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The value of using Bayesian Networks in Environmental Decision Support Systems to support natural resource management.

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Abstract: Environmental Decision Support Systems (EDSS) are one of a suite of tools that natural resource management (NRM) practitioners may use to support the development of, or help report on the success, of NRM programs. This paper outlines two DSS that are being developed for state government or NRM agencies in Australia to assist them to develop, implement and manage programs aimed at improving resource condition. IBIS is an EDSS that models ecological outcomes of environmental flows. VegBN models the effectiveness of NRM interventions on native vegetation quality on private land in northern Victoria. The underlying model base of each EDSS is comprised of Bayesian Network (BN) models linked with other BN or component models. Bayesian networks have proved to be a flexible and highly valuable approach to modelling such highly complex and uncertain environmental systems. They are an approach that can add rigour and transparency to decision-making processes and have in Australia gained considerable interest from researchers as well as government and other organisations involved in the management of natural resources.

***Keywords**:* Environmental Decision Support Systems; Bayesian Networks; model development

1. INTRODUCTION

Researchers are increasingly required to analyse and present data in a way that reflects the need of natural resource management (NRM) practitioners. By offering a way of exploring and explaining trade-offs or impacts and providing a transparent, visible and accessible collection of models, visualization and other tools Environmental Decision Support Systems (EDSS) have the potential to support improved management of natural resources. They can also be used to focus discussion and enable integration by researchers and stakeholders.

This paper reports on two EDSS being developed for application to real-world natural resource management issues: IBIS and VegBN. IBIS is an EDSS that models ecological outcomes of environmental flows. Applications of IBIS are being developed for three wetlands systems in inland New South Wales (NSW), Australia. The Victorian Native Vegetation Change EDSS (VegBN) is being developed as part of the Landscape Logic research hub (www.landscapelogic.org.au; Accessed 22 March 2010) and models the effectiveness of NRM investments aimed at improving native vegetation quality on private land in northern Victoria in the light of macrodrivers (e.g. climate and demographics). . Both DSS are being developed to support NRM decision-makers explore the factors influencing ecological outcomes and, through the use of scenario modelling, develop alternate management interventions aimed at achieving maintenance and/or improvement of wetland ecology (IBIS) and native vegetation quality (VegBN) (Table 1).

2. DSS DEVELOPMENT

A similar process is being used to develop the two EDSS (Figure 1). Researchers and EDSS users scoped the focus issue(s) and scale of the EDSS which informed the development of the EDSS framework. The EDSS models are comprised of Bayesian Networks (BNs) either linked with other BNs (VegBN) or other types of models (IBIS).

Table 1. Intended use of the IBIS and VegBN EDSS (X – minor role, XX – moderate role, XXX – major role).

Role of the DSS	IBIS	VegBN
Scenario modelling	XXX	XXX
Facilitation / group consensus building	-	-
Collection of models, visualisation methods and other tools	X	X
Allow transparent analysis	XXX	XXX
Project memory	X	XX
Capture and test assumptions	XXX	XX
Focus for integration across researchers and stakeholders	X	XXX

Bayesian Networks are one approach that is increasingly being used in environmental modelling, particularly where focus is on the interface between science and management. The strengths and limitations of BNs have been well documented (e.g. Uusitalo, 2007; Kumar, et al. 2008; Ticehurst et al. 2008). In the development of the IBIS and VegBN EDSS they have proved to be a useful tool with which to explore and communicate logic (e.g. causality and model structure) across a wide range of audiences, from experienced numerical modellers to NRM practitioners and other stakeholders who may have no (or limited) prior modelling experience. The capacity of BNs to use different types and sources of data from diverse disciplines (e.g. social science and ecology), and explicitly represent uncertainty has the potential to support NRM by describing realistic outcomes and adding flexibility to the decision-making process. Major challenges to the use of BNs in modelling complex environmental systems include the elicitation of expert knowledge and updating of beliefs in large networks, incomplete data sets with which to train the network, and the difficulty of incorporating feedback loops (Kumar, et al. 2008).

