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Bayesian Network Modelling for assessing the biophysical and socio-economic impacts of dryland salinity management

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Abstract: Improving dryland salinity management at catchment scales requires an integrated modelling approach, in which the dominant bio-physical and socio-economic drivers, processes and impacts are considered. This paper presents and evaluates the use of a Bayesian Decision Network (BDN) model as an integrated approach for considering the trade-offs associated with the management of dryland salinity, a major environmental problem in Australia. The ability and effectiveness of the BDN approach in building integrated catchment assessment and management tools are demonstrated through a case study in the Little River Catchment (LRC) in the upper Macquarie River basin, NSW. This integrated model was developed to co-ordinate the various disciplines involved in salinity problems, integrate available data and information, and to allow the investigation of the potential outcomes arising from implementing salinity management options at the catchment scale. A conceptual model framework underlying the BDN for salinity management in the LRC was developed. This framework incorporates ecological, physical, economic and social aspects of dryland salinity problems in the catchment. To complete the BDN model, a range of techniques, data and information was used. Various outcomes of implementing 32 possible salinity management scenarios at the catchment scale are investigated and discussed. The investigation was conducted based on the following indices from different disciplines: surface runoff, baseflow, stream salt concentration, terrestrial habitat condition, community attitude, establishment costs, and total gross margin. The BDN approach implemented in this research serves as a valuable tool to represent the catchment system as a whole, to incorporate output from models and expert judgment, to examine the trade-offs among outcomes necessary for decision-making, and to communicate uncertainty of the parameters in the BDN model. The analysis of the trade-offs presented in this paper also shows that due to the influences of the various possible outcomes on decision-making analysis, as well as the diversity in the factors influencing the characteristics of stream flow, blanket solutions for managing the quality and quantity of stream flow cannot be suggested. To reach informed and feasible decisions for salinity management the social and economic preferences and priorities, along with the ecological and hydrological consequences of salinity management options, need to be considered in quantifying the trade-offs among salinity management outcomes.

Keywords: *Bayesian networks, Dryland salinity, Integrated modelling approach, Little River catchment.*

1. INTRODUCTION

Dryland salinity is a major environmental problem in some parts of the world (Ghassemi et al., 1995). There have been attempts to manage this issue worldwide, through implementing vegetative and/or engineering management options. Land and water salinity is increasing in Australia (National Land & Water Resources Audit, 2001) and has serious negative effects on the environmental and socio-economic health of catchment systems. Addressing this complex problem, at both large and small scales, requires an integrated catchment modelling approach, in which key bio-physical and socio-economic drivers, processes and impacts are all considered. In Australia, since encountering the outbreaks of human-induced salinity over the past few decades, land cover alternatives suitable to manage salinity have been explored. It is very important to use an integrated methodology for the modelling of such a complex issue and provide a decision-making tool for assessing how to manage dryland salinity. An integrative modelling approach assists stakeholders and policy makers in understanding the trade-offs associated with management options. This, in turn, can lead to more informed decision-making for better and more feasible salinity management at a catchment scale. The aim of this paper is to investigate the value of Bayesian decision networks as an integrative tool for assessing how to manage dryland salinity at a catchment scale. The focus of this research is on the process of integration and building the model components, taking into account the general diversity and paucity of data and knowledge available.

2. CASE STUDY: THE LITTLE RIVER CATCHMENT

The Little River is a tributary of the Macquarie River. It is located southwest of Wellington in central western NSW, Australia and is one of the headwaters of the Murray-Darling River system (see Figure 1). The LRC (approximately 2300 km^2) is located upstream of the Macquarie Marshes and joins the Macquarie River between Dubbo and Wellington, downstream of the Burrendong Dam. Because most of the LRC is based on marine sediments or metamorphosed geology, the salinity hazard in the catchment has been identified as being in a very high class

Figure 1. Location of the LRC

Since most of the catchment has been cleared, it is expected to experience increasing salinisation. It is also anticipated that the loss of productive land due to the salinity will have serious negative effects on the farming community. The average annual rainfall in the catchment varies from approximately 560 mm in the northern part of the catchment to about 730 mm in the southwest. Because of substantial rainfall through the summer, there is a need to maintain vegetation cover during this period in order to avoid excessive runoff, soil erosion and deep drainage (IVEY & DPMS, 2000). From a salinity hazard perspective, since 67% of the catchment has been identified as having the soils prone to salinisation problems, soil-derived salinisation is likely to be a serious issue in the LRC. Improved pasture and native pasture are the dominant land cover in the LRC.

