Bayesian inference for oil spill related Net Environmental Benefit Analysis

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Abstract

This paper investigates the applicability of Bayesian inference to oil spill related situation assessment in order to facilitate the Net Environmental Benefit Analysis (NEBA) based decisions in evaluating the threat or probable overall environmental impact of the spill. Bayesian networks are believed to be useful in integrating the NEBA related information imported from 1) oil spill scene surveillance, 2) simulation results on an oil spill incident with human response, and 3) ecological sensitivity maps. This paper exemplifies the use of Bayesian Belief Networks in answering the questions: can the oil spill be combated at sea, and if it cannot then is the oil threatening a sensitive environment?
Keywords: net environmental benefit analysis, Bayesian inference, oil spill response simulation, Gulf of Finland (Baltic Sea).

1 Introduction

At the International Maritime Organization's (IMO) Marine Environment Protection Committee's 53rd session in July 2005, the Baltic Sea was designated as a Particularly Sensitive Sea Area (PSSA). At the same time, oil transportation is growing significantly in the Baltic Sea area and especially in the Gulf of Finland exceeding 200 million tons a year by 2010. Despite improving navigation measures, there is a growing risk for incidental oil spills and associated oil pollution.

In an actual spill situation, everything possible is done to prevent oil washing ashore. The Net Environmental Benefit Analysis (NEBA) is defined as a method

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to determine the most appropriate response option(s) in order to minimize the overall environmental impact of an oil spill [1, 2]. The NEBA based oil spill response related decision making is considered as essentially a multi stage process. Any stage of decision making starts with the inputs which are oil spill surveillance data collected from diverse sources. With the state of the oil spill appraised, an assessment of the situation is conducted next which, among other aspects, involves assessing 1) expected drift, behaviour and fate of the spilled oil, 2) predicting its future behaviour, and 3) the level of threat it poses to sensitive environment. The oil spill response decision maker is now in a position to weigh the appropriateness of alternate courses of oil combat action and decide upon one – and the cycle starts again.

Bayesian inference is an important statistical tool that is increasingly being used by ecologists in general to evaluate decision making alternatives: in a Bayesian analysis, information available is summarized in a prior probability distribution while posterior probability distributions provide a direct measure of the degree of belief that can be placed on models, hypotheses, or parameter estimates [3–5]. The use of Bayesian techniques in ecological risk assessment has recently attracted considerable attention because (1) they are able to employ subjective interpretations of probability, and (2) they immediately direct the analyst to the full distributional qualities of parameter uncertainty, through the posterior distribution function [6].

This paper investigates the applicability of Bayesian inference to oil spill related situation assessment in order to facilitate the NEBA based decisions in selecting the best available oil spill response alternative, and in evaluating the threat or probable overall environmental impact of the spill.

2 Material and methods

The BBN for situation assessment are constructed using HUGIN RESEARCHER software. General relationships between the variables of interest, in terms of the relevance of one variable to others, are taken into account in a graphical representation capturing the conditional dependencies in a qualitative fashion (parent–child nodes). The links in the graphical representation are then assigned conditional probabilities (Bayesian networks). The BBH constructed for this study is representing the uncertainties in oil spill accident situation assessment. Prior probabilities are obtained from knowledge of the prevailing situation (relevant literature, oil spill surveillance and modelling data) by converting a state of knowledge to a probability assignment.

In the Baltic Sea region the Seatrack Web on-line oil drift forecasting system is used to support the NEBA decision making in oil spill related emergency situations [7]. System covers the entire Baltic Sea area and the eastern North Sea. PISCES (Potential Incident Simulation Control and Evaluation System) is used to simulate development of an oil spill incident with human response and it calculates both the changes to the spill mass due to dynamically varying environmental parameters (e.g. currents, wind, sea state etc.), and also due to the deployment of oil spill response resources, such as booms, skimmers and chemical dispersants [8]. Integrated Seatrack Web and PISCES modelling suite is used to generate the necessary values of input variables for BBNs root nodes.

