessels and icebreakers (46%) and tug and barge vessels (42%) which were likely supporting general cargo [18]. However, from 2000 to 2015, as Figure 13 shows, the distribution of government vessels and icebreakers and tug and barge vessels have decreased to 27% and 16% respectively, and the other type of vessels have substantially increased [18]. Not only the relative proportion of ship traffic by vessel type has changed but also the overall vessel traffic for all vessels have intensified within the Kitikmeot region [18]. Special attention is also given to the increase of large tanker ships over time, which used to represent less than 1% of the traffic (before 2005) and currently makes up about 9% of total kilometers travelled by all vessels in the region (see Figure 15)[18].

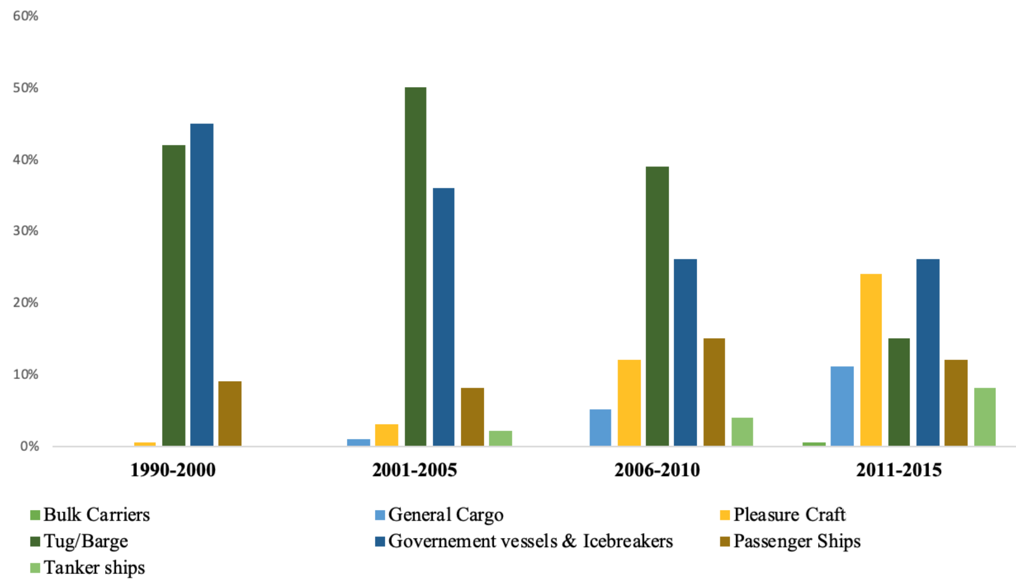

Figure 13: Relative proportions of ship traffic in the Kitikmeot region based on annual distance travelled, 1990-2015. Source: modified from [18].

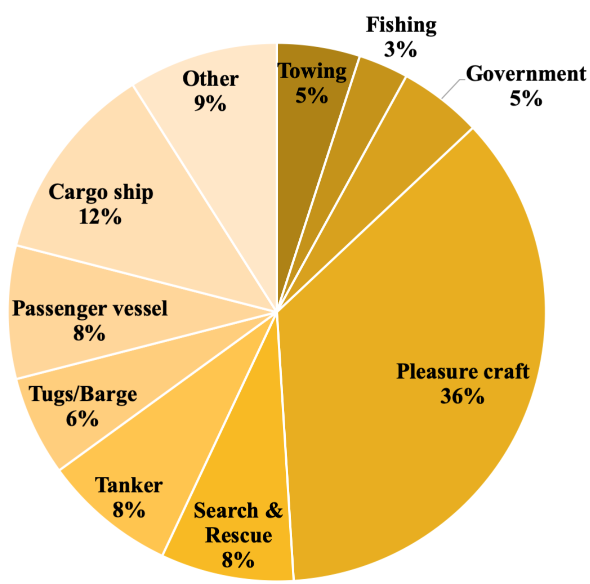

Figure 14: Breakdown of vessel classes that entered the Kitikmeot boundaries between 2011 and 2018 during shipping season. This pie chart shows the percentage of each vessel type among the total of 157 unique vessels.Source:AIS data provided by exactEarth and refined by MEOPAR.

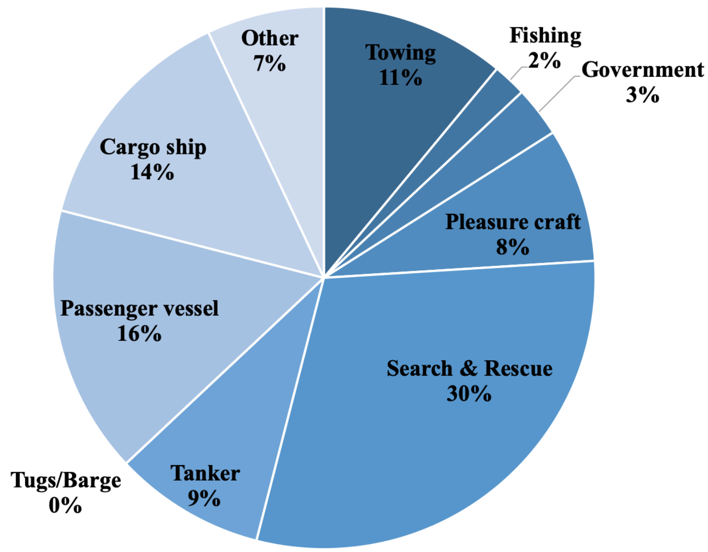

Figure 15: Breakdown of vessel classes that entered the Kitikmeot boundaries between 2011 and 2018 during shipping season. This pie chart shows the relative proportions of ship traffic based on distance travelled. Source: AIS data provided by exactEarth and refined by MEOPAR.

Vessel type	Total KM travelled (2011-2018)
Fishing vessel	15,301
Towing vessel	80,475
Pleasure craft	58,103
Gov vessel	19,650
S&R	217,618
Cargo ship	103,128
Passengers	115,727
Tanker	65,624
Tug/Barge	4,668
Other	52,217

Figure 16: Total km travelled by vessel type during period of 2011 to 2018. Source: AIS data provided by exactEarth and refined by MEOPAR.

4.3 Application of CRA in Kitikmeot

In the following sections (from 4.3.1 to 4.3.7), each step from the CRA framework, proposed previously in the methodology chapter (see Figure 3 for reference), will be applied and its results presented.

4.3.1 Identify relevant problems and policy aims

Through participatory mapping, focus group discussions, workshops and interviews with local communities in the Kitikmeot region, [11] was able to address 'Inuit people's' concerns regarding the increase of shipping activity in the Nunavut waters, from two major Kitikmeot communities, Cambridge Bay and Gjoa Haven, as listed in Table 6. Some of these concerns are related to the impacts of a possible event of oil spill (e.g. contamination of Arctic waters, water quality) and noise pollution (e.g. behavioral changes in wildlife).

Cambridge bay	Gjoa Haven
Contamination of Arctic waters, animals, and people	Employment opportunities, increased local travel costs.
Behavioral changes in wildlife, destruction of animal habitat	Behavioral changes in wildlife, destruction of animal habitat.
Increased food insecurity	Positive and negative cross-cultural interactions.
Increased incidence of dangerous ice conditions for local	Threats to security, and exchange of alcohol and drugs.
Travel, and threats to water quality	Gaining supplies and equipment, more timely cargo delivery.
Limited employment/income opportunities	Increased incidence of dangerous ice conditions for local travel.

Table 6: Inuit local concerns regarding shipping activity in Kitikmeot region. Source: [11].

4.3.2 Identify temporal and spatial boundaries

The assessment was restricted to the region of Kitikmeot, which is an administrative region of Nunavut. The calculation for CRA was performed for each gridded polygon of area of 25 km x 25 km (see Figure 17). A 25 km x 25 km grid cell is considered a good compromise between the entire supply of commercial shipping activity and the computational work necessary to extract the ship tracks from AIS, which would be more intensive with smaller grids [19]. In total, there was 2475 grid cells.

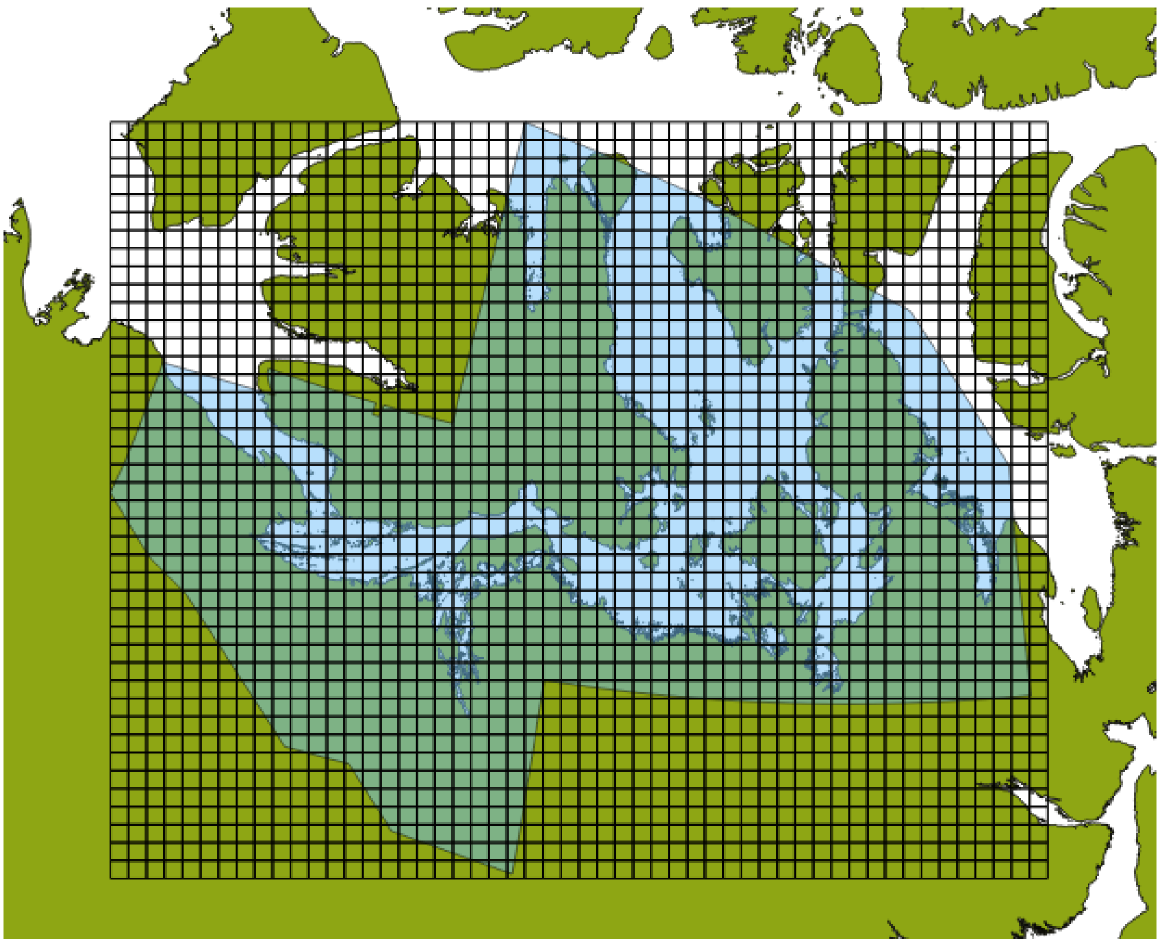

Figure 17: Gridded polygon of Kitikmeot region of size of 25km2, used to calculate the risk scores through equation 2.

In terms of the temporal boundary, even though the Northern communities follow six different seasons throughout the year [11], the assessment was made only for the seasons that presented significant amount of shipping activity over the period of 2011 to 2018, according to Table 5.

4.3.3 Identify receptors

For the case study, the following marine mammals are the receptors: Beluga, Bowhead and Narwhals. These animals require special attention from public organizations when considering new policies for shipping in the Canadian Arctic. Different than Beluga, Bowhead and Narwhal are still not considered endangered species, although they are listed as special concern by the Committee on the Status of Endangered Wildlife in Canada [15]. From a local perspective, these animals are important to traditional Inuit subsistence hunting as communities rely heavily on them to maintain their food security and also culturally important to many Inuit communities in the Arctic [11]. From a global perspective, the conservation and protection of these animals and their habitats can try to avoid some of the consequences of a warming climate. Another important characteristics is the location of these whales, which can vary throughout the seasons due to migration patterns [11]. Through the contribution of traditional knowledge (Inuit knowledge), the seasonal location of these marine mammals was able to be determined and used for the present CRA [11].

4.3.4 Identify relevant stressors

From Table 6, it can be seen that both Kitikmeot communities have expressed concerns about behavioral changes in wildlife and destruction of animal habitat which is strongly related to potential impacts from a potential oil spill event or increase of noise pollution from shipping [30]. Contamination of Arctic waters, animals and people are also a major threat that can result from an oil spill incident [91]. Therefore, based on these local concerns it was decided to use oil spill and noise pollution for the present case study.

4.3.5 Data Collection and CRA implementation

4.3.5.1 Stressor factor - ship-source oil spill

The stressor factor computed for ship-source oil spill is understood as the the probability of an event of a ship-source oil spill for each grid cell and shipping season. As mentioned previously, thresholds to chemical contamination for marine species are not adequately understood in the literature [44]; Therefore, it was assumed that the event of an oil spill itself can cause stress to the marine receptors.

In the context of this submodel, as mentioned in the case study limitations, any spills occur from products transported by tankers as refined cargo carriers, but not considering the oil spills from transferring oil between a vessel and an oil handling facility (OHF), nor oil spill from fuel leaking that is used for vessel propulsion.

Therefore, only fuel transported as cargo will be included in this case study. Considering the fact that there has been an increase in the number of tankers transiting through Kitikmeot waters in the last few years (see Figure 13) and that, according to Table 1, the most dramatic and catastrophic oil spills in history occurred with tankers, the ship-source oil spill model presented here is exclusively tanker-source oil spills.

Additionally, the consequences of an oil spill in the Arctic could be disastrous because of its remoteness, shallow waters, home to highly sensitive animals, and ice presence, which makes this issue more complicated to be addressed there than in lower latitude areas. Therefore, it is paramount to include this potential stressor in the present CRA.

The causes and circumstances of oil spills are diverse, including collision, grounding, hull failure, equipment failure, fire/explosive and others [42]. From Figure 18 below, it can be concluded that the most common causes for ship-source oil spill greater than 7 tonnes are collision and grounding, and for that reason they were included in this study.

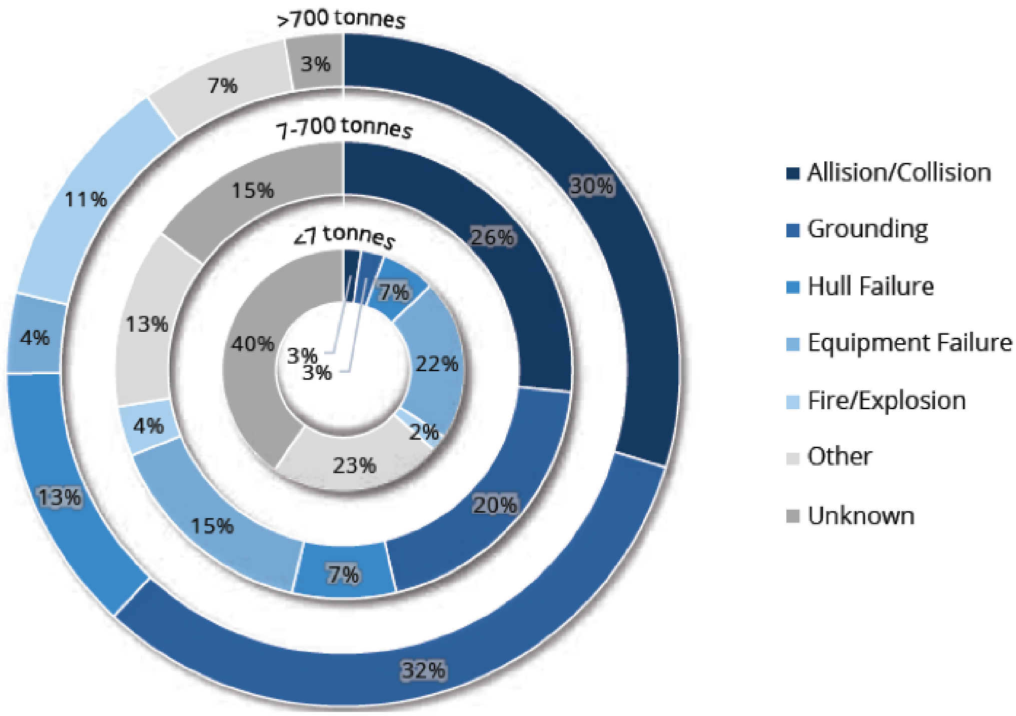

Figure 18: Cause of spills, worldwide data. Source: [42].

In order to calculate the probability of a ship-source oil spill, the event tree models for collision and grounding (previously proposed in the methodology section, (Figures 8 and 10) have to be populated with the following probabilities:

Collision event tree probabilities		
Initiating event	"Other vessel" and "tanker" crossing within half a nautical mile of each other	P1
Sub-event 1	Collision given initiating event	P2
Sub-event 2	Tanker sinks given collision	P3
Sub-event 3	Tanker does not sink given collision	P4
Outcome	Probability of oil spill	O1 & O2

Table 7: Collision event tree probabilities.

Powered-grounding event tree probabilities		
Initiating event	Tanker-tracck results in a way-point within or less than 20 minutes of a landfall	P5
Sub-event 1	Grounding given initiating event	P6
Sub-event 2	Tanker sinks given grounding	P7
Sub-event 3	Tanker does not sink given collision	P8
Outcome	Probability of oil spill	O3 & O4

Table 8: Powered grounding event tree probabilities.

For the initiating event for collision (P1), each grid cell was tested for the following condition: 'Other vessel' and 'Tanker' crossing within a half nautical mile of each other given that both vessels must have different MMSI (code used to uniquely identify a ship) and their instance overlap in time by using its start date and end date attribute from AIS data (see Figure 7). For season 1, only two grid cells (441 and 2375) satisfied these conditions, however these grid cells fell into another Nunavut Region, called Queen Elizabeth Islands, which is located in the north of Kitikmeot region. For season 2 and 3, there were 92 and 191 grid cells satisfying these conditions, respectively. Once more, 38 and 40 grid cells that fell outside of Kitikmeot boundaries were found for season 2 and 3, respectively. Part of these outliers fell into Baffin region (east side of Kitikmeot region) and a few of them fell into the Queen Elizabeth Islands area. It is important to note that these outliers did not affect the final risk score outcome since the receptor data was restricted to the Kitikmeot boundaries only, therefore, canceling out the outliers. These probabilities were ranging from 0.036 to 0.118 for season 1, for season 2 ranging from 0.003 to 1.0 and for season 3, from 0.0015 to 1.0. Figure 19 shows the grid cells (id 563 and 1288) with the greatest values of P1 for season 2. For season 3, those same grid cells were found to have the greatest value as well.

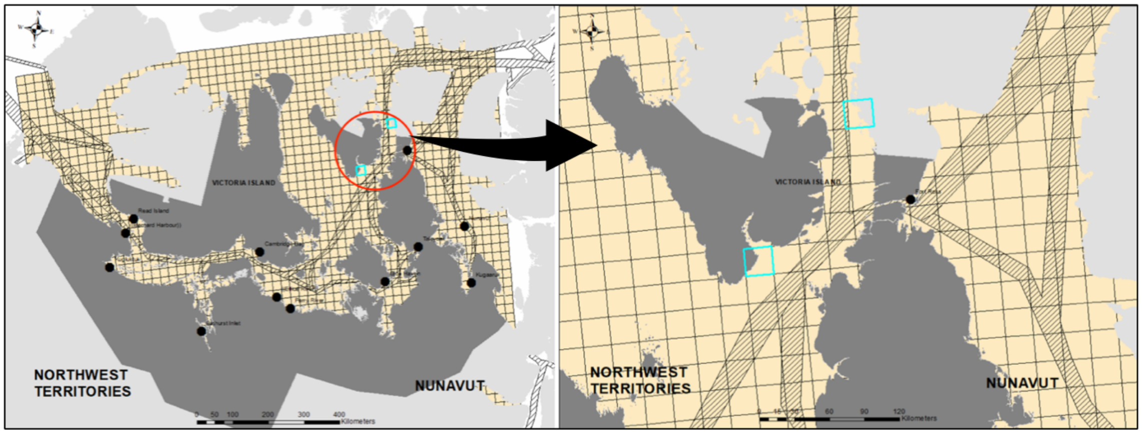

Figure 19: Grid cells where probability of other vessel and tanker encounter is equal to 1.0 for season 2.

For the initiating event for powered grounding (P5), each grid cell was tested for the following condition: Tanker track that resulted in a way-point within or less than 20 minutes of a landfall (see Figure 10). For season 1, only four grid cells (101, 440, 441 & 911) satisfied these conditions. Similarly to the initiating events for collision, grid cells 440 and 441 fell into another Nunavut Region, called Queens Elizabeth Islands, which is located in the north of Kitikmeot region. For season 2 and 3, there were 21 and 24 grid cells satisfying these conditions, respectively. Only 2 and 3 outliers occurred for seasons 2 and 3, respectively. These outliers all fell into the Queen Elizabeth Islands area. The initiating event probabilities for powered grounding were ranging from 0.004 to 0.30 for season 1, from 0.00013 to 1.0 for seasons 2 and for season 3, from 0.000015 to 0.61. Figure 20 and 21 shows the grid cells where the probability of initiating event for powered grounding is at its greatest for seasons 2 and 3, respectively. These probabilities do not represent the final risk score, therefore, so a final conclusion can not be drawn based solely on these values. Instead, the closeness of two Kitikmeot communities (Kugluktuk and Cambridge Bay) to these grid cells with highest probabilities for the initiating event for powered grounding can be seen as a potential red flag for policy makers.

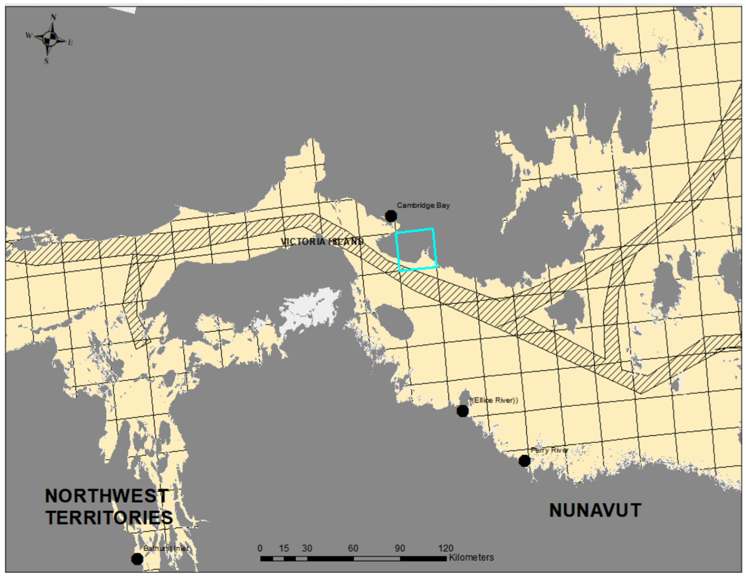

Figure 20: Grid cells where probability of tanker track results in a way-point within, or less, than 20 minutes of a landfall is at its greatest for season 2.

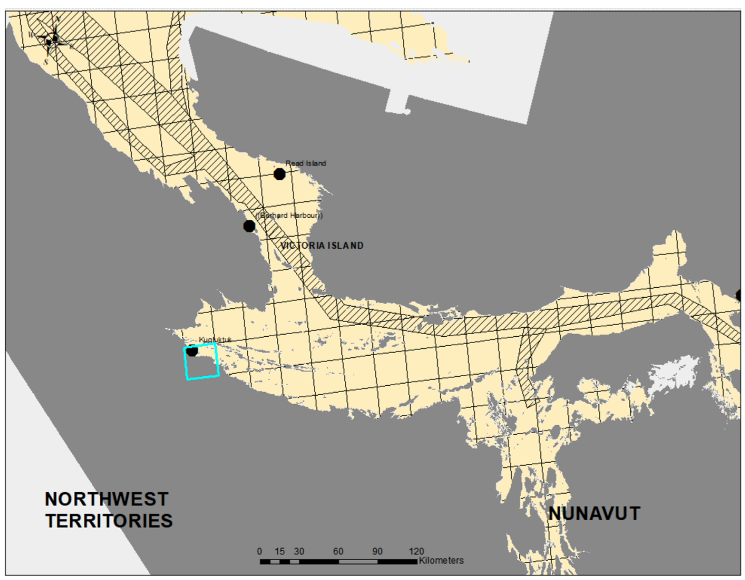

Figure 21: Grid cells where probability of tanker track results in a way-point within, or less, than 20 minutes of a landfall is at its greatest for season 3.

The next step is to calculate the probability of collision and powered grounding happening given the materialization of their respective initiating events (P2 & P6). A commonly applied approach for estimating the probability of collisions and groundings in maritime traffic was defined by [24] and [55] and have been applied in more recent maritime risk assessments [73], [48], [39] & [46]. This approach estimates the potential number of collisions or groundings by calculating the number of possible accident candidates, which is then multiplied by the so-called causation probability. The causation probability (Pc) is the probability of a vessel failing to avoid the accident while being on a dangerous course. Failing in this case can be a result of either a technical failure such as failure of the steering system or propulsion machinery, human failure, or environmental factors [23], [48].

According to [48], applying a causation probability value derived from a study in another sea area or estimating it based on the difference in accident statistics is a way to save some effort, although not addressing the actual elements can bring a lot of uncertainty to the model. To have more accurate accident probabilities, the causation factor should ideally reflect the specific characteristics of the studied area (e.g. environmental conditions) and the properties of the vessels in question. However, as indicated by [48], after calculating the general causation probability through a more sophisticated Bayesian network model for a crossing area in the Gulf of Finland, it is concluded that all the causation probabilities in the literature are about the same order of magnitude. The following table shows some causation probability (Pc) found from the literature and associated remarks. Even though the study region is a VTS zone Northern Canada Vessel Traffic Services Zone (NORDREG), there is no evidence about environmental conditions or human performance issues, so it is difficult to pick a single value from Tables 9 and 10. For that reason, it was decided to use 1×10^{-4} as causation probability for both collision and grounding.

Source	(Pc)	Remarks
Fujii (1974)	1.2E-4	Based on collision statistics in Japanese waters.
Fowler (2000)	8.48E-5	North Sea area. In good visibility
Fowler (2000)	6.83E-5	North Sea area. In good visibility within VTS zone
Fowler (2000)	5.8E-4	North Sea area. In poor visibility
Fowler (2000)	4.64E-4	North Sea area. In poor visibility within VTS zone
Kujala (2010)	2.56E-4	Gulf of Finland. Good environmental conditions and good human performance
Kujala (2010)	2.94E-4	Gulf of Finland. Poor environmental conditions and good human performance
Kujala (2010)	1.97E-3	Gulf of Finland. Poor environmental conditions and poor human performance
Kujala (2010)	4.27E-4	Gulf of Finland. Good environmental conditions and poor human performance
Kujala (2010)	2.70E-4	Gulf of Finland. No evidence about environmental conditions and no evidence about human performance

Table 9: Causation probability for collision.

Source	(Pc)	Remarks
Pedersen (1995)	3.5E-4	European waters.
Fowler (2000)	3.07E-4	North Sea area. In good visibility
Fowler (2000)	2.47E-4	North Sea area. In good visibility within VTS zone
Fowler (2000)	8.57E-4	North Sea area. In poor visibility

Table 10: Causation probability for grounding.

