Chapter 10

Assessing the risk of potential oil spills in the Arctic due to shipping

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1 Introduction

The effects of climate change can be positive and negative. The negative side includes flooding, heat waves, extreme temperatures in some jurisdictions, wild fires, draughts, and tropical storms (Ng et al., 2018). The potential positive side, however, is the melting of ice in the Arctic at an unprecedented rate. This means that the Arctic is gradually becoming ice-free in the summer season and so the likelihood of increased activities of maritime transportation and resource exploration is high (Afenyo et al., 2017a). These activities translate to economic and social improvement in the lives of the populace living in this area. The shipping industry, for example, has already recorded an increase in the number of ships being built to take advantage of this opportunity. Recent industry news shows that many companies have signed in an order for vessels to be built for Arctic voyages. However, these opportunities, along with the economic implications, also bring with them the risk of a potential oil spill (Afenyo et al., 2017a). An oil spill has environmental and socio-economic implications for the affected area and people. For the local communities, it may even go as far as affecting their culture. The oil spill affects the reproductive cycle of species and disrupts the social make-up of the affected communities (Afenyo et al., 2016a). It is therefore important to assess the risk to make decisions for resource allocation, contingency planning, and response (Lee et al., 2015). In fact, some researchers have even advocated the idea of no shipping in the Arctic. This view is refuted by another group that sees the opportunity as a way to open up the remote areas that are linked to the Arctic for economic benefits. Furthermore, for security and strategic planning for Arctic countries, it would be unwise to lag behind while other countries advance in this regard (Ng et al., 2018).

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With the above opportunities and challenges there is need to assess the risk of a potential oil spill in the Arctic. However, there are some challenges that include: (1) spill is a rare event and so difficult to track; (2) uncertainty and variability in climate conditions affect how the fate and transport of the potential spill is predicted; (3) there is limited data on terrestrial conditions which is critical for fate and transport modeling; (4) there is variability and uncertainty on receptor (ecological or human) data which is critical for exposure modeling; and (5) there is limited (no) data on the toxicity of ecological (aquatic and terrestrial species) for different contaminants, which is critical for risk estimation.

The issues related to the effect of climate change in the Arctic has prompted policymakers, industrial practitioners, and academic researchers to work together to generate knowledge on such. The activities carried out by some of the authors of this book include the International Workshop on Climate Change Adaptation Planning for Ports, Transportation Infrastructures, and the Arctic (CCAPPTIA) workshop held in Winnipeg, MB, Canada, in May 2018. The workshop was a key gathering forum for top academic and industrial players. Furthermore, some oil and gas companies and academia have worked together on the Arctic Response JIP (Camus and Smith, 2019). This project has generated significant knowledge on the subject matter. This is a follow-up to the pioneering work of SINTEF and other oil and gas companies (Faksness et al., 2011). Such collaboration only goes to show how urgent the issue of oil spill has become to the Arctic community. Further, the Microbial Genomics for Oil Spill Preparedness in the Canadian Arctic (GENICE)[a] project, which aims to address risk factors related to oil spill in the Arctic, is another flagship project by researchers in Canada. Emphasis is placed on shipping in the Arctic. The consortium is made up of the University of Manitoba, University of Calgary, McGill University, and the University of Ottawa (see https://www.genice.ca/).

Dealing with oil spill is a problem that often involves a lot of resources and personnel. It becomes even more challenging when there is the presence of ice where the oil is spilled (Lee et al., 2015). This is the case because in ice-covered waters, oil behaves differently. Generally, the processes of weathering and transport that occur after the release of oil are slow compared to a scenario where ice is not present. Releases are mostly from pipeline rupture, blowouts from oil and gas production, and exploration and shipping (Afenyo et al., 2016b).

The rest of the chapter is structured as follows: Section 2 describes the concept of risk; Section 3 presents the potential ways to conduct source, fate, transport, and exposure modeling of hydrocarbons from oil spills; Section 4 addresses the uncertainties and variabilities. To demonstrate the tools for oil spill modeling a scenario is presented for such purpose; this is followed by Section 5 where the scenario is analyzed with the description of tools. Discussions and conclusions are presented in Section 7 while future works are discussed in Section 8.

a. A Genome Canada sponsored project which is aimed at using genomics for oil spill mitigation in the Arctic. The project is worth $10.4 M and is for a period of 4 years.

