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Dynamic fugacity model for accidental oil release during Arctic shipping

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A B S T R A C T

Improved understanding of ecological risk associated with Arctic shipping would help advance effective oil spill prevention, control, and mitigation strategies. Ecological risk assessment involves analysis of a release (oil), its fate, and dispersion, and the exposure and intake of the contaminant to different receptors. Exposure analysis is a key step of the detailed ecological risk assessment, which involves the evaluation of the concentration and persistence of released pollutants in the media of contact. In the present study, a multimedia fate and transport model is presented, which is developed using a fugacity-based approach. This model considers four media: air, water, sediment, and ice. The output of the model is the concentration of oil (surrogate hydrocarbons-naphthalene) in these four media, which constitutes the potential exposure to receptors. The concentration profiles can subsequently be used to estimate ecological risk thereby providing guidance to policies for Arctic shipping operations, ship design, and ecological response measures.

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1. Introduction

The Northern Sea Route (NSR) and the North-West Passage (NWP) are already navigable. The number of vessels going through the Arctic shipping routes has increased over the past decade (Østreng et al., 2013; Marchenko, 2012). It is estimated that using the NWP will save more time and money compared to using the Panama Canal (Østreng et al., 2013). This presents opportunities for transportation and tourism. These opportunities also come with risks, such as the potential accidental release caused by sinking, collision and grounding of shipping vessels. For instance the oil spill incident involving the Odyssey off the coast of Nova Scotia, Canada, resulted in the release of approximately 43 million gallons of oil (Black, 2012). An area of 16 km by 5 km of water was polluted. Some of the oil also started drifting towards England. The 27 people on board were not found and there was significant impact on the flora and fauna in that area. The harsh conditions on the sea mean that the Canadian coast guard could not respond in a timely manner (Hooke, 1997).

At the moment, shipping traffic volume is low in the Arctic but an oil spill during Arctic shipping and operations has potential high consequences on the marine ecosystem (Afenyo et al., 2015; Østreng et al., 2013). These include the distortion of the reproduction cycle of Arctic species, chemical toxicity of the released oil, ecological changes, smothering, elimination of valuable ecological species, and air pollution. These effects depend on the quantity of spilled oil, type of spilled oil, ambient environment and seasonal variation. The aforementioned effects could be short term or long term (Lee et al., 2015). These potential impacts on the Arctic ecosystem require an Ecological Risk Assessment (ERA).

Ecological risk is defined as the likely impact of the exposure of a stressor (e.g. oil) to an environment. The steps required for an ERA are shown in Fig. 1. The three main phases of ERA include: 1) the problem formulation phase, 2) the exposure analysis and effects phase and 3) the risk characterization phase. Before the main phase of problem formulation, risk managers and other stakeholders plan the risk assessment (Anon, 1998; Burgman, 2005; Nazir et al., 2008). The key to conducting an ERA for an accidental release of oil in ice-covered waters is the exposure analysis, which seeks to achieve the following:

i) to determine the extent of contamination in all media, ii) to identify organisms exposed and exposure pathways, iii) to identify the routes and path of exposure. The potential exposure paths include: ingestion of contaminated food and water, inhalation, and dermal absorption of hydrocarbons and iv) to identify how organisms respond to the exposure of a stressor over time (Burgman, 2005). The focus of this paper is to accomplish the first objective. This requires the estimation of the concentration of the stressor in different media of contact (Nazir et al., 2008; Anon, 1998). In order to achieve this, a partition model is used. An important approach to performing partition modeling is the use of the fugacity concept. The outcome of the exposure analysis is subsequently used for risk characterization.

The fugacity concept has been used by researchers Clark et al. (1990); Mackay (1991); Sadiq (2001); Golding et al. (2008); Nazir et al. (2008) and Bock et al. (2010) to address different ecological problems. This paper uses the fugacity approach to estimate the

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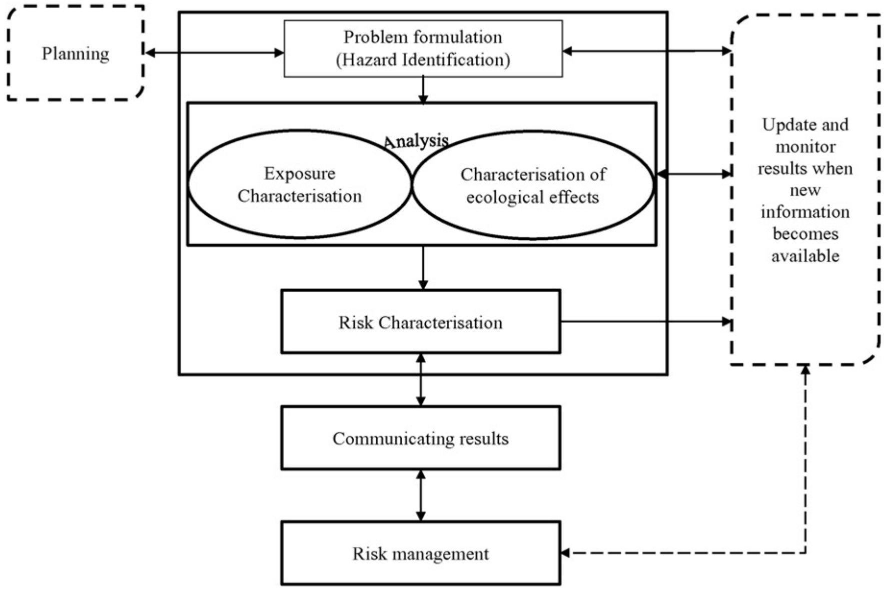

