A Bayesian Decision Support System Model: Dryland Salinity Management Application

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Abstract

Addressing environmental management problems at catchment scales requires an integrated modelling approach, in which key bio-physical and socio-economic drivers, processes and impacts are all considered. Development of Decision Support Systems (DSSs) for environmental management is rapidly progressing. This paper describes the integration of physical, ecological, and socio-economic components in a Bayesian Decision Network (BDN) and its implementation in the Interactive Component Modelling System (ICMS) software to build a prototype DSS for salinity management in the Little River catchment in the upper Macquarie River basin, NSW Australia. Salinity is a major environmental problem in the country. This integrated model implemented in a DSS has been developed to co-ordinate the various disciplines involved in salinity problems, integrate data and information available, and allow the investigation of the potential outcomes arising from implementing salinity management options at the catchment scale. The analysis of the trade-offs presented in this study shows that there is no single or ultimate solution to salinity management problems for the catchment, but the Little River catchment BDN decision support system, as a decision toolbox, does clarify the impacts of management options. It assists users to reach their own conclusions on the basis of their improved understanding of the system and of the trade-offs among various outcomes arising from implementing salinity management scenarios.

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1. Introduction

Nature is complex, comprising multiple components. These interconnected components interact with each other making a complex system with specific characteristics and also with spatial and temporal patterns of elements and factors (Jakeman *et al*., 2005). As a result, natural resource management as an attempt to deal with this multi-dimensional system is also complex. To manage such systems, good management strategy and practices should be able to deal with existing and future conflicts between long-term and short-term benefits to the stakeholder community living in or dependent on the system. The conflict between upstream and downstream interests also needs to be addressed to attain the objectives of management (Brooks *et al*., 2003). These facts indicate that it is necessary to seek and reach a compromise among the various outcomes of management interventions in a management system (catchment) (Sadoddin, 2010). That is, the stakeholder community of the management system should be prepared to 'trade' and reach a consensus view-point that in turn, will assist the community to make a final management decision (Sadoddin, 2006).

Additionally, in natural resources management, uncertainty results from the inherent variability in the prediction of alternative states of nature and of natural processes over time. It can be usually characterised by a probability distribution (Mowrer, 2000). Stakeholders' participation and uncertainty analysis have a key role in successful integrated natural resource management. Therefore, there is a need for tools and methodologies that make it easier to meet these requirements (Castelletti and Soncini-Sessa, 2007). Bayesian Networks (BNs) use probability theory to manage uncertainty by explicitly representing the conditional dependencies between the different knowledge components (Varis and Kuikka, 1999). The BNs explicitly represent uncertainty in a way that can be understood clearly by users (Cain, 2001).

In terms of an approach to a successful management strategy, community acceptance and adoption often require approaches that represent a 'compromise' management scenario, reflecting trade-offs among social, economic, ecological, and physical outcomes at the catchment scale. This approach is a stakeholder-centered approach that allows stakeholders to be actively involved in the process of decision-making. This can be undertaken through an investigation of various management scenarios and their potential outcomes and trading off to reach a learned decision (Jakeman *et al*., 2005). The use of DSS tools in integrated natural resource management facilitates this process effectively.

A DSS has been defined in many different ways, but it can be regarded in general as an interactive, flexible, and adaptable computer-based information system especially developed for supporting the appreciation and solution of a complex, poorly structured or unstructured, strategic management problem for improved decision-making (BfG, 2000 cited in Matthies *et al*., 2007). In addition, a

DSS is built by an interactive process, supports one or more phases of decision-making, and may include a knowledge component (Matthies *et al*., 2007).

Bayesian Decision Networks (BDNs) are effective tools for not only communicating decision models among decision analysts and decision makers, but also for communication between the analyst and the computer (Dorner *et al*., 2007).

This capability of BDNs was introduced in this paper to build a Decision Support System (DSS) for dryland salinity management, a major environmental problem in Australia. The BDN developed in this study was implemented in a modelling platform known as the Interactive Component Modelling System (ICMS). The ICMS software is an object-oriented modelling environment incorporating data and models used in catchment management modelling (Letcher and Weidemann, 2004). ICMS has demonstrated its utility in the delivery of decision support for management to stakeholders (see for example Reed *et al*.1999; Letcher, 2004; Newham *et al*., 2004; Ticehurst *et al*., 2007). The object-oriented structure of ICMS and its generic approach to modelling allow for easy upgrades to the model over time and/or extension of models to new catchment situations (Newham *et al*., 2004).