Bayesian networks

Pearl (1988 p.117) defines Bayesian Networks as 'direct acyclic graphs (DAGs) in which the nodes represent variables, the arcs signify the existence of direct causal influences between the linked variables, and the strengths of these influences are expressed by forward conditional probabilities'. A direct acyclic graph is a graph that has directed arcs and no cycles. Each node or variable may take one of a number of possible states or values. In Bayesian networks, Bayesian calculus is used to calculate probabilities of various outcomes. BNs are capable of representing and considering uncertainty in system knowledge. Krieg (2001) considers the conditional probability as a basic concept in the Bayesian treatment of uncertainties. A substantial number of applications exist in natural resource management, mostly completed recently (see Varis, 1997; Varis and Kuikka, 1999; Ames and Neilson, 2001; Ames, 2002).

There are several advantages of using BNs. The possibility of using observed data, results from model simulations, or even expert knowledge in order to calculate the conditional probability between variables is one main advantage (see Ames, 2002; Pearl, 1988; Varis, 2002). BNs allow integration of qualitative information and knowledge with the types of quantitative information generally included in integrated models. Bayesian networks are also an appropriate method to deal with uncertainty, which is a key issue in natural systems. BNs are furthermore a useful tool for representing the decision process and relationships between variables, and for analysing the expected effects of management decisions while accounting for the associated uncertainties (Ames and Neilson, 2001).

Bayesian Decision Networks (BDN) are defined as Bayesian Networks that have been modified to include decision (management option) variables and utility (benefit-cost) variables. A Bayesian Network (BN) approach has been used to consider effects of management options in the catchment.

3. MODEL DEVELOPMENT USING A BAYESIAN DECISION NETWORK

Figure 2 shows the current conceptual framework underlying the BDN being developed for Little River. This framework incorporates ecological, physical, economic and social aspects of the salinity problem.

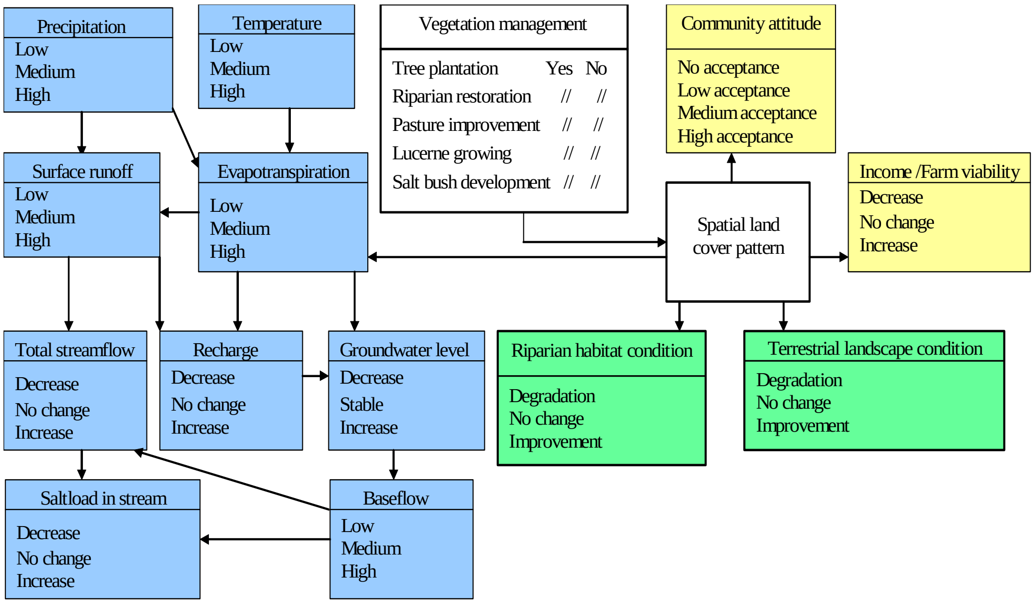

Figure 2. Conceptual model framework for considering salinity management in the LRC

4. SCENARIO DEVELOPMENT FOR SALINITY MANAGEMENT IN THE LITTLE RIVER

As shown in Figure 2 a specific node named 'spatial land cover pattern' has been incorporated into the conceptual model, reflecting the influence of different combinations of management actions on land cover spatially throughout the catchment. To simulate potential land cover patterns under different management options, significant effort was made to determine the areas in the catchment suitable for each of the land cover options. Table 1 summarises the scenario rules for each salinity management action in the catchment.