2 The concept of risk

In order to assess the risk of oil spills, a number of tools are employed which represent the focus of this chapter. At each critical stage of the oil spill phenomenon, the tools available are contextualized and demonstrated. It is noted that the focus of this chapter is the release from Arctic shipping activities. Pipeline and blowouts are not addressed, although the principles and tools described here can also be applied to pipelines and blowouts with slight modifications. While risk can be static and dynamic in nature, the key determinants are almost the same, except that in describing dynamic risk, its evolution with respect to time and space is taken into consideration. Static risk is defined in Eq. (1):

$$\text{Risk} = F\{s(c,f)\} \tag{1}$$

Eq. (1) shows that it is a function of the particular scenario under study, a consequence of the event, and the frequency or probability of that particular event. In Eq. (1), s represents the scenario; c, the consequence; and f, the frequency or probability. Fig. 1 shows graphs of dynamic and static risks.

Ideally, risk is dynamic in nature and so should be treated as such. Risk can be incorporated in every stage of the engineering process. This includes conceptual design, detailed design, installation, and operation. The dynamic risk is described by Eq. (2) and it contains an element of time as illustrated in Fig. 1B.

$$\text{Dynamic risk} = F\{s(c,f),t\} \tag{2}$$

The process of risk modeling for an oil spill from shipping involves source modeling, fate and transport modeling, and exposure modeling.

3 Source, fate and transport, partition, and exposure modeling

The process of source modeling can be challenging as the release changes with time. Fig. 2 shows some factors to be considered for the source modeling process. Source modeling here entails the release and subsequently leads up to dispersion.

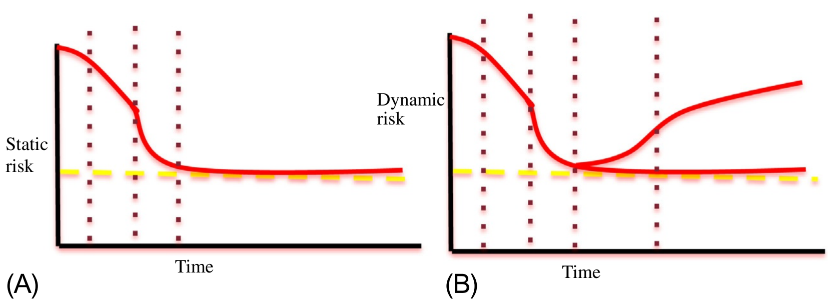

FIG. 1 (A) Static risk shows risk remains unchanged with time and (B) dynamic risk demonstration. Evolution of risk with time.

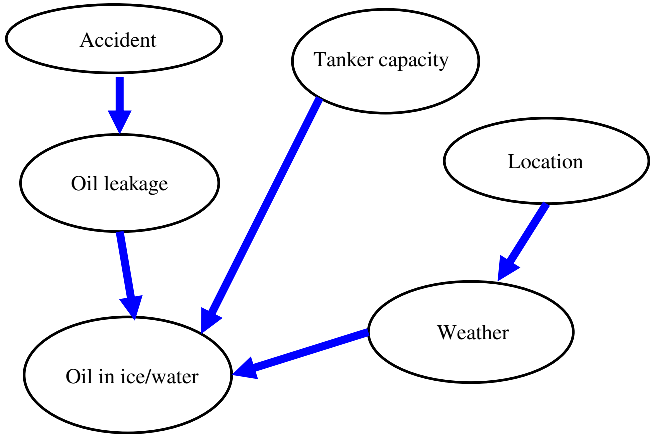

FIG. 2 Factors to consider when undertaking source modeling.

Following the source modeling is the dispersion modeling. Dispersion modeling describes how much distance the pollutant (oil) could travel in a given time after the release of hydrocarbons. Fig. 3 is taken from Afenyo et al. (2017a) and shows the dispersion of oil from a vessel. The dimensions of the plume of the pollutant are very important. In order to describe this mathematically, Eq. (3) is used.

$$C(r,t,x,y,z) = Q\frac{\exp\left[\frac{-(x-Wt)^2}{4D_x t}\right]}{\sqrt{4\pi D_x t}}\frac{\exp\left[\frac{-(y)^2}{4D_y t}\right]}{\sqrt{4\pi D_y t}}\frac{\exp\left[\frac{-(z)^2}{4D_z t}\right]}{\sqrt{4\pi D_z t}} \tag{3}$$

