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A general method to combine environmental and life-safety consequences of Arctic ship accidents

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ARTICLE INFO

ABSTRACT

Risk aggregation is the process of combining multiple individual risks to develop a better understanding of the overall risk on a system. Different risks can have different consequences and different units of measure. This study contributes to the process of risk aggregation by presenting a general method to combine multiple consequences posed by an Arctic ship accident. The method considers ecological and socio-economic consequences of a potential oil spill, and life-safety consequences of a potential ship evacuation. Existing models for each consequence type are adopted. Individual consequence types are monetized and combined to quantify total consequence cost for a given accident scenario. A framework is proposed to assign a qualitative rating for total consequence severity. The qualitative scales of the framework are established using the quantitative method. Total consequence severity is evaluated for different ship types and regions in the Canadian Arctic. Results indicate that Arctic ship accidents involving oil tankers in environmentally sensitive regions and cruise ships in regions associated with long response times are worst-case scenarios, with similar total consequence severity levels. Implications for safe Arctic shipping are that on the basis of total consequence severity, mitigating the potential consequence severity of Arctic cruise operations is of near equal priority to that of Arctic tanker operations. Evaluating total consequence severity of potential Arctic ship accidents provides decision-makers and risk analysts with a data-driven tool to integrate multidisciplinary knowledge for the assessment, management, and communication of Arctic shipping risks.

1. Introduction

Arctic maritime operations are complex socio-technical systems exposed to multiple risks (Browne et al., 2020; Kujala et al., 2019; Smith et al., 2018; Haimelin et al., 2017). A ship accident in the Arctic poses potential consequences to the vessel, crew and passengers, environment, local communities, and other Arctic stakeholders (Browne et al., 2020; Browne et al., 2021; The PEW Charitable Trusts, 2016; Arctic Council, 2009; Marchenko et al., 2018). Specific to environmental and life-safety consequences, an oil spill in Arctic waters poses the potential for severe ecological and socio-economic consequences (Afenyo et al., 2022; Helle et al., 2020), while a ship evacuation in Arctic waters poses the potential

for severe life-safety consequences to crew and passengers (Browne et al., 2021).

The holistic management of safe ship operations requires consideration of multiple risk perspectives, as there are competing interests among Arctic stakeholders with respect to the promotion of the Arctic maritime industry and the mitigation of associated risks. Some stakeholders favour increasing ship activity and development of Arctic regions in order to realize the associated economic benefits, while others advocate for protection of the Arctic environment and communities (Afenyo et al., 2022). Evaluating the total consequence severity of potential ship accidents in Arctic waters contributes to evidence-based decision-making for safe ship operations, Arctic maritime governance,

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emergency response planning, and environmental protection.

Risk aggregation is the process of summing multiple individual risks to gain a better understanding of the overall risk to a system. (Bjørnsen and Aven, 2019). Risk can be characterized as the combination of the consequences of an activity and the associated uncertainty (Aven et al., 2018). Aggregating risk characterizations refers to the aggregation of multiple individual risk characterizations (i.e. separate combinations of consequence and uncertainty). For the aggregation of risk characterizations, individual consequences are combined while the associated uncertainty is typically expressed as a single measure. The current study focuses on combining different consequences of Arctic ship accidents, thus contributing to the aggregation of risk characterizations.

The contribution of this paper is a general method to combine environmental and life-safety consequences posed by an Arctic ship accident. The method is presented in two forms. A quantitative method is presented in which the combined consequence severity is estimated as a total consequence cost. Following this, a framework is proposed to qualitatively rate total consequence severity. The total consequence severity of Arctic ship accidents is evaluated for different ship types and regions of the Canadian Arctic.

The quantitative method adopts existing models for ecological and socio-economic consequences of Arctic oil spills (WSP Canada, 2014), and life-safety consequence of Arctic ship evacuations (Browne et al., 2021). Different consequence types are combined through monetization and summing of individual consequence costs. The combined consequence severity is estimated as the total consequence cost for a given accident scenario.

To support the assessment, management, and communication of Arctic shipping risks, a framework to qualitatively rate total consequence severity is proposed. The framework uses predefined matrices to evaluate and combine qualitative categories for environmental (i.e. ecological and socio-economic) and life-safety consequence, based on ship type and geographic region. The qualitative categories of the framework are defined based on the quantitative method.

The study complements a previously proposed Arctic shipping operational risk management framework that incorporates consequences into the operational decision-making for ships navigating in polar regions (Browne et al., 2020). Modelling the associated uncertainty, causal factors (e.g. grounding, collision), or other consequence types (e.g. vessel damage, property damage to third parties) is out of scope for the current study.

The remainder of this section introduces the concept of risk aggregation, approaches for evaluating environmental consequences of oil spills and life-safety consequences of ship evacuations in Arctic waters, and the valuation of maritime oil spills and fatalities.

1.1. Risk aggregation

This section provides a review of approaches for risk aggregation, highlighting several Arctic maritime applications. The relation to integrated risk management is discussed.

Risk aggregation is a common practice used to gain an understanding of a more complete risk picture, improving risk management and communication (Bjørnsen and Aven, 2019; David, 2016). While risk aggregation as a concept is a common practice in risk management, multiple definitions and applications of risk aggregation exist in the literature. Discussions on the concept of risk aggregation and reviews of various ways in which it is defined and performed are provided by Bjørnsen and Aven (2019) and David (2016).

Bjørnsen and Aven (2019) distinguish between characterizing aggregate risks and aggregating risk characterizations. Characterizing aggregate risks refers to single measures for the consequence and uncertainty associated with the realization of multiple separate activities. The multiple separate activities are effectively treated as a single risk. Aggregating risk characterizations refers to the combining of individual measures of consequence for multiple separate activities. The

uncertainty associated with the multiple activities is expressed as a single measure. The strength of knowledge informing risk characterizations may also be considered in the aggregation process. The current study focuses on the combination of different consequence types.

One approach to combine different consequences is to monetize individual consequence types. WSP Canada (2014) combine socio-economic consequences of an oil spill in the Canadian Arctic through the summation of individual monetized consequence values. Leva et al. (2017) use monetization to combine different consequence types across business units of a company. The combined consequence severity supports prioritization of company-wide risk control options.

Several studies incorporate risk matrices in the risk aggregation process. Using a combination of risk matrices and Bayesian Networks (BN), the risks of damage and besetting for ships navigating in ice are aggregated. Individual risks are assessed using matrices (Zhang et al., 2020). Risk matrix information is transferred to conditional probability tables and the total aggregated risk is estimated through the BN.

Three methods to aggregate risk matrices and quantitatively express qualitative risk ratings are proposed by Bao et al. (2019): fuzzy sets, interval numbers, and probability density functions. The quantitative expressions are aggregated and then transformed back to discrete risk values.

While risk matrices are a popular means to categorize and rank risks (Anthony TonyCox, 2008), there is an inherent ambiguity associated with risk matrices (Leva et al., 2017; Bao et al., 2019; Anthony TonyCox, 2008). When qualitative categories of risk matrices are defined by an underlying quantitative relation, the qualitative and quantitative comparison of two risks may not align, e.g. one risk may receive a higher qualitative rating than a second risk, but is evaluated to have a lower quantitative value.

Integrated risk assessment and multi-risk assessment share similarities with risk aggregation, yet are distinct concepts. Integrated risk assessments and multi-risk assessments support the consolidation of risk information, but they do not provide structured methods to aggregate risk. An example of integrated risk management in Arctic shipping is the Integrated Arctic Corridors Framework (The PEW Charitable Trusts., 2016). The framework promotes safe Arctic shipping in Canada by defining safe shipping corridors through consideration of environmental features and Inuit rights. Outside of the maritime industry, the World Health Organization provides a general framework for integrated risk assessment for risks posed to humans, ecology, and natural resources from chemical exposures (World Health Organization, 2001). The European Commission provides guidance on multi-risk assessment for hazard interactions during disaster management (European Commission, 2010).

1.2. Environmental consequence of Arctic oil spills

This section provides an overview of environmental consequences of Arctic oil spills. Existing approaches for evaluating ecological and socio-economic consequences are introduced. Methods that combine different consequence types are highlighted.

The prevention of an oil spill, particularly in ice-covered waters, has been considered the highest priority for protection of the Arctic environment (Arctic Council, 2009). Environmental consequences of an oil spill include impacts to species and habitats (i.e. ecological consequences) (Helle et al., 2020; Nevalainen et al., 2017) and stakeholder use of the Arctic (i.e. socio-economic consequences) (The PEW Charitable Trusts., 2016; Arctic Council, 2009; Afenyo et al., 2022; WSP Canada, 2014). Evaluating the impact of an Arctic oil spill is challenging. The environmental consequences are complex and poorly understood (Helle et al., 2020) and there is no definite strategy for evaluation (Afenyo et al., 2022).

A probabilistic evaluation of socio-economic consequences of an oil spill in the Canadian Arctic is presented by Afenyo et al. (2022). The method combines a multi-period consequence model with Bayesian

Networks to evaluate cumulative effects over time. Indigenous socio-economic indicators specific to the Canadian Arctic are modelled. Multiple consequence types are combined by monetizing consequence severities and summing the costs.

Studies have focused on acute, short-term ecological impacts to individual species (Helle et al., 2020) and ecosystem functional groups (e.g. apex predators, bottom feeding mammals) (Nevalainen et al., 2017). A probabilistic method to quantify species-specific ecological consequences of an Arctic oil spill is presented by Helle et al. (2020). Consequence severity is assessed as the proportion of a given population that dies within two weeks of the spill. Nevalainen et al. (2017) propose an ecosystem food web based model. Consequence severity is assessed as the percentage decrease in population of an ecosystem functional group. These studies provide valuable information on ecological impacts of Arctic oil spills, but they do not provide a means to combined consequence severities for different species or functional groups.

Several studies propose the use of sensitivity as a proxy for ecological and socio-economic consequence severity (WSP Canada, 2014; Hauser et al., 2018; Santos et al., 2013; Dillon Consulting, 2017; Helle et al., 2016; WSP Canada, 2014; Det Norske Veritas, 2011). The conservation value of threatened species and habitats in the northern Baltic Sea is used as a proxy for ecological consequence severity of oil spills (Helle et al., 2016). Individual conservation values are combined by summation. The total ecological risk is the product of the probability for oil to be present and the combined conservation value. Santos et al. (Santos et al., 2013) estimate the vulnerability of a region to oil spills using ecological and socio-economic indicators. Individual indicator values are combined to estimate total vulnerability.

The methodologies discussed thus far support species- and region-specific evaluations. Several studies evaluate environmental consequence of oil spills on a more global scale. The concept of sensitivity as a proxy for consequence severity is often employed.

An Arctic Council report evaluates areas of heightened ecological significance across the entire Arctic (AMAP/CAFF/SDWG, 2013). The assessment considers the sensitivity of fauna to oil spills and ship disturbances. An attempt was made to establish areas of heightened cultural significance but was not completed due to a lack of data.