For P3 & P6, probabilities were taken from the Formal Safety Assessment (FSA) study on tankers based on worldwide data for the SAFEDOR project [80]. The methodology used for this risk assessment consists of linking fault trees with event trees in order to represent a full accident scenario of major hazards from large oil tankers [80]. For their collision and grounding model, the scenarios take into account a more broad sequence of events than this present case study, including the probability of a tanker being the struck or striking vessel, the operational state which accounts for the characteristics of different seaways and ports, tanker loading conditions, severity of the damage and, finally, the final event which is the probability of the tanker sinking given that all the previous events happened. For this case study, considering an open sea type of operational state and assuming a worst case scenario where the tanker is the struck vessel, loaded and breach of both hulls (inner and outer), the probability of tanker sinking is 0.2 for collision (P3) and 0.17 for grounding (P6) [80]. Table 11 below summarizes all probabilities for collision and powered grounding retrieved from the literature.

Collision	Powered grounding
P2 = 1.10e-4	P6 = 1.10e-4
P3 = 0.2	P7 = 0.17
P4 = 0.8	P8 = 0.83

Table 11: Probabilities from literature to populate collision and powered grounding event trees.

After populating the event trees for collision and powered grounding, the probability of a ship-source oil spill could be computed for each season. For season 1, the grid cells found to have highest probability of oil spill were located outside of the Kitikmeot region (Queen Elizabeth Islands). For season 2, on the other hand, the grid cells with probability of oil spill are the ones relatively close to three Kitikmeot communities (Kugltuktuk, Cambridge Bay, Gjoa Haven and Fort Ross) as Figure 22 shows. The following Figures 23, 24, 25 & 26 show in more details the grid cells and their probabilities for areas close each of these communities. Again, these probabilities solely do not represent the final risk scores but can be used to indicate areas that are more likely to experience an event of oil spill.

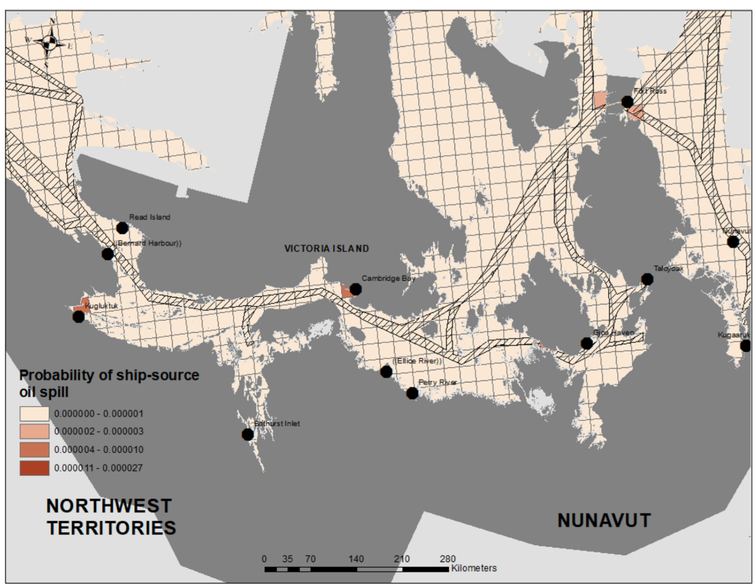

Figure 22: Grid cells with probability of oil spill for season 2.

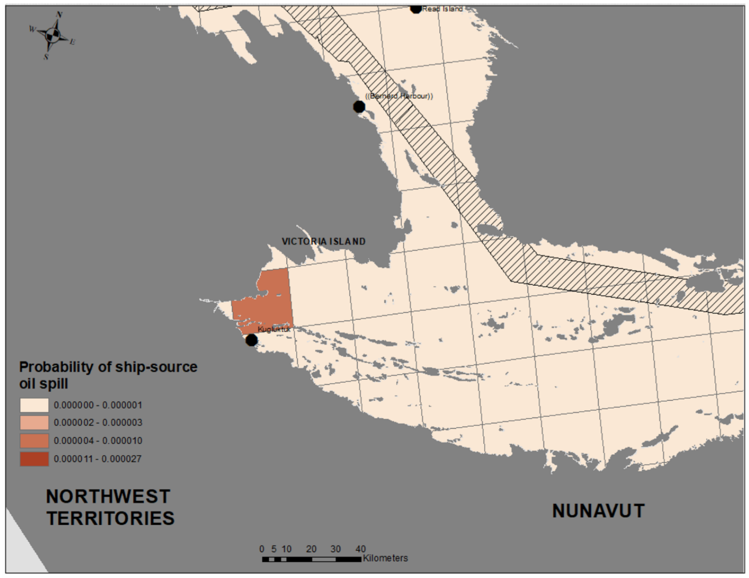

Figure 23: Grid cells with probability of oil spill for season 2 close to Kugluktuk community.

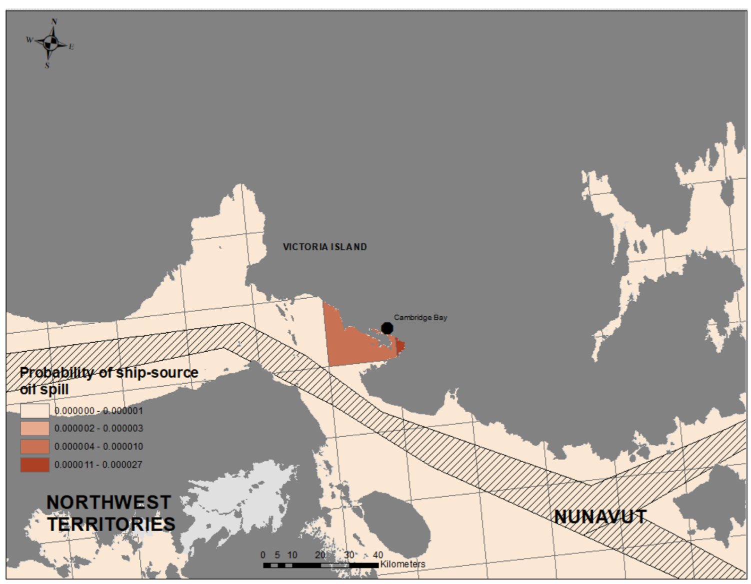

Figure 24: Grid cells with probability of oil spill for season 2 close to Cambridge community.

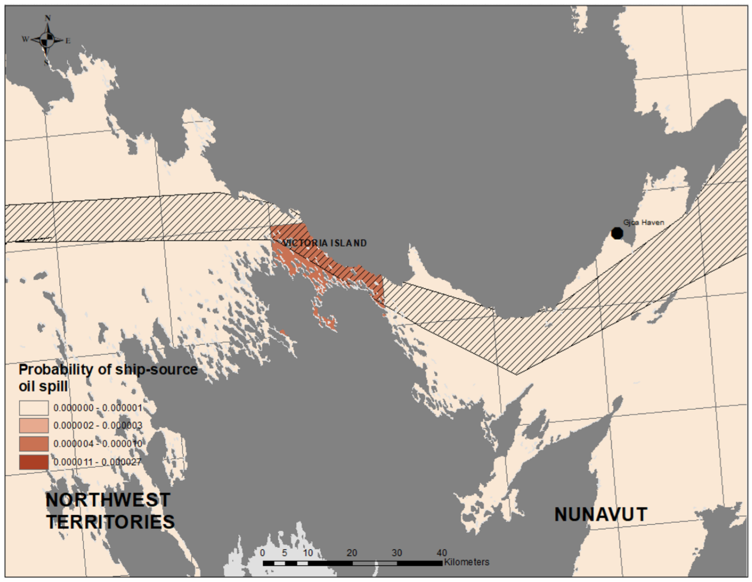

Figure 25: Grid cells with probability of oil spill for season 2 close to Gjoa Haven community.

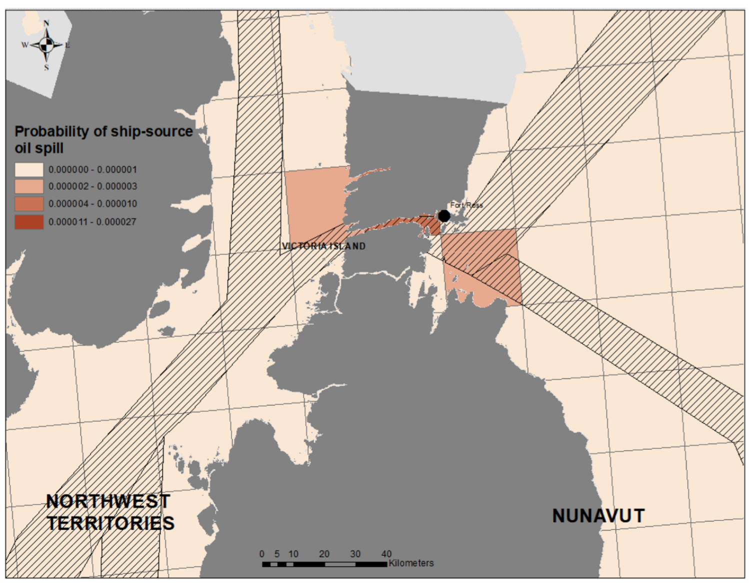

Figure 26: Grid cells with probability of oil spill for season 2 close to Fort Ross community.

4.3.6 Stressor factor - ship-source noise pollution

The stressor factor computed for ship-source noise pollution is understood as the probability of the ship sound source level exceeding ambient noise for each grid cell and shipping season. As mentioned previously, this threshold was chosen because whales are able to hear the ship noise when it exceeds ambient noise levels, which can cause behavioral disturbance and/or overlap with their social interactions [9].

For the present acoustic modelling, raw Automated Identification System (AIS) vessel tracking data was extracted for the study region for the period of 2011 to 2018 and refined by a program at the Marine Environmental Observation Prediction and Response (MEOPAR) network. AIS data points were transformed to segment representations by using an algorithm that links each of them according to its vessel information in order to define a straight linear interpolation between reported positions with a maximum separation time of 360 minutes.

Each vessel segment contains the following attributes: Maritime Mobile Service Identity (MMSI), IMO, call sign, AIS class, vessel name, length (in meters), breadth, average speed over ground (in knots), draught, start and end data of AIS data capture, course type, season and year and the grid cell id into which the vessel segment fell. Vessel trajectories that were not within the Kitikmeot boundaries were then removed via the ArcMap 10.5 clipping toolbox function. This resulted in 154 unique vessels and 1,806,921 vessel segments total. An important point to highlight is that, since the data used to generate equation (6) were for ships underway, it is not expected that this model performs well for vessels going below than 1 knot, which usually happens in ports. Therefore, from 1,806,921 original records, 68,187 presented an average speed (v) below 1 knot and were decided to be excluded from this study, leaving 1,738,734 records.

The remaining records were organized per shipping season and the SL calculations were performed through Python programming language (Python Software Foundation, https://www.python.org/). For data visualization purposes, the SL at frequency 1 kHz was organized into a probability density function (PDF) for the study region, as Figure 27 shows. As can be observed in Figure 27, the PDF of SL for the entire region behaves like a bi-modal distribution due to the variation in vessel length and type that navigated through Kitikmeot region during the period of 2011 to 2018. Since SL is dependent on vessel length, smaller vessels will produce smaller SLs, and they include pleasure craft, passenger and fishing vessels. Larger vessels, on the other hand, will produce larger SLs and they are general cargo, tankers, government vessel and icebreakers.

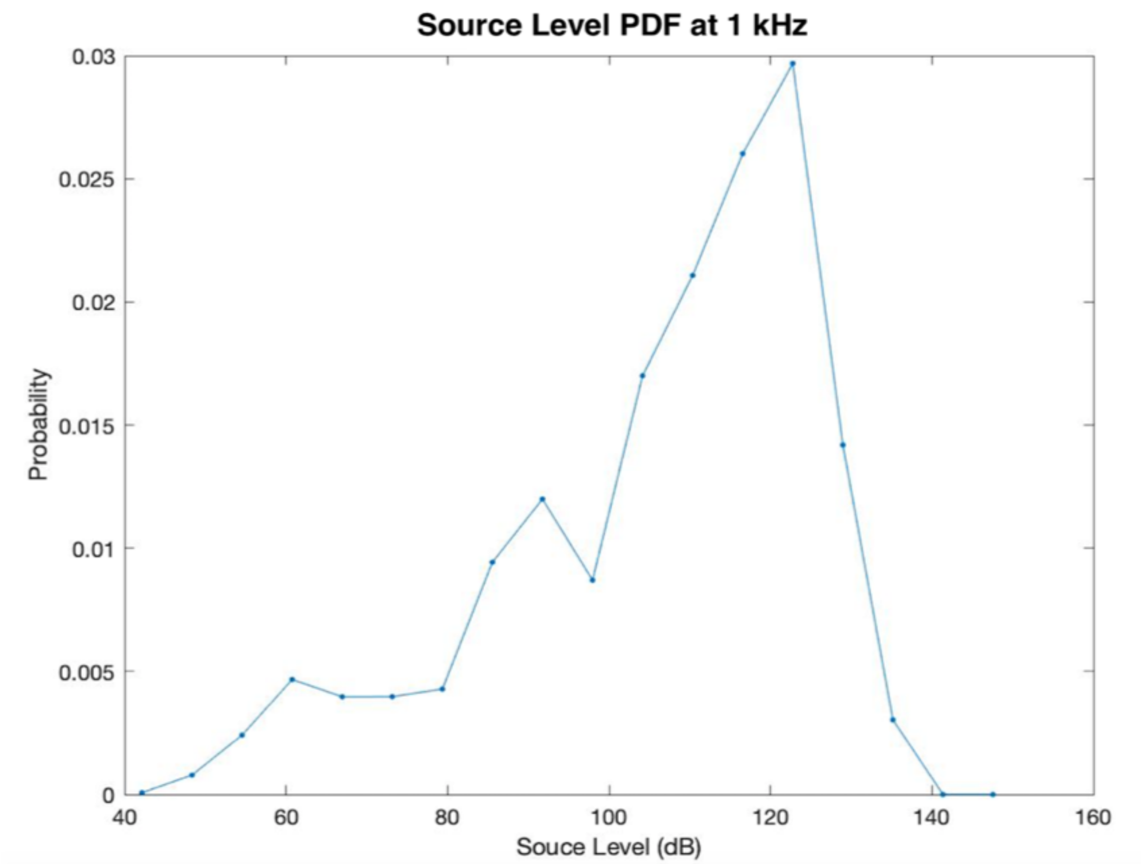

Figure 27: The probability density function (PDF) of the source levels for all vessels that transited through Kitikmeot waters during shipping season (June 1st to August 14th) between 2011 to 2018.

Calculated SELs showed that all the receptors can hear noise emitted from ships, at intensities greater than ambient noise (AN) levels (above 60 dB ambient mean) at 1000 Hz. During season 1 and 2, however, there were grid cells where ships went through that the SEL did not exceed AN. These grid cells were located very close to the shoreline, where vessels would normally slow their speed, therefore, reducing the ship noise generated.

Figure 28 shows the PDF of AN and SEL plotted for grid cell 24 in season 1. In order to calculate the area of P(SEL>AN) through the MATLAB trapz function, the first point on the curve of the probability distribution function of SEL (blue curve in Figure 28) that was closest to the curve from the probability density function the AN (red curve in Figure 28) was identified. After that, the resolution of the blue curve was increased by decreasing the number of bins. This way, the closest point identified previously is very close to the intersection of the two lines. In this example, the integral of the area of the graph where P(SEL) is higher than P(AN) is approximately 0.77, which means that there is 77% chance of a receptor present at grid cell 24 that can hear the ship noise. Each grid cell resulted in different probabilities for each shipping season, as Figure 29, 30 and 31 display below. That is due to significant variance in the ship traffic intensity and vessel type distribution from season 1 to season 3.

Interestingly, neither instantaneous RLs nor cumulative SELs at frequency of 1000 Hz reached the 179 and 178 dB Temporary Threshold Shift (TTS), as set out by NOAA [69].

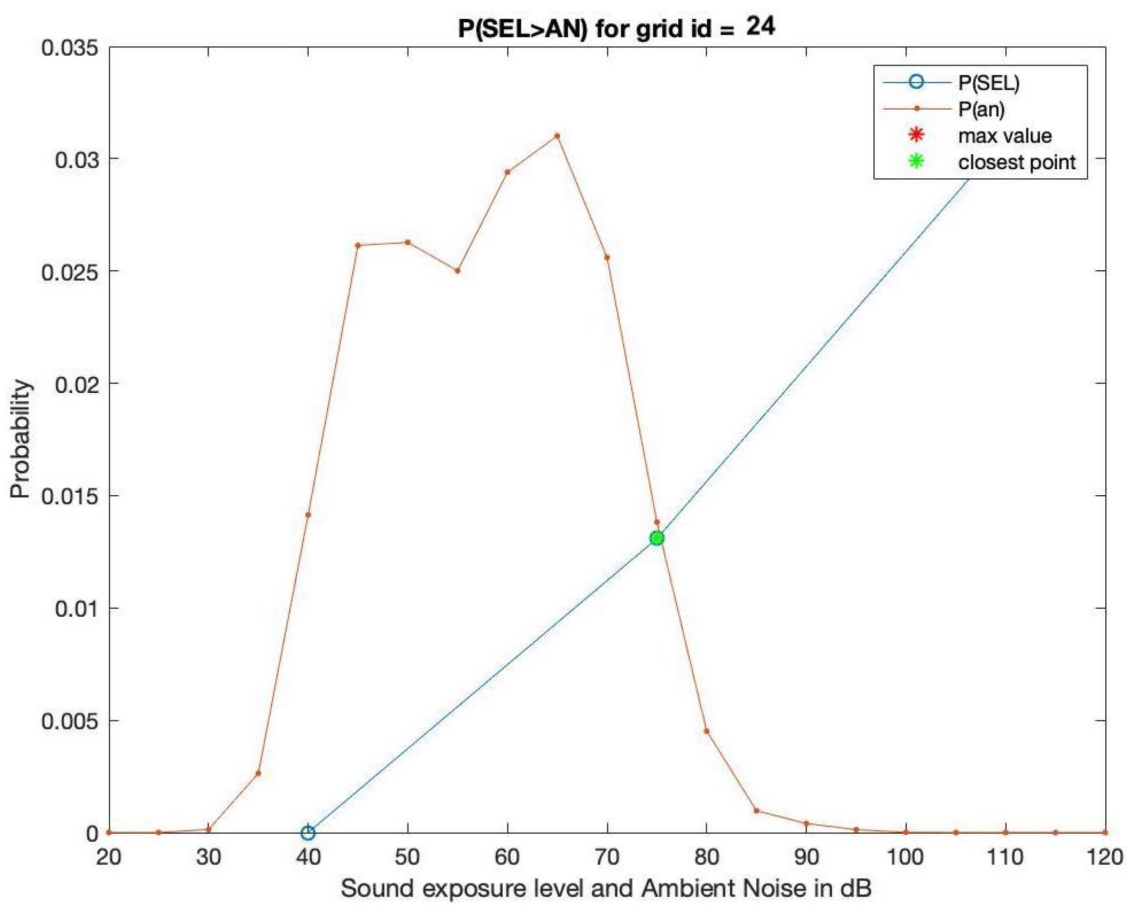

Figure 28: The probability density function of source exposure level (SEL) and ambient noise (AN), and the point where the two curves cross each other.

The final maps for the ship-source noise pollution stressor factor, which displays for each grid cell, the probability of sound exposure level exceeding ambient noise for each shipping season 1, 2 and 3 are given in Figure 29, 30 and 31, respectively. All seasons yielded a significant amount of grid cells with high probabilities of SEL exceeding AN. Season 1 (Figure 29), though, seemed to be a quieter period and that is partially due to its low traffic intensity compared to the other seasons, where season 2 is almost 6 times busier than season 1, and almost 3 times busier than season 3. The vessel type distribution plays an important role in this analysis since larger vessels produce louder noise. Season 3 had a high presence of cargo ships (16%), tow vessels (25%) and tankers (14%) compared to the other seasons. The average length of cargo vessel for season 3 was around 142 meters, and for tankers it was 160 meters. Season 2, on the other hand, was dominated by the presence of passenger vessels (23%) , tow vessels (15%) and search and rescue vessels (24%). The average length of passenger vessel for season 2 was around 134 meters and for search and rescue it was around 90 meters. In season 1, pleasure craft had higher presence (15%) compared to the other seasons. These vessels produce less noise, which can be explained by their relatively small size (average length approximately 24 meters).

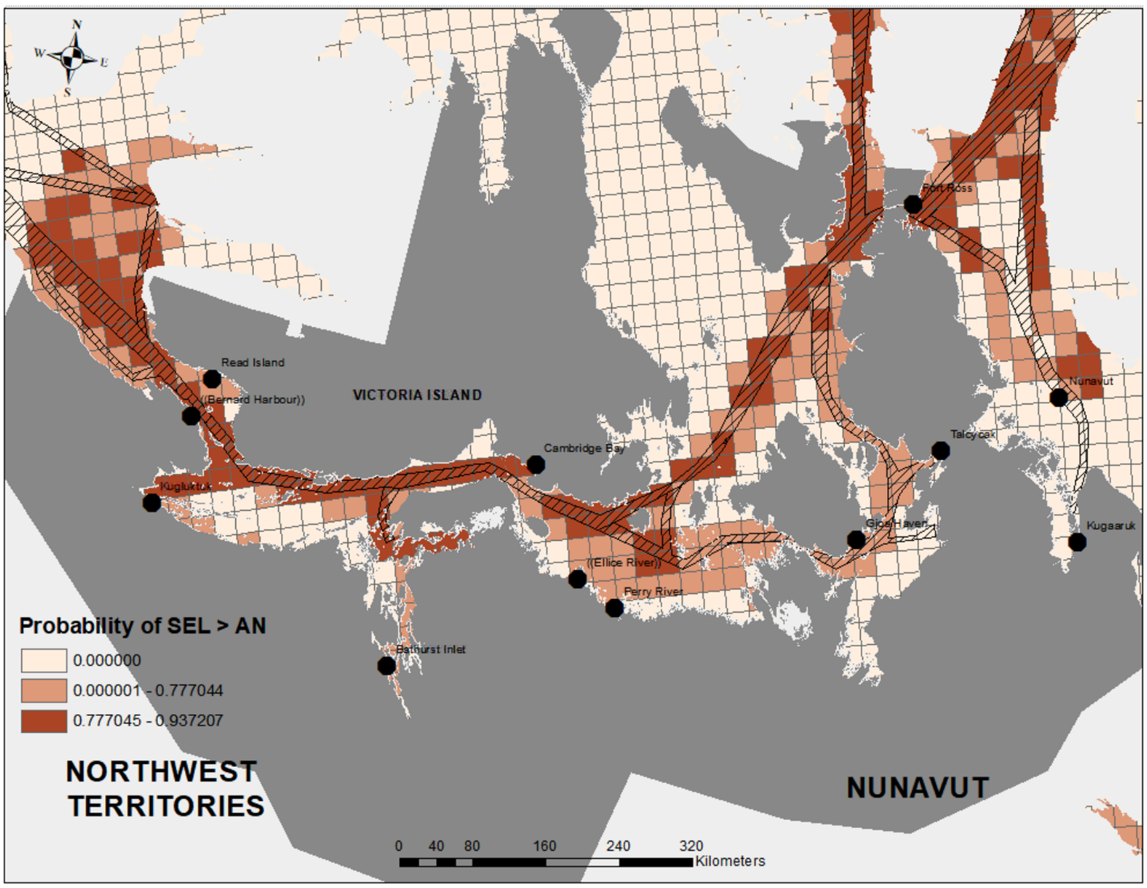

Figure 29: Grid cells with probability of SEL exceeding AN for season 1.

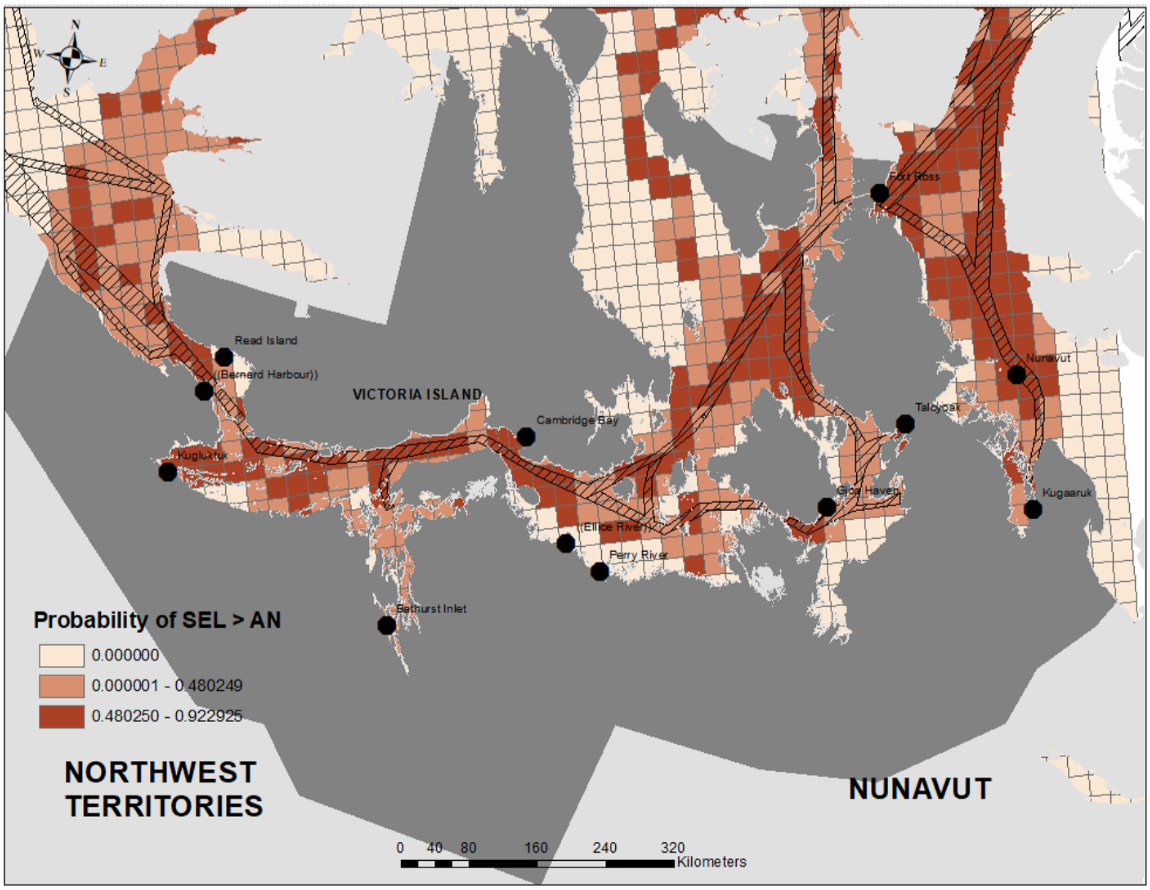

Figure 30: Grid cells with probability of SEL exceeding AN for season 2.