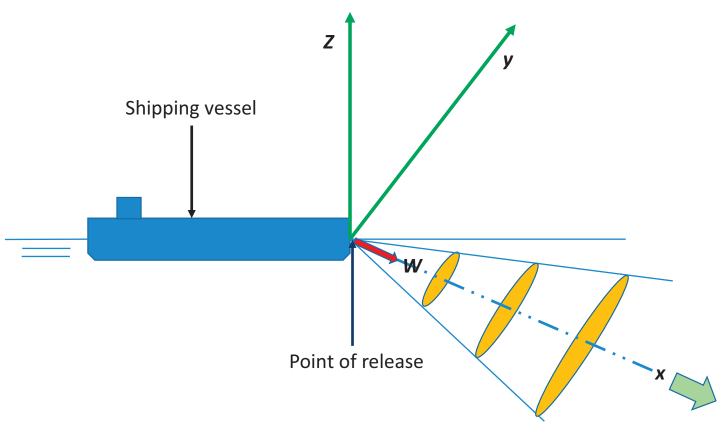

FIG. 3 The release and subsequent dispersion of oil from a vessel. *(Courtesy of Pixabay.)*

where Q is the quantity of the oil released per area, W is the wind speed, t is the time, and D is the dispersion coefficient. Once the oil is dispersed, it begins to partition into different media and considering the scenario we are looking at, it would involve four media: air, ice, water, and sediment. This is shown in Fig. 4.

The partitioning of the oil in different media can be modeled using different methods. One of the more modern and the most efficient approaches is the use of Computational Fluid Dynamics (CFD). The CFD involves the use of equations in specific software to model fluid flow. This however requires thorough verification and precise equations. Some of the most popular software for CFD include ANSYS fluent, Autodesk CFD, and SolidWorks Flow Simulation. Another method is the fugacity approach. The approach is based on the fugacity concept. Fugacity is basically described as the escaping tendency of a chemical (Afenyo et al., 2016a). It is analogous to partial pressure. The relationship describing the concentration of the released oil and the fugacity is described in Eq. (4) (Mackay, 2001). The equation to describe fugacity can be found in Eq. (4).

$$C = Z \times f \tag{4}$$

where C is the concentration (mol/L), f is the fugacity (Pa), and Z is the fugacity capacity (mol/L Pa). Here, it is important to note that a medium with a higher

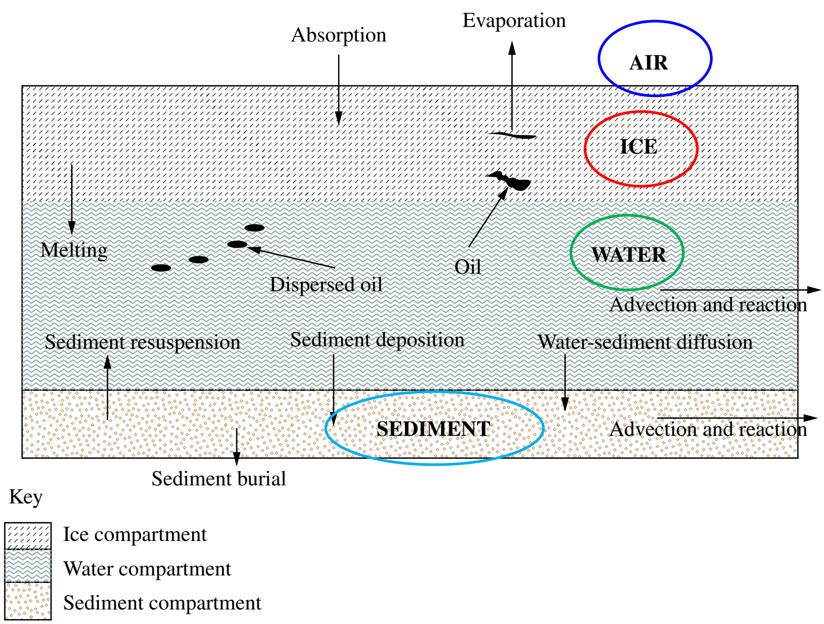

FIG. 4 Different processes and media involved when oil spills in ice-covered waters. *(From Afenyo, M., Khan, F., Veitch, B., Yang, M., 2016a. Dynamic fugacity model for accidental oil release during Arctic shipping. Mar. Pollut. Bull. 111(1–2), 347–353.)*

fugacity capacity has a high tendency to absorb more chemicals and vice versa. The fugacity-based models are divided into four distinct types namely levels 1, 2, 3, and 4 (Afenyo et al., 2016a). The focus of this chapter is the Tier IV fugacity model. This approach gives the modeler the opportunity to calculate the concentration of the pollutant with time. The result of the partition modeling is the concentration of the oil in different media. It is termed as the Predicted Exposure Concentration (PEC). This is subsequently used to estimate the level of risk in the various media described earlier.

