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A Multiperiod Model for Assessing the Socioeconomic Impacts of Oil Spills during Arctic Shipping

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As the rate of ice melt in the Arctic increases, the potential for shipping activities is also increasing. However, infrastructure along the northwest passage (NWP) in Canada's Arctic is almost nonexistent. This presents major challenges to any response efforts in the case of a natural disaster. Also, the Arctic is home to many indigenous communities, as well as flora and fauna. Thus, it is of vital importance to protect the livelihood of the rights holders in this area and the Arctic marine environment. To do this, it is necessary to develop a decision-making tool to assess the potential risk of pollutants arising from increased shipping activity. Understanding such, this article assesses the impacts of a potential oil spill on communities in the Canadian Arctic. The consequences of risk are presented using a multiperiod model while the likelihood is analyzed using Bayesian Network. The output of the multiperiod model is incorporated into an influence diagram for risk assessment purposes. The Bayesian model benefits from expert elicitation from the crew aboard a research ship passing through the NWP. Information was also obtained from marine insurance companies, government representatives, and other Arctic specialized professionals. The risk-based model is subsequently applied to the Canadian Arctic area, with the aim of evaluating the impact of a potential oil spill through shipping.

KEY WORDS: Arctic; Northwest passage; oil spills; risk

1. INTRODUCTION

The need for proper preparation for anticipated economic activities in the Arctic has been proposed in the literature (Afenyo, Jiang, & Ng, 2019). While it is debatable as to how quickly and how completely Arctic waterways will open, there is little debate that Arctic shipping activities have increased. For example, according to AGCS (2019), approximately 46 incidents of Arctic accidents were reported in 2018. Shipping activities through the northern sea route (NSR) have also increased, compared to that of the northwest passage (NWP), due to large investments in this region by the Russian Federation. The People's Republic of China (hereinafter called 'China') has also identified the future importance of Arctic shipping routes and has given these routes the same importance to those touted in its belt and road initiative (BRI) (Afenyo et al., 2019). Despite different instruments, such as the Polar Code, presenting a direction for operating in such waters, insurance companies and other stakeholders are skeptical about the accurate estimation of the impacts of a disaster (e.g., oil spill) in this area (Fedi, Faury, & Gritsenko, 2018). They argue that data about this region are still scarce

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with many unknowns interms of potential hazards and their consequences (Afenyo et al., 2019).

One pillar of the BRI is the polar initiative. In this inititaive, the Chinese government views the Arctic waterways as strategic to the fulfillment of the core goals of the BRI. Further, the opportunities for shipping and the viable economic activities that come with the melting of sea ice has created an incentive to make the BRI a reality in the Arctic (Afenyo et al., 2019). In this regard, China has already gained observer status on the Arctic Council along with other non-Arctic countries (e.g., India, Italy, Singapore, and South Korea). These countries use their observer status to influence the decisions of the permanent members for strategic economic and safety benefits. The Yamal liquified natural gas (LNG) project,[1] a partnership among three companies from China, Russia, and France, respectively, highlights the new shipping trend in the Arctic. It should be noted that it is not the countries that developed the Yamal LNG plant but companies with different nationalities. The footnote further explains the details. Similar collaborations are likely to soon follow and create an economic boom in the forseeable future (Østreng et al., 2013).

It is anticipated that Europe and Asia are the major benefactors from using the Arctic routes, where regional trade between them would improve tremendously (NMFA, 2014; Østreng et al., 2013). The economies linked to Arctic shipping and exploration already accounts for a substantial amount of the economy world wide. The bulk of this is in the Russian Federation (Borgerson, 2013).

Despite the potential worldwide benefits in regard to Arctic shipping, they may be somewhat overstated as not all regions can benefit from this development. In fact, Africa, South America, and Australia are the regions that are less likely to benefit directly. Recently, the Panama Canal was expanded to accommodate bigger ships and higher shipping traffic (Gooley, 2018).

[1]This project is located in Russia and started in 2017. The partners for this project are Novatek, Total, Petroleum, China National Petroleum Corporation (CNPC), and the Silk Road Fund. Through this project an extensive transportation network has been built for gas transport as well as a new international airport and the Sabetta port. The Yamal LNG project is located along the Ob River, an area that is frozen 7 to 9 months in a year and temperatures going as low as −50 °C. The project is already producing 16.5 million metric tons of gas per year. Novatek has since lunched a second LNG project scheduled to start producing 20 million metric tons of gas per annum.

Against such background, the economic viability of Arctic shipping has been under scrutiny. Lasserre (2014) identified the following challenges about studies on the viability of Arctic shipping routes. They are (i) an overestimation of outputs from Arctic shipping, (ii) unreliability of data used in the analysis, and (iii) overlooking uncertainties in the models. These notwithstanding, the majority of studies have overlooked some of these factors. A study conducted by Cariou and Faury (2015) shows that most studies that compares the NSR and the Suez Canal route (SCR) fail to account for a critical factor, that is, the spot freight rate to fuel ratio, therefore overestimating the attractiveness of the NSR. However, Faury and Cariou (2016) concluded that the NSR provides a competitive advantage over the SCR for oil products transportation from Russia to Asia from July/August to November. In fact, transit shipping is only a small portion of the traffic in the Arctic region. However, the media has projected a different picture making transit shipping the more dominant one in the eyes of the public, even though the Figures show otherwise (Lasserre, 2019). Also, the bulk of the shipping activities in the Canadian Arctic are not just tanker related but also cargo ships and ships transporting tourist. One of the interesting trends in the NSR is that the European and Russian ships have dominated these voyages (Gunnarsson, 2021; Lasserre, 2019) clearing the public perception that the Asian ships dominate Arctic shipping.

Apart from the economic activities, secruity is another issue when dealing with the Arctic (e.g., Fu, Zhang, Montewka, Yan, & Zio, 2016; 2018a; 2018b). For example, how safe is it using the NWP and the NSR? While Russia and some other countries, such as Norway, are investing heavily in icebreakers, other Arctic countries have yet to invest to the same extent. It should be noted that in some cases there are plans on the drawing board but these have not been executed to the fullest. For example, the Canadian federal government plans to roll out several icebreakers in the coming years, but the number is uncertain and, so far, only a small portion of the projected quantity has been delivered. Therefore, a more aggressive approach is required to get to the same level as Russia and Norway. Countries like Norway already have a well-established Arctic policy and, on many occassions, has offered to host studies related to the consequences of Arctic shipping, such as the effects of oil spills. These sorts of activities elevate the preparedness of the entire Arctic region to respond in the case of an oil spill. For Canada, successive governments have produced Arctic policies but the implementation is always the problem and so not much gets done in that regard (NMFA, 2014).

Increased shipping and natural resource exploration in the Arctic also means that there should be a way to ascertain the level of socioeconomic impacts of these activities in the Arctic. Activities asscociated with Arctic oil and gas exploration in Canada have fluctuated over the years depending on the government in power. In Canada, Arctic activities include but are not limited to: (i) resource development, (ii) community resupply, and (iii) international shipping. Recent heightened interest in these activities means that governments and other coporate organizations are ready to invest in this area. While such ventures can create job opportunities, it may affect the culture of the local population and the environment (Byers, Sharp, & Lodge, 2016). Indeed, not every organization in the shipping industry agrees with delivering goods through the Arctic. Some major entities (e.g., MSC, CMA-CGM) are boycotting the use of Arctic shipping, arguing that it is not worth taking the risks (Boyd, 2020). Others point out the potential policy uncertainty related to the use of Arctic shipping (e.g., Kong, Jiang, & Ng, 2021). Clearly there is a tug-of-war between the increasing economic growth and opportunity and the preservation of the environment in the Arctic.

Projected estimates reveal that between 2010 and 2017, a loss of 3.5 billion dollars was attributed to the Deepwater Horizon oil spill in terms of economic impacts from recreational fishing alone (Grubesic et al., 2017). There is a cumulative effect over time in respect to the impact of an occurrence such as oil spill and clearly, the consequences can be dire. For example, the Dalian, China oil spill on July 16, 2010 resulted in the release of approximately 60,000 tons of oil over a period of seven days according to Greenpeace (Stanway, 2010) and resulted in economic losses estimated at 0.75 billion USD (Pan, Qiu, Liu, & Hu, 2015). Recently, the Mauritius oil spill caused irreparable consequence to the communities living along the area where the spill occured (Peltier, 2020; DW, 2020). Two UNESCO wetlands and other marine protected areas are at risk of contamination (Pasnin, Sunassee, Tatayah, Turner, & Ward, 2020) for the Mauritius oil spill. In the case of the Deepwater Horizon oil spill, water bodies were contaminated and people lost their livelihood (Afenyo, Khan, & Veitch, 2015). In addition to those consequences, oil spills can potentially increase the risk of cancer, affect both human and nonhuman reproduction and cause critical human organ damage.