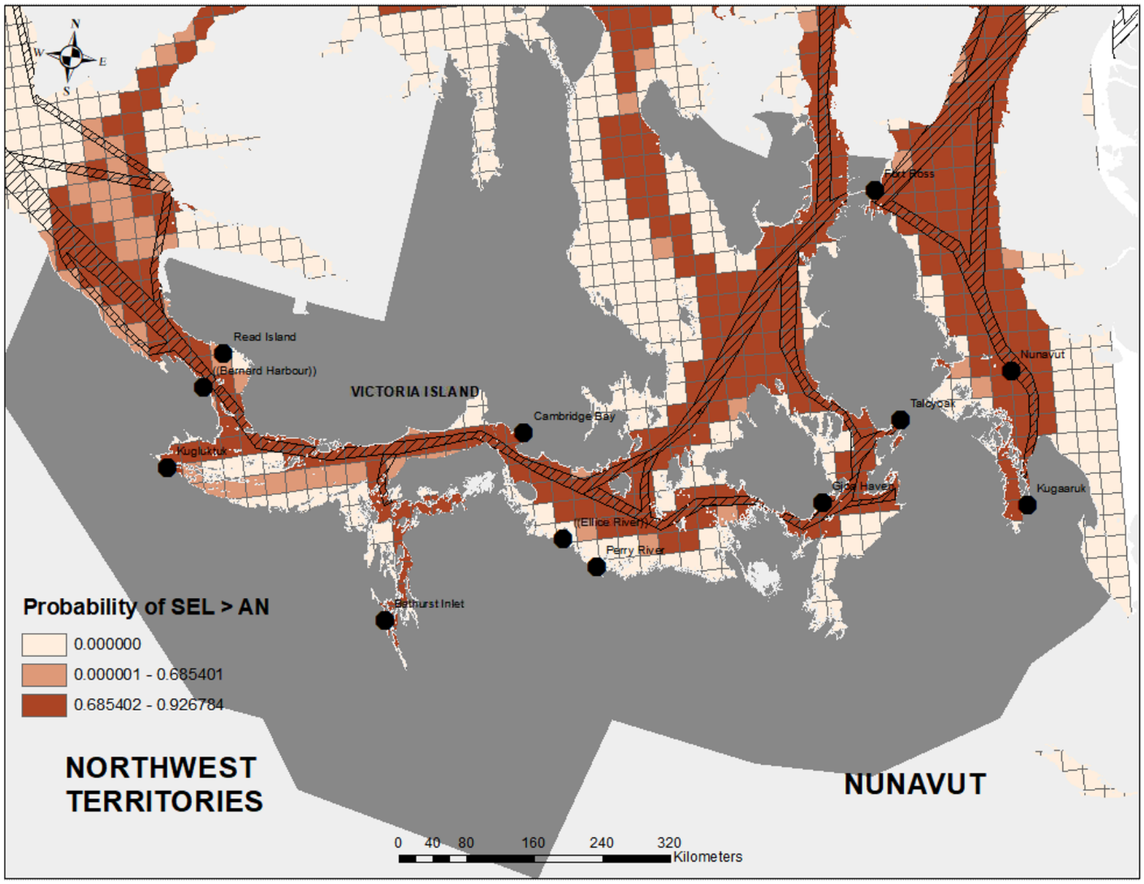

Figure 31: Grid cells with probability of SEL exceeding AN for season 3.

4.3.7 Receptors exposure

This section displays the receptor exposure maps for the three whales, Narwhal, Bowhead and Beluga for shipping season 1, 2 and 3. These maps represent the element (E_j) in the CRA equation. Narwhal geographical location has a slight change from shipping season 1 and 2 to 3 as Figure 34 shows. Bowhead and Beluga, on the other hand, remain in the same geographical location throughout the shipping seasons as Figures 37, 36, 35 and Figures 38, 39, 40 show.

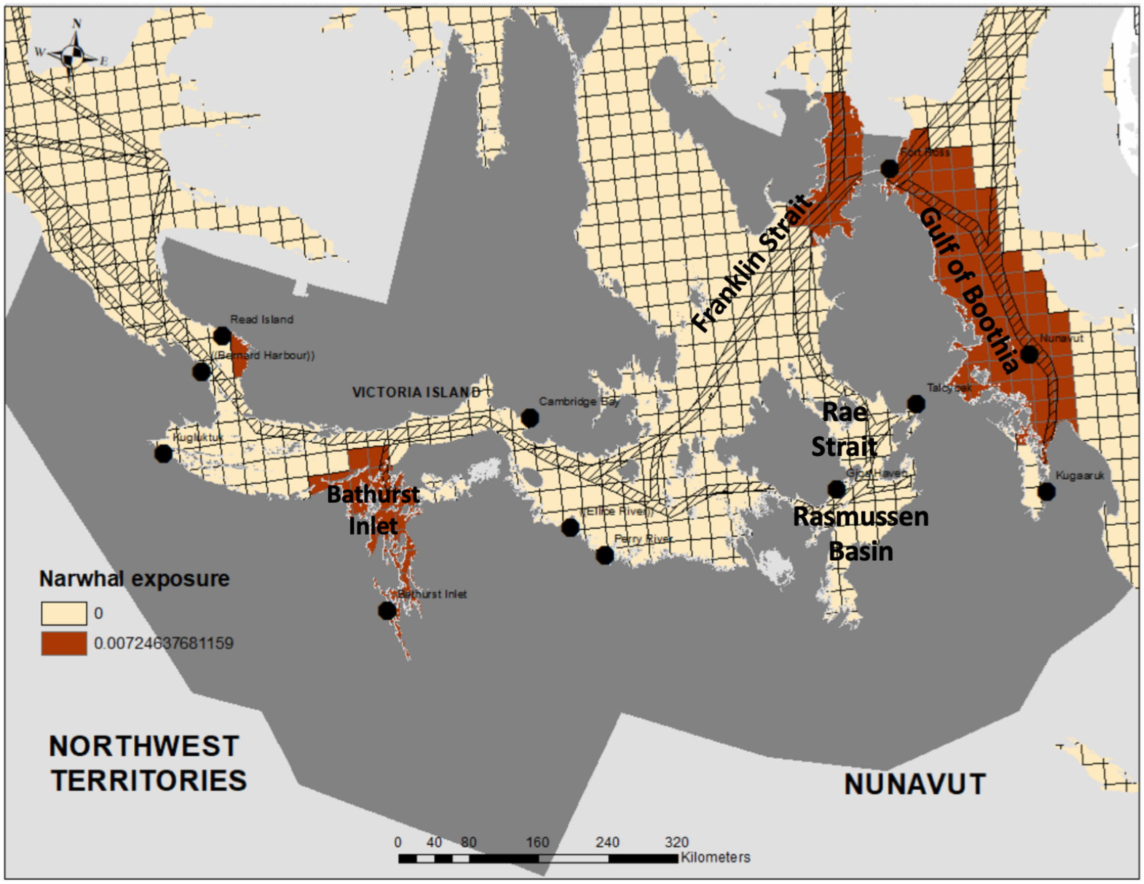

Figure 32: Narwhal exposure map for season 1.

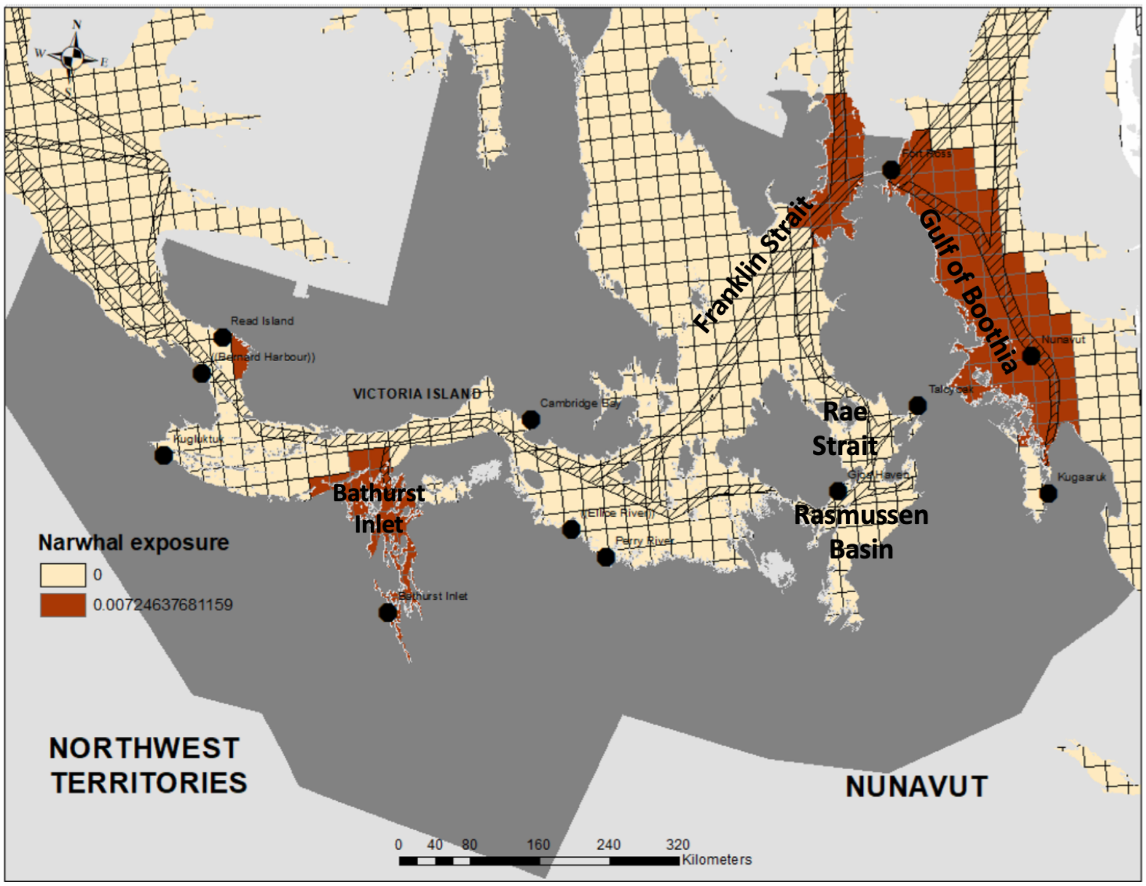

Figure 33: Narwhal exposure map for season 2.

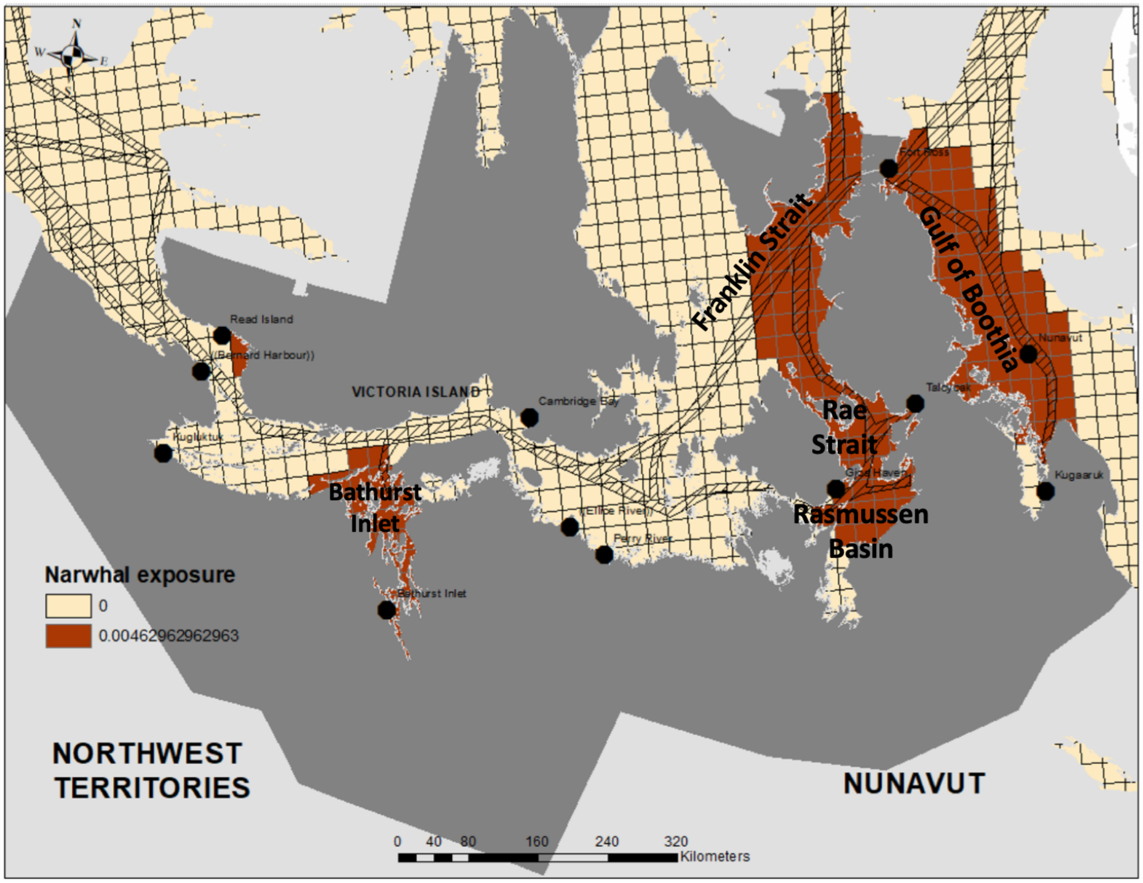

Figure 34: Narwhal exposure map for season 3.

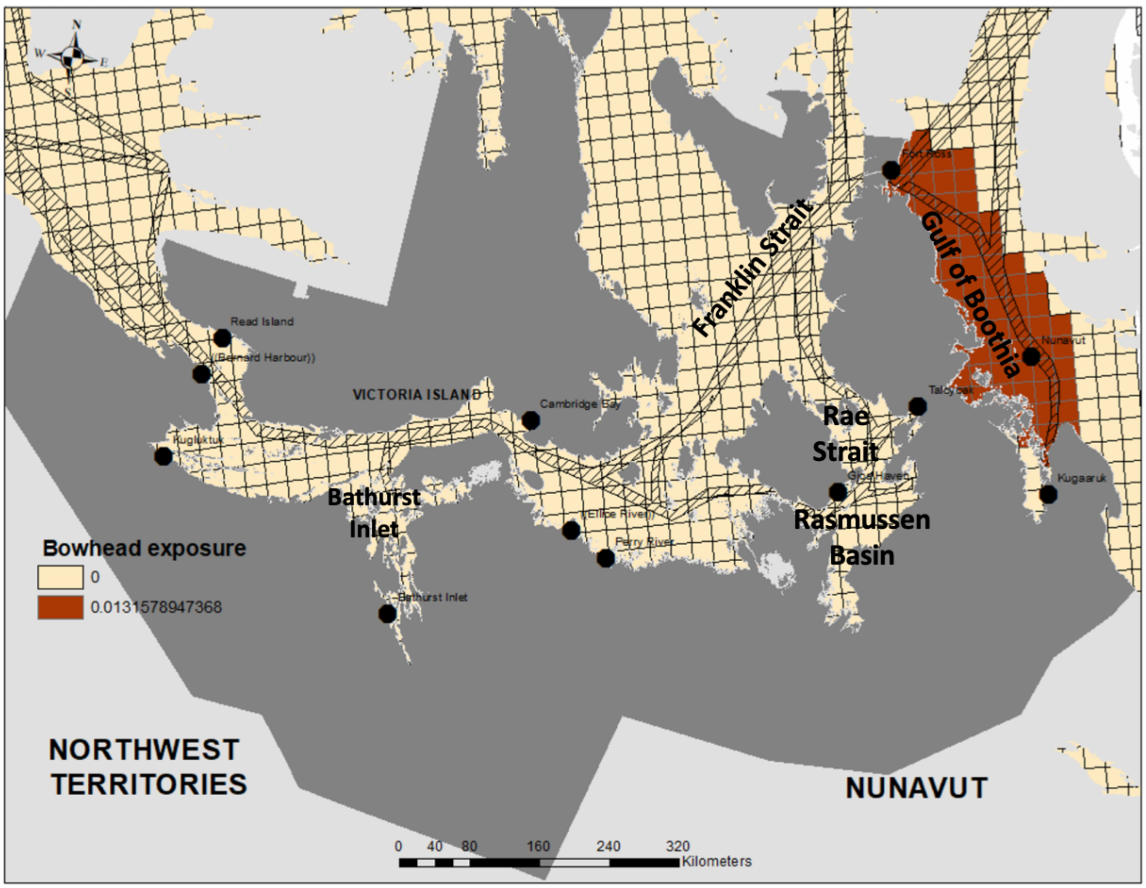

Figure 35: Bowhead exposure map for season 1.

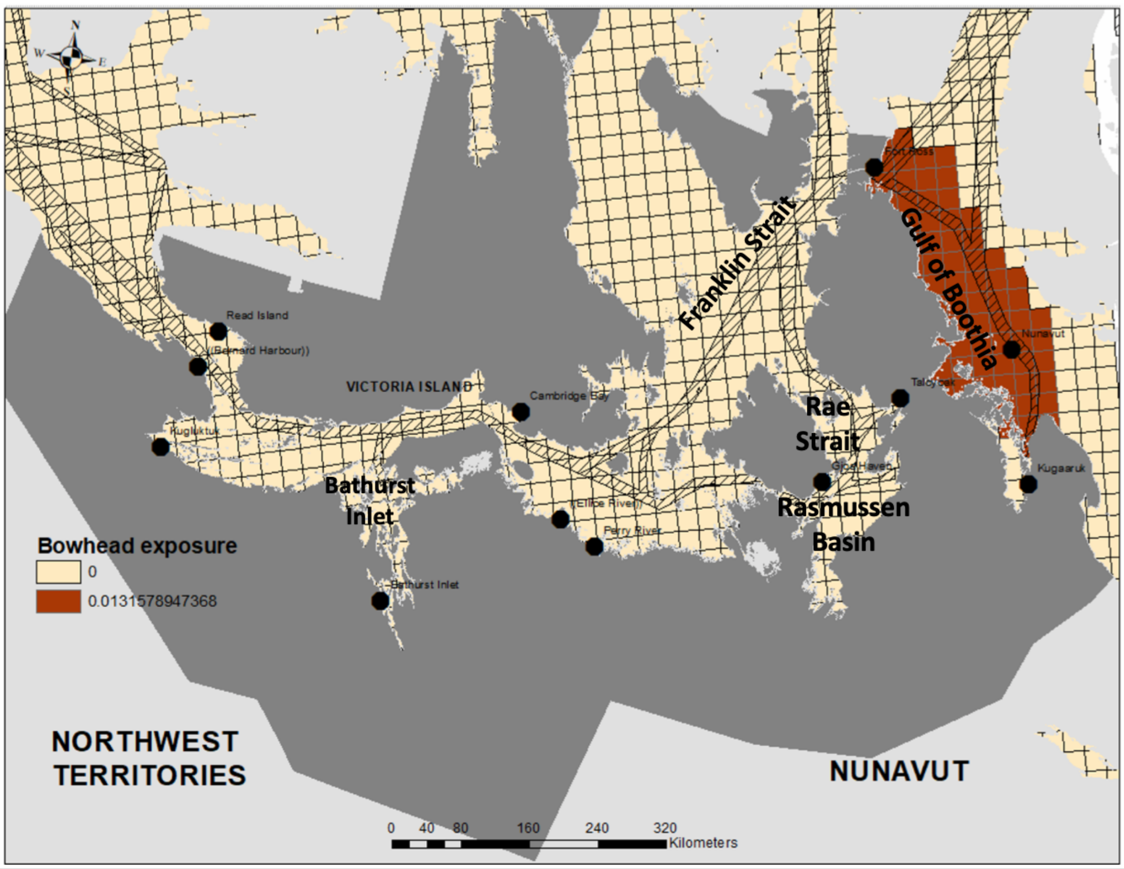

Figure 36: Bowhead exposure map for season 2.

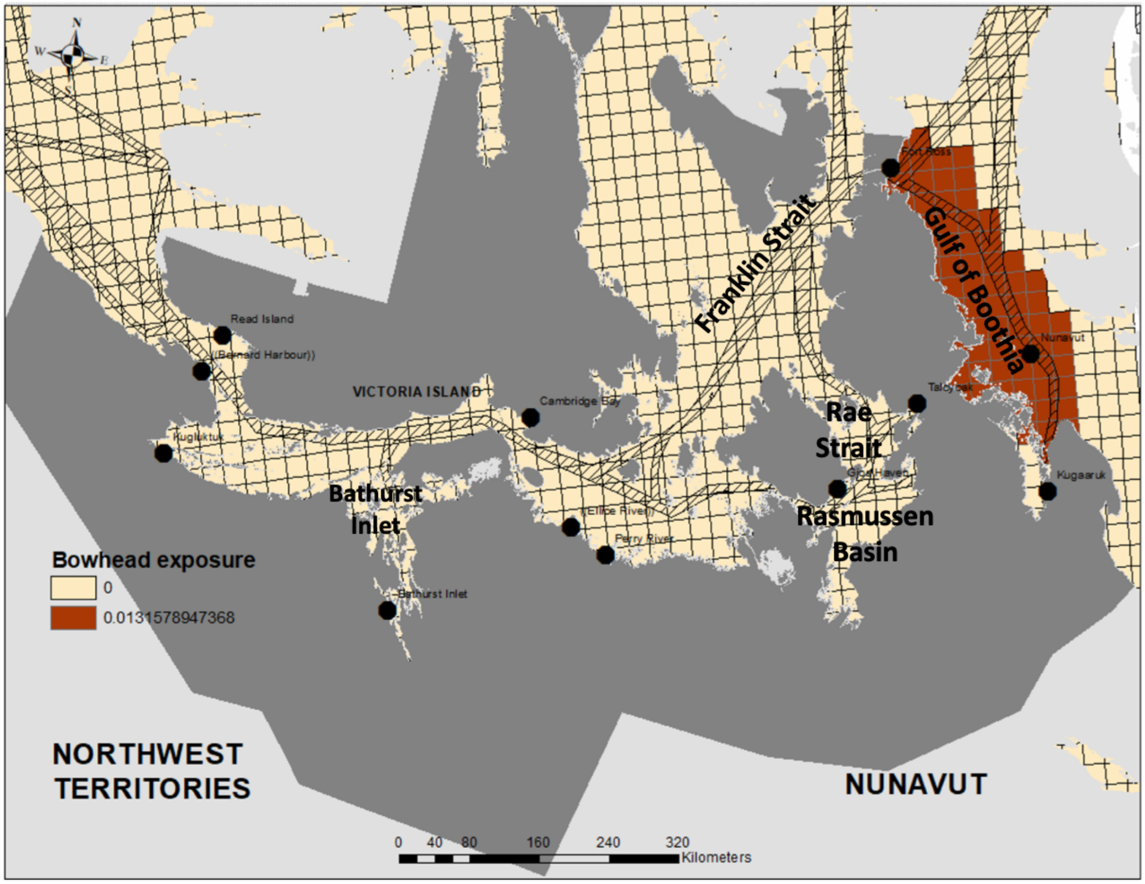

Figure 37: Bowhead exposure map for season 3.

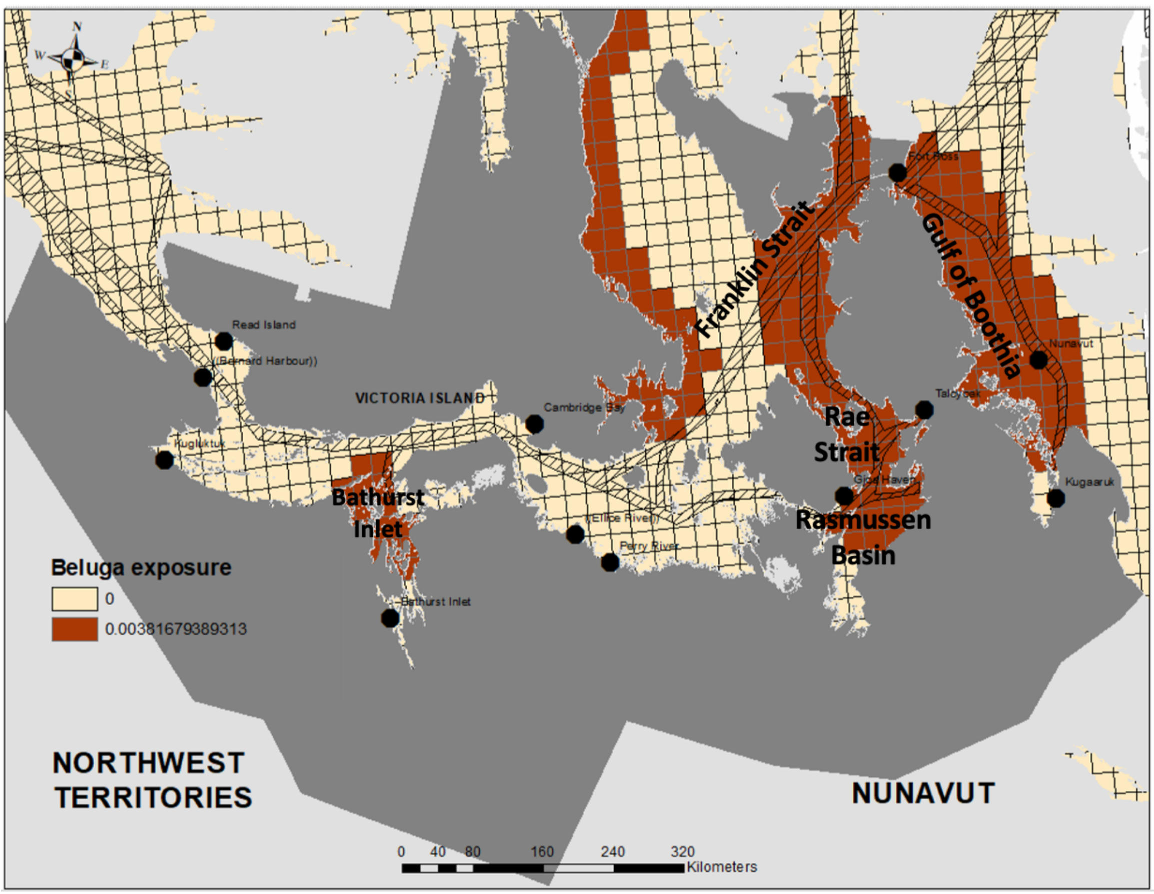

Figure 38: Beluga exposure map for season 1.

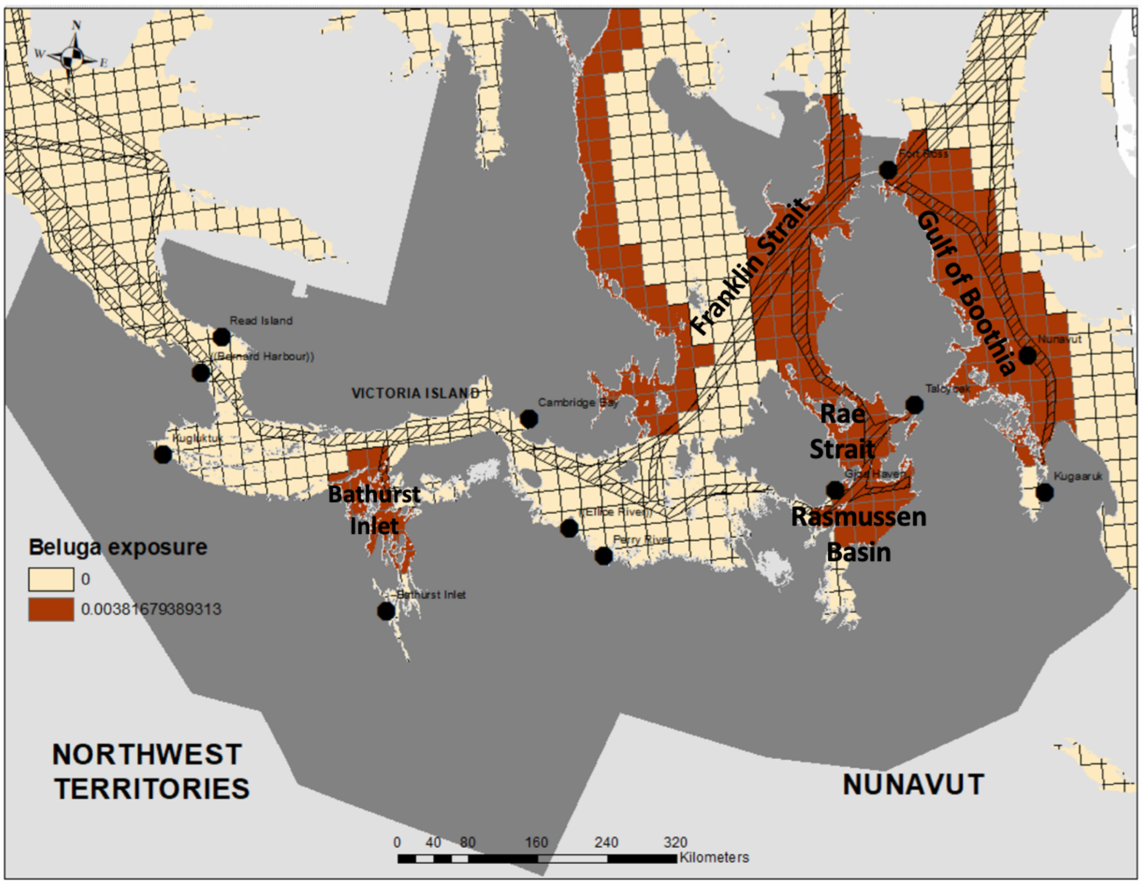

Figure 39: Beluga exposure map for season 2.

