

International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
<http://www.iemss.org/society/index.php/iemss-2012-proceedings>

Modelling ecosystem services using Bayesian belief networks: Burggravenstroom case study

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Abstract: While being studied by scientists for decades, the term ecosystem services was only recently introduced to the general public. This introduction intended broad-scale recognition of ecosystems and their value for human well-being. Both quantitative and qualitative research on ecosystem services became emerging topics in scientific research. Ecosystem service prediction models were developed varying from basic qualitative models to complex mechanistic models which enable quantification of ecosystem services. The introduction of Bayesian belief networks in ecosystem service modelling has led to an intermediate approach between both methods. Major advantages of this Bayesian network modelling approach are the model transparency which enables stakeholder involvement in model development and evaluation, the possibility to incorporate both empirical data and expert knowledge, a straightforward combination with valuation studies and the inherent consideration of uncertainties in a transparent way. Our research focuses on the application of Bayesian belief networks to predict the ecosystem services delivered by the Burggravenstroom, a small river catchment located in the Port of Ghent region. This modelling approach enables identification of trade-offs or win-win scenarios between produced ecosystem services, evaluation of different management scenarios, assessment of effects of human interaction and enhanced system understanding.

Keywords: ecosystem service; Bayesian belief network; decision support

1 INTRODUCTION

Ecosystem services (ESS) represent the benefits humans derive from ecosystems. Flood mitigation, food production, recreation and nutrient regulation are only a few examples of services we generally benefit from. The concept of ESS was introduced to the general public during the last decade [MEA, 2005] and, although scientific research on ESS has been conducted since the '70, has since led to emerging research on production, management and valuation of ESS. A major challenge for applying this concept is the combined consideration of human activities and ecosystem processes. Often, ecosystem models merely describe processes in isolated ecosystems such as rivers, lakes, wetlands, without having a good quantitative insight on how human activities like urbanization, crop production, affect these systems and influence service provision. This leads to

difficulties in generating insights how management of ESS can be optimized and how models can be used to guide the management process.

Numerous ESS prediction models have been developed on both international and local scale [e.g. Kundhlande *et al.*, 2000; Karahalil *et al.*, 2009; Lane and D'Amico, 2010; Bagstad *et al.*, 2011; Kareiva *et al.*, 2011]. Recently, Bayesian belief networks (BBNs) were introduced in environmental modelling of habitat suitability and ESS [Ames *et al.*, 2005; Barton *et al.*, 2008; Aguilera *et al.*, 2011] after broad-scale application in medical diagnosis, classification systems and multivariate regression models. Major advantages of BBNs in this context are the possibility to combine expert knowledge and empirical data, implicit treatment of uncertainties, high model transparency, straightforward sensitivity analysis and the possibility to combine multiple submodels enabling a multidisciplinary modelling approach [Uusitalo, 2007; Aguilera *et al.*, 2011].

However, the possibilities of current applications of BBNs in ESS modelling are still limited. Simultaneous prediction of multiple ESS is often limited to a small number of services. This impedes a thorough analysis of trade-offs or win-win situations between multiple services. Therefore, possibilities to couple BBNs with geographical information systems (GIS) tools and valuation studies has to be further explored [Haines-Young, 2011; Kragt *et al.*, 2011].

In this paper we discuss the development of a BBN model to analyse multiple ESS in a small case study area in an attempt to lift up a corner of the veil covering the potential of BBNs in ESS modelling. We will focus on ESS delivered by freshwater ecosystems and more specific river systems. The Burggravenstroom subbasin located north of Ghent was selected as study area. Our final aim is to improve the ability of BBNs to model multiple ESS, to analyse trade-offs between services, to evaluate alternative ecosystem management scenarios and to include valuation studies in the model. This paper presents the first steps of our research including model development, data acquisition and expert consultation.