In situ measurements of flow fields along the Estonian coast of the Gulf of Finland (Baltic Sea) were performed using an oceanographic measuring complex called RDCP-600 from AADI Aanderaa. It applies the Doppler Effect to measure vertical distribution of velocity. Atmospheric forcing conditions are provided by the Estonian Meteorological and Hydrological Institute (EMHI).

The sensitivity maps were based on three different ecosystem elements: the EU Habitat Directive Annex 1 habitats and associated habitat forming species, birds and seals. In each raster cell the maximum value of different layers was calculated to give the final assessment of ecosystem sensitivity by coastal water bodies and the seasons (Figure 1).

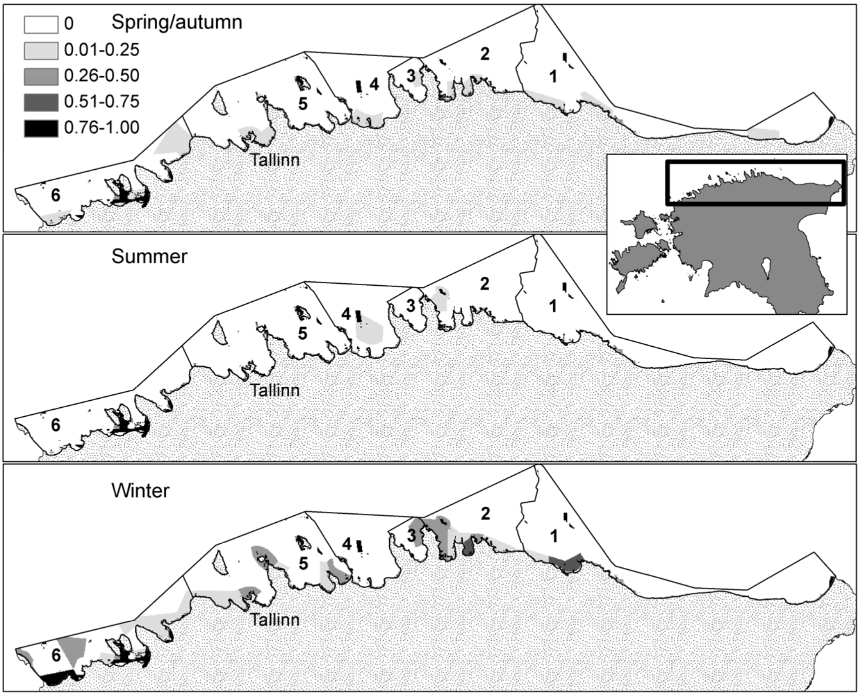

Figure 1: Ecological sensitivities by coastal water bodies of the southern Gulf of Finland (1 – 6) and seasons (spring/autumn, summer and winter). Sensitivity scale according to sensitivity criteria applied: (0) – no sensitivity, (0-0.25) – low sensitivity, (0.26-0.50) – medium sensitivity, (0.51-0.75) – high sensitivity, and (0.76-1.00) – very high sensitivity [9].

3 Results and discussion

3.1 What are the expected drift, behaviour and fate of the spilled oil?

As soon as coastal authorities are notified of an oil pollution incident, they need to gather information on the oil spill (size, location, and the type of oil) and the environmental (weather) conditions in order to evaluate the threat or probable overall environmental impact of the spill [2]. Immediately after notification of a pollution incident at sea, the NEBA is to be performed, and a quick decision is to be taken on the most appropriate response option(s). This decision is based on the following information: 1) what are the expected drift, behaviour and fate of the spilled oil, 2) can the oil spill be combated at sea, and 3) is the oil threatening a sensitive resource?

In a case of oil spill the spatio-temporal fate of spilled oil (transport by currents and wind, spreading, evaporation, dispersion, emulsification) is simulated using the comprehensive modelling suite Seatrack Web [7]. Seatrack Web is providing access to forecast current fields of the Hiromb model, which is a 3-dimensional circulation model covering the whole Baltic Sea out to the North Sea. The horizontal grid resolution is 3 nautical miles. The wind forecasts used in Seatrack Web originate from the weather model at the European Centre for Medium-Range Weather Forecasts (ECMWF). The wind forecasts used in Seatrack Web are from 10 meters height. The oil drift model PADM jointly developed by Swedish Meteorological and Hydrological Institute and the Royal Danish Administration of Navigation and Hydrography is executed whenever a Seatrack Web is used for simulation.