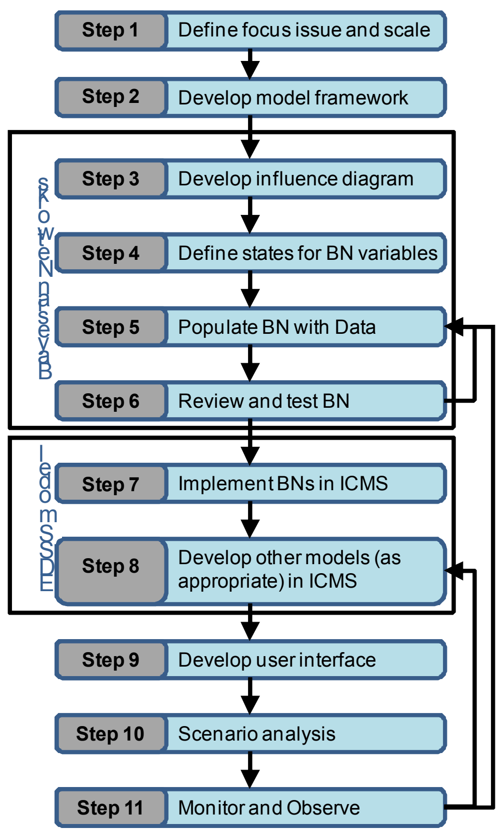

Figure 1. EDSS development process (adapted from Ticehurst et al [in press]). Step 8 is only implemented for the IBIS EDSS.

The general process used to develop the BNs implemented in the IBIS and VegBN EDSS – steps 1 to 6 and 10 to 11 in Figure 1 – has been discussed in detail by Ticehurst et al. (2008). BNs were developed using the Netica© software (http://www.norsys.com/; Accessed 22 March 2010). This software supports the rapid development and testing of BNs and use for either inference or diagnosis. It is not possible to link BNs to other models [BN or otherwise] in Netica and for reasons discussed by Kumar et al. (2008) and others, namely the large increase in network size and required knowledge it is also problematic to incorporate temporal dynamics and feedback loops (an essential capacity of the IBIS

EDSS) into BNs developed within Netica. The EDSS models have thus been coded using the Integrated Component Modelling System (ICMS) an object oriented based approach to model building and delivery (Reed et al. 2000). A graphical user interface (GUI) has been constructed for both EDSS which allows users to create and run scenarios, and facilitates their analysis of model outputs and behaviour.

3. ENVIRONMENTAL FLOWS AND WETLAND RESPONSE (The IBIS EDSS)

The IBIS EDSS is being developed to predict the ecological outcomes of environmental flows in wetland systems in NSW. The EDSS development project has had two phases. In Phase 1, the methodology was developed and prototype EDSS applications were developed for the Gwydir Wetlands and Narran Lakes. Client requirements and methodology were then refined for the second phase of the project which involved three applications are being developed: one each for the Gwydir Wetlands, Macquarie Marshes and Narran Lakes. A discussion of the prototype Narran Lakes application is provided in Merritt et al. (2009).

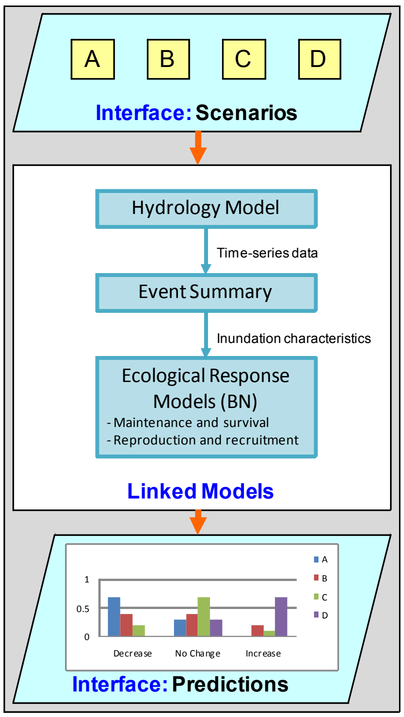

Figure 2. Structure of the IBIS DSS

The purpose of the IBIS EDSS is to enable the primary user of the EDSS (managers from the NSW Department of Environment, Climate Change and Water [DECCW]) to compare scenarios relating water delivery (volume and timing) to ecological outcomes in order to provide a consistent, transparent and scientifically rigorous decision-making process. The EDSS houses models and data from DECCW (and other) research programs and is being developed to allow updates over time as information and knowledge improve.