In addition, customised user-interfaces can be developed which communicate with the ICMS software to allow easier access to models by non-technical stakeholders (Cuddy *et al*., 2002). Thus, stakeholders are able to develop their understanding of the system components and also run scenarios and explore the possible outcomes of scenarios being tested without having specific modelling skills. This has meant that the BDN model, described briefly in this paper, has been able to be implemented as a fully functioning DSS for dryland salinity management through using ICMS.

2. Experimental protocols
2.1. The Little River catchment description

The Little River is a tributary of the Macquarie River lying southwest of Wellington in central western NSW, Australia and is one of the headwaters of the Murray-Darling River system (see Figure 1). The Little River catchment (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. The average annual rainfall in the Little River catchment varies from approximately 560 mm in the northern part of the catchment to about 730 mm in the southwest. Summer-dominant rainfall is one of the climatic characteristics of the region. The elevation in the Little River catchment varies from about 280 metres above Mean Sea Level adjacent to the catchment outlet to approximately 800 metres along the southern border. More than three quarters of the catchment has slopes less than 16%. The geological setting of the Little River catchment is

one of the factors that influence salinization (Watson *et al.*, 2002). Almost 67% of the catchment has been identified as having soil types which are prone to salinization problems. Therefore, soil-derived salinization is likely to be a serious issue in the Little River catchment.

Since the arrival of Europeans in the 19th century, approximately 80% of native vegetation in the Little River catchment has been cleared for agricultural purposes, especially on fertile soils (Seddon *et al.*, 2002). Therefore, most of the remaining native woodlands occur on less fertile soils and steep terrains, or is extremely fragmented.
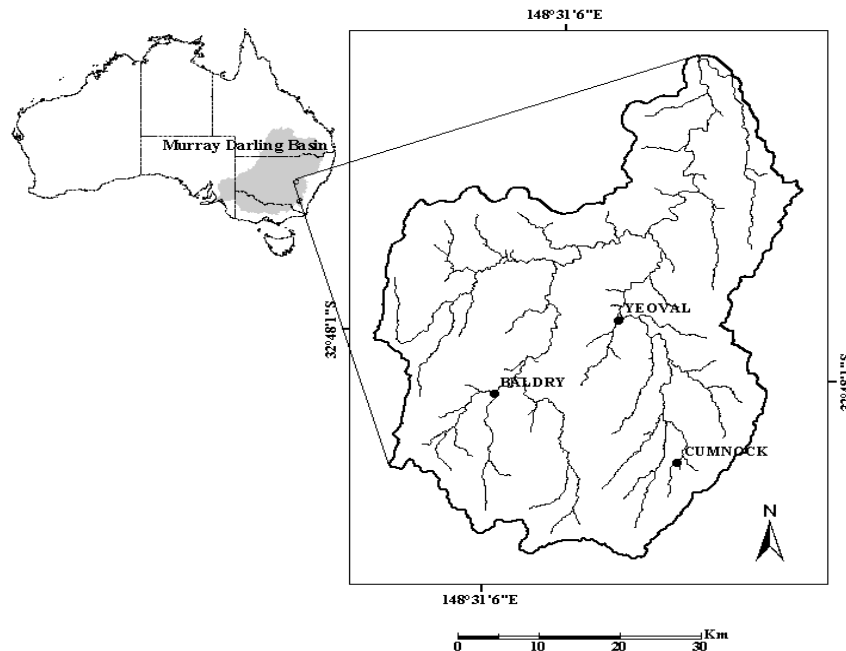

Figure 1. Location of the Little River catchment

2.2. Overview of the BDN decision support system structure

The BDN decision support system for salinity management in the Little River catchment is a computer-based tool which can be used to trade-off biophysical and socio-economic outcomes resulting from changes in salinity management practices. The biophysical components include hydrologic and ecological impacts. These are linked to an economic component which describes the impacts on establishment costs and farm returns. A link is also made with a social component that assesses the acceptability of the scenarios to the farming community of the Little River catchment (Sadoddin *et al.*, 2009). Figure 2 shows the conceptual framework of the