The environmental sensitivity and risk to oil spills for the Canadian Arctic is evaluated using an Environmental Sensitivity Index (ESI) (WSP Canada, 2014). The Canadian Arctic is partitioned into eighteen zones and an ESI is calculated for each zone. The ESI value captures ecological and socio-economic factors. Three indicators are calculated for physical sensitivity (e.g. data on shoreline type, ice coverage), biological resource (e.g. data on ecological and biological significant areas), and human-use resource (e.g. data on coastal population, tourism, freight tonnage). The ESI value is estimated by a weighted summation of the three indicator values. Similar analyses have been completed for non-Arctic Canadian waters (Dillon Consulting, 2017; WSP Canada, 2014). ESI values for the Canadian Arctic (WSP Canada, 2014) are adopted for the current study, representing the environmental (i.e. ecological and socio-economic) sensitivity of a region to an oil spill.

1.3. Life-safety consequence of Arctic ship evacuations

This section introduces definitions for life-safety risk and consequence severity in the maritime industry. An overview of studies supporting the evaluation of life-safety consequence of Arctic ship evacuations is provided.

The International Maritime Organization (IMO) revised guidelines for Formal Safety Assessment (FSA) (IMO, 2018) define life-safety risk as an area of risk concerning the level of harm to humans, considering illness, injury, and death. Life-safety consequence severity is typically expressed as an expected number of equivalent fatalities. Injuries are linked to fatalities using equivalence ratios: 10 minor injuries equates to 1 severe injury, and 10 severe injuries equates to 1 fatality.

Ship evacuations in Arctic waters expose crew and passengers to a number of challenges and the potential for loss of life. Remote regions and a lack of search and rescue (SAR) infrastructure can lead to increased emergency response times. Life-saving appliances may be inadequate to support survival for longer response times. The presence of sea ice can impede launch of survival craft. (Browne et al., 2021; Marchenko et al., 2018; Simões Ré and Veitch, 2008).

A number of studies investigate Arctic shipping risk based on historical accident data. Studies have analyzed data across the entire Arctic (Arctic Council, 2009; Allianz, 2020; Allianz, 2017; Fedi et al., 2018; Kum and Sahin, 2015), while other studies have focused on specific regions, e.g. Canada (Council of Canadian Academies, 2016; Kubat and Timco, 2003), Russia (Fedi et al., 2020; Machenko, 2012), and the Atlantic Arctic (Marchenko et al., 2018). Studies have also investigated factors influencing the potential for loss of life during Arctic ship evacuations. Factors include SAR capabilities and capacities (Marchenko et al., 2018; Ikonen, 2017; Schmied et al., 2017), performance of life-saving appliances (Power et al., 2016), and emergency response times (Kennedy et al., 2013; Piercey et al., 2019; Farrell et al., 2021). Response time estimates throughout the Canadian Arctic were proposed by Kennedy et al. (Kennedy et al., 2013). The SARex exercises were a large scale initiative evaluating procedures for escape, evacuation, rescue, and survival under Arctic conditions (Solberg et al., 2016; Solberg et al., 2017; Solberg and Gudmestad, 2019). These studies provide insight into accident frequencies and risk factors, but the data are insufficient to support an evaluation of life-safety consequence severity.

The SAFEDOR project evaluates the life-safety risk for different accident scenarios and ship types, but the study is not specific to Arctic shipping (IMO, 2007; IMO, 2008; IMO, 2008). Life-safety consequence severity is measured as an expected number of fatalities, estimated as a percentage of the total number of persons on board (POB).

Specific to Arctic maritime operations, Browne et al. (Browne et al., 2021) establish a life-safety consequence model for Arctic ship evacuations using expert knowledge. The consequence model consists of a qualitative conceptual framework of the factors influencing consequence severity, and quantified severities for a range of evacuation scenarios. Evacuation scenarios consider ship type, the number of POB, and combinations of response time, season, ice conditions, metocean conditions, and time available to evacuate. Response time is identified as the most significant factor influencing the consequence severity of an Arctic ship evacuation. Among ship types, the evacuation of high POB passenger vessels, e.g. cruise ships, pose a particularly high life-safety consequence severity. The current study adopts and combines the life-safety consequence severity model developed by Browne et al. (Browne et al., 2021) and the response time estimates established by Kennedy et al. (Kennedy et al., 2013).

1.4. Valuation of consequences

The valuation of maritime oil spills and fatalities are discussed in this section.

1.4.1. Valuation of maritime oil spills

The total cost of an oil spill is often separated into clean-up costs, environmental damage, and socio-economic costs (IMO, 2018; IMO, 2011; Skjong et al., 2005). At a more granular level, costs can be associated with asset damage, containment, clean-up, lost oil, lost income to businesses, lost consumer value, natural resource damage, and litigation for the party responsible for the spill as well as government and stakeholders impacted by the spill (Cohen, 2010). The cost of an oil spill is influenced by the type of oil, the location of the spill, characteristics of the region, spill volume, and the efficacy of response operations (Skjong et al., 2005). Despite the complexities of oil spills and the associated costs, cost estimates are often simplified to a function of spill volume (IMO, 2018; IMO, 2011; Skjong et al., 2005).

Average oil spill clean-up costs by region were published through the SAFEDOR project (Skjong et al., 2005). A significant regional variation

Table 1
Summary of existing models adopted for the current study.

| Model	Original source	Application
Spill volume class	Dillon (Dillon Consulting, 2017)	Ecological & socio-economic consequence
Environmental Sensitivity Index (ESI)	WSP (WSP Canada, 2014)	
Life-safety consequence severity index function	Browne et al. (Browne et al., 2021)	Life-safety consequence
Response time estimates	Kennedy et al. (Kennedy et al., 2013)	
Valuation of maritime oil spills & fatalities	IMO FSA (IMO, 2018)	Monetization
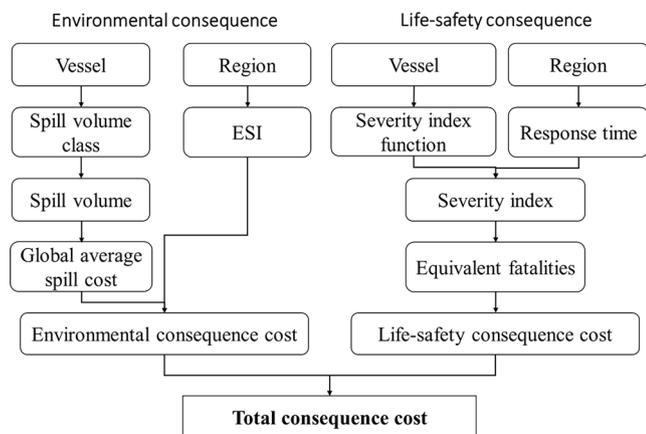
Fig. 1. Process for calculating total consequence cost of an Arctic ship accident scenario.

is observed, ranging from a minimum of 1,300 USD per tonne in the Middle East to a maximum of 33,300 USD per tonne in Asia. The global average is 15,900 USD per tonne, while the North American average is 24,000 USD per tonne.

Oil spill cost data from the IOPCF (IMO, 2011) and the SAFEDOR project (Skjong et al., 2005) suggest that environmental damage and socio-economic costs of a spill are approximately 1.5 times the clean-up cost, or 60% of the total spill cost. Based on the clean-up cost data from the SAFEDOR project, total spill cost, as a global average and for North America, is estimated at 39,750 and 60,000 USD per tonne, respectively.

Alternative methods for the valuation of Arctic oil spills are proposed in the research literature. The socio-economic impacts of an Arctic oil spill are estimated through summation of defined cost functions for environmental damage, economic impacts, and clean-up (Afenyo et al., 2019). Afenyo et al. (Afenyo et al., 2022) propose a multi-period model for the socio-economic cost of an oil spill over time in the Canadian Arctic. The model considers unit costs for socio-economic factors, including psychological distress and crime on a per capita basis, and the compensation amounts stipulated in indigenous lands claim agreements.

Contingent valuation studies assess the public's willingness to pay (WTP) for oil spill risk mitigation measures. Noring et al. (Noring et al., 2016) assess the value of ecosystem services (e.g. habitat, biodiversity, recreation) at risk to oil spills in the Norwegian Arctic. Carson et al. (2003) assess the WTP in the US to prevent another oil spill in the Arctic with the same spill volume as the 1989 Exxon Valdez accident. While WTP estimates provide an indication of the public's perception of the economic importance of risk reduction, they do not provide an estimate of total cost.

For the valuation of an Arctic oil spill, the current study adopts the IMO FSA estimate for total spill cost. The estimate is modified to reflect the increased sensitivity of Arctic regions. Full details are provided in Section 2.

1.4.2. Valuation of maritime fatalities

In risk management, the cost of a fatality is established for the purpose of evaluating cost-effectiveness of risk control options. A common measure is the cost of averting a fatality (CAF), also referred to as the value of a statistical life (VSL). The CAF is the ratio of the additional cost of a risk control option to the reduction in risk in terms of fatalities averted. CAF values have been established through contingent valuation studies, historical data on risk mitigating measures, and societal indicators, such as life quality indices (IMO, 2018; IMO, 2000).

A range of CAF values have been established for different countries, industries, and organizations. The SAFEDOR project provides a summary of such valuations (Skjong et al., 2005). In the US, the Federal Aviation Industry and the Department of Transportation suggest 3 million USD, the Occupational Safety and Health Administration suggests 3.5 million USD, and the Environmental Protection Agency suggests 6 million USD. Offshore energy companies adopt values as high as 9 million USD. In Canada, CAF estimates have ranged from 1 to 3 million USD.

Specific to the maritime industry, the IMO FSA guidelines adopt a CAF value of 3 million USD for use in cost-benefit analysis of risk control options (IMO, 2018). This value is considered appropriate when equivalent fatality estimates include the risk of illness and injury. As such, a CAF of 3 million USD is adopted as the cost of an Arctic maritime fatality for the current study.

2. Method

A general method to combine different consequences posed by Arctic ship accidents is presented in this section. The method is presented in two forms. A quantitative method estimates total consequence severity as a total consequence cost (Section 2.1). A framework is proposed to qualitatively rate total consequence severity (Section 2.2). The quantitative and qualitative methods are illustrated using two ship accident scenarios.

2.1. Quantitative method to estimate total consequence severity

Potential ecological and socio-economic consequences of an oil spill, and life-safety consequences of a ship evacuation, are combined to estimate total consequence severity. Individual consequence severities are evaluated, monetized, and summed to estimate the total consequence cost of an Arctic ship accident scenario.

Five existing models are adopted for the evaluation and monetization of consequence severity. Adopted models and their application in the current study are summarized in Table 1.

The process for calculating total consequence cost of an Arctic ship accident scenario is presented in Fig. 1. The process is described in the following sections.

