DECISION FRAMEWORK FOR NATURAL DIVERSITY PROGRAM

SCOPING PROJECT

FINAL REPORT

TO THE DEPARTMENT OF CONSERVATION AND LAND MANAGEMENT

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1.0 INTRODUCTION

1.1 Background

Despite widespread vegetation clearance for agriculture (George e*t al.* 1995) and related hydrological change (Ferdowsian *et al.* 1996), recent surveys of the Western Australian wheatbelt revealed a surprising biological diversity (Halse *et al.* 2004, McKenzie *et al.* 2004). A substantial public investment for the conservation of this biological diversity where it is threatened by salinity involves identification and management of a suite of natural diversity recovery catchments (Wallace *et al.* 2003, Walshe *et al.* 2004).

The key aim of the Department of Conservation and Land Management's (CALM) natural diversity recovery catchments is to protect high priority biodiversity assets, particularly wetlands, that are at risk from salinity, and which are regionally [1] significant. In addition, work in recovery catchments will contribute to the development of technologies to combat salinity throughout the agricultural region.

Recognising the complexities and uncertainties associated with achieving these aims, CALM seeks to develop a decision framework that:
(a) Takes into consideration hydrological and other threatening processes in recovery catchments;
(b) Provides a method for combining outputs from complex models and expert judgements in decisions;
(c) Allows the feasibility, costs and risks of management options to be compared; and
(d) Documents the decision process and the underlying assumptions and resources used to make specific decisions within the total decision process.

This report documents findings in relation to the brief of this scoping project, which sought:
1. Explanation of logic trees and their potential for decision-making to officers involved in the natural diversity recovery catchments; and
2. Development of draft logic trees for hydrological decisions in natural diversity recovery catchments.

1.2 Environmental decision-making under uncertainty

Possingham (2001) lists seven stages in the application of a decision theory approach to biodiversity issues.
1. Specify the management objective
2. List the management options (the decision variables)
3. Specify the current state of the system
4. Develop a model of the dynamics of the system being managed.
5. Specify constraints that limit the decision variables
6. Be honest about what we don't know (specify ranges of uncertainty)
7. Find solutions to the problem

Pannell (2003) suggests ecological science and management has particular problems with steps 1 and 4, and emphasises the need to investigate the sensitivity of the solutions to changes that reflect our uncertainty about the parameters of the problem.

A range of candidate management actions aimed at mitigating risks posed by elevated salinity levels and waterlogging/flooding could be considered for any recovery catchment, including water diversion structures, enhanced water storage, groundwater pumping, agronomic change, revegetation with perennials, and the protection of remnant native vegetation. The selection of a subset of these candidate actions for implementation in an individual catchment would ideally be informed by detailed

[1] Note that the region in this case refers to that part of the south-west agricultural zone of WA where dryland salinity is an important environmental issue.

knowledge regarding (a) current and future hydrological spatial and temporal trends across the landscape; and (b) the ecological and physiological sensitivity of the biota to those trends. However, both these aspects of the decision problem are characterised by high uncertainty.

Although coarse trends in salinity have been predicted for the wheatbelt over 50 year time scales (National Land and Water Resources Audit 2000), the management of recovery catchments requires higher resolution information at a more local scale. The load and concentration of salt and the volume of water affecting conservation values needs to be considered in a broader hydrological context that includes evapotranspiration, rainfall, surface runoff and groundwater dynamics. These hydrological elements are variable and uncertain, even where water balance models provide a general understanding (Hart *et al.* 2003).

The capacity of management interventions to reverse salinity trends is difficult to predict. Pannell (2001) notes how management recommendations arising from our hydrogeological understanding as recent as the 1980s and 1990s suggested the careful placement of small pockets of perennial vegetation in recharge zones would be sufficient to halt environmental degradation. Contemporary understanding suggests that, in many circumstances, considerably larger proportions of the landscape require treatment where plant-based solutions are pursued. The selection of management interventions also needs to be mindful of time lags between implementation and positive change. If conservation values are threatened in the immediate term, the responsiveness of plant-based approaches may need to be augmented with engineering approaches. Again, there is much uncertainty surrounding the exact nature of these dynamics.