3.1 Model Structure

IBIS links outputs from hydrological models (producing daily time series of inundation area, flow, and volume), to ecological response models (ERM) (Figure 2). The ERM are Bayesian networks representing important ecological function, vegetation species and communities, and waterbird and fish species in the wetland system.

A major criticism of BNs in the scientific literature has been the inability to incorporate temporal dynamics or feedbacks in the network (e.g. Uusitalo et al. 2007; Kumar et al. 2008). Given that most complex environmental systems (e.g. wetlands, estuaries) are highly dynamic in their behaviour – further complicating the task of the managers of these systems – greater emphasis is starting to be placed on developing dynamic BNs (e.g. Shihab, 2008). In the IBIS EDSS we implement BNs within a dynamic domain. Time-series data from the hydrology model is summarised into ecologically important events based on inundation depth thresholds. Outcomes of the ERM for the first event inform the modelled ecological response to the 2nd event and so on. This is demonstrated for the Gwydir Wetlands IBIS application later in this paper. This allows users of the EDSS to track ecological response over time for different environmental water delivery scenarios.

The IBIS EDSS is being used to build applications for three systems (the Gwydir Wetlands, Macquarie Marshes and Narran Lakes). To date, the implementation of the EDSS architecture to different wetland systems has been relatively straightforward. This has in part been facilitated by a common issue across the three systems – that being the delivery of environmental water to ecological assets – and a consistent approach to development of the component models. The flexible nature of Bayesian Networks mean that very different ecological response models can be developed and implemented within the IBIS framework as long as they are driven by data produced by the hydrological model. Across the three applications of IBIS that are being built we are developing models for species and communities and whole wetland function, The BNs can be quite simple habitat condition models as implemented in the Gwydir Wetlands application to a more detailed and mechanistic model of the factors affecting recruitment of waterbird fledglings implemented in the Narran Lakes (Merritt et al. 2009).

3.2 Gwydir Wetlands IBIS Application

Simple use of objects and links are used to develop the models underlying an IBIS EDSS application. Figure 3 shows the structure of the Gwydir Wetlands application currently under development. Vegetation maps together with flooding patterns predicted from a hydrodynamic model of the Gwydir Wetlands were used to define discrete storages to represent in the EDSS. The NSW Office of Water is building an Integrated water Quantity and Quality Model (IQQM – Simons et al. 1996) of the Gwydir Wetlands representing the defined storages in the model network. IQQM outputs of daily flow, inundation area, and inundation depth are loaded into the storage ( ) objects in the EDSS model. This data is passed through routines that summarise the time-series data into ecologically relevant time periods (i.e. flow events). The ERM ( ) use this information to describe the likely ecological response to the hydrology regime. In Figure 3, vegetation ERM are linked to each of the storages.

