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A Bayesian network approach for assessing the sustainability of coastal lakes in New South Wales, Australia

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Abstract

Coastal lakes are ecosystems of significant value generating many ecological, social and economic benefits. Increasing demands resulting from urban development and other human activities within coastal lake catchments have the potential to result in their degradation and can lead to conflicts, for example between lake users and upstream communities. There are many techniques that can be used to integrate the variables involved in such conflicts including system dynamics, meta-modelling, and coupled component models, but many of these techniques are too complex for catchment managers to employ on a routine basis. The overall result is the potential to compromise the sustainability of these important ecosystems. This paper describes research to address this problem. It presents the development of an integrated model framework based on a Bayesian network (Bn). Bns are used to assess the sustainability of eight coastal lake-catchment systems, located on the coast of New South Wales (NSW), Australia. The paper describes the potential advantages in the use of Bns and the methods used to develop their frameworks. A case study application for the Cudgen Lake of northern NSW is presented to illustrate the techniques. The case study includes a description of the relevant management issues being considered, the model framework and the techniques used to derive input data. Results for the case study application and their implications for management are presented and discussed. Finally, the directions for future research and a discussion of the applicability of Bn techniques to support management in similar situations are proffered.
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Keywords: Bayesian network; Sustainability; Integrated assessment; Coastal lakes; Environmental management; Pathogens; Decision support

1. Introduction

Coastal lakes are ecologically important systems that support a diverse range of species, many of which are unique to their estuarine conditions. They generate a range of ecological, social and economic benefits, enjoyed in Australia by a large proportion of the community. Coastal lakes often play a significant role in regional economies through industries such as fisheries and tourism, and they are often of great importance to local communities. Unfortunately, increasing demands resulting from pressures such as urban development, agricultural intensification, recreational use, wetland drainage, industrial development and tourism have the potential to result in their degradation. The problem is compounded because although there are a range of integration techniques available, e.g. system dynamics, meta-models, and coupled component models (Letcher and Weidemann, 2004), these are often too complex to assist managers and policy makers to investigate holistically the balance between human activities and their environmental effects. This results in the potential to compromise the sustainability of these important ecosystems.

With recognition of the ecological, economic, social and cultural significance of coastal lakes and their sensitivity to human influences, it is essential that these lake systems be

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managed in a sustainable manner (Newham et al., 2004b). To do so, there needs to be an understanding of the processes and pressures affecting coastal lakes and the policy and institutional setting (Letcher and Giupponi, 2005 provide a discussion of catchment management policies and their impacts).

This paper describes the use of Bns for assessing the sustainability of social, economic and environmental values within coastal lake catchments. For other recent case studies of Bn use see Bromley et al. (2005), Little et al. (2004) and the following papers in this issue: Martin de Santa Olalla et al. (2007), Henriksen et al. (2007), Castelletti and Soncini-Sessa (2007a), Pollino et al. (2007) and Voie (Submitted for publication). The case study is a component of the Comprehensive Coastal Assessment (CCA) project requested by the NSW government, and it forms part of a pilot investigation that aims to assess the sustainability of eight coastal lakes on the New South Wales (NSW) coast, viz. Cudgen, Myall, Coila, Merimbula, Back and Burrill Lakes, Lake Wollumboola and Narrawallee Inlet. The paper describes the Cudgen Lake case study and focuses on how a Bn can be used to assist decision makers. It includes a description of the participation and integration activities and a selection of results from the study. A discussion of the direction of ongoing research in the context of the case study application is presented in the final section.

1.1. Bayesian networks

Bns consist of a series of nodes and causal links that are used to conceptualise a system under consideration (Pearl, 1988). Causal links represent the relationship between nodes using conditional probability tables (CPTs). Bns have several advantages as integrating frameworks including the ability to combine quantitative and qualitative data, explicitly consider uncertainty and they can be easily updated as new knowledge about a system becomes available (Castelletti and Soncini-Sessa, 2007b). A detailed description of Bns, and their pros and cons in participatory modelling can be found in Castelletti and Soncini-Sessa (2007b). Bns have been selected for this case study in preference to other integrative techniques because the method is an efficient means of integrating social, economic and ecological variables where each variable and process does not have to be explicitly represented at a common scale. Also, various methods can be used to generate the input data, with a varying degree of certainty in the CPTs. In this paper, we focus our attention on presenting a case study of Bn development to assist in the management of coastal lakes.

2. Case study: assessing the sustainability of Cudgen Lake

This section describes the application of the Bn approach for the Cudgen Lake and illustrates the sustainability assessment process. A brief background to the issues impacting on the lake and catchment are presented. This is followed by a description of the conceptual framework, which was developed in consultation with relevant stakeholders. Results from the study for several management actions are then presented.

2.1. Background: Cudgen Lake

Cudgen Lake (28°19′ S, 153°33′ E) is a shallow tidal back barrier lake located adjacent to the small town of Bogangar on the north coast of NSW, Australia, approximately 130 km south of the city of Brisbane. The Lake has a surface area of 1.7 km^2 and a catchment area of approximately 75 km^2. It is linked to the ocean via the narrow and meandering, 9 km-long, Cudgen Creek. Cudgen Lake has important environmental, social and economic values: the lake is used for a range of recreation activities; it has significant habitat value, for example adjacent to the lake is the Cudgen Nature Reserve which contains many threatened flora and fauna species; the catchment contains high value wetland areas and one of the largest remnants of littoral rainforest on the NSW coast; and it was once a renowned location for prawning and fishing. The Cudgen Plateau, situated on the hills above Cudgen Creek, is a highly productive vegetable cropping area, while on the flood plain between Reserves and Clothiers Creek, sugar cane production dominates (Fig. 2).