Table 1. Scenario rules for salinity management actions

Vegetation management	Rules for distribution	Extent of implementation
Tree plantation (F)	Entire catchment is potentially suitable Not in areas currently under non-riparian forest and/or riparian forests Not in the potential riparian areas	Implemented at 10% of suitable areas
Riparian restoration (R)	Only in potentially riparian areas (Seddon *et al.* 2002) Not in areas currently with trees	Implemented at 50% of suitable areas
Pasture improvement (I)	Only in areas currently under native pasture	Implemented at 50% of suitable areas
Lucerne growing (L)	Only in areas currently under improved pasture	Implemented at 10% of suitable areas
Saltbush development (B)	Only in potentially waterlogged areas (Dowling, 2000) Not in areas currently under trees	Implemented at 50% of suitable areas

Considering all five management actions listed in Table 1, the total number of different combinations of the actions gives 31 scenarios (2^5-1) in addition to the base case scenario (current situation). Equation 1 calculates the number of individual scenarios considered.

$$S = 1 + B + 2L + 4I + 8R + 16F \qquad (1)$$

where S is scenario number, B, L, I, R, F are different management actions (see second column of Table 1). The values of B, L, I, R, F equal 1 if Yes, otherwise they equal 0.

For management scenarios with multiple actions, the actions were implemented in the following order of land allocation: 1) tree plantation, 2) riparian restoration, 3) saltbush development, 4) pasture improvement, and 5) lucerne establishment. Using spatial datasets in raster format, land allocation for each scenario was determined on a grid basis with a cell size of 316.23 meters. This grid cell size was selected to establish appropriate habitat size and in consideration of realistic on-ground management interventions (Williams et al., 2002). To extract the probability distribution of outcomes of salinity management actions, some 50 samples of each scenario option were randomly synthesised. It means that for the 50 samples, the suitable area for each land cover was allocated randomly to corresponding management action. The result is a range of different spatial land cover maps assigned for each specific scenario option. This reflects the variability associated with land cover patterns arising from management implementation. Using established GIS datasets including current land cover, and the five maps of potential areas for each management option, the samples were synthesised. Land cover scenario maps have been generated in ArcInfo using ARC Macro Language (AML) code.

5. MODELLING IMPACTS OF SALINITY MANAGEMENT OPTIONS

A catchment hydrology model has been used to evaluate the impacts of some possible dryland salinity management scenarios on total stream flow that can then be separated into baseflow and surface runoff. The hydrology model was developed by Carlile (2005) in the LRC in order to investigate the effects of different land covers and soils on recharge within each Hydrological Response Unit (HRU), and on baseflow and runoff in each subcatchment. A detailed description of this hydrology model is given by Sadoddin (2006). Then the probability distributions of flow discharge predicted by the model for all salinity management scenarios were presented. The analysis of flow was conducted for baseflow, surface runoff, and also total stream flow as different variables of the physical sub-network of the BDN. Using the dependency established between flow discharge and EC, the probability distributions of EC were estimated. These constitute another end point in the physical sub-network of the general Bayesian Decision Network (BDN) structure for the catchment.

Each set of salinity management actions corresponds to a set of potential spatial land cover patterns across the catchment, and these patterns are associated with different potential impacts on terrestrial and riparian ecology. To construct these links in the integrated model, conditional probability tables were derived linking the vegetation management options with spatial land cover patterns and then with the impacts on terrestrial and riparian condition. Four ecological indices were used in this study and then those indices are combined to achieve a single qualitative measure of ecological impact (see Figure 3). The estimates of the conditional probability tables, along with joint probability distributions for the variables in the ecological sub-network, provide the components required to calculate total probability distributions for the state variables of the BDN model in this study.

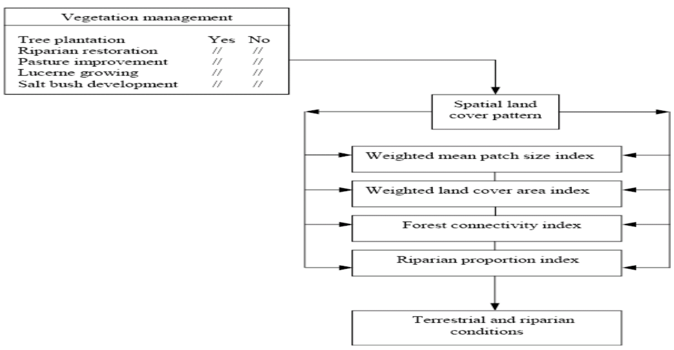

Figure 3. Bayesian decision sub-network in relation to terrestrial and riparian ecology

To investigate the economic impacts of dryland salinity management options, an economic sub-network of the BDN framework for salinity management in the catchment was developed. This sub-network comprises three types of economic impacts on the farming community resulting from the implementation of the salinity management options. These are: 1) Total gross margin, 2) Fencing costs, and 3) Establishment costs. Each of these measures a different type of economic impact on the farming community resulting from implementing changes. To investigate the social impacts of dryland salinity management options, the social sub-network in the conceptual model framework for salinity management in the LRC was considered. The social sub-network establishes the links between land cover management options (vegetative practices) and a node in the framework that was conceptualised as 'Community attitude'. The 'binomial probability distribution' was used to analyse likely social outcomes of attempts to implement the salinity management scenarios in the LRC. In analysing the community acceptance, using the binomial distribution, four levels (classes) of acceptability were considered: zero, low, moderate and high.