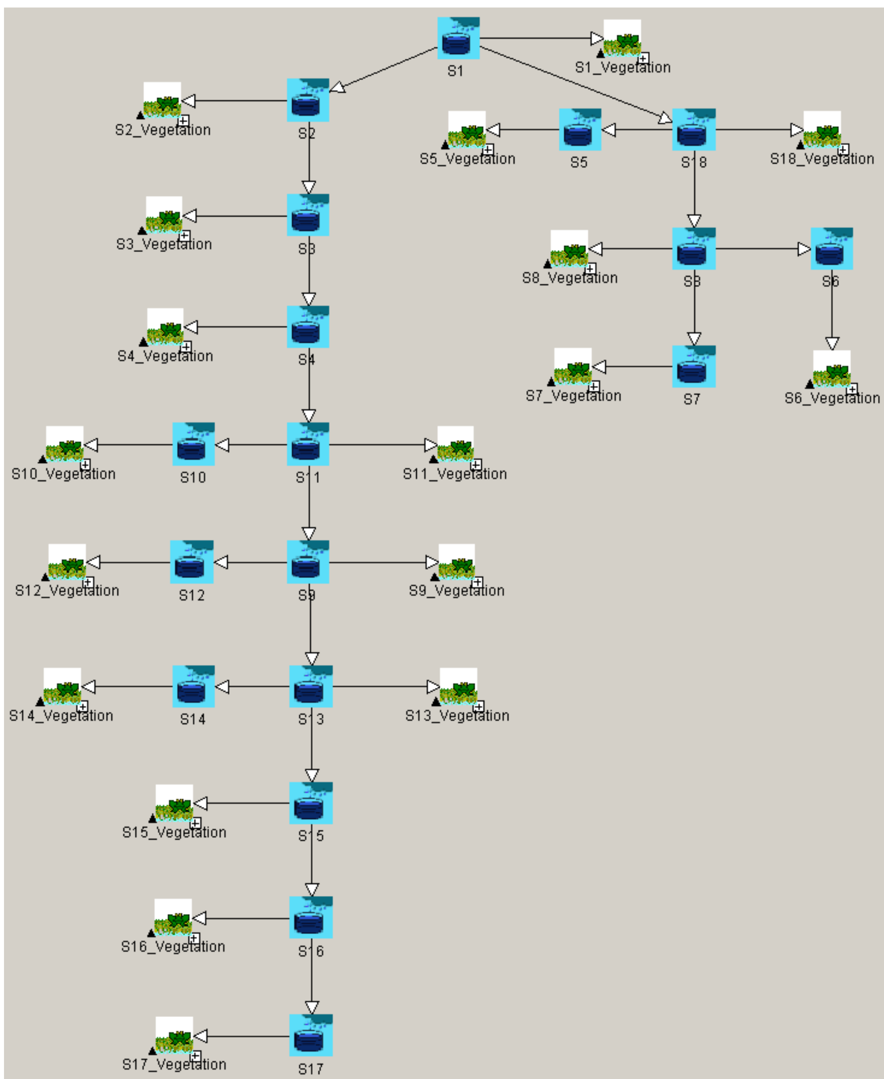

Figure 3. Structure of the Gwydir Wetlands application of the IBIS DSS.

The vegetation response models in the Gwydir Wetlands application of the IBIS EDSS are based on the CCARP database (Rogers 2009a,b) which considered four components of the inundation regime: flood duration (number of months), flood timing (month), flood area index and the inter-flood dry period (number of months). An example of the ERM for the storage S6 (Figure 4) shows that the maintenance and survival of both *Bolboschoenus fluviatilis* (Marsh club-rush) and the weed species *Phyla canescens* (Lippia) (Bolboschoenus MS (S6) and Pcanescens MS (S6) respectively in Figure 4) are determined by all four components of the inundation regime. The reproduction and recruitment of *B. fluviatilis* (Bolboschoenus RR (S6) in Figure 4 is determined by the duration, depth and timing of inundation.