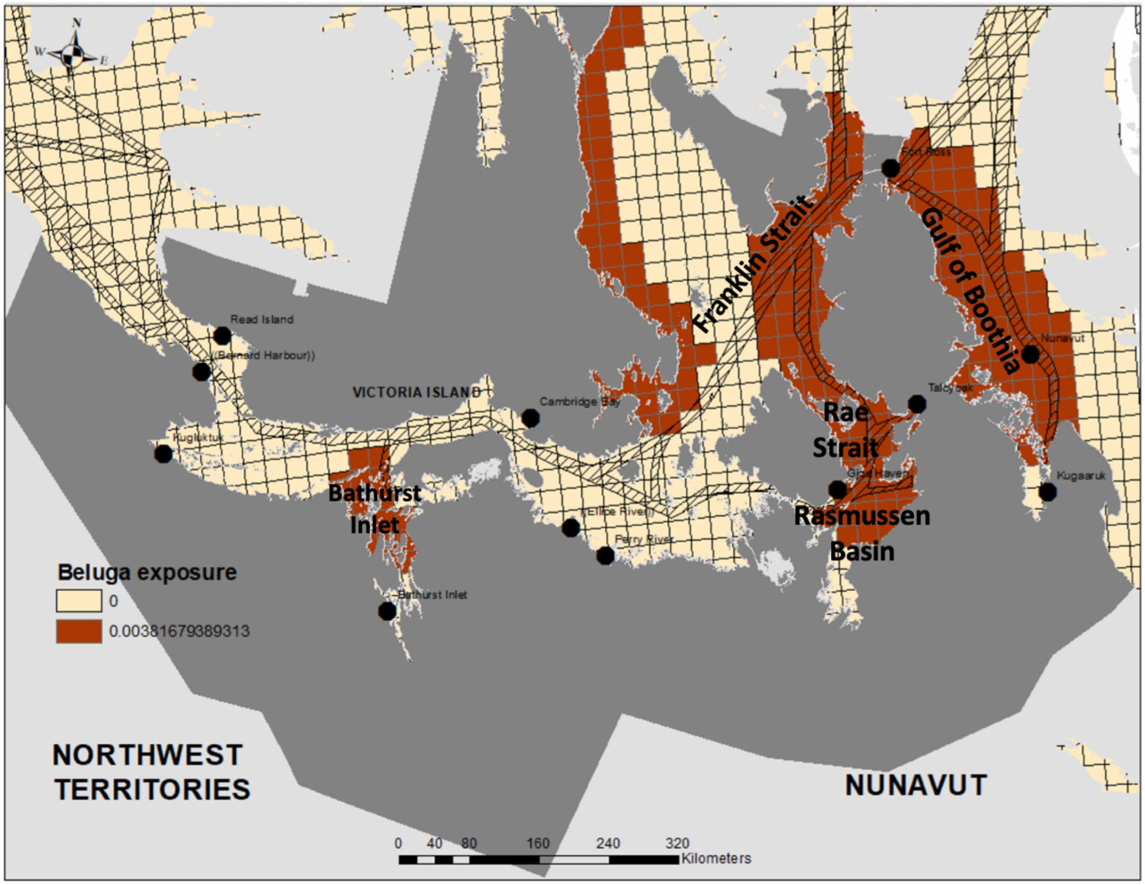

Figure 40: Beluga exposure map for season 3.

4.3.8 Vessel presence

This section displays the maps indicating the probability of vessel presence for shipping season 1, 2 and 3. These maps represent the (P_s) in the CRA equation. Season 1 was the least busy (Figure 41) shipping season whereas season 3 was the busiest one (Figure 43). This was expected since in early June there is still some sea ice, which will be melting throughout the shipping seasons. These probabilities account for the stressor source presence (vessel) in equation 2.

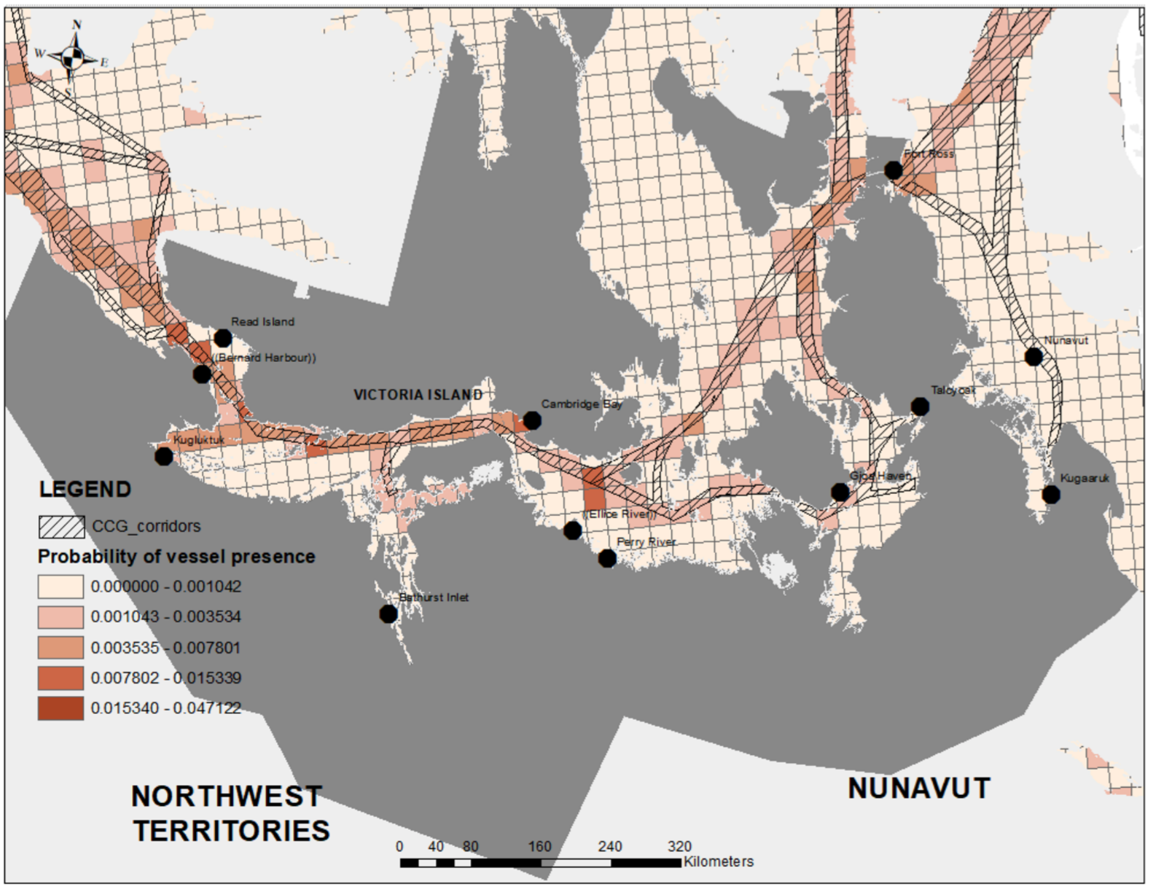

Figure 41: Probability of vessel presence map for season 1.

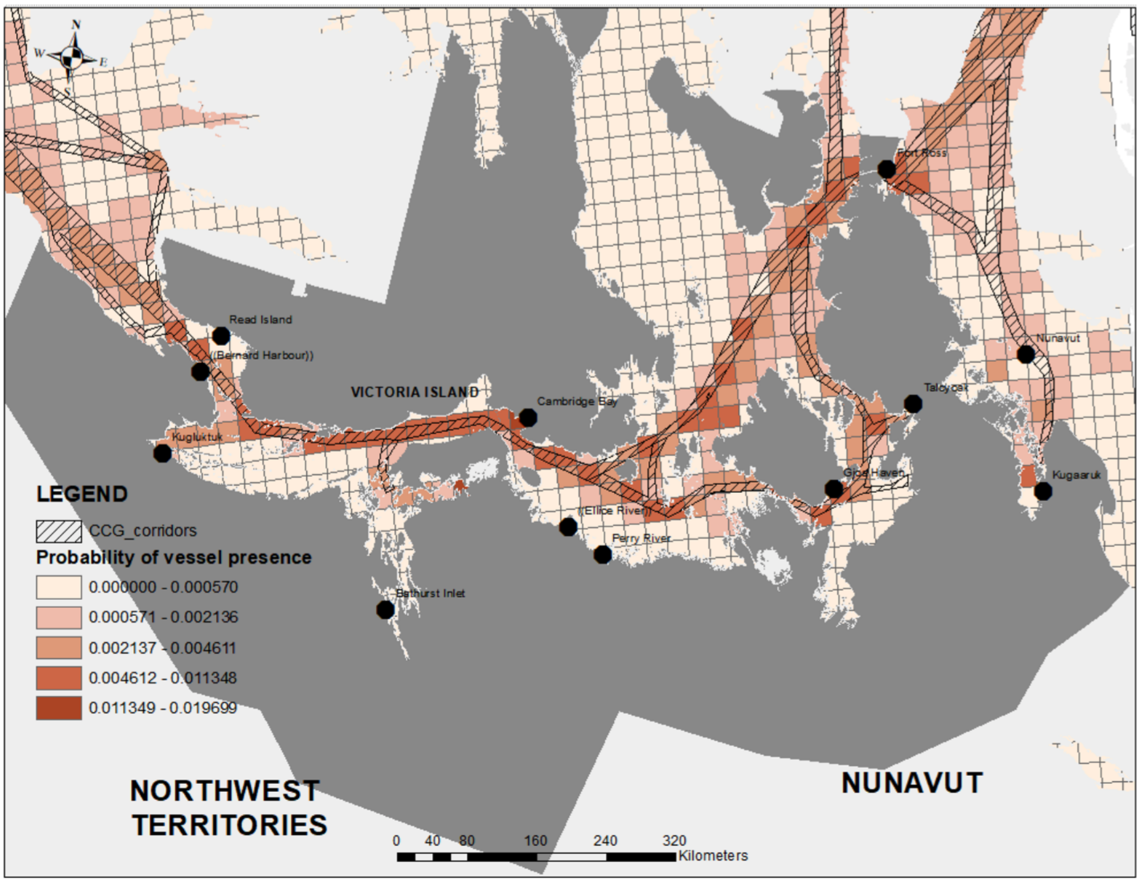

Figure 42: Probability of vessel presence map for season 2.

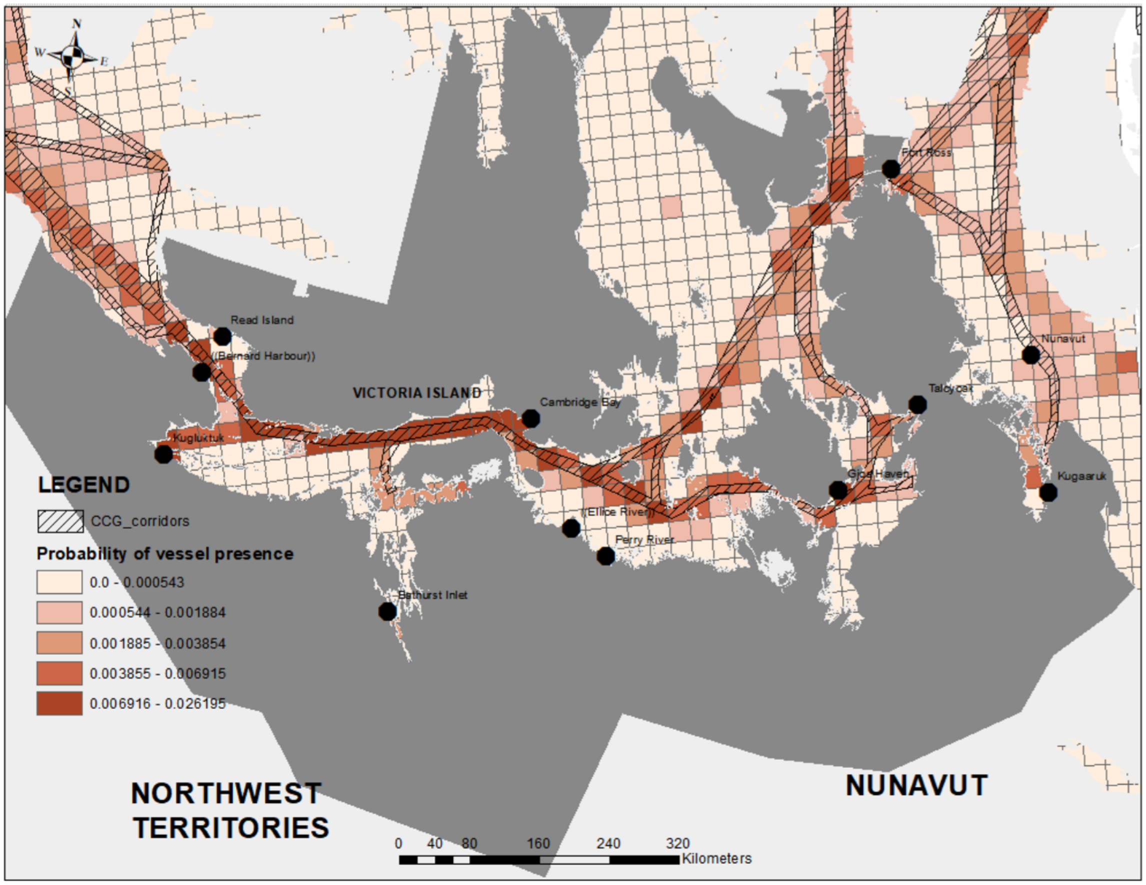

Figure 43: Probability of vessel presence map for season 3.

4.3.9 Sensitivity assessment - expert survey

From the sensitivity assessment, the S_{ij} element from equation 2 was obtained for each combination of stressor-receptor: oil spill-Beluga, oil spill-Bowhead, oil spill-Narwhal, noise-Beluga, noise-Bowhead and noise-Narwhal. The sub-factors for each receptor-stressor combination were determined based on previous studies [91], [101]. In a similar study performed by [91] the vulnerability of several biological components to ship-source oil spills, including marine mammals, was assessed through the following two sub-factors: mechanical and chemical. According to [91], the mechanical sub-factor are determined based on physiological characteristics (e.g. feeding structures) that can increase the magnitude of impact from exposure to oil. In terms of the chemical sub-factor, the marine mammals that are more sensitive to the toxic effects of oil are more likely to experience permanent effects or even death [91]. Another sub-factor, also related to chemical impacts, is related to the food availability, since these marine mammals can be in danger if they eat oiled prey [91].

In terms of ship noise, as stated by [21], anthropogenic noise is perceived in quite different ways by marine mammals with different auditory systems, therefore, some receptors can be more sensitive to noise pollution than others. Similar to oil spill, noise pollution can impact physiological characteristics (e.g. hearing ability) of marine mammals, resulting in a mechanical impairment [101]. Another important sub-factor to be considered is the social disturbance, which can impact these receptors psychological characteristics, for example, masking communication among them [21]. A third sub-factor is the behavioural disturbance, where increasing shipping activity can potentially cause the marine mammals to abandon their natural habitat [21]. Based on these findings, the following sensitivity framework was used to assess the sensitivity of these animals:

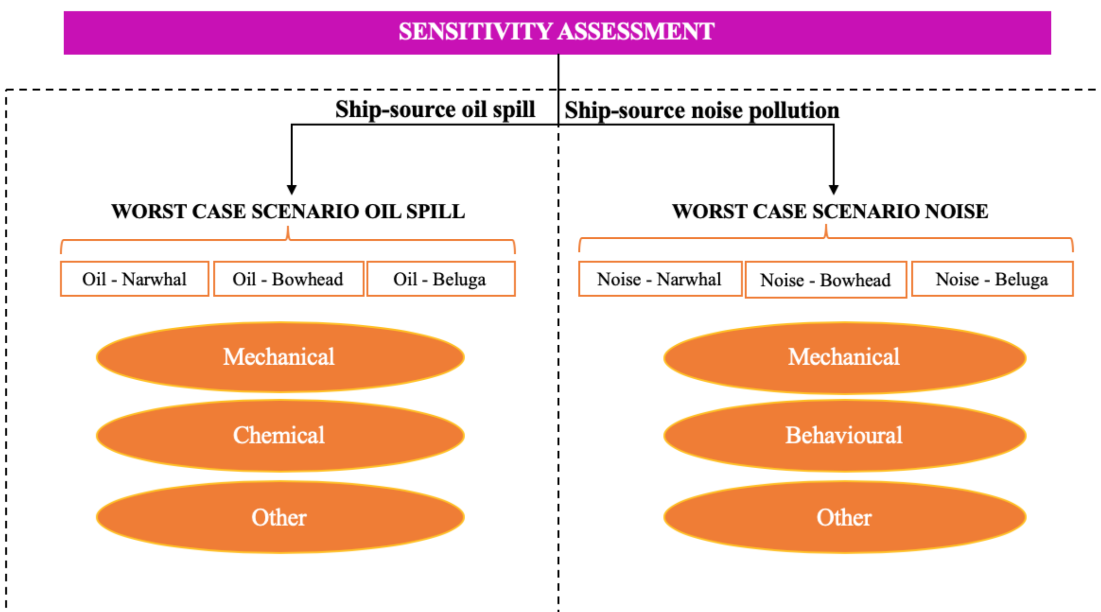

Figure 44: Sensitivity questions for receptor-oil, the justification behind it and the scoring guidance.

For the expert survey, the selection of the experts was made based on their profile in the Research Gate website (https://www.researchgate.net). It was verified whether the expert had knowledge in one of these fields: oil spill, noise pollution and/or marine wildlife preservation and then he/she was contacted by email. If participants did not reply to the initial recruitment email after 48 hours, a follow-up email was sent. Once participants were identified and have confirmed their interest in participating in the research, a consent form (Appendix B) was sent out. A briefing note outlines the purpose of the study, background information and methods. These two documents cover the procedures for handling all data and confidentiality. In case the participant had any follow up questions, the contact information of the lead researcher and supervisor was provided.

In the sequence, after having the final consent from the expert, a briefing note (Appendix A) was sent along with the questionnaire (Appendix C). The briefing note gives some background information on the research topic and also guidance for the questionnaire. The questionnaire is the actual document to collect input from the experts.

In terms of time commitment, it was expected that the expert would need only 1.0 hour maximum to finish the survey. The format of the questionnaire was semi-structured, including both structured questions (assign impact score and degree of certainty) and an open format (justification) which gives participants the chance to justify his/her answer (Appendix C). The data was collected through an excel spreadsheet.

Initially, the goal of the the sensitivity assessment proposed here was to assess the sensitivity of Narwhal, Bowhead and Beluga to ship-source oil spill and ship-source noise pollution through an online survey with 33 experts total. However, this research faced an unforeseen challenge: questionnaires were sent out during field trip season (summertime in North America), therefore not all experts were able to answer the questionnaire since there was a short time (15 days) to conclude the survey. Time was a constraint but one expert from the 33 listed was able to give his input. For privacy reasons his identity will be preserved but his inputs were wisely used for the present case study.

Tables 12 and 13 show the questions asked in the expert survey, the reasoning behind them and a scoring guidance. The range of scores used follows the procedure previously presented in Table 4 of the methodology section (chapter 3). The experts were asked to answer these questions for each receptor-stressor combination by having in mind the worst case scenario as a baseline scenario and to consider a 1:1 ratio (1 vessel to 1 whale) when ranking sensitivity.

For oil spill, the worst case scenario was assumed to be an oil spill size between 1,000 to 10,000 m3, with the receptor in contact with the oily area. Spill sizes bigger than 10,000 m3 could also heavily impact the Arctic ecosystem, however this magnitude of an oil spill has never happened in Canada [57]. Similarly to what Nevalainen et al. (2018) considered in her study, the time-span considered here is the first two weeks after an accident [67] during which, accordingly to Boehm and Page (2007), the oil at the water's surface is likely to have maximum exposure potential [8].

For noise pollution, the worst case scenario was assumed to be when the receptor is exposed to chronic ship-noise and SEL being (Sound exposure level) is above ambient noise levels. The receptor is assumed to be physically very close to the source noise for a reasonable amount of time.

OIL SPILL			
Sensitivity sub-factor	**Question**	**Justification**	**Scoring guidance**
Mechanical	To what extent does the direct contact with oil result in the mechanical impairment of structures that can impact energetics of this receptor (i.e. animal's ability to digest and absorb foods)?	Fouling of feeding structures by oil may reduce the ability of organisms to feed, degrading body condition and reproductive capacity, and increasing time spent feeding.	Level of impact from contact with oil on this receptor in terms of mechanical impairment such as feeding.
Chemical	To what extent does the direct contact with oil result in severe, irreversible effects or death for this receptor?	Organisms that are more sensitive to toxic effects of oil are more likely to experience irreversible effects or death.	Level of impact from contact with oil on this receptor in terms of irreversible effects or death due to oil toxicity. Acute effects from direct contact include: the inability of animals to digest and absorb foods, reproductive failure, respiratory failure, lesions, hermorrhaging, neurological impairment, and mortality.
Others	To what extent does the oil spill reduce food availability of this receptor for possible continamation of invertebrates, fish and plankton (their prey)?	Cetaceans are in danger if they eat oiled prey. Bigg's (transient) killer whales can consume oil adhering to the bodies and fur of their mammalian meals, and ingestion of oil can cause serious long-term damage to internal organs.	Level of impact from contact with oil on this species in terms of reliability on prey that would most likely be oiled, therefore contaminating the marine mammals as well.

Table 12: Sensitivity questions for receptor-noise, the justification behind it and the scoring guidance.

NOISE POLLUTION			
Sensitivity sub-factor	**Question**	**Justification**	**Scoring guidance**
Mechanical	To what extent can chronic or increasing ship noise can induce hearing loss on this receptor?	Noise has the potential to induce temporary hearing loss (combination of frequency and duration), also known as temporary threshold shift (TTS), if it is loud or long enough in duration. In general, the higher the sound level and/or longer the duration, the more likely TTS is to occur. If exposure is prolonged or repeated or even as a result of one very loud noise event, the hearing damage can become permanent, also known as a permanent threshold shift (PTS).	Level of impact from ship noise on this species in terms of hearing impairment.
Behavioural	To what extent can chronic or increasing ship noise mask acoustic signals that are important for this receptor (i.e. foraging, predator avoidance, communication, etc)?	Sound plays an important role in the lives of marine mammals. All marine mammal species produce sound, and sound production has been associated with a variety of behaviours including those related to mating, rearing of young, social interaction, group cohesion, and feeding.	Level of impact from ship noise on this species in terms of masking important acoustic signals, such as foraging, communication, etc.
Other	To what extent can chronic or increasing ship noise cause the marine mammals to abandon their natural habitat?	Displacement from critical feeding and breeding grounds has been documented in a number of marine mammal species exposed to noise.	Level of impact from ship noise on this species in terms of habitat avoidance or displacement.

Table 13: Sensitivity and its sub-factors for oil spill and noise pollution.

The results from the expert survey assigned a sensitivity score of 9 to the combination of Narwhal-oil, Bowhead-oil and Beluga-oil and 6 to the combination of Narwhal-noise, Bowhead-noise and Beluga-noise as shown in Table 45 below.

Stressor-receptor	Sensitivity score
Oil-Beluga	9
Oil-Bowhead	9
Oil-Narwhal	9
Noise-Beluga	6
Noise-Bowhead	6
Noise-Narwhal	6

Figure 45: Sensitivity scores obtained from expert survey for each stressor-receptor combination.

The justification given by the expert for oil spill scoring higher than noise lies in the fact that the direct exposure with oil could highly impair the abilities of the three marine mammals to feed, and also cause high degree of toxicity.

Noise sub-factor scores, on the other hand, were justified differently for each marine mammal. For the mechanical sub-factor, shipping levels would have to be significantly intense to cause permanent hearing damage to all these marine mammals. Since this is not the current scenario of the study region, and given that even busier southern areas such as the Salish sea (British Columbia) have not reached such levels yet, this sub-factor got a score of 1 (low impact). In terms of the behavioural sub-factor, masking, which is a phenomenon that happens when shipping noise interferes with the receptor's ability to perceive sound, it occurs as soon as vessel noise is present in the hearing bandwidth of species. Therefore, masking will potentially occur and it will have an impact on foraging and communication. For that reason, expert opinion scored a 3 for this sub-factor for all three receptors. Even though experts scored it as high impact for this sub-factor, the extent of that impact will depend on where the masking activity occurs and its frequency.

Due to lack of empirical data (audiogram measurements) for Narwhal and Bowhead, there is still some uncertainty around the hearing bandwidth of these receptors. There is less uncertainty around hearing abilities of Beluga because there are good, wild-animal audiograms for them [63]. Lastly, the sub-factor 'other' was scored as 2 (medium impact) to all three receptors. For Narwhal and Beluga, the expert justified this score based on previous studies on habitat abandonment, where there is a possibility that they may become acclimated and stop showing an avoidance behaviour [101]. For Bowhead, previous studies have shown that it tends to ignore noise when foraging [56], but they show a strong avoidance behaviour when migrating.

However, it is acknowledged that for Narwhal and Beluga there have been very few studies showing a very sensitive reaction from these two receptors with a strong avoidance behaviour. Additionally, there is also a good possibility that they may become acclimated and stop showing an avoidance behaviour. Bowheads, on the other hand, have been shown to ignore noise when foraging, but show a strong avoidance behaviour when migrating. Out of all Arctic marine mammals, the largest number of studies have focused on this receptor, so there is reasonable certainty for this species.

These results demonstrated that an oil spill has worse impacts than noise pollution on Narwhal, Bowhead an Beluga. These values were then normalized to 1 accordingly to equation 16, where the maximum value of x corresponds to 9 and the minimum to 0, which is then added to the equation 2.

$$z = \frac{x - min(x)}{max(x) - min(x)} \tag{16}$$

4.3.10 HOTSPOT maps

Below are the final hot spot maps, where noise and oil spill are combined through equation 2, organized by risk score for each receptor and each shipping season (Figures 46 to 54) and the total risk score for all three receptors for each shipping season (Figures 55, 56 and 57). As shown in the maps 46, 47 and 48, the proposed NMTC overlap with grid cells where Narwhals have the risk score at its highest. In season 3 (Figure 48), the area where NMTC overlaps with grid cells which have the highest risk score for Narwhals is the largest one if compared to season 1 and season 2, indicating a risky season for Narwhals. Belugas and Bowheads hotspot maps (from Figure 49 to 54) also present an overlap of NMTC with grid cells at their highest score. When the final risk scores from these three receptors are then combined, the CRA is provided (Figure 55, 56 and 57). The area which presented higher cumulative risk score for each shipping season is the east part of Kitikmeot, as shown in Figure 55, 56 and 57. The largest risk score across all seasons and sub—regions of Kitikmeot is 10-4, knowing that the upper bound is 1 and lower bound is 0. This value can be used to give a scale of how risky is the area and then comparison can be made.

