CM 2007/C:07

EVAGULF – Protection of aquatic communities in the Gulf of Finland: risk-based policymaking

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Abstract

Most of the analyses related to eutrophication focus on cyanobacterial blooms or increased primary production. However, eutrophication may also lead to disappearance of species, which is a real risk to the ecosystem. In this paper, we introduce the first version of a decision model that takes into account the biodiversity risks of eutrophication. The model is being developed within the EVAGULF project and it will also include a Bayesian classification tool for water areas, needed in the implementation of the EU water framework directive. Existing monitoring databases, knowledge from published literature and expert knowledge will be integrated and analysed by Bayesian risk assessment methodology. The selected computational methods enable combining data that are of different nature as well as concrete elucidation of benefits and risks associated with alternative management decisions. The anticipated results will enable determining the factors that are likely to cause changes in the occurrence of species and the effects of abatement measures: e.g. which populations can be managed only by national management actions and in which cases international co-operation is needed to achieve the objectives. This knowledge will enable more cost-effective use of the available financial resources.

Keywords: eutrophication, risk assessment, Bayesian methodology

1. Introduction

When making decisions on the conservation and possible restoration of the environment, e.g., in planning nature reserves, endangered populations are usually of particular interest. Conservation measures and resources need to be targeted to safeguard environmental diversity and the survival of native species. To reach the objectives, the viability of the populations needs to be analyzed, and the probable consequences of different conservation measures evaluated, including the risks associated with not acting (Ludwig 1996). A proper risk analysis should also include a comprehensive assessment of the uncertainties related to the predictions. The magnitude of acceptable risks must be defined by the values of the society (Burgman 2005).

However, in water management the risks for single species are not commonly evaluated. The water quality and the state of the ecosystem in the Gulf of Finland have deteriorated with an accelerating pace during the last years. This has happened despite considerable investments on environmental protection, research, and international protection programmes and agreements. The largest problem is still eutrophication, primarily caused by nutrient loading from the catchment area (e.g., HELCOM 2005). The public interest in the eutrophication of the Gulf of Finland has so far focused on a narrow scope, dealing mostly with nuisance algae and recreational values, and being limited mostly to the summer season.

Instead of focusing year after year on phenomena that we want to get rid of, we should also study the species and populations we risk to loose if the development continues unchanged. The discussion, both in the public and within the research community, is missing a concrete view of what kind of risks exist in the form of disappearing species if the current eutrophication trend continues. Having one might aid both the public and political debate and give the problem the attention it deserves.

The Gulf of Finland has been widely studied, and several long-term monitoring data sets exist (e.g., Elken et al. 2003). Traditionally, each of the possessors of data sets has analyzed their own data separately from the others. In addition, there are hundreds of single studies, whose results have been left totally unutilized after their publication. Because the resources to protect the Gulf of Finland are limited in all the surrounding countries, they should be used in the most cost-effective way possible to improve the state of the water area.

Combining the information contained in existing monitoring data and studies and analyzing them simultaneously would considerably increase its value and the benefit that can be obtained from it. Based on such analysis, the relevance of current monitoring programmes could also be evaluated. However, this requires co-operation and increased openness between research institutes, both internationally and within countries. In addition, tools are needed for combining data sets and model results, and for clearly visualizing the results and the related uncertainties.

The improvement of the state of the Gulf of Finland requires considerable effort from all three surrounding countries: Finland, Estonia and Russia. A joint understanding of the current and target states of the Gulf of Finland is needed among the countries for visible results and the optimal use of available financial resources. Also, the effects of national decisions and changes in nutrient loading from different parts of the catchment area on the different areas in the Gulf of Finland should be predicted to evaluate the regional importance of international co-operation.

1.1 Project EVAGULF

EVAGULF is a Finnish-Estonian joint project that aims for communicating the likely impacts of eutrophication in the Gulf of Finland. The project also aims to evaluate the effects of protective actions already done and to assess the existing risks related to the present state of the ecosystem. The project is constructing risk and decision analysis tools to ease the work of those who decide about conservation investments, and plan and execute monitoring programmes.