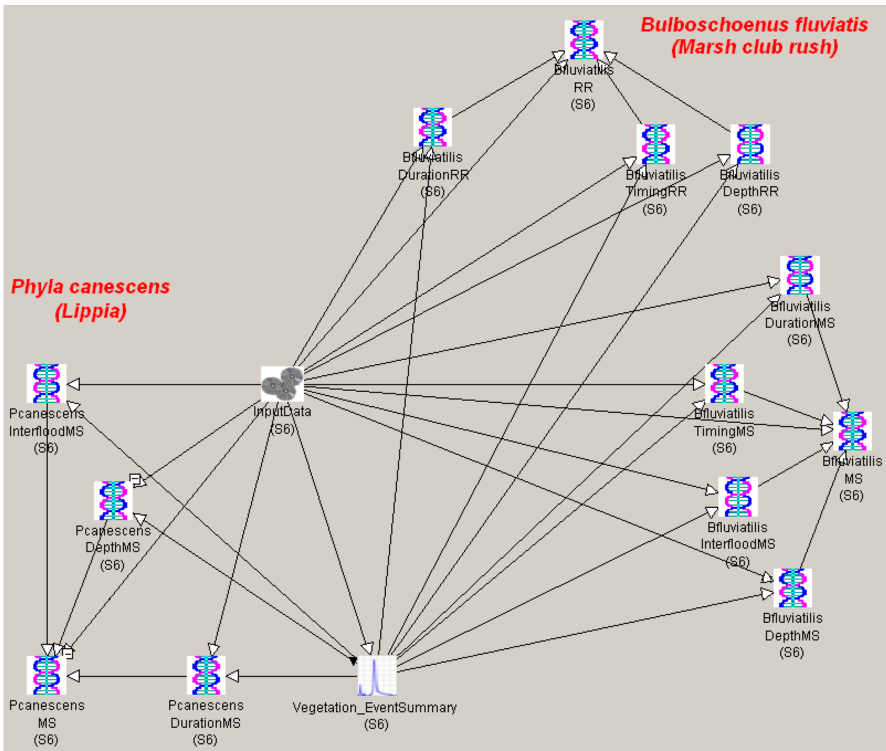

Figure 4. Ecological response model for the S6 storage.

4. The Landscape Logic EDSS

Landscape Logic is a research hub funded by the Australian federal government CERF program. The project aim is to "improve the way scientific information is used as an aid to decision making, and to establish links between management actions and natural resource condition" (www.landscapelogic.org.au; Accessed 22 March 2010). One theme of the research hub aims to integrate new and existing knowledge on the efficacy of management interventions and model the impact of these interventions on resource condition (focusing on native vegetation and aquatic health). The primary modelling technique selected at the outset of Landscape Logic were BNs because they can be used to integrate across complex systems and scientific disciplines, communicate predictions effectively, and thus assist catchment managers make informed management decisions (Ticehurst and Pollino, 2007).

The audience for Landscape Logic research outcomes are primarily the natural resource management (NRM) agencies that work with community and partner organisations to implement and manage programs aimed at improve natural resource condition. Software interfaces for the BN models are being developed to assist users run the models, interrogate the data and assumptions used to develop the BNs and interpret the model predictions. Ultimately, it is intended that the tool will assist NRM agencies quantify the impact of their investments on natural resource condition and estimate the likely impact of future investment strategies, a reporting requirement of the Australian Government.

Two EDSS are being developed as part of the Landscape Logic project: the Tasmanian Aquatic Condition EDSS (TasBN) and the Victorian Native Vegetation Change EDSS (VegBN). VegBN models the effectiveness of NRM interventions on native vegetation quality on private land in northern Victoria, Australia, whilst TasBN simulates the impact of land, estuary and river use on water quality and aquatic health. Conceptually both EDSS are similar: BNs are the integration tool and both implementations are based on linking output probability distributions from one model to another. However, due to the different way in which spatial aspects are represented and how scenarios are constructed and results are viewed, VegBN and TasBN have been developed as separate EDSS with tailored GUI. The VegBN DSS is discussed in more detail below.

4.1 Drivers of native vegetation change in Victoria

Understanding how past human activities and environmental events have altered native vegetation extent and quality is critical for managing native vegetation into the future. A retrospective analysis of native vegetation change in three NRM regions in northern Victoria (undertaken by researchers at the Victorian Department of Sustainability and Environment [DSE]) identified changes in native vegetation over time, and related these changes to land use and management practices. This knowledge, together with social research that identified why past and present management practices were adopted, (undertaken by researchers at Charles Sturt University [CSU]) will be used to support future decision-making by the NRM regions.