2 BAYESIAN BELIEF NETWORKS

A Bayesian belief network is a multivariate statistical model that consists of two structural components: a directed acyclic graph (DAG) as the qualitative component and conditional probability tables (CPTs) denoting the strengths of graph connections as the quantitative component [Aguilera *et al.*, 2011]. The directed acyclic graph comprises a structured set of variables or nodes $U = \{X_1, X_2, X_3, \dots\}$ which influence the modelled system. The statistical dependencies between different nodes are indicated by directed edges which represent causal links between variables. Each edge connects a parent node with the child nodes it affects. The graph is acyclic and therefore cannot contain feedback loops. Each network variable is described by a limited number of states to which its realized value can belong. The strength of BBNs is their ability to take into account uncertainties so that realized values of a variable X_i can belong to different states with varying probability. The probability that a variable is manifested in a certain state depends on the realized states of its parent nodes and is described by a conditional probability distribution $P(X_i | \text{parents}(X_i))$ [Jensen, 2001; Aguilera *et al.*, 2011]. Logically, the network's input nodes, i.e. nodes without parents, are defined by unconditional probability distributions. Both conditional and unconditional probabilities are called prior probabilities. After running the model posterior probabilities $P(X_i)$ are calculated for every system variable using Bayesian inference (1).

Model updating by putting more evidence (e) in the model will result in different posterior probabilities $P(X_i|e)$ of every variable X_i [Jensen, 2001; McCann et al., 2006; Aguilera et al., 2011].

An advantage of the application of BBNs in ESS modelling is the possibility to evaluate alternative management scenarios for maximizing delivered ESS. Ecosystem management scenarios and joined economic valuation of the modelled services can be integrated in the model structure. General BBN structures used in ESS modelling for evaluating alternative management scenarios are so-called decision networks. These decision networks contain decision nodes and utility nodes next to the common nature nodes present in every BBN (Fig. 1). These decision nets represent the links between management options and their influence on ecosystems, between ecosystem characteristics and delivered ecosystems and between delivered ecosystems and their monetary value [Ames et al., 2005; Barton et al., 2008; Molina et al., 2009; Kragt et al., 2011].

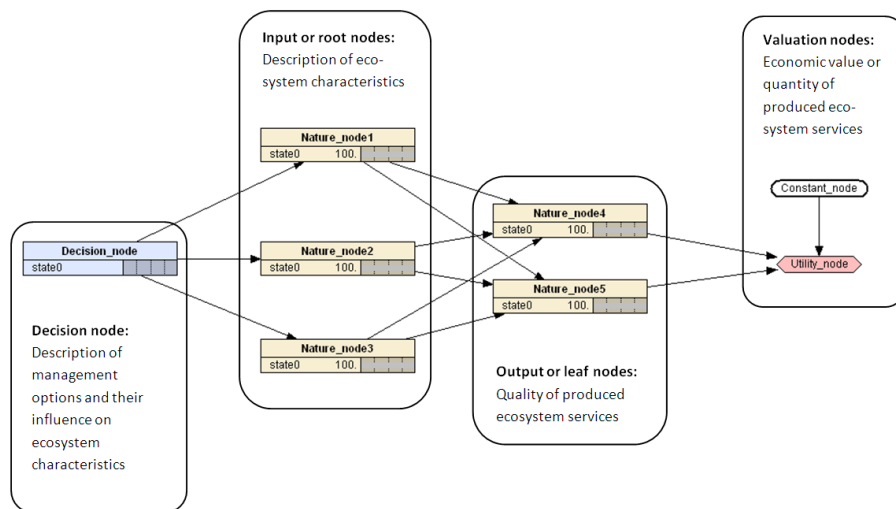


Figure 1. General layout of a Bayesian belief decision network, frequently used in ESS modelling.

The software platform we selected to develop, learn, validate and run the ESS BBN model is Netica [Norsys, 1998]. This software package integrates several useful tools like network structure development, data and expert learning of conditional probability tables, model validation and simulation and sensitivity analysis in a user-friendly environment.

3 CASE STUDY AREA

The Burggravenstroom subbasin is a small catchment with heterogeneous land use and conflicting stakeholder demands. It is located north of Ghent and covers an area of 16,852 ha. In the east, it is attached to the industrial port of Ghent. Most important rivers in the subbasin are the river Bruggravenstroom, the river Sleidingsvaardeken, the river Molenvaardeken and the river Avrijevaart. They drain to the canal Ghent-Terneuzen, that in turn discharges into the river Scheldt.