The EVAGULF tool is based on a probabilistic Bayesian model, which integrates information from different sources. It enables the assessment of the risks posed by eutrophication on population, community and ecosystem levels. It can also be used to assess the cost-effectiveness of national nutrient management policies and their effectiveness, e.g. which populations can be managed by the Finnish conservation actions alone and in which cases international co-operation is required. The results will also enable sorting out the main actors behind the shifts in occurrence of different species. Due to the use of the Bayes rule, the model will enable both the assessment of the system (information flow from effects to causes) and the prediction of impacts of the management actions (from cause to effect). In standard point estimate models, only the second option is usually available.

The model will also be able to take into account the predicted effects of the global climate change on the eutrophication process and on the organisms, so that the chances of the surrounding countries to affect the survival of the species can be evaluated. This will ease the effective targeting of resources available for conservation measures. The joint development of the tool will also promote the development of a shared view and conservation policy between Finland and Estonia.

The EVAGULF project is going on from September 1st 2006 to December 31st 2007 and a three year continuation is being negotiated. During the current pilot stage, a prototype of the risk assessment and decision support system (RADSS) will be created. With the RADSS, the susceptibility of certain populations to eutrophication can be evaluated, as well as how different nutrient abatement measures in the catchment area will affect the biodiversity in the Gulf of Finland. The analysis will be based on existing ecosystem models, monitoring data sets, and literature and expert knowledge on the water quality and organisms of the Gulf of Finland.

In this paper, we introduce the first version of a decision model that takes into account the biodiversity risks of eutrophication.

2. Materials and methods

2.1 Bayesian networks

In the EVAGULF model, Bayesian networks (BNs, e.g., Charniak 1991), based on conditional probabilities and known cause-effect chains, is the methodological tool used to combine results from separate loading, ecosystem and population models. The method enables the combination of data sets of different forms and with different precision to a single analysis, and the assessment of the origin, type and magnitude of the uncertainties related to the cause-effect relationships and decisions.

Decision support system (DSS) is a term for a method that provides a quantitative means to study different alternative decisions (Clemen 1996). They ease the work of decision-makers by helping to make consistent and justifiable choices. Through Bayesian networks enhanced with decision and utility variables, the management actions and their consequences can be evaluated, taking uncertainty fully into account. Thus, BNs are flexible tools what comes to the construction of different kinds of decision support and analysis systems being applied in many environmental issues (e.g. Varis 1997, Marcot et al. 2001, Borsuk et al. 2004).

A Bayesian network is a way to analyze and visualize, what we think of some phenomenon. It consists of discretized variables, each having a defined number of possible outcomes, i.e. discrete classes of variables. The links between the variables have been defined based on how the variables are thought to be related in the light of current knowledge. For each variable having incoming links from parent variables, a conditional probability is determined for every possible level on the condition of all combined levels of the parents. Afterwards, the Bayesian network can be used to evaluate the functioning of the system by manipulating the state of some variables and calculating the effects on others. The network algorithm calculates probability distributions for the variables based on how the conditional probabilities have been defined. In the EVAGULF model, the conditional probabilities are estimated computationally with the help of the models described below.

Bayesian networks have been used to help in the search for optimal decision strategies under uncertainties (Varis 1997). More lately, they have been used in modelling complex environmental questions and interactions containing significant uncertainties (e.g. Reckhow 1999, Marcot et al. 2001, Borsuk et al. 2004). Bayesian networks are especially suitable for questions where uncertainty plays an important role, but, at the same time, the processes and cause-effect relationships are relatively well known (Uusitalo 2007).

One of the significant benefits in using Bayesian networks is that they are illustrative and relatively easy to understand. They fit very well to the risk assessment framework by enabling the study of the tails of probability distributions, i.e., extreme scenarios, the most serious outcomes with small probabilities, which in many cases are particularly in focus when risks are analysed. Different policy scenarios can be determined with the decision variable of the network. State alternatives resulting from the decisions can be valuated in relation to the other possible states by using a utility function. By calculating through the network, the decision alternative most likely producing the greatest utility and minimizing the risks can be determined. The presentation of predictions as probability distributions gives decision-makers a more realistic picture of the uncertainties related to the ecological processes and the effects of the conservation measures (Borsuk et al. 2004).

Another important benefit is also the easy updating of a Bayesian network: the network updates itself based on a change made in a certain part of it, i.e., knowledge related to one or more variables is updated. The new knowledge affects the shape of the probability distribution either by narrowing or spreading it, depending on whether the new observation is in line with earlier results or not. The Bayesian networks and the decision analysis are carried out in the EVAGULF project by the Hugin software (Madsen et al. 2005). In the RADSS, the Bayesian Networks for Java software (Hsu 2003) will be used.

