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How to Model the Oil Combatting Technologies and Their Impacts on Ecosystem: a Bayesian Networks Application in the Baltic Sea

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Abstract

Oil spills from ship grounding and collision, are increasingly feared, as oil transports have increased in, for instance, the Baltic Sea and the Turkish Straits. Mitigation of negative biological and economic consequences is a difficult resource-consuming task where the effectiveness of counter-measures is dependent on technological factors and environmental conditions, the time development of which are uncertain. Such measures are, for instance, sealing of cracks in the tanker hull, limiting the use of the load carrying capacity of tankers, use of dispersants, use of oil combating vessels with certain deployment time and collection capacity. The assessment of the effectiveness of oil combating technologies, implemented singly or jointly in the case of oil spill, entails probabilistic modelling of their influences with respect to consequences. The paper introduces a Bayesian Network that can be used for analysing mitigation options under user-defined scenarios, where the scenarios are defined in terms of technological performance and weather conditions. The consequences are assessed with respect to changes in the population states of birds, herring, seal and benthos. Intermediate consequences are computed for the amount of oil in the water and the amount of polluted shore length. Environmental conditions are taken into account in terms of wave height, time of year and location of oil spill (open sea area / coastal area). By performing scenario (what-if) analyses, the decision-makers improve their understanding of the adequacy of the existing oil combating capabilities for the specified scenarios. Thus, the approach can be utilised to design contingency plans for oil spills.

Keywords: Oil combatting, Oil spill response, Oil spill effect, Baltic Sea, Environmental impact

1 Introduction

Recent major oil spills in the Europe (Prestige 2002, Erika 1999), combined with increased oil transportation in the Baltic Sea area, have caused a lot of concern and public interest on the safety of oil transportations. Because of terminal development in Russia, the transportation rates in the Gulf of Finland (GOF) have gone up and the risk of major oil spill has increased significantly. The oil transportation in the GOF amounted to 40 million tonnes in 2000, and

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estimations were carried out for the year 2005 yielding an expected transport rate of 85 million tonnes (VTT, 2002). The long-term prognosis according to recent knowledge of development plans show that oil transportation will rise to 230 million tonnes by the year 2010 (Fig. 1).

Gulf of Finland, as part of world's largest brackish water body, is extremely vulnerable to oil spills. Brackish water combined with low water temperatures, regular ice cover, shallow waters, partly permanent stratification, poor water exchange and vast archipelago are the reasons why the area is so vulnerable. Rich nature life and important fisheries are at risk in the case of oil spill. GOF has many conservation areas, and whole Baltic Sea was given Particularly Sensitive Sea Area (PSSA) status in year 2004.

A variety of models have been created to predict movement and dispersion of oil on the water surface, but models trying to estimate potential impacts on nature are few. Flint et al. (1999) modelled total bird mortalities in oil spill based on carcasses collected on the beaches. Downing and Reed (1996) constructed an oil impact model based on migration patterns of ringed seals (*Phoca hispida*) and polar bears (*Ursus maritimus*) to estimate impacts of oil spill to their populations. A probabilistic model that combines technical, environmental and financial aspects related to oil spill, is presented in French McCay et al. (2004). Bayesian Networks have, however, not been utilised in the assessment of biological effects oil spill to the knowledge of the authors.

Bayesian networks (BN) is a methodology, which has been developed for the assessment of the relative goodness of decision options in decision-making under uncertainty, where the uncertainty can be resolved by combining different types of evidence. BNs have been applied to a variety of environmental problems, such as fisheries management (Varis et al., 1994, Kuikka et al., 1999), but not to oil spill management, even though the management problems typically involve multiple criteria where the effects are uncertain and probabilistically dependent. The main advantage of the BN methodology is the ease by which the risk analyst and the decision-maker can test the sensitivity of the results to decision options (put in effect singly or jointly) and modelling assumptions.

This paper presents a BN model to support oil spill management. The BN model can be used to assess the effect of oil combating technologies to mitigate negative biological consequences. The BN modelling approach allows the risk analyst or decision-maker to perform what-if analyses (scenario analyses) and thereby gain insight into the decision problems related to oil spill management, in particular, contingency planning. Some predefined scenarios in the GOF area are defined and analysed to demonstrate how the BN model works and how it can be used in decision-making.

2 Decision model for oil spill management

The factors incorporated in the BN model are grouped into five groups: Oil transportation factors, Oil recovery factors, Environmental factors, Oil dispersion factors and Biological effects factors (Fig. 2). Factors in these groups are in a causal relation with each other, influencing the outcome of the sequence of events that ultimately will determine the biological effects of an oil spill. The structure of the causal relationships is known but the quantitative relationships between the variables are uncertain. Thus, the factors are modelled by random variables. The grouping of the factors is deemed very generic by the authors. The specific factors that are defined within the groups are, however, partly application specific, i.e. they are determined by the decision context.

The BNs in Fig. 3 show the structural relationships and the probabilistic dependencies between essential random variables in an oil spill management decision model. The part shown in Fig 3a is generic for oil spill management problems in general, whereas the BNs in Figs 3b and 3c are relevant for sea areas with populations of herring (*Clupea harengus membras*), birds, seals and benthos. Four decision options are defined in the BN model: limiting the tanker size, the oil recovery capacity, stopping of oil leakage and the use of dispersants, all indicated by squares in the BN.

