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Human–environment interaction in the Baltic Sea

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ABSTRACT

A model based on a Bayesian Belief Network (BBN) has been constructed for the Baltic Sea with the aim of investigating future scenarios of human activities in the region and informing environmental management strategies, such as those developed under a Science and Policy Integration for Coastal Zone Assessment Systems Approach Framework application. This paper describes necessary refinements to take into account historical influences on this relatively enclosed system. BBNs are static models and therefore do not incorporate feedback loops, whereas natural systems clearly display feedback mechanisms. This paper describes the implementation of one step feedback loops into a BBN model in an attempt to partly remove this constraint. Feedback loops within this stochastic model were shown to improve its accuracy. The drivers, both natural and anthropogenic, having greatest impact on the environment are identified. These refinements were made to improve its accuracy in modelling the system and gives insights into the functioning of that system.

1. Introduction

During the EU Framework 6 project entitled "European Lifestyles and Marine Ecosystems" (ELME), Bayesian Belief Networks were constructed for four European regional seas, the Black, Mediterranean, Baltic and North Seas. The purpose of the models was, "through improved understanding of the relationship between European lifestyles and the state of marine ecosystems, to analyse the consequences of alternative scenarios for human development in post accession Europe on the marine environment" [1]. This systems approach provided stochastic models and scenarios which could be used in management frameworks such as those developed through the EU Framework 6 SPICOSA project [2]; the SPICOSA Systems Approach Framework (SAF) uses modelling to inform management strategies for a chosen issue within a system, and stochastic modelling allows this modelling to be undertaken even when data availability is poor for that system. The models developed in the ELME project were designed to run simulations based on scenarios of social and economic change over a 20 year time horizon. The outcomes of these simulations were summarised by Langmead et al. [1]. This paper examines the functioning of the combined social, economic and ecological Baltic system and also the functioning of the model, refinements needed for model accuracy, and the iterative process that led to increased accuracy.

The behaviour of individual components of a large system are influenced by a cascade of interactions with other components within the system. This is true of the Baltic where environmental, economic and social issues interact together to determine the system's status. The mix of social, economic, physical and ecological drivers make mechanistic models problematic as there is often no common currency in the metrics used to measure variables across disciplines [3]. However, stochastic models allow the use of varying types of data to model interactions within a system, enabling the whole system to be modelled, therefore overcoming the need to establish parity between variables. Instead, each variable within a model is converted into a probability of being in a particular state (generally a 'high' or 'low' state) and this probability is the common currency used throughout the model. Bayesian belief networks have the added advantage that they do not require detailed understanding of the complex interactions linking each set of variables. They calculate the probability of change in state of one variable given the state of another based on empirical evidence [4].

Bayesian belief networks allow the joint use of objective and subjective information and, where hard data is absent, can perform calculations based on the opinion of specialists [3]. First used in the health service [5,6] and in artificial intelligence [7], Bayesian belief networks have more recently been used for aquatic environmental management, initially investigating the management of fisheries [8,9], and developing into studies of regeneration of

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forestry [10] and eutrophication [11]. Watershed management has also been investigated at river catchment scales [12,13], although in the present study Bayesian belief networks are used on a larger scale to investigate the influence of human activities on the marine environment of a regional sea.

A mechanistic model, MARE NEST [14,15], focusing on eutrophication, is already available for the Baltic Sea. This decision support tool allows quantification of outcomes under different scenarios. A systems approach however, requires a wider range of system attributes to be modelled if properties emergent from interactions between subsystems are to be captured [16]. This is where stochastic modelling has strength. The interaction between subsystems which would normally be prohibitively complex can be simply implemented with a relatively small quantity of data. This study therefore complements the MARE NEST model by providing soft system simulations, in contexts where hard system mechanistic modelling is still not possible. Functionally, this could therefore be used to support a SPICOSA SAF application to develop management strategies in areas where mechanistic models are unable to be produced, either due to lack of data or poor understanding of the system.

2. Methodology

2.1. Study area

The Baltic, a semi-enclosed sea in Northern Europe, is the largest body of brackish water in the world. Some 80 million people live in its catchment, and this pressure together with stratification and poor exchange between the Sea and the neighbouring North Sea, has put the environmental system of this water body under stress. Damage to this ecosystem has affected the economies of the surrounding countries through loss of fisheries and tourism revenue (e.g. [17,18]) as well as the social deprivation caused by these losses.