2.2 Decision options

For Finland, the biological impacts of the following reductions in nutrient loading to the Gulf of Finland are considered: 10 %, 20 – 25 % and 40 – 45 % reductions in both nitrogen and phosphorus loading. The first option is regarded as “business as usual” option, which may be reached with current policy. The second option is regarded as realistic, and the third option as optimistic requiring high political commitment.

For Estonia, two scenarios are considered. In the first option the nutrient loading from agriculture to the Gulf of Finland stays at the current level. In the second option the loading from agriculture increases 10 % due to increased production.

Two scenarios are considered also for Russia. In the first option, 80 % of the phosphorus in municipal waste water is removed in the current water treatment facilities. In the second option, all municipal waste water is treated, and 70 – 80 % of both nitrogen and phosphorus are removed.

The combined effects of all possible combinations of management actions can be modelled and their impacts on species risks estimated.

2.3 Regional division

In the EVAGULF RADSS, the coastal areas of Finland and Estonia in the Gulf of Finland are divided according to the division that is made for the implementation of the EU Water Framework Directive (European Commission 2000): the Finnish coast to eastern and western inner and outer archipelago zones, and the Estonian coast to eastern and western coastal zones. The pelagic area from the Hanko peninsula to the border of Russian water area is divided into two parts. This division is based on a similarity analysis conducted in the Finnish Institute of Marine Research (FIMR). The Russian water area is treated as one separate area (Fig. 1).

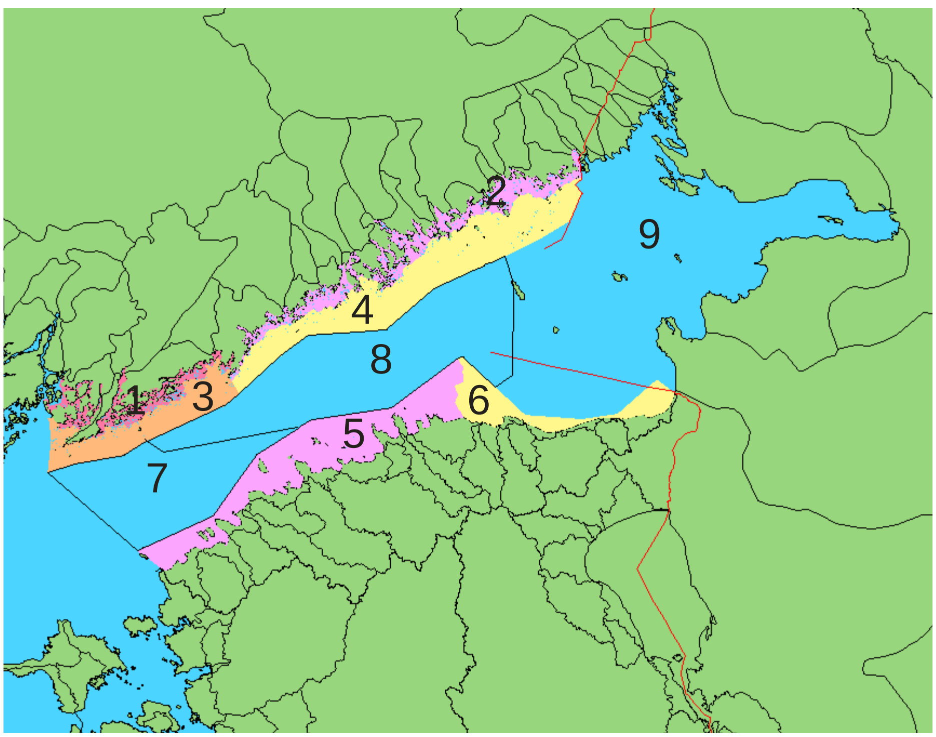

Fig. 1: Regional division of the Gulf of Finland in the EVAGULF tool. Finnish coastal areas: 1. Western inner archipelago, 2. Eastern inner archipelago, 3. Western outer archipelago and 4. Eastern outer archipelago. Estonian coastal areas: 5. Western coast and 6. Eastern coast. Open sea-areas: 7. Western open sea, 8. Central open sea and 9. Russian territorial waters.