Most important assumptions and restrictions in the current BN model:

1. Applicable only for the ice free period
2. Accident types are grounding and collision
3. Leakage calculations are based on double hull tanker designs
4. Restricted to cargo oils (not tankers own fuel or bunker oils)

5. Mitigation measures considered are ‘limiting the tanker size’, ‘degree of oil recovery capacity’, ‘use of dispersants’ and ‘stopping of leakage’.

The BN model is developed for predicting biological effects in different environmental and intervention scenarios. By doing ‘what-if’ analyses the risk analyst or decision-maker can gain insight of the effect of the interventions on the biological impacts on species populations given an accident type and environmental conditions. The aimed decision support is thus for oil spill contingency planning, rather than real time decision support for steering oil combating actions. (The BN model can be developed also for operative decision-making where observations on the development of an oil spill situation can be used as evidence for updating our predictions on the future states of the oil spill accident.)

3 Decision analysis based on the Bayesian Network for the Baltic Sea area

3.1 Specification of variables

The random variables in Fig. 3 are defined in Table 1. Variables describing oil transportation, *Tanker_Capacity*,, *Oil_Type* and *Max_Tanker_Size* are used to model tanker traffic in the area of interest. Decision variable *Max_Tanker_Size* can be used to rule out largest tankers (in this case 150 000 dwt) to see if it would have positive impact on predicted environmental impacts. Prior distributions for tanker capacities and oil types represents current situation in the GOF (Hänninen ja Rytkönen 2004).

Variables describing oil recovery are *Oil_Recovery_Capacity*, *Deployment_Time and Recovery_Efficiency*. Decision variable *Oil_Recovery_Capacity* represents total sum of large vessels capable for oil collecting in GOF area. Possible states for the variable are the present collecting capacity, the present capacity multiplied by 1.5, and the present capacity multiplied by 2. *Deployment time* is the time when 80 % of the available vessels are in the area ready for work. The prior distribution for *Recovery_Efficiency* is derived from a simple model, which calculates the percentage of oil removed from water depending on oil type, recovery efficiency and environmental conditions.

Environmental conditions in the area are described by *Location*, *Wave_Height* and *Time_of_Year*. *Location* has only two states, open sea and coastal area. Probabilities for accidents to happen in these areas are obtained from past accident in the GOF (HELCOM, 2001, HELCOM, 2002). *Wave height* is measured as significant wave height and prior distribution is got from wave buoy observations (Kahma and Petterson, 1993). *Time of year* is an important variable and has significant impact on the scale of the biological consequences. In the GOF area, a particularly vulnerable season is spring. Many important fish species spawn in spring. Birds migrate in million numbers to their northern breeding grounds through GOF in May, and seals have cubs which are more vulnerable to oil than adults (Davis and Anderson, 1976).

Oil dispersion; the amount and movement of oil in the GOF, is represented using the following variables: *Amount_of_Spilled_Oil, Evaporation, Oiled_Coastal_Waters, Type_of_Accident* and *Stop_Leaking*. *Amount_of_spilled_oil* is calculated from the International Maritime Organization's (IMO) outflow calculations (Herbert Engineering corp., 1998, IMO, 2002). Oil has a wide variety of different weathering processes but only evaporation is considered in this model. *Evaporation* is the only process where oil actually disappears from the water. In the other processes, oil stays in the water in some form. *Type_of_accident* can be grounding or collision and the distribution between these two is derived from accidents that have happened in the area (HELCOM, 2001, HELCOM, 2002). Decision variable *Stop_Leaking* represents the possibility to cut down the amount of oil leaking through a crack in the hull of a tanker. This decision option demonstrates the effectiveness of fast response to an oil spill accident in situations where the leakage is stoppable. *Oiled_coastal_waters* is an important variable being the major determinant of the biological consequences. A simple model is used to calculate the length of coastal waters affected by oil. It is determined by spilled oil, recovery efficiency and evaporation rate.

Biological consequences consist of individual level and population level impacts. At the population level the variables of main interest are the immediate and long-term impacts on herring, birds, seals and benthos. The decision option *Use_of_dispersant* is closely related to the biological consequences. Dispersant can be used to save valuable bird colonies or seal haul outs but at the same time pelagic and benthic animals suffer more from toxic effects of oil as it becomes more dissoluble (Singer et al. 1998). Expert judgments were elicited to estimate prior distributions for both individual and population level environmental impacts.

Acute impact on the herring populations is measured as percentage of how large a proportion of herring fries die because of oil. Long-term impact is measured in terms of the size of the recruited year classes. During 10 years, there should be at least one good year class. The instant impacts on birds and seals are measured as the number of dead animals. Long-term impact on birds is measured in terms of the state of the affected populations: has the number of the individuals returned back to the same level as before the accident. Benthos is considered here to include only invertebrates. The instant impact on benthos is measured in the size of the bottom area, which is affected by the oil. Long-term impact is measured in increased PAH – concentrations and possibly changed abundance between benthic species in oiled areas. In the GOF there are not any crab fisheries or commercially important mussel species.