BDN for salinity management in the Little River catchment implemented in ICMS (Sadoddin *et al.*, 2011). In Figure 2, the nodes represent decision and/or state variables (see Table 1) and the links show the existence of direct causal influences between the variables. The probability distributions are passed through the network by the links.
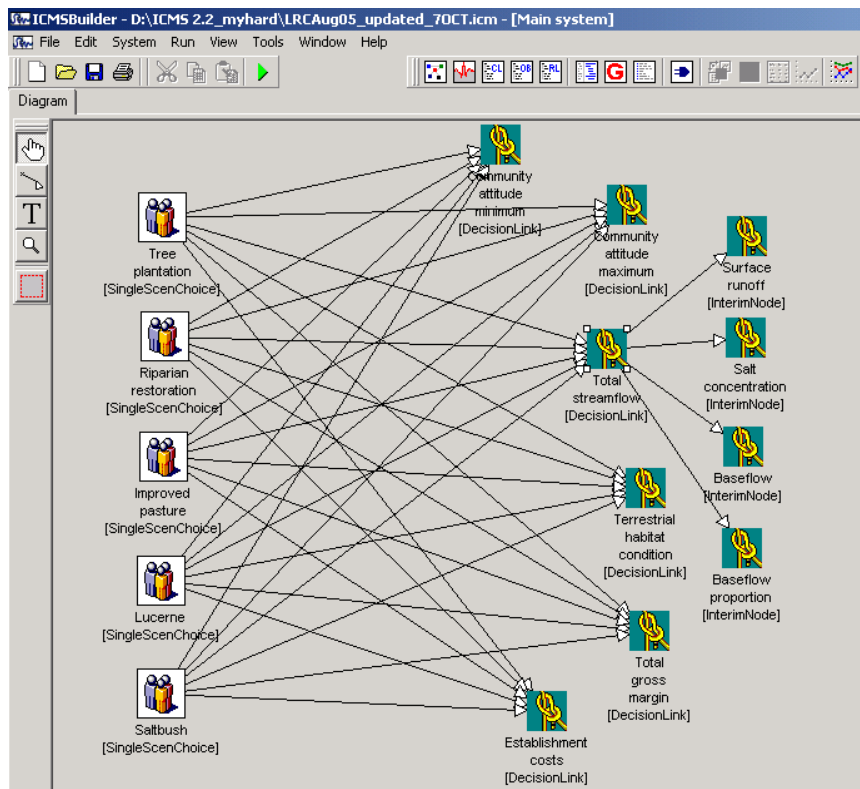

Figure 2. ICMS Conceptual View of the BDN decision support system for salinity management in the Little River catchment

A description of the sources of information and the methods used to derive the conditional probability tables for the BDN can be seen in Sadoddin (2006).

An explanation of the variables of the BDN decision support system is given in Table1.

Table 1. Description of the decision and state nodes of the Little River catchment BDN decision support system

Type: Decision	
Name	Description
Tree plantation	From the current land cover to planting non-commercial hardwoods in 10% of the area suitable for tree plantation.
Riparian restoration	From the current land cover to restoring riparian trees in 50% of the area suitable for this action.
Pasture improvement	From current native pasture to improved pasture (in 50% of the current native pasture).
Lucerne growing	From current improved pasture to lucerne (in 10% of the current improved pasture).
Saltbush development	From the current land cover (except trees) to saltbush in 50% of the potential waterlogged areas
Type: State	
Name	Description
Total streamflow	The change in the frequency of different states of total stream flow measured in ML/Days over all days of observation due to salinity management actions.
Surface runoff	The change in the frequency of different states of surface runoff measured in ML/Days over all days of observation due to salinity management actions.
Baseflow	The change in the frequency of different states of base flow measured in ML/Days over all days of observation due to salinity management actions.
Salt concentration	The change in the frequency of different states of salt concentration measured in μS/cm over all days of observation due to salinity management actions.
Terrestrial habitat condition	Change in terrestrial habitat condition (including the riparian proportion) from the base case for possible salinity management scenarios measured by using four ecological indices.
Community attitude minimum	Qualitative measure of the support of farming community to proposed salinity management actions (lower-bound of the acceptability).
Community attitude maximum	Qualitative measure of the support of farming community to proposed salinity management actions (upper-bound of the acceptability).
Establishment costs	Establishment costs per hectare, including fencing costs, of salinity management scenarios.
Total gross margin	Change in annual total gross margin, excluding establishment costs, for salinity management scenario.