In our study area agriculture is the major occurring land use type next to urbanization, recreation and industry (water abstraction included). Forestry and nature conservation zones are less represented in the area. Industrial land use is mainly located in northern Ghent, close to the canal Ghent-Terneuzen. As a result of diverse land uses, the hydrology of the area is strongly modified. Agricultural drainage channels lower the groundwater level and pumping of surface water at the drinking water reservoir affects flow rates of some water bodies of the subbasin. Consequently, conflicting land use causes major problems in the local

water system. Urbanization and growing industry contribute to the increase of paved surface, leading to an increase in flood frequencies downstream. Frequent discharge of storm water and domestic waste water in paved areas leads to inefficient natural waste water treatment and frequent sewer overflows. Together with the polluted runoff caused by application of fertilizers and pesticides in agriculture, these discharges decrease surface water quality, which in turn affects recreational fishery and water abstraction. Water is frequently pumped out of the rivers into a nearby reservoir to produce drinking water. Water abstraction both by industry and water companies leads to decreasing water levels, negatively affecting agricultural production and water-dependent areas of ecological importance [Depoorter, 2011].

Due to this diversity in stakeholders and their needs, multiple objectives need to be considered when selecting management scenarios. The ESS concept offers a promising potential to consider all objectives by combining human activities with ecosystem processes and optimizing provided ESS related to human demand. Integrated modelling of the most relevant ESS will support the development of sustainable management plans. Water-related ESS, included in the model, are flood mitigation, recreation (fishery), water supply, nutrient regulation and habitat provision.

4 MODEL DEVELOPMENT

As a first step, ESS were selected according to their relevance in the study area, measurability and model convenience. As an important model goal is to support policy decisions, ESS that are adaptable by policy and management interventions were preferably included in the model. This resulted in a selection of five services that are relevant to the study area. Flood mitigation and recreational fishery are local services of major importance to the stakeholders living in or making use of facilities within the subbasin. Water supply and nutrient regulation are more regional services related to environmental policies, drinking water abstraction and industrial water use. These services are related to local sanitation facilities for handling domestic waste water and polluted discharges from agriculture. The habitat provision service supports previous services and is especially linked with recreational fishery in this case study.

Model development was initiated according to the first steps in the development protocol of Cain [2001]. A general network structure was developed, representing the essential connections between the selected ESS and some important environmental variables. To refine the network structure, submodels related to specific ecological processes or specific services were edited separately (Fig. 2). More variables and connections were added to the network according to information extracted out of existing models, literature and expert knowledge. After submodel refinement, aggregation into an integrated model was carried out. To validate the integrated model structure, ESS experts were consulted during a workshop discussion. Raised concerns were related to high model complexity and its incompatibility with transparent decision support. Therefore, additional efforts to lower model complexity will be carried out.

Until now, research results are limited to the network structure of the integrated model. Therefore, some additional model development remains to be done. Next stages in research will be knowledge rule definition to quantify the causal relations between the network variables, simplification of the model structure to improve model transparency, valuation of the modelled services and a GIS implementation of the model to map impacts of changes in input nodes (e.g. adjacent land use, nitrogen discharge,...) on the produced services on the scale of VHA river segments.