Uncertainty in decision-making can be adverse or favourable. Adversity refers to the risk of failure, while favourability concerns the possibility of sweeping success. Where uncertainty is not explicitly documented in a decision problem, poor management options that ignore risks and opportunities are likely to ensue. For example, the hypothetical scenario depicted in Figure 1 involves three alternative management strategies with different probabilities of success and varying confidence in the inference of success. If uncertainty is ignored, Strategy 3 will be selected, however the relatively high uncertainty associated with this option may expose the investment to unforseen and intolerable risk. When presented with the range of uncertainty, a risk-averse manager may choose Strategy 2. The opportunity for sweeping success may make Strategy 1 attractive to a manager with an appetite for risk. Where the magnitude of uncertainty associated with one or more alternative management strategies is considered too high, a decision can be deferred until further information is obtained through research or monitoring. Of course, all strategies need to be considered against the option of doing nothing, and the costs and feasibility associated with their implementation.

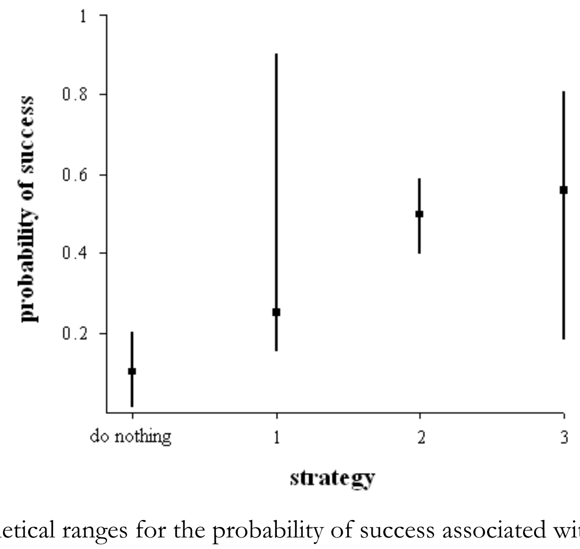


Fig 1 Best estimates and hypothetical ranges for the probability of success associated with three alternative management strategies relative to the option of 'do nothing'.

Although management decisions involving resource allocation can always be improved through access to better information, the collation of error free data is constrained by time and cost. The synthesis of knowledge and uncertainty in a decision theory framework is necessary for effective and robust investment of conservation resources (Possingham 2001). This report explores the utility of simple tools described and developed by Burgman (2005), Hart *et al.* (2004), and Walshe *et al.* (2005) that explicitly account for uncertainty in providing risk-based decision-support.

The remainder of this report comprises three sections. In the next section, an outline of the principles of ecological risk assessment is provided, and a protocol for the use of simple, subjective and more detailed quantitative risk assessment tools is outlined. In Section 3, logic trees and associated extensions developed with CALM staff for each of the six recovery catchments are presented. The last section discusses the utility of risk-based approaches to decision-making and emphasises future needs in research and development.

2.0 ECOLOGICAL RISK ASSESSMENT

2.1 Overview

The prominence of uncertainty in planning and management for recovery catchments suggests a suitable decision-support framework would build on approaches to risk assessment. Risk assessment has been a common element of planning and management in occupational health and safety, engineering and process industries for several decades, and an Australian Standard has been developed for its application (AS/NZ 4360; AS/NZS 2004).

Ecological Risk Assessment (ERA) is the process of estimating likelihoods and consequences of the effects of human actions or natural events on plants, animals and ecosystems of ecological value, that is, the study of risks to the natural environment (Barnthouse and Suter 1986). This is not as straight-forward as it might appear. The multitude of perspectives that people bring to the environmental debate makes it difficult to clearly identify ecological values of broad social relevance (Pannell 2004). Even where values are unambiguously identified, the task of estimating the likelihood and consequences of various hazards is hampered by the ignorance and uncertainty that characteristically accompanies our scientific understanding of ecological systems.

Steps involved in the continuous improvement cycle underpinning the Australian Standard are illustrated in Figure 2, and include

- *Establishing the context* - identifying important ecological values and defining the scope of the assessment,
- Identifying relevant hazards, threats or stressors,
- *Analysing the risks* – the consequences and likelihood for each of the hazards,
- *Evaluating the risks* where the risks are compared, ranked and prioritised in terms of their seriousness with respect to the management objectives identified in the initial problem formulation.

