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Modeling the effectiveness of oil combating from an ecological perspective – A Bayesian network for the Gulf of Finland; the Baltic Sea

Inari Helle[a,*], Tiina Lecklin[b], Ari Jolma[c], Sakari Kuikka[a]

[a] Fisheries and Environmental Management Group (FEM), Department of Environmental Sciences, University of Helsinki, PO Box 65, FI-00014 University of Helsinki, Helsinki, Finland
[b] Fisheries and Environmental Management Group (FEM), Department of Environmental Sciences, University of Helsinki, Kotka Maritime Research Center, Mussalontie 428 B, FI-48310 Kotka, Finland
[c] Department of Civil and Environmental Engineering, Aalto University, Niemenkatu 73, FI-15140 Lahti, Finland

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ABSTRACT

Maritime traffic poses a major threat to marine ecosystems in the form of oil spills. The Gulf of Finland, the easternmost part of the Baltic Sea, has witnessed a rapid increase in oil transportation during the last 15 years. Should a spill occur, the negative ecological impacts may be reduced by oil combating, the effectiveness of which is, however, strongly dependent on prevailing environmental conditions and available technical resources. This poses increased uncertainty related to ecological consequences of future spills. We developed a probabilistic Bayesian network model that can be used to assess the effectiveness of different oil combating strategies in minimizing the negative effects of oil on six species living in the Gulf of Finland. The model can be used for creating different accident scenarios and assessing the performance of various oil combating actions under uncertainty, which enables its use as a supportive tool in decision-making. While the model is confined to the western Gulf of Finland, the methodology is adaptable to other marine areas facing similar risks and challenges related to oil spills.

1. Introduction

Economic growth has augmented the volume of sea traffic around the world, as maritime transportation is the most efficient way to ferry goods among countries. This trend has also negative side-effects such as accidental oil spills, which pose a threat to coastal ecosystems.

The Gulf of Finland (GOF), the easternmost part of the Baltic Sea, has many features that make it exceptional among the world's water bodies and also sensitive to oil spills. Due to low salinity (0–7‰), relatively short geological history and northern location the biota is a fairly species-poor mixture of marine and freshwater species capable of dealing with low temperatures and ice-cover in wintertime. The GOF is also an important migratory route for the arctic birds, and it harbors numerous conservation areas [1,2]. Nowadays, being one of the most heavily trafficked sea areas in the world and with over 12 million people inhabiting its drainage area [3], the GOF is suffering from serious environmental problems like eutrophication and invasive species [1].

A new major threat to this fragile ecosystem is the risk of a large-scale oil spill. The volume of oil transportation has increased substantially in the area during the last 15 years. In 2007, over 145 million tons of crude oil and refined products were transported via the GOF [4], and the volume is expected to be 250–300 million tons by year 2015 [5]. The drastic increase is mainly due to the construction and development of new terminals especially in Russia and Estonia [6]. In addition, the GOF is facing rapidly growing maritime cargo and passenger traffic. Although there have been major improvements in maritime safety [6], the risk of a major accident is evident. The worst-case scenario in the GOF is assumed to be a collision of two tankers, which can result in an oil spill of approximately 30 000 t of crude oil; if a tanker is lost due to sinking, explosion or intense fire, the resulting spill can be even larger [5]. An accident of this magnitude could have a devastating and long-lasting effect on the GOF ecosystem.

After an accident, effective oil combating can play an essential role in minimizing any harmful effects. At present oil combating in the GOF is based on mechanical recovery, which is in accordance with the recommendations of the Baltic Marine Environment Protection Commission [7]. However, the characteristics of the GOF make oil combating a challenging task. Since the GOF is narrow and shoreline is occupied by vast archipelago especially on the northern coast, the time window for response measures is very narrow. Furthermore, the wintertime ice-cover reduces the efficiency of combating.

It is essential to have extensive knowledge of the behavior and movement of drifting oil as well as of the ecological effects oil induces in order to mitigate the negative impacts oil spills may

* Corresponding author. Tel.: +358 9 191 58443; fax: +358 9 191 58754.
E-mail address: inari.helle@helsinki.fi (I. Helle).

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have. There is a large number of models that can be used for predicting the fate and trajectory of spilled oil (reviewed e.g. by ASCE [8] and Reed et al. [9]). While these models use fairly sophisticated ways to calculate the physical and chemical processes spilled oil undergoes, they seldom can be applied to assess the impacts on biota, and they usually do not include uncertainty estimates, i.e. impacts having low probability cannot be evaluated. The relatively few models focusing on the ecological effects of oil spills include models developed for birds [10], fur seals [11], sea otters [12] and intertidal invertebrates [13]. However, also a more comprehensive model combining the physical fate of spilled oil with ecological and economic impacts has been devised [14,15]. Although some of developed models include also oil combating options, they are mainly designed for operational or educational purposes, and thus their capability to assess the effectiveness of oil combating activities in a general environmental context is highly limited.