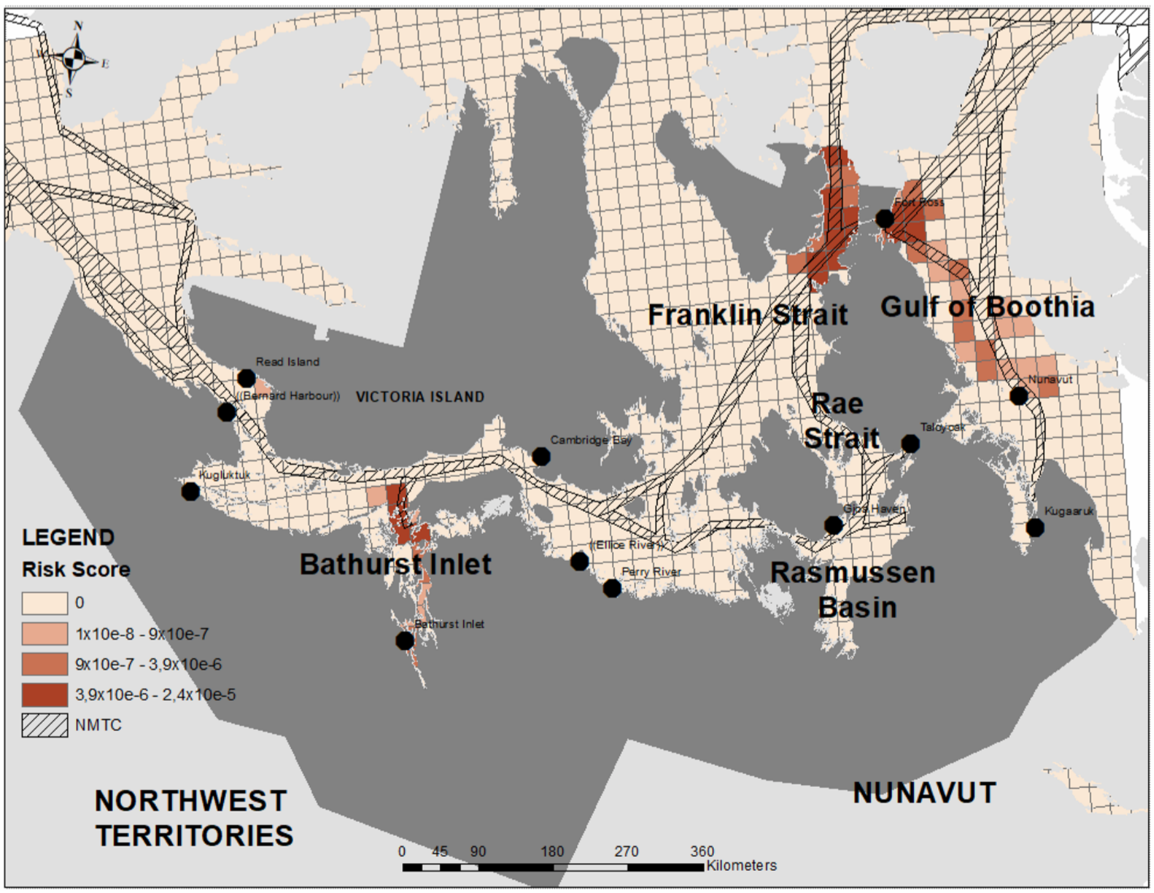

Figure 46: Risk score to Narwhal for season 1.

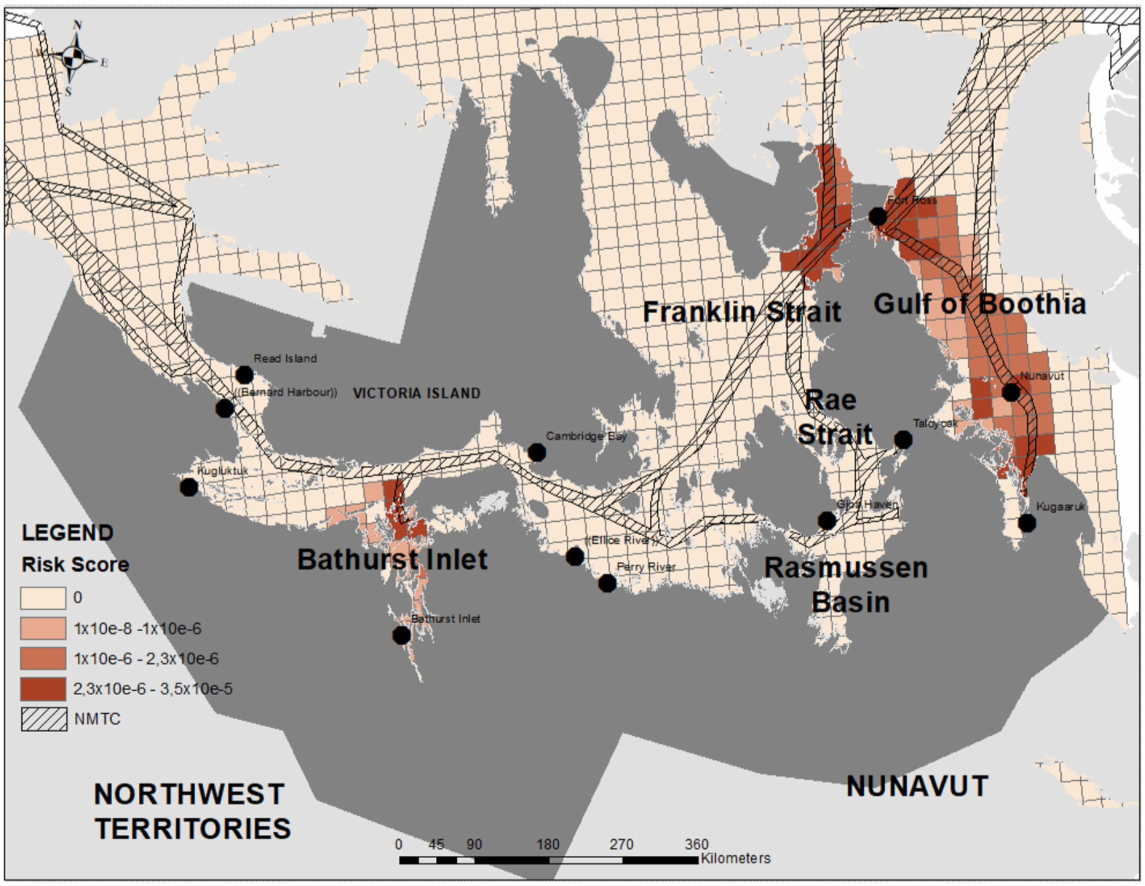

Figure 47: Risk score to Narwhal for season 2.

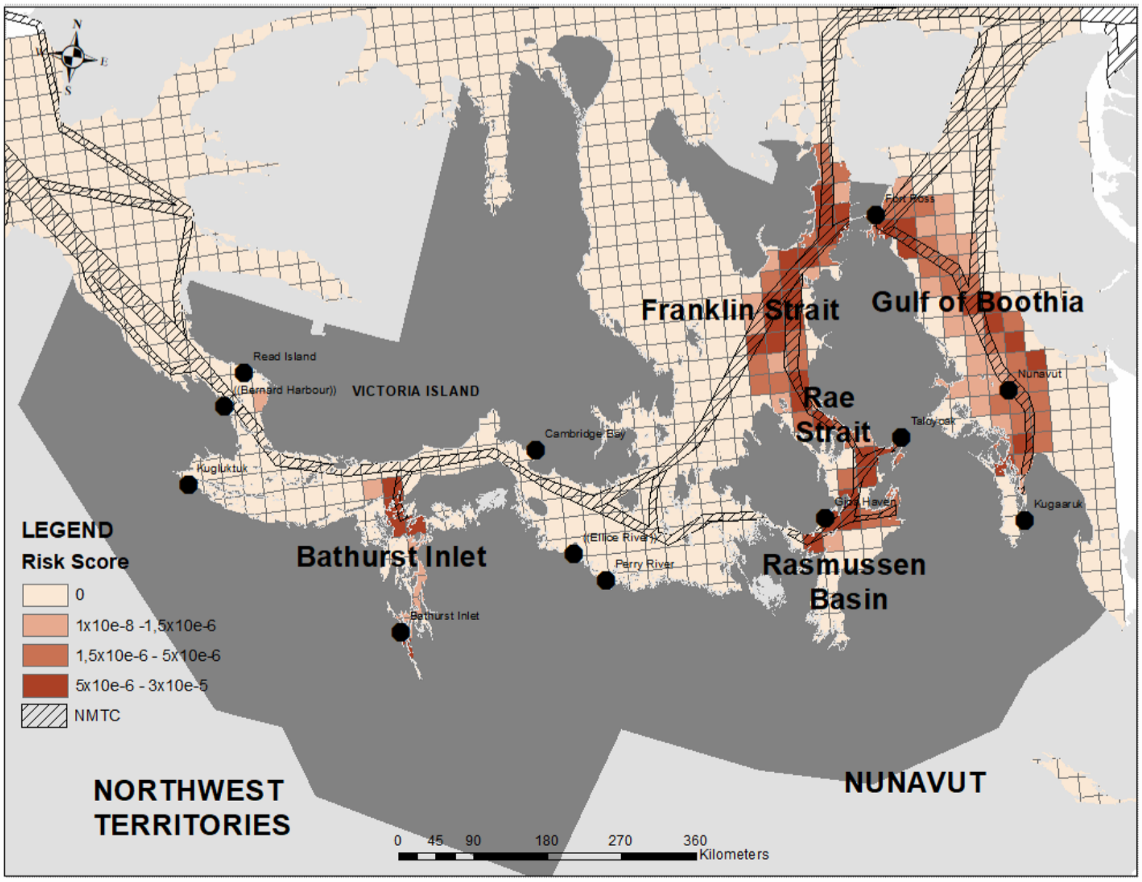

Figure 48: Risk score to Narwhal for season 3.

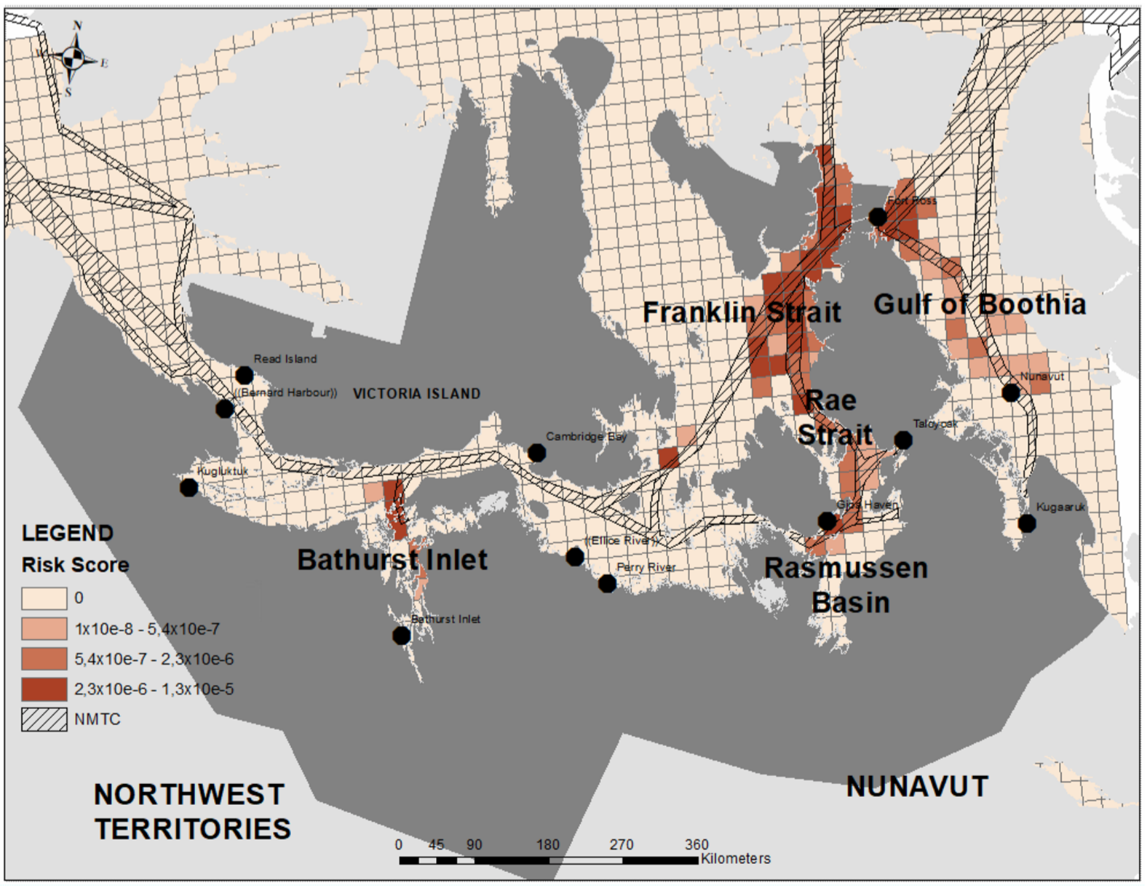

Figure 49: Risk score to Beluga for season 1.

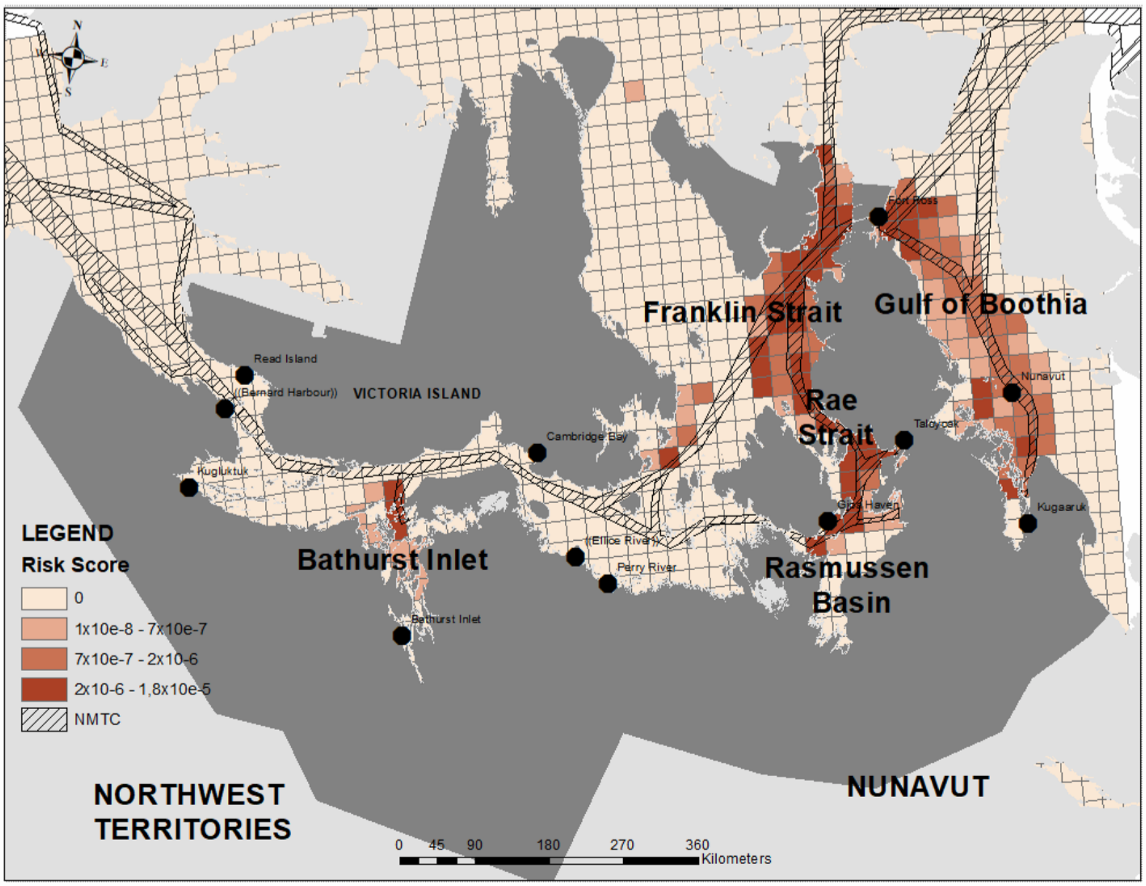

Figure 50: Risk score to Beluga for season 2.

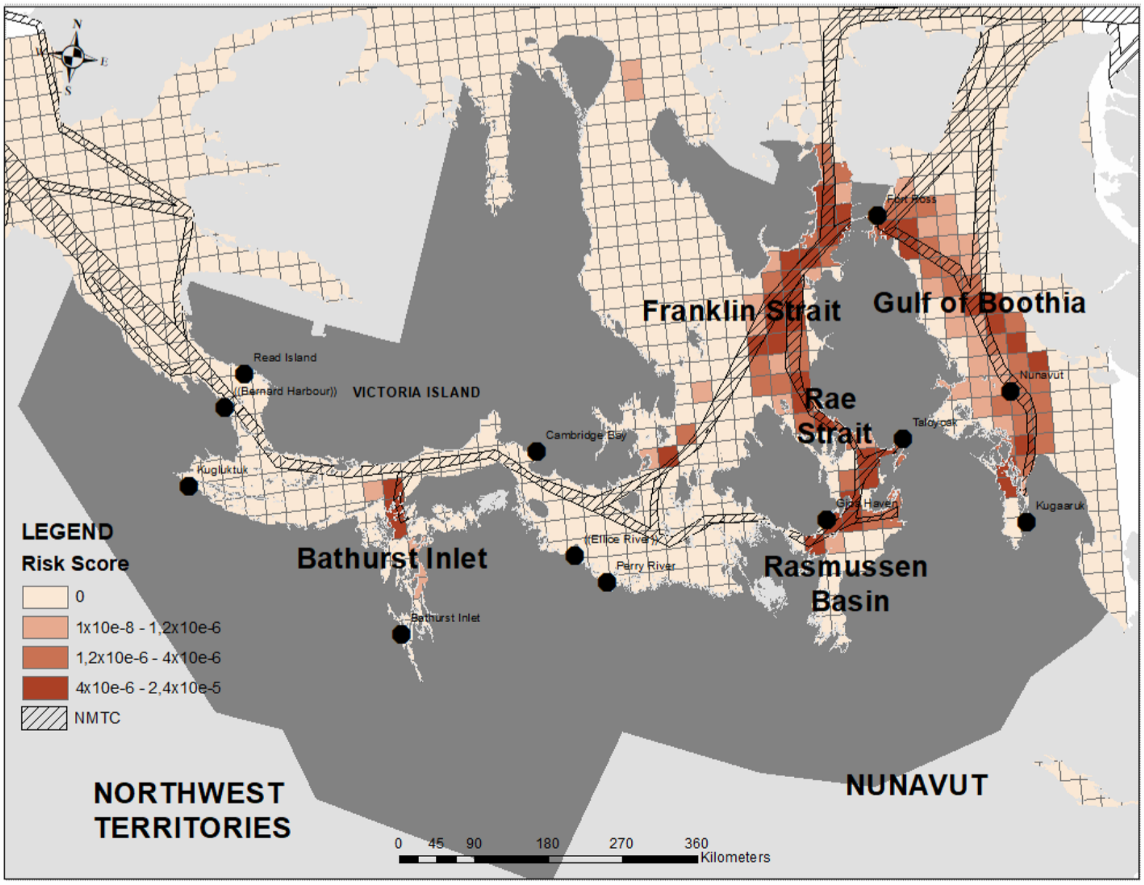

Figure 51: Risk score to Beluga for season 3.

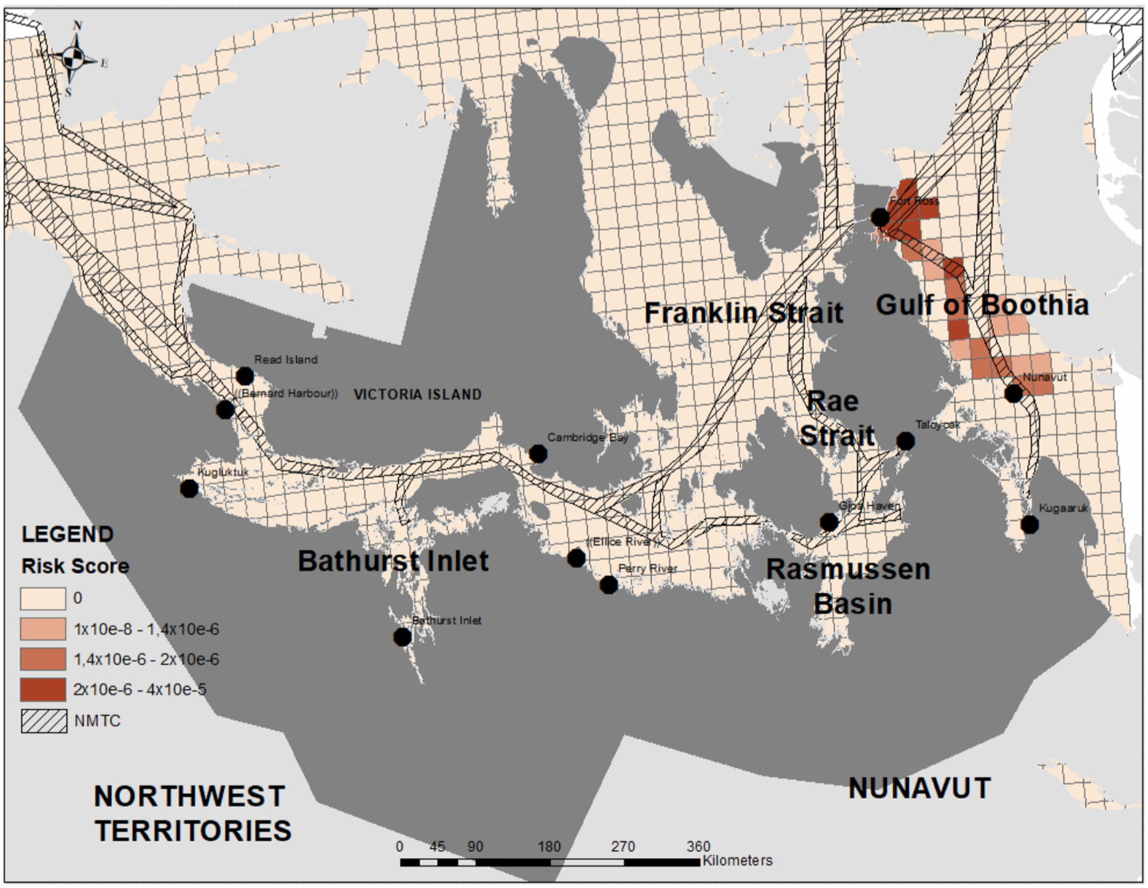

Figure 52: Risk score to Bowhead for season 1.

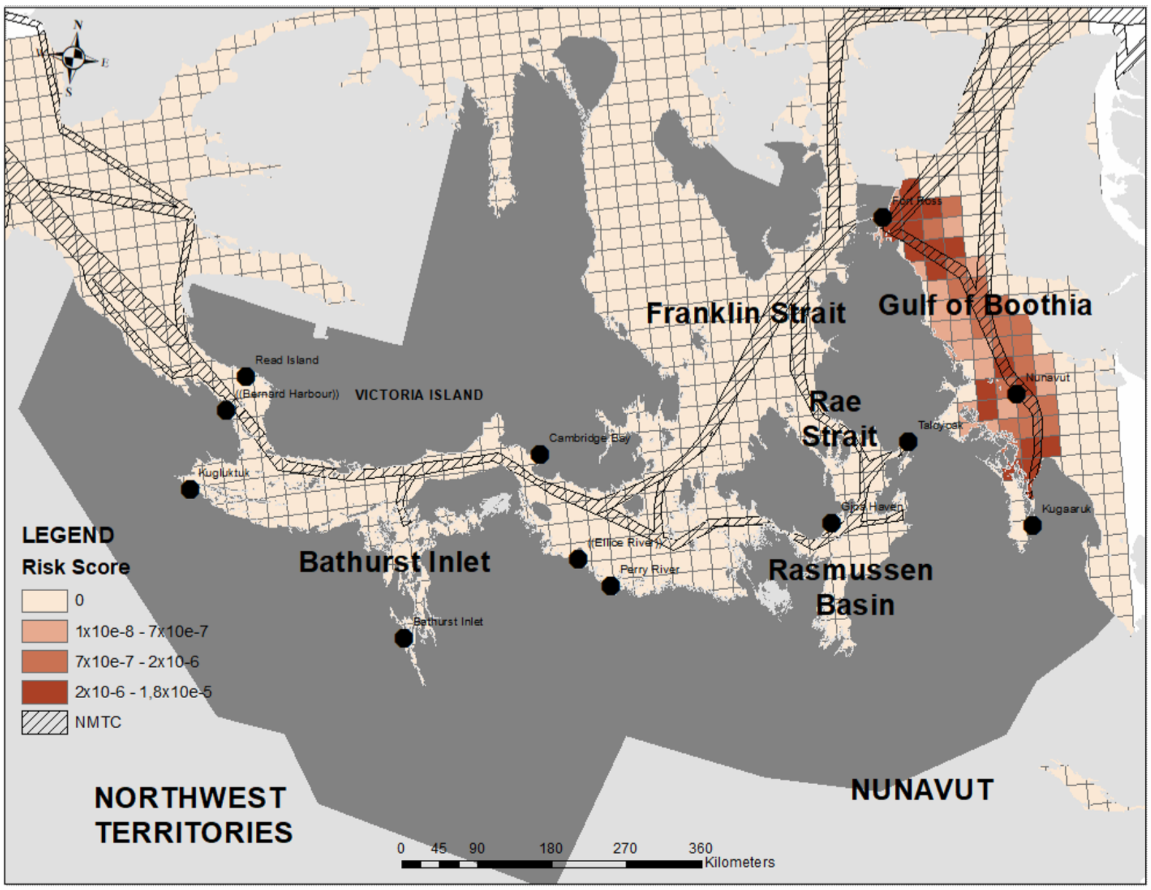

Figure 53: Risk score to Bowhead for season 2.