The sustainability of the lake-catchment system is under considerable threat. The impacts of the following factors have the potential to further threaten the sustainability of the lake and catchment system: increased urban development resulting from an expansion in population of the coastal zone (e.g. Shepherd, 2005); acid runoff from exposed acid sulphate soils resulting from the extensive drainage of land for agriculture and urban development; and sedimentation and eutrophication resulting from agricultural activities, particularly from areas used to grow vegetables and sugar cane.

Because of these pressures and community expectations of a consistent and transparent process of assessment, tools are required to assist local managers and policy makers (including State and Local Government and community-based management organisations) to investigate how to balance human activities and their environmental effects. Bns were selected as a potentially useful method to underpin these sustainability assessments.

2.2. Model construction process

The following sequential process has been used for the development of the Bn models for the Cudgen Lake system.

2.2.1. Review phase

The initial step in the model construction process was a review of relevant local, regional and state management plans and other scientific literature to build an understanding of the constraints, issues and drivers impacting on lake and catchment values important to the local community. As part of this review an initial Bn framework and series of possible management actions were identified.

2.2.2. Identification of Bn structure

The Bn framework and potential actions, developed during the review phase, were presented to stakeholders for discussion and to test that applicable management actions and community values of catchment sustainability were included. The

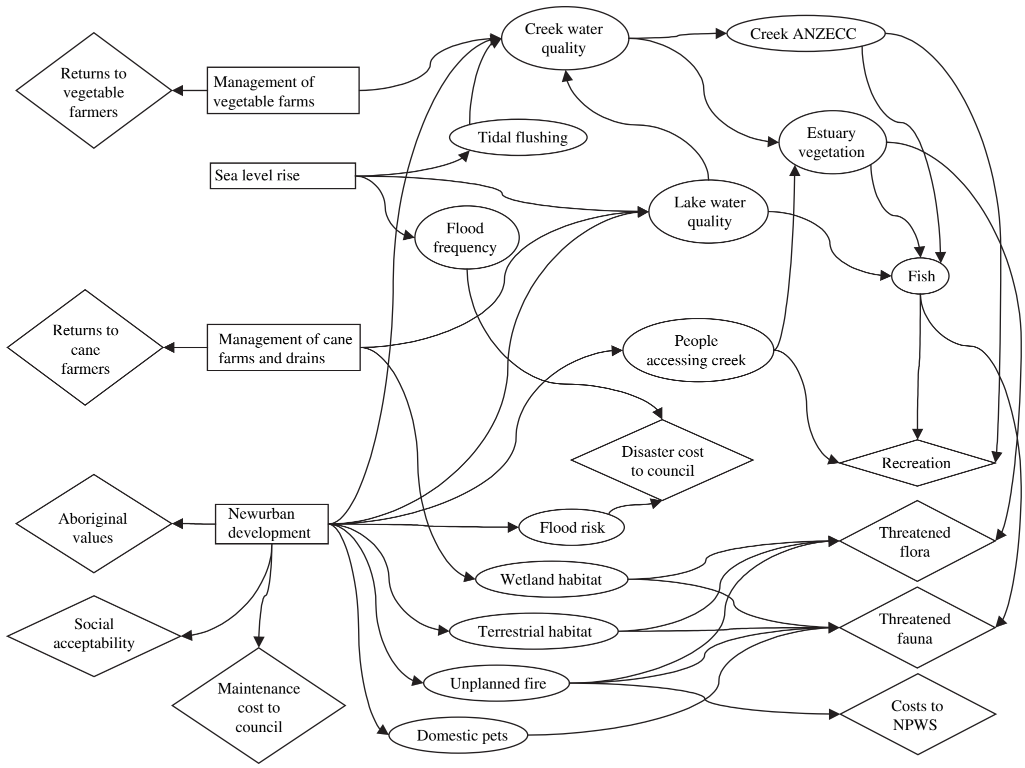

Fig. 1. The framework for the Cudgen Lake Bn following revisions made in consultation with stakeholder groups. NPWS − National Parks and Wildlife Service; ANZECC − Australian and New Zealand Environment and Conservation Council guidelines.

Bn framework and associated actions were reviewed by representatives from groups responsible for the management of the Cudgen Lake catchment through a series of workshops. The groups that were consulted included the Tweed Shire Council (Local Government), several NSW Government agencies, natural resource management consultants and local community leaders. The participatory activities were used to refine the conceptual framework and to clarify the types of actions to be included in the Bn. As a result of our participatory activities, several nodes considered redundant by these groups were removed, others were added to enable consideration of a broader range of values and actions.

The original Bn is not shown here, but the revised version, shown in Fig. 1, can be viewed as an example. The framework

Table 1
Description of the Decision nodes of the Cudgen Lake Bn, and their output states

Decision node	Descriptions	Management action options
Management of vegetable farms	Management options for the vegetable cropping area on the Cudgen Plateau	No change, inclusion of buffer strips within crops, 10% reduction in fertiliser application, inclusion of buffer strips within crops and 10% reduction in fertiliser application
Management of cane farms and drains	Management options for the sugar cane are on within the catchment	No change, improved system (laser levelling, water pumping to maintain the water table above potential acid sulphate soils, stubble retention and incorporation of crops
New urban developments	Urban development for areas known as Hansen's, Kings Forest, Seaside City, Cudgen Paddock, Rural residential, SALT and Tanglewood	All combinations of: • No change, low density and medium density for Kings Forest and Cudgen Paddock • No change and low density for Tanglewood and Seaside City • No change and medium density for Hansen's • No change and 8 people/ha for rural residential, and • No change and increased buffers around the SALT development. • The option of increasing current development restrictions of no weed species or domestic pets, and increased riparian buffers (50 m) available for all new developments
Sea level rise	Change in the sea level height given various predictions for rise	No change, predicted levels for the year 2030, 2050 and 2100

The baseline decision option is to remain under the current management conditions (No change). Note that sea level rise is included in the table as a decision node; however, it is more correct to think of it as a scenario node as sea level is essentially uncontrollable in the context of the Cudgen case study.

has been simplified for presentation in this paper. For example lake water quality is represented as a single node in Fig. 1, but in the Bn framework it includes six individual nodes: nitrogen, phosphorus, suspended sediment, pathogens, acidity and salinity. The revised action options for the decision nodes and the output states for the state and utility nodes are described in Tables 1–3, and should assist in interpreting the Bn.