3.2 Specification of scenarios

The ‘what-if’ analyses are based the specification of scenarios where environmental conditions and interventions (decision options) are set to certain states. A base or reference scenario has to be defined first. Other scenarios are subsequently compared to the base scenario to accumulate insight about the sensitivities of the conditions and interventions on the biological effects. In the following, we define three scenarios chosen for demonstrative purpose.

In the base scenario, decision variables are locked to represent current rules and practices, i.e. the current contingency plan. The base scenario reflects long-term average effects of oil spills given the current ‘state of affairs’. According to the accident frequency analysis of tanker traffic in the GOF, double hull tankers encounter accidents resulting in a ruptured cargo tank once every four years (Lampela, 2004). In the base scenario, bird populations seem to suffer the most harm, whereas as herring and benthos populations are quite unaffected. Long-term consequences are anticipated for birds and seals only (Fig. 4). Uncertainties related to oil type, weather conditions, location and season downplay the impacts of the optional interventions, rendering the contingency plan very ineffective.

The ‘worst case’ scenario is defined by locking states in the BN model such that it represents a situation where a large (150 000 dwt) tanker loaded with heavy oil collides with another vessel at open sea in spring. It is noticeable that the scenario represents worst states concerning tanker size, accident type, location and season, but not the amount of oil spilled in the water. Because of the oil type selected, we assume that dispersants are not applicable in this situation and we only assess the effects of the two other available decision variables, *Oil_Recovery_Capacity* and *Stop_Leaking*.

Table 2 shows probability tables of both acute and long-term population level consequences. Doubling oil recovery vessels did not have any effect. Short-term impact on herring seems to be relatively small. Long-term effects occur in herring under 10 % probability. Over 100 000 birds are killed with probability of 32 %, and if leakage is stopped, this drops to 21 %. Long-term effects can be severe for birds. Without stopping leakage, there is 38 % probability for medium changes in bird populations, which means that one or more species has disappeared from GOF or from its breeding grounds. Seals are also affected heavily, but long-term consequences are minor. In benthos there are 50 % chance for some effect and a high percent 36 % for no impact at all. The probability that there are any long-term changes in benthos is under 10 %.

In the third scenario a 75 000 dwt tanker carrying crude oil runs aground in coastal waters in autumn. We compare the consequences in two different cases. In the first case (Case 1) decision variables are in their initial states. In the other case (Case 2) oil recovery capacity is doubled, leakage is stopped and dispersants are used (Table 3).

In this third scenario acute environmental impacts are more severe in benthos and seals. Some effects in benthos occur with probability 46 % and with probability 48 % bird casualties are measured in thousands. There is also a 23 % probability that more than 10 seals are killed and a 6 % probability that more than 25 % of the herring's year class die because of oil in the whole GOF area. If leakage is stoppable, dispersants are used and we have doubled the recovery capacity, the expected impacts on birds are lighter. Seals and herring have a slightly increased chance to survive. For benthos there is virtually no change in the consequences. This is partly because of the use of dispersants, which put more stress on benthos and counteracts the positive effects from the increased recovery capacity and stopping of leakage.

Any noticeable long-term impacts are likely to occur only for birds and seals with approximately 10 % probability.

3.3 General observations on the results

By restricting tanker traffic to tankers under 100 000 dwt did not have a clear effect on the biological consequences. This is partly because of the relative small fraction (3,0 %) of such large tankers in the traffic in the GOF area. Therefore, the probability of oil spill from accidents involving big tankers is negligible. However, the trend in oil transportation is towards larger tankers (Rytkönen et al., 2002).

According to the BN model, an increase in oil recovery capacity would have little or no impact on environmental consequences. This is partly due to the observation from past accidents that only relative small percentage of oil can be recovered from the water (ITOPF, 1987), and partly due to simplifications in the BN model structure. The BN model does not separate the fraction of the oil that drifts on the surface, the fraction that sinks to the bottom, and the fraction that disperses in the water column. By increasing oil recovery capacity, we may be able to collect significantly more floating oil and thus prevent oil spill from smothering shore line, birds and marine mammals.

Dispersant usage seemed to be effective in mitigating consequences especially on birds but also on seals. HELCOM does not recommend the use of dispersants in the Baltic Sea and the same conclusion is put forward in Lindgren et al. (2001). Both recommend dispersants usage only in extreme cases where a rare bird colony is in threat and in deep water However, dispersant-based techniques have improved and became more environmental friendly and HELCOM has launched a new study to reassess their dispersant policy. Dispersants proved useful in the Sea Empress accident where 17 000 t of oil was dispersed preventing the shoring of 70 000 – 100 000 t of emulsion (Lunel et al., 1997).

According to the BN model, the biological effects would be smaller if oil leakage from a ruptured hull is stopped. This is quite obvious, but emphasizes the point that immediate response to oil spills is important. Another interesting decision option, not included in this version of model, is to tow a leaking tanker into one of the predefined safe havens where the leakage can be restricted in a smaller area. The success of the operation would be highly dependent on the weather conditions, location and the size of the rupture.

