Assessing the ecological impacts of salinity management using a Bayesian Decision Network

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Abstract: This paper outlines a component of a study currently being undertaken to provide a new tool for the holistic management of dryland salinity. The Little River catchment in the upper Macquarie River basin of New South Wales (NSW), Australia, is used as a case study. The model uses a Bayesian Decision Network (BDN) approach to integrating the various system components – biophysical, social, ecological, and economic. The method of integration of the system components is demonstrated through an example application showing the impacts of various scenarios on terrestrial and riparian ecology. The paper outlines these scenarios and demonstrates the way in which they are spatially incorporated in the model. The ecological impacts of management scenarios have been assessed using a probabilistic approach to evaluating ecological criteria for a range of management actions compared with the present situation.

Keywords: Salinity management, Bayesian decision networks, terrestrial and riparian ecology

1. INTRODUCTION

Salinisation is a major environmental problem affecting land and water resources in Australia. Employing a holistic approach to consider all components in a catchment system, in a cause and effect context, is essential to address this deteriorating situation. This paper presents a method for investigating some of the ecological impacts of salinity management options in the Little River Catchment as a component of an integrated model of salinity management at the catchment scale. The model uses a Bayesian Decision Network (BDN) approach to integrating the various system components – biophysical, social, ecologic, and economic.

2. CASE STUDY: THE LITTLE RIVER

The Little River is a tributary of the Macquarie River lying southwest of Wellington in central western NSW and is part of the headwaters of the Murray-Darling Basin. The catchment covers an area of 2310 km^2. Approximately 80% of the vegetation communities in the catchment have been disturbed for agricultural purposes (Seddon *et al.*, 2002) and there are severe salinity outbreaks in some parts of the catchment. It is estimated that approximately 12% of the salt load of the Macquarie River at Dubbo originates from the catchment (IVEY & DPMS, 2001: 6.6). Assessment of saline sites in the catchment between 1988 and 1998 estimates that the spatial extent of saline lands increased by a factor of 4.6 in this period of time (Nicholson and Wooldridge, 2001).

3. A CONCEPTUAL MODEL FOR SALINITY MANAGEMENT

In this study a Bayesian decision network approach is applied to consider the influence of management options on environmental, physical, social, and economic outcomes. Sadoddin *et al.*, (2003) describes the development of the BDN approach and advantages of the use of them in more detail. Figure 1 shows the current conceptual framework underlying the BDN being developed for the catchment. This framework incorporates ecological, physical, economic and social aspects of the salinity problem. This paper focuses on evaluating the links between management decisions and terrestrial and riparian ecological impacts. Each set of salinity management actions corresponds to spatial land cover patterns across the catchment, and in turn has potential impacts on terrestrial and riparian ecology. Several criteria have been set up to assess the ecological consequences of salinity management using a probabilistic approach. The links between salinity management and terrestrial and riparian ecology in the system are a key component of the integrated model (see ecological subset marked out by bold boxes in Figure 1). In order to construct these links in the integrated model, conditional probabilities tables must be derived linking the vegetation management options with spatial land cover patterns and then with the impacts on terrestrial and riparian habitats. These estimates, along with joint probability distributions for the variables in the ecological subset, provide required components to calculate total probability distributions for the state variables of the BDN model.