The information from the risk assessment then feeds into a decision-making process that includes economic, social and political inputs, to develop a risk management plan, including a robust monitoring program to provide information on the success (or otherwise) of management actions and a review process to ensure the management plan is upgraded as knowledge improves and priorities change.

After identifying important ecological values and defining the scope of the assessment, hazard elicitation involves generating an exhaustive list of processes or events that might compromise identified values or assets. The hazards listed by an analyst that conducts ERA alone will be limited to the personal experience and professional bias of the individual. Although better lists can be generated through the collective insights of a group of experts from varying disciplines, access to a breadth of expertise is limited for regionally-based recovery catchment planning. To help overcome this limitation, a generic hazard matrix has already been developed as a 'checklist' for assessing catchment assets (Wallace *et al.* 2003; Appendix A). The generic matrix can be used to further stimulate the thinking of recovery catchment officers in the elicitation of hazards specific to their catchment. In Table 1, a selection from a list of hazards elicited for the Muir-Unicup recovery catchment is shown. The relevance of each hazard to each of five hypothetical assets is indicated by a cross.

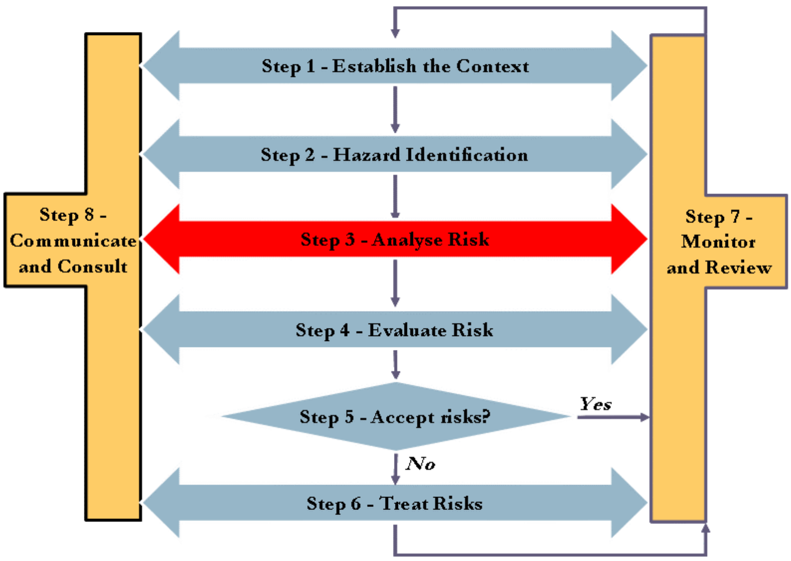


Figure 2 The risk management cycle (Source: AS/NZS 4360). The risk analysis stage is the central emphasis of case studies explored in Section 3 of this report.

Table 1. An example of a hazard matrix which can be used as a checklist for considering all potential hazards, threats or stressors that might impact an asset, A. The hazards listed in the table were elicited for the Muir-Unicup recovery catchment with assistance from Roger Hearn, Department of Conservation and Land Management. The assets, $A_1 - A_5$ are hypothetical.

Hazard	A_1	A_2	A_3	A_4	A_5
Hydrologically related					
Salt concentration		×		×	×
Acidity	×	×			
pH mediated toxicity	×				
Aseasonal wetting				×	
Aseasonal drying			×		
Inundation		×		×	×
Drought stress			×		
Nitrogen toxicity	×				
Eutrophication	×				×
Turbidity or sedimentation	×				×
Low dissolved oxygen	×				×
Non-hydrologically related					
Inappropriate fire regime		×			
Phytophthora			×		
Biocides	×				
Weed invasion or introduced species				×	
Grazing – native herbivores			×		×
Grazing – non-native herbivores			×		×

The outcomes of a risk analysis can inform where investment in management action is warranted and where it is of low priority. Where uncertainty is high, it can also identify knowledge gaps that might require research or monitoring. Risk analysis under the Australian Standard 4360 involves subjective use of a matrix that defines the risk of a hazard as the product of its consequence and likelihood (Table 2).