The need to determine the level of socioeconomic risk of an oil spill is, therefore, crucial if Arctic shipping is to increase. This would improve decision making in terms of resource allocation by governments and determination of insurance premiums by insurers. Determining the socioeconomic risk and impact of an oil spill is extremely challenging as it must consider how it affects the natural flora and fauna. For example, how does one assess the impact on fish stocks? Is it based simply on how many fishes are killed, or die over time; is it how the spill affects their habitat, food source and ultimately the future health of the fish stocks? How can this realistically be monitized? Also, an oil spill will incur legal and environmental costs and would pose social implications on the lifestyle of the affected communities.

In Canada, the government and the rights holders[2] in the Arctic have agreements on natural resource exploration in the region through the *Lands Claim Agreement* (LCA) (Anon, 1993). To protect the environment, certain areas have been designated as special areas (referred to as the NORDREG[3]) to be compliant with the LCA (OMJ, 2019). The LCA requires a comprehensive risk assessment before undertaking any form of economic activity. The NORDREG is made up of (i) zones designated as safe shipping control zone as prescribed in the shipping safety control order, (ii) waters in the territories of Ungava Bay, Hudson Bay, and Kugmallit, Bay, Chesterfield Inlet and Baker Lake, which do not fall within the shipping safety control zone, and (iii) waters within the territories of James Bay, Moose River (from James Bay to Moosonee), and Feuilles Bay (from Ungava to Tasiujaq) (Government of Canada, 2010; OMJ, 2019).

Some tools have been developed and used over the years to fully assess the economic viability of aquatic ecosystem restoration projects. One such tool is the habitat equivalent analysis (HEA). This tool was implemented in an institutional context by Scemama and Levrel (2016). The outcome shows that these tools are still very limited in their ability to

[2]Right holders are referred to the indigenous people who have semijurisdiction over the Canadian Arctic. The Government of Canada administers the region together with the indigenous people.

[3]NORDREG means the Northern Canada Vessel Traffic Services Zone, which has been established under Section 2 of the Northern Canada Vessel Traffic Services Zone Regulations (Government of Canada, 2010).

provide accurate risk estimates. While no particular mathematical formula has been developed over the years for assessing the socioeconomic impact of oil spills, there is a genuine need for such a thing. Governments and other organizations have come up with some guidelines to address this, but they are incomplete. Currently, available tools are mainly based on imposing fines on the amount of spill per ton. This is often criticized for its subjectivity and the lack of scientific basis (Innis, 2005). Kim, Yang, Min, and Koh (2014) have developed a tool that seeks to address the need in a global context. However, no tool exists for regional analysis. Zhang, Zhang, Zhang, Lang, and Mao (2020) used Bayesian analysis technique to assess the risks of a ship getting stuck in ice and the ship-ice collision during Arctic navigation. These two risks were aggregated to obtain the overall risk. They employ an integration of the risk matrix with the Bayesian model proposed earlier by Afenyo, Khan, Veitch, and Yang (2017a), providing a robust risk assessment tool for Arctic shipping.

Furthermore, Afenyo et al. (2019) has developed the socioeconomic impact model for the Arctic (SEMA), a scientific tool that helps to determine the level of fair compensation after an oil spill (Afenyo et al., 2019). SEMA is used to assess the socioeconomic impact of oil spill from shipping activities in a global context rather than a regionally specific scenario. Thus, a complete scientific tool for determining compensation after an oil spill remains elusive in the literature and in the practical world. The focus of this article is therefore, to develop and present our state-of-the-art, multiperiod model for assessing the socioeconomic impact of an oil spill incident in the Canadian Arctic. Our study is one of the very few in the literature that focuses on the Canadian Arctic with very specific characteristics. For example, the Nunavut Land Claim Agreement (often referred as the "Land Claim Agreement") and the profound impact of shipping on the rights holders have not been accounted for in many economic models in literature. The Canadian Arctic is also unique in the semiautonomous administration structure, with joint administration between the indigenous government and the Canadian Federal Government. Furthermore, the method adopted also utilizes the Influence Diagram (ID) to assess the potential risks in dollar terms. The methodology is very comprehensive as it accommodates both qualitative and quantitative inputs and could be used to assess not only the socioeconomic impacts but also the environmental consequences.

The rest of the article is organized as follows. Section 2 consists of the literature review. Section 3 introduces the research framework, the methodology, and the model. Section 4 applies the model to Rankin Inlet (Nunavut, Canada) as an illustrative example. Section 5 concludes the article.

2. LITERATURE REVIEW

The methods used for oil spill assessment can be broadly classified into (i) cost benefit analysis; (ii) environmental accounting; (iii) natural resource assessment; and (iv) legal claims (Maes, 2005). Some works in the literature have implemented these methods in different forms. They are discussed in the next paragraphs.

Previous works have studied the socioeconomic impact of oil spills. This includes a study conducted by Pérez (2003), which addressed the power play between those affected by the *Prestige* oil spill off the Galician coast and the role of those in power. This study sought to understand how a government process could affect the consequences resulting from an oil spill. Lui and Wirtz (2006) applied an environmental economic model to the *Prestige* oil spill. They acknowledged that the model was difficult to validate as it is based on empirical results and past accidents. Cohen (1995) employed a market model to assess the economic impacts of the *Exxon Valdez* oil spill, but it does not consider the social implications of the oil spill. Kim et al. (2014), on the other hand, described the potential approach to evaluate the social and ecological impact of the *Hebei Spirit* oil spill on the west coast of South Korea. The proposed methodology, however, lacked a holistic approach in terms of incorporating the critical components of cost incurred for the oil spill. The validation of this methodology also remains a problem. Grubesic et al. (2017), presented a model for evaluating cleanup efforts during an oil spill. The model focused on the activities leading up to the cleanup of the oil spill but did not assess the cost of legal procedures resulting from an oil spill.

A statistical approach was adopted to evaluate the economic impact of the *Prestige* oil spill on the northwestern coast of Spain (Negro, Villasante, Penela, & Rodríguez, 2009). This is an important study as it attempts to monetize the effect of the oil spill through the impact on the fishing industry. Similar studies exist for the effect oil spills have on tourism (Ritchie, Crotts, Zehrer, & Volsky, 2014). A recent study conducted by Ha (2018), explored the analytic hierarchy process (AHP) to assess the risk of an oil spill in Korea. This was necessitated by oil spills, such as the *Hebei Spirit* oil spill. The authors utilized two key components: probability, which encompasses oil transport, capacity of oil storage facilities, number of vessels; and the volume of oil spills. In this study, probability was multiplied by the postaccident sensitivity to obtain the risk. The postaccident sensitivity is made up of the culture of the area, status of sensitive sea area, and the number of beach users. Eide, Endresen, Brett, Ervik, and Røang (2007) developed a model that takes automatic identification system (AIS) inputs to identify the vessels that are likely to spill oil and how much oil is spilled. Goerlandt & Montewka (2015), developed a risk analysis framework for maritime transport which was applied to a tanker–tanker collision. The framework utilized the Bayesian network (BN) in its analysis.

The current regulations for oil spill compensation available, which includes the 1992 Civil Liability Convention (CLC), does not entirely reflect the economic, environmental, and social value of an oil spill. There is a gap, therefore, in terms of how to compensate affected parties. For example, the definition of the consequence of an oil spill, as used by courts and governments, is not comprehensive. According to Kim et al. (2014), this shortcoming has put restrictions on how much fair compensation offending parties are required to pay to the affected parties.

The environmental damage assessment (EDA) is one of the most used models, but it is over simplified and ignores critical details of economic analysis. For example, the use of data obtained from other jurisdictions to estimate the impact of an oil spill is another weakness of the EDA. The EDA is intended to be used by insurance companies and judges. However, currently it does not consider the economic impact on the affected flora and fauna in its assessment. As a consequence, this has created a large disparity between levied fines and the actual damage caused by the oil spills (Innis, 2005, in Maes, 2005).