2.4 Loading models

Finnish Environment Institute (SYKE) is responsible for the production of nutrient loading scenarios according to the different decision alternatives. With the help of loading models, the effects of each decision on the total nutrient loading to the Gulf of Finland are predicted. Nutrient loading data of SYKE and Estonian Marine Institute (EMI) from rivers, including River Neva, are used.

The global climate change is predicted to impact precipitation and thus the run-off from the catchment area of the Gulf of Finland (Hyvärinen 2003). This affects e.g. the amount of nutrients leaching from the catchment. The EVAGULF tool includes a climate change scenario function, with which the climate change can be included in the loading predictions. The function is carried out by running the loading model for several years with the values of an exceptionally warm winter.

2.5 Ecosystem models

SYKE and FIMR provide the EVAGULF project large biological and water quality data sets. The institutes have developed advanced 3D ecosystem models (e.g. Kiirikki et al. 2001, Stipa et al. 2003, Stipa 2004, Kiirikki et al. 2006), with which nutrient cycles, eutrophication and algal bloom predictions, effects of climate change on the ecosystem of the Gulf of Finland etc. are computed. The outcomes of these models will then be used as input to the Bayesian network models, which are used as meta-models, integrating the information from several other models.

The long-term physical and chemical water quality monitoring data sets of SYKE, FIMR and EMI are used in the models. The 3D models are suitable for modelling surface currents and water exchange (Andrejev et al. 2004), onset and development of phytoplankton blooms (Stipa 2002, Stipa 2003), sediment processes and internal loading (Kiirikki et al. 2006) and algal biomass (Inkala & Pitkänen 1999, Kiirikki et al. 2001, Pitkänen et al. 2007), among others. Based on the results of these model runs, conditional probability distributions for the key environmental correlates (KECs, e.g., Marcot et al. 2001) of organisms will be determined. These include, depending on the organism in question, the amount of oxygen, light and sedimenting material, temperature, salinity and ice cover.

The predicted effects of the global climate change are taken into account also in the ecosystem modelling. The effects of the climate change on the salinity and the duration and extension of ice cover in the Gulf of Finland are included in the EVAGULF model using the same principles as in the loading models.

2.6 Population analyses

The likely effects of the KECs, predicted by the ecosystem models, on the population of a studied organism and its viability predictions can be assessed by population analyses. Information of the effects of physical, chemical and biological variables on organisms is gathered mainly from literature and also from expert interviews, in a case that there are no reliable or applicable publications available. In cases where more intensive monitoring data is available, it is also utilized in population analyses. These include species regularly found in the monitoring of macrophyte vegetation, plankton community and zoobenthos.

Existing results of the distribution and ecology of different species, some of them dating even back to the early 20th century, are studied simultaneously with water quality data from the same areas and time periods. Historical results can be used as reference material in comparison with the years of maximum nutrient loading and current situation and further to predict the likely future reactions of the populations.

Traditional population models, based on averages and confidence intervals, have been found to underestimate the extinction risk of species (Ludwig 1996). In addition, the material used in population analyses is heterogeneous, the precision varying from verbal descriptions to exact numeric estimates. In many cases data cannot cover all the elements of required knowledge, subjective expert judgements and degrees of belief being the only source for defining those (Uusitalo et al. 2005). All of these facts support the use of probability-based methods in population analyses. Differing observations, reports or expert opinions increase the uncertainty by spreading the probability distribution of the phenomenon, thus providing clear information of the uncertainty concerning the subject in stead of an overconfident single value.

Single and combined effects of the KECs on “data rich species” are modelled by using Bayesian MCMC-simulations of the WinBUGS software (Bayesian Inference Using Gibbs Sampling, Spiegelhalter et al. 2005) or in cases, where numerical data is not available, by Bayesian networks built according to expert evaluation. The attained conditional probabilities are further used as a basis in the population viability analyses (PVAs, e.g. Morris et al. 1999) when predicting the probability of a population to fall below a certain threshold within a time period. Endpoints in focus are the deadline years 2015 of the Water Framework Directive (European Commission 2000) and 2021 of the Marine Strategy of European Union (European Commission 2006).

When the population model is used for risk analysis purposes, the absolute population density or distribution area is not in focus, but the relative values in comparison with a certain reference level. Despite the huge uncertainties of the DSS recommendations based on absolute PVAs, decision rankings produced by corresponding relative PVAs have been found to be quite robust to uncertainty (McCarthy et al. 2003). In the EVAGULF population models, the studied variable is proportioned either to the current or to a historical value, depending on the risk approach used (see the next chapter).