The VegBN EDSS is being developed to evaluate the effectiveness of NRM interventions on native vegetation quality, in light of other influences (e.g. climate, and/or demographics). One application of the EDSS is in development covering three case study areas in northern Victoria, Australia. The EDSS consists of three linked BNs (Figure 5). The *Landholder Actions* BN represents the factors influencing a landholders' decision to implement revegetation, protect remnant native vegetation or promote the natural regeneration of native vegetation. The *Current Vegetation Quality* BN estimates the current state of native vegetation based on the level of works being undertaken by landholders in conjunction with climate and environmental conditions (Figure 6). This generates inputs to the *Change in Vegetation Quality* BN – an implementation of the state-and-transition BN developed by researchers at the University of Melbourne and DSE to look at native (non-riparian) woodland vegetation dynamics at a site.

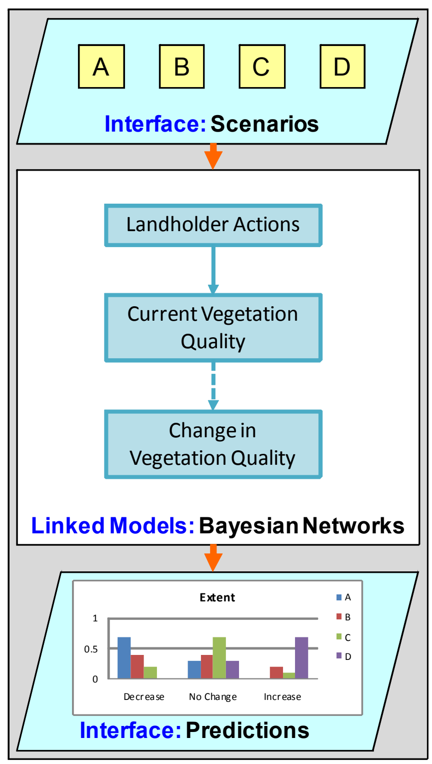

Figure 5. Structure of the VegBN DSS

The purpose of the *Landholder Actions* and *Current Vegetation Quality* BNs are to describe what the vegetation quality looks like now within the landscape (private land in rural northern Victoria) and explain the social and environmental context for the current condition. Given the likely current condition, the *Change in Vegetation Quality* BN can be used to explore how a site will respond to interventions.