In most countries, major projects require an environmental impact assessment (EIA) as part of this process. One of the most critical and difficult stages of this process is evaluating the socioeconomic impact of the project as finding the right metrics to monetize social impacts is a challenge. In 2007, Anon (2007) identified several indicators that can be considered when investigating the social aspect of an event, or project. They include, (i) health and social well-being (ii) quality of the environment where such projects are to take place, (iii) economic impact and the value of material acquired, (iv) cultural implications, (v) impact of activities on family and the society, (vi) implications on the legal regime, political landscape and equity, vii) impacts on relationships and families, (viii) risk and safety implications, and (ix) relocation, and compensation of displaced people during such activities. These indicators have since been applied to a number of projects, including resource exploration in the Mackenzie Valley area.

According to Cohen (1995), the cost of an oil spill can be categorized as follows, (i) response, (ii) natural resource damage, (iii) economic loss, (iv) legal cost, and (v) social cost. The response cost entails the containment of the spill which is geared toward reducing further oil spillage and spreading of the slick. Another type of expenditure related to response cost is related to cleanup. This cost may come from both private industry-related activities as well as that of the government. The natural resource damage cost entails the cost incurred from damage to resources in the ecosystem. Examples include fish, plants, and other marine mammals. The economic loss includes lost income as a result of the oil spill. These losses may come from sectors such as fisheries, tourism, and shipping. The economic loss may also include the consumer value loss as a result of shifts in consumer behavior. Loss of equipment, and infrastructure due to the spill, as well as impact on private entities and governments are also another category of costs. Legal costs include the cost of litigation for individuals and government; other penalties may be incurred by breaking both domestic and international law (e.g., OPA 1990, Garick, 1993). Finally, the social impact includes the cost associated with the loss of life, depression, social unrest, and other social vices.

The studies conducted by Cohen (1995), Anon (2007), and the other EIA works presented earlier have all attempted to evaluate the impact of natural disasters, such as oil spills. However, none of them possess the capacity to comprehensively evaluate the impact of an oil spill in the Arctic from shipping using provisions of specific Canadian indigenous regulations, like the LCA, and also capture the impact on the culture of the people. The current study seeks to predict the socioeconomic risk of an oil spill in the Arctic. The study employs a BN for the estimation of the probabilities and multiperiod model for the consequence analysis, respectively.

3. METHODOLOGY AND MODEL

The methodology is illustrated in Fig. 1. A review of the literature identifies the different factors related

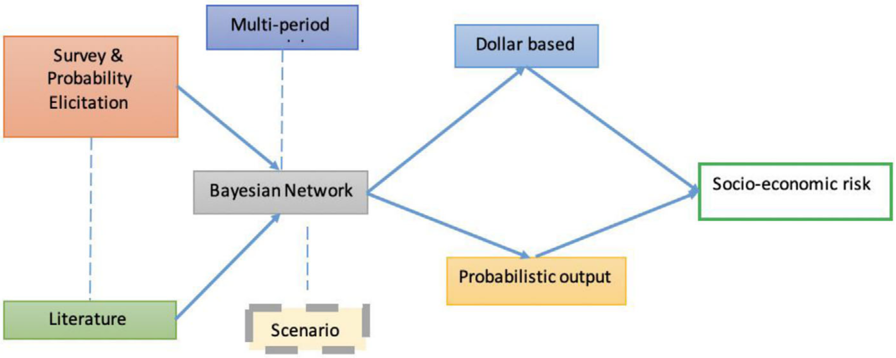

Fig 1. The methodology adopted for the development of the model. This figure shows that the first step is to conduct a literature review, which can be done in parallel with conducting a survey. In some cases, the literature review is completed before conducting the survey. Afterwards, the inputs from both the literature review and the survey are used in building the BN. This is parametrized and use to run different scenarios to produce the desirable socioeconomic impact.

to the socioeconomic impact of oil spills in open and ice-covered waters. The emphasis is predominantly on those factors contributing to the impact of an oil spill in ice-covered waters as our study is focused on an oil spill in the Canadian Arctic, specifically, the NWP where ice is present for most of the year. A survey is conducted to identify as many causative factors as possible to be included in the model. Information from the literature review and the survey become inputs to the probabilistic based model. The details of the probabilistic based model (i.e., the Bayesian model) are described later.

As described in Aven et al. (2018), risk can qualitatively be described in different ways. One of such ways is "risk is the occurrences of some specified consequences of the activity and associated uncertainties." Risk can be measured or described by the probability of an event occurring and the consequences emanating from the event for a particular scenario and time. The estimation of the probability of the event could be calculated using a range of tools. Each has its own challenges and limitations. Some of these tools include the Fault Tree and the BN. The latter is preferred due to its dynamic nature, the ability to incorporate the opinions of stakeholders and the ability to update information in the model when new data becomes available.

The consequences are designated in USD. As stated by Aven et al. (2018), there a number of matrices/descriptions. One of such specific ones is used in this article and described as Equation (1). The risk science literature points to the need for applying risk metrics based on expected values as in Equation (1) with care, see discussions in for example Haimes (2015), Paté-Cornell (1999), and Aven (2012).

$$\text{Risk metric} = \{\text{Probability} \times \text{Consequence, time, scenario}\} \quad (1)$$

These four factors are very important to describe risk. Without these factors considered together, the results would be inadequate and not addressing key aspects of risk. This risk metric is referred to as the dynamic risk as it depicts the evolution of risk of time (Afenyo, Khan, Veitch, & Yang, 2017b). The model consists of two main components: probability and consequences. The consequence component would be described first followed by that of the probabilistic element and eventually the risk model. The scenario is illustrated through the simulation shown later in the text.

To assess the risk posed by a particular scenario simulated by the risk model at a given point in time, the consequence model is combined with the probabilistic based model. This model is multiperiod in nature and, therefore, not static. From now on, it will be referred as the "multiperiod model."

3.1. The Multiperiod Model (The Consequential Component)

The consequence component of the model is multiperiod in nature and has the capability of predicting the socioeconomic impact for any time period after the incident, (e.g., 10 years from the occurrence of the incident).

The multiperiod model is an improvement on the SEMA model. The SEMA model has some challenges, for instance, the tool does not account for the

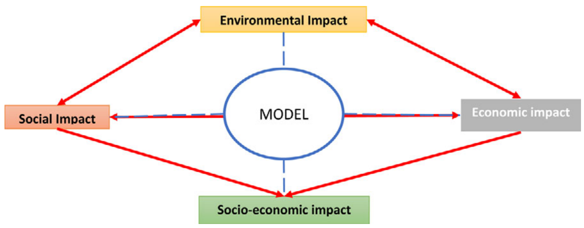

Fig 2. Main contributing factors in the multiperiod model (Consequence model). In the diagram, social impact refers to the impact of oil spills on the social set up of the communities affected; economic impact refers to the impact of oil spills on the finances and the general economic well-being of business entities and individuals in this region; and environmental impact refers to the negative implications of oil spills on the flora and fauna and other parts of the Arctic marine ecosystem. The socioeconomic impact is the combination of the social and economic impacts in the diagram.

freshly added pollutants (in this case oil). This concept is essential because the entire service life needs to be accounted for in order to accurately estimate the socioeconomic impact of an oil spill. If there is no account for pollutant (oil) discharged during different time periods, the single period predicted by the SEMA model is likely to overestimate the socioeconomic impact. Another issue of concern is the existence of the LCA between the rights holders and Canadian federal government. This document clearly outlines the compensation process for an oil spill. In our current study, this information is considered in the multiperiod model. Fig. 2 identifies the main contributing factors in the multiperiod model.

The steps involved in the development of the multiperiod model are detailed below. The single period, as described in Ng and Song (2010) and Afenyo et al. (2019), is given in Equation (2). It describes the total impact of the pollutant in a particular area at a particular time. It is an aggregation of different forms of impacts. These impacts include economic, environmental, and social. They are captured differently in terms of natural damage, economic loses, and response cost. There is also an extra cost factor that covers potential impacts that might not fall under any of the aforementioned. The equations that follow from this point onwards in the text are obtained from mathematical inference.

$$\mathrm{TC}_A = N_P + S_P + R_P + X_P, \tag{2}$$

where $N, R, S, X > 0$. TC is the impact cost in the defined area under study. A is the area under study, P is the pollutant, N is the natural damage, S is the economic losses, R is the response, and X is the other costs which do not encompass N, S, and$R$.