2.3. Modelling platform

The ICMS is free under compliance with the license agreement and can be ordered by potential users.

The model building component, ICMSBuilder, provides a simple C-like internal language for writing models, as well as a drag-and-drop palette for linking objects and their models to describe the flow of processes and/or information through a catchment system (Cuddy *et al.*, 2002). In this paper, an application which is completely self-contained in aicm file was developed as an ICMS Project. The project is built within ICMSBuilder using its System View canvas to define classes (in this case Decision and State classes) and then create objects of these classes. Objects are connected by linking the output data from one object to input data of another (Cuddy *et al.*, 2002).

Decision class objects exist for each of the management decision choices able to be undertaken. These objects connect decision choices to a scenario number, used to access relevant scenario results. There are two types of state nodes: Decision Link nodes which have only decision nodes as parents, and Interim Nodes which have only state nodes (not decision nodes) as parents. As illustrated in Figure 2, all decision nodes are connected to all Decision Link nodes. The state node 'Total stream flow is the parent node of four Interim Nodes 'Surface runoff', 'Baseflow, 'Salt concentration', and 'Base flow proportion'. Decision Link and Interim Node nodes propagate the impacts of scenarios on outcomes through the network by passing probability distributions for state variables and using conditional probability information. Each model is associated with a class.

Cuddy *et al.* (2002) stated that separating the interface from models and data allows the same set of models (captured in an ICMS Project) to be made available to different groups of users through providing different Views into the Project to suit particular audiences. The role of ICMS is to provide for maximum technical access when necessary, while allowing for customisation of an interface when the details of processing do not need to be shown or automatic results of scenario runs need to be produced (Cuddy *et al.*, 2002). This is achieved through building custom Views into ICMS that have access to all of the ICMS' functions and data. The following section describes the user-interface of the BDN decision support system for the Little River catchment.

User-interface of the BDN decision support system for the Little River catchment Recent developments show a continuum between integrated assessment modelling and DSS with different levels of stakeholder participation in both DSS development and application (Matthies *et al.*, 2007). The delivery of science to catchment managers and stakeholders in a sensible and informative way is an important component of building successful DSSs for managing catchments in an integrated way (Cuddy *et al.*, 2002; Alvarez, 2010). In this way, stakeholders' participation and adoption will be improved. In this paper, instead of developing a

large DSS which attempts to predict many management questions, there is a focus only on the impacts of dryland salinity management scenarios through using some impact indicators.

The user-interface of the BDN for the Little River catchment facilitates communication with the stakeholders of the catchment and more importantly increases the transparency of modelling for the stakeholders through transferring the science required for salinity management purposes, in an easy and quick manner.

The implementation of a generic user-interface created using the Borland Delphi 5 software by Ticehurst *et al.* (2007), was undertaken for the Little River catchment case study using the following set of information (Sadoddin *et al.*, 2011):

• Several files of html and rtf format to provide potential users with some general information and background for the application including a brief description of the Little River catchment, sources of information including GIS maps and photographs, a description of the modelling approach, a description of each salinity management action, and a description of each variable.

• An initial text files containing a description of key project features required by the interface code to tailor the interface to the application. This comprises features of the interface, including a list of management actions as well as a list of variables in the Output view page, and a description of states for each variable.

• A set of maps illustrating some information on the catchment;

• Photographs illustrating management issues and scenarios related to the BDN application.

The background information compiled and presented in the interface will assist users of the BDN in understanding the system variables and processes in relation to salinity management. Additionally, the quality of the data used to extract the probability distribution tables can be either described in the Input view page of the interface or reported in the output of the BDN modelling support system. This feature also assists users to determine their level of confidence in the outputs and assess where more detailed information is required to improve predictions.