Exposure modeling involves the assessment of oil concentration and its existence in the media of contact. In marine species, pollutant existence could be due to inhalation, ingestion of contaminated water and food, and absorption of hydrocarbon. In dynamic risk assessment, the study of temporal variability of the exposure and fate of the spilled oil is important. Season and temperature variations are temporal variables in such environments. Although the concentration in species is not the subject of this chapter, the information from such a study is used to determine the Predicted No Effect Concentration (PNEC). An oil spill in the ocean can be lethal to birds, fishes, mammals, and other marine organisms due to toxic components present in oil. An oil toxicity data and a robust toxicity model can support ecological risk assessments of spilled oil and environmental impact assessment of spills. The toxicity of oil to marine species depends on species presence and the extent of exposure of the toxic oil component. Species presence and toxicity is a function of time, space, and concentration.

The problem is that there is very limited data of oil toxicity of aquatic species in cold regions. To evaluate the risk to marine species, exposure concentration may not be sufficient. There is a need to evaluate the concentration of oil in the body of species exposed to oil. This concentration is responsible for deaths of species under study.

Dynamic risk helps to assess and manage risk in evolving conditions. It is quantitative in nature and enables the capturing of uncertainty. Also, it assists in modeling scenarios with limited data. Once the level of concentration of oil in the different media is determined, it is used to estimate the level of risk in each medium. This is achieved by comparing the estimated concentration to a standard concentration for that oil type in the medium. However, since oil is made up of different types of hydrocarbons, a surrogate may be used for the purpose of estimating the risk profile in different media. Naphthalene is a good example for a surrogate. The risk in this case is described through the risk quotient and is calculated using Eq. (5).

$$RQ = PEC / PNEC \tag{5}$$

where Predicted Exposure Concentration (PEC) is measured through fugacity modeling and the Predicted No Effect Concentration (PNEC) is obtained from ecotoxicological studies. PNEC represents the ecosystem response. A value of $RQ > 1$ shows condition requiring attention. The dynamic risk concept could be extended to socio-economic risk modeling (Afenyo and Chaming, 2019). This is discussed further in the following section.

4 Addressing uncertainty and variability

While the approach described so far is one of the most adopted, there is a growing literature on the use of Bayesian Network (BN) to address the same problem. This approach helps to address uncertainty and variability. In the sections that follow, we will discuss how the BN could be used in this regard. Further, an advanced form of the BN described as the OOBN is presented as well.

BN is a graphical probabilistic-based model that is used to describe different engineering problems (Afenyo et al., 2017b) including oil spills. In the context of the oil spill, the BN is used to describe the release, fate and transport, and the socio-economic impact of an oil spill in the Arctic from shipping in this chapter. The latter is achieved by the use of Influence Diagram (ID). The ID is an extension of the BN with utility and decision nodes (Davies and Hope, 2015). Some of the many uses of the ID include the evaluation of response measures for oil spill and the evaluation of the socio-economic impact of same (Davies and Hope, 2015). To illustrate the use of the equations and tools described earlier, a scenario is presented for such purpose. The set-up is potentially an oil spill scenario that we anticipate. The sections that follow seek to illustrate the use of the tools described.

5 The scenario

The Arctic remains a place where an oil spill incident has not been recorded and so we can only rely on potential scenarios to demonstrate the tools described earlier. The intention of the scenario is not depicting the accuracy of the result but to present potentially what the outcome could be when using such tools. The scenario is taken from (Afenyo et al., 2017a) with some modifications.

The scenario involves the collision of an oil tanker in the West Siberian lowlands. The collision resulted in the release of approximately 115 kg of oil. The approximate area of the region affected by the oil spill is 1000 m^2 while the entire body of water is $300 \times 10{,}000\ m^2$. The depth is however approximately 200 m. The ice covers the surface of the water during most part of the year. In summer, the average temperature is 0°C to 9°C and in winter it is −1.8°C to −1.2°C. The average wind speed of this area is $7\,\frac{m}{s}$ and the longitudinal diffusion coefficient is $5{,}400{,}000\,\frac{m^2}{s}$. Further, assuming that the area affected has a population of about 1000 people and depends on fish which is worth USD 400 per ton the tools are used to estimate different parameters for decision-making.

6 The analysis

Eq. (3) is applied to model the release and dispersion of the oil and the results are shown in Fig. 5. It shows the evolution of the oil in space and time. From