The community values represented by each node are spatially based with temporal aspects accounted for in the detailed definition of what each node represents. For example, detailed in Table 2, the lake water quality (pathogens) node was defined as the probability that on any given day during a year the pathogen concentration would fall into the given output states. Future work intends to explore the importance and sensitivity of the model to its current static state, and explore the benefits of actively running temporal models with the Bn structure.

The participation of stakeholder groups in the process of identifying the Bn structure ensured that due consideration was given to information availability, i.e. relevant local knowledge, management reports and scientific literature. It also ensured that the links between management options and community values were consistent with stakeholder expectations and needs.

2.2.3. Action development

The decision nodes described in Table 1 represent a summary of the actions that can be investigated in the Cudgen Lake Bn. The base case option is for the actions to remain the same as current conditions. The individual actions that

Table 2
Description of the State nodes of the Cudgen Lake Bn, and their output states

State node	Description	Output states
Creek ANZECC	Expected exceedence of the ANZECC guideline thresholds	Healthy ecosystem, No aquaculture, No primary contact, No secondary contact.
Creek water quality	Nitrogen: The annual nitrogen load to the creek	<2000 kg/yr, 2000–4000 kg/yr, 4000–6000 kg/yr, 6000–8000 kg/yr, >8000 kg/yr
Creek water quality	Phosphorus: The annual phosphorus load to the creek	<600 kg/yr, 600–800 kg/yr, 800–1000 kg/yr, 1000–1200 kg/yr, >1200 kg/yr
Creek water quality	Suspended sediment: The annual suspended sediment load to the creek	<6 mg/L, 6–10 mg/L, 10–20 mg/L, >20 mg/L
Creek water quality	Pathogen: The likely lake pathogen concentration on any given day in a year	<14 cfu/100 ml, 14–150 cfu/100 ml, 150–1000 cfu/100 ml, >1000 cgfu/100 ml
Creek water quality	Acidity: The average pH of the creek	pH > 8, 6–8, 5–6, <5
Creek water quality	Salinity: The median salinity in the creek	<18.5 ppt, 18.5–21.0 ppt, 21.0–26.0 ppt, >26 ppt.
Domestic pets	Change in the number of cats and dogs kept by residents in the catchment	Decrease, no change, increase
Estuary vegetation	Change in valued estuary vegetation such as seagrass and salt marsh	>10% decrease, <10% decrease, no change, <10% increase, >10% increase
Fish	Change in the fish population in the lake and creek	Decrease, no change, increase
Flood frequency	Change in the frequency of floods above the 1 in 100 year flood line	Decrease, no change, 5% increase, >5% increase
Flood risk	The risk of infrastructure being flooded given its location	Decrease, no change, increase
Lake water quality	Nitrogen: The annual nitrogen load to the lake	<2000 kg/yr, 2000–4000 kg/yr, 4000–6000 kg/yr, 6000–8000 kg/yr, >8000 kg/yr
Lake water quality	Phosphorus: The annual phosphorus load to the lake	<600 kg/yr, 600–800 kg/yr, 800–1000 kg/yr, 1000–1200 kg/yr, >1200 kg/yr
Lake water quality	Suspended sediment: The annual suspended sediment load to the lake	<6 mg/L, 6–10 mg/L, 10–20 mg/L, >20 mg/L
Lake water quality	Pathogens: The likely lake pathogen concentration on any given day in a year	<14 cfu/100 ml, 14–150 cfu/100 ml, 150–1000 cfu/100 ml, >1000cgfu/100 ml
Lake water quality	Acidity: The average pH of the lake	pH > 8, 6–8, 5–6, <5
Lake water quality	Salinity: The median salinity in the lake	<2.4 ppt, 2.4–2.7 ppt, 2.7–3.4 ppt, >3.4 ppt
People accessing creek	Change in the number of people who access the creek annually	>10% decrease, <10% decrease, No change, <20% increase, >20% increase
Terrestrial habitat	Change in the area and quality of bushland	>10% decrease, <10% decrease, no change, increase, does not consider impacts from water quality
Tidal flushing	Change in the annual volume of water exchanged with the ocean	No change, 1–5% increase, 5–10% increase, >10% increase
Unplanned fire	The number of occurrences of unplanned and unauthorised fire within the Cudgen Nature Reserve	Decrease, no change, increase
Wetlands habitat	Change in the area and quality of wetlands	>10% decrease, 5–10% decrease, <5% decrease, no change, <5% increase, >5% increase. Does not consider water quality impacts

Table 3
Description of the Utility nodes of the Cudgen Lake Bn, and their output states