According to the BN model, consequences to the herring population would be minor in most of the scenarios. Long-term consequences 10 years after the accident would also be negligible. In a recent study of short-term impacts of oil spills in the waters of Nordic Countries, the outcome was much the same: the impact on pelagic fish stocks would be minor (IVL, 2004). However, Birtwell and McAllister (2002) concluded that in the British Columbia, oil spills should not be underestimated, as the threat to the local herring fisheries and to the ecosystem supporting it.

The BN model seems to underestimate the instant impact on birds. In several cases, the estimated death toll has increased to hundreds of thousands. For example in 1980 an oil spill of only 40 t killed approximately 100 000 to 500 000 marine birds in the North Sea (Swedish Coast Guard 2003) and in 1976, an oil spill of 10 t killed, approximately 60 000 wintering long-tail ducks (*Clangula hyemalis*). The BN model also predicts long-term changes in bird populations that could be severe in some scenarios. After Exxon Valdez, there has been much discussion whether oil spill have had any long-term impacts in the Prince William Sound (Irons et al., 2002, Wiens et al., 2004). It is very hard to show, after long period, if the population has diminished because of oil spill or some other reason.

The number of dead seals may be significant compared to the population size in the GOF. Previous oil spills affecting Finnish territorial waters have not had any impact on seals (Stenman, 1980, Hario, 1990). Seals are, however, highly concentrated in small areas, and if these are badly oiled, the impact could be severe. No significant long-term effects are expected for seal populations. Especially, this is the case with the gray seal (*Halichoerus grypus*), whose population growth has been fast in recent years.

The acute impact on benthos would not be big in many scenarios. The probability of large effects are minimal. This is supported by IVL (2004) which concluded that the effects on benthos would have a significance only in case where oil sinks to bottom and suffocates benthic animals in large areas. Long-term consequences should not appear, according to the BN model. This is supported by recent studies in the Baltic Sea where only slightly elevated PAH-concentrations were measured in animals living in tidal area in the immediate vicinity of still reactive oil remaining under the stones (Pahtamaa et al., 1998).

Based on the BN model, it can be concluded that in the case of large oil spills, there will be biological damages to bird and seal even if the scale of intervention is substantially increased. This result emphasises prevention of oil spill accidents as the foremost strategy in oil spill management.

4 Discussion

The BN model introduced incorporates both technical and environmental aspects related to oil spills. The BN model is developed for application in the Baltic Sea area and especially in the Gulf of Finland. With some changes and new input data, the BN model can be modified to support oil spill management in other sea areas.

At this development stage, the BN model is, however, not yet adequate to reliably judge between oil spill management decisions or predict biological consequences. Input data should be collected more carefully and the discretization of the distribution functions of the variables should be denser. Because of the introductory nature of the study, only one expert was used in the estimation of the conditional probabilities related to the biological consequences. The utilisation of more elaborate oil dispersion and drift models, for instance, 3D oil dispersion models (Skognes and Johansen, 2004), would increase the accuracy of the predictions of the biological effects.

Despite the inadequacies for reliably computing numerical results, the BN model structure can advantageously be utilised for communicating oil spill management issues to stakeholders (Bromley et al., 2005).

The BN model described above has been complemented with a BN sub-model for cost assessments related to oil spill: cost factors for oil recovery at sea, oil cleanup of smothered shoreline and maintenance costs of the oil combatting equipment are computed to support cost-benefit analyses. The next stage in developing the BN- cost model is to price environmental values to get estimates for total costs of oils spills.

The Hugin Ver. 6.3 BN application environment was used in constructing and running the BN model due to its easy-to-use interface, fast calculations and visualization features. Hugin also supports extendibility and linkage of separate BN models.

It is the belief of the authors that the proposed modelling approach to support oil spill management has the potential of a valuable decision-support tool for decision–makers.

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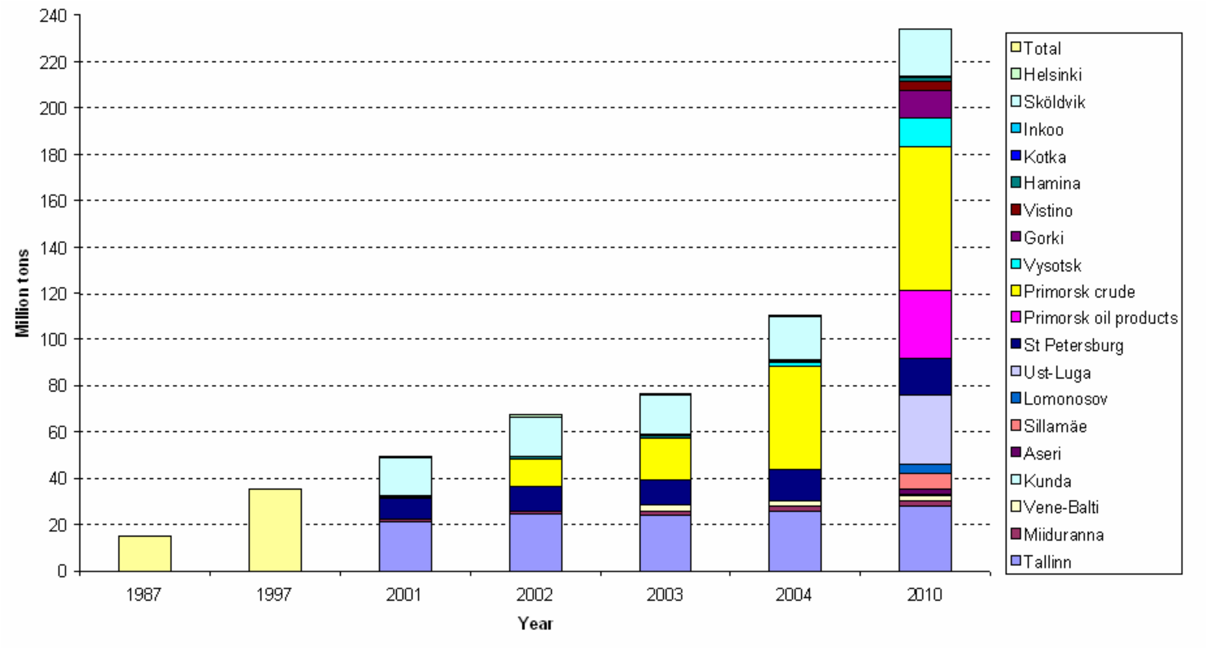