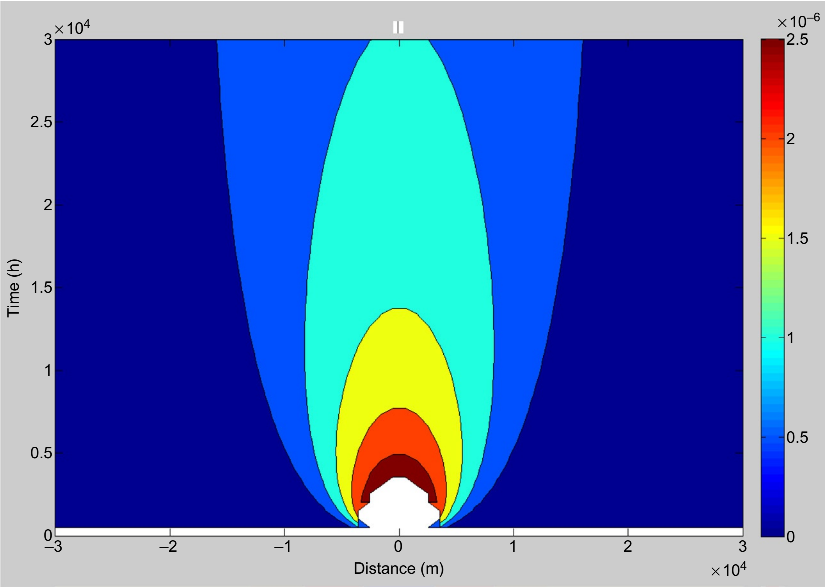

FIG. 5 Concentration profile of spilled oil in time and space. *(From Afenyo, M., Khan, F., Veitch, B., Yang, M., 2017a. A probabilistic ecological risk model for Arctic marine oil spills. J. Environ. Chem. Eng. 5(2), 1494–1503.)*

the diagram it can be inferred that the concentration of the oil is highest at the source but reduces as it moves away from it.

To obtain the concentrations in the different media under consideration, the concentration of the dispersed oil is used in the fugacity equation to estimate the concentration in air, water, ice, and sediment. The approach adopted is that the mass balance equations are derived for each of the media considering the various processes involved and then solved simultaneously using the 4th-order Runge-Kutta method. The outcome is the fugacity for each of the media and this is multiplied by the fugacity capacity of the corresponding media. The fugacity capacities (Z) are media dependent. Fig. 6A and B show samples of the concentration profile for the oil in air and in sediments. This outcome gives the level of pollution of the media.

From the graphs, it can be inferred that the concentration in the sediment is high compared to that of air. Also, the initial concentration is generally high but reduces with time. This result is subsequently compared to the PNEC for each media and the result is shown as the risk profile through the Risk Quotient (RQ). The result is obtained in a probabilistic mode by implementing a Monte-Carlo Simulation technique, details of which can be obtained from Afenyo et al. (2017a) (Fig. 7).

The risk profile shows that the quotient does not exceed 1 even at the highest probability and so the level of risk is acceptable.