Utility node	Description	Output states
Aboriginal values	Impact on the current values of Aboriginal people including both physical heritage and landscape significance	>25% decrease, <25% decrease, No change, <25% increase, >25% increase
Cost to National Parks and Wildlife Service	The annual value, including staff salary and direct financial outlay, required to fight fires within and surrounding the Cudgen Nature Reserve	<5% increase, 5–15% increase, 15–25% increase, >25% increase
Disaster cost to council	Change in the cost to council for the amelioration of infrastructure and services following a natural disaster	Decrease, no change, <5% increase, >5% increase
Maintenance cost to council	Change in the annual cost to the council for general maintenance of services	No change, 0–50% increase, 50–100% increase, >100% increase
Recreation	Change to the number of people swimming and fishing in the Cudgen Creek entrance during a 12-month period	>20% decrease, 5–20% decrease, NO change, 5–20% increase, >20% increase
Returns to cane farmers	Average change in the annual gross margin per hectare for cane farmers	>100% reduction, 100% to 50% reduction, 50% to 10% reduction, no change, 10% to 50% increase, 50% to 100% increase, >100% increase
Returns to vegetable farmers	Average change in the annual gross margin per hectare for vegetable farmers	>100% reduction, 100% to 50% reduction, 50% to 10% reduction, no change, 10% to 50% increase, 50% to 100% increase, >100% increase
Social acceptability	Qualitative measure of the public support of proposed actions (here new urban developments)	Not acceptable, Slightly acceptable, Moderately acceptable, Highly acceptable
Threatened flora	The number of threatened flora that will become increasingly vulnerable	large increase (>20%), small increase (5–20%), no change, small decrease (5–20%), large decrease (>20%)
Threatened fauna	The number of threatened fauna that will become increasingly vulnerable	large increase (>20%), small increase (5–20%), no change, small decrease (5–20%), large decrease (>20%)

can be implemented are quite detailed and very often spatially explicit. For example, there are several potential areas for urban development, and each is modelled as a separate action. A total of 18,432 unique action combinations can be modelled in the case study application, calculated from the number of action options for each decision node (Table 1). Although sea-level rise cannot be controlled by catchment managers, it is included as an option action in this tool so decision makers can explore the impact of various sea level changes on their decision. All combinations are possible, but their feasibility may be dependent on the resources and goals of the user and other physical catchment constraints such as the location of existing infrastructure.

2.2.4. Populating conditional probability tables

The nature of the actions being simulated resulted in the need to obtain and integrate a substantial amount of information. It is not practical to provide detailed descriptions of the methods used to populate all the CPTs for the Cudgen Lake Bn in this paper, but this information is presented in the software tool. Instead the following is a general discussion on the various methods used to populate the CPTs for the Cudgen Lake Bn.

The Cudgen CPT data was derived by a combination of means: data analysis; literature review; simulation using existing models; or expert opinion. Model simulation and data analysis were generally used to generate quantitative data while expert opinion and literature reviews, generated qualitative inputs.

The models used for simulation varied in complexity. Simple models used included a general bucket model of soil water content. A more complex modelling technique was used to estimate the CPTs for the lake pathogen concentrations (Ferguson et al., in press) and the water quality (Baginska et al., 2004). The probability of the input values was predetermined from data analysis (e.g. the probability of a defined sized rainfall event), and the model was run using all possible combination of the input values. The joint probabilities were used to determine the CPTs of the model outputs. In other cases the model inputs were varied within the expected ranges identified by experts and the literature to generate the CPTs. The model would typically be run 5000 times with the input values selected randomly within the defined range. The output results were then used to determine the CPT.

Expert opinion was gained through various means depending on how confident the expert was about the specific topic. In some cases a formal questionnaire was derived from the input links and output state requirements, and the expert estimated the CPT for each of the input links. While in other cases the experts were reluctant to generate the CPTs, but were happy to review completed questionnaires for inaccuracies. Alternatively a general discussion could be had with the expert, and the information gained was interpreted into a CPT, which was then rechecked. In some cases the experts used to generate and review CPTs were also catchment stakeholders who were involved in the initial development of the Bn. This is not optimal but in many cases valuable complex information is held by locals who have extended practical experience in the area.

Field monitoring to generate input CPTs was outside the scope of this project. Some existing data sets were used (e.g. rainfall) but other suitable monitoring data was difficult to access in the time available for the construction of the Bn.

This approach to Bn development can assist in targeting future research through identifying nodes that were only

Table 4
Action options explored in this paper

Action number	Action description
1	Base case scenario with current management conditions
2	Cudgen Paddock urban development at medium density
3	Kings Forest urban development at medium density
4	Cudgen Paddock and Kings Forest urban developments at medium density
5	20 ha rural residential development in the upper catchment
6	Best management practice for ecological purpose. Includes buffer strips and 10% reduction in fertilizer application, 100% change to new drain management system, no new urban developments, increased riparian buffer widths around new coastal developments

understood through expert opinion rather than through data analysis or detailed model simulation.

2.2.5. Model validation and verification

The Bn as a whole has not been systematically verified or validated. This is because the integrative nature of the framework means there is not a single time series or other data set available to validate the whole model. Also, given the model is run to investigate the future impact from management decisions, data cannot exist for validation until such management changes have been implemented. Instead the model and input data for each of the nodes have been validated using existing data for current conditions, where possible, but at least through review by local experts. Validation of the whole Bn is completed in a less systematic way through the use of the tool by experts and local stakeholders to check that the model is behaving as expected. This process is completed during the training workshops for the stakeholders.

Future research of the Bns developed here will include sensitivity analysis of the model structure in order to determine if the information gained is altered by the structure. Also tests will be carried out to determine what level of certainty is required in the CPT data for a decision to be made. This will test whether contributing a substantial amount of resources to improve the certainty in CPTs will actually change the output decision made by the user.