The criteria for population viability in different PVAs vary depending on the context. Ludwig (1996) and McCarthy et al. (2003) criticise the use of complete extinction as a threshold, because the random environmental factors make predicting to moment of total extinction, i.e., when the last individual has died, difficult, which increases the uncertainty both in the results of the analysis and in the decision ranking. Therefore, Ludwig (1996) recommends the use of the probability that the population size becomes so small that it is in danger to disappear, as the criteria. McCarthy et al. (2003) also find this kind of a minimum population approach to work better for e.g. populations, which have a very low probability for total extinction, and for populations which are already very small. In the EVAGULF PVAs, the criteria and threshold values are determined by the selected risk approach (see the next chapter).

2.7 Risk calculation

The concept of risk contains the probability of a certain event and the magnitude of harm caused if it becomes true. Thus, the magnitude of risk is always somewhat subjective (Burgman 2005). The risk approach of the EVAGULF RADSS is not designed to reflect the views and values of its creators, but to produce risk assessments that are commonly acceptable and follow the current concerns and decisions of the society. Therefore, the valuation of harm is based on recommendations and threshold values defined in international agreements, classification systems and legislation.

What comes to the biodiversity and ecological quality of the Gulf of Finland ecosystem, even the commonly accepted definitions of targets, indicators and criteria vary greatly depending on the context. In the pilot stage, the EVAGULF RADSS uses two different risk approaches, one based on the criteria of the international conservation status classification (World Conservation Union, IUCN 2001) and another on the coastal water classification system of the EU Water Framework Directive (European Commission 2000). Both aim to secure the biological diversity and a good environmental status of the Gulf of Finland, but their emphasis and indicators vary. It is of interest to assess, whether the different aims lead to different policy recommendations.

In the risk calculation of the EVAGULF model, the probability of an event, i.e., the probability that the population size or some other attribute in focus falls below a certain threshold, is reached by calculating through the whole previously described Bayesian network from the decision variables to the PVAs. Different values of the variables are valued according to the logic of each valuation argument (Table 1). The utility variable of the Bayesian network can be turned into “a harm variable” by giving the largest expected value to the most harmful alternative. When the valuation factor is multiplied by the probability, the result is the risk, and the largest value also describes the largest risk.

Table 1. Classification states of the EU Water Framework Directive (WFD), international conservation status of the World Conservation Union (IUCN) and the harm values (scale 0-100) they are given in the EVAGULF valuation. In WFD, the critical limit is between the classes “Good” and “Moderate”. IUCN classes: LC = least concerned (vital), NT = near threatened, VU = vulnerable, EN = endangered and CR = critically endangered.

WFD classes:	High	Good	Moderate	Poor	Bad
Harm value	0	0	100	100	100
IUCN classes:	LC	NT	VU	EN	CR
Harm value	0	40	60	80	100

2.8 User interface

The EVAGULF RADSS will be available as a freely usable interactive graphical application in the Internet. Interactivity enables what-if analyses and even real-time updating of the model in the light of new information and data. Open access offers both the potential end-users and the general public an equal opportunity to evaluate the information produced by the tool, its function and usability. Thus it will be possible to critically assess the RADSS, a prerequisite for its international approval and further development. In addition, the RADSS is hoped to initiate public discussion on eutrophication, global climate change and the need for international co-operation.

In the user interface, the user may select the nutrient abatement scenario for Finland, Estonia and Russia, the sub-area of interest in the Gulf of Finland, inclusion or exclusion of the climate change scenario and the valuation principle. The program then takes these selections to the Bayesian network, which provides the risk figures and measure recommendations.

The RADSS provides the user also a more in-depth access to the Bayesian network, if one is needed. The program will also contain information and visualization tools related to the topic.

3. Functioning of the EVAGULF Risk Assessment and Decision Support System

With the EVAGULF RADSS, population and ecosystem level risks can be calculated for different nutrient loading options with the conditions defined by the user. The BN calculates the probability distributions for the amount of external nutrient loading to the water area X from the catchment area, conditional to the measure options selected. This information is further processed in the ecosystem model part, where the conditional probability distributions for the predicted environmental conditions due to changes in primary production are modelled. The output distributions of the ecosystem model serve as input data for the population analyses, which model the probable response and the survival of the species in the conditions in question (Fig. 2).