2.1.1. Environmental consequence
The process for calculating environmental consequence cost for an oil spill in Arctic waters is depicted on the left-hand side of Fig. 1.

The environmental consequence model is based on the vessel and region of an Arctic ship accident scenario. The vessel is assigned a spill volume class which provides an indication of the expected spill volume. A global average spill cost is estimated as a function of spill volume. The environmental sensitivity of the region to oil is modelled using an ESI, which reflects ecological and socio-economic impacts. The environmental consequence cost is estimated as the product of global average spill cost and the ESI value.

2.1.1.1. Spill volume class.
Spill volume classes originally derived for the assessment of oil spill risks in Canadian waters (Dillon Consulting, 2017) are adopted for the current study. Spill volume class associates an expected spill volume range with typical ship types. Minimum and

Table 2
Spill volume classes (modified from the Transport Canada Area Risk Assessment (Dillon Consulting, 2017).

Spill volume class	Average spill volume (tonnes)	Typical ship type
1	14	Fishing, Recreation
2	81	Small commercial
3	512	Medium commercial
4	2,670	General purpose, Med. range tanker
5	8,900	Long range tanker, Panamax
6	20,025	Aframax
7	57,850	New Panamax, Suezmax
8	> 89,000	Very and Ultra Large Crude Carriers

Table 3
ESI ratings, sensitivity descriptions, and ESI values (modified from WSP (WSP Canada, 2014).

ESI	Relative sensitivity description	ESI value
1	Very low	1
2	Low	2
3	Medium	4
4	High	8
5	Very high	16

maximum expected oil spill volumes have been established through statistical analysis of ship accident data, considering, amongst other things, accident and spill occurrence frequencies and typical locations and capacities of fuel and cargo oil tanks.

Average oil spill volumes are adopted for the current study. Spill volume classes and average spill volumes for typical ship types are presented in Table 2.

2.1.1.2. Environmental sensitivity index. The ecological and socio-economic sensitivity of a region to oil is evaluated using an Environmental Sensitivity Index (ESI). The ESI method was originally developed for assessment of marine oil spill risk in Australia (Det Norske Veritas, 2011). The method was later adapted and applied to the Canadian Arctic (WSP Canada, 2014).

ESI values are estimated by a weighted summation of three indicator values: Physical Sensitivity Indicator (PSI), Biological Resource Indicator (BRI), and Human-use Resource Indicator (HRI).

PSI accounts for the difficulty of shoreline clean-up operations, considering, e.g. presence of ice along shorelines and shoreline length. BRI accounts for the sensitivity of natural resources to oil, considering, e.g. protected areas, species at risk, and biological functions of marine fauna. HRI accounts for commercial losses and impacts to social resources and human activities, considering, e.g. coastal population, tourism, and national and international freight tonnage.

The Canadian Arctic is partitioned into eighteen zones and ESI values established for each zone (WSP Canada, 2014). ESI values for the Canadian Arctic are evaluated using a five-point relative index, from 1 (very low) to 5 (very high). The eighteen zones and associated ESI ratings are presented in Appendix A.

The underlying quantitative scale for ESI value was not presented (WSP Canada, 2014). For the purpose of this study, the ESI value is assumed to follow a geometric progression, as per Table 3.

Justification for the assumption of a geometric progression is that the Transport Canada Area Risk Assessment established a similar index following the original ESI method (Dillon Consulting, 2017; Det Norske Veritas, 2011). The index is referred to as a Consequence of Exposure (COE) and estimates the sensitivity of non-Arctic Canadian waters to oil. The five-point COE index follows a geometric progression.
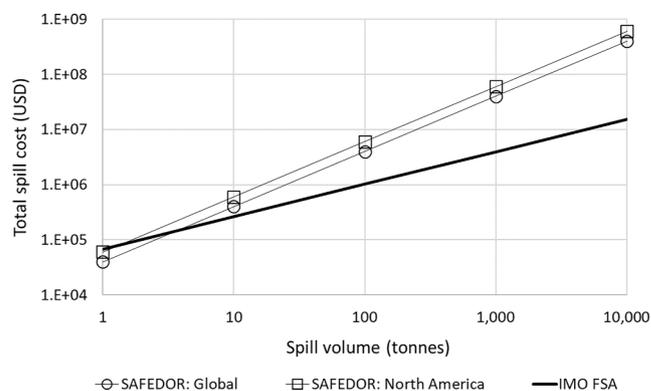
Fig. 2. Comparison of IMO FSA (IMO, 2018) and SAFEDOR (Skjong et al., 2005) total spill cost estimates.

Table 4
Life-safety consequence severity index (originally presented by Browne et al. (Browne et al., 2021), modified from the IMO FSA guidelines (IMO, 2018).

Severity index	Severity	Effects on human safety	Equivalent fatalities
1	Minor	Single or minor injuries	0.01
2	Severe	Multiple or severe injuries	0.1
3	Significant	Single fatality or multiple severe injuries	1
4	Catastrophic	Multiple fatalities	10
5	Disastrous	Large number of fatalities	100

2.1.1.3. Environmental consequence cost. Environmental consequence severity of an oil spill is estimated by an environmental consequence cost. Equations to estimate total spill cost as functions of spill volume are proposed in the literature. Estimates provided in the IMO FSA guidelines (IMO, 2018) and the SAFEDOR project (Skjong et al., 2005) are plotted in Fig. 2. The IMO FSA total spill cost function models a decrease in cost per tonne with increasing spill volume (i.e. the slope of total spill cost as a function of spill volume on the log–log plot is less than 1). The SAFEDOR project models a linear relationship between spill volume and cost (i.e. the slope on the log–log plot is equal to 1). This explains the increasing discrepancy between the estimates with increasing spill volume.

The total cost of an oil spill from ships is provided in the IMO FSA guidelines (IMO, 2018) and is adopted for the current study (Eq. (1)). The total spill cost reflects clean-up operations, property damage, economic losses, environmental damage, and legal costs (IMO, 2011). The estimate is a global average based on consolidated data from the International Oil Pollution Compensation Fund (IOPCF), the US, and Norway.

$$global\ average\ spill\ cost = 67,275V^{0.5893} \tag{1}$$

where V is spill volume in tonnes, and spill cost is in US dollars (USD).

To account for the sensitivity of Arctic regions, the global average spill cost is multiplied by the regional ESI value (Eq. (2)). Costs are in USD.

$$environmental\ consequence\ cost = global\ average\ spill\ cost \times ESI\ value \tag{2}$$

2.1.2. Life-safety consequence

The process for calculating life-safety consequence cost for a ship evacuation in Arctic waters is depicted on the right-hand side of Fig. 1.

The life-safety consequence model is based on the vessel and region of an Arctic ship accident scenario. The vessel has an associated life-safety consequence severity index function. An expected response time for the region is estimated. The severity index is calculated as a function of response time, and equates to an expected number of equivalent

Table 5
Average life-safety consequence severity index values for different response times (modified from Browne et al. (Browne et al., 2021).

Ship type	POB	Response time (hrs)			
		12	24	48	120
Fishing	10	1.8	2.1	2.9	3.4
Pleasure	10	1.6	2.1	2.7	3.3
Cargo	25	1.5	1.9	2.6	3.4
Passenger	250	1.9	2.4	3.1	3.9
Passenger	1000	2.6	2.9	3.6	4.4

Table 6
Severity index functions for defined ship types and POB.

Ship type	POB	Severity index function	R^2	
Fishing	10	$SI = 0.72\ln(t) - 0.04$	0.98	Eq. 3
Pleasure	10	$SI = 0.74\ln(t) - 0.21$	0.99	Eq. 4
Cargo	25	$SI = 0.86\ln(t) - 0.74$	0.99	Eq. 5
Passenger	250	$SI = 0.86\ln(t) - 0.26$	0.99	Eq. 6
Passenger	1000	$SI = 0.80\ln(t) + 0.51$	0.98	Eq. 7

Table 7
Average response time estimates by location (modified from Kennedy et al. (Kennedy et al., 2013).

Location	Lat.	Long.	Average response time (hrs)	
			Air asset	Marine asset
Amundsen Gulf	70.79	−125.51	20.5	89.5
Coronation Gulf	68.12	−112.63	19.0	44.5
Viscount Melville Sound	74.28	−102.63	32.5	31.0
Bathurst Island (North)	77.12	−98.53	34.5	144.5
Greely Fjord	80.56	−81.14	38.0	142.5
Lancaster Sound	74.10	−80.64	23.5	19.0
Foxe Basin	67.11	−78.41	21.5	88.0
Davis Strait	68.77	−65.08	19.5	33.5

fatalities. The life-safety consequence cost is estimated based on the number of equivalent fatalities and the CAF.

2.1.2.1. Severity index function. A five-point index for life-safety consequence severity is defined by the IMO (Table 4). Severity indices correspond to orders of magnitude of equivalent fatalities.

Life-safety consequence severity index functions for different ship types are established based on the consequence model developed by Browne et al. (Browne et al., 2021). Arctic shipping experts rated consequence severity for Arctic ship evacuation scenarios using the five-point index defined in Table 4. Average consequence severity index values (decimal values) were estimated as the mean of the expert ratings.

Response time was identified as having the greatest influence on consequence severity. Four evacuation scenarios tested the effect of response time on consequence severity. Selected response times were 12, 24, 48, and 120 h. All other evacuation scenario factors were held constant: summer, sea ice present, calm metocean conditions, and a controlled evacuation (i.e. time available for evacuees to don PPE and board and launch survival crafts).

Average consequence severity index values for five ship types and POB for the four response times are presented in Table 5.

For the current study, severity index functions for each ship type are established through regression analysis with the data in Table 5. The equations estimate life-safety consequence severity index value *SI* as a function of response time *t*. Severity index functions (Eq. 3 to 7) with coefficients of determination R^2 are presented in Table 6.

2.1.2.2. Response time. Response time estimates established by

Kennedy et al. (Kennedy et al., 2013) are adopted for the current study. Response times for eight locations throughout the Canadian Arctic are estimated through an expert knowledge elicitation study. Response time estimates assume a ship evacuation with 18 POB in the summer and all POB successfully evacuate in survival craft.

Two response time estimates are established for each location, assuming an emergency response with 1) an air-based SAR asset (i.e. a helicopter), and 2) a marine-based SAR asset (i.e. a vessel). Minimum and maximum response times (i.e. best- and worst-case scenarios) for each location and SAR asset scenario were estimated.

Average response times are adopted for the current study. Average response times for each location and SAR asset scenario are presented in Table 7.

Response time estimates assume an evacuation of 18 POB, which is the rescue capacity of a Cormorant helicopter. A marine-based SAR asset is assumed to have a much greater capacity (Kennedy et al., 2013).