Fig. 1. Oil transportation in the Gulf of Finland. Actual volume in years 1987-2004 and estimated development for 2010. Source: VTT, 2005.

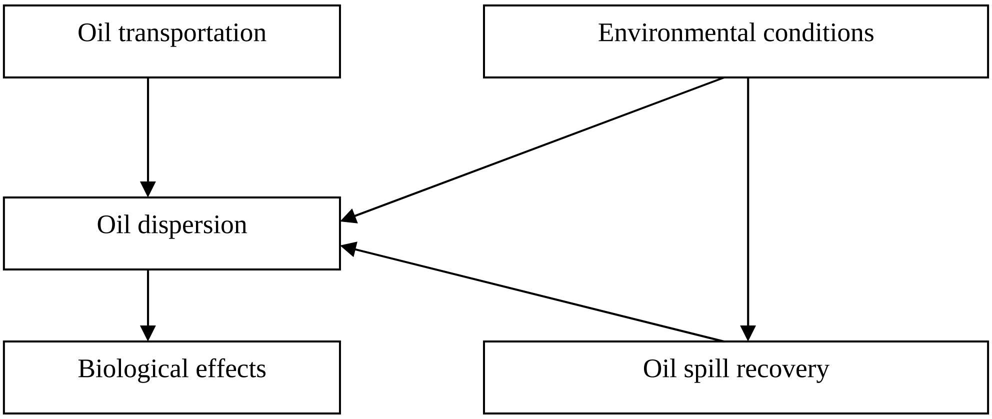

Fig. 2. Causal relationships between different types of factors in the oil spill management model.