3.2 Influence of hydrodynamic situation on oil spill

Hydrodynamic patterns in the Gulf of Finland are rather complex and highly variable. The circulation scheme is mostly wind-driven and although certain statistical long-term patterns can be found [10], in any given moment the situation likely differs from that long-term resulted velocity vector. For correct results, the modelling tool should be operational or nearly operational and to take into account the real wind situation.

While Seatrack Web with grid resolution of 3 nautical miles is capable to simulate the general hydrodynamic situation of the sea area (i.e. the whole Gulf of Finland) with reasonable degree of approximation (Figure 2), it fails in resolving certain meso-scale hydrodynamic phenomena, such as upwelling and the related baroclinic coastal jets. The typical width (cross-section extension) of coastal upwelling is mainly determined by the barcoclinic (internal) Rossby radius, which in this part of the Baltic Sea ought to be (also depending on stratification conditions) around 1-5 km [11, 12]. The width of the upwelling can be larger due to lateral spread of upwelled water and formation of filaments, though. Still, to resolve the process itself and its accompanying hydrodynamic features (rise in pycnocline, Ekman drift, baroclinic jet), the grid-size should be, according to the published data, about 1/2...1/4 of the Rossby radius [10].

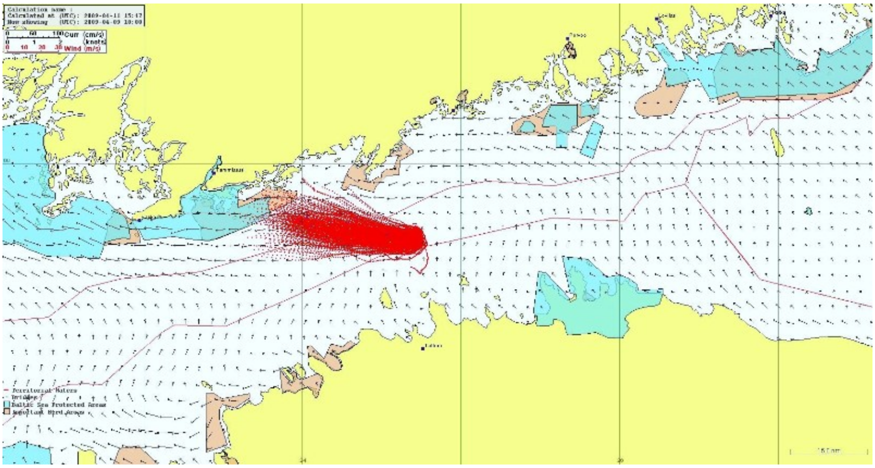

Figure 2: Seatrack Web calculated scenario case: accidental spill of 100 t of fresh medium oil in the Gulf of Finland between Tallinn and Helsinki. Start calculations on 09.04.2009 at 10.00 UTC, and the end of calculations on 06.04.2009 at 15.00 UTC. Arrows are showing the direction and speed of the surface current. Locations of Important Bird Areas and the Baltic Sea Protected Areas are shown along the coasts.

Altogether, 5 measuring sets of multi-layer current dynamics with RDCP has obtained, 2 of them include measurements during extensive upwelling. The first one occurred on July-August 2006 [13, 14], and the second one on August-September 2008. According to MODIS satellite sea surface temperature (SST) images, the upwelling events are more frequent along this relatively straight section of the coast [14]. However, they are rarely covered by direct measurements of hydrodynamics. The frequency of occurrence of upwelling (or downwelling) can be as much as 20-30% in some suitable coastal sections of the Gulf of Finland [15]. As a general rule, persistent westerlies may evoke upwelling along the Finnish coast of the Gulf of Finland, while easterlies and north-easterlies along the North Estonian coast.