For the purpose of this study, if the number of evacuees exceeds the capacity of a single SAR asset, deployment of multiple assets is assumed. It is acknowledged that the evacuation of a high POB passenger vessel may exceed the combined capacity of multiple SAR assets. In these scenarios, multiple trips between the accident location and a safe port would be required to rescue all evacuees.

Estimating the number and combination of SAR assets that would be deployed for a given evacuation scenario is beyond the scope of the current study. Piercey et al. (Piercey et al., 2019) provide a model to estimate response time considering SAR capacity and the number of evacuees.

For low POB evacuations (i.e. fishing vessel, pleasure craft, and cargo vessel), the minimum average response time between air- and marine-based estimates is used for the calculation of life-safety consequence severity. For high POB passenger vessel evacuations, in which the number of evacuees exceeds the capacity of an air-based asset, marine-based response time estimates are used.

2.1.2.3. Life-safety consequence cost. Life-safety consequence severity of a ship evacuation is estimated by a life-safety consequence cost. The number of equivalent fatalities is estimated based on the logarithmic relation between the severity index *SI* and the order of magnitude of equivalent fatalities defined in Table 1 (Eq. (8)).

$$equivalent\ fatalities = 10^{3-SI} \qquad (8)$$

Life-safety consequence cost is estimated by multiplying the number of equivalent fatalities by the CAF (Eq. (9)). A CAF of 3 million USD is adopted for the current study as it is recommended by the IMO for use in maritime industry risk assessments for cost-benefit analysis of risk control options (IMO, 2018). The CAF value is used for both crew and passenger fatalities. It is acknowledged that while the IMO FSA guidelines (IMO, 2018) and associated studies (IMO, 2007; IMO, 2008; IMO, 2008; Skjong et al., 2005) distinguish between crew and passenger life-safety risk in terms of acceptable risk tolerance thresholds (i.e. likelihood of occurrence), the same CAF value is applied to both crew and passengers.

$$life\text{-}safety\ consequence\ cost = equivalent\ fatalities \times CAF \qquad (9)$$

2.1.3. Total consequence cost
The combined consequence severity of a ship accident scenario is estimated by a total consequence cost. Total consequence cost is estimated by summation of the environmental and life-safety consequence costs (Eq. (10)).

$$\begin{aligned} total\ consequence\ cost = &\ environmental\ consequence\ cost \\ &+ life\text{-}safety\ consequence\ cost \end{aligned} \qquad (10)$$

2.1.4. Illustrative examples
Two ship accident scenarios are used to illustrate the quantitative

Table 8
Quantitative results for illustrative ship accident scenarios.

| Ship type	Cruise ship	Oil tanker
POB	1000	25
Region	Bathurst Is. (North)	Lancaster Sound
Spill volume class	4	5
Average oil spill volume (tonnes)	2,670	8,900
Global average spill cost (million USD)	7	14
ESI	1	4
ESI value	1	8
Environmental spill cost (million USD)	**7.0**	**114.4**
Response time	144.5	19
Severity index value	4.5	1.8
Equivalent fatalities	32.4	0.1
Life-safety consequence cost (million USD)	**97.2**	**0.2**
Total consequence cost (million USD)	**104.3**	**114.6**
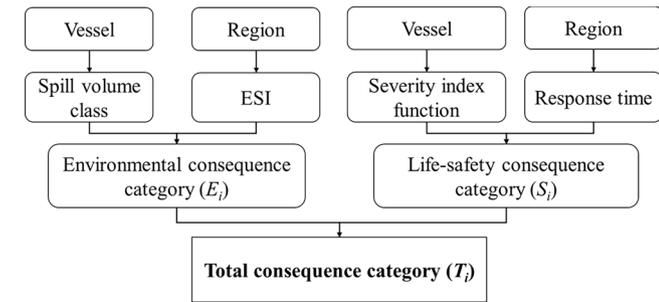
Fig. 3. Framework for evaluating total consequence category.

Table 9
Spill volume class with minimum and maximum global average spill cost.

Spill volume class	Global average spill cost (million USD)	
	Min	Max
1	–	0.5
2	0.5	1.2
3	1.2	3.7
4	3.7	9.5
5	9.5	18.2
6	18.2	27.3
7	27.3	55.5
8	55.5	> 55.5

method: a cruise ship with 1000 POB in Bathurst Island (North), and an oil tanker with 25 POB in Lancaster Sound (Table 8).

The cruise ship is assigned spill volume class 4, with an average spill volume estimated at 2,670 tonnes. The global average spill cost, as a function of spill volume, is 7 million USD. The ESI for Bathurst Island (North) is 1 (Very Low), with an associated ESI value of 1. The environmental consequence cost is equal to the global average spill cost.

The life-safety consequence severity index function for a cruise ship with 1000 POB is presented in Eq. 7. A marine-based SAR response is assumed for high POB passenger vessels. The average marine-based response time for Bathurst Island (North) is 144.5 h. The severity index value SI is estimated at 4.5, corresponding to 32.4 equivalent fatalities. Multiplying by the CAF (3 million USD), the life-safety consequence cost is estimated at 97 million USD.

The total consequence cost for a ship accident scenario with a 1000 POB cruise ship in Bathurst Island (North) is 104 million USD.

The oil tanker is assigned spill volume class 5, with an average spill volume of 8,900 tonnes. The global average spill cost is 14 million USD. The ESI for Lancaster Sound is 4, with an associated ESI value of 8. Multiplying the global average spill cost by the ESI value, the

environmental consequence cost is 114 million USD.

For life-safety consequence modelling, the oil tanker is equivalent to a cargo vessel, and the severity index function is presented in Eq. 5. The minimum response time in Lancaster Sound is associated with a marine-based SAR response, at 19 h. The severity index value is estimated at 1.8, corresponding to 0.1 equivalent fatalities. Multiplying by the CAF, the life-safety consequence cost is estimated at 0.2 million USD.

The total consequence cost for a ship accident scenario with a 25 POB oil tanker in Lancaster Sound is 115 million USD.

The cruise ship in Bathurst Island (North) poses a high life-safety consequence severity and a low environmental consequence severity. In contrast, the oil tanker in Lancaster Sound is dominated by a high environmental consequence severity, with a very low life-safety consequence severity. However, modelling the combined environmental and life-safety consequence demonstrates that the two vessels pose similar total consequence severities.

2.2. Qualitative framework to rate total consequence severity

In this section, a framework is proposed to qualitatively rate the total consequence severity of an Arctic ship accident scenario. The framework consists of matrices used to rate and combine individual consequence categories. The qualitative scales of the matrices are defined based on the quantitative method.

A total consequence category is rated based on four factors: vessel spill volume class, regional ESI, vessel life-safety consequence severity index function, and regional response time estimate.

Spill volume class and ESI define the environmental consequence category. The life-safety consequence severity index function and response time define life-safety consequence category. The environmental and life-safety consequence categories define the total consequence category. The framework for evaluating the total consequence category is presented in Fig. 3.

2.2.1. Environmental consequence category

The environmental consequence category E_i for a ship accident scenario is determined by the vessel spill volume class and regional ESI.

Each spill volume class is defined by a minimum and maximum expected spill volume (Dillon Consulting, 2017). The associated range for global average spill cost is calculated using Eq. (1) and presented in Table 9.

Multiplying by ESI value, the range for potential environmental consequence cost is determined for each combination of spill volume class and ESI.

For example, consider spill volume class 2 and ESI 4. The spill volume range is 27 to 134 tonnes, the global average spill cost range is 0.5 to 1.2 million USD, and multiplying by an ESI value of 8, the environmental consequence cost range is 3.7 to 9.6 million USD.

An environmental consequence cost matrix is established with vessel spill volume on the horizontal axis and ESI on the vertical axis (Fig. 4). The value in each cell of the matrix is the maximum potential environmental consequence cost for the associated combination of spill volume class and ESI.

The qualitative environmental consequence category C_i is rated on a five-point index, based on the maximum potential environmental consequence cost for an accident scenario (i.e. spill volume class and ESI). Environmental consequence categories, severity descriptions, and cost ranges are defined in Table 10.

The environmental consequence cost matrix is converted into a qualitative environmental consequence category matrix (Fig. 5) using the environmental consequence category cost ranges. The environmental consequence category matrix allows for the qualitative rating of environmental consequence severity based on spill volume class and ESI.

Again, consider spill volume class 2 and ESI 4. The environmental consequence category is rated E2 (Low). E2 corresponds to a cost range of 5 to 20 million USD, which captures the maximum potential

Environmental consequence cost (million USD)

ESI								
5	7.5	19.3	58.9	152.0	290.5	437.0	888.5	≥ 888.5
4	3.7	9.6	29.4	76.0	145.2	218.5	444.2	≥ 444.2
3	1.9	4.8	14.7	38.0	72.6	109.3	222.1	≥ 222.1
2	0.9	2.4	7.4	19.0	36.3	54.6	111.1	≥ 111.1
1	0.5	1.2	3.7	9.5	18.2	27.3	55.5	≥ 55.5
	1	2	3	4	5	6	7	8

Spill volume class

Fig. 4. Environmental consequence cost matrix.

Table 10
Environmental consequence categories and cost ranges.

Environmental consequence category (E_i)	Severity	Environmental consequence cost (million USD)	
		Min	Max
E1	Very low	–	5
E2	Low	5	20
E3	Medium	20	80
E4	High	80	320
E5	Very high	320	≥ 320

environmental consequence cost estimate of 9.6 million USD.

2.2.2. Life-safety consequence category

The life-safety consequence category S_i for a ship accident scenario is determined by the vessel's severity index function and the regional response time estimate.

Each life-safety consequence severity index is associated with an order of magnitude of equivalent fatalities. For the purpose of this study, the order of magnitude is assumed to correspond to a range of potential fatalities. Multiplying by the CAF, the range for life-safety consequence cost is determined.

For example, life-safety consequence category S2 has an order of magnitude of 1, corresponding to an equivalent fatality range of 1 to 9. Multiplying by the CAF, the consequence cost range is 3 to 27 million USD. To ensure continuity between the consequence cost ranges, the upper limit of the cost range is treated as 30 million USD.

Life-safety consequence categories, orders of magnitude of equivalent fatalities, and consequence cost ranges are presented in Table 11.

Note that under the quantitative method, the life-safety consequence severity index value is treated as a continuous variable, whereas the qualitative consequence categories are discrete. A calculated severity index value is round down to determine the consequence category, e.g. a severity index value of 3.9 corresponds to consequence category S3.

2.2.3. Total consequence category

The total consequence category T_i for a ship accident scenario is determined by the environmental and life-safety consequence categories.

Each environmental and life-safety consequence category has a range of potential consequence costs. The total consequence cost range for a combination of environmental and life-safety consequence categories is determined by summation of the respective minimum and maximum cost values.

For example, consider environmental and life-safety consequence categories of E2 and S4. The environmental consequence cost range is 5 to 20 million USD, the life-safety consequence cost range is 30 to 300 million USD, and by summation, the total consequence cost range is 35 to 320 million USD.