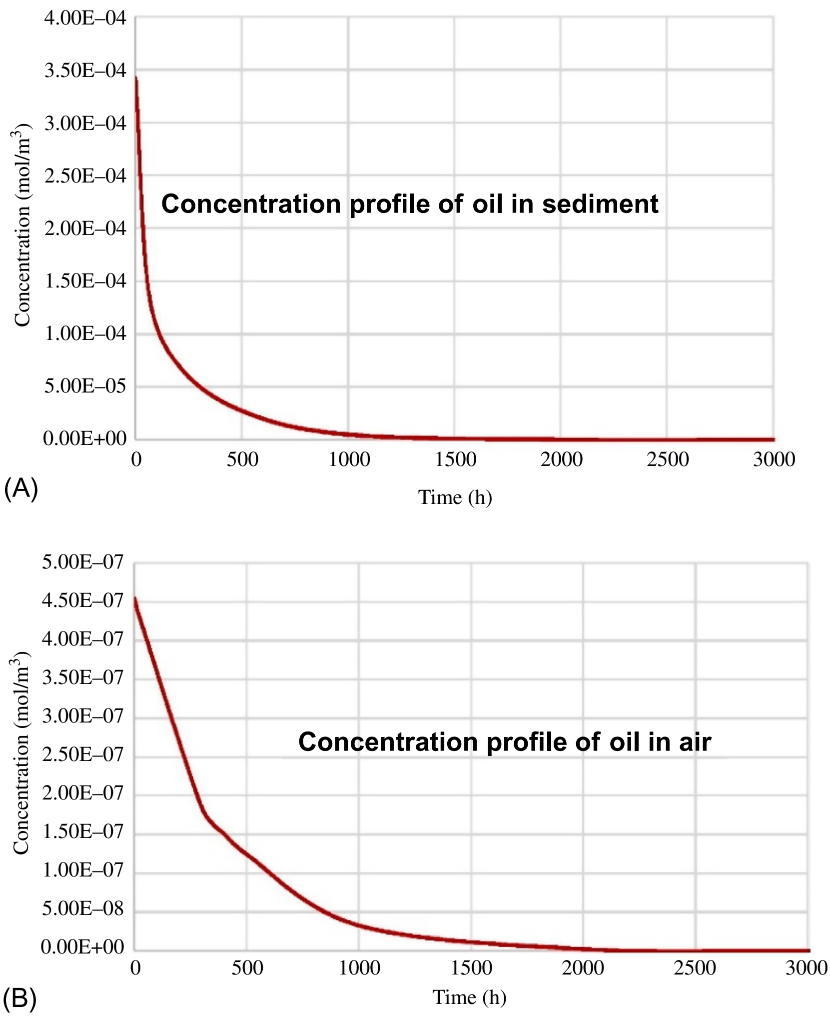

FIG. 6 (A) Concentration of oil in sediment and (B) concentration of oil in air. *(From Afenyo, M., Khan, F., Veitch, B., Yang, M., 2017a. A probabilistic ecological risk model for Arctic marine oil spills. J. Environ. Chem. Eng. 5(2), 1494–1503.)*

To evaluate the potential response measures that could be used to address the oil spill, the Object-Oriented Bayesian Network (OOBN) is used and extended to an Influence Diagram (ID). Fig. 8 is the OOBN that captures the various stages of the oil spill and Fig. 9 is the ID. A criterion called the cost-effectiveness is used for this purpose. This is the ratio of the cost to the effectiveness of each response method.

The results of the simulation are shown in Fig. 10. Here A is the in situ burning, B is the use of dispersants, C is the mechanical recovery, and D is the manual recovery.

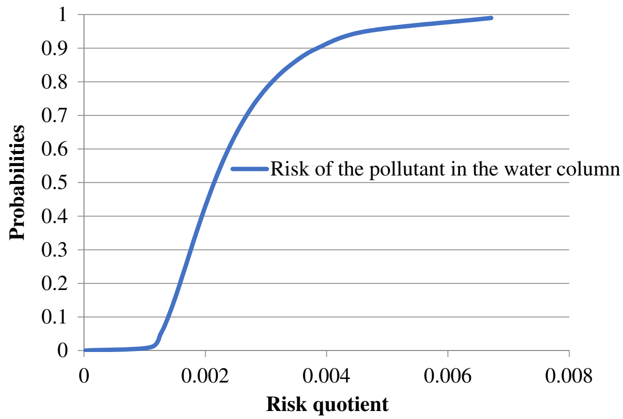

FIG. 7 Risk profile of oil in water column. *(From Afenyo, M., Khan, F., Veitch, B., Yang, M., 2017a. A probabilistic ecological risk model for Arctic marine oil spills. J. Environ. Chem. Eng. 5(2), 1494–1503.)*

Fig. 10 shows that the best combination for this scenario is the use of dispersant and in situ burning. It should be noted that no two scenarios are the same and so, the ranking may differ for other conditions.

Furthermore, to evaluate the socio-economic impact in dollar terms the ID shown in Fig. 11 is implemented.

The simulation produces the impact in dollar (USD) terms. Using the illustrated model, it is possible to simulate different scenarios. Using the information given, the socio-economic impact simulated is approximately USD101, 242,480.

7 Discussion and conclusions

The results of the simulations illustrate the flexibility that the various tools offer. That is to say that different tools can be used to evaluate the same problem, depending on what the end user really wants. There are still challenges to assessing the risk of oil spills in ice-covered waters. The first is the absence of algorithms to describe some of the processes that are very dominant when it comes to oil spill in ice. One of such processes is oil encapsulation and decapsulation in ice-covered waters.

Furthermore, there is a level of restriction on conducting outdoor experiment because of the environmental implications of oil in ice. The disposal of the oil is difficult to deal with as environmental fines for violating such laws can be consequential. However, this is changing considering the recent Arctic Oil Spill Response JIP, which produced substantial knowledge on oil-ice interaction and response of oil spill in the Arctic. In this case, the BN models can be improved tremendously with an extensive data collection regime. This will further create confidence in the method and subsequently the results. In countries,

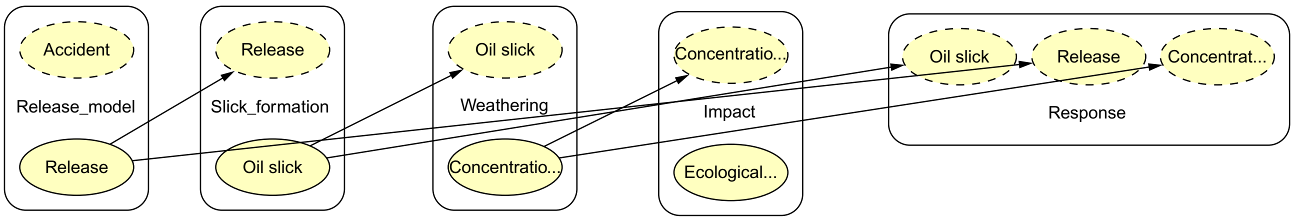

FIG. 8 The OOBN for oil release, impact due to a shipping accident.