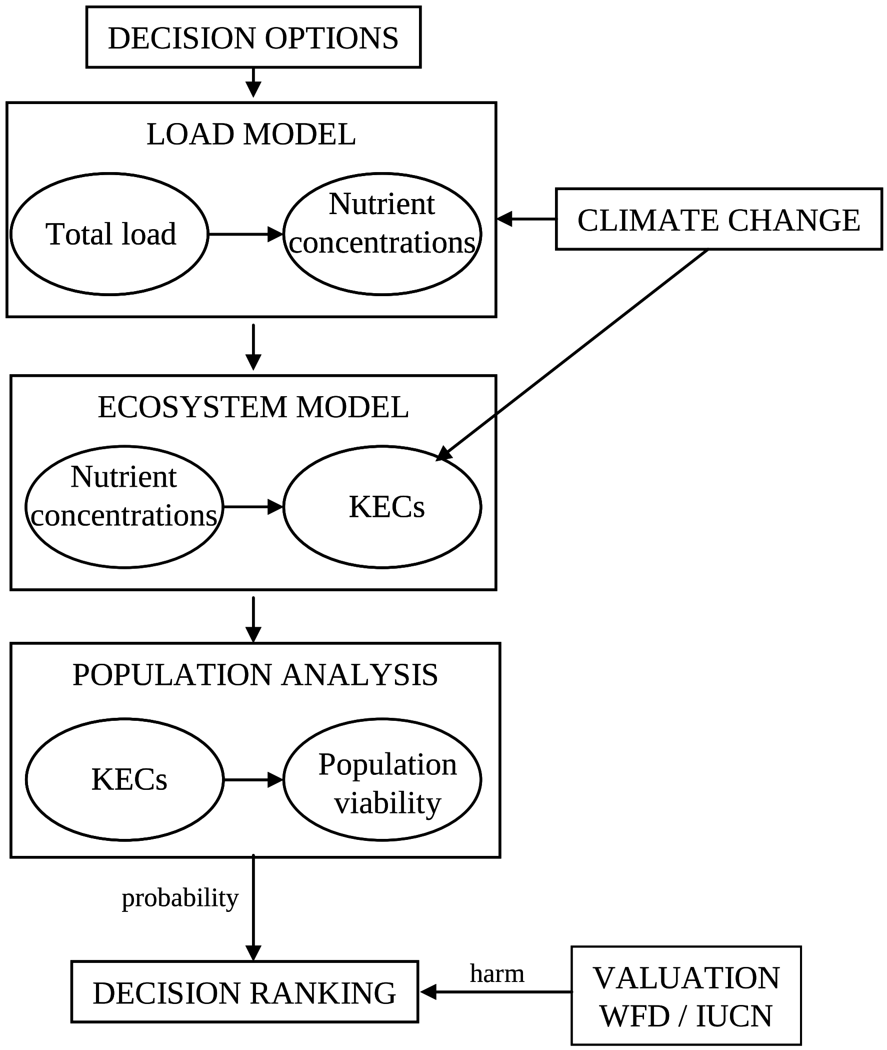

Fig. 2. The simplified structure of the EVAGULF model. KECs = key environmental correlates, WFD = EU Water Framework Directive, IUCN = international conservation status classification.

After the valuation factors for each alternative endpoint have been defined in the harm variable, the Bayesian network calculates the rankings for the measure options that have been defined in the decision variable (Fig. 2). When the utility function is used as a harm function, the decision option probably producing the largest population risks gets the largest value whereas the option probably best for the populations gets the smallest value.

By choosing a certain decision option, the probability distributions produced by the choice can be assessed in the different parts of the network, depending on the estimated causal uncertainties between variables. Thus, the likely effects of a certain decision and the amount of uncertainty related to them can be viewed along with how the uncertainty is divided between different parts of the network. By standardizing variables in the network to a certain level, it can be assessed, in which part of the chain more precise knowledge would most decrease the uncertainty related to the decision ranking.

With the EVAGULF RADSS model, the user can compare the risks produced by different national decisions and thus regional nutrient loading options for the communities of the Gulf of Finland. The tool also enables the assessment of uncertainties related to decision-making. The possibility to evaluate regional loading responsibility is useful when analyzing the importance of national and international effort in different parts of the Gulf of Finland. The assessment of the role of the climate change gives information on what can in general be done on the catchment area to preserve the communities of the Gulf of Finland.