A total consequence cost matrix is established with environmental

Table 11
Life-safety consequence categories and cost ranges.

Life-safety consequence category	Severity	Equivalent fatalities (Order of magnitude)	Life-safety consequence cost (million USD)	
			Min	Max
S1	Minor	0.01	–	0.3
S2	Severe	0.1	0.3	3
S3	Significant	1	3	30
S4	Catastrophic	10	30	300
S5	Disastrous	100	300	3,000

Environmental consequence category

ESI								
5	E2	E2	E3	E4	E4	E5	E5	E5
4	E1	E2	E3	E3	E4	E4	E5	E5
3	E1	E1	E2	E3	E3	E4	E4	E5
2	E1	E1	E2	E2	E3	E3	E4	E4
1	E1	E1	E1	E2	E2	E3	E3	E4
	1	2	3	4	5	6	7	8

Spill volume class

Fig. 5. Environmental consequence category matrix.

Total consequence cost (million USD)

Life-safety consequence category	E1	E2	E3	E4	E5
S5	3005	3020	3080	3320	≥ 620
S4	305	320	380	620	≥ 350
S3	35	50	110	350	≥ 323
S2	8	23	83	323	≥ 320.3
S1	5.3	20.3	80.3	320.3	≥ 320

Environmental consequence category

Fig. 6. Total consequence cost matrix.

Table 12
Total consequence categories and cost ranges.

Total consequence category	Severity	Total consequence cost (million USD)	
		Min	Max
T1	Very low	–	<6
T2	Low	6	< 30
T3	Medium	30	< 150
T4	High	150	< 750
T5	Very high	750	≥ 750

consequence category on the horizontal axis and life-safety consequence category on the vertical axis (Fig. 6). The value in each cell of the matrix is the maximum potential total consequence cost for the associated combination of environmental and life-safety consequence categories.

The qualitative total consequence category T_i is rated on a five-point index, based on the maximum potential total consequence cost for an accident scenario (i.e. combination of environmental and life-safety consequence categories). Total consequence categories, severity descriptions, and cost ranges are defined in Table 12.

The total consequence cost matrix is converted into a qualitative total consequence category matrix (Fig. 7) using the total consequence category cost ranges. The total consequence category matrix allows for the qualitative rating of total consequence severity based on the environmental and life-safety consequence categories.

Again, consider environmental and life-safety consequence categories E2 and S4, respectively. The total consequence category is rated T4 (High). T4 corresponds to a cost range of 150 to 750 million USD, which captures the maximum potential total consequence cost estimate of 320 million USD.

2.2.4. Illustrative examples

The same ship accident scenarios are used to illustrate the qualitative framework: a cruise ship with 1000 POB in Bathurst Island (North), and an oil tanker with 25 POB in Lancaster Sound. The two scenarios are evaluated and compared in Table 13.

The cruise ship is assigned spill volume class 4 and the ESI for Bathurst Island (North) is 1. The associated environmental consequence category is E2 (Low). A cruise ship with 1000 POB and a response time of 144.5 h receives a severity index value of 4.5, corresponding to life-safety consequence category S4 (Catastrophic). The associated total consequence category is T4 (High).

The oil tanker is assigned spill volume class 5 and the ESI for Lancaster Sound is 4. The associated environmental consequence category is E4 (High). The life-safety consequence severity index value for a cargo vessel with 25 POB and a response time of 19 h is 1.8, corresponding to the life-safety consequence category S1 (Minor). The associated total consequence category is T4 (High).

Similar results are obtained with the qualitative framework as with

Table 13
Qualitative ratings for illustrative ship accident scenarios.

Ship type	Cruise ship	Oil tanker
POB	1000	25
Region	Bathurst Is. (North)	Lancaster Sound
Spill volume class	4	5
ESI	1	4
Environmental consequence category E_i	**E2**	**E4**
Response time	144.5	19.0
Severity index value	4.5	1.8
Life-safety consequence category S_i	**S4**	**S1**
Total consequence category T_i	**T4**	**T4**

Total consequence category

Life-safety consequence category	E1	E2	E3	E4	E5
S5	T5	T5	T5	T5	T5
S4	T4	T4	T4	T4	T5
S3	T3	T3	T3	T4	T5
S2	T2	T2	T3	T4	T5
S1	T1	T2	T3	T4	T5

Environmental consequence category

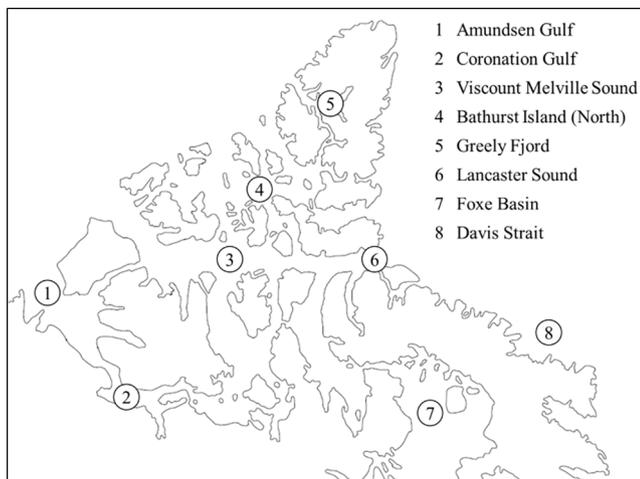**Fig. 7.** Total consequence category matrix.

Fig. 8. Canadian Arctic locations evaluated for total consequence severity (map modified from Natural Resources Canada ("Reference maps," Natural Resources Canada, Government of Canada website, 2007).

the quantitative method. The cruise ship in Bathurst Island (North) poses a potential catastrophic life-safety consequence severity and a low environmental consequence severity. The oil tanker poses a potential high environmental consequence severity and a minor life-safety consequence severity. Modelling the combined environmental and life-safety consequence demonstrates that both vessels pose the potential for high total consequence severities.

3. Results

Results are presented for six combinations of ship type and POB at eight geographic locations throughout the Canadian Arctic. Thus, forty-eight accident scenarios are evaluated in total.

Combinations of ship type and POB correspond to those evaluated for life-safety consequence severity by Browne et al. (Browne et al., 2021) (see Table 5 and Table 6). For life-safety consequence, the bulk carrier and oil tanker are modelled as cargo vessels. Geographic locations correspond to those evaluated for response time by Kennedy et al. (Kennedy et al., 2013) (see Table 7). Geographic locations are mapped in Fig. 8.

Results for the quantitative method are presented in Section 3.1.

Results for the qualitative framework are presented in Section 3.2.

3.1. Quantitative method to estimate total consequence severity

Total consequence costs are plotted in Fig. 9. Locations are on the horizontal axis with the six ship types plotted for each location. Detailed quantitative results are tabulated in Appendix B.

The highest total consequence cost scenarios are for the oil tanker with 25 POB in Coronation Gulf and Lancaster Sound, both estimated at 114.56 million USD. The next highest total consequence scenarios are for the 1000 POB passenger vessel in Greely Fjord and Bathurst Island (North), at 108.83 and 104.27 million USD, respectively.

Of the locations considered in the scenarios, Viscount Melville Sound is the location with the lowest average (of the six ship types) total consequence cost.

Among ship types, the fishing vessel and pleasure craft, each with 10 POB, are associated with the lowest total consequence cost estimates at all locations, ranging from 0.65 to 2.85 million USD.

The corresponding environmental and life-safety consequence costs are plotted in Fig. 10 and Fig. 11, respectively.

Environmental consequence cost is the predominant contributor to total consequence cost for the oil tanker and bulk carrier at all locations. Environmental consequence cost is determined, in part, by the modelled spill volume class and associated average spill volume. The oil tanker is modelled with spill volume class 5; the bulk carrier is modelled with spill volume class 4. These are the two highest spill volume classes modelled in the current study, and are thus associated with the highest environmental consequence cost at each location.

The 1000 POB passenger vessel is also modelled with spill volume class 4, resulting in the same environmental consequence cost estimates as the bulk carrier. However, the 1000 POB passenger vessel is associated with high life-safety consequence costs, resulting in total consequence costs above that of the bulk carrier. Similarly, but to a lesser extent, the total consequence costs for 250 POB passenger vessel are comprised of appreciable environmental and life-safety consequence costs.

Aside from the passenger vessels, all other ship types are estimated to have relatively low life-safety consequence costs at all locations, ranging from 0.19 to 1.18 million USD.