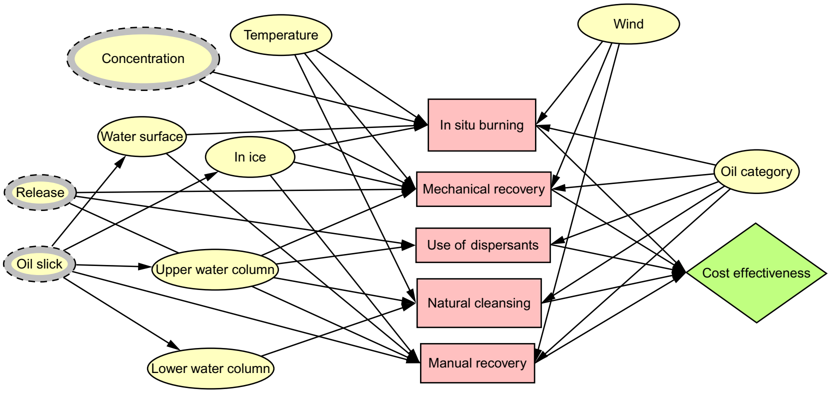

FIG. 9 Influence diagram for evaluating the response measures.

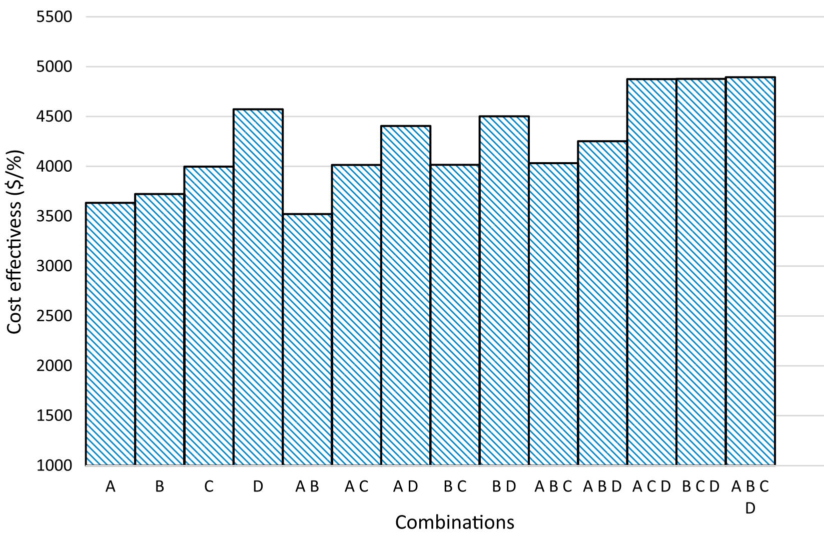

FIG. 10 Results of the simulation for the scenario.

such as Canada, where the bulk of the Arctic falls in the jurisdiction of the first nations, the involvement of these groups in developing and creating inputs for the models would go a long way to make the models acceptable. Moreover, it is noted that risk as a concept is evolving and so the methods that are required to evaluate these also need to be adapted appropriately. So, while climate change may be positive for Arctic shipping, it is also important to adequately prepare for the implications of the activities that come with it. The tools presented in this chapter are important for contingency planning, resource allocation, and emergency response.