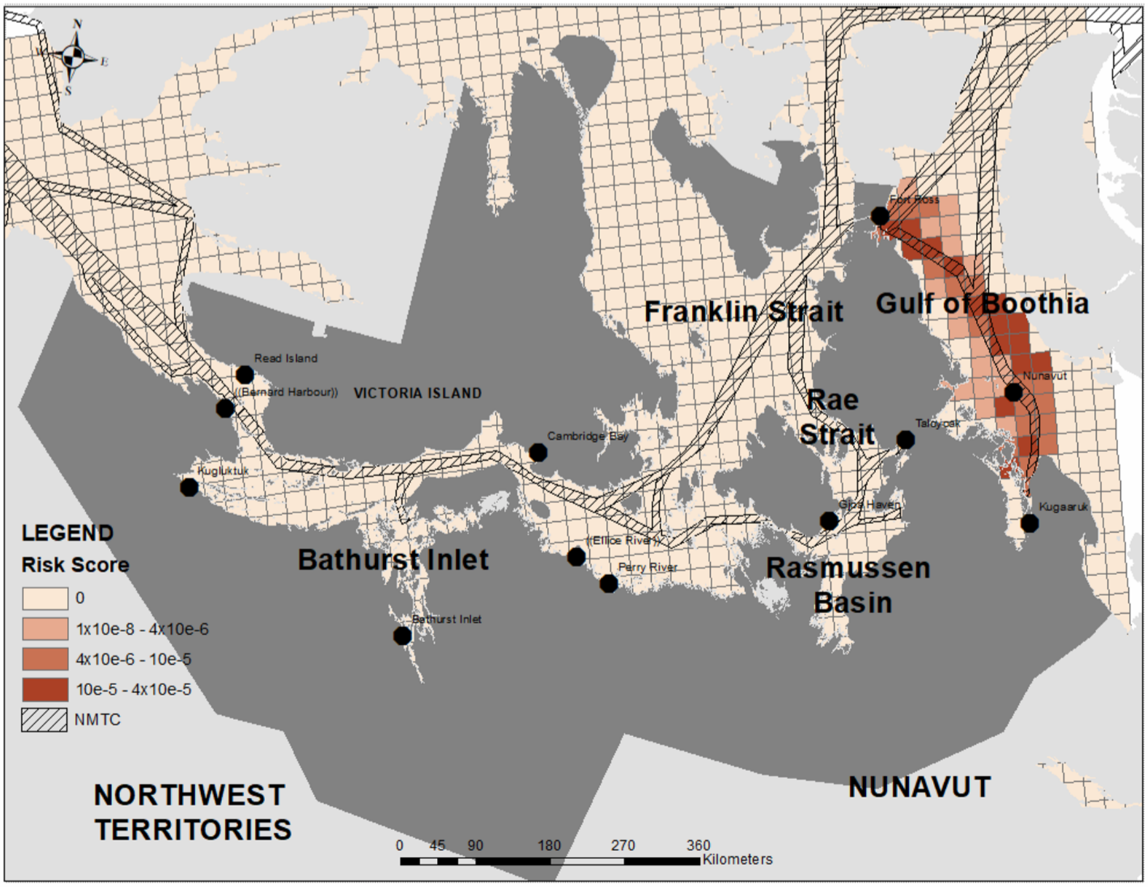

Figure 54: Risk score to Bowhead for season 3.

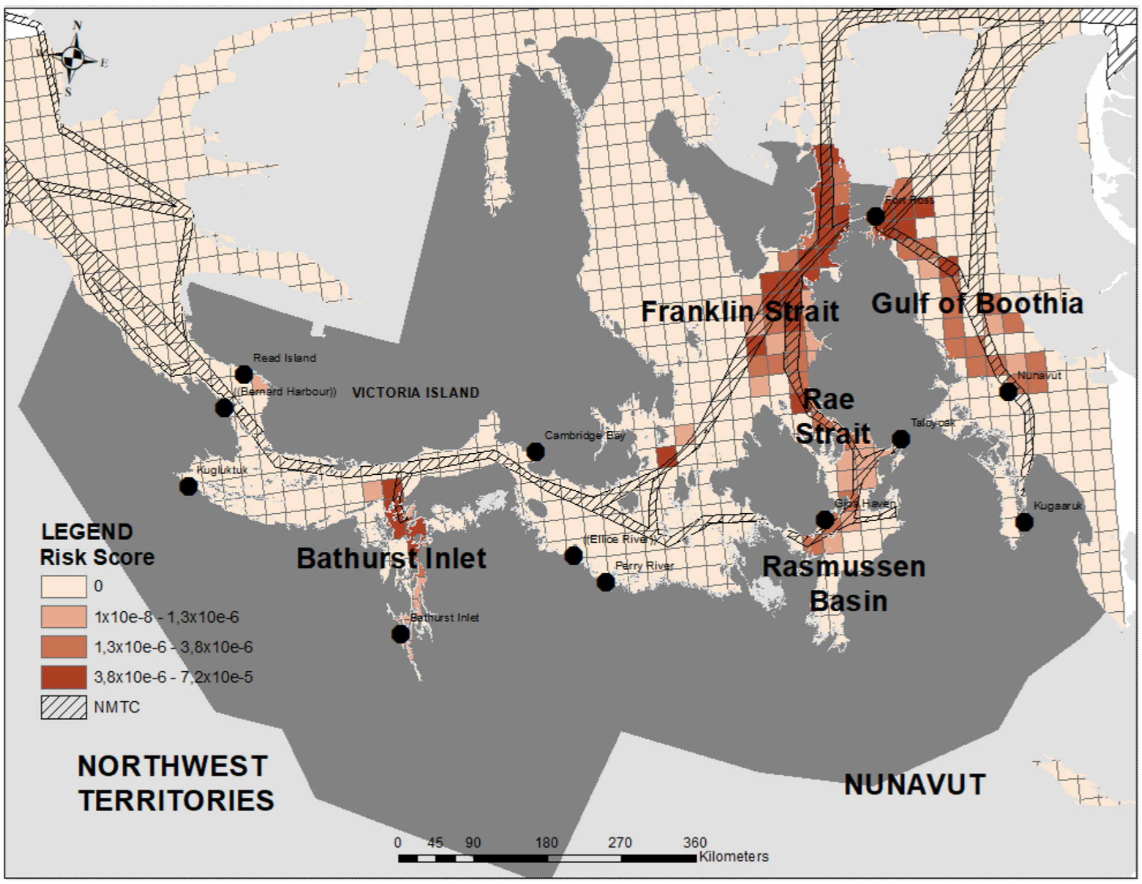

Figure 55: Risk score for season 1 for all species: Beluga, Bowhead and Narwhal.

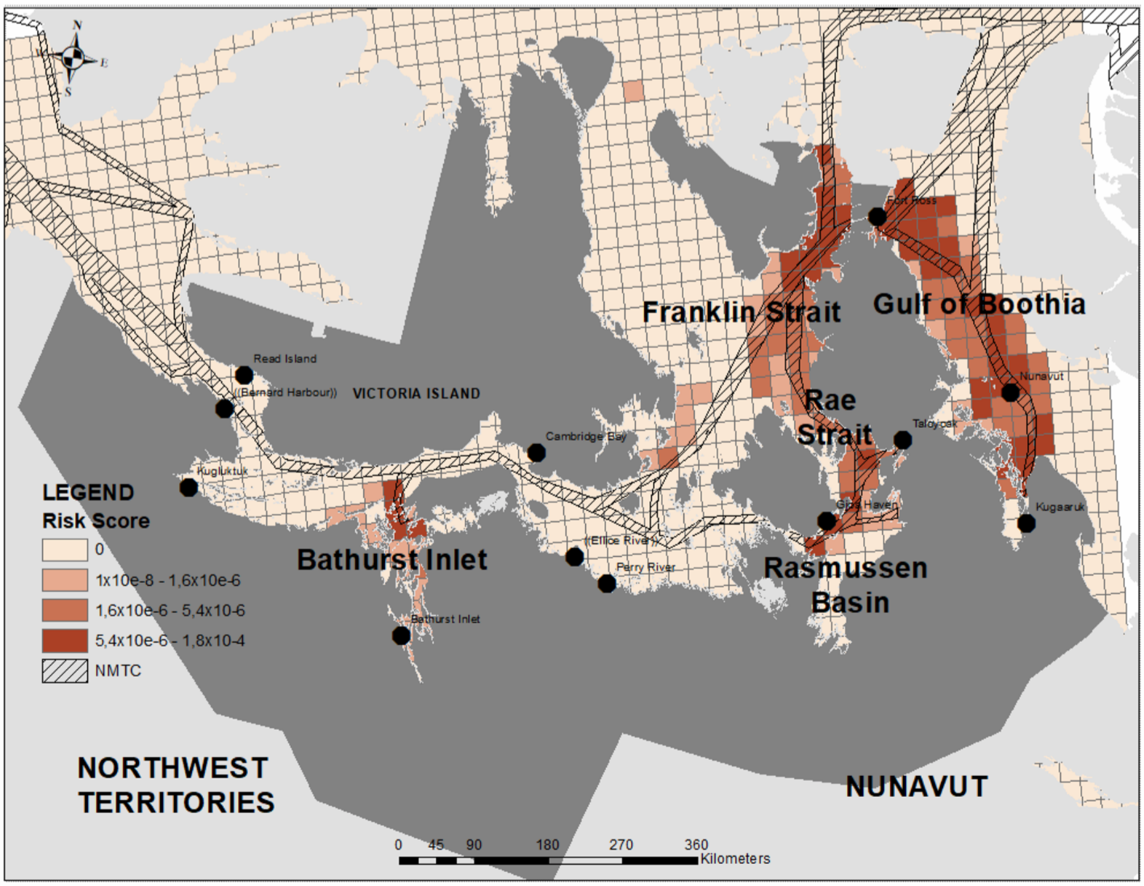

Figure 56: Risk score for season 2 for all species: Beluga, Bowhead and Narwhal.

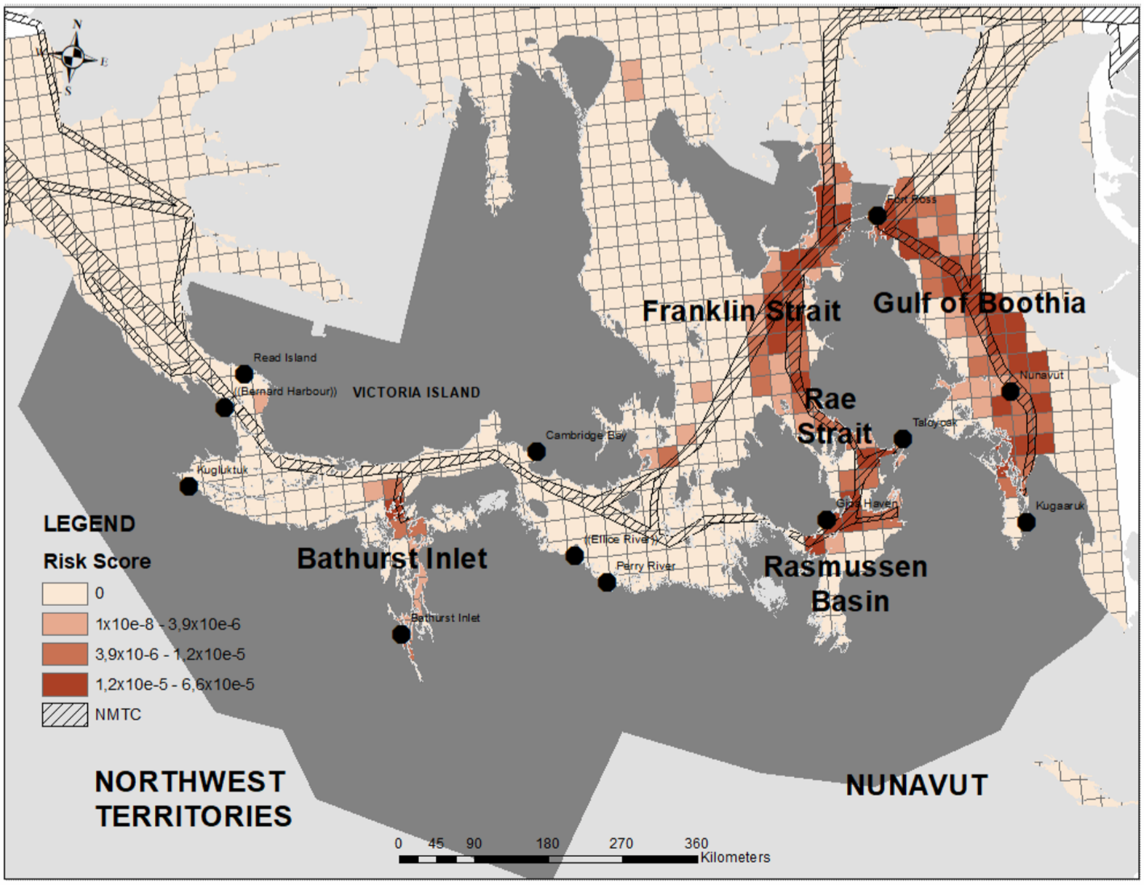

Figure 57: Risk score for season 3 for all species: Beluga, Bowhead and Narwhal.

4.3.11 Uncertainty Assessment

A general analysis of the uncertainty along the CRA process was done through the assistance of the uncertainty matrix proposed by [98] (See Table 14). With respect to the **context location**, the main scenario uncertainties are primarily related to the temporal boundary of the CRA analysis in the Kitikmeot region and other geopolitical elements. In terms of the temporal boundaries, it is important to note that this decision was based on the AIS data availability solely from 2011 to 2018, and not defined by stakeholders choices. This model used historical data to assess the cumulative risk of shipping in the Kitikmeot region and support the claim that the increase of shipping activity in the Arctic can threaten the natural ecosystem for local whales. However, despite the analysis contemplating different shipping seasons, the future scenario of shipping activity in the area may not be best represented by the

2011-2018 AIS data.

As the world keeps changing, geopolitical subjects continue to shift directions [82], which contributes to more uncertainty in risk modelling that attempts to accurately assess the real world. One key geopolitical subject directly related to the Arctic environment is Arctic Sovereignty. Currently all the territorial and maritime zones in the Arctic, including the Exclusive Economic Zone (EEZ) are under the jurisdiction of one of the eight Arctic coastal states: Canada, Norway, Russia, Denmark (via Greenland), Iceland, Sweden, Finland and the United States. Even though international law enforces order over this region, the ownership of the Arctic is not clear and the regulations have become a highly contested issue recently because of climate change [72]. With the extent of Arctic ice rapidly shrinking, and expanding interest in northern shipping and resource exploitation, issues surrounding sovereignty loom ever larger over the northern landscape [72]. As a result of these unclear sovereign conditions, a greater uncertainty pertains to policies, activities, and regulations.

Another uncertainty in the contextualization of CRA is the global consumption of fossil fuel, which has been shaping the geopolitical map over the last two centuries. The increased navigability of Arctic waters has been justified, among other reasons, by the global appetite for untapped natural resources [29], however, as the world dynamics related to renewable energy are changing, the shift from fossil fuels to renewable energy is expected to increase progressively [41]. Therefore, the validity of the statement that oil and gas extraction in the Arctic is a major driver is still uncertain and for that reason, the assertion around the increase of shipping in the Arctic can also be questioned.

Last but not least important is the uncertainty around the ban of Heavy Fuel Oil (HFO) from Arctic shipping, which oil spill would be more drastic than other type of fuel oil. The IMO has already banned its use in the Antarctic, but it is still uncertain whether this policy will also be applicable in the Arctic. High expectations were set during the IMO Marine Environment Protection Committee (MEPC 73) in London (2018) where IMO has agreed that the Sub-Committee on Pollution Prevention and Response (PPR) should develop a ban on HFO for use and carriage as fuel by ships in Arctic waters, based on an assessment of the impacts of such a ban [35]. Even though there has been some serious movement towards an HFO—free Arctic lately, no policies were created to formally ban this fuel which leaves an uncertain scenario for the consequences of a possible oil spill in the Northern waters. These uncertainties present in the context of CRA were categorized as variability uncertainty due to the fact that they go beyond the control of the modeller.

Uncertainties in the **model location** include the following 4 factors: the lack of a proper oceanographic model to simulate the impacts of oil spill and noise pollution; the fact that the baseline environmental conditions are not considered; sensitivity subfactors are equally weighted and the interaction among stressors, which by nature is a very complex topic, has had little research conducted. Conservative assumptions were made as appropriate (listed in section 3.4), for instance for sensitivity assessment, a worst-case scenario was assumed. These uncertainties were categorized as recognized ignorance but they can be reducible if more dedicated research is conducted in those fields.

The uncertainty in the **system data** comes primarily from gaps in the AIS data, from the exclusive use of traditional knowledge for the seasonal location of receptors, lack of a better quality Kitikmeot shoreline shapefile and of a comprehensive empirical information on the selected receptors-stressors interactions (sensitivity scores). In the AIS data, it was found that a reasonable number of vessels do not report to AIS satellites, therefore this dataset might not accurately represent the real traffic data of the study region. For instance, this occurs frequently when vessels turn off their AIS when entering port. In terms of the receptors' shapefiles, these datasets were based on traditional knowledge, without any further scientific validation and/or empirical studies, hence, the receptor data coverage might contain a good amount of uncertainty but it was decided to use it since this is the only source of information available at the present moment. The Kitikmeot shoreline shapefile retrieved from the Canadian government website was found to be missing some of the inland portions. As a result of this flaw, it was not possible to compute the powered grounding probabilities for a few areas, producing uncertainty. This can be fixed once a better shoreline representation is provided.

In terms of the sensitivity scores, there is a lack of comprehensive empirical information on these selected receptors-stressors interactions, therefore expert opinion was needed. The use of expert knowledge allows researchers to gain knowledge about subjects where there is uncertainty due to a lack of data. However, they are not always highly certain about the topic as they use a series of heuristics when judging, which may cause serious bias [49]. which brings a lot of uncertainty to the assessment. In fact, during the expert web survey in this CRA, the level of certainty of their answers was questioned when scoring the sub-factors and from that it be concluded that the noise pollution impact on marine mammal's science is still lacking empirical studies.

Lastly, the **parameter** uncertainty is related to the grid resolution with respect to the dataset resolution and the uncertainties of the CRA **outcomes** derived from the combination and dispersion of the uncertainties present in the models and input data.

Location		Sub-location	Level			Nature	
			Statistical uncertainty	Scenario uncertainty	Recognized ignorance	Epistemic uncertainty	Variability uncertainty
Context	*External economic, environmental, political, social, and technological situation*	Temporal boundary of CRA analysis		x			x
		Arctic Sovereignty		x			x
		Global consumption of fossil fuels		x			x
		Ban of Heavy Fuel Oil from Arctic shipping		x			x
Model	*Model structure*	Oceonographic models			x	x	
		Environmental conditions as a baseline for impacts			x	x	
		Sensitivity sub-factors importance weight			x	x	
		The nature of the interaction among stressors			x	x	
System data		AIS shipping datasets coverage		x		x	
		Receptors shapefiles		x		x	
		Kitikmeot shoreline shapefile		x		x	
		Sensitivity final scores			x	x	
Parameters		Grid resolution with respect to the dataset resolution GIS			x	x	
Model outcomes		Cumulative impacts score		x		x	

Table 14: Location, Level and Nature of Uncertainty in the CRA.

Chapter 5

Discussion

5.1 Seasonal cumulative risk from vessels to receptors in the Kitikmeot region

This study found that vessels transiting the Corridors through the Kitikmeot waters have the potential to cause harm to very sensitive and endemic Arctic marine mammals through ship-source noise pollution and an eventual ship-source oil spill. During season 1, as Figure 52 shows, Bowheads presented the highest risk scores (6.1x10-5); However, in terms of the total area at risk, the receptor that presented a wider geographical area at risk is the Beluga (Figure 49). This can be justified by the Beluga exposure map for season 1 (Figure 38) which shows that this receptor is more present in the Kitikmeot waters when compared to the other 2 receptors (Figure 35 and 32). It is also important to highlight that even though the shipping traffic is less during season 1, which makes the probability of vessel presence lower at this time of the year (Figure 41), there were grid cells with high probability of SEL exceeding AN (Figure 29). This can be justified by the presence of large vessels during season 1, such as tankers, cargo vessels and icebreakers although season 3 was the busiest season for these vessel types. A similar trend can be observed during season 2 and 3, where Bowheads (see Figure 53 and 54), when compared to the other 2 receptors, presented the highest risk scores, 6.4x10-5 and 4.0x10-5, respectively. In terms of the range of the area at risk, Beluga is again the receptor with wider geographical area at risk for both seasons, 2 and 3 (Figures 50 and 51).

5.2 Overlap Between the Corridors and risky areas for Narwhal, Beluga and Bowhead

This study demonstrates how risky areas are identified in a more systematic approach than just purely accounting for the overlap between the Corridors and the marine mammals as indicated in the PEW Cheritables report on the Integrated Arctic Corridors framework [92]. A high degree of congruence between the receptors and the Corridors does not necessarily mean that these receptors are at risk. This could be observed in the final hotspot maps (Figures 55, 56 and 57) where there are areas that the receptors spatially overlap with the Corridors but the risk score is not at its highest, whereas there are areas where the overlap happens and the CRA scores are at its highest, for example the greatest part of the east side of Kitikmeot during seasons 2 and 3.

The main reasons for that lie in three important factors, which are commonly missed in several risk assessments: the sensitivity of these receptors to the stressors, which measures the degree of impact the stressor has on the receptor once a threshold is reached; a more detailed ship traffic-based collision and powered grounding risk assessment, which gives detailed spatial and temporal information about the oil spill risk; and more detailed acoustic modelling based on vessel's unique characteristics. A recent study on the risk of oil spill in the Canadian Arctic [57] has divided the region into sub areas and classified the risk level for each of them but it did not calculate the frequency of oil spill based on a more detailed analysis based on AIS traffic data such the method used in the CRA presented here. Since the sensitivity scores for each stressor-receptor combination of the present case study have not being studied in the literature, it was decided to run an expert survey. The results from this assessment demonstrated that Narwhal, Beluga and Bowhead are impacted in different ways from oil spill and noise pollution. Not only the sub-factors are different, but also the extent to which these animals are impacted by each shipping stressor. According to the results, an oil spill is least likely to happen in the area however these receptors are highly sensitive to it when compared to noise pollution, which has a higher likelihood of disturbing them but the consequences are not as dramatic as an oil spill. This study also demonstrates the importance of GIS software for risk assessment, which can be used to spatially and temporally display areas where the accumulation of shipping stressors have the potential to disturb marine mammals.

In terms of contributions to CEA literature, the new CRA equation proposed is a more sophisticated algorithm than the one developed by Halpern et al. (2008). This new algorithm addresses the uncertainty associated with the main elements of a cumulative effects assessment, the stressors and receptors, by accounting for the probability that each stressor exceeds established thresholds for each receptor instead of just accounting for its intensity. Additionally, different than Halpern et al. (2008), a uniform probability was used to account for receptor exposure instead of just accounting for its presence/absence. This risk-based approach of CEA is important since CEAs are inherently complex and seldom linked to real-world management processes [88]. As Gissi et al (2017) and Stelzenmller et al. (2018) have identified in previous CEA studies, there is a challenge in this field when it comes to recognizing and handling the uncertainty and the CRA proposed here helps by establishing a standard framework that treats uncertainty in a more transparent manner.

5.3 Implications of CRA to risk management

The importance of CRA for risk management, instead of using solely the traditional single-stressor risk assessment, can be justified when their separated output are visually compared. As an example, Figures 58 and 59 show the final risk score map for oil spill and noise pollution for season 3 and the risk score map for oil spill for season 3, respectively. The first map shows a more realistic and overall scenario of risks from shipping activity on the three marine receptors, whereas the second map (Figure 59) contains only information about the risk of an oil spill harming these three receptors. As it can be seen, the second map contains less alarming information and does not fully represent the overall risk of shipping activity in the Kitikmeot region. Since shipping activity is rising in this region, it is important for decision makers to see the total risk associated with it over the seasons and geographical area. If a risk assessment of one-single stressor is used instead, it could mislead decision-makers by giving them a wrong perception of overall shipping risk, which may make them conclude that there is no need to prioritize resources for risk control options for Kitikmeot region. Therefore, it can be concluded that the use of CRA satisfies the overall goal of risk management by assessing the total cumulative risk of shipping activity although a single-stressor risk assessment might be more effective for choosing the best risk treatment due to the stressors' different natures.

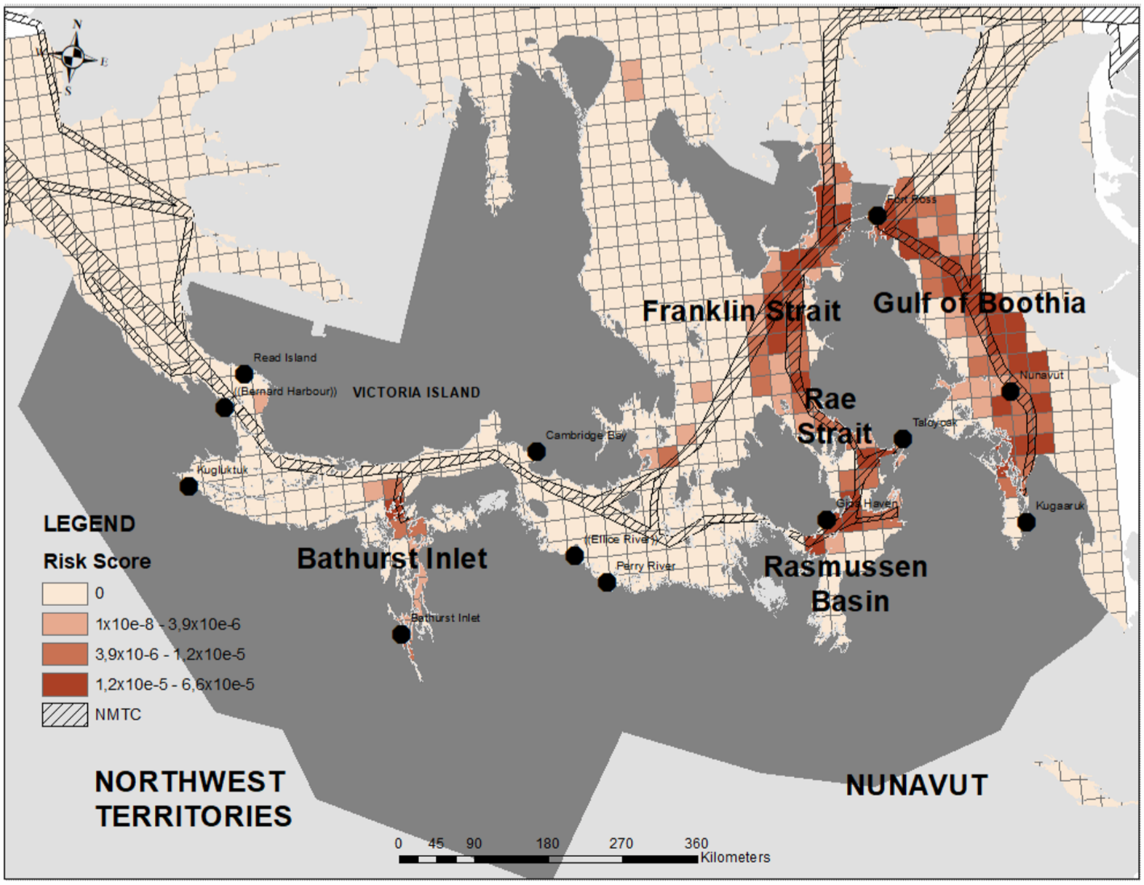

Figure 58: Risk score of oil spill and noise pollution on three marine receptors, for season 3.