6. RESULTS

The bio-physical and socio-economic outcomes of the salinity management scenarios have been translated into multivariate data sets. Segment diagram presentation was utilised to represent the outcome variables corresponding to each salinity management scenario. In the segment diagrams, the values of variables are scaled independently so that the maximum value (or 'best') in each variable is 1 and the minimum (or 'worst') is 0. To facilitate comparison among the management scenarios in segment diagrams for those variables with adverse impacts, their inverted values are represented in the diagrams. This is the case for 'establishment costs', 'baseflow', 'salt concentration', and 'baseflow proportion'. Hence, the radii of the diagrams show the level of achievement of management objectives considering all impact indicators.

Figure 4 shows segment diagrams of the medians of values of nine outcomes, respectively, from implementing each management scenario in the LRC. The median of values of impact indicators is used to represent the changes in the impact indicators from implementing the 32 management scenarios. This summary statistics reduce the collection of values of the impact indicators to a piece of information about the properties of those values (Smithson, 2000). The medians rather than modal values were chosen to describe the distribution because while the median is somewhat more sensitive to overall distribution than the mode, it is most sensitive to cases that are near the middle of the distribution and is unaffected by extremes (Smithson, 2000). When there are a few extreme values in a distribution (also known as 'outliers') the median is much less influenced by them than the mean (Smithson, 2000).

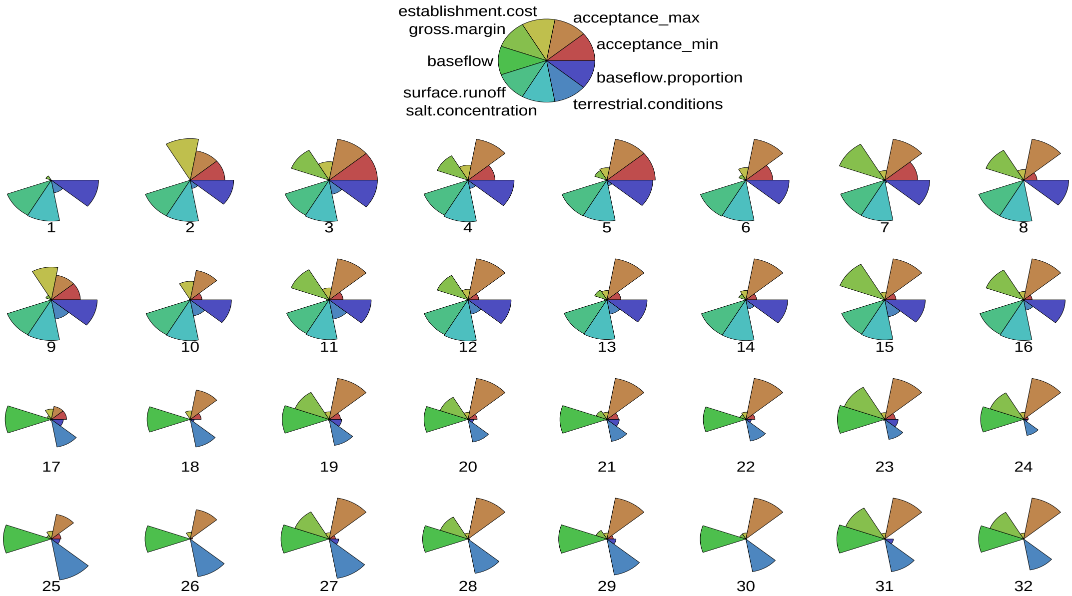

Figure 4. Median values of impact indicators for 32 salinity management scenarios in the LRC