2.2.6. Software and distribution

The Cudgen Lake Bn was incorporated into a user-friendly software platform to enable application and testing by stakeholders. The Bn was programmed in the Interactive Component Modelling System (ICMS) (Reed et al., 2000) using its embedded and simple C-like language. The model building component ICMSbuilder provides an efficient drag and drop method to construct Bns with each node having the appropriate model attached (Cuddy et al., 2002). A 'plugin' for ICMS was programmed using Delphi language to act as a simple user interface and communicate with the Bn in ICMS. Other example applications of ICMS in environmental modelling include Newham et al. (2004a) and Cuddy et al. (2002).

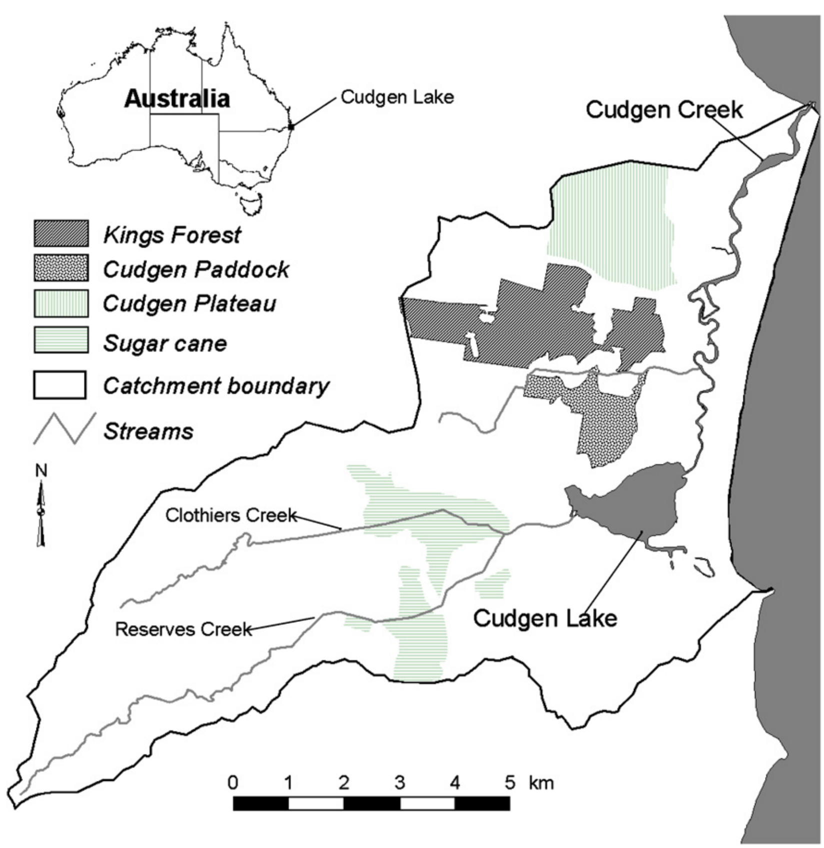

Fig. 2. Location of the Cudgen Lake catchment, showing actions, agricultural regions and waterways referred to in the text.

The Bn is currently being distributed to stakeholders with appropriate training in its use. This will enable the stakeholders to update scenario actions, nodes and data so the tool can remain current and useful.

2.3. Results: Use of the Bn

There are a large number of available results due to the complexity of the Cudgen Lake Bn and the large number of possible actions. It is impossible to discuss them all in this paper. Instead, we present a subset of the results and discuss how the Bn results can be used to assist in the management of Cudgen Lake.

Details of the actions explored in this application are given in Table 4. Action 1 is the base case action where all conditions are kept at their current state of management. Actions 2 and 3 refer to urban developments shown in Fig. 2 developed at a medium density, while Action 4 shows the impact if both those developments were completed. The rural residential scenario addressed in Action 5 has not been located on the map because there is not any land in the upper catchment zoned and planned for rural residential development, so it has been included only as a hypothetical comparison. The 'best case' scenario (Action 6, Table 4), captures management actions available to improve the environmental quality of the lake and its catchment. The impact of the actions upon selected nodes is reflected by a change in the output CPT compared to the base case. The output CPTs, presented as bar charts, for several nodes are shown in Figs. 3–5.

The *Cudgen Paddock* development (Action 2) marginally increases the likelihood of a greater nitrogen load to the lake, shown in Fig. 3. One might expect a larger change in the nitrogen load to the lake given that the current land use of the area zoned for this development has a typical nitrogen loading of 1.0–1.5 kg/ha/yr, while a medium density development has 6.1–12.0 kg/ha/yr (Baginska et al., 2004). However,