In Equation (3), n is the natural habitat affected by the pollutant and V_n is the unit value of the injured party, Y is the service recovery time, that is, the time spent by the injured party to recover, Q is the quantity of the pollutant released into the environment. The corresponding equation for the damage to the natural habitat due to the pollutant is as follows:

$$N_P = \sum_n V_n Q_P Y_n. \tag{3}$$

In Equation (4), i is the injured party that is affected by the pollutant. The quantity of pollutant is the sum of the previously nondecayed discharged pollutant and the newly discharged pollutant, as follows:

$$S_P = \sum\nolimits_i V_n Q_i Y_n = \sum\nolimits_i V_n Q_P Y_n, \tag{4}$$

$Q_{P,t}$ = quantity of pollutant (P) at a time, t, is expressed as

$$Q_{P,t} = Q_{P(t-1)}\,(1-d_P) + q_{P,t} + L_C + S_c, \tag{5}$$

where d_P is the rate of decay.

In order to convert Equation (5) to Equation (6), we consider that relative to a particular year t, the previous year is denoted as $(t-1)$ and the year before $(t-2)$ and so on. This inference analogy then gives rise to Equation (6).

$$\begin{aligned} Q_{P,t} &= Q_{P(t-3)}(1-d_P)^3 + Q_{P(t-2)}(1-d_P)^2 \\ &\quad + Q_{P(t-1)}\,(1-d_P) + q_{P,t} + L_C + S_c, \end{aligned} \tag{6}$$

$$\begin{aligned} Q_{Pt} &= q_o(1-d_P)^t + q_1(1-d_P)^{t-1} + \cdots q_{P(t-2)}(1-d_P)^2 \\ &\quad + q_{P(t-1)}\,(1-d_P) + q_{P,t} + L_C + S_c. \end{aligned} \tag{7}$$

The socioeconomic impact of a pollutant unit associated with the injured party, i, is given as follows:

$$\mathrm{SEI} = V_{n0}\,b + V_{n1}\frac{b\,(1-d)}{1+r} + V_{n2}\left(\frac{b\,(1-d)}{1+r}\right)^2 \tag{8}$$

where $b = Q_P Y_n$. Q_P is the quantity of discharged pollutant. Y_n is service recovery time. r is the discount rate and d is the rate of pollutant decay.

If the market price of the injured party is constant, expanding Equation (8), using least common multiple (i.e., $(1+r)$), $V_n b^2\,(1+r) = b(d+r) \times$ SEI.

Dividing both sides by $b(d+r)$ gives rise to Equation (9):

$$\mathrm{SEI} = V_n\,\frac{b\,(1+r)}{r+d} = V_n\,Q_p Y_n\,\frac{(1+r)}{r+d}. \tag{9}$$

Incorporating legal costs, social costs, and other relevant costs will translate the general equation into the following equation:

$$T_{CA} = N_P + S_P + R_P + X_P = \left(V_n \frac{b(1+r)}{r+d} = V_n Q_p Y_n \frac{(1+r)}{r+d}\right)_N + \left(V_n \frac{b(1+r)}{r+d} = V_n Q_p Y_n \frac{(1+r)}{r+d}\right)_S + \left(V_n \frac{b(1+r)}{r+d} = V_n Q_p Y_n \frac{(1+r)}{r+d}\right)_R + \left(V_n \frac{b(1+r)}{r+d} = V_n Q_p Y_n \frac{(1+r)}{r+d}\right)_X + \mathrm{LCA}, \quad (10)$$

where LCA is the value of compensation in the L.C.A.

Therefore, Equation (10) is expanded accordingly using the expanded forms of the individual costs, or losses described earlier.

Compensation, according to the LCA, is that the rights holders get 50% of the first 1.4 million USD of resource royalty per year and then 5% of any additional royalty received in that year (Anon, 1993). This is incorporated in our model.

3.2. The Probabilistic Component

The probabilistic model and subsequently the ID are improvements in the SEMA model. The factors have been revised following a survey conducted on Arctic shipping stakeholders. The model is based on the Bayes's theorem, the details of which are described by Afenyo et al. (2019). The fundamental equation controlling the ID is shown in Equation (11):

$$P(A|B) = (P(B|A) \times P(A)) / P(B), \quad (11)$$

where A and B are events, $P(B|A)$ is the probability of an event B given A. $P(A)$ and $P(B)$ are the probabilities of A and B, respectively.

The main parts of the ID are the edges, independent and dependent nodes, decision node, as well as the utility node (Afenyo et al., 2019). The utility node concept is an extension of the Bayesian theory to address group decisions. Keeney and Nau (2011) proposed a series of theories to accommodate group decision when modeling under uncertainties. In this study, the simple use of the utility node is implemented. The utility node expresses the focused preference for all potential combinations of the variables under investigation. The model's output is the highest utility (output) after setting the decisions and target variables. It expresses the focused preference for all potential combinations of the variables under investigation. This is expressed as follows:

$$M_u(Z_i) = U(V_j, Z_i) P(V_j|W), \quad (12)$$

where M_u is the maximum utility output for a particular scenario u. Z_i is the decision i made. V_j is the state of the variable. $U(V_j, Z)$ is the utility assuming that V_j is true if K_i is implemented. W is the evidence.

The independent variables are those variables, which do not rely on any other variables for their output. Dependent variables rely on other variables for their output, implying they have parents. Parents do not depend on any variables and normally stand on their own. The decision node is used to model different choices in the model. In this case, the decisions are the type of response methods to be adopted including *in situ* burning, use of dispersants, mechanical recovery and manual recovery.

The use of the Bayesian theory to solve environmental pollution issues has been well documented. Table I shows some of the applications of the BN to environmental problems. For more applications readers can refer to Barton et al. (2012).

As shown in Fig. 1, the approach adopted involves reviewing literature for background information and simultaneously conducting a survey to ascertain the knowledge base of relevant experts in the field. A sample of the survey questionnaire can be found in Appendix A. This can be modified for other studies. The combination of the literature review and survey is very important for developing the probabilistic based model. The information obtained from these exercises is then used in building the Bayesian Model to predict the probability component of the risk while the multiperiod model is used to predict the consequence of the potential oil spill in monetary terms. As pointed out by Marchenko, Borch, Markov, and Andreassen (2015), the probabilities differ from one region to another for incidents. In this study our focus is on the Canadian Arctic, hence the probabilities used are specific to outcomes of questionnaires administered mostly in the Canadian Arctic.

To build the probabilistic-based model, a second questionnaire (Appendix B) was conducted to obtain expert elicitation of probability using information obtained from the experts. The multiperiod model has as its output the cost of damage. This can be used as a standalone decision-making tool on oil spill. This model would also be useful for the courts during litigation for payment for an oil spill. It is integrated with the probabilistic based BN to form the ID. The latter is used to predict the socioeconomic

Table I. Some Applications of Bayesian Network

Study	Details
Aalders and Aitkenhead (2006)	Application of Bayesian theory and Bayesian Network to land use. Other artificial intelligence tools such as neural network and decision tree were also explored.
Voie, Johnsen, Strømseng, and Longva (2010)	Assessing the environmental risk of white phosphorous (P_4) from munitions.
Afenyo et al. (2019)	Assessing the socioeconomic impact of oil spills.
Pascoe (2018)	Assessing the economic impact of fisheries in the Great Australian Bight.
Axelson, Standal, Martinez, and Aursand (2009)	Classification of two different types of salmon: wild and farmed.
Liu and Callies (2019)	Application to response of oil spill in the German Bight.
Lecklin, Ryömä, and Kuikka (2011)	Evaluating the short and long-term impact of an oil spill in the Gulf of Finland.
Aadland, Caplan, and Phillips (2007)	Adopted Bayesian theory to update information when making decisions under uncertainties regarding information flow.
Carman and Kooreman (2014)	Applied Baye's model in the spread of diseases in public spaces.

impact of the oil spill from Arctic shipping and account for uncertainties in the model.

Below are the descriptions of the participants in the survey. The participants include representatives from insurance companies, scientists, government workers, and rights holders. This group is highly representative of people involved in Arctic shipping. The table II shows the profile and the characteristics of the people interviewed during the pilot study. Part of the pilot study was conducted while onboard a ship in the Arctic. Other participants were contacted via email and/or telephone. A total of 42 people was interviewed. The interviewees are people from Environment Canada, Laval University, University of Calgary, University of Manitoba, McGill University, Geological Survey of Canada, Insurance Bureau of Canada, Natural Resources Canada, and various indigenous communities.