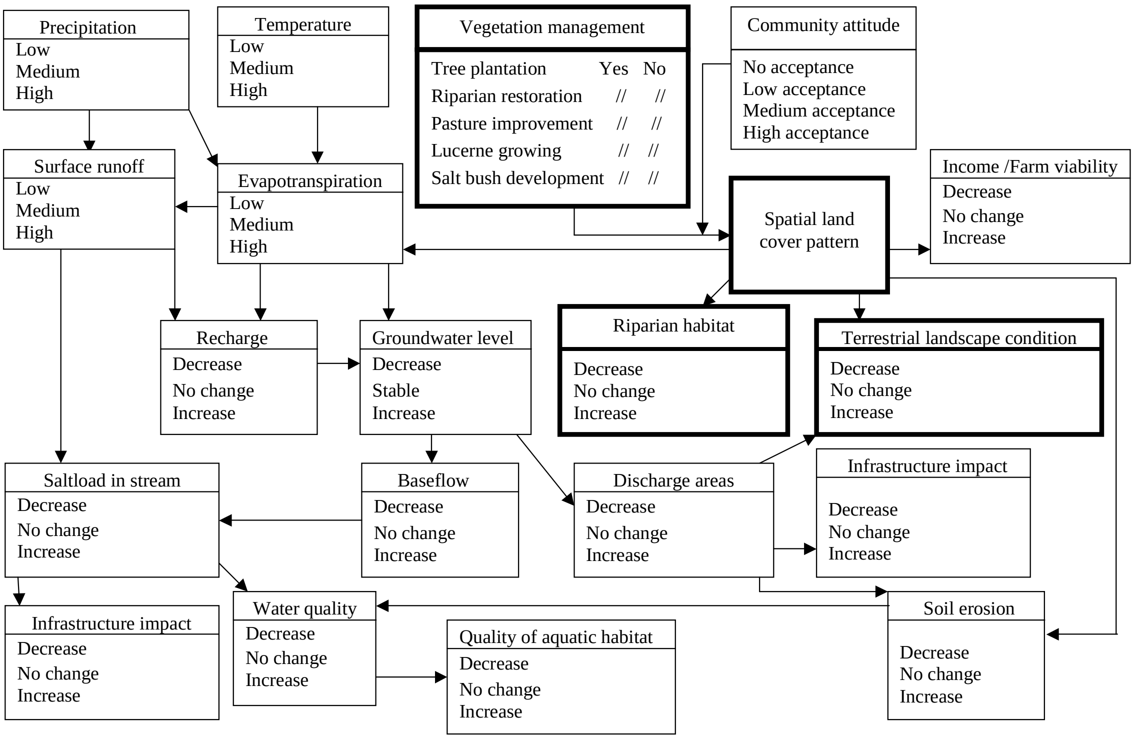

Figure 1. BDN conceptual framework for the Little River Catchment adapted from Sadoddin *et al.,* (2003)

4. SCENARIOS

As shown in Figure 1 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 spatial land cover patterns under different management options, a significant effort has been made to determine the areas in the catchment suitable for each of the land cover options. Table 1 summarises the scenario rules for each of salinity management actions in the catchment.

Only areas with annual rainfall greater than 700 mm are suitable for commercial tree plantation in the region (Hall *et al.,* 2003). Only a very narrow strip (approximately 6% of the catchment) in the south of the catchment meets this criterion. Hence, implementation of commercial tree planting in the catchment has little economic justification due to the small area and the large distance to sawmills and markets (Hall *et al.,* 2003). Therefore, in this study, salinity management by tree plantation action is assumed to consist of local native trees rather than commercial species. The potential riparian area has been predicted by Seddon *et al.,* (2003) using a combination of geology, soil, elevation, slope and topographic position layer maps using a statistical analysis. Pasture improvement and lucerne establishment have been considered as the management actions applicable in areas currently under native pasture and improved pasture respectively. The area potentially suitable for planting saltbush has been determined by applying the FLAG model in the catchment (Dowling, 2000). FLAG model is an approach incorporating terrain analysis that uses a number of topographic indices derived from elevation map to provide a wetness index map indicative of potential groundwater discharge and salinity.

Considering all five management actions given 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 can calculate the number of each individual scenario considered in this paper.

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

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

Table 1. Scenario rules for salinity management

Management action	Rules for distribution	% Of suitable areas
Non-commercial tree plantation (F)	Entire catchment except: -areas currently under forest - riparian areas	10
Riparian restoration (R)	Only in riparian zone, not in areas currently with trees	50
Pasture improvement (I)	Only in areas currently under native pasture	50
Lucerne establishment (L)	Only in areas currently under improved pasture	10
Saltbush development (B)	Only in potential waterlogged areas, not in areas currently under trees	50

For each scenario, the management actions described in Table 1, have been 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 cell size of 10 hectares. This grid cell size was selected to establish appropriate habitat size and considering realistic on-ground management interventions (Williams *et al.,* 2002). In order to lay out the frequency distribution of outcomes of salinity management actions, some 50 samples of each scenario option have been randomly synthesised. This has been carried out by using established GIS datasets including current land cover, and the five maps of potential areas for each management option. Land cover scenario maps have been generated in ARCINFO using ARC Macro Language (AML) code. The ecological indicators described in the next section were also evaluated for each of the 50 samples of each scenario to derive a probability distribution of ecological impacts for each scenario.