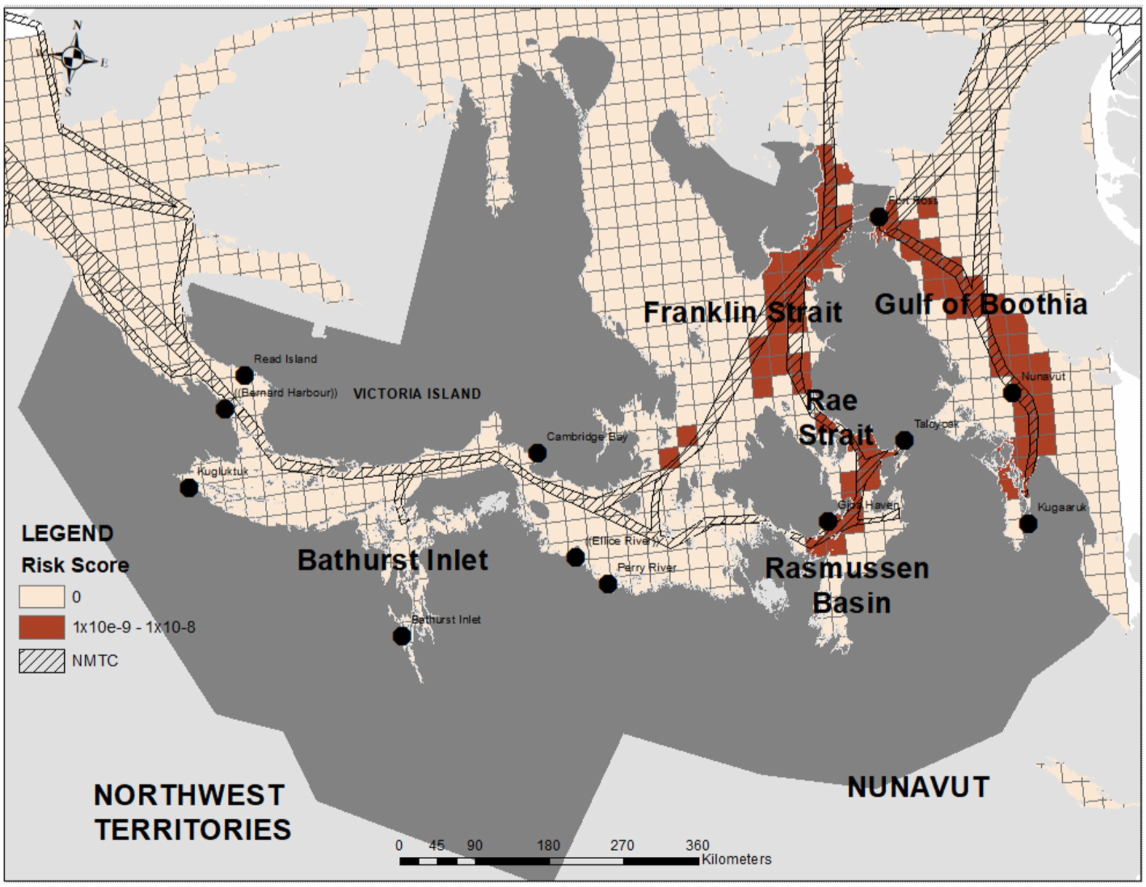

Figure 59: Risk score of oil spill on three marine receptors, for season 3.

5.4 Suitability of CRA for the two selected shipping stressors: noise pollution and oil spill

The CRA is a great tool to inform decision makers when allocating resources and indicating where are the most critical areas in the region. However, in terms of risk treatment, this might not be suitable since CRA outcomes can mislead stakeholders when combining stressors of different nature by masking the ones that are less likely to happen but if so, would cause higher impacts, such as oil spill. These two stressors are qualitatively different and therefore require different risk management strategies as suggested by the International Risk Governance Council (IRGC). This is the case for the two stressors assessed in this present study, oil and noise, which both have different natures making it hard to combine them into a single equation. One has high probability and medium consequences (noise) and the other one (oil) has very low probability but high consequences. However, as mentioned previously, this methodology has significant value by showing the importance of a more comprehensive risk assessment instead of just overlaying spatial elements to find areas at risk and also showing the importance of considering more than one stressor in order to help decision makers prioritize risk mitigation resource allocation.

5.5 Decision-making process based on CRA framework

The CRA framework helps to better understand the potential risks from marine vessel activity on the environment in order to support evidence-based decisions that guide economic growth while preserving the marine ecosystem. This framework assesses the total risk accumulated from shipping activity and does not include the identification and implementation of measures to control, minimize or prevent the adverse effects from these cumulative risks. Similarly, it does not create new legislative requirements or indicate which policies should be created; rather it informs and guides the policy makers. The use of such framework is an acute need for shipping in the Arctic, seeing that the demand for natural resources is growing rapidly and the context for new development in this particular area is becoming more complex.

Therefore, the final maps from CRA should communicate to decision makers the overall risk of shipping activity through. In case new policies are created and targeted to mitigate the risk of a specific shipping stressor, this is then reflected in the overall risk score.

5.6 Suggestions for future research

This study established a framework for cumulative risk assessment (CRA) that can be used to identify areas where receptors are at most risk because of the accumulated risk from multiple marine shipping stressors. However, since the proposed framework is a product of different and complex elements such as sensitivity score, dynamic receptors, probabilistic and deterministic shipping stressors, among others, more dedicated research is needed for each of these elements. Further research should focus on gathering empirical data for the sensitivity assessment in order to improve the accuracy of the CRA results and reduce uncertainty. This can be done by performing field studies in order to investigate the potential effects of oil spills and noise pollution on the Bowheads, Narwhal and Belugas. The case study had a time constraint when the expert survey for the sensitivity assessment was conducted, which can be overcome by a more focused study on this topic.

Future research should also focus on the implications of the results from the case study to policy making processes and on identifying effective risk mitigation initiatives for reducing the impacts of these shipping stressors on marine mammals and developing a management plan specific to the Kitikmeot region for vessels transiting the Corridors.

The uncertainty assessment included in the CRA framework had as a goal to identify the location, level and nature of the uncertainty in the model. A deeper analysis of how large these uncertainties are and the implications are outside of the scope of this study and should be used as a research topic for future investigations.

A future study can also include more shipping stressors in the CRA so that policy makers can have a more representative picture of the current scenario of shipping risks to marine receptors in the area of study. Spatial and temporal data on marine receptors and shipping stressors present in the Kitikmeot area should then be used in future research to model the cumulative risk caused by vessels in other marine areas of the Canadian Arctic outside of the Kitikmeot region.

Chapter 6

Conclusion

This study demonstrates the importance of a more comprehensive risk assessment that includes more than one stressor in the same analysis, and takes into account the interaction between stressor-receptor, instead of just considering their overlap. The final hotspot maps have shown that a more elaborate and comprehensive risk assessment, such as the proposed CRA framework, can indeed be more effective in terms of assessing the total risk accumulated from different shipping stressors. However, CRA is not recommended for risk treatment, because of the different nature that shipping stressors have (i.e. one being deterministic and other probabilistic). Therefore, each shipping stressor would require different risk mitigation options. Furthermore, this study pinpoints the weakness of the proposed CRA framework and describes the uncertainties in the CRA model.

In terms of its relevance to the case of Kitikmeot region, as shipping activity continues to increase in this area, it is becoming fundamental for policy makers to consider all the risks associated with vessels, including potential disturbance from shipping stressors to local marine species. Based on historic shipping tracks (AIS dataset) through the study region of Kitikmeot during the period of 2011 to 2018, this study was able to assess the cumulative risks derived from two different shipping stressors, oil spill and noise pollution. The final hotspot maps for each shipping season (Chapter 4) indicate that these two shipping stressors, derived from vessels transiting the Corridors, have the potential to cause harm to these three highly-sensitive, Arctic marine mammals. During season 1, Figure 55 indicates that special attention should be given to the Franklin Strait, Gulf of Boothia and Bathurst Inlet. As for season 2 and 3, these same regions continue to present high-risk levels, in addition to Rae Strait and Rasmussen Basin as Figure 56 and 57 show. From these results, it can be concluded that the current shipping season overlaps with the seasonal location of these three marine mammals in the Kitikmeot region, with the season Ukiaqsaaq (season 3) being the period when these animals are at the highest risk.

Although the final hot spot maps have shown low risk scores in the study region because the shipping traffic is still considerably low when to compared to southern waters, the results from this assessment can be used to improve current resource allocation policies and create more awareness of this worrisome issue that can worsen in the foreseeable future.

These results can also be used to determine which sections of the Corridors require more elaborate regulations to reduce the impacts from vessels for a long term safety of these marine mammals and consequently the local communities. For instance, Transport Canada may implement speed restrictions for vessels in areas of the Corridors where there is a high risk of noise pollution for marine mammals, similar to what they have done in the western part of the Gulf of St. Lawrence followed by five deaths of the endangered North Atlantic right whale in the region. Transport Canada, as the lead federal regulatory agency responsible for the Oil Spill Preparedness and Response regime may also develop a better Oil Spill Preparedness and Response infrastructure in the Corridors where there is a high risk of oil spill occurring. Seeing that shipping activity in the Arctic has been significantly increasing in recent years, it is primordial to assess the risks associated with it. This issue requires a great deal of attention, research and collaboration amongst scientists, managers and local communities due to its multidisciplinary nature. This study also shows the importance of including the Traditional Knowledge in Western research in order to gain more meaningful insights on the valuable Arctic marine ecosystem.

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Appendix A

Sensitivity assessment - Briefing note

DALHOUSIE UNIVERSITY

BRIEFING NOTE

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1. Topic

This research proposes a potential framework for Cumulative Risk Assessment (CRA) for shipping stressors and then apply it in a case study in Kitikmeot region (Figure 2) for two selected shipping stressors, ship-source oil spill and ship-source noise pollution and three marine mammals' receptors: Narwhals, Beluga and Bowhead.

2. Purpose

The purpose of this briefing note is to effectively provide enough context information related to the topic of this research in order to support the experts in the elicitation process. The experts will be assessing the sensitivity of selected marine mammals' receptors to selected shipping stressors, which will be presented below. This assessment is important when combining multiple stressors into one single risk equation (see section Cumulative Risk Assessment below) by allowing the assessment of how much each shipping stressor contributes to the overall risk score.

Additionally, different scenarios will be presented on which the experts will have to consider when scoring each sensitivity sub-factor, by using the attached excel spreadsheet that comes along with this briefing note.

3. Contextualization

Due to increasing average temperatures, the area covered by sea ice during summer months in the polar areas has decreased by about 10 to 15% since the late 1950s (WHO,2003).

The shortening of sea ice in the summer season has caught the attention of the global shipping community due to the potential of the Northwest Passage through the Canadian Arctic becoming a shorter and cheaper alternative route to Panama Canal (Khon et al, 2010; Howell and Yackel, 2004, Smith and Stephenson 2013; Pizzolato et al. 2014). This growing utilization of the ocean could pose different risks to the marine animals in this region, such as noise pollution, habitat alterations, and potential spill of contaminants (Dawson et al., 2016).

In order to develop shipping governance in this region that ensure a safe and sustainable shipping route and at the same time reduce the risk of oil/chemical discharges (Chenier et al, 2017) the 'Low

Figure 60: Briefing note for sensitivity assessment page 1.

Impact Corridors' initiative has been created, an initiative co-led by the Canadian Coast Guard (CCG).

The Northern Marine Transportation Corridors (NMTC) (Figure 2) were established at the national level, based on current traffic patterns and marine crew safety, with limited consultation with territorial or Inuit governments. Hence, important areas for marine mammals and fish stocks in the region were not considered, leaving a serious gap regarding the receptors to potential shipping stressors in the framework (PEW Charitable Trusts, 2016). Furthermore, the NMTC does not incorporate a cumulative risk assessment that combines different shipping stressors. Therefore, an evidence-based approach for improved shipping governance is needed, including a more comprehensive cumulative risk assessment of shipping stressors to the local marine mammals' receptors in the Nunavut waters. Coincidentally, Transport Canada (TC) has also recently initiated studies on better methods for cumulative effects of marine shipping through the Oceans Protection Plan, for different coastal environments around Canada including in the Eastern Arctic (Government of Canada, 2017).

Within this context, a framework for Cumulative Risk Assessment (CRA) for shipping stressors has been developed (Figure 1) based on an existing algorithm developed by Halpern et al (2009). It provides a means to combine different stressors into one single risk equation and presents the results in a simple visualization format using a GIS (Geographic Information System) software.

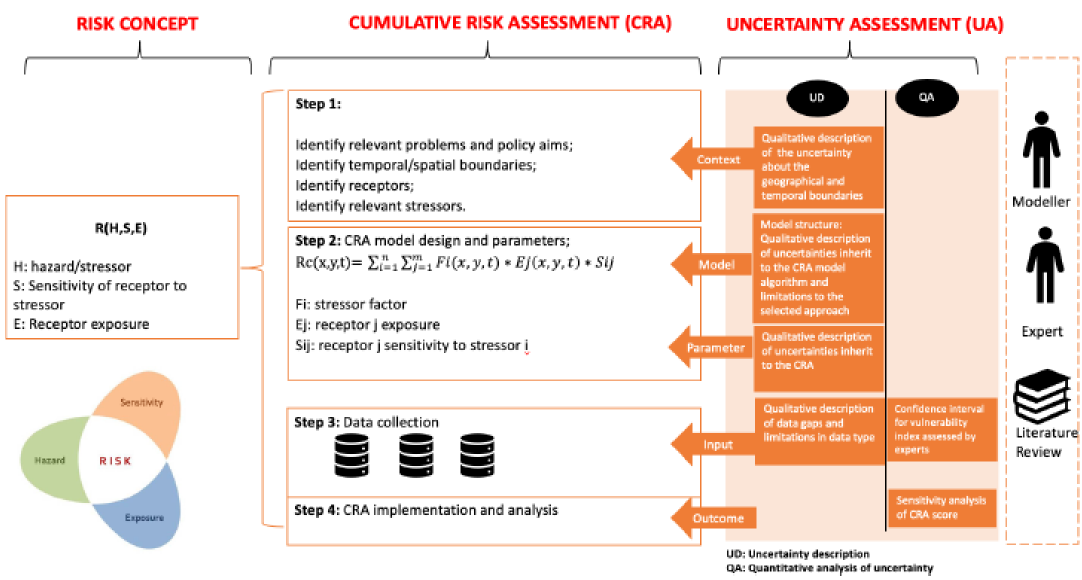

Fig. 1 - Proposed framework for Cumulative Risk Assessment of shipping stressors (adapted from Gissi et al (2017), Schmitz, P. (2019)

Figure 61: Briefing note for sensitivity assessment page 2.

4. Study area for the case study

For the case study, the geographic area selected is the Kitikmeot region (Figure 2), in which marine traffic has increased considerably over the past decade and current studies foresee a continuing growth due to sea ice reduction (Dawson, et al., 2016).

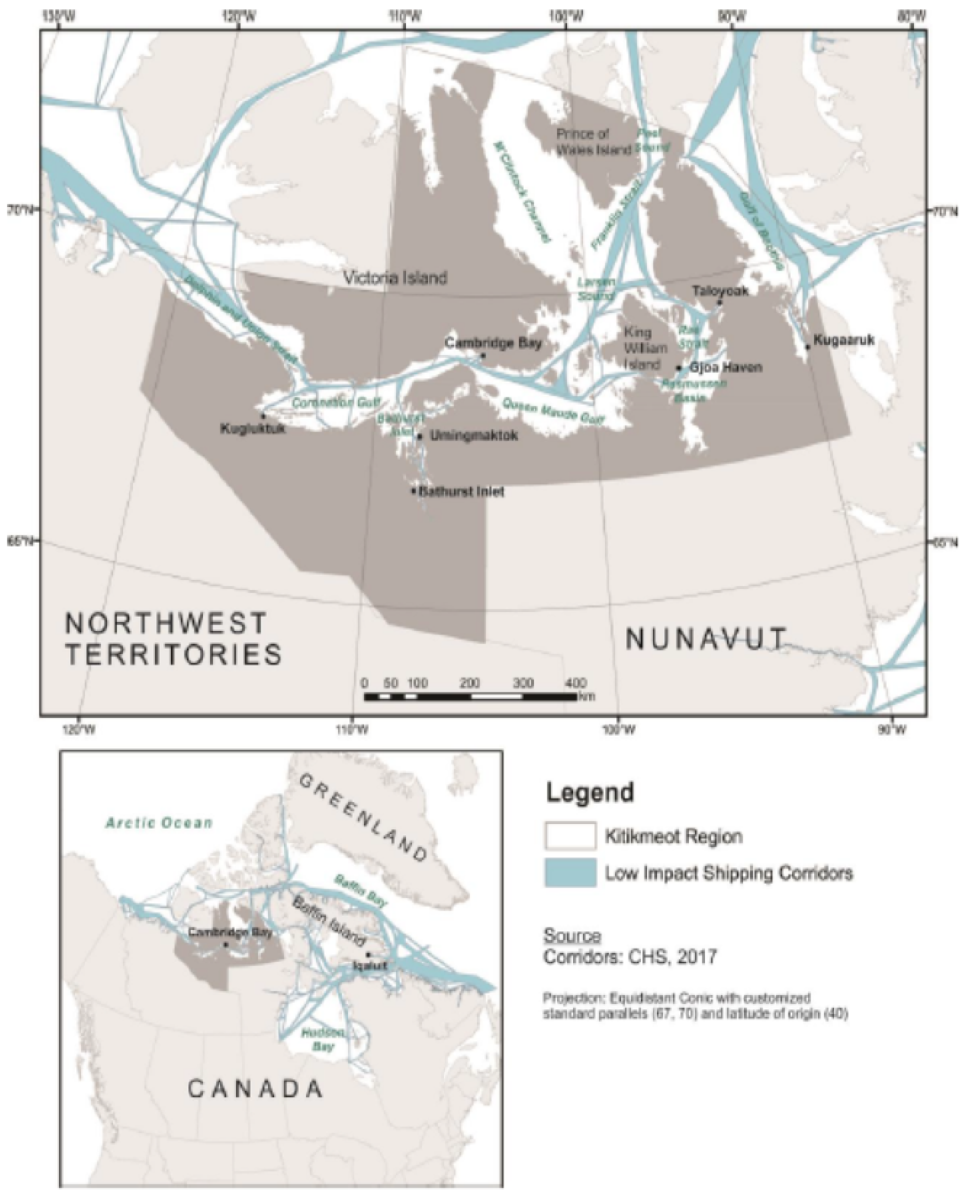

Fig. 2 - Kitikmeot region and the Low impact shipping corridors (NMTC)

Figure 62: Briefing note for sensitivity assessment page 3.

5. Shipping in the Kitikmeot region

Amongst all Nunavut regions, Kitikmeot is the one experiencing the most increase in ship traffic and for this reason this area was selected for the case study. As you can see in Figure 3 below, in different periods of time, the distribution of ship traffic by vessel type has changed. For example, in the period of 1990-2000, Government vessels and Icebreakers used to share the Kitikmeot waters with Tug/Barge vessels mostly; however, in the most recent years (2011-2015), Pleasure crafts and Tanker ships' presence have significantly increased, gaining special attention among local stakeholders (Dawson et al., 2017).

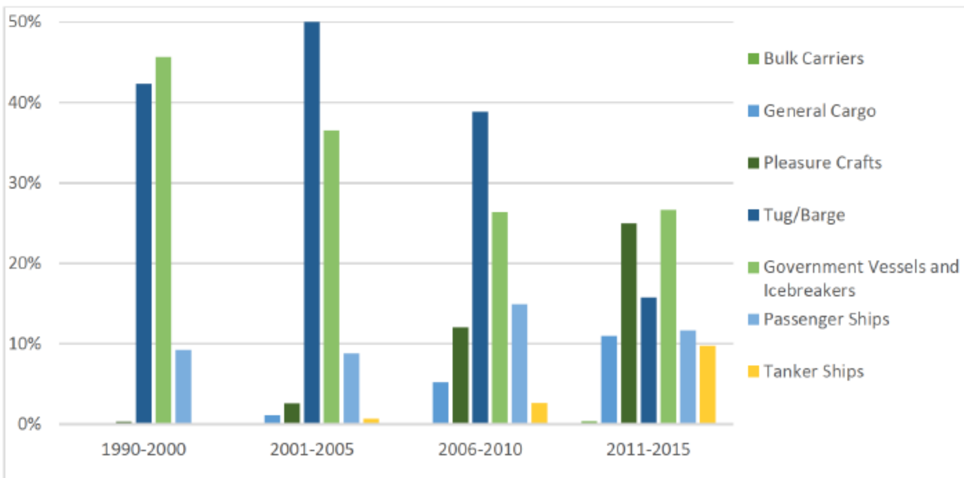

Fig. 3 - Distribution of ship traffic in the Kitikmeot region based on annual distance travelled, 1990-2015. Source: Jenna (2018), Dawson et al. (2017).

6. Cumulative Risk Assessment

By using the following equation, a risk score will be calculated for each grid cell within Kitikmeot region:

$$\textbf{Rc (x,y,t)}= \sum_{i=1}^{n} \sum_{j=1}^{m} \boldsymbol{Fi\ (x,y,t) * Ej(x,y,t) * Sij} \quad (1)$$

- Fi: stressor factor, which is established by combining the statistical frequency of occurrence of the stressor and the magnitude of the event;
- Ej: variable that represents the presence/absence of receptor j at location (x,y) for season t;
- Sij: integer variable that represents the sensitivity of receptor j to stressor i;
- Rc: cumulative risk score at location (x,y) for season t;
- Location (x,y): a grid cell within the study region, size 25kmx25km.

Figure 63: Briefing note for sensitivity assessment page 4.

SENSITIVITY FRAMEWORK

❖ *Sensitivity (Sij)*

Given that multiple stressors do not affect the receptors equally, it is necessary to assess the sensitivity of each receptor to each stressor, based on stressor-specific criteria (sub-factors) (Figure 4). In order to do that, a measure of sensitivity from each receptor to each stressor is incorporated, represented by the Sij index in equation (1). Unfortunately, sensitivity data of marine life receptors to shipping stressors are not available in all cases or able to be collected empirically, for ethical reasons (Nevalainen, Helle & Vanhatalo 2018).

Therefore, due to lack of comprehensive empirical information on receptor–stressor interactions, expert inputs are needed to make existing research directly useful to policy makers. Ecological sensitivity is an inherently complex concept, hence structuring the collection of expert knowledge on sensitivity into sub-factors creates more consistency and transparency to the use of expert opinion. Moreover, based on previous studies on expert bias, it was noticed that eliciting through more than one sub-factor (e.g. mechanical subfactor, chemical sub-factor, etc.) results in better calibrated expert assessment than eliciting the target index (in this case sensitivity) directly (O'Hagan et al., 2006).

The criteria chosen (e.g. Mechanical, Chemical, Behavioral, Others) to assess receptor's sensitivity for ship-source oil spill and ship-source noise pollution were identified based on literature review and consultation with experts in the fields.

Based on a similar study performed by Hannah et al. (2017), where the vulnerability of several biological components to ship-source oil spills were assessed, two main criteria (sub-factors) were selected to assess the receptor's sensitivity for oil spill: mechanical and chemical. According to these authors and Thornborough et al. (2017), these criteria are assessed "based on physiological characteristics (e.g. feeding structures) that can increase the magnitude of impact from exposure to oil".

In terms of ship noise, as stated by Erbe et al. (2014), "anthropogenic noise is perceived in quite different ways by marine mammals with different auditory systems", therefore, some receptors are more sensitive to noise pollution than others. Similar to oil spill, noise pollution can impact physiological characteristics (e.g. hearing ability) of marine mammals, resulting in a mechanical impairment (Weilgart, 2007). Another important criterion to be considered is the behavioural disturbance, which can impact these receptors' psychological characteristics, for instance, masking communication among them (Erbe et al., 2016).
The questionnaire spreadsheet (see Appendix A) attached along with this briefing note contains more information about the sensitivity framework.

Figure 64: Briefing note for sensitivity assessment page 5.

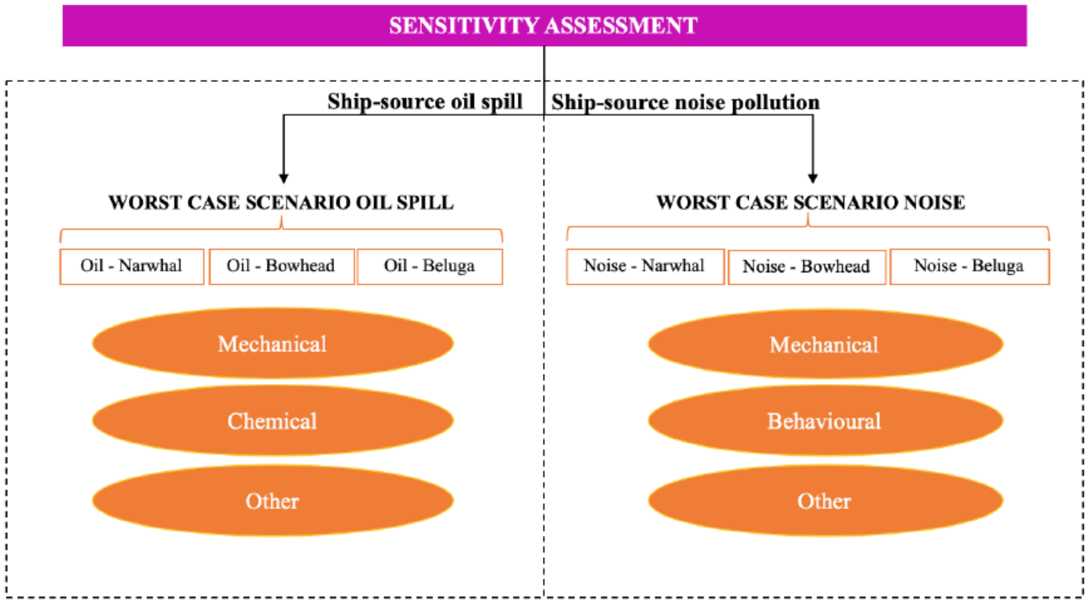

Fig. 4 - Sensitivity sub-factors Mechanical, Chemical, Behavioural and Other (see Appendix A for further information) for oil spill / noise pollution to Narwhals, Belugas and Bowheads. Source: Schmitz, P (2019)

Figure 65: Briefing note for sensitivity assessment page 6.

7. Scope

Due to time and budget constraints, the present framework has limitations, such as:

1. It is limited to considering only the direct effects of oil/noise to each receptor, not including potentially significant indirect effects.
2. The receptors selected for this assessment do not represent all the marine life in the Kitikmeot region; However, this framework can be used as an example for similar future applications.
3. This framework does not assess spatial planning areas such as Ecologically or Biologically Significant Marine Areas (EBSAs) and Marine Protected Areas (MPAs);
4. The main goal is to focus on the **generalised** impacts from initial stages of large ship-based spill for oil spill stressor AND from a consistent ship-source noise pollution where the animal is assumed to be very close to the source for a reasonable amount of time for noise stressor.
5. Consider a 1:1 ratio (1 vessel to 1 whale) when ranking sensitivity.

❖ *Selected Shipping stressors for the case study*

Based on local concerns, ship-source oil spills and ship-source noise pollution are considered as two of the shipping stressors of greatest concern among the Northern communities.

❖ *Selected Receptors for the case study*

The Kitikmeot region is home to numerous important marine wildlife areas; However, for this case study it will be selected as receptors the following marine mammals: Beluga whales, Bowhead whales and Narwhales (Arctic Council, 2009; Explore Nunavut, 2006) due to time and budget limitations.

❖ *Baseline scenario*

When scoring the questionnaire, please have in mind the baseline scenario:

For Oil Spill: worst case scenario, oil spill size between 1,000 to 10,000 m3, with the receptor in contact with the oily area, and similar to what Nevalainen et al. (2018) considered in her study, the timespan considered here is the first two weeks after an accident, which accordingly to Boehm & Page (2007), during this period the oil at the water's surface is likely to have maximum exposure potential.
For Noise pollution: worst case scenario, where the receptor is exposed to chronic ship-noise, physically very close to the source noise for a reasonable amount of time.

Figure 66: Briefing note for sensitivity assessment page 7.