Usually, upwelling along one side of the gulf is paired with downwelling along the other coast. Coastal jet appears due to rise in pycnocline during upwelling and evolution of thermohaline stratification. The alongshore current is vertically stratified as well: strong downwind alongshore current in upper layer and relatively weak current (or undertow) in deeper layers. The reason for large surface velocities is simple: a relatively small momentum input is required for driving the relatively thin upper layer. Thus, despite modest wind speeds during upwelling-favour conditions, the velocity can reach 0,6-1 m/s (Figure 3), while much stronger westerly storm winds are capable to yield nearshore velocities up to 0,3-0,6 m/s, which are vertically rather homogeneous, though.

In conclusion, in upwelling-favourable summertime the spilled oil fate may be considerably influenced by changed hydrographical conditions (Figures 3–4).

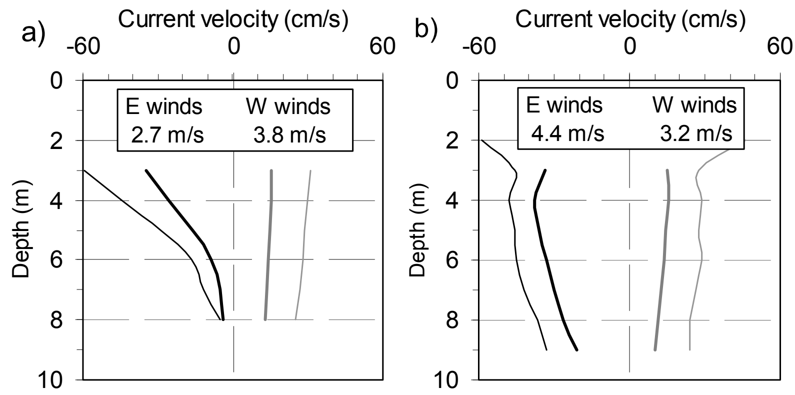

Figure 3: Vertical distribution of alongshore currents velocities at the instrument deployment site (59.56°N, 26.67°E) in the Gulf of Finland (Baltic Sea) in August-September 2006 (a), and August-September 2008 (b) under upwelling conditions (negative values which correspond to westward motions and E-wind forcing) and ordinary conditions (positive current velocity values). Thin lines represent fastest momentary currents and bold lines averages for 5 days with maximum velocities. Possible higher values in upper layers are discarded due to uncertainties in near-surface measuring procedure. Corresponding 5-days average wind forcing is given in the text box.

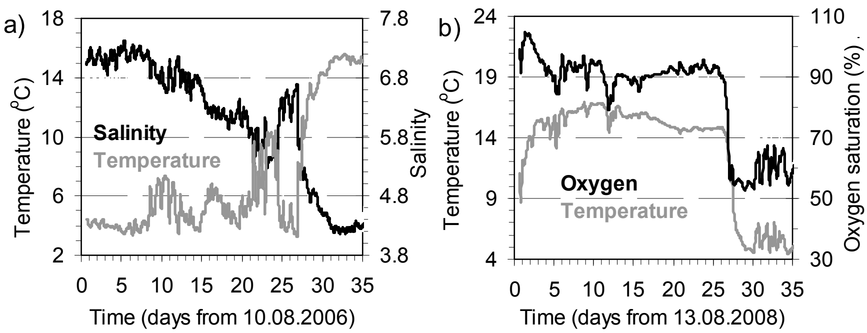

Figure 4: Variations in salinity and water temperature (a) and oxygen saturation and water temperature (b) at the depth of about 10 m at the instrument deployment site (59.56°N, 26.67°E) in the Gulf of Finland (Baltic Sea) during upwelling events in 2006 and 2008. Upwelling conditions apply to low temperature and oxygen content, and high salinity.

Depending on the wind conditions the spilled oil may travel alongshore with a speed up to 50 km per day. The upwelling event itself, however, may last for some weeks. In addition to that, due to low water temperatures (frequently as low as 4....10ºC as opposed to normal summertime water temperatures around 20ºC in adjacent waters), and lowered oxygen content in the water the spreading, evaporation, dispersion, and emulsification of the spilled oil may also be affected.