Fig. 1. An Ecological Risk Assessment framework (after Burgman, 2005; Nazir et al., 2008).

concentration of oil (surrogate: naphtalene) in air, ice, water and sediments which are the likely media of contact for an accidental release during Arctic shipping. The Level IV approach has been used to analyze different environmental problems (e.g. Wania et al., 2006; Wania and Mackay, 1995). The application of the Level IV fugacity model to an accident scenario of an instantaneous oil release during Arctic shipping is new. This fugacity model simplifies the modeling and analysis of contaminant transfer between phases in Arctic environments because fugacity is continuous between phase interfaces while concentration is not. The QWASI (Quantitative Water Air Sediment Interaction) model in Mackay (1991) forms the basis for this work, as well as works by Yang et al. (2015); Nazir et al. (2008); Sweetmen et al. (2002) and Sadiq (2001). The uniqueness of this work is the development of a Level IV fugacity based model with the capability to predict the concentration of oil in an ecosystem involving ice. The model is of less computational cost, hence facilitating efficient decision making.

This paper is organised as follows: Section 2 describes the multimedia partition models with a focus on fugacity models. Section 3 presents the methodology adopted for this paper, and an illustration of the methodology through a hypothetical example. Section 4 discusses the results, and Section 5 presents the conclusion and recommendations of the paper.

2. Multimedia partition modeling

An essential detail of exposure analysis is the estimation of the concentration and persistence of the stressor in the media of contact. In order to achieve this, Multimedia Mass Balance Models (MMBMs) are utilised. Important uses of MMBMs include: identification of fate processes, estimation of long range transport, estimation of residence time of a pollutant, bioaccumulation of chemicals in organisms, identifying the potential for persistence and the tendency for intermedia transport, and the evaluation of ecological concentration (MacKay and MacLeod, 2002; Gouin et al., 2001). Similar to other models, MMBMs may not be an exact representation of the real problem, likewise the corresponding solution but provides a tool to simplify and analyze a complex problem (MaCleod et al., 2010).

As a decision supporting tool, MMBMs are useful for documenting the origins and nature of pollutants and potential recovery strategies, performing risk assessment, as well as assessing impacts of alternative actions (Macleod et al., 2010). In MMBMs, compartments are represented by boxes and the chemical released is assumed to be homogeneous throughout the boxes. Predicted MMBMs results could vary by a factor of 2 from the actual data (Mackay et al., 2001). The most used MMBM is that which uses the fugacity concept.

2.1. Fugacity approach

The fugacity concept is used as a substitute for chemical potential as a thermodynamic equilibrium to describe the fate of a chemical. Fugacity describes the escaping tendency of a particular chemical and is analogous to partial pressure. In the mass balance equations, fugacity is used as a surrogate for chemical potential (Mackay et al., 2001). Mathematically, it is described by Eq. (1), which shows fugacity, f, and concentration, C, are related by a term referred to as the fugacity capacity, Z; that is the tendency of a medium to absorb a chemical. A medium with a higher fugacity capacity has a high tendency to absorb more chemicals, hence will have higher concentration, assuming two media have the same fugacity (Mackay, 1991; Yang et al., 2015). It is important to note that Z depends on the type of compartment and the partition coefficient. Z partly describes the solubility of the pollutant in the media. Therefore dissociation for example causes an increase in Z-value. The more a substance can take or allow dissociation in it, the higher the Z value and the higher the concentration of the media (Mackay, 1991).

$$C = Z \times f \tag{1}$$

where C is the concentration $(\frac{\text{mol}}{\text{m}^3})$, f is the fugacity (Pa) and Z is the fugacity capacity $(\frac{\text{mol}}{\text{m}^3\text{Pa}})$.

There are four levels of complexity of fugacity models: Level I, Level II, Level III and Level IV. The Level I involves a fixed quantity of pollutant in a closed environment; that is, it involves the partitioning of a non-reacting chemical in equilibrium in a closed steady state system. Level II provides a solution for a steady state scenario of a chemical in equilibrium. It builds upon Level I by introducing exit pathways and the processes of reaction and advection. The same fugacity applies. Level III accounts for intermedia mass transport between well mixed media. It applies to compartments in non-equilibrium, where each medium has its own fugacity. Level IV is an unsteady state version of the Level III (MacKay and MacLeod, 2002).

In the steady state models, the situation is that, the pollutant emissions and environmental related parameters are static with respect to time. In the Arctic marine ecosystem, the temporal variability of the

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