Fig. 3 represents the connection between the qualitative and the quantitative questionnaires which is used in building the ID. Initially, the qualitative model is built then converted to a quantitative model forming the Bayesian model.

The qualitative model is made up of different variables which are described in Table III and illustrated by the ID (Fig. 3). While the factors are not exhaustive, they include as many variables as possible obtained from our literature review (see section 2) and the questionnaire developed for the qualitative and quantitative questionnaires in Appendices A and B, respectively. Table III shows the justification for inclusion of each of the factors as well.

For the factors to be included and to avoid bias, it needs to be identified by at least three respondents or appear in at least three scientific literary works, or

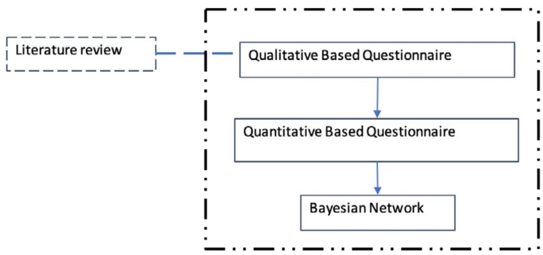

Fig 3. Connection between the qualitative questionnaire, quantitative questionnaire, and Bayesian model used in building the influence diagram. The information obtained from the literature review helps to fine tune the qualitative questionnaire. Afterwards, the quantitative model is implemented using the output from the quantitative questionnaire. This then produces the output in the Bayesian Model when initialized. Fig. 3 focusses on how the various questionnaires and literature review are linked to the Bayesian network.

a combination of both. It should be noted, however, that depending on the background of the individual analyzing the responses, there could be a slight difference in the definition of the factors. Two examples illustrate this issue. Wind, which can be classified as *calm* or *strong*, was not included as separate factor; it is captured in the Sea state variable as, *calm or turbulent sea state* (see Table III). The Polar Code is one of the most important instruments for Arctic shipping governance. It has two main parts, that is, the international convention for the prevention of pollution from ships (MARPOL) and the international convention for the safety of life at sea (SOLAS). The former deals with the environmental implications, while the latter is related to the operational aspects of the code. The variable NORDREG (meaning the

Table II. Characteristics and the Profile of Participants in the Pilot Study

Description	Code	Expertise	Education Level	Affiliation
Scientist	Sc. I	Oil spill research	Postgraduate	University of Calgary
	Sc. II	Arctic research	Postgraduate	University of Manitoba
	Sc. III	Oil spill research	Postgraduate	University of Laval
	Sc. IV	Oil spill research	Undergraduate	University of Toronto
	Sc. V	Oil spill research	Postgraduate	University of Calgary
	Sc. VI	Shipping research	Postgraduate	McGill University
	Sc. VII	Oil spill research	Postgraduate	University of Laval
	Sc. VIII	Oil spill research	Postgraduate	University of Manitoba
	Sc. IX	Arctic research	Postgraduate	Memorial University of Newfoundland
	Sc. X	Arctic research	Undergraduate	University of Laval
Government workers	GW I	Arctic survey	Postgraduate	Geological Survey of Canada
	GW II	Oil spill recovery	Postgraduate	Natural Resources Canada
	GW III	Indigenous culture	Postgraduate	Natural Resources Canada
Insurance company employee	IC. I	Marine Insurance	Undergraduate	Insurance Bureau of Canada
	IC. I	Marine Insurance	Undergraduate	Insurance Bureau of Canada
	IC. I	Marine Insurance	Postgraduate	Insurance Bureau of Canada
Coast Guard officers	CG 1-XVII	Shipping in Arctic waters, all have over five years' experience	All have passed through the training to become a full Canadian Coast Guard	All from the Canadian Coast Guard
Ship operators	S.O. I	Shipping in Arctic waters with more than 5 years' experience	Undergraduate	Amundsen ice breaker
	S.O. II	Engineering work on Arctic going ships for more than 4 years	Undergraduate	Amundsen ice breaker
	S.O.III	Engineering work on Arctic going ships for more than 6 years	Postgraduate	Amundsen ice breaker
	S.O. IV	Captain of Arctic going ship for more than 6 years	Undergraduate	Amundsen ice breaker
	S.O. V	Assistant Captain for Arctic going ship for more than 6 years	Postgraduate	Amundsen ice breaker
	S.O. VI	Engineering work on Arctic going ships for more than 5 years	Undergraduate	Amundsen ice breaker
Indigenous	I.D I	A native who has lived in the community for more than 5 years	High school leaving Certificate	Rankin Inlet
	I.D II	A native who has lived in the community for more than 5 years	High School leaving Certificate	Rankin Inlet
	I.D III	A native who has lived in the community for more than 5 years	Diploma	Chesterfield Inlet

Table III. Variables Selected and their Justification for Inclusion in the Influence Diagram

Variable	Justification
Accident	Incidents that can result in the release of oil. It was identified by stakeholders as the most potential source of release.
Age of vessel	The older the vessel the more vulnerable it is to oil release and the more expensive maintenance activities are.
Cost of compensation	This variable addresses the cost of oil spill damages to different entities. For example, it is necessary to compensate the owners of properties and individuals and families affected. The land claim agreement, for example, has a one-time fee for pollution and an incremental increase in compensation with time, depending on the extent of damage.
Culture disruption	When an oil spill occurs in the Canadian Arctic, the culture of the rights holder is likely to be disrupted. For example, some practices of worship and other ways of life may no longer take place. This can have significant implications for the relationships between individuals and groups in the community.
Days spent at sea	The more days spent on the sea, the more likely it is for the ship and the crew to pollute the sea through an oil spill and other pollutants. This variable is however a function of age of the vessel, experience of the crew, size of the ship, and the year of manufacture of the ship.
Destruction of flora and fauna	When an oil spill occurs in the Arctic the flora and fauna in the Arctic marine environment would be impacted.
Interruption of social harmony	During and after an oil spill, respondents believe the association among the community members is likely to be disrupted.
Economic effect	This variable is a sum of all factors contributing to the economic impact of an oil spill in the Canadian Arctic.
Effect on water supply	Some communities in the Arctic rely on desalination for drinking water. However, for the respondents, desalination of water does not take place in the Canadian Arctic. Therefore, the effect of an oil spill on drinking water is minimal.
Environmental effect	This variable is the sum of all the contributing factors in terms of how the environment is affected in response to an oil spill in the Canadian Arctic
Experience of crew	This variable measures how long the crew have been involved in shipping in the Arctic. Officers identified experience as very important to a successful Arctic shipping voyage. Without experience the potential for an accident is very high.
Geography of voyage	Depending on the location of the vessel in the Arctic, the likelihood of a spill is higher compared to other places in the world according to the respondents.
Hole size	This variable describes the size of the hole indented in the ship as a result of an accident from shipping in Arctic waters.
Hull	The thickness and the type of hull plays a significant role in preventing the release of oil in the Arctic waters.
Hunting disruption	The rights holders rely extensively on hunting for meat. An oil spill in this region would affect this activity and possibly result in a cessation of hunting until clean-up is completed.
Ice cover	The presence of ice cover impedes, delays, and increases the cost of response efforts.
Legal cost	The legal costs involved with the consequences of an Arctic oil spill
Location	Recovery of an oil spill in a remote location with limited accessibility would be more difficult than a spill near a community with easier access for recovery teams.
Level of trust	Trust between the Canadian Federal Government and the rights holders may be significantly affected if there are delays in the recovery.
NORDREG Zone	The Arctic has been designated into special zones to protect the pristine environment as well as species in this region. Due to region-specific regulations, recovery costs are likely to be higher if a community or affected location is within one of these special zones.
Personnel	This variable refers to preidentified and pretrained, oil spill recovery personnel. Factors affecting this variable include whether there are enough personnel and personnel with appropriate skill sets to deal with the recovery process.
Piracy	Marine piracy is not currently an issue in the Arctic. However, increased shipping in these waters may provide an opportunity for this criminal activity.
Psychological effect	This variable seeks to measure the mental effect of the oil spill on the locals. This may be in the form of depression and other psychological related disorders.
Quantity of oil	The amount of oil released is a key variable to the impacts of the oil spill. The more oil released the higher the impact.