5. MODELLING IMPACTS ON TERRESTRIAL AND RIPARIAN ECOLOGY

Biodiversity is a broad and complex ecological concept that can be focused in different ways, and at different organizational levels (for example. genetic, species, population), and also with different degrees of complexity (for example Chevalier *et al.,* 1997). Measuring or modelling biodiversity is extremely difficult because of these problems. As such, the model considered in this paper uses several indicators of impacts to demonstrate conditions that are likely to affect biodiversity and ecosystem health rather than attempting to model biodiversity impacts directly. Indirectly, landscape diversity and forest fragmentation are important concepts in revegetation and salinity management. Since there is a relationship between the spatial configuration and composition of landscape elements and biological diversity, this concept is addressed in the framework instead of targeting biodiversity directly (McGarigal *et al.,* 1994). A significant number of mathematical indices have been developed and appeared in the literatures that allow the description of different aspects of landscape diversity. Fragmentation indices can be applied to assess the condition of ecosystem processes and quality of habitat for a significant percentage of all mammal, reptile, bird, and amphibian species that are found in forest habitats (Riitters *et al.,* 2002). There are however, relatively few metrics sufficient to capture landscape pattern (Lausch and Herzog, 2002). This section describes the indicators of terrestrial and riparian ecosystem health used to assess ecological impacts in the integrated model. Four indices have been chosen to represent the impact of salinity management on terrestrial and riparian ecosystems in the catchment. For all indices the index i denotes the scenario number (1, …, 32) while j denotes the sample (1, …, 50). All indices are dependent on i and j. The criteria have been evaluated for the current situation and also for synthesised land cover maps corresponding to different management actions across the catchment as a whole. The impact of management change is measured as a percentage change from the base case situation. That is, the probability distribution of impact for each indicator is calculated from $Y_{i,}$ where

$$Y_{i,j} = \left(\frac{I_{i,j} - I_1}{I_1} \right) * 100 \qquad (2)$$

$I_{i,j}$ is index value for each sample j (j=1, …, 50) of each scenario i (i =2, …, 32)
I_1 is index value for the base case, and $Y_{i,j}$ is percentage change from the base case.

a) Weighted Mean Patch Size Index (WMPSI $_{ij}$)

The weighted mean patch size index measures the direct impact of each management scenario on patch sizes for each land cover type across the catchment. It also reflects the biodiversity conservation value of each land cover. It has been selected because in a patchy landscape, patch size is an important criterion in determining what species of animals are able to survive. The negative effect of fragmentation increases where the patch size is smaller. Also there is a direct correlation between the patch size and the positive influence of ecotone development. Thus, in a small patch the positive effects of ecotone development are less than for a bigger patch (Odum, 1993). The equation used to calculate WMPSI is:

$$WMPSI = \sum_{m=1}^{7} \frac{\alpha_m}{n_m} \sum_{k=1}^{n_m} P_{k,m} \qquad (3)$$

where m is type of land cover (see Table 2)
n_m is number of patches of land cover m type, $P_{k,m}$ is size of each of the patches, (k = 1, …, n_{m}), α_m is the weight value for each land cover type m.

The weight values used for different land covers are given in Table 2. These subjective values have been derived from expert ecological knowledge and are subject to change in different contexts. In particular, the weight values are sensitive to the history of management. An increase in WMPSI denotes an improvement of biodiversity conservation value of the region.

Table 2. Weight values for different land covers

Management action	m	α_m
Trees	1	1
Riparian	2	1
Lucerne	3	0.1
Improved pasture	4	0.3
Native pasture	5	0.6
Crops	6	0.05
Saltbush	7	0.3

b) Weighted Land Cover Area Index ($WLCAI_{ij}$)