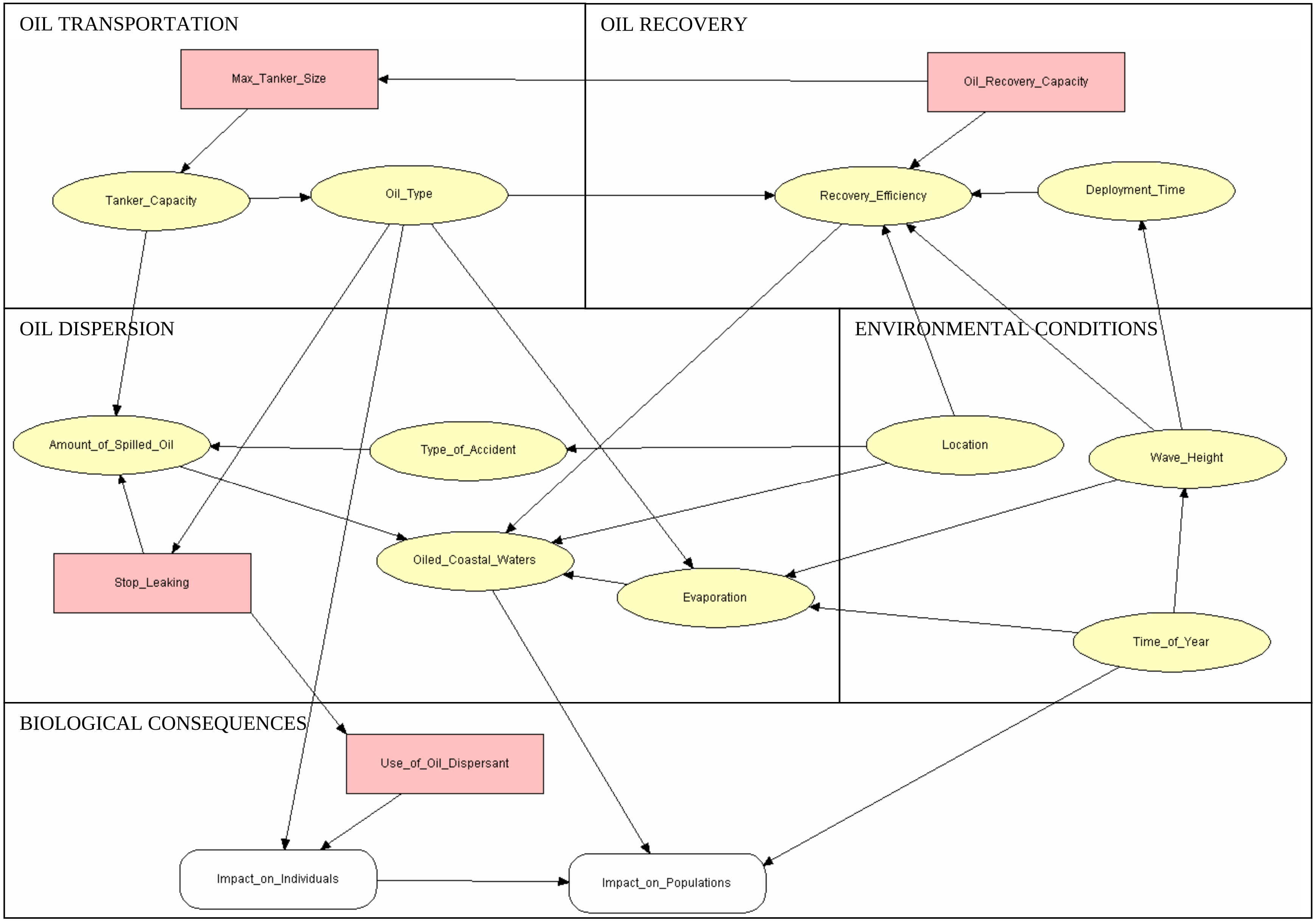

Fig. 3a. Bayesian network depicting the causal relationship between variables related to oil recovery efficiency and biological effects. The square boxes denote decision options, the ovals denote random or chance nodes, the outcome of which are dependent on the outcome of the previous nodes and decisions.

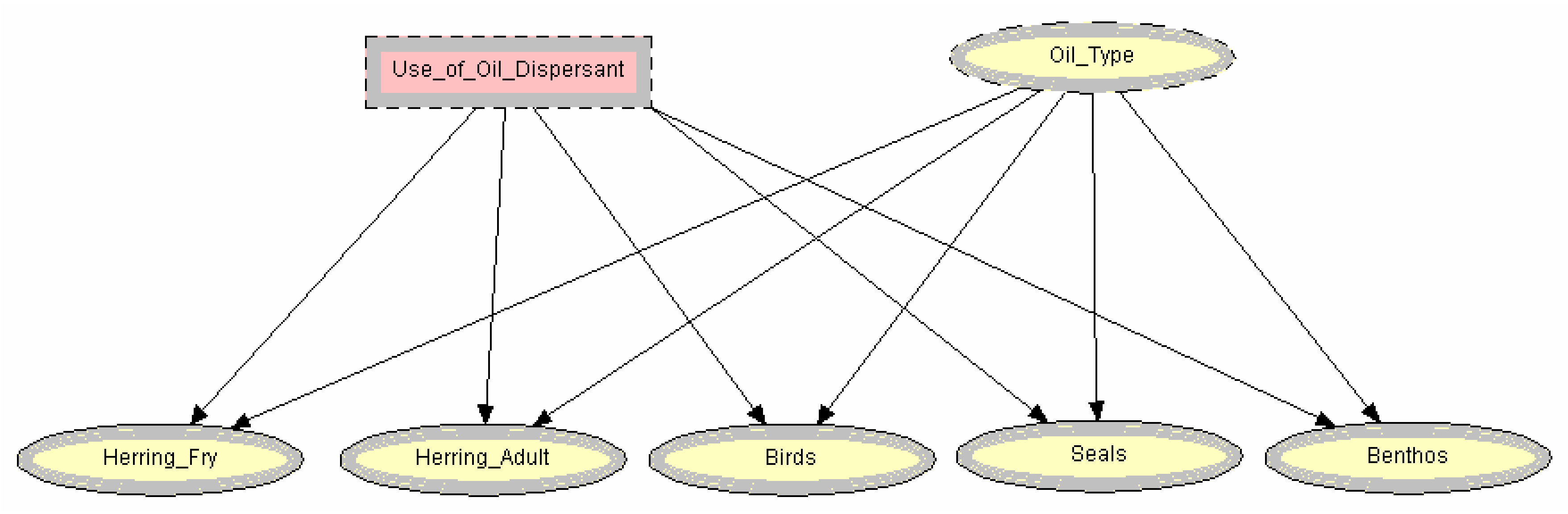

Fig. 3b. Sub network detailing the causal relationships of variables related to the effects of oil spill on specific species at individual level.