The segment diagrams show that the 32 management scenarios at first sight can be placed into two distinct sets: scenarios 1 to 16 with, in general, larger sizes of segments in the diagram, which show a greater total achievement of management objectives, considering all of the impact indicators but regardless of their significance to a stakeholder community or policy makers; and scenarios 17 to 32 with, in general, smaller sizes of segments in the diagram The scenarios placed in the first set show a better performance in relation to some of the impact indicators, while scenarios belonging to the second set cause an improvement in some other impact indicators. The most distinguishable characteristic of the scenarios placed in the second set (scenarios 16 to 32) is extending tree plantation on the terrestrial areas of the LRC. In contrast, scenarios 1 to 16 do not carry out terrestrial tree plantation. The segment diagrams also suggest that within each set, in particular in the first set, some changes in the impact indicators take place. These changes reflect the impacts of implementing other vegetative salinity management actions in the catchment. Scenarios 2 to 16 all show an improvement in those impact indicators that do not have a good status under scenario 1. These impact indicators are: community acceptability, establishment costs, and gross margin. Similarly, implementing scenarios 17 to 32 will cause an improvement in some of the impact indicators compared to the base case scenario (for example, baseflow and terrestrial conditions), while some other impact indicators deteriorate as a result of implementing these scenarios (for example, surface runoff and salt concentration). In addition, in relation to the impact indicators that appear to have a good status under the base case scenario, Scenarios 2 to 16 provide similar performance, with slight changes from one scenario to another. These impact indicators are: baseflow proportion, surface runoff, and salt concentration.

7. DISCUSSION AND CONCLUSIONS

Cause and effect relationships and spatial links between upstream and downstream are important features of catchment systems. In natural resource management types, integration includes integration across disciplines, data and models, scales, and stakeholders (Jakeman et al., 2005). The LRC BDN is available to stakeholders in the catchment and to policy makers as a management tool that can help them comprehend scenarios and explore the possible outcomes of scenarios being tested. It will also inform policy makers and downstream interests of the likely scope for, and catchment scale outcomes of altering land cover in the LRC. This can assist policy makers by suggesting the preferred management options and also setting targets and deciding on policy instruments such as incentives/penalties at a catchment scale. For instance, the analysis of results suggests that riparian restoration with relatively low establishment costs and medium to high acceptability is likely to be adopted by the faming community in the catchment.

Considering the fact that environmental and socio-economic data in the LRC are sparse, scattered and of varying quality, an approach has been developed through this paper that can be used to represent the catchment system as a whole. In terms of temporal characteristics, the tool aims to investigate the hydrological and ecological impacts of vegetative management options using the conditions prevailing when new vegetation cover reaches its mature state. Therefore, the LRC BDN is a lumped-temporal modeling system in which the impacts are estimated for a specific period of time. However, the structure of the model is flexible enough to accommodate investigation of scenario impacts over a range of time horizons.

It is also useful to note that in the development of the BDN, it is important to keep a balance in the level of complexity among different model components involved in an integrative conceptual framework. In strict terms, a model can never be validated (Oreskes et al, 1994), but a completed BDN can be corroborated using independent information when available. When conditional distribution tables are derived from sources other than observed data, or when no new data become available for assessing the BDN models, validity tests can be challenging (Ames, 2002). Deficiencies in the case study presented here are primarily associated with the lack of independent data for most of its components to ‘validate’ the BDN models.

The focus of this work has been on the process of integration and building the model components. This has been a valuable integrated modelling practice because, in the field of natural resource management, the number of studies that integrate a wide range of disciplines through using BDN models is not significant (for example, O’Brien et al., 2002). The number of multidisciplinary integration studies for salinity management per se using the BDN approach is even more limited. The analysis of trade-offs among different outcomes of the management scenarios also shows that there is no single or ultimate solution to salinity management problems for the LRC, considering the influences of the various possible outcomes on decision-making analysis. To reach informed and feasible decisions for salinity management the social and economic preferences and priorities, along with the ecological and hydrological consequences of salinity management options, need to be considered in quantifying the trade-offs among salinity management outcomes.

The application of the BDN approach shows that model development requires careful consideration of all relevant disciplinary components involved in dryland salinity management, and a synthesis of a combination of observed data, model simulation and expert knowledge into a single model framework. The BDN approach described here has enabled the rapid and comparatively easy integration of several complex and diverse processes. This approach has also enabled communicating uncertainty of the parameters throughout the sub-networks of the BDN model and also to the users by characterising the outcomes of the salinity management scenarios in a probabilistic context. The generic approach presented here to developing and using a BDN for assessing salinity management at a catchment scale is applicable to a variety of catchments with similar characteristics. However, it should be noted that only part of the picture, in relation to salinity management problems, the component disciplines involved, and the possible outcomes of management options, has been drawn in this study. Further study and additional data collection are necessary to capture the other possible disciplinary components and also to further improve the parameters used in the BDN models.

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