3.2. Qualitative framework to estimate total consequence severity

Results using the qualitative framework are presented in Tables 14-
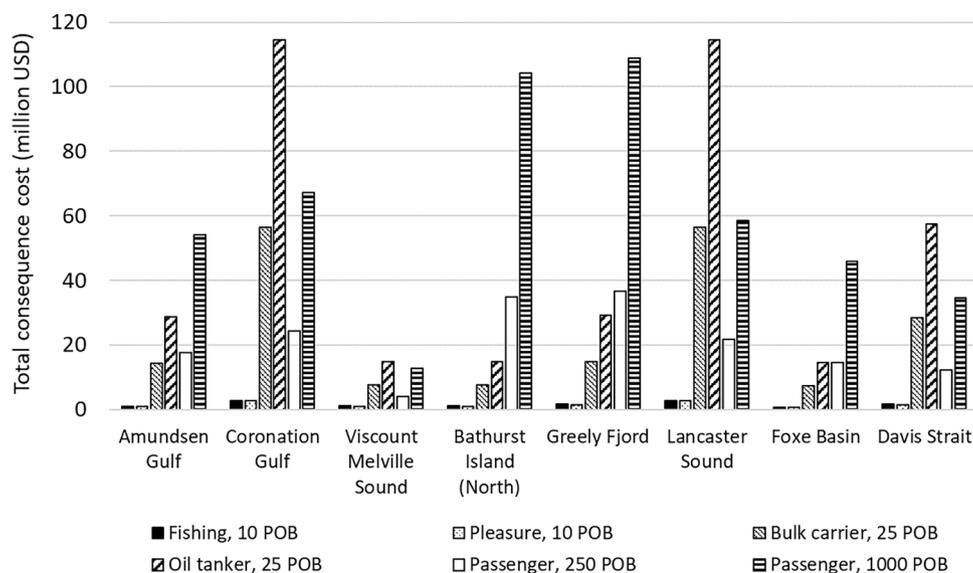
Fig. 9. Total consequence cost by location for different ship types.
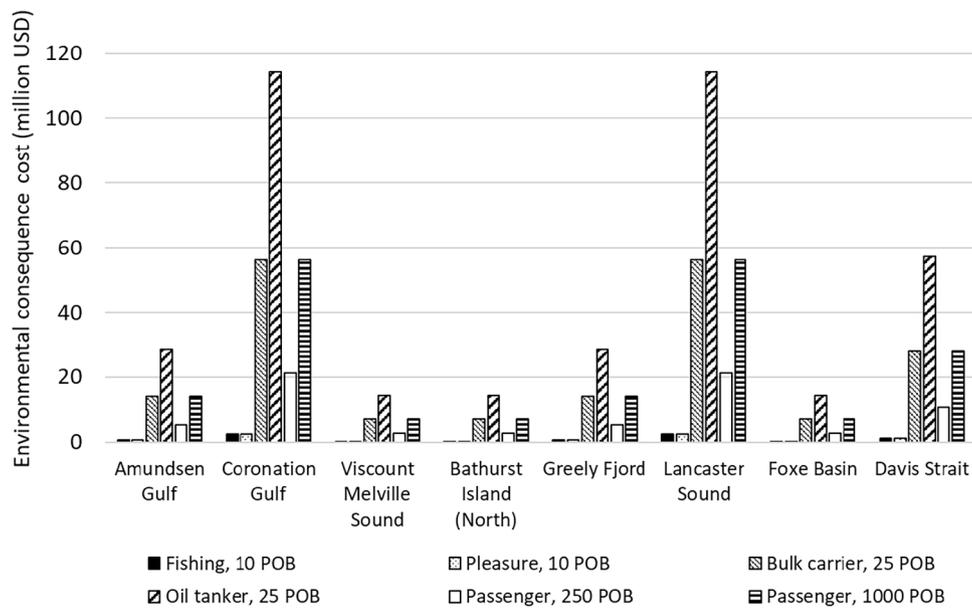
Fig. 10. Environmental consequence cost by location for different ship types.
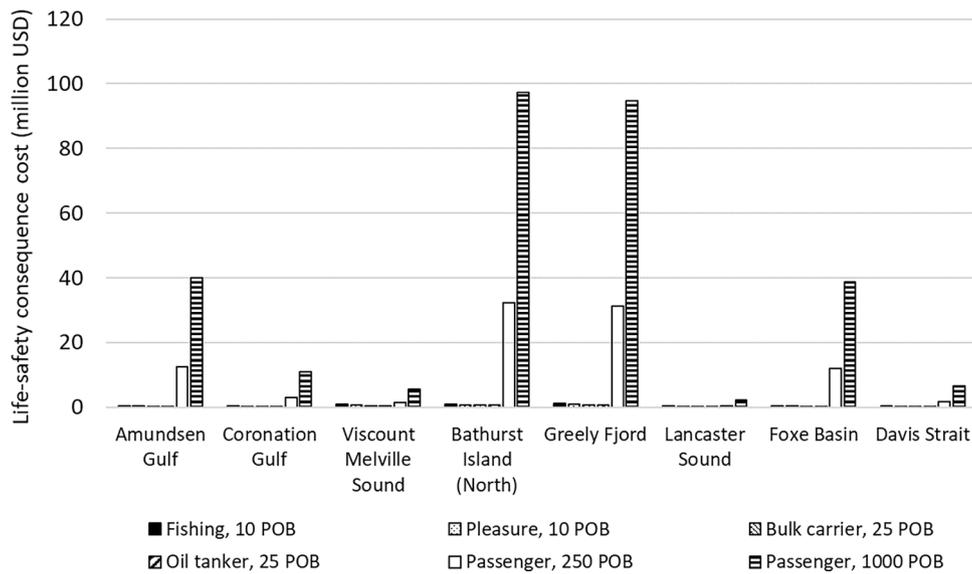
Fig. 11. Life-safety consequence cost by location for different ship types.

Table 14
Qualitative consequence severity ratings by location; Fishing vessel, 10 POB.

Location	Spill volume class	ESI	Environmental conseq. cat.	Response time (hour)	Severity index value	Life-safety conseq. cat.	Total conseq. cat.
Amundsen G.	1	2	E1	20.5	2.15	S2	T2
Coronation G.	1	4	E1	19.0	2.09	S2	T2
VMS	1	1	E1	31.0	2.45	S2	T2
Bathurst I. (N)	1	1	E1	34.5	2.52	S2	T2
Greely Fjord	1	2	E1	38.0	2.59	S2	T2
Lancaster S.	1	4	E1	19.0	2.09	S2	T2
Foxe Basin	1	1	E1	21.5	2.18	S2	T2
Davis Strait	1	3	E1	19.5	2.11	S2	T2

Table 15

Qualitative consequence severity ratings by location; Pleasure craft, 10 POB.

Location	Spill volume class	ESI	Environmental conseq. cat.	Response time (hour)	Severity index value	Life-safety conseq. cat.	Total conseq. cat.
Amundsen G.	1	2	E1	20.5	2.02	S2	T2
Coronation G.	1	4	E1	19.0	1.97	S1	T1
VMS	1	1	E1	31.0	2.33	S2	T2
Bathurst I. (N)	1	1	E1	34.5	2.41	S2	T2
Greely Fjord	1	2	E1	38.0	2.48	S2	T2
Lancaster S.	1	4	E1	19.0	1.97	S1	T1
Foxe Basin	1	1	E1	21.5	2.06	S2	T2
Davis Strait	1	3	E1	19.5	1.99	S1	T1

Table 16

Qualitative consequence severity ratings by location; Bulk carrier, 25 POB.

Location	Spill volume class	ESI	Environmental conseq. cat.	Response time (hour)	Severity index value	Life-safety conseq. cat.	Total conseq. cat.
Amundsen G.	4	2	E2	20.5	1.86	S1	T2
Coronation G.	4	4	E3	19.0	1.80	S1	T3
VMS	4	1	E2	31.0	2.22	S2	T2
Bathurst I. (N)	4	1	E2	34.5	2.31	S2	T2
Greely Fjord	4	2	E2	38.0	2.39	S2	T2
Lancaster S.	4	4	E3	19.0	1.80	S1	T3
Foxe Basin	4	1	E2	21.5	1.90	S1	T2
Davis Strait	4	3	E3	19.5	1.82	S1	T3

Table 17

Qualitative consequence severity ratings by location; Oil tanker, 25 POB.

Location	Spill volume class	ESI	Environmental conseq. cat.	Response time (hour)	Severity index value	Life-safety conseq. cat.	Total conseq. cat.
Amundsen G.	5	2	E3	20.5	1.86	S1	T3
Coronation G.	5	4	E4	19.0	1.80	S1	T4
VMS	5	1	E2	31.0	2.22	S2	T2
Bathurst I. (N)	5	1	E2	34.5	2.31	S2	T2
Greely Fjord	5	2	E3	38.0	2.39	S2	T3
Lancaster S.	5	4	E4	19.0	1.80	S1	T4
Foxe Basin	5	1	E2	21.5	1.90	S1	T2
Davis Strait	5	3	E3	19.5	1.82	S1	T3

Table 18

Qualitative consequence severity ratings by location; Passenger vessel, 250 POB.

Location	Spill volume class	ESI	Environmental conseq. cat.	Response time (hour)	Severity index value	Life-safety conseq. cat.	Total conseq. cat.
Amundsen G.	3	2	E2	89.5	3.62	S3	T3
Coronation G.	3	4	E3	44.5	3.01	S3	T3
VMS	3	1	E1	31.0	2.70	S2	T2
Bathurst I. (N)	3	1	E1	144.5	4.03	S4	T4
Greely Fjord	3	2	E2	142.5	4.02	S4	T4
Lancaster S.	3	4	E3	19.0	2.28	S2	T3
Foxe Basin	3	1	E1	88.0	3.60	S3	T3
Davis Strait	3	3	E2	33.5	2.77	S2	T2

Table 19

Qualitative consequence severity ratings location; Passenger vessel, 1000 POB.

Location	Spill volume class	ESI	Environmental conseq. cat.	Response time (hour)	Severity index value	Life-safety conseq. cat.	Total conseq. cat.
Amundsen G.	4	2	E2	89.5	4.13	S4	T4
Coronation G.	4	4	E3	44.5	3.56	S3	T3
VMS	4	1	E2	31.0	3.27	S3	T3
Bathurst I. (N)	4	1	E2	144.5	4.51	S4	T4
Greely Fjord	4	2	E2	142.5	4.50	S4	T4
Lancaster S.	4	4	E3	19.0	2.88	S2	T3
Foxe Basin	4	1	E2	88.0	4.11	S4	T4
Davis Strait	4	3	E3	33.5	3.34	S3	T3

19. Each table is associated with a single ship type and POB combination.

Similar findings to the quantitative method are observed when comparing the qualitative ratings between ship types and locations. The oil tanker is rated with a total consequence category T4 (High) in Coronation Gulf and Lancaster Sound. The environmental consequence category is the predominant contributor at these locations, rated E4 (High).

Both the 1000 and 250 POB passenger vessels are rated with total consequence categories T4 (High) in Greely Fjord and Bathurst Island (North). The 1000 POB passenger vessel is also rated with a total consequence category T4 (High) in Amundsen Gulf and Foxe Basin.

The bulk carrier is rated with total consequence categories ranging from T2 (Low) to T3 (Medium) at all locations. The environmental consequence category is the predominant contributor, ranging from E2 (Low) to E3 (Medium). Note that the environmental consequence category ratings for the bulk carrier and the 1000 POB passenger vessel are equivalent at each location, as both are modelled with spill volume class 4.

The fishing vessel is rated with a total consequence category T2 (Low) at all locations. The pleasure craft is rated with total consequence categories ranging from T1 (Very Low) to T2 (Low). The predominant contributor to total consequence category rating for these ship types is the life-safety consequence category; both vessels are rated with an environmental consequence category of E1 (Very Low) at all locations.

Aside from the passenger vessels, all other ship types are rated with life-safety consequence severity categories ranging from S1 (Minor) to S2 (Severe).

3.3. Benchmark case study

A case study presented by Afenyo et al. (Afenyo et al., 2022) evaluates the socio-economic consequence cost of an oil spill in the Canadian Arctic. In this section, the case study cost estimate is used to benchmark the environmental consequence model developed for the current study.

The case study evaluates the multi-period socio-economic cost associated with an oil spill of 10.8 million barrels (approximately 37,000 tonnes) in Rankin Inlet. The oil spill volume is equivalent to that of the 1989 Exxon Valdez oil spill in Alaska. The cost estimate reflects a worst-case scenario in which no oil spill recovery or intervention takes place (Afenyo et al., 2022).

The multi-period model estimates consequence costs over time. A socio-economic consequence cost of 500 million USD is estimated for the first year following the oil spill. After five years, the socio-economic consequence cost grows to 7 billion USD.

The same oil spill scenario is examined using the environmental consequence model of the current study. Rankin Inlet has an ESI of 4 (WSP Canada, 2014). For an oil spill volume of 37,000 tonnes, the environmental consequence cost is estimated at 265 million USD. The environmental consequence category is rated E5 (Very High).