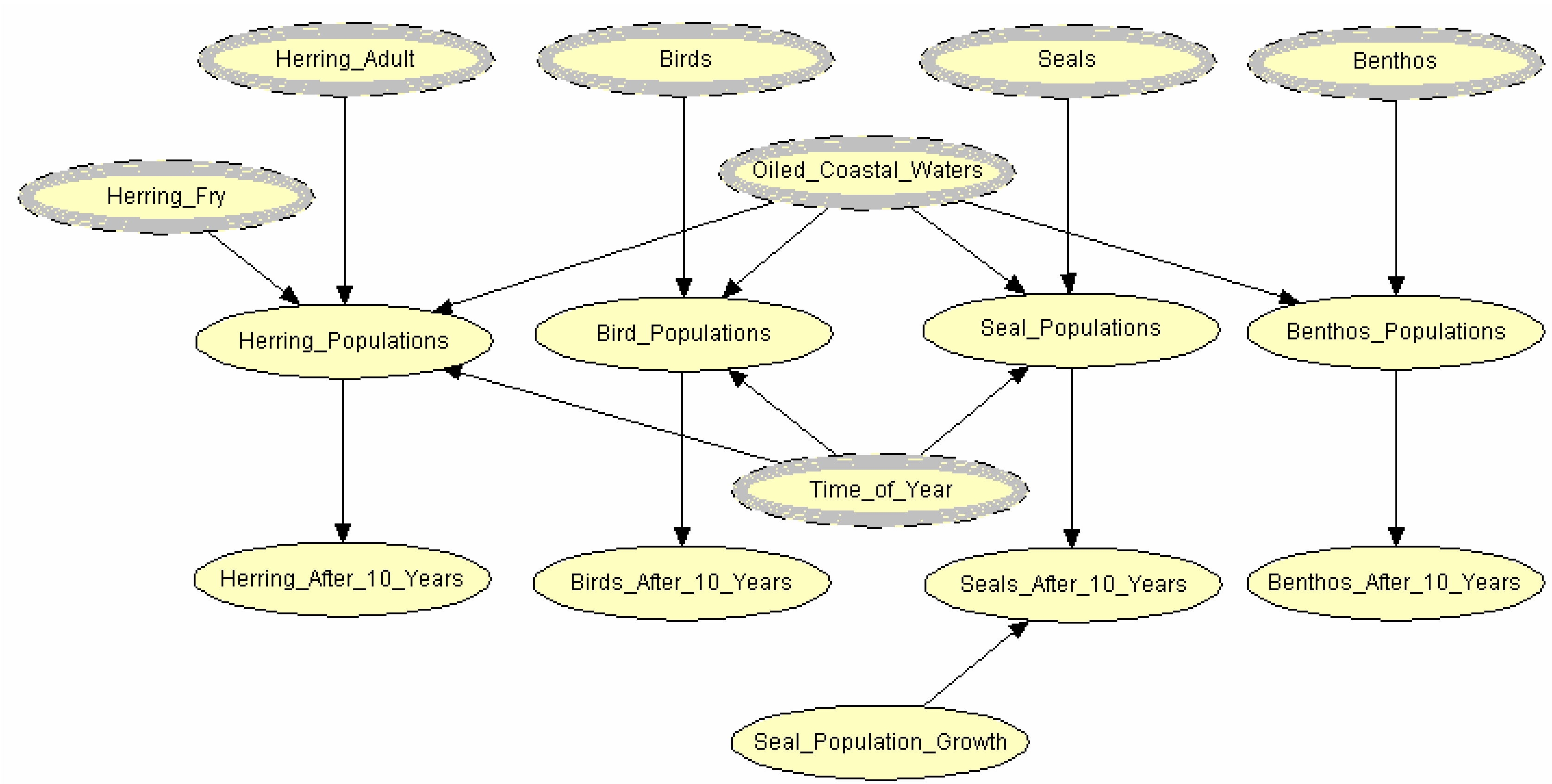

Fig. 3c. Sub network detailing the causal relationships of variables related to the effects of oil spill on specific species at the population level.

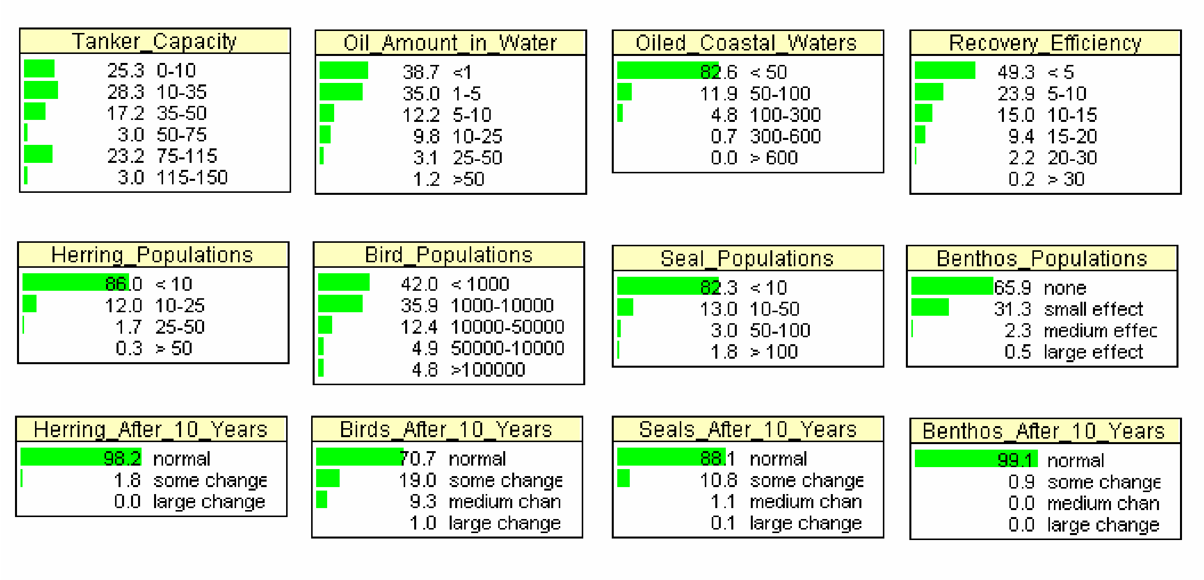

Fig. 4. Selected probability distributions of variables in base scenario.