Figure 3 shows a screen grab of the 'Scenario' page of the user-interface of the BDN. It shows the five decision choices that can be chosen for salinity management purposes in the catchment in order to run all 32 scenarios and explore the possible outcomes of the scenarios being tested.
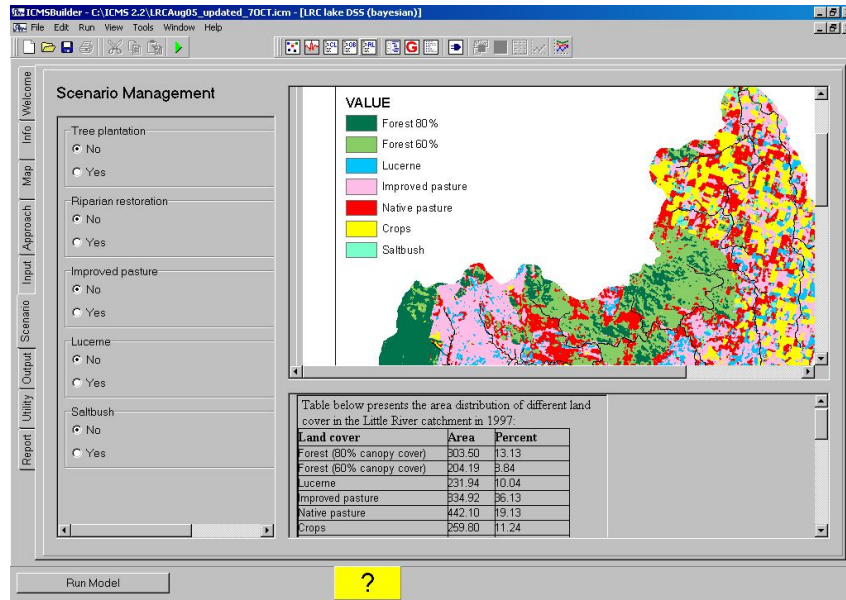
Figure 3. The 'Scenario' view page of the user-interface for the BDN modelling support system for salinity management in the Little River catchment which shows the 31 management scenarios developed in this study and their management actions

Table 2. A list of salinity management scenarios for the Little River catchment and their management actions

Scenarios / Action	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Tree plantation in terrestrial areas (F)																
Riparian restoration (R)									■	■	■	■	■	■	■	■
Saltbush development (B)		■		■		■		■		■		■		■		■
Pasture improvement (I)					■	■	■	■					■	■	■	■
Lucerne growing (L)			■	■			■	■			■	■			■	■

Scenarios / Action	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Tree plantation in terrestrial areas (F)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Riparian restoration (R)									■	■	■	■	■	■	■	■
Saltbush development (B)		■		■		■		■		■		■		■		■
Pasture improvement (I)					■	■	■	■					■	■	■	■
Lucerne growing (L)			■	■			■	■			■	■			■	■

F= tree plantation in terrestrial areas (10%), R= riparian restoration (50%), B= Saltbush development (50%), I= pasture improvement (50%), L= lucerne growing (10%); the values in precent correspond to the extent of implementation of each action at suitable areas.

The following section presents an analysis of the bio-physical and socio-economic trade-offs associated with the salinity management scenarios in the Little River catchment.