The environmental consequence cost estimate reflects clean-up costs, environmental damage, and socio-economic consequences. Environmental damage and socio-economic consequence costs are estimated to represent 60% of the total oil spill cost, i.e. clean-up costs account for the other 40% (IMO, 2018; Skjong et al., 2005). The cost associated with environmental damage and socio-economic consequence is thus estimated at 159 million USD, and is roughly one third the first year estimate by Afenyo et al. (Afenyo et al., 2022).

Several points warrant consideration when comparing the cost estimate of the current study against the benchmark case study.

Afenyo et al. (Afenyo et al., 2022) assume a worst-case scenario in which no oil spill recovery or intervention efforts take place. The

environmental consequence model of the current study assumes clean-up operations take place.

Afenyo et al. (Afenyo et al., 2022) model consequence on a more localized scale, whereas the ESI used for the current study reflects a more global scale (WSP Canada, 2014). Further, different socio-economic indicators are used by each study. The ESI models socio-economic value using a Human-use Resource Indicator (HRI), which is quantified considering coastal population, tourism, and national and international shipping freight tonnage. Afenyo et al. (Afenyo et al., 2022) consider indigenous socio-economic indicators, such as the oil spill compensation stipulated in the region's indigenous land claims agreement, and costs associated with psychological distress and crime.

The current study estimates environmental consequence cost based on the IMO global average spill cost function (IMO, 2018). The spill cost is based on a single value: spill volume. This is a practical approach but may not reflect the complexity of an oil spill and the associated environmental impacts. Further, 60% of the global average spill cost is estimated to be associated with environmental damage and socio-economic consequences. This proportion may not accurately represent the environmental consequence of an Arctic oil spill.

4. Discussion

4.1. Main findings

Total consequence severity of an Arctic ship accident is dependent on ship type and accident location. Combining different consequence types allows for the total consequence severity of different ship accident scenarios to be evaluated and compared.

The worst-case accident scenario is an oil tanker in an environmentally sensitive region, e.g. Coronation Gulf or Lancaster Sound, or a high POB passenger vessel in a region associated with a long response time, e. g. Greely Fjord or Bathurst Island (North).

Accident scenarios in regions with lower environmental sensitivity, e.g. Viscount Melville Sound or Foxe Basin, and ship types with lower spill volume class, e.g. fishing vessels or pleasure craft, are associated with lower environmental consequence severity.

Accident scenarios in regions associated with shorter response times, e.g. Lancaster Sound or Viscount Melville Sound, and ship types with relatively low life-safety severity indices, e.g. cargo vessels, are associated with lower life-safety consequence severity.

Results for the quantitative method are based on average values, providing a comparative indicator between potential ship accident scenarios. Environmental consequence costs are based on average spill volumes for a given spill volume class. Life-safety consequence costs are based on average response time estimates for a given region. The consequence severity realized from a ship accident in the Arctic will depend on the actual spill volume and response time.

The qualitative framework captures the maximum potential consequence costs of a ship accident scenario. The qualitative framework rates consequence severities based on ranges of potential consequence costs. Environmental consequence categories consider the spill volume range associated with each spill volume class. The life-safety consequence categories consider the range of values encompassed by the order of magnitude of equivalent fatalities defined for each severity index.

There is a degree of ambiguity associated with the qualitative framework. For example, accident scenarios for a 1000 POB passenger vessel in Greely Fjord and Foxe Basin receive the same qualitative rating for total consequence category: T4 (High). The quantitative method distinguishes the two scenarios, estimating the total consequence cost in Greely Fjord to be 2.4 times greater than in Foxe Basin.

The issue of ambiguity is not unique to the current study. Ambiguity

is inherent in all qualitative matrices established on the basis of an underlying quantitative relation (Leva et al., 2017; Bao et al., 2019; Anthony TonyCox, 2008). Despite ambiguity, matrices remain a common and practical approach in risk management.

4.2. Implications for safe Arctic shipping and risk management

Evaluating total consequence severity for Arctic ship accident scenarios allows for comparison of the overall risk exposure between ship types and operating regions. The qualitative framework provides risk analysts and decision-makers with a systematic and coherent process for assessing, ranking, and communicating Arctic ship accident scenario severities. The framework uses pre-defined matrices established using the quantitative method. As such, the results between the quantitative and qualitative methods are aligned.

Results suggest that an oil tanker accident in the Arctic is the worst-case scenario, due almost exclusively to the associated environmental consequence. High POB passenger vessels are associated with appreciable environmental and life-safety consequence severities. Combining different consequence types demonstrates that a high POB passenger vessel accident in the Arctic poses a comparable total consequence severity level to that of an oil tanker.

An oil spill has been recognized as the greatest threat facing the Arctic maritime environment (Arctic Council, 2009). The current study suggests that on the basis of total consequence severity, mitigating the potential consequence severity associated with Arctic cruise operations is of near equal priority to that of Arctic tanker operations. Previous studies suggest the need for enhanced regulatory oversight of Arctic cruise operations (Dawson et al., 2014).

Although Arctic ship operations pose risks to the environment and life-safety, they provide positive economic impacts to Arctic communities and stakeholders. Economic benefits must be considered in risk management of the Arctic maritime industry.

The Integrated Arctic Corridors Framework (The PEW Charitable Trusts., 2016) is an example of balancing risk management and the realization of the benefits of Arctic shipping. The Integrated Arctic Corridors Initiative, a proposed expansion of the Canadian Coast Guard's Northern Marine Transportation Corridors Initiative, accounts for environmental features and Inuit rights in defining safe marine traffic corridors. Life-safety consequence is not considered.

While Arctic cruise operations pose a high total consequence severity, Arctic cruise operators are recognized for exercising operational risk management best practices. For example, cruise ships typically operate in close proximity with a support vessel when in remote regions. The recent voyages of the Crystal Serenity cruise ship through the Northwest Passage are recognized for having established a high standard for risk management and regulatory oversight (Browne et al., 2021).

The consequence severity of an Arctic ship accident will be impacted by the availability and capability of SAR services. The life-safety consequence severity of an Arctic ship evacuation has a strong dependence on emergency response time and capacity (Browne et al., 2021). There is a need for the continued enhancement of, and international cooperation between, Arctic SAR services in order to decrease the consequence severity of Arctic ship accidents (Solberg et al., 2016; Solberg et al., 2017; Solberg and Gudmestad, 2019; Council, 2011). This is particularly true for accident scenarios with high POB vessels which require the deployment and coordination of multiple SAR assets (Ikonen, 2017; Schmied et al., 2017).

An operational risk management framework for Arctic ship navigation and voyage planning is proposed by Browne et al. (Browne et al.,

2020). The framework integrates ecological, socio-economic, and life-safety consequences into the Polar Operational Limit Assessment Risk Indexing System methodology (IMO, 2016). The total potential consequence level informs the assignment of operating criteria for ships in ice. Ships posing higher potential consequence severities are required to operate more conservatively. The method developed for the current study supports the further development of the proposed operational risk management framework.

The current study focuses on the combination of multiple consequence types, ultimately contributing to risk aggregation. Risk aggregation allows decision-makers to consider the total exposure to loss for a system, and supports holistic risk management (Bjørnsen and Aven, 2019; David, 2016).

It is important to consider if risk aggregation is suitable. Potential issues related to information loss and independence are highlighted by David (David, 2016). While aggregated risk supports a better understanding of the complete risk picture and the context of individual risks, it should not replace the detailed information of single risks. The relation between individual risks must also be considered. Aggregating risks that are not independent may not be appropriate.

The method proposed in the current study supports holistic data-driven risk management in the Arctic maritime industry. Decision-makers and risk analysts should consider the total consequence severity data together with the individual environmental and life-safety consequence data.

4.3. Future work

The environmental consequence severity of an Arctic oil spill is modelled as a function of the regional ESI for the accident location. Regional ESI values are modelled, in part, based on a HRI value which considers coastal population, tourism, and shipping freight tonnage for the region. The HRI is intended to reflect the socio-economic value of the region (WSP Canada, 2014).

Socio-economic value in the Canadian Arctic should consider indigenous rights and land and marine uses. Several studies propose ways to capture indigenous values and consequence severities (The PEW Charitable Trusts., 2016; Afenyo et al., 2022; Nunavut Planning Commission, 2016). Expansion of the definition and calculation of regional ESI value to capture indigenous socio-economic impacts is necessary.

Life-safety consequence severity of an Arctic ship evacuation is a function of response time. Regional response time estimates assume the deployment of a single SAR asset. Multiple SAR assets may be deployed to an accident location. In the case of high POB evacuation, all available SAR assets, including nearby vessels of opportunity, may assist in the emergency response.

The number and combination of SAR assets will impact response time, and thus life-safety consequence severity. Studies have investigated the impact of SAR resource allocation and the presence of vessels of opportunity on response time (Piercey et al., 2019; Farrell et al., 2021), and may support the refinement of the life-safety consequence model.

Life-safety consequence cost is estimated using published CAF values. The same CAF value is used for fatalities of crew and passengers. The IMO distinguishes between crew and passengers with respect to life-safety risk tolerance criteria (i.e. likelihood of occurrence) but use the same CAF value. Vidmar & Perković (Vidmar and Perković, 2018) argue that life-safety risk criteria should be evaluated separately for crew and passengers, as well as different ship types. Continued debate and calibration over CAF values and life-safety risk criteria is necessary.

In the Canadian Arctic, cruise ships are often escorted by an ice

capable vessel as a risk mitigation strategy. The escort vessel provides icebreaking assistance and support in the event of an emergency. The use of vessel convoys is another risk mitigating practice. Future studies may investigate the potential efficacy of such approaches for reducing SAR response time and consequence severity.

The collection and analysis of Arctic ship accident case studies will contribute to the continued validation of consequence models and the valuation of oil spills and fatalities in Arctic waters.

The method provides decision-makers and risk analysts with a tool for risk management in the Arctic maritime industry. Next steps include investigating how modelling total consequence severity and risk aggregation in general supports existing efforts towards safe Arctic shipping and risk assessment (Browne et al., 2020; The PEW Charitable Trusts., 2016; IMO, 2018). Expansion of the method to model causal factors, other consequence types, and associated uncertainties is necessary for the aggregation of risks for Arctic ship accidents.

Eliciting stakeholder feedback on the method and the assignment of consequence category thresholds is an area for future work. Relevant stakeholders include seafarers, ship operators, insurance underwriters, policy makers, indigenous communities, and risk analysis practitioners.

5. Conclusion

A general method to combine multiple consequence posed by Arctic ship accidents is presented. Ecological, socio-economic, and life-safety consequences are considered. Existing models for each consequence type are adopted. Total consequence severity is estimated through monetization of and summation of individual consequence severities. A quantitative method estimates total consequence cost, and a qualitative framework assigns a rating for total consequence severity. The qualitative framework provides risk analysts and decision-makers with a data-driven and practical procedure to support the assessment, management, and communication of Arctic shipping risks.