3.3 Can the oil spill be combated at sea?

There are obvious advantages if an oil slick that threatens the sensitive coastal sea area can be removed while it is still at sea [16]. Usually, booms and skimmers are the first technique employed to remove oil from marine environments but this technique can usually recover relatively small proportion of the spilled oil. No boom is capable of containing oil against water velocities much in excess of 0.58 m/s acting at right angles to it. The critical current velocity for many crude oils and refined products ranges from 0.7 (0.34 m/s) to 1.2 knots (0.58 m/s). Generally 0.7 knots (0.34 m/s) is accepted as a conservative estimate. Skimmers are used to remove oil from water and put it into storage tanks but how well a skimmer works depends on the type of oil spilled, the thickness of the slick and, the weather conditions.

Salinity, water temperature and depth are problems in the Baltic Sea if dispersants are used [17]. Due to the sensitive ecological conditions in the Baltic Sea area, response to oil should take place by the use of mechanical means as far as possible while response by using dispersants should be limited [18]. Therefore, the option of dispersants use is not considered within this study.

In situ burning has not been usually considered as oil combating response option for the Baltic probably because of very limited window of opportunity and accompanied environmental concerns. This option is also not analyzed in this study.

According to HELCOM Recommendation [19] the Contracting Parties should be able to respond to spillages of oil and 1) to reach within six hours from start any place of a spillage that may occur in the response region of the respective country, 2) to ensure well organized adequate and substantial response actions on the site of the spill as soon as possible, normally within a time not exceeding 12 hours. Decision on deployment of booms and skimmers can be made if mobilization time is less than the calculated time for oil to wash ashore.

The BBN is constructed to assess general situation when answering the question: can the particular oil spill be combated at sea using booms and skimmers? Current and wind speed in the oil incident sea area, predicted time interval of oil coming ashore are imported from Seatrack Web simulations. Mobilization time – the time for a ship/aircraft to get on oil incident scene depends on the time to be ready to go and the time to reach the location of the spill – is imported from the PISCES modelling suite simulation results.

When a Bayesian model is actually used the new information is inserted (current speed, wind speed, oil type, time from spill event, and mobilization time) to bring a variable (alternative: use or no use of booms and skimmers) to a state that is consistent with the new information. For example, the BBN modelling outcome for the favourable weather conditions is presented in the Figure 5.

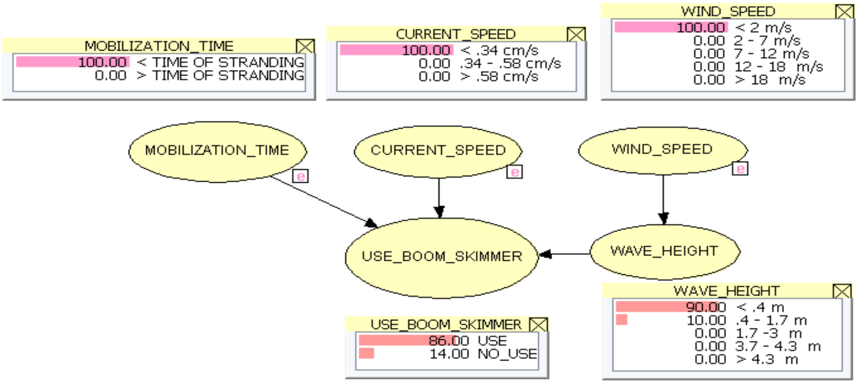

Figure 5: Low current < 0.34 m/s, and a calm wind < 2 m/s. Mobilization time is less than time for oil to wash ashore. Use of booms and skimmers is efficient with probability of 0.86, and inefficient with probability of 0.14.

However, according to results of the BBN simulations the efficiency of booms and skimmers use is rather low under unfavorable weather conditions (Figure 6).