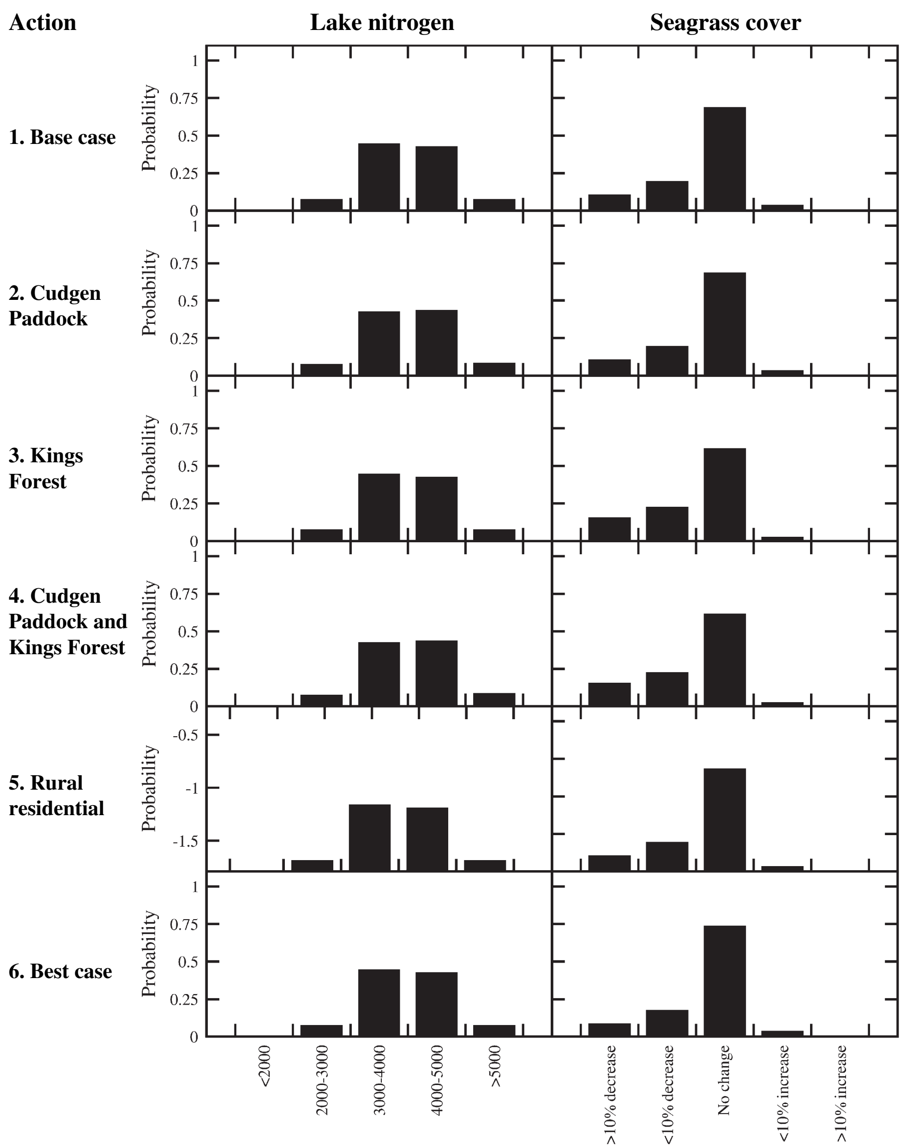

Fig. 3. CPTs, represented as distributions, for the nitrogen load into Cudgen Lake and the seagrass bed cover given the management actions.