The method allows for the total consequence severity of different Arctic ship accident scenarios to be evaluated and compared. The total consequence severity of different ship accident scenarios throughout the Canadian Arctic are evaluated.

Results show that total consequence severity is dependent on ship type and accident location. Arctic ship accident scenarios involving oil tankers in environmentally sensitive regions, and high POB passenger vessels in regions associated with long response times, are worst-case scenarios.

While oil spills are recognized as the greatest threat facing the Arctic environment, the current study suggests that mitigating the potential consequence severity associated with Arctic cruise operations is of near equal priority to that of Arctic tanker operations.

Recommendations for future work include the continued development of environmental and life-safety consequence models. Accurately modelling the socio-economic impacts of Arctic ship accidents incurred by indigenous communities is necessary. Next steps include eliciting stakeholder feedback on the method for combining consequence types and investigating how it may support existing efforts for safe Arctic shipping and risk assessment.

CRediT authorship contribution statement

Thomas Browne: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rocky Taylor:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Brian Veitch:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition. **Inari Helle:** Methodology, Investigation, Conceptualization. **Tuuli Parviainen:** Methodology, Investigation, Conceptualization. **Faisal Khan:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Doug Smith:** Writing – review & editing, Supervision, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Appendix A. Regional ESI ratings for the Canadian Arctic

Regional ESI ratings for the Canadian Arctic were established by WSP for the assessment oil spill risk in Canadian waters [WSP 2014a]. Table A1.

Table A1
ESI ratings for the Canadian Arctic [WSP 2014] with locations used for the current study.

Sector	Region	ESI	Location in current study
1	Arctic Ocean	1	
2a	Beaufort Sea (West)	4	
2b	Beaufort Sea (East)	2	Amundsen Gulf
3a	High Arctic Islands	1	Viscount Melville Sound, Bathurst Island (North)
3b	High Arctic Islands	2	Greely Fjord
4	Southwestern Arctic	4	Coronation Gulf
5a	Foxe Basin (South)	1	
5b	Foxe Basin (Central)	1	Foxe Basin
5c	Foxe Basin (North)	3	
6a	Hudson Bay & James Bay (North)	4	Rankin Inlet
6b	Hudson Bay & James Bay (Central)	2	
6c	Hudson Bay & James Bay (South)	5	
7a	Hudson Strait (West)	4	
7b	Hudson Strait (East)	4	
8a	Eastern Arctic (Lancaster Sound)	4	Lancaster Sound
8b	Eastern Arctic (Davis Strait)	3	Davis Strait
8c	Eastern Arctic (Labrador Sea)	2	
9	Mackenzie River & Great Slave Lake	4	

Appendix B. Result tables for quantitative method

Tables B1-B6.

Table B1
Quantitative consequence severity estimates by location; Fishing vessel, 10 POB.

	Amundsen Gulf	Coronation Gulf	VMS	Bathurst Is. (N)	Greely Fjord	Lancaster Sound	Foxe Basin	Davis Strait
Spill volume class	1	1	1	1	1	1	1	1
Average spill volume (tonnes)	13	13	13	13	13	13	13	13
Global average spill cost	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
ESI	2	4	1	1	2	4	1	3
ESI value	2	8	1	1	2	8	1	4
Environmental consequence cost	**0.62**	**2.48**	**0.31**	**0.31**	**0.62**	**2.48**	**0.31**	**1.24**
Average response time (hour) *	20.5	19.0	31.0	34.5	38.0	19.0	21.5	19.5
Severity index value	2.15	2.09	2.45	2.52	2.59	2.09	2.18	2.11
Equivalent fatalities	0.14	0.12	0.28	0.33	0.39	0.12	0.15	0.13
Life-safety consequence cost	**0.42**	**0.37**	**0.84**	**1.00**	**1.18**	**0.37**	**0.46**	**0.39**
Total consequence cost	**1.04**	**2.85**	**1.15**	**1.31**	**1.80**	**2.85**	**0.77**	**1.63**

Costs are in million USD.
* Minimum average response time between air- and marine-based estimates.

Table B2
Quantitative consequence severity estimates by location; Pleasure craft, 10 POB.

	Amundsen Gulf	Coronation Gulf	VMS	Bathurst Is. (N)	Greely Fjord	Lancaster Sound	Foxe Basin	Davis Strait
Spill volume class	1	1	1	1	1	1	1	1
Average spill volume (tonnes)	13	13	13	13	13	13	13	13
Global average spill cost	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
ESI	2	4	1	1	2	4	1	3
ESI value	2	8	1	1	2	8	1	4
Environmental consequence cost	**0.62**	**2.48**	**0.31**	**0.31**	**0.62**	**2.48**	**0.31**	**1.24**
Average response time (hour) *	20.5	19.0	31.0	34.5	38.0	19.0	21.5	19.5
Severity index value	2.02	1.97	2.33	2.41	2.48	1.97	2.06	1.99
Equivalent fatalities	0.11	0.09	0.21	0.26	0.30	0.09	0.11	0.10
Life-safety consequence cost	**0.32**	**0.28**	**0.64**	**0.77**	**0.91**	**0.28**	**0.34**	**0.29**
Total consequence cost	**0.94**	**2.76**	**0.95**	**1.08**	**1.53**	**2.76**	**0.65**	**1.53**

Costs are in million USD.
* Minimum average response time between air- and marine-based estimates.

Table B3
Quantitative consequence severity estimates by location; Bulk carrier, 25 POB.

	Amundsen Gulf	Coronation Gulf	VMS	Bathurst Is. (N)	Greely Fjord	Lancaster Sound	Foxe Basin	Davis Strait
Spill volume class	4	4	4	4	4	4	4	4
Average spill volume (tonnes)	2,670	2,670	2,670	2,670	2,670	2,670	2,670	2,670
Global average spill cost	7.03	7.03	7.03	7.03	7.03	7.03	7.03	7.03
ESI	2	4	1	1	2	4	1	3
ESI value	2	8	1	1	2	8	1	4
Environmental consequence cost	**14.06**	**56.26**	**7.03**	**7.03**	**14.06**	**56.26**	**7.03**	**28.13**
Average response time (hour) *	20.5	19.0	31.0	34.5	38.0	19.0	21.5	19.5
Severity index value	1.86	1.80	2.22	2.31	2.39	1.80	1.90	1.82
Equivalent fatalities	0.07	0.06	0.17	0.20	0.25	0.06	0.08	0.07
Life-safety consequence cost	**0.22**	**0.19**	**0.50**	**0.61**	**0.74**	**0.19**	**0.24**	**0.20**
Total consequence cost	14.28	56.45	7.53	7.64	14.81	56.45	7.27	28.33

Costs are in million USD.
* Minimum average response time between air- and marine-based estimates.

Table B4
Quantitative consequence severity estimates by location; Oil tanker, 25 POB.

	Amundsen Gulf	Coronation Gulf	VMS	Bathurst Is. (N)	Greely Fjord	Lancaster Sound	Foxe Basin	Davis Strait
Spill volume class	5	5	5	5	5	5	5	5
Average spill volume (tonnes)	8,900	8,900	8,900	8,900	8,900	8,900	8,900	8,900
Global average spill cost	14.30	14.30	14.30	14.30	14.30	14.30	14.30	14.30
ESI	2	4	1	1	2	4	1	3
ESI value	2	8	1	1	2	8	1	4
Environmental consequence cost	**28.60**	**114.37**	**14.30**	**14.30**	**28.60**	**114.37**	**14.30**	**57.19**
Average response time (hour) *	20.5	19.0	31.0	34.5	38.0	19.0	21.5	19.5
Severity index value	1.86	1.80	2.22	2.31	2.39	1.80	1.90	1.82
Equivalent fatalities	0.07	0.06	0.17	0.20	0.25	0.06	0.08	0.07
Life-safety consequence cost	**0.22**	**0.19**	**0.50**	**0.61**	**0.74**	**0.19**	**0.24**	**0.20**
Total consequence cost	**28.81**	**114.56**	**14.79**	**14.91**	**29.33**	**114.56**	**14.54**	**57.38**

Costs are in million USD.
* Minimum average response time between air- and marine-based estimates.

Table B5

Quantitative consequence severity estimates by location; Passenger vessel, 250 POB.

	Amundsen Gulf	Coronation Gulf	VMS	Bathurst Is. (N)	Greely Fjord	Lancaster Sound	Foxe Basin	Davis Strait
Spill volume class	3	3	3	3	3	3	3	3
Average spill volume (tonnes)	512	512	512	512	512	512	512	512
Global average spill cost	2.66	2.66	2.66	2.66	2.66	2.66	2.66	2.66
ESI	2	4	1	1	2	4	1	3
ESI value	2	8	1	1	2	8	1	4
Environmental consequence cost	**5.31**	**21.25**	**2.66**	**2.66**	**5.31**	**21.25**	**2.66**	**10.63**
Average response time (hour) *	89.5	44.5	31.0	144.5	142.5	19.0	88.0	33.5
Severity index value	3.62	3.01	2.70	4.03	4.02	2.28	3.60	2.77
Equivalent fatalities	4.14	1.03	0.50	10.74	10.45	0.19	4.01	0.59
Life-safety consequence cost	**12.43**	**3.10**	**1.51**	**32.22**	**31.34**	**0.57**	**12.02**	**1.76**
Total consequence cost	**17.74**	**24.35**	**4.17**	**34.88**	**36.65**	**21.82**	**14.67**	**12.39**

Costs are in million USD.

* Average marine-based response time estimates.

Table B6

Quantitative consequence severity estimates by location; Passenger vessel, 1000 POB.

	Amundsen Gulf	Coronation Gulf	VMS	Bathurst Is. (N)	Greely Fjord	Lancaster Sound	Foxe Basin	Davis Strait
Spill volume class	4	4	4	4	4	4	4	4
Average spill volume (tonnes)	2,670	2,670	2,670	2,670	2,670	2,670	2,670	2,670
Global average spill cost	7.03	7.03	7.03	7.03	7.03	7.03	7.03	7.03
ESI	2	4	1	1	2	4	1	3
ESI value	2	8	1	1	2	8	1	4
Environmental consequence cost	**14.06**	**56.26**	**7.03**	**7.03**	**14.06**	**56.26**	**7.03**	**28.13**
Average response time (hour) *	89.5	44.5	31.0	144.5	142.5	19.0	88.0	33.5
Severity index value	4.13	3.56	3.27	4.51	4.50	2.88	4.11	3.34
Equivalent fatalities	13.35	3.66	1.87	32.41	31.59	0.76	12.94	2.16
Life-safety consequence cost	**40.05**	**10.98**	**5.62**	**97.24**	**94.76**	**2.27**	**38.82**	**6.49**
Total consequence cost	**54.12**	**67.24**	**12.66**	**104.27**	**108.83**	**58.53**	**45.85**	**34.62**

Costs are in million USD.

* Average marine-based response time estimates.

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