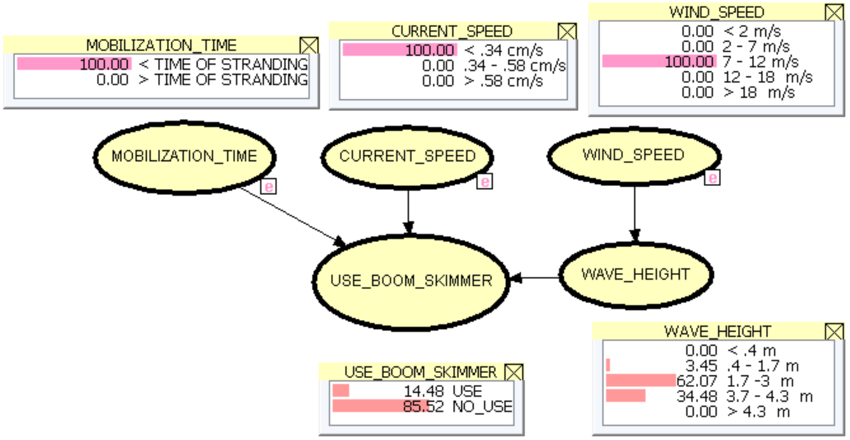

Figure 6: Low current < 0.34 m/s, and a strong breeze 7-12 m/s. Mobilization time is less than time for oil washing ashore. Use of booms and skimmers will be efficient with probability of 0.15, and inefficient with probability of 0.85.

3.4 Is the oil threatening a sensitive resource?

If BBN simulations show that the use of the booms and skimmers is expected to be inefficient, it is almost impossible to prevent the oil from reaching ashore. In this case the advice on sensitive ecological resources likely to be impacted by the oil washing ashore is of critical importance in order to support decisions whether or not a response is necessary or what kind and extent of response is appropriate.

A simple BBN described in more detail in [9] was constructed with an aim to perform the potential oil pollution related predictive ecological risk assessment for the southern part of the Gulf of Finland. A BBN is primarily used to update the ecological risk probability distribution over the states of a hypothesis variable, which is not directly observable. Ecological risk distribution then helps a decision maker in deciding upon an appropriate course of action. According to the requirements of the EU Water Framework Directive the Estonian coastal waters of the Gulf of Finland are divided into 6 water bodies (sea areas) and each water body represents the smallest assessment unit of e.g. water quality and risk analyses (Figure 1). Based on BBN scenario modelling results it is possible to conclude that the western water body of Estonian coastal waters in the Gulf of Finland could be considered as an area of the highest ecological risk for the all seasons.

For example, Figure 7 shows ecological risk distribution calculated for variable “Season” in a state equal to “Winter” and the variable “Ecological Sensitivity” in a state equal to “Low”.

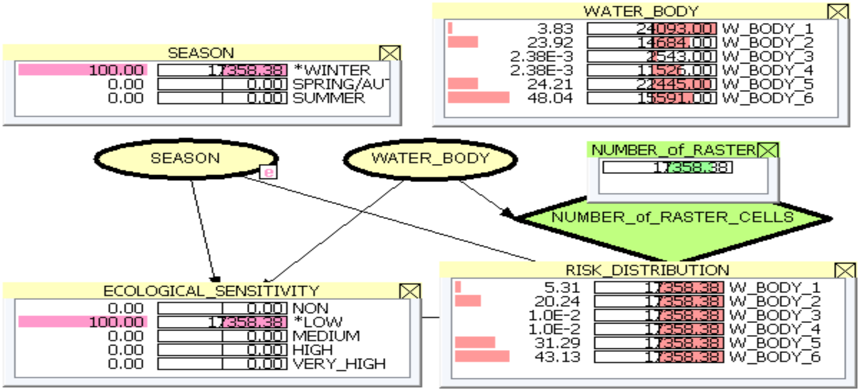

Figure 7: Ecological risk assessment BBN for the southern Gulf of Finland (Baltic Sea) coastal sea area (winter, low ecological sensitivity)

In this case the highest ecological risk is associated with the water bodies 6, 5 and 2 (43.13%, 31.29% and 20.24% respectively). If the variable “Ecological Sensitivity” state is changed to “Medium” (Figure 8) then the highest ecological risk is associated with the water bodies 5, 6 and 2 (30,54%, 26,77%, and 21,83% respectively).

Figure 9 shows ecological risk distribution calculated for variable “Season” in a state equal to “Winter” and the variable “Ecological Sensitivity” in a state equal to “Very High”.