3. Results

As stated earlier, using the DSS prototyped in this study, a user is able to view and understand various possible management scenarios, explore the likely outcomes of implementing the chosen scenarios, and reach to an understanding of the trade-offs among the outcomes. Figure 4 illustrates a screen grab of the 'Examine Outputs' page of the user-interface of the BDN. It shows bar charts of the nine outcome variables of the scenarios being tested for the catchment.
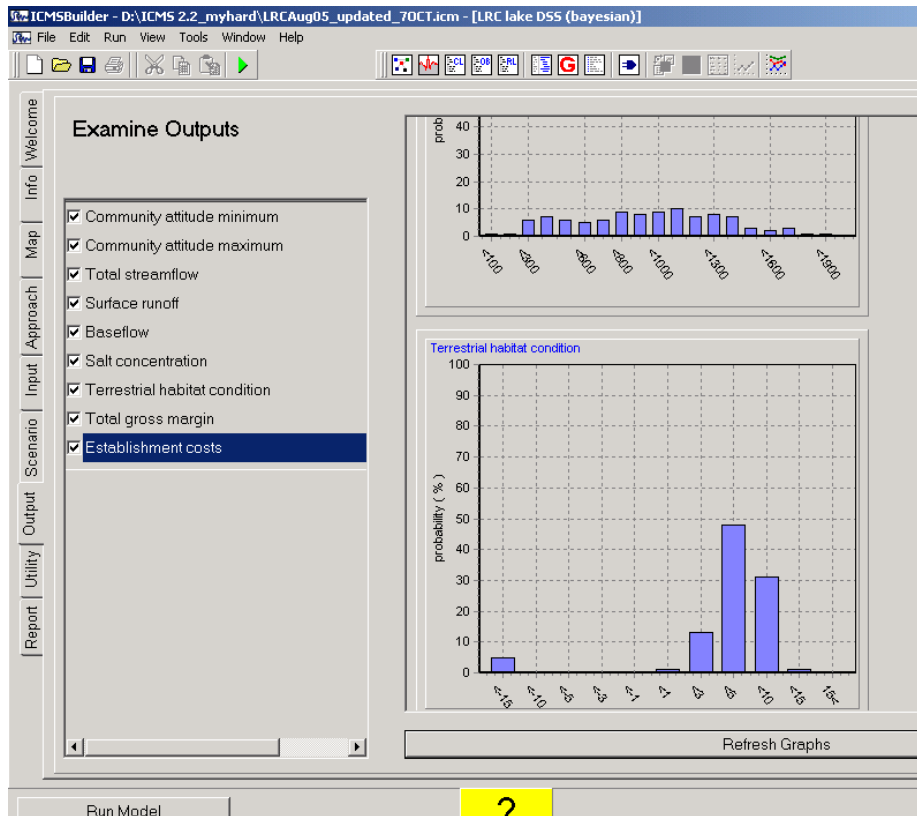

Figure 4. The 'Examine Outputs' view page of the user-interface for the BDN modelling support system for salinity management in the Little River catchment

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. Segment diagrams represent p measurements of a case on equally spaced radii extending from the centre of a circle (du Toit, 1986). The value of a variable is shown by the radius of the segment representing the variable (Dye, 2005). Such a visual technique is useful for comparing various outcomes of management interventions considered as impact indicators for the 32 salinity management scenarios.

Figure 5 shows segment diagrams of the medians of values of nine outcomes, from implementing each management scenario in the Little River catchment. In this figure, 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', 'base flow', 'salt concentration', and 'base flow proportion'. Hence, the radii of the diagrams show the level of achievement of management objectives considering all impact indicators.

The median of values of impact indicators are used to represent the changes in the impact indicators. This measure of central tendency assists in addressing some questions that cannot be answered through displaying the probability distributions of the impact indicators. For example, describing typical values and the trend in data can be addressed by measures of central tendency (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).

The segment diagrams for the median of the values of the impact indicators 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 (see Table 2 for a list of the management scenarios).