The weighted land cover area index is an aggregated measure of the extent of natural versus modified landscapes in the catchment. It has been selected because measuring the area of different land covers and considering a corresponding weight provides an estimate of the degree of naturalness in the catchment. In a biodiversity conservation context, measuring the degree of 'naturalness' provides useful information to contribute to broader conservation value assessments (Parkes *et al.*, 2003). Additionally, a comparison between different land cover types is another essential process that is required for assessing native vegetation quality ((Parkes *et al.*, 2003). Pre-clearing distribution of vegetation communities in the Little River Catchment predicated by Seddon *et al.*, (2003) shows that the entire catchment was covered by six native tree communities. This can be seen as a benchmark representing the average characteristics of mature and long- undisturbed stands of vegetation communities in the catchment (Parkes *et al.*, 2003). The equation used to calculate WLCAI is:

$$WLCAI = \sum_{m=1}^{7} \alpha_m \sum_{k=1}^{n_m} P_{k,m} \qquad (4)$$

Variables are as defined previously and the same weight values for each land cover (see Table 2) are used as for WMPSI. An increase in WLCAI denotes improving the catchment situation in terms of degree of naturalness.

c) Forest Connectivity Index (FCI_{ij})

The FCI measures the spatial pattern of forested areas. Since a given amount of forest can be arranged in many patterns and the spatial pattern has significant effect on fragmentation characteristics, an index measuring forest connectivity has been used. When the spatial pattern of forest changes, the wellbeing of forest dependant organisms and competitive arrangements among populations will be affected (O'Neill *et al.*, 1988 cited in Riitters *et al.*, 2002). Fragmentation also increases the energy cost/benefit ratio of movement due to contortion in movement pattern (Gardner *et al.*, 1991 cited in Riitters *et al.*, 2002). The FCI has been measured on raster land cover map. In order to calculate forest connectivity index, at first each pixel edge needs to be labelled according to the cover types of the two adjacent pixels. Then FCI is calculated as a ratio of the number of pixel edges in the landscape that border two forest pixels to the total number of pixel edges that have a forest pixel on at least one side (Riitters *et al.*, 2002). With measuring FCI, the degree of isolation or integration of forest can be quantified. The equation used to calculate FCI is:

$$FCI = e_{pf,pf} / (e_{pf,pn} + e_{pf,pf}) \qquad (5)$$

where $e_{pf,pf}$ is number of edges between two forest pixels, $e_{pf,pn}$ is number of edges between forest pixels and non-forest pixels, p_n is a non-forest pixel or land cover with m=3, …, 7. p_f is a forest pixel or land covers with m = 1 & 2 (see Table 2). An increase in FCI denotes a higher connectivity of forest pixels indicating a higher degree of integration of forest.

d) Riparian Proportion Index (RPI_{ij})

Riparian zones can be considered as a boundary between terrestrial and aquatic ecosystems. Forests along waterways, also known as riparian forests, are an important resource that function to maintain the integrity of the stream channel, reduces the impact of pollution sources and supply food and habitat resources to wildlife (Newsom *et al.*, 2001). The proportion of the riparian zone that is forested is a useful indicator of ecosystem health. One of the salinity management actions investigated in this study is reforestation along streams in the catchment. Water quality and habitat benefits have direct relationships with riparian proportion along stream networks (Newsom *et al.*, 2001). Thus, the riparian proportion index is calculated as:

$$RPI = \frac{r_2}{\sum_{m=2}^{7} r_m} \quad (6)$$

where r_m is number of grid cells with land cover m along waterways, r_2 is number of grid cells with riparian forests.

The influence of the various management actions on the ecological endpoints in the BDN model framework have been estimated through calculation of the change in the indices from the base case scenario. For each ecological index, the values of Y_i (see Equation 2) for all management scenarios (2, …, 32) across 50 samples have been grouped using five class intervals. Probability distributions for each scenario have then been extracted.

6. RESULTS

The resultant probability distributions for each ecological indicator were placed into several categories according to the level of effects of the management scenarios on the indicators. The categories were ranked from best to worst ecological outcomes. A lower category number indicates less degradation in relation to WMPSI and FCI and/or greater improvement in relation to WLCAI and RPI.

The results of the scenarios classification for all indices are illustrated in Figures 2 to 5. The change from the base case for WMPSI, WLCAI, FCI, and RPI covers a range of 31.3, 20.7, 5.5, and 127.5 percent respectively. The results show that the response of the four indices to a management scenario does not occur in the same direction. In general, applying management actions that increase the number of patches in the catchment decreases the values of mean patch size and forest connectivity indices. This is particular as so for tree plantation action, because the weight value for trees is greater than for other land covers (see Table 2). In contrast, the land cover area and riparian proportion indices improve under management scenarios associated with tree plantation. The influence of implementing the scenarios associated with improved pasture and lucerne on land cover area index is not large. This is because of the lower weight values for improved pasture and lucerne.