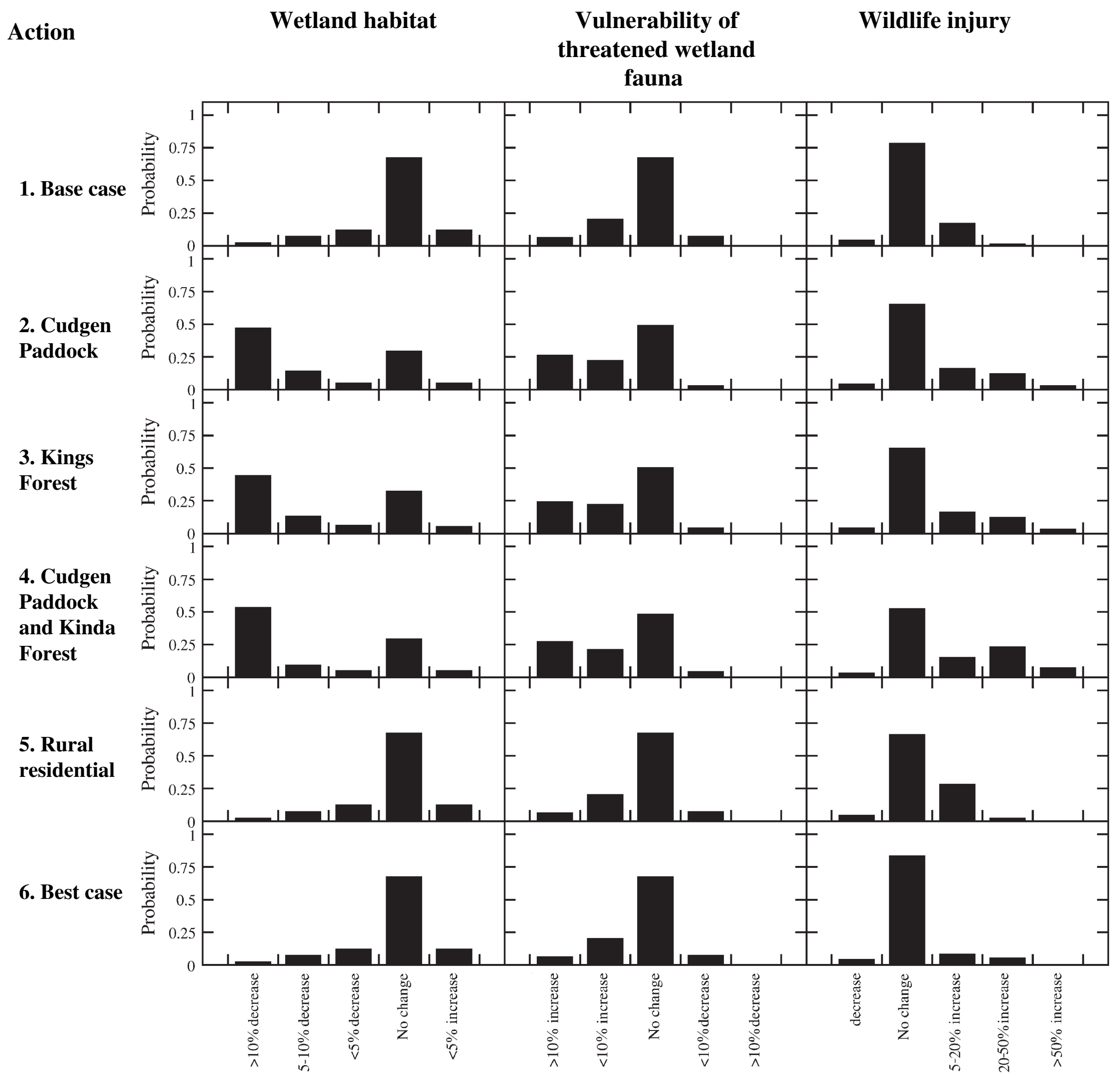

Fig. 4. CPTs, represented as distributions, for wetland habitat, vulnerability of threatened wetland fauna and wildlife injury given the management actions.

at the scale of modelling used here the key determinant on the nitrogen load is the area of the catchment under a particular land use, and Cudgen Paddock is less than 3% of the area of the Cudgen Lake catchment. A more detailed model may be used to reflect the proximity of the Cudgen Paddock development to the lake, which may lead to greater certainty in an increase in nitrogen load.

The *Kings Forest* development (Action 4) has no impact upon the nitrogen load delivered to the lake. This is because the Kings Forest development, as shown in Fig. 3, is located in the Cudgen Creek catchment, rather than the lake catchment, and the current model structure does not allow for the creek water quality to impact upon the lake. However, lake water quality is modelled to affect creek water quality. This should not be misinterpreted to mean that the Kings Forest development does not impact upon the quality of the Cudgen waterways.

Thus the impact on nitrogen load from the combined Cudgen Paddock and Kings Forest developments is the same as that for Cudgen Paddock alone.

The seagrass cover is more likely to decline by more than 10% if the Kings Forest development proceeded, and consequently if the Kings Forest and Cudgen Paddock developments proceeded, but the Cudgen Paddock development on its own does not reflect any impact upon the seagrass cover (Fig. 3). This is likely to be because the Cudgen Paddock development is mainly in the Cudgen Lake catchment, while the seagrasses are mainly along the Cudgen Creek. Therefore the potential impact on the creek water quality and therefore the seagrass cover is quite different to the Cudgen Paddock development. The 'Best Management' action is more likely to maintain the seagrass cover through improving the water quality in the Cudgen Creek.

Cudgen Paddock and Kings Forest are both situated upon wetland habitat, thus by developing those locations is likely to decrease the wetland habitat in the Cudgen Lake and Creek catchments (Fig. 4). This causes an increase in the vulnerability of threatened wetland fauna in the region. These urban developments are also likely to increase the number of wildlife injuries in the catchment due to increases in traffic. Therefore

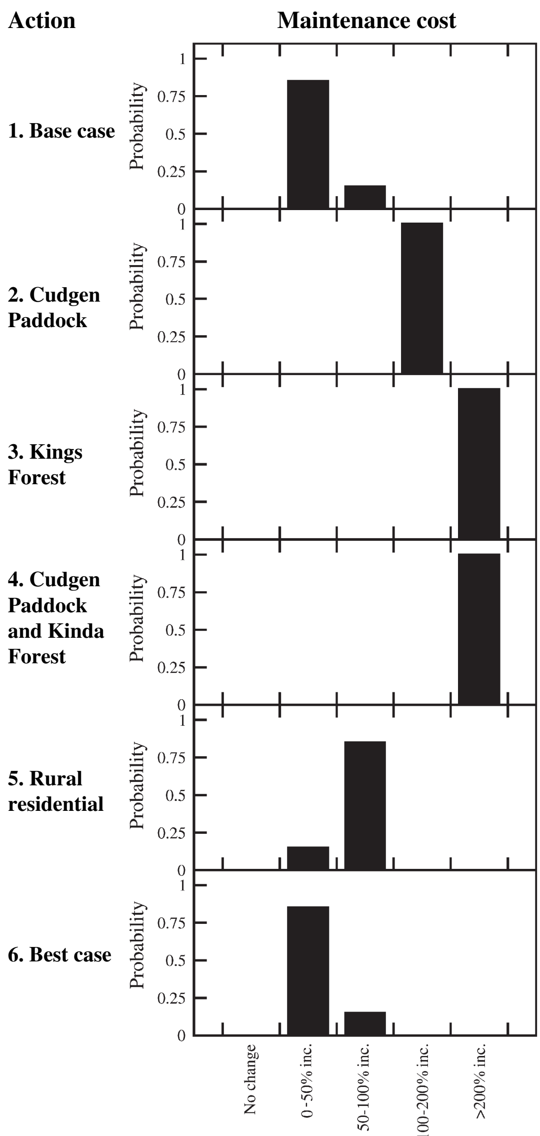

Fig. 5. CPTs, represented as distributions, for maintenance costs to council given the management actions.

although the impact upon the water quality and associated habitats may be minimal from the developments discussed here, the impact upon wetland fauna is distinct.

The rural residential development in the upper catchment has a smaller likelihood of increasing wildlife injury compared to the other urban developments discussed here (Fig. 4). This is likely to be because the urban developments are located closer to the water sources and Cudgen Nature Reserve, which provide valuable wildlife habitat.