Table 1. The variables in the decision model.

Factor Group	**Name**	**Type of variable**	**Outcome categories**
Oil Transportation	Max_Tanker_Size	*decision*	100 000 or 150 000 (dwt)
	Tanker_Capacity	chance	0-10, 10-35, 35-50,50-75, 75-115, 115-150 (1000 t)
	Oil_Type	chance	light oil, medium heavy oil, heavy oil
Oil Recovery	Oil_Recovery_Capacity	*decision*	present, x1,5, x2
	Deployment_Time	chance	2, 3, 4, 5 (days)
	Recovery_Efficiency	chance	<5, 5-10, 10-15, 15-20, 20-30 ,>30 (%)
Environmental Conditions	Location	chance	open sea, coastal area
	Wave_Height	chance	0-1, 1-2, 2-3, >3 (m)
	Time_of_Year	chance	spring, summer, autumn
Oil Dispersion	Amount_of_spilled_oil	chance	<1, 1-5, 5-10, 10-25, 25-50, >50 (t)
	Evaporation	chance	<33, 33-66,>66 (%)
	Oiled_Coastal_Waters	chance	<10, 10-50, 5-100, 100-300, 300-600, >600 (km)
	Type_of_Accident	chance	grounding, collision
	Stop_Leaking	*decision*	yes or no
Biological Consequences	Use_of_Oil_Dispersant	*decision*	yes or no
Individual	Herring_Fry	chance	none, deformations, death
	Herring_Adult	chance	none, exposure, death
	Birds	chance	none, smothering, death
	Seals	chance	none, smothering, death
	Benthos	chance	none, exposure, death
Population	Herring_Populations	chance	<10, 10-25, 25-50, >50 (%)
	Bird_Populations	chance	<1, 1-10, 10-50, 50-100, >100 (dead birds x 1000)
	Seal_Populations	chance	<10, 10-50, 50-100, >100 (dead seals)
	Benthos_Populations	chance	none, small, medium, large effect
	Long_Term_Herring	chance	normal, some, large changes
	Long_Term_Bird	chance	normal, some, medium, large changes
	Long_Term_Seal	chance	normal, some, medium, large changes
	Long_Term_Benthos	chance	normal, some, medium, large changes
	Seal_Reproduction	chance	<5, 5-10, >10 (%)

Table 2. Probability tables of environmental variables in 'worst case' scenario for three different decision combinations.

	As it is	Recovery capacity x 2	Stop leaking		As it is	Recovery capacity x 2	Stop leaking
Herring_Populations				**Herring_ After_ 10_ Years**			
< 10	67	68	77	normal	90	90	94
10-25	22	21	16	some_changes	10	9	6
25-50	10	10	6	large_changes	0	0	0
> 50	1	1	0				
Bird_Populations				**Birds_After_10_Years**			
> 1000	23	23	29	normal	34	34	43
1000-10000	13	13	18	some changes	24	25	24
10000-50000	17	18	18	medium changes	38	37	29
50000-100000	15	16	14	large changes	5	5	4
> 100000	32	30	21				
Seal_Populations				**Seals_After_10_Years**			
< 10	55	55	63	normal	81	81	84
10-50	22	23	21	some changes	16	15	14
50-100	10	14	10	medium changes	3	3	3
>100	13	8	6	large changes	0	0	0
Benthos_Populations				**Benthos_After_10_Years**			
none	36	36	44	normal	93	94	96
small effect	50	51	47	some changes	6	6	4
medium effect	9	8	7	medium changes	1	0	0
large effect	5	5	3	large changes	0	0	0

Table 3. Probability tables of environmental variables in second scenario for two different decision combinations.

	Case 1	Case 2		Case 1	Case 2
Herring_Populations			**Herring_ After_ 10_ Years**		
< 10	72	80	normal	94	99
10-25	21	19	some_changes	6	1
25-50	5	1	large_changes	0	0
> 50	1	0			
Bird_Populations			**Birds_After_10_Years**		
> 1000	52	70	normal	87	94
1000-10000	43	30	some changes	12	6
10000-50000	4	0	medium changes	1	0
50000-100000	1	0	large changes	0	0
> 100000	0	0			
Seal_Populations			**Seals_After_10_Years**		
< 10	77	85	normal	88	90
10-50	18	13	some changes	10	10
50-100	4	1	medium changes	1	1
>100	1	0	large changes	0	0
Benthos_Populations			**Benthos_After_10_Years**		
none	54	53	normal	98	99
small effect	40	43	some changes	2	1
medium effect	5	4	medium changes	0	0
large effect	1	0	large changes	0	0