WMPSI and FCI are sensitive to the number of patches, while the other indices are not. The general trends in the data show that there is a positive relationship between the scenario number and management scenario 'category' for both mean patch size and forest connectivity indices (Figures 2 and 4). The reverse trend can be seen for weighted land cover area, and riparian proportion indices (Figures 3 and 5).

The mean values of the indicators WLCAI, FCI, and RPI over 50 samples clearly indicate that four groups of management scenarios can be identified. Table 3 gives the four scenario groups. In particular, for FCI and RPI, the variation of the means inside each group is negligible. While, for WMPSI two distinct groups can be identified and there is significantly a continuous change in the value of WMPSI in the second group.

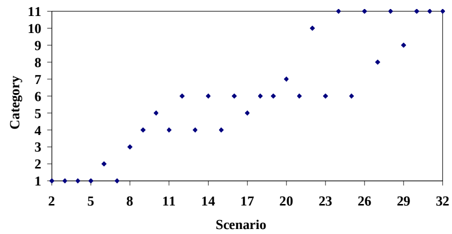

Figure 2. Rank of management scenarios (WMPSI)

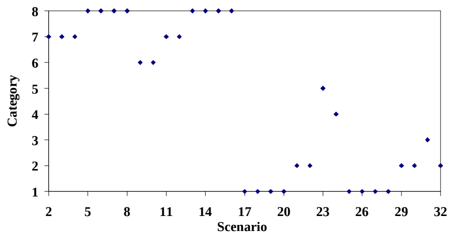

Figure 3. Rank of management scenarios (WLCAI)

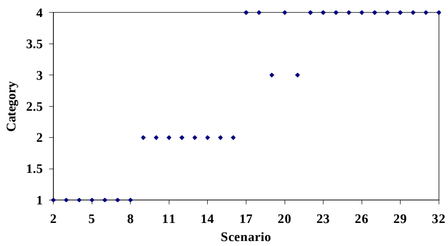

Figure 4. Rank of management scenarios (FCI)

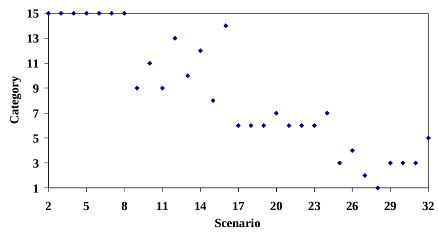

Figure 5. Rank of management scenarios (RPI)

Table 4 gives the range of standard deviation values for each ecological index and the number of class intervals with non-zero probability values.

Table 3. Groups of management scenarios

Group	Scenario number	Key attribute
1	2-8	No tree plantation in terrestrial or riparian areas
2	9-16	No tree plantation in terrestrial area
3	17-24	No tree plantation in riparian area
4	25-32	Tree plantation in terrestrial and riparian areas

Table 4 shows that the values of indicators over the 50 samples are clustered together. In addition, the maximum numbers of class intervals for which non-zero probability values exist is two, reflecting relative certainty in the derived probability distributions.

Table 4. Statistical information for indices

Indicator	No. of non-zero class intervals	Min. st.dev (%) for all scenarios	Max. st.dev (%) for all scenarios
MPSI	2	0.11	0.51
LCAI	2	0.02	0.32
FCI	2	0.00	0.11
RPI	2	0.00	7.10

7. DISCUSSION AND CONCLUSIONS

The implementation of management scenarios for dryland salinity can result in many different spatial patterns of land cover. A BDN is an appropriate approach to deal with the spatial variability associated with different land cover patterns from management implementation. It is also an appropriate tool to systematically represent the uncertainties associated with the different components in the model. This research uses four indicators to assess ecological consequences of salinity management actions using a probabilistic approach. Changes in the indices do not occur in the same direction across all scenarios. Thus, a method for interpreting these changes into "better" or "worse" ecological outcomes must also be developed. This is required so that managers are given clear direction on the impacts of scenarios in the model. This will be achieved through consultation with ecologists on appropriate weights to recombine changes in these indices to achieve a qualitative measure of ecological impact.

8. ACKNOWLEDGEMENTS

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