5 RESULTS

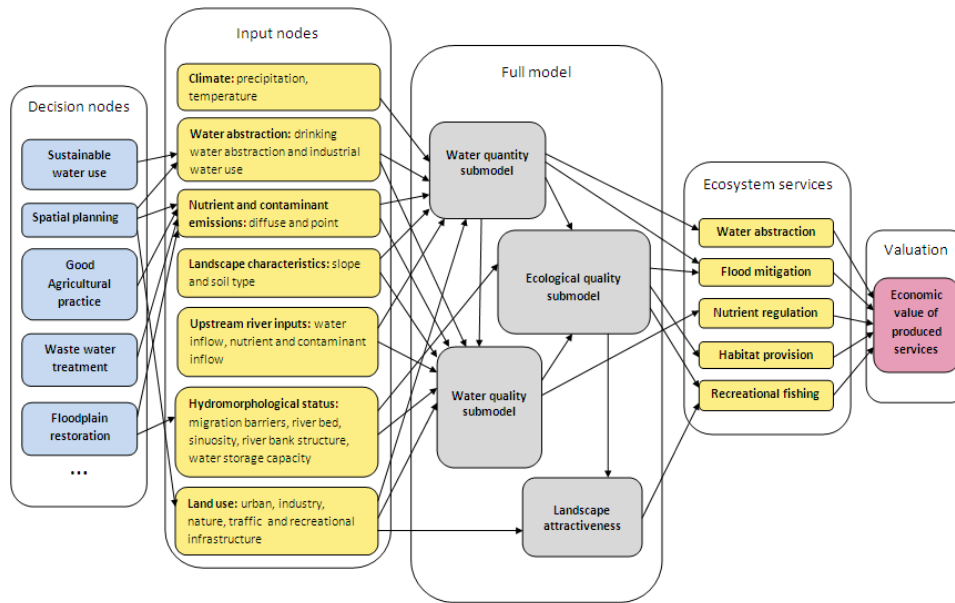


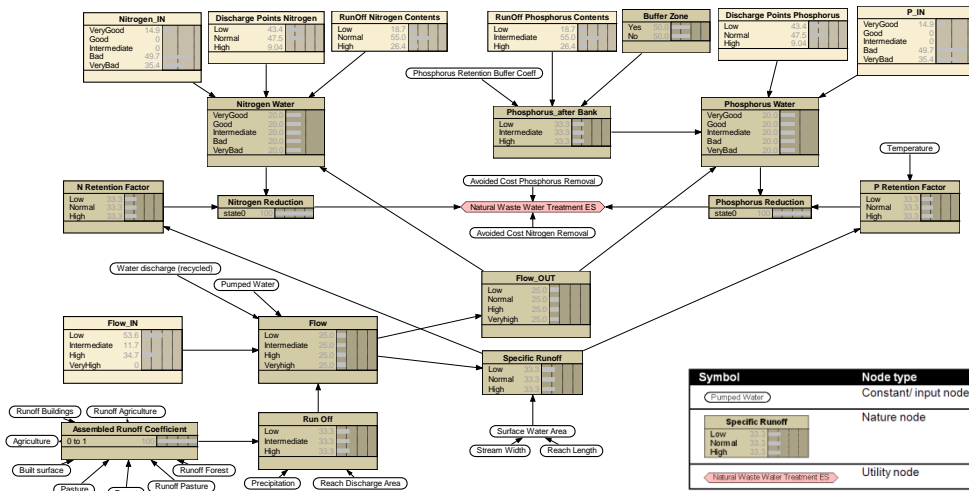
Figure 2. Schematic overview of the BBN model and integrated submodels

The general structure of the developed BBN consists of a water quantity, a water quality, an ecological quality and a landscape attractiveness submodel, which are strongly interlinked (Fig. 2). The water quantity model concerns both droughts and floods and relates to habitat quality and flood mitigation. The water quality model considers hydromorphology and ecological processes to comprise both chemical and physical water quality. Decision and utility nodes, representing possible management scenarios and economic valuations, are presented at both ends of the graph. Relations between multiple nodes can be easily deduced from the scheme. Management scenarios will affect the status of multiple input nodes, will be propagated through multiple submodels and will subsequently be reflected in a varying provision of multiple ESS.

The core nodes of the developed BBN model describe the processes that influence the *nutrient regulation* or waste water treatment capacity and the water quality of the ecosystem (Fig. 3). The abiotic processes include nutrient and contaminant input into the system and water quantity related features. Nutrient and contaminant inputs are considered separately for runoff and direct discharges. To analyse the effect of buffer strips along the river banks, a buffer strip node, indicating the presence or absence of buffer zones, is added to the model. Nutrient regulation capacity is also influenced by biotic processes. However, in order to obtain a model with manageable complexity, these biotic processes are not included in the nutrient regulation submodel. The derived nutrient regulation capacity together with nutrient inputs define the nutrient regulation service of the water ecosystem and will be valued through avoided cost valuation methods. Relationships between this submodel and the other ESS are based on water quality. The services flood mitigation, recreational fishing, water abstraction and habitat support all depend on the state of water quality. Nodes describing chemical and physical water quality link this network to these of the other services.