A comparison of how the different risk approaches affect the conservation measure recommendations produced by the tool in the Gulf of Finland is interesting as such. It would be an important achievement to be able to show computationally, that the recommendations are similar regardless of the approach. This would prove, that the probability of reaching basically similar objectives can be maximized with the same measures, no matter which approaches, emphases and indicators are used. On the other hand, if the recommendations calculated for the different risk approaches differ considerably, it is interesting to test, which factors in the different approaches affect the differences in results the most, and in the future focus the research and debate on these areas.

4. Discussion

Because biological processes are complex and include a lot of stochasticity, a probabilistic approach has many advantages when studying those (Borsuk et al. 2004). A narrow probability distribution with a distinct expectation value usually requires large-scale long-term monitoring of the studied variables. It is to be expected, that with current data and knowledge, the uncertainties related to interactions of physical, chemical and biological factors and relationships between organisms are too large for the EVAGULF RADSS to produce very strong differences between measure options. On the other hand, the decision analysis may in many cases be quite robust to uncertainties (Drechsler et al. 2003). This rests on the fact that a part of the uncertainties have no significant effect on the decision ranking order. However, the role of the uncertainty in management recommendations is very dependent on the risk attitude assumed, and the current legislation and international agreements are not very informative in this sense.

Although the differences in risks calculated for different loading options would be small due to the uncertainties, the decision analysis still points out the measures which would most likely maximize the survival probability of populations and most effectively minimize the risks directed at them (Drechsler et al. 2003). Moreover, the analysis network in itself is a valuable tool for evaluating the importance of different factors for the robustness of the decision ranking, thus helping to steer monitoring to produce information relevant for the control of the eutrophication process. This kind of knowledge could serve as a basis for the design of a common monitoring system between the countries surrounding the Gulf of Finland.

Ecological data sets are quite well available, but their regional and temporal coverage are rarely sufficient to run detailed simulation models (Borsuk et al. 2004). Because Bayesian modelling enables the combination of heterogeneous data into the same analysis, the information value of current separate data sets can be increased. Despite the quality of results produced by the Bayesian decision analysis in the light of current knowledge, valuable knowledge of the uncertainties related to the decisions is gained.

According to the Rio Declaration on Environment and Development (UNEP 1992), ”*Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation*.” Thus, society is asking for recommendations, and scientists must asses how large uncertainties are included in them. The likely losses from not acting to rectify the eutrophication problem in the Gulf of Finland are likely to be serious and to some extent, irreversible. Therefore, measures must be taken despite incomplete scientific knowledge, and tools to support the measures should be developed.

Due to the complexity of the eutrophication chain and the function of the ecosystem and several stochastic factors, the greatest challenge in creating a tool like the EVAGULF is to develop a model, which takes into account all the relevant, but no other than the relevant factors (Etterson & Bennet 2006). It does not need to be a detailed description of the ecosystem of the Gulf of Finland. The aim is to produce a model, which as truly as possible describes our *current view* of how the system works (Borsuk et al. 2004). In this case it should especially describe the current knowledge of the links between nutrient loading and the survival probability of populations.

Another important challenge is related to the clear, understandable presentation of the probabilistic thinking and uncertainty in the user interface. If the user is not familiar with this kind of an approach, there may be some erroneous interpretations. At their best, results presented as probability distributions are considerably more informative than traditional point estimates and confidence intervals, and they give excellent support both for discussion and decision-making in the society (Uusitalo 2007). However, if they are insufficiently explained and visualized, they can cause confusion and misconceptions, and the user may loose faith in the reliability of the whole system. Participation of potential end-users in the design process of this kind of tools is highly recommended (Borsuk et al. 2004), which has and will be done in the creation of the EVAGULF user interface.

Acknowledgements

EVAGULF is carried out as a part of the INTERREG III A Southern Finland and Estonia programme and it is financed mainly from the European Regional Development Fund (ERDF). Co-financers are Southeast Finland Regional Environment Centre, Estonian Ministry of the Interior and University of Tartu. We also wish to acknowledge our partners of co-operation, including Kotka Maritime Research Centre (Merikotka ry), South-East Finland Regional Environment Centre, Radiation and Nuclear Safety

Authority, Estonian Ministry of the Environment, EuroUniversity of Tallinn and Estonian Environment Information Centre.

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