(*Continued*)

Table III. (Continued)

Variable	Justification
Recovery method	This is a decision node. It covers the potential recovery methods that would be employed. This includes the dispersant use, *in situ* burning and mechanical recovery (use of headers and booms).
Release	The seepage of the oil into Arctic waters is represented by this variable.
Response	This variable deals with the level of response; that is whether responses that are quickly put into place versus those that are slow to be put in place possibly due to poor organization.
Response equipment	The response equipment variable encompasses the quantity of equipment and their availability.
Sea state	This describes the conditions of the sea, in terms of its calmness or roughness.
Season	The seasons refer to the four seasons.
Size of ship	The size of the ship could determine the quantity of oil spilled.
Social disruption	This variable refers to the social make-up of the communities affected by the oil spill.
Social effect	This variable is the sum of all the effects of the oil spill in a social context.
Socioeconomic impact	This variable encompasses the social and economic effects.
Speed of vessel	The speed of the vessel is known to be contributing variable in the economic effect.
Temperature	The air and water temperature are described by this variable.
Thickness of material	The thickness of material used in the construction of the vessel could determine how much damage may be done to the hull of the ship and, subsequently, the hole created in the hull through which the oil is released.
Time	The time variable addresses the time it takes for help, or response to arrive to the oil spill site and the ship.
Type of engine	The type of engine in the vessel can also affect the vessel speed and, to some extent, the economic impact.
Type of hydrocarbon released	This refers to the type of hydrocarbon released in the spill.
Type of oil	This variable covers the type of oil released in the spill; light, medium, heavy, or extra heavy.
Type of ship	The purpose of a ship depends on the type of ship. For example, the purpose of a tanker is to move oil. Purpose of tugboat is to guide larger boats. This can also influence the speed of the vessel and to some extent the economic impact according to the respondents.
Year of ship manufacture	The year of manufacture can also influence which laws applies to its operation and subsequently, days spent on the sea. Very old ships have a higher risk of more serious consequences when an accident occurs.

Northern Canada Vessel Traffic Services Zone) was used as a proxy for the Polar Code, as it covers most aspects (i.e., the environmental as well as the operational provisions) of the Polar Code for the Canadian Arctic. The environmental part has been addressed through several factors like the “destruction of flora and fauna,” “season,” “effect on water supply,” “environmental effect,” “recovery method,” “season,” and “type of hydrocarbon released.” The operational factors taken into account in our model include “type of engine,” “speed of vessel,” “type of ship,” “age of ship,” and “hull.”

Furthermore, it is noted that since heavy fuel oil (HFO) is to be banned for this area in the coming years, it has not been considered in the model and subsequent analysis.

The model validation is implemented in two stages: (i) after the qualitative model was developed it was shown to a group of stakeholders to make sure it represents what happens in the Canadian Arctic, in terms of shipping, oil spill, and indigenous knowledge; (ii) part of the data was used to test the output of the model and the feedback on the output was also validated by the same group of stakeholders. The studies by Nuka Research (2021) on the Baffinland Bulk Carriers Spill Scenario has been used as a guide to predict the model’s output. Furthermore, although during the qualitative validation the stakeholders agreed that the logic of the model was sound and it integrated rather nicely all the potential factors that could be considered, they have pointed out the possibility of missing out on some potentially important factors. For example, since Arctic development is still evolving, there is always going to be new things required to be incorporated. The positive side of using the Bayesian Model for this study is that, should changes occur in the future, the model can be updated. A variable named “Polar Code” is missing in the model. However, the focus of this study is a regional one, therefore the NORDREG variable covers most aspects (i.e., the environmental as well as the operational provisions) of the Polar Code for the Canadian Arctic. Approximately 20% of the data collected was used for the validation exercise. In the future, more data will be collected to improve the accuracy of prediction so as to increase the confidence in the model structure and results. The data used for the model testing and validation are consistent. In particular, the same form and structure of data is used (i.e., both quantitative and qualitative data).

3.3. DEMONSTRATION OF THE MODEL AND RESULTS

We assess our model to estimate the socioeconomic impact of an oil spill over five years by simulating the conditions of the *Exxon Valdez* in the Rankin Inlet region located in the Canadian Arctic (Fig. 5). Rankin Inlet has been selected because it is a critical regional hub for Arctic shipping and has been receiving increased shipping traffic since 2010. The population and other demographics of this region are reported by Statistics Canada's census profile for 2016.[4] Some of the notable information in the census includes the following:

- As of 2016, the regional population was 3,847, with a growth rate of 4.1% (2011–2016).
- The unemployment rate in this area was 5.4%.

The following oil spill conditions were used in our model:

- a spill of 10.8 million U.S. gallons of oil
- 3,364 USD cost of psychological distress (Chui, Lebenbaum, Cheng, De Oliveira, & Kurdyak, 2017) per capita
- cost of crime estimated at 461.23 USD[5] per capita in Canada (Eaton, Furness, & Brantigham, 2014)
- a rate of 0.02133 $\frac{mg}{Lhr}$ for the biodegradation of naphthalene (proxy of oil) (Zhang & Bouwer, 1997)

These conditions were then used in the model to predict the socioeconomic impacts of the Rankin Inlet region for the next five years. The calculation for the social discount rate is 0.035. This value is the discount rate used to bring the future social impacts described in the case like crime, alcoholism related diseases, to the present value in monetary terms. The discount rate 0.035 was used because the projection of the analysis is less than 50 years; this meets the criteria for social discount rate proposed by Moore, Boardman, Vining, Weimer, and Greenberg (2004). We assumed the LCA's royalty to be three million USD for the first year, and five million USD for each subsequent year up to year five.

3.3.1. *Analysis of the Case*

Using the equations derived earlier for both the multiperiod model and combining it with the probabilistic model, the following equations are added to those presented earlier for evaluating the current scenario (Kim, Opaluch, Moon, & Petrolia, 2017):

$$\text{Socioeconomic Impact } (S_p) = V_s\, b\frac{(1+r)}{(r+d)} = V_s\, Q_P Y_n \frac{(1+r)}{(r+d)}, \quad (13)$$

$$\text{Natural damage } (N_P) = V_n\, Q_P Y_n \frac{(1+r)}{(r+d)}, \quad (14)$$

$$\text{Response } (R_P) = \left[V_p \sum_{t=P_0}^{T_L} \frac{P_t}{(1+r)^{(t-P_0)}} \right], \quad (15)$$

where $V_s$is value per unit amount of resource services provided to injured habitat; V_p is value per unit amount of resource services provided by restored habitat; $P_t$is restored amount of habitat at time t; $P_0$is time when restoration projects begin; $T_L$is final time restoration services are provided; $r$is discount rate a value 3.5% (Boardman, Moore, & Vining, 2010).

For legal damage cost as described in the Oil Pollution Act (OPA) of 1990, tank vessels larger than 3,000 gross tons is increased to 1,200 USD per gross ton, or 10 million USD whichever is greater.

Simulation of this scenario was done using the ID (Fig. 4) in GeNIe Software.

4. Results

The response from the survey questionnaire shows that many of the participants identified similar factors that contribute to oil spills. These factors are presented in Table III. Most of the respondents agree that if nothing is done to prevent oil spills, the results can be devastating. The responses to the ques-

[4]Statistics Canada (2016). Census Profile, 2016 Census: Nunavut, Rankin Inlet, and Manitoba. Accessible at: https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/details/page.cfm?Lang=E&Geo1=POPC&Code1=1320&Geo2=PR&Code2=46&Data=Count&SearchText=Rankin%20Inlet&SearchType=Begins&SearchPR=01&B1=All

[5]The original cost was set in Canadian Dollars (CAD). The exchange rate for Canadian Dollar to the US Dollar is 1 CAD = 0.77 USD (based on the rate in April 2021).