The aim of this paper is to present a probabilistic Bayesian network model that combines the behavior of oil, ecological effects and oil combating options, and which can be used to assess the effectiveness of different oil combating methods from an ecological perspective. Bayesian networks are graphical models that enable the assessment of different management decisions and thus help the decision-making under high uncertainty. First we provide a short introduction to the methodology and describe the structure of the model, after which we present a scenario that offers possibility to assess, how different decisions in oil combating in the GOF affect the state of the populations of interest. Finally we examine our results in the light of present oil combating practices.

2. Materials and methods

2.1. Bayesian networks

Bayesian networks (BNs, also known as belief networks [16]) are graphical models describing probabilistic relationships between a set of variables. Formally they are directed acyclic graphs (DAGs) with nodes and arcs. The nodes represent discretized random variables and arcs represent probabilistic dependencies between the variables. As they handle uncertainty explicitly, they are suitable for examining systems containing complex and uncertain interactions. BNs can be constructed as influence diagrams by including decision and/or utility nodes in the network, which further improves their use as decision tools. By choosing one decision option at a time one can examine the possible consequences of planned actions as the information is propagated through the network. For more detailed information, e.g. Jensen [17,18] offers an extensive presentation of the methodology related to BNs in general.

BNs originate from artificial intelligence research, and in addition to their use in e.g. medical [e.g. [19–21]] and social sciences [e.g. [22,23]], BNs are increasingly applied to solve problems concerning environmental issues and management [24–33]. As described above, they enable the assessment of different decision options and thus offer an effective and user-friendly tool for decision-making under uncertainty. This makes BNs applicable to oil spill management, seen as a field of environment management encountering very high uncertainty. BNs also allow the combination of information from different sources (e.g. simulation models, observed data and expert knowledge) with differing accuracies (quantitative or qualitative), and they are also able to cope with missing data and small datasets. However, there are also some issues that have to be taken into account when using them, e.g. their ability to handle continuous variables is limited, and they cannot operate with loop structures in the model. Uusitalo [34] offers a detailed review of the advantages and challenges of BNs in environmental problems.

2.2. Description of the model

The model includes three oil combating options and several environmental and biological variables, which are needed to describe the overall uncertainty related to the management problem (Fig. 1, Table 1). The combating options considered in the model are: (1) mechanical recovery offshore, (2) dispersants (i.e. chemicals that break up the oil slick into small dispersible droplets) offshore, and (3) oil deflection booms inshore, i.e. three combating options that can potentially be applied in the GOF during the ice-free period. Mechanical recovery and deflection booms are widely used in oil combating in the GOF today, whereas chemical dispersants have not been considered as a countermeasure since the 1980s. The latter were nevertheless included in the model because they are still seen as a possible combating option in situations where there are no other means to avoid e.g. severe losses of seabirds within endangered breeding colonies [7]. Yet, quantitative analyses on the subject in the GOF are lacking. They are however needed, if the rationale behind the management decision ought to be evaluated.

The model is a continuation of the work of Juntunen et al. [35], who studied the effects of different oil combating strategies (limiting the tanker size, stopping of oil leakage, mechanical and chemical combating offshore) on the ecosystem of the GOF. The present study widens the repertoire of combating options and focuses on a detailed ecological analysis with a realistic spatial scale, while the work of Juntunen et al. [35] presented an elaborate analysis of the leakage event and had a more general approach to the ecosystem effects.

The final outcome of the model is the probability distributions describing the decrease in the population sizes of selected species after an oil accident. The model includes six species: (1) the grey seal (*Halichoerus grypus*) and (2) the common eider (*Somateria mollissima*) representing mobile animals living in a close contact with both littoral zone and water surface, (3) the blue mussel (*Mytilus trossulus*) and (4) the Baltic herring (*Clupea harengus membras*) representing subsurface organisms, and (5) the prickly saltwort (*Salsola kali kali*) and (6) the scarab beetle *Aegialia arenaria* representing terrestrial species living onshore. The species were chosen so that they describe the effects of an oil spill on different parts of the ecosystem. In addition, they all can be considered important in the context of the GOF either on ecological, economic or conservational basis. Four first-mentioned species are fairly common in the GOF, whereas the latter two species are considered threatened in Finland [36].

Since the effectiveness of deflection booms is highly dependent on local conditions like the topography of the shore, the model is spatially confined to the Hankoniemi area (Fig. 2) in the western GOF to make the assessment and comparison of different combating methods more realistic. Due to geological as well as geographical reasons, an exceptional mixture of habitats can be found in Hankoniemi, including e.g. rocky shores, groves, seashore meadows, leas and dunes. As the peninsula is a continuation of the Salpausselkä end moraine, long sandy beaches and underwater reefs, i.e. habitats absent from elsewhere in Finland, are also present. The uniqueness of habitats is expressed also via biodiversity, and Hankoniemi can the seen as a “hot spot” of biodiversity in the GOF, especially when considering endangered species.

The occurrence data of the common eider, the grey seal, the prickly saltwort and the scarab beetle *Aegialia arenaria* in the Hankoniemi area were retrieved from the databases of the Finnish Environment Institute and delineated by experts if needed. Since the exact occurrence data of the Baltic herring and the blue mussel do not exist, the occurrence for the former was assumed to cover sea areas deeper than 1 m (spring and summer) and 10 m (autumn), and for the latter the sea areas that were 0–20 m deep.