All actions show an increase in the maintenance cost to council (Fig. 5). In the base case action the probability distribution shows a definite increase in maintenance costs to council. This is the case because there are developments along the coastline currently under construction, and following completion and occupation, Council will be required to maintain these. The *rural residential* development will not require as much maintenance cost as the other urban developments. This is likely to be because the rural residential population likely to be less than 200, while the Kings Forest and Cudgen Paddock developments are over 13000 and over 4000 people respectively, and a larger development would require more council resources. The cumulative impact of both the Cudgen Paddock and Kings Forest development on the maintenance costs is not reflected here because the Kings Forest development independently generates a probability of 1 in the highest output state defined. This means there is not any capacity for the probability of the cost to increase. Increasing the number of output states for the maintenance costs might shows a cumulative impact from these developments.

Table 5 shows a summary of the model outputs discussed above. From this study the Cudgen Paddock and Kings Forest developments are likely to have a negative impact upon many ecological values within the Cudgen Lake and Creek catchments. The Rural Residential option has fewer negative impacts, which may make it a more desirable development option. However the rural residential option only accommodates a small fraction of the potential population in the Kings Forest and Cudgen Paddock developments.

The 'best case' management action shows improvement in seagrass cover and wildlife injury, with a small increase in maintenance costs, most likely from the increase in riparian zones around existing developments. However, the 'best' management practice comes at a higher cost to the catchment, seen mainly through a decrease in gross margin for the vegetable farmers, shown by the values given in Table 6. Catchment managers would need to consider whether the preservation of ecological values is more valuable than the gross margin for the vegetable farmers, and increased development.

Perhaps more importantly the user should interrogate the reliability of the input information for the nodes of interest (available in the software tool). This shows that the information on nitrogen loads, as mentioned above, is from course

Table 5
Summary output table for the impact on the nodes for each action (Table 2)

Action number	Lake nitrogen	Seagrass	Wetland habitat	Wetland fauna	Wildlife injury	Maintenance cost to council
1	0	0	0	0	0	–
2	–	0	–	–	–	–
3	0	–	–	–	–	–
4	–	–	–	–	–	–
5	0	0	0	0	–	–
6	0	+	0	0	–	–

0 = no change, – = negative impact, + = positive impact.

Table 6
Summary the monetary utility nodes for the actions explored in this investigation

Action number	Vegetable Farmers GM ($/yr)	Cane farmers GM ($/yr)	Increase in cost to NPWS	Disaster cost to council ($)	Maintenance cost to council ($/yr)	Total change ($)
1	0	0	−67	−16	−24471	−24554
2	0	0	−119	−19	−112946	−113084
3	0	0	−119	−19	−263541	−263679
4	0	0	−172	−23	−263541	−263736
5	0	0	−105	−16	−50826	−50947
6	−162476	46173	−67	−16	−24471	−140857

GM, gross margin; NPWS, National Parks and Wildlife Service.

scale modelling, the maintenance costs to council and the wildlife injury is developed from the analysis of existing data, and the information on the change in seagrass cover, wetland habitat and the vulnerability of threatened wetland fauna has been derived through assumptions and expert opinion. Thus the certainty in the impact of the urban developments upon the ecological values may not be considered to be high enough to make a decision. More detailed studies on these ecological values may show that the ecological impact is minimal, or that with added precautions the developments could proceed.

3. Discussion and conclusions

The coastal lakes of NSW and their associated catchments are ecologically important systems that face growing pressure from human activities. They require careful management to ensure their long-term sustainability. For this purpose, managers need to be able to balance often conflicting pressures and to evaluate the impacts of management changes on environmental, social and economic values. However, there are few tools available to assist in this difficult process. The paper has presented modelling techniques that assist in addressing this significant gap.

The use of Bn techniques affords several advantages as integrating frameworks, including the ability to combine quantitative and qualitative data from a range of sources, explicitly consider uncertainty and easily update the modelling as new knowledge becomes available. They can be represented by a conceptualised system, and do not require the explicit representation of all processes in the system (Borsuk et al., 2004). Thus, the complexity of the system can be represented without the need to integrate processes at different scales, but only at the separate scale of behaviour recognition for each process. Using CPTs to populate the links inherently implies the uncertainty in the results (Sadoddin et al., 2005). This characteristic is also reported in Castelletti and Soncini-Sessa (2007b), where it is shown that Bns implicitly account for 'process error'. Representation of uncertainty in results is a concept that is becoming increasingly important for modelling in support of decision-making.

Once the states of the input links of a node are known, the CPTs for it can be determined without relying on instantiation of the input data. Thus the CPT for each node could be considered independent, so the distribution can be populated using the best information available for that particular node. In this respect Bns have the advantage of being able to integrate a range of data types in a single conceptual system. The independence of each link also means that the population densities behind them can be easily updated following an increase in available data, or policy changes (Walters, 1986). Importantly, the quality of the data used can be reported in the output of the model. This feature can assist users to determine the level of confidence that they might have in the outputs and assess where more detailed information is required to improve predictions.

The application of Bn techniques using a case study of Cudgen Lake shows that model development requires careful consideration of relevant management issues, participation with a broad range of interest groups and the synthesis of a combination of observed data, model simulation and expert knowledge into a single model framework. The Bn approach described here enabled the rapid and comparatively easy integration of complex and diverse processes. It also allows the potential for the adaptation of the conceptual model structure and the CPTs as new knowledge and preferences for actions become available.

The Bn tool presented in this paper is not a finished product, but an initial attempt to assist catchment managers in making more informed decision to management their coastal lake catchments. The tools are designed so that the stakeholders can take ownership of them, and with training, can update the data and framework to meet their needs.

Future research into the Bns developed here will include sensitivity analysis of the model structure in order to determine if the information gained is altered by the structure. Also, tests will be carried out to determine what level of certainty is required in the CPT data for a decision to be made. This will test whether contributing a substantial amount of resources to improve the certainty in CPTs will actually change the output decision made by the user.

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