The scenarios placed in set 'a' show a better performance in relation to some of the impact indicators, while scenarios belonging to the second set 'b' cause an improvement in some other impact indicators. The most distinguishable characteristic of the scenarios placed in set 'b' (scenarios 16 to 32) is extending tree plantation on the terrestrial areas of the Little River catchment. In contrast, scenarios 1 to 16 do not carry out terrestrial tree plantation. Table 3 presents the key attributes of the four groups of management scenarios notable in this study.
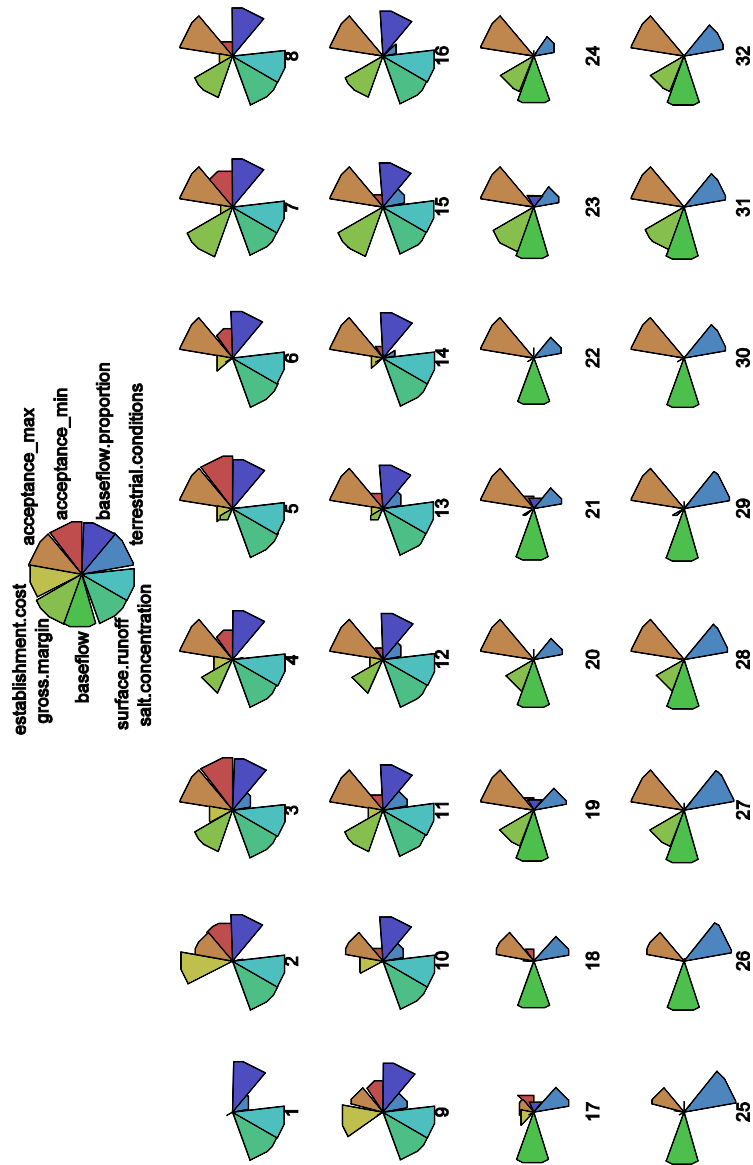
Figure 5. Median values of impact indicators for 32 salinity management scenarios in the Little River catchment

Table 3. Groups of salinity management scenarios for the Little River catchment

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

4. Discussion

The development of a decision analysis tool using the BDN approach for the Little River catchment has addressed the need for an integrated approach arising from the nature of environmental management, in general, and management of dryland salinity in the catchment, in particular.

The Little River catchment BDN decision support system has been prototyped to develop understanding of the system components and to provide a decision-making tool which can be used to run salinity management scenarios and explore the possible outcomes of the scenarios being tested. This, in turn, develops understanding of the trade-offs among various outcomes of management options, which is necessary for catchment management to be achieved.

The trade-offs represented in Figure 5 show that the contributions to various outcomes of the salinity management options differ among the 32 scenarios. That is, changes in the median values of the impact indicators from one scenario to another are not identical. Between the two sets of scenarios (scenarios 1 to 16 and scenarios 17-32) the changes are very different, indicating the large impacts of tree plantations in the Little River catchment on outcomes. A range of outcomes can be achieved in future by implementing different salinity management scenarios now.

Figure 5 also demonstrates that a limited envelope of outcomes from vegetation-based salinity management options will be feasible in the catchment and each set of outcomes from implementing one specific scenario is associated with costs in attaining the outcomes. The analysis provides a context for valuing vegetative salinity management options where multi-disciplinary outcomes are at issue.

The analysis of trade-offs also shows that there is no single or final solution to salinity management problems. This result is in agreement with that found by Nordblom *et al.* (2005) that due to the diversity in the factors influencing the characteristics of stream flow, good blanket solutions for managing the quality and quantity of stream flow can not be suggested. To reach informed and feasible decisions for salinity management the social and economic preferences and priorities, along with the ecological consequences of salinity management options need to be considered in quantifying the trade-offs among salinity management

outcomes. The BDN decision support system developed in this study meant to facilitate this process.

Multiple-course scenarios for management purposes in the catchment provide more choices to the farming community in the catchment. This type of scenario (see Table 2), with a wider range of activities and possible outcomes, would not only meet some of the salinity management requirements, but would also be likely to satisfy selectively some other social, economic, and ecological requirements and/or constraints.

Dryland salinity management is a field in which the number of variables and their interactions require management tools to integrate information and support decision-making. The BDN decision support system developed here has also addressed the problems encountered due to sparse and scattered bio-physical and socio-economic data. Finally, the BDN approach implemented in this study has served as a valuable tool to communicate uncertainty of the parameters in the BDN decision support system of the Little River catchment.

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