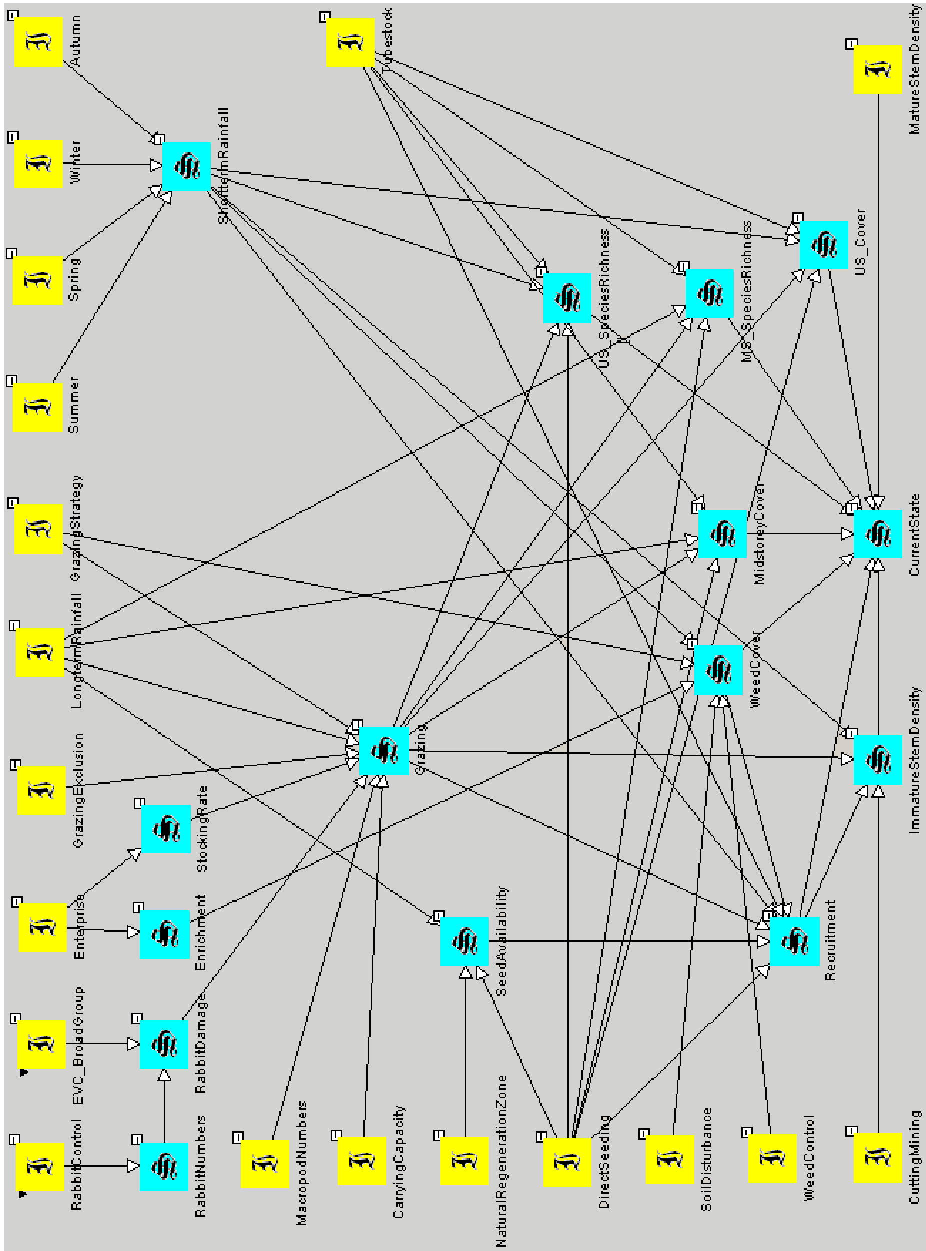

Figure 5. Structure of the Gwydir Wetlands application of the IBIS DSS.

5. DISCUSSION AND CONCLUSION

This paper has outlined two Environmental Decision Support Systems being developed to support aspects of natural resource management in Australia. The nature of the two tools belong more to the 'static' category described by Sànchez-Marrè et al. (2008) of Intelligent Environmental Decision Support System (IEDSS) where the intention of the tool is to support decision-making of water managers (IBIS) and NRM agencies involved in management of native vegetation (VegBN) through scenario modelling and exploration of the magnitude and sensitivity of model responses. The EDSS are not intended to be used on a day-to-day basis: for example the IBIS DSS is intended to be used for planning over annual to decadal time periods. It could be used to predict the ecological response to augmenting a natural flood event but not in real-time as it is not linked to live-flow data information. This is in accordance with its intended use as a strategic planning tool and consistent with the way the hydrological and ecological linkages within the wetlands work (i.e. ecological responses to hydrological events occur over week to month or longer periods).

A criticism of some IEDSS is that they can be very specific (e.g. Sànchez-Marrè et al. 2008). Whilst this is true, there is a compromise between generality of design and modelling approach and the need for an approach tailored to the audience who will use the tool (or its outputs). The latter requires considerable effort throughout the development process to understand how they will use it, what is the management environment in which they operate, and the nature of the system being modelled.

IBIS and VegBN both use BNs in the modelling framework. In Australia there has been a large interest in BNs within all levels of government (local, state and federal) and other groups or individuals involved in natural resource management over the last five years. From our experience in building EDSS in Australia, there is no other approach as well suited to modelling highly complex and uncertain systems where social, political and management context is as important to defining outcomes as (for example) as the physical system. BNs are capable of providing transparency and rigour to the decision-making process which, together with explicit representation of uncertainty and their inherent compatibility with adaptive management processes, makes them an attractive tool for decision-makers. As developers of integrated environmental models they have proved invaluable to us, allowing us to work with researchers and practitioners across a range of disciplines (including ecologists, economists, hydrologists and social scientists) and, in the case of the IBIS EDSS, develop state of the art integrated hydrological-ecological models which will support the environmental flows decision-making process of the NSW Department of Environment, Climate Change and Environment (DECCW) in inland wetland systems in NSW, Australia.

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