The *habitat provision* submodel is based on the hydromorphology, the water quality and on surrounding land use which are incorporated in the ecological quality submodel of the BBN (Fig. 2). Habitat preferences of some key species are used as a proxy for modelling habitat quality. The habitat provision submodel is an expansion of the nutrient regulation submodel, which also comprises water quality, biological composition and hydromorphology. Additional nodes are included to

describe the effects of the surroundings on habitat quality. Habitat quality is also strongly linked to the viability of the fish population and thus to the recreational fishing service of the ecosystem.



The *recreational fishing* submodel is based on both the added value of the surroundings that support recreational fishing and the available fish to be caught. The added value of the surroundings to the stakeholders depends on landscape attractiveness, accessibility and the presence of fishing spots. Both landscape attractiveness and the status of the fish population depend on the environmental quality. Therefore, a habitat quality node connects the recreational fishing submodel with the habitat provision submodel.

Flood mitigation is directly linked to the submodel of water quantity and to the environmental quality submodel. A qualitative valuation of this ESS can be determined by both the capacity as the opportunity of the system to mitigate floods. The capacity of the river system to mitigate floods is determined by the water storage capacity and the active water level management. The water storage capacity is linked to the environmental quality because most water dependant habitats in the catchment function as potential water storage reservoirs. Also the presence of controlled flooding areas will determine this storage capacity. On the other hand, the opportunity to provide flood mitigation is determined by the flood risk in the area. The chance of flooding is mainly determined by the water quantity submodel, which feeds into a flooding frequency node. Both flood risk and water storage capacity determine the quality of the flood mitigation service.

The *water abstraction* service of the ecosystem depends on the amount of available surface water and on the presence of populated areas. Availability of surface water depends on runoff, precipitation and water inflow. Consequently, the water quantity submodel is coupled with the other ESS submodels through its input nodes. Because water abstraction influences groundwater level stability that in turn influences the quality of water dependent habitats, a water stability node is included to couple the water abstraction submodel with the habitat provision submodel.

6 DISCUSSION

During this initial research stage, in which both a cause-effect influence diagram was developed and most of these causal relationships were quantified, several clear advantages of BBNs in ESS modelling were highlighted. On the other hand, also interesting challenges came forward concerning the interaction between data

availability, desired model complexity and the model development process, the use of uncertainty through the model and the legitimacy of the use of expert knowledge in model development.

The use of BBN models in this research was mainly driven by their potential to use expert knowledge for complementing empirical data which is often limited available in ESS modelling. Due to this inclusion of expert knowledge a higher level of model complexity could be obtained and both well studied and less understood services could be regarded in the model. However, eliciting expert knowledge on causal relations and their associated uncertainties can be difficult and can significantly influence the objectivity of the model. This is especially problematic when no intensive expert or stakeholder engagement process can be conducted. To reduce the influence of expert knowledge in the final model, an alternative model development process than the one we adopted might be preferred. In our experience, starting model development from an influence diagram, increases the risk of being unable to quantify all causal relations using empirical data alone. In a more pragmatic approach, the model development process could be initiated with data collection, allowing to sufficiently consider data availability in selecting relevant system processes for the influence diagram. The benefits of this and other alternative model development strategies are subject to further research. Concerning uncertainties in the developed model, we observed important dilution of the output nodes' probability distributions. Output nodes generated from a large set of intermediary nodes to the input data, often display flattened probability distribution due to uncertainty propagation through the network. Although this uncertainty reflects our partial ignorance on the functioning of ecosystem processes, the added value of these uncertainties is often not recognized in policy and river basin management. Nevertheless, rising interest in for example risk assessments and occurrence of extreme events could increase the value of these Bayesian modelling techniques in the future.

ACKNOWLEDGMENTS

This research was carried out within a PhD funded by the Flemish Institute for Technological Research (VITO). Input from Ghent University was facilitated via the fund BOF09/24j/092.

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