Appendix B

Sensitivity assessment - Consent form

Consent Form

Project title: Application of a framework to assess the sensitivity of Narwhal, Beluga and Bowhead to ship-source oil spill and ship-source noise pollution in the marine environment in the Canadian Arctic.
MASc student: Priscilla Einecke Schmitz (pr761206@dal.ca)
Industrial Engineering, Dalhousie University, Halifax, Nova Scotia
Supervisor Dr. Ronald Pelot (ronald.pelot@dal.ca)
Industrial Engineering, Dalhousie University, Halifax, Nova Scotia
Co-supervisor Dr. Floris Goerlandt (floris.goerlandt@dal.ca)
Industrial Engineering, Dalhousie University, Halifax, Nova Scotia
Funding provided by: NRI – Nunavut Research Institute. Initially established in 1984, NRI's mandate is to develop, facilitate, and promote scientific research as a resource for the well-being of people in Nunavut.

Introduction
You are being invited to take part in a research study being conducted by Dr. Ronald Pelot, a professor in the Department of Industrial Engineering at Dalhousie University and Priscilla Einecke Schmitz, a MASc student in the Department of Industrial Engineering at Dalhousie University. Participating in this research is entirely voluntary. You may withdraw from the study and choose not to continue within 10 days after you submit your answers. The information below tells you about what is involved in the research, what you will be asked to do and about any benefit, risk, or inconvenience that you might experience.

Please feel free to ask any questions you may have about your participation in this study or the purpose of the research. Questions can be directed to the lead researcher (Dr. Ronald Pelot) by phone +1 (902) 494-6113 or email ronald.pelot@dal.ca, or the MASc student (Priscilla Einecke Schmitz) by phone +1 (902) 809-3058 or email pr761206@dal.ca.

Purpose and Outline of the Research Study
The proposed study is an explorative case study to assess the sensitivity of selected receptors (Narwhals, Beluga and Bowhead whales) to selected shipping stressors (ship-source oil spill and ship-source noise pollution), given the lack of existing research. Given that multiple stressors do not affect the receptors equally, it is necessary to assess the degree to which marine features respond to shipping stressors, which are deviations of environmental conditions beyond the expected range. The resulting sensitivity score for each stressor-receptor combination will be incorporated in a cumulative risk assessment.

Who Can Take Part in the Research Study?
You may participate in this study if you have knowledge on one of these topics or even both:
- Impacts of ship-source oil spill on marine mammals
- Impacts of ship-source noise pollution on marine mammals
Participants must be over the age of 18 years old.

Figure 67: Consent form for sensitivity assessment page 1.

What You Will Be Asked to Do?

Participants will be asked a series of questions related to the sensitivity of selected receptors (Narwhals, Beluga and Bowhead whales) to selected shipping stressors (ship-source oil spill and ship-source noise pollution), given the lack of existing research. For each combination stressor receptor, participants will be asked a series of questions where they have to assign a score for the level of impact (from 0 not at all to 3 high impact) that the stressor would potentially have on the receptor based on their expertise. It will also be asked for the expert to select the degree of certainty (from 0 not certain at all to 4 extensive empirical work exists and/or the expert has extensive personal experience. Empirical work exists for species in the same family) that his/her answer has in order to reduce possible bias and errors when calculating final score for sensitivity. In case the expert feels necessary, there will be an open space provided for further justification/comments. The estimated time commitment for each participant is approximately 1.0 hour maximum. The format of the questionnaire will be semi-structured, which will include both structured questions (assign impact score and degree of certainty) and an open format (justification) which gives participants the chance to justify his/her answer. The data will be collected through excel spreadsheet, therefore there will be only electronic data.

Possible Benefits, Risks and Discomforts

The participation of participants will benefit indigenous communities from Kitikmeot region in the Canadian Arctic and government agencies interested in this topic by assessing how sensitive each receptor is in terms of shipping stressors, seeing that an increase of ship traffic is already happening in this region, which has been rising concerns among local communities. The risks associated with this study are minimal, and there are no known risks for participating in this research beyond being bored or fatigued. You will not be required to answer questions that you do not wish to answer. The steps that will be taken to protect your privacy are described below.

Compensation / Reimbursement

This study is entirely voluntary and there will be no compensation provided for your involvement. However, your participation in and contribution to this research is greatly appreciated.

How your information will be protected?

Your personal information and interview data will be protected in the following ways. The only people who will have access to personal and interview data collected in the study will be the MASc student and the supervisor and the co-supervisor. Your personal information will be used only for internal records and for the purposes of contacting you, if needed. Your participation in this study is confidential. This will be ensured by replacing your name with an alpha numeric code immediately following your participation in all the interview materials. For data analysis, this code will identify you, and your name will not appear in any analyses. This ensures that administrative data with identifying information such as your contact information is kept apart from interview data. All the electronic data will be stored on an encrypted USB, which will be stored in a locked file at Dalhousie University. Study data will be retained for five years after the completion of the study and disposed after. Administrative data (i.e. contact information and consent forms) will be permanently discarded within 15 days of the study withdrawal date. We will be very careful to only talk about group results so that no one will be identified. This means that you will not be identified in any way in our reports.

Figure 68: Consent form for sensitivity assessment page 2.

If You Decide to Stop Participating?

If you wish to stop participating in this study for any reason, you can do so at any time. You may also request to have any information you contributed to this study removed from it up until the researchers have completed a draft of the results of all questionnaires and sent a digital copy of the draft report to the interviewees for review and possible editing. After that time, it will become impossible for us to remove it because the results will already be analyzed. Each of the participants will have 5 working days to alter the material pertaining to them in the report. If participants choose to withdraw, all information that was provided will be destroyed within 15 days of the study withdrawal date.

How to Obtain Results?

This study is expected to be completed by June 2019. If you would like a summary of the results, please include your contact information at the end of the signature page, advising on the preferred method of receiving the results (email or mail). No individual results will be provided. The results may also become public in the form of a written report.

Questions?

Please contact the lead researcher (Dr. Ronald Pelot) at ronald.pelot@dal.ca or +1 (902) 494-6113, or the MASc student (Priscilla Einecke Schmitz) at pr761206@dal.ca or +1 (902) 809-3058, who can answer any questions, comments or concerns you have about the study, or your participation in it. You will be contacted if any new information comes up that may affect your decision to participate.

If you have any ethical concerns about your participation in this research, you may also contact Research Ethics, Dalhousie University at (902) 494-1462, or email: ethics@dal.ca (and reference REB file # 2019-4758).

Figure 69: Consent form for sensitivity assessment page 3.

Signature Page

I, ________________________ have read and understand the purpose of this study. I have been given the opportunity to discuss it and my questions have been answered to my satisfaction. I understand that I have been asked to answer a questionnaire in a spreadsheet format. I agree to take part in this study. I realize that my participation is voluntary and that I am free to withdraw from the study at any time, until the researchers have completed a draft of the results of all of the questionnaires and sent a copy of the draft report to the participants for review and possible editing.

_____________________ _____________________
Signature Date (dd/mm/y)

1. ☐ Yes, I would like to receive a summary of the study's results.
Please send them to me at this email address:

____
☐ No, I do not want to receive a summary of the study's results.

DALHOUSIE
UNIVERSITY

Figure 70: Consent form for sensitivity assessment page 4.

Appendix C

Sensitivity assessment - Questionnaire

SENSITIVITY ASSESSMENT

Factor	Description
Sensitivity	"The degree to which marine features respond to stresses which are deviations of environmental conditions beyond the expected range" (Zacharias, 2005).
Certainty	Confidence level of the value assigned by the expert to each sensitivity sub-factor. As argued by uncertaintity experts in the literature (Goerlandt & Reniers, 2016), it is necessary to consider uncertainty when assessing risk in order to account for potential bias, poor or unreliable evidence and so on.

*The questions for oil spill sensitivity sub-factors were retrieved from Hannah et al. (2007) and adapted when necessary.

OIL SPILL			
Sensitivity sub-factor	Question	Justification	Scoring guidance
Mechanical	To what extent does the direct contact with oil result in the mechanical impairment of structures that can impact energetics of this receptor (i.e. animal's ability to digest and absorb foods)?	Fouling of feeding structures by oil may reduce the ability of organisms to feed, degrading body condition and reproductive capacity, and increasing time spent feeding (Hannah et al., 2007, Reich et al. 2014).	Level of impact from contact with oil on this receptor in terms of mechanical impairment such as feeding.
Chemical	To what extent does the direct contact with oil result in severe, irreversible effects or death for this receptor?	Organisms that are more sensitive to toxic effects of oil are more likely to experience irreversible effects or death. (Hannah et al., 2007)	Level of impact from contact with oil on this receptor in terms of irreversible effects or death due to oil toxicity. Acute effects from direct contact include: the inability of animals to digest and absorb foods, reproductive failure, respiratory failure, lesions, hermorrhaging, neurological impairment, and mortality.
Others	To what extent does the oil spill reduce food availability of this receptor for possible continamation of invertebrates, fish and plankton (their prey)?	Cetaceans are in danger if they eat oiled prey. Bigg's (transient) killer whales can consume oil adhering to the bodies and fur of their mammalian meals, and ingestion of oil can cause serious long-term damage to internal organs (Hannah et al., 2007, Rosenberger et al., 2017)	Level of impact from contact with oil on this species in terms of reliability on prey that would most likely be oiled, therefore contaminating the marine mammals as well.

Figure 71: Questionnaire for sensitivity assessment page 1.

NOISE POLLUTION			
Sensitivity sub-factor	**Question**	**Justification**	**Scoring guidance**
Mechanical	To what extent can chronic or increasing ship noise can induce hearing loss on this receptor?	Noise has the potential to induce temporary hearing loss (combination of frequency and duration), also known as temporary threshold shift (TTS), if it is loud or long enough in duration. In general, the higher the sound level and/or longer the duration, the more likely TTS is to occur. If exposure is prolonged or repeated or even as a result of one very loud noise event, the hearing damage can become	Level of impact from ship noise on this species in terms of hearing impairment.
Behavioural	To what extent can chronic or increasing ship noise mask acoustic signals that are important for this receptor (i.e. foraging, predator avoidance, communication, etc)?	Sound plays an important role in the lives of marine mammals. All marine mammal species produce sound, and sound production has been associated with a variety of behaviours including those related to mating, rearing of young, social interaction, group cohesion, and feeding (Erbe et al., 2016)	Level of impact from ship noise on this species in terms of masking important acoustic signals, such as foraging, communication, etc.
Other	To what extent can chronic or increasing ship noise cause the marine mammals to abandon their natural habitat?	Displacement from critical feeding and breeding grounds has been documented in a number of marine mammal species exposed to noise (Weilgart, 2007)	Level of impact from ship noise on this species in terms of habitat avoidance or displacement.

Figure 72: Questionnaire for sensitivity assessment page 2.

Baseline scenario: When scoring the questionnaire below, please have in mind the baseline scenario for **Oil Spill:** worst case scenario, oil spill size between 1,000 to 10,000 m3, with the receptor in contact with the oily area, and similar to what Nevalainen et al. (2018) considered in her study, that the timespan considered here is the first two weeks after an accident, which accordingly to Boehm & Page (2007) is when the oil at the water's surface is likely to have maximum exposure potential. For **Noise pollution:** also worst case scenario, where the receptor is exposed to chronic ship noise, physically very close to the source noise (vessel type) for a reasonable amount of time. Please, consider a 1:1 ratio (1 vessel to 1 whale) when ranking sensitivity.				
Impact scoring: 0 - not at all 1 - low impact 2 - medium impact 3 - high impact	Certainty scoring: 0 - Not certain at all. 1 - Very little and/or no empirical work exists and/or the expert has no personal experience with this. 2 - Some empirical work exists and/or expert has some personal experience. 3 - Body of empirical work exists and/or the expert has direct personal experience. Study conducted on a related species in the same genus. 4 - Extensive empirical work exists and/or the expert has extensive personal experience. Empirical work exists for species in the same family.			
Sensitivity to oil spill				
Subfactor	**Question**	**Assigned impact score**	**Certainty**	**Justification**
Mechanical	To what extent does the direct contact with oil result in the mechanical impairment of structures that can impact energetics of this receptor (i.e. animal's ability to digest and absorb foods)?	0	0	
Chemical	To what extent does the direct contact with oil result in severe, irreversible effects or death for this receptor?	0	0	
Other	To what extent does the oil spill reduce food availability of this receptor for possible continamation of invertebrates, fish and plankton (their prey)?	0	0	
	TOTAL	0		
Sensitivity to noise pollution				
Subfactor	**Question**	**Assigned impact score**	**Certainty**	**Justification**
Mechanical	To what extent can chronic or increasing ship noise can induce hearing loss on this receptor?	0	0	
Behavioural	To what extent can chronic or increasing ship noise mask acoustic signals that are important for this receptor (i.e. foraging, predator avoidance, communication, etc)?	0	0	
Other	To what extent can chronic or increasing ship noise cause the marine mammals to abandon their natural habitat?	0	0	
	TOTAL	0		
Stressor	**Overall sensitivity value**			
1. Sensitivity to Oil	0			
2. Sensitivity to Noise	0			

Figure 73: Questionnaire for sensitivity assessment page 3.

Appendix D

MATLAB algorithm - Acoustic modelling

```
%%%% SSL, TL and RL
%Calculate SSL, TL and RL for season 1
%n_runs MC simulations
%
%
% Priscilla, 20-Jun-2019


clear, close all
freq=csvread('freq.csv',0,0,'A1..A11');
freq1 = freq.';
freqchoose = 1000;
a = 25;
distance =1:1:25;
distance=distance';
Grids1=readtable('SL_S1.csv'); % Read Source level calculated on excel from season 1;
u1 = unique(Grids1.id);
checkplotFlag = 1; %=0 no plots, =1 plots check TL plots

tic
%Assign SL values per grid cell for separate cell arrays
for k = 1:numel(u1)
    Grids_season1{k} = Grids1{Grids1.id==u1(k),:}; %Extract submatrices season 1 (per grid cell) from SL_PDF matrix
end

ii = find(freq1 == freqchoose); %ii variable is the column number of the freq we chose
if isempty(ii)
    disp('error')
    return
end
```

Figure 74: MATLAB part I - Calculate SL (Source Level), TL (Transmission Level) and RL (Received Level) from 1000 runs of MC (Monte Carlo) simulation.

```
RN = rand(1,1000); %Random Number


for RR = 1:length(RN)
    for jj = 1:length(Grids_season1)

        %%Random Source Level SSL
        SL_freqchoose{jj} = Grids_season1{jj}(:,ii);
        [n_SL{jj},bincenter_SL{jj}] = hist(SL_freqchoose{jj},10);
        N_SL{jj}=sum(n_SL{jj});
        dbin_SL{jj}=bincenter_SL{jj}(1,2)-bincenter_SL{jj}(1,1);
        PDF1_SL{jj}=n_SL{jj}/N_SL{jj}/dbin_SL{jj};
        PDF2_SL{jj}=PDF1_SL{jj}/trapz(bincenter_SL{jj},PDF1_SL{jj}); %normalization PDF SLs
        BCC_SL{jj} = cumsum(PDF2_SL{jj}); %CDF SL
        if RN(RR)<BCC_SL{jj}
            SSL_index{jj} = 1;
        else
            SSL_index{jj} = find(BCC_SL{jj}<=RN(RR),1,'last');
        end
        SSL(:,jj) = bincenter_SL{jj}(SSL_index{jj}); %Synthetic Source Level

        %%Random distance between whale and ship
        distance_cell{jj}=distance;
        PDF3{jj}(1:25,1)=1/length(distance); %uniform distribution distance from 0 to 25km
        BCC_d{jj} = cumsum(PDF3{jj}); %CDF distance
        if RN(RR)<BCC_d{jj}
            dist_index{jj} = 1;
        else
            dist_index{jj} = find(BCC_d{jj}<=RN(RR),1,'last');
        end
```

Figure 75: MATLAB part I - Calculate SL (Source Level), TL (Transmission Level) and RL (Received Level) from 1000 runs of MC (Monte Carlo) simulation.

```
        dist{jj} = distance_cell{jj}(dist_index{jj}); %Synthetic distance value
        Pd(:,jj) = (2*dist{jj}(1,1)*(-4*dist{jj}(1,1)/(a^3)+pi/(a^2)+dist{jj}(1,1)^2/(a^4)));

        %%Random TL
         TL(:,jj) =20*log10(Pd(:,jj)); %Transmission loss equation
         [n_TL(:,jj),bincenter_TL(:,jj)] = hist(TL(:,jj),10);
         N_TL(:,jj)=sum(n_TL(:,jj));
         dbin_TL(:,jj)=bincenter_TL(2,jj)-bincenter_TL(1,jj);
         PDF1_TL(:,jj)=n_TL(:,jj)/N_TL(:,jj)/dbin_TL(:,jj);
         PDF2_TL(:,jj)=PDF1_TL(:,jj)/trapz(bincenter_TL(:,jj),PDF1_TL(:,jj));
         BCC_TL(:,jj)=cumsum(PDF2_TL(:,jj));
         if RN(RR)<BCC_TL(:,jj)
             TL_index(:,jj) = 1;
         else
             TL_index(:,jj)=find(BCC_TL(:,jj)<=RN(RR),1,'last');
         end

         STL(:,jj)=bincenter_TL(TL_index(:,jj)); %Synthetic Transmission loss

         %%Random RL
         RL(:,jj) = SSL(:,jj) + STL(:,jj); %Received level equation
         RLmt =RL.';
    end

    SSL_MC_1(RR,:)=SSL;
    dist_MC_1(:,RR)=dist_index;
    RL_MC_1(:,RR)=RLmt;
    TL_MC_1(:,RR)=STL;

end
```

Figure 76: MATLAB part I - Calculate SL (Source Level), TL (Transmission Level) and RL (Received Level) from 1000 runs of MC (Monte Carlo) simulation.

```
% test code
%for jj = 1:length(Grids_season1)
%%Plot pdfs of SSL to check if matches with SL raw data
%[SSL_freqchoose_hist(:,jj),bincentersS(:,jj)] = hist(SSL_MC_1(:,jj),10);
%N_hist_tot1(:,jj)=sum(SSL_freqchoose_hist(:,jj));
%dbin1(:,jj)=bincentersS(2,jj)-bincentersS(1,jj);
%PDF_test(:,jj)=SSL_freqchoose_hist(:,jj)/N_hist_tot1(:,jj)/dbin1(:,jj);
%PDF_final(:,jj)=PDF_test(:,jj)/trapz(bincentersS(:,jj),PDF_test(:,jj));
%end


%%Plot pdfs of  TL generated by MC to check with TL raw data
%  [n_TL_MC(jj,:),bincenter_TL_MC(jj,:)] = hist(TL_MC_1(jj,:),10);
%  N_TL_MC(jj,:)=sum(n_TL_MC(jj,:));
%  dbin_TL_MC(jj,:)=bincenter_TL_MC(jj,2)-bincenter_TL_MC(jj,1);
%  PDF1_TL_MC(jj,:)=n_TL_MC(jj,:)/N_TL_MC(jj,:)/dbin_TL_MC(jj,:);
%  PDF2_TL_MC(jj,:)=PDF1_TL_MC(jj,:)/trapz(bincenter_TL_MC(jj,:),PDF1_TL_MC(jj,:));
%  end

% for kk = 1:length(Grids_season1)
%     if checkplotFlag == 1
%         figure(1),clf
%         title(['grid id = ',num2str(kk)])
%         xlabel('TL')
%         ylabel('pdf')
%         hold on
%
%         plot(bincenter_TL_MC(kk,:),PDF2_TL_MC(kk,:),'.-');
%
%         hold off
%         pause
%     end
% end
```

Figure 77: MATLAB part I - Calculate SL (Source Level), TL (Transmission Level) and RL (Received Level) from 1000 runs of MC (Monte Carlo) simulation.

```
save
odn = '/Users/priscilla/Desktop/projectnoise/MATLAB/outputdata/';
ofn = 'RL_season1.mat';
Comments = {'This code calculates SL, TL and RL for season 1';
    ['saved on ',date];
    'RL_MC_1: received levels [dB]'};
save([odn ofn],'RL_MC_1','u1','Comments')
toc
```

Figure 78: MATLAB part I - Calculate SL (Source Level), TL (Transmission Level) and RL (Received Level) from 1000 runs of MC (Monte Carlo) simulation.

```
%%%% PDF RL
%generate probability density function(pdf) for RL for each grid cell based on
%n_runs MC simulations
%
%
% Priscilla, 19-Jun-2019

clear, close all
checkplotFlag = 0; %=0 no plots, =1 plots

tic
md = '/Users/priscilla/Desktop/projectnoise/MATLAB/';

%%load RLs for season 1

sdn = 'outputdata/';
fn = 'RL_season1.mat';
load([md,sdn,fn])

%min_RL = min(RL_MC_1);

%test code
%for jj = 1:378
    %RL_MC_1(jj,:) = normrnd(60,10,[1,2000]);
%end
```

Figure 79: MATLAB code part II - generate probability density function(pdf) for RL (Received Level) for each grid cell based on Monte Carlo simulations.

```
for kk = 1:size(RL_MC_1,1)
    [n1(kk,:),bincenters1(kk,:)] = hist(RL_MC_1(kk,:),40:35:120);
    N_hist_tot(kk,:)=sum(n1(kk,:));
    dbin(kk)=bincenters1(kk,2)-bincenters1(kk,1);
    PDF1(kk,:)=n1(kk,:)/N_hist_tot(kk,:)/dbin(kk);
    PDF2(kk,:)=PDF1(kk,:)/trapz(bincenters1(kk,:),PDF1(kk,:));
    disp('Integral')
    disp(trapz(bincenters1(kk,:),PDF2(kk,:)));

    if checkplotFlag == 1
        figure(1),clf
        plot(bincenters1(kk,:),PDF2(kk,:),'o-')
        title(['kk = ',num2str(kk)])
         xlabel('bins')
         ylabel('pdf')
         pause
     end
end


%save
odn = '/Users/priscilla/Desktop/projectnoise/MATLAB/outputdata/';
ofn = 'PDF_RL.mat';
Comments = {'This code does bla bla';
    ['saved on ',date];
    'PDF1: PDF of received levels [units]'};
save([odn ofn],'PDF1','PDF2','u1','bincenters1','Comments')
toc
```

Figure 80: MATLAB code part II - generate probability density function(pdf) for RL (Received Level) for each grid cell based on Monte Carlo simulations.

```
%%%% P(SEL>AN)
%Calculate P(SEL>AN)
%
%
%
% Priscilla, 27-Jun-2019

clear, close all
checkplotFlag = 0; %=0 no plots, =1 plots
D = 13; %25km = 13 nautical miles
md = '/Users/priscilla/Desktop/projectnoise/MATLAB/';

tic

%%load p(an)
sdn_pan = 'rawdata/';
fn_pan = 'p(an)_1000hz.csv';

pan=csvread([md,sdn_pan,fn_pan]);

%%load SOG AIS
sdn = 'outputdata/';
fn = 'SOG_data.mat';

load([md,sdn,fn])

%%load RLs from season 1
sdn = 'outputdata/';
fn = 'RL_season1.mat';
```

Figure 81: MATLAB code part III - generate probability density function(pdf) for SEL (source exposure level) and AN (ambient noise) for each grid cell based on Monte Carlo simulations in order to calculate the probability of SEL be above AN.

```
load([md,sdn,fn])

%%ambient noise integral
an = pan(:,1);
prob = pan(:,2);
an_integral = trapz(an,prob);

SOG1 = table2array(SOG_data1); %convert SOG table to array for season 1
whales_prob = table2array(whales); %convert whales table to array
ship_pres = table2array(Ship_presence); %convert ship presence table to array

%probability whale presence for season 1
for k = 1:numel(u1)

    whales_index(k) = find(whales_prob(:,1) == u1(k));
    NW_1(k) = whales_prob(whales_index(k),3);
    Bel_1(k) = whales_prob(whales_index(k),5);
    Bow_1(k) = whales_prob(whales_index(k),8);

end

%probability ship presence for season 1
for k = 1:numel(u1)
    ship_index(k) = find(ship_pres(:,1) == u1(k));
    Ps_s1(k) = ship_pres(ship_index(k),2);
end

%calculate time dependent intensity TdB
for k = 1:numel(u1)
T_s1(k)=D/SOG1(k,2); %T in hours
TdB_s1(k)=10*log10(T_s1(k)/1);
end
```

Figure 82: MATLAB code part III - generate probability density function(pdf) for SEL (source exposure level) and AN (ambient noise) for each grid cell based on Monte Carlo simulations in order to calculate the probability of SEL be above AN.

```
%calculate SEL=RL+TdB
for w = 1:numel(u1)
SEL_MC_1(w,:)=RL_MC_1(w,:)+TdB_s1(w);
end

%PDF of SEL
for kk = 1:size(SEL_MC_1,1)
    [n1(kk,:),bin(kk,:)] = hist(SEL_MC_1(kk,:),40:35:130);
    N_hist_tot(kk,:)=sum(n1(kk,:));
    dbin(kk)=bin(kk,2)-bin(kk,1);
    PDF(kk,:)=n1(kk,:)/N_hist_tot(kk,:)/dbin(kk);
    PDF_2(kk,:)=PDF(kk,:)/trapz(bin(kk,:),PDF(kk,:));
    disp('Integral')
    disp(trapz(bin(kk,:),PDF_2(kk,:)));
end

%probability of P(SEL)>P(AN)-integral
for kk = 1:size(SEL_MC_1,1)
    sel = bin(kk,:);
    probrl = PDF_2(kk,:);
    sel_integral(kk) = trapz(sel,probrl);
    [x(kk),y(kk)] = find(bin(kk,:)>70,1,'first');
    diff(kk) = trapz(sel(y(kk):3),probrl(y(kk):3));
end
```

Figure 83: MATLAB code part III - generate probability density function(pdf) for SEL (source exposure level) and AN (ambient noise) for each grid cell based on Monte Carlo simulations in order to calculate the probability of SEL be above AN.

```
%%plot PDF of SEL and AN
for kk = 1:size(RL_MC_1,1)
if checkplotFlag ==  1
figure(1),clf
plot(bin(kk,:),PDF_2(kk,:),'o-')
title(['P(SEL>AN) for grid id = ',num2str(kk)])
xlabel('Sound exposure level and Ambient Noise in dB')
ylabel('Probability')
hold on
plot(pan(:,1),pan(:,2),'.-');
plot(bin(kk,y(kk)),PDF_2(kk,y(kk)),'r*');
plot(bin(kk,y(kk)),PDF_2(kk,y(kk)),'g*');
hold off
legend('P(SEL)','P(an)','max value','closest point');
pause
end
end

%risk score noise season 1
for j = 1:numel(u1)
risk_noise_nw_s1(j) = Ps_s1(j)*NW_1(j)*diff(j);
risk_noise_bel_s1(j) = Ps_s1(j)*Bel_1(j)*diff(j);
risk_noise_bw_s1(j) = Ps_s1(j)*Bow_1(j)*diff(j);
end

u1_s1 = u1.';
NW_m1 = NW_1.';
Bel_m1 = Bel_1.';
Bow_m1 = Bow_1.';
output_s1 = [u1_s1;risk_noise_nw_s1;risk_noise_bel_s1;risk_noise_bw_s1]
```

Figure 84: MATLAB code part III - generate probability density function(pdf) for SEL (source exposure level) and AN (ambient noise) for each grid cell based on Monte Carlo simulations in order to calculate the probability of SEL be above AN.

```
save
odn = '/Users/priscilla/Desktop/projectnoise/MATLAB/outputdata/';
ofn = 'p(sel)_p(an).mat';
Comments = {'This code calculates P(SEL)>P(AN)';
    ['saved on ',date];
    'P(SEL)>P(AN): Probability of whales hearing ships'};
save([odn ofn],'output_s1','Comments')
toc
```

Figure 85: MATLAB code part III - generate probability density function(pdf) for SEL (source exposure level) and AN (ambient noise) for each grid cell based on Monte Carlo simulations in order to calculate the probability of SEL be above AN.