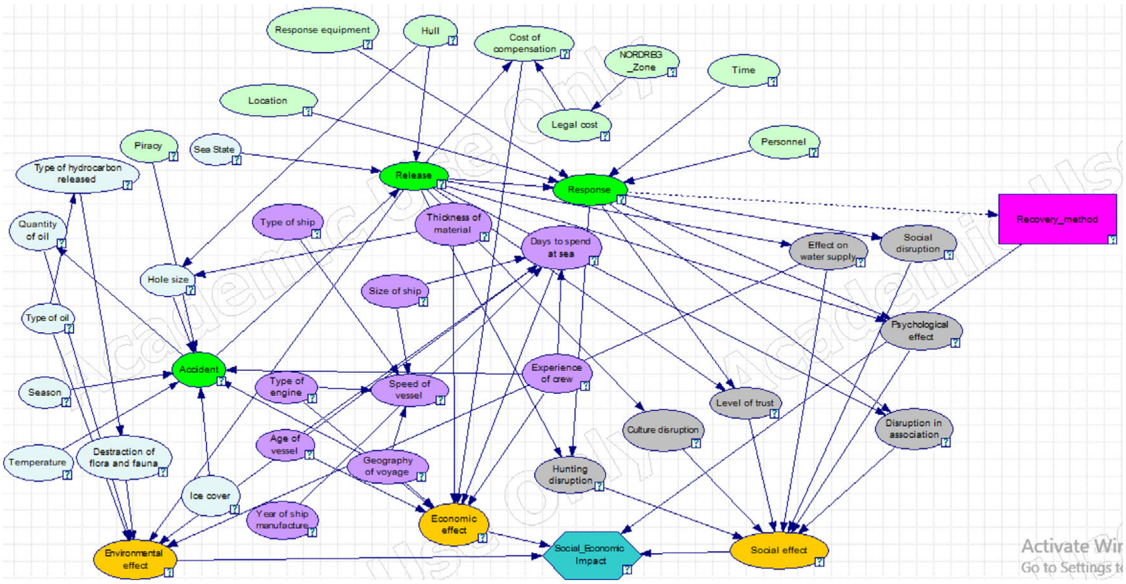

Fig 4. The influence diagram for the impacts of a ship oil spill on the Socioeconomic impacts in the Canadian Arctic.

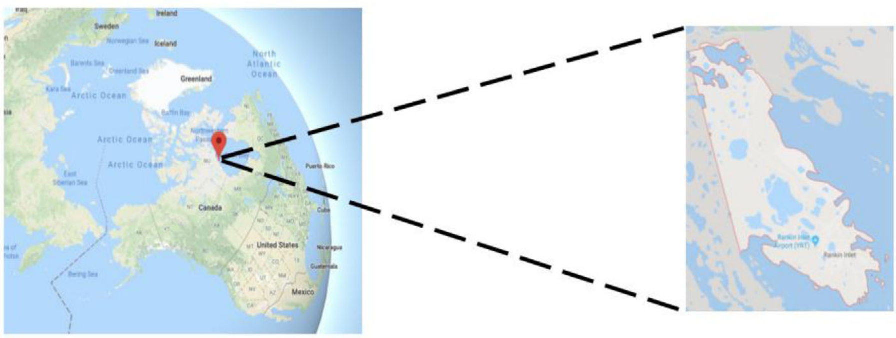

Fig 5. The location of the Rankin Inlet region. Source: Photo courtesy: https://es.123rf.com/photo_5022659_canad%C3%A1-mapa-vector.html and google map.

tionnaires show that the Arctic is not ready for regular shipping through the NWP.

Furthermore, the methodology presented is unique and offers a tool that could help address this issue. The results of the study show that there is a gradual increment in the socioeconomic impact with each successive year due to an accumulation of oil along the coast, the passage itself, and the habitats of marine organisms (see Fig. 6).

This is very true as we can see the first year recorded approximately 500 million USD in impacts, and this Fig. increased to approximately 1.5 billion USD in the second year. This jump between the first and second years shows an accumulation of the previous year's impact to that of the second year. Damage to the natural flora and fauna, negative effects

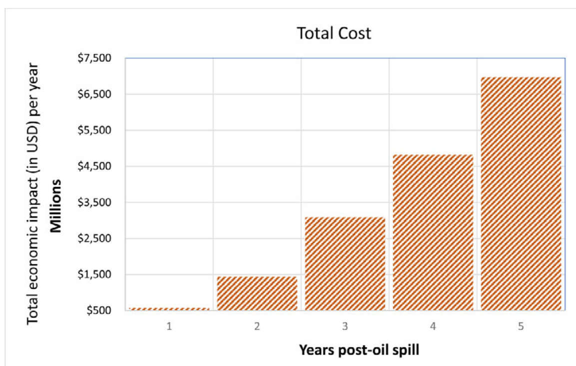

Fig 6. Simulated total cost of socioeconomic impact of oil spill in Rankin inlet region. Fig. 6 shows the results of the socioeconomic impact simulation, in USD dollars, for five years following an oil spill in the Rankin Inlet region.

on hunting, local economy, cultural and social activities, and negative psychological effects on individuals will contribute to greater legal costs and those costs involved in the LCA. By the second year the number of claims will increase, more people will leave their homes, more jobs lost and in cases where new jobs are secured in other places, the cost of relocation is a lot and will not easily offset the lost. This trend continues to the third and fourth years and so on.

It should be noted that our results assume that no recovery efforts were conducted based on the Monitored Natural Attenuation (MNA) intervention. MNA allows nature to deal with the oil being spilled. At a certain point in the future, the environmental impact may subside, but the legal and social implication increases. The impacts may follow the same trend but with less consequences even if other recovery methods were introduced. Thus, in the long term the environmental effect may be minimized, but the overall social and economic impacts linger on. Another interesting thing to note is that no two years recorded the same impact. Even taking only a particular year alone, the current year always records a higher impact. This is because apart from the previous years accumulated impact, the more the oil remaining in the system, the greater the impact on the Arctic marine ecosystem. Fauna and Flora will die miles away when they encounter the toxic oil released. These are not accounted for in the previous years. Also, the spread of the oil increases with time as the sea waves and the wind drives oil slicks and plumes miles away from the point or area of release.

This article does not present results of the intervention of the other oil spill response activities and technology as the aim is to examine what the impact will be without any intervention. This will give the worst-case scenario and would be the best scenario to use in making decisions for insurance, resource allocation, and contingency planning. Also, a worst-case scenario analysis gives decisionmakers the opportunity to put in place intervention that will help mitigate risks to bare minimum.

4.1. Discussion

The multiperiod model is a tool that helps to determine a fair compensation on the socioeconomic impacts of a region following an oil spill. More specifically, it allows a multiperiod assessment of the socioeconomic impact, that is, over a period of days, weeks, months, years or even decades.

The result of the simulated oil spill in our case study demonstrates that the socioeconomic impacts of the spill increase continuously and, indeed, accelerate in subsequent years if there is no intervention (i.e., allowing only for natural attenuation). The socioeconomic impacts may be reduced should a recovery intervention take place.

To achieve minimum negative socioeconomic impacts in response to an oil spill, stringent enforcement of regulations is urgently required. In the case of the Rankin Inlet region and the NWP, the challenge will be how the Canadian federal government should collaborate with indigenous people to respond rapidly to an oil spill. The Chiefs and the Hunters and Trapper's Association would have to be involved in the coordinating efforts with the Canadian federal government and the Coast Guards. The LCA would have to be updated to better reflect the changing dynamics of the Arctic so that the impact is reduced to bare minimum. For example, the indigenous people and the Canadian federal government would need to insist on approving response and contingency plans of companies operating in this region before allowing them to embark on shipping and natural resource exploration activities in the area. Furthermore, training programs on the culture of the people in the NWP need to be conducted for any crew, or individuals who would work in this region. The potential work to be done includes shipping and hydrocarbon exploration and production.

As demonstrated by the recent Mauritian and the famous Deepwater Horizon oil spills which occurred in the Gulf of Mexico, substantial damage could occur if response to the spill does not come in a timely manner. In the case of the Mauritius oil spill, cleaning and other response efforts were largely done by the local population and communities. The polluter (Mitsui OSK) contributed a small amount to response efforts and only promised about USD 9.4 million, well below the 34 million USD the Mauritian government is looking for. In countries where governmental regulations are more strongly enforced, such as Canada and the United States, companies are more likely to be held responsible for oil spills. For example, British Petroleum (BP) was held fully accountable for the oil spill that occurred in the Gulf of Mexico in 2010. BP was fined 20 billion USD while other cleanup activities cost 40 billion USD. As of 2013, Canada raised the cap for oil spill liability to one billion USD (McCarthy, 2013).

Also, there is an urgent need to develop a good communication network between indigenous nations within the region, the Canadian federal government, and companies that are looking to work in the region. This could facilitate communications between the appropriate authorities and decision-makers in an oil spill or other natural disaster. Furthermore, there is a need for proper training of local, indigenous people and others involved in oil spill response efforts in the Canadian Arctic.

The results from the model require further output validation by stakeholders and right holders. Another way of improving upon the results would be to employ a value-based approach for estimating the intangible factors like "culture". The concept of the value-based approach is assigning values based on perceived impact of variables.