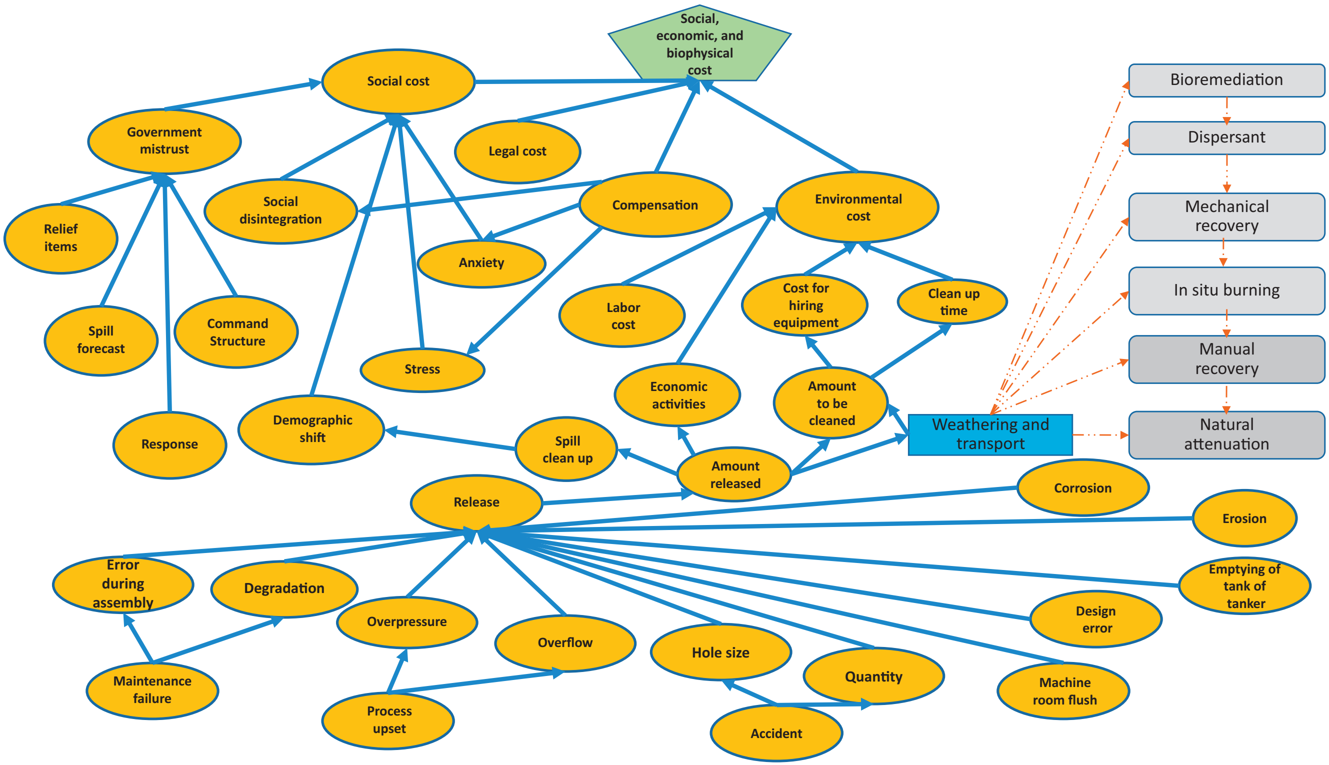

FIG. 11 An influence diagram for evaluating the socio-economic impact of oil spill given the scenario. *(From Afenyo, M., Chaming, J., Ng, A.K.Y., 2019. Climate change and Arctic shipping: a method for assessing the impacts of oil spills in the Arctic. Transp. Res. D (in press.)*

Finally, the tools introduced in this chapter can inform regulatory framework for environmental risk assessment for oil spill in the Arctic. For example, Canada is in the process of developing a national Arctic policy. The illustrated tools can be used to determine the most vulnerable areas that require more attention. This information will enable the federal government, as well as the provincial governments, to enact laws appropriately. The indigenous communities have advocated for more involvement in issues related to the Arctic. The tools presented give the flexibility to achieve this. Thus, while collecting data from these regions, the inputs would form part of the modeling work. Also, the output would be useful to the communities as they can determine how much impact an oil spill of a particular magnitude will have on the communities.

However, the question on how much political will exists to address Arctic oil spill issues remains. In this regard, Arctic countries like Norway have already taken the lead, while Russia has also demonstrated its readiness to harness the full potential of the Arctic. Hence, it is critical for the Arctic Council to take into consideration a standard for conducting an impact risk assessment in the Arctic with regard to oil spills. Much progress has taken place especially with regard to the Polar Code. More collaborations by Arctic and non-Arctic countries are needed.

8 Future work

Despite the progress with regard to risk assessment tools for the Arctic, a lot still needs to be done. For example, there is a need to develop an innovative way to collect data for the Conditional Probability Tables (CPT) for the BN and ID diagrams. A comprehensive impact assessment needs to be performed for the Arctic shipping routes to determine the most vulnerable areas. This can be done by incorporating the models presented with real-time oceanographic database. In this way, the environmental, social, and economic impacts of an oil spill can be determined in real time as an oil spill incident happens. Also, a simulation can be made to determine where the oil would go and the overall impacts on the routes throughout the Arctic region.

Finally, other areas that need to be addressed include the evaluation of oil spills on the cruise industry, considering the significant increase of such vessels. What are the regulations in place to enable the local communities to fully benefit from this surge? Other questions that urgently need answering are: How to make the Arctic economy sustainable, considering the small number of people in this area despite the huge deposit of natural resources? How much investment should go into such areas and how would government be able to attract people to these areas to justify the investment? We hope that this chapter offers some valuable contributions to answer these questions.

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