The Baltic Sea (Fig. 1) is an internal sea with a surface area of around 415,000 km^2, containing some 21,500 km^3 of water. It is composed of five major parts, the Gulf of Bothnia, Gulf of Finland, Gulf of Riga, Baltic Proper and the Belt Sea, each separated by shallow areas or sills. Annual freshwater inflow from the rivers contributes some 2% of the total volume of water and the sea is brackish with average salinity at the surface varies from almost oceanic conditions, 20 Practical Salinity Units (PSU) to 1–2 PSU [19]. The time needed for total exchange of water with the adjacent North Sea is 25–35 years [20,21]. With such a slow flushing rate, internal processes such as nutrient recycling are critical factors for determining environmental status.

Nine countries border the sea: Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia, and Sweden. All derive monetary benefit from the Baltic, especially through revenue from fisheries and tourism, and damage to its ecosystem would therefore be expected to have adverse economic effects with a potential for consequent social deprivation. Five additional countries (Belarus, Czech Republic, Slovak Republic, Norway and Ukraine) contribute to the Baltic catchment area which at 1,720,000 km^2 is over four-fold larger than the sea itself [22]. Some 80 million people live in the Baltic catchment and the effects of agriculture, industry, fossil fuel combustion, fishing and modern lifestyles have increased pressures on the naturally variable Baltic Sea environment. Some wastewater discharges are treated but this is not always sufficient to remove pollutants. Consequently, nutrients, particularly phosphorus, are accumulating and these exacerbate hypoxia from climate driven stagnation [23,24]. Fishing pressure compounds the effects of natural variability on the recruitment of stocks of economically-important species, whilst at the same time shifts in the environment are occurring that favour other, less economically desirable species including increased pelagic system production supporting greater number of small planktiverous fish species while the larger species which predate on them are selectively targeted by the fishing industry.

Large quantities of nitrogen and phosphorus have entered the Baltic from agricultural fertiliser run-off and from sewage discharges and tend to accumulate in the water column and sediments as a result of slow flushing rates. Eutrophication stimulates algal growth and causes benthic oxygen stress generally resulting in less complex, ephemeral pelagic communities flourishing at the expense of more diverse, stable, benthic communities. Low salinity and low nitrogen/phosphorous in the Baltic has led to filamentous algae in coastal, benthic systems and cyanobacteria blooms in open waters, a phenomenon more typical of eutrophic freshwater environments. Also, the occurrence of drifting algal mats as a result of eutrophication is increasingly reported [25]. These mats adversely affect benthos by fostering hypoxia resulting in increased concentrations of hydrogen sulphide in sediments. The area affected by hypoxia during long stagnation periods has increased from about 10,000 km^2 in the early 20th century, to about 40,000 km^2 today; the increase seems attributable to anthropogenic eutrophication [26,27]. As well as high phytoplankton concentrations in the water column, the maximum depth that macrophytes such as the sea grass *Zostera marina* are observed can be considered an indication of eutrophication [14]. Eutrophication results in an increase in water turbidity either directly as a result of particulates in the water from terrestrial discharges, or through induced plankton blooms. These reduce the depth to which solar radiation penetrates the water column and thus the capacity of macrophytes to survive. Therefore a more eutrophic environment implies that the maximum depth at which macrophytes are found is reduced. The intricacies of the Baltic system mean that models and indicators of eutrophication must be locally specific to the system to be of any use [28].

A further major concern is the decline in population of economically important fish species. In particular, Food and Agricultural Organisation data [29] show that, until recently, there has been a general trend towards declining cod, *Gadus morhua*, stocks and increasing populations of the less-important sprat (*Sprattus sprattus*). Baltic cod lay eggs in deeper, saltier water than sprat and so are more vulnerable to hypoxia. The two species have different food preferences, with the abundance of prey species related to climatic conditions. Cod feed on sprat, whereas sprat sometimes prey on cod larvae, and so the two stocks are interdependent. Recruitment of the young of these two species is highly variable as a result of complex interactions between fishing pressures and environmental conditions.

2.2. Conceptual model

The SPICOSA project employed the Drivers, Pressures, States, Impacts, Responses (DPSIR) framework to visualise the system to which the SAF application was to be run, and from there develop a mechanistic model in support of this SAF application. Although effective, this model development was a long process, requiring large amounts of data to properly populate and calibrate which risked loss of momentum in the SAF application [2]. Under the SPICOSA project, researchers generally worked on this on a full time basis, however in a situation where the SAF is being used as a management tool, resources were not always available to do this. Various forms of this framework have been employed in previous studies [30–35]. DPSIR helps to visualise the feedback loops between social and ecological components of coupled social-ecological systems and particularly the role of Drivers (e.g by altered nature of human consumption), Pressures (e.g. industrial