5. Conclusions

The challenge related to oil spill impact is one that keeps changing. From estimating the impacts of an oil spill to devising a scientific scheme to compensate affected communities and individuals. Even more challenging is the problem of impact of oil spills on the indigenous social set up. This study seeks to answer those questions. When these challenges are answered in an Arctic setting, it becomes even more important considering the scarce data and information available about this region. Compared to the SEMA model in Afenyo et al. (2019), the multiperiod model developed in this study is more accurate and comprehensive. Furthermore, the multiperiod model addresses the concerns of the indigenous communities in that it encompasses specific indigenous culture in the Arctic, incorporates regulations that dictate fair compensation to the indigenous community through the LCA. Rankin Inlet region and, indeed, other areas with similar social and physical conditions in the Canadian Arctic could benefit immensely from the model's output for planning and response of oil spill purposes.

In fact, oil spills due to shipping present even more challenges especially for ship operators and insurers in different regions around the world. For example, the Mauritius oil spill that occurred recently shows how the negligence of a captain and lax international laws can cause devastating environmental, economic, and social effects on the communities affected. For Arctic shipping accidents, the consequences would be even more devastating. Insurers were at a lost as to what to do while there was no law to hold the company accountable. Mauritius only received economic aid and little help in terms of dealing with the spill. In the end, the people of Mauritius took matters into their own hands and devised crude means to try and clean the oil since they are the ones feeling the effect of the spill. The polluting company is far away in Japan and the captain will face no serious consequence. Therefore, it is in the best interest of governments to be proactive and prepare for emergency response for potential oil spills. The current tool developed in this study is an answer to this problem.

Today Arctic shipping continues to be a controversial issue. There are many indigenous groups, including the Inuit, who believe that Canadian Arctic waterways should only be used in a way that respects the culture and interests of the indigenous communities (Boyd, 2020). However, despite recent opposition to shipping in this region (Boyd, 2020), there are others that are in favor of this activity. Some rights holders view the opening of the Arctic as an opportunity to develop the region. They argue that exploring the natural resources and taking advantage of the shipping activities will open up the region to trade and thereby creating jobs. Furthermore, with an increased accessibility to the area by different organizations both local and foreign investments will flow easily into developing this region.

In comparison to the NSR (especially along the Russian coastline), shipping infrastructure in the Canadian Arctic is much less developed. However, based on the success of the Yamal LNG project, it may be only a matter of time before similar projects become possible along the NWP. Despite the risks, shipping along the NWP is still justified as it would create substantial opportunities for the local population, as well as increase accessibility to food and other essential commodities. In addition, the blockage of the Suez Canal and the economic implications by the mega-sized containership *Ever Given* in early 2021 further supports the notion that alternative shipping routes might be necessary to support the global supply chains. For this to occur, the availability of a comprehensive socioeconomic assessment tool is an absolute necessity. Thus, our model is a key tool to address this issue, as it enables government and industry to study the socioeconomic impacts of an oil spill over time and in a variety of scenarios accurately and comprehensively. Such information will be pivotal in making key decisions on the future of shipping in the Canadian Arctic, and the Arctic region as a whole.

There is need for significant investments by the Canadian provincial, federal governments, and private companies, presumably in shipping infrastructure, environmental protection, and emergency response systems. Of course, there is always a question on whether the government and industry are ready to commit substantial financial resources into a sparsely populated area. Furthermore, it is subject to debate on whether such investments would really lead to significant increase in employment opportunities and economic benefits for the local population. These are pressing issues that need to be addressed in future research.

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APPENDIX A

Questionnaire for Qualitative Interview

Part A: The overview of Arctic shipping and oil spill

A1. In your opinion what are the benefits of Arctic shipping? For example, to the government, First Nations, and other communities along the Arctic shipping routes *(Northwest Passage & Northern Sea Route)?*

A2. What are the consequences of an oil spill from shipping on the Arctic marine environment? Your description could be economic, social, regulatory, and environmental in nature.

Part B: Environmental related risk factors

B1. In your opinion what are the potential risk factors to the environment. What are the things that could cause an impact on the environment when an oil spill occurs from Arctic shipping? For example, the type of oil spilled and the presence of ice *[Please outline as many as possible]*

B2. Of the many factors you outlined, which of those do you think are the most critical in terms of likelihood and consequence?

B3. How do you think the above factors are related? Do some of risk factors depend on each other. If yes, which of them and how?

B4. Which response measures are you currently aware of as viable for dealing with oil spill in ice (e.g., use of dispersants, *in situ* burning, mechanical recovery, and natural attenuation)?

B5. What is your opinion about how the risk factors identified could be mitigated and incorporated into policy when planning terms of government policy, International Maritime Organization (IMO) laws and domestic environmental laws?

Part C: Social and psychological-related risk factors

C1. Oil spills affect the social structure of the affected communities. What factors do you think are responsible for this? What extra factors would you add in the case of the Arctic? *[Please outline as many as possible]*

C2. Of the factors you have identified in C1, which of them are the most critical?

C3. How are the factors you have identified in C1 related to each other? How does the occurrence of one affect the other?

Part D: Economic/financial and legal risk factors

D1. What factors account for the economic impacts of an oil spill from shipping accidents in the Arctic? *[Please outline as many as possible]*

D2. What are the factors to consider when insuring a ship? What extra factors do you think would be considered in the case of shipping in the Arctic? *[Please outline as many as possible]*

D3. How does the legal regime impact the economic implication of an oil spill?

D4. What factors would you consider determine the legal costs of an oil spill in the Arctic? *[Please outline as many as possible]*

D3. How are the factors identified related to each other?

APPENDIX B

Questionnaire for Quantitative Interview

Answer the following questions by indicating on a scale of 1–10, what your response will be. Where 10 means a certainty and 1 no chance at all.

(1) What is the probability that there will be an event of piracy in the Arctic?
(2) What is the probability of having a double hull ship navigating the Arctic?
(3) What is the likelihood that response equipment is located near the area of spill in the Arctic?

(4) What is the probability of having an inexperienced crew taking charge of an Arctic shipping voyage?
(5) What is the probability of having ice cover during the period of navigating in the Arctic (a year period)?
(6) What is the probability of having a disruption to the culture when a large quantity of oil is released?
(7) What is the probability of having a disruption to the culture of this area assuming there was a low amount of oil released into marine environment?
(8) What is the probability of having a reduction in water supply in this area assuming there was a high amount of oil released into marine environment?
(9) What is the probability of having a reduction in water supply in this area assuming there was a low amount of oil released into marine environment?
(10) What is the probability that if the released hydrocarbons are toxic, it will result in the destruction of flora and fauna?
(11) What if the released hydrocarbon is less toxic?
(12) What is the level of interruption of social harmony given that the response to the oil spill was prompt from a large amount of oil released?
(13) What is the level of interruption of social harmony given that the response to the oil spill was prompt from a low amount of oil released?
(14) What is the level of interruption of social harmony given that the response to the oil spill was slow from a high-level release?
(15) What is the level of interruption of social harmony given that the response to the oil spill was slow from a low-level release?
(16) What is the level of hunting disruption given that the response to the oil spill was slow from a high-level release?
(17) What if the scenario in question 11 is true but the release is low in volume?
(18) What is the level of trust, given that the response to the oil spill was slow from a high-level release?
(19) What is the level of trust, given that the response to the oil spill was slow from a low-level release?
(20) What is the level of psychological effect given that the response to the oil spill was slow from a high-level release?
(21) What is the level of psychological effect given that the response to the oil spill was slow from a low-level release?
(22) What is the probability that the resultant damage from a grounding incident involving a single hull ship made of thin material will be a large hole in the hull?
(23) What is the probability that the resultant damage from a grounding incident involving a single hull ship made of good material will be a large hole in the hull?
(24) What is the probability that the resultant damage from a grounding incident involving a double hull ship made of thin material will be a large hole in the hull?
(25) What is the probability that the resultant damage from a grounding incident involving a double hull ship made of thick steel will be a large hole in the hull?
(26) What is the probability that the resultant damage from a grounding incident involving a double hull ship made of thin steel will be a small hole in the hull?
(27) What is the probability that the resultant damage from a grounding incident involving a double hull ship made of thick material will be a small hole in the hull?
(28) What is the legal cost if the response equipment is closer to the place of occurrence of the spill?