Now, the highest ecological risk is associated with the water bodies 6 and 5 (61,91% and 12,99% respectively) while the ecological risk distribution over the rest of the water bodies is rather uniform and on a low level.

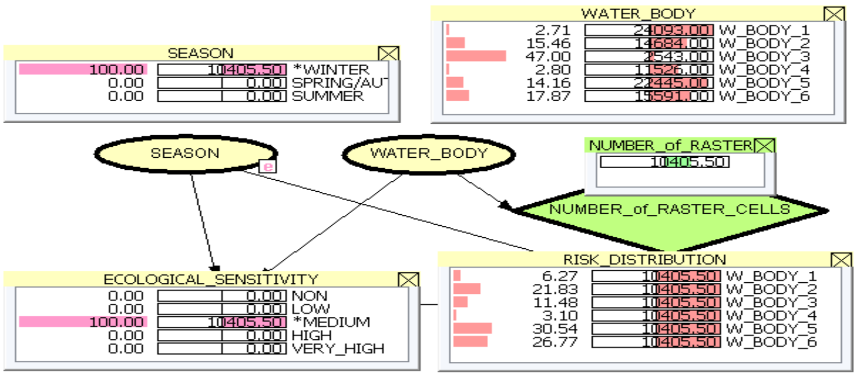

Figure 8: Ecological risk assessment BBN for the southern Gulf of Finland (Baltic Sea) coastal sea area (winter, very high ecological sensitivity).

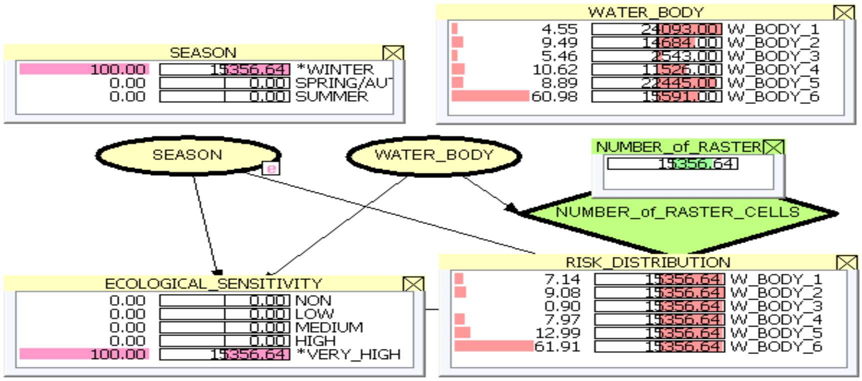

Figure 9: BBN for ecological risk assessment in the southern Gulf of Finland (Baltic Sea) coastal sea area (winter, high ecological sensitivity).

Throughout the paper, the issue of integrating BBN with other simulation tools proved to be an efficient technique in performing the potential oil pollution related predictive ecological risk assessment for the southern part of the Gulf of Finland. Furthermore, it is believed that the combined modelling approach presented in this paper would also be applicable with some modifications to a wide range of oil spill related ecological risk assessment problems.

4 Conclusions

In a case of oil spill the spatio-temporal fate of spilled oil (transport by currents and wind, spreading, evaporation, dispersion, emulsification) can be efficiently simulated using the comprehensive modelling suite Seatrack Web. However, it fails in resolving certain meso-scale hydrodynamic phenomena, such as upwelling and the related baroclinic coastal jets. In reality, depending on the wind conditions the spilled oil may travel alongshore with a speed up to 50 km per day.

Usually, booms and skimmers are the first technique employed to remove oil from marine environments but this technique can usually recover relatively small proportion of the spilled oil because of quite narrow window of opportunity depending on the actual weather conditions.

BBN integrated with other simulation tools proved to be an efficient modelling approach in performing the potential oil pollution related predictive ecological risk assessment for the southern part of the Gulf of Finland. A BBN is primarily used to update the ecological risk distribution over the states of a hypothesis variable, which is not directly observable. Ecological risk assessment is used then to support a decision maker in deciding upon an appropriate course of action.

Acknowledgements

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