Table 2. The Australian Standard 4360 suggests use of semi-quantitative descriptors of consequence and likelihood to enable clearer ranking of risks. In the table below, an ordinal scale of five levels is used to describe the likelihood and consequence of a hazard. Unshaded = low risk, light grey = moderate risk, dark grey = high risk.

Likelihood		**Consequence**				
		Insignificant **(1)**	Minor **(2)**	Moderate **(3)**	Major **(4)**	Catastrophic **(5)**
Almost certain	**(5)**	5	10	15	20	25
Likely	**(4)**	4	8	12	16	20
Moderately likely	**(3)**	3	6	9	12	15
Unlikely	**(2)**	2	4	6	8	10
Rare	**(1)**	1	2	3	4	5

Outcomes of risk assessments based on the Australian Standard depend on the capacity of the analyst to (a) identify ecologically and socially relevant values or assets, (b) elicit an exhaustive list of potential hazards, and (c) use subjective judgment for each potential hazard to estimate the likelihood that an event will occur and the severity of its consequences. Although the approach has a number of frailties, it is important to recognize that a process that encourages the considered identification and assessment of values and hazards is a distinct improvement on *ad-hoc* environmental planning and management. Advantages of the 'minimalist' approach to risk assessment described in the Australian standard include:

- It's simple and fast
- It accounts for probability of harm and magnitude of harm
- It communicates environmental risk in the same language used for financial and social risk
- It provides an informal means of combining data and expert judgment
- It provides an auditable record of priorities

Frailties associated with a minimalist subjective approach to risk assessment include the personal and professional biases of the analyst, the ambiguity of language inherent in qualitative assessment, and the distinct tendency for overconfidence in description of the likelihood and consequences of hazards (Burgman 2005). Collectively, these deficiencies tend toward false alarmism (implying a negative impact when none exists) or a false sense of security (implying no negative impact when in fact one exists). Greater rigor in the conduct of a risk assessment seeks to better distinguish real risks from perceived risks.

Tools and techniques exist to address frailties and deficiencies. In their development of a framework for application in irrigation industries, Hart *et al.* (2005) sought to extend the Australian Standard through incorporation of a selection of tools and techniques in a way that the authors thought represented a reasonable trade-off between rigor and ease of application. Especially prominent in the approach advocated by Hart *et al.* (2005) relative to that of the Australian Standard is explicit quantitative description of uncertainty in estimates of the consequence and likelihood of hazards. A core motivation for quantitative extensions to risk assessment is to encourage experts and stakeholders to cross-examine the bases of their perception of risk.

Intrinsically, a decision to invest in any management action involves a system understanding that, in the face of considerable scientific uncertainty and ignorance, suggests one course of action is preferable to another in securing outcomes consistent with objectives. Often, these system understandings remain unspoken, unspecified and undocumented. Alternative understandings and courses of action may be entirely plausible, and on consideration, may prove preferable.

Assessment of the consequence and likelihood of hazards requires the risk analyst to form links between cause and effect, which is subject to uncertainties associated with natural environmental variability and lack of knowledge. Experts and non-experts alike are predisposed to overconfidence in their capacity to predict. Lewandowsky and Kirsner (2000) note that although exceptional performance is a defining attribute of expertise, experts sometimes exhibit striking errors and performance limitations. Hart *et al.* (2005) recommend the use of conceptual models to document assumptions regarding cause and effect and the quantification of these models to explicitly communicate uncertainty in a risk assessment.

Logic trees are an extension of conceptual models and include decision trees, event trees and fault trees. Bayesian Belief Networks can also be regarded as a tool that builds on insights from conceptual models. Section 3 of this document outlines preliminary examples of use of the tools in selected aspects of recovery catchment planning and management.

2.2 A protocol for recovery catchment planning

Quantitative description of uncertainty and risk can be costly and time-consuming, and may not always substantially benefit decision-making. Hart *et al.* (2005) developed a protocol for identifying circumstances where quantitative approaches beyond the Australian Standard are likely to prove worthwhile. Essentially, these authors recommend quantitative analysis when a qualitative assessment based around the Australian Standard (AS/NZ 4360) indicates a hazard is of high risk or where stakeholders and experts disagree on the importance of a hazard. Figure 3 shows how the tools and techniques of a more rigorous approach to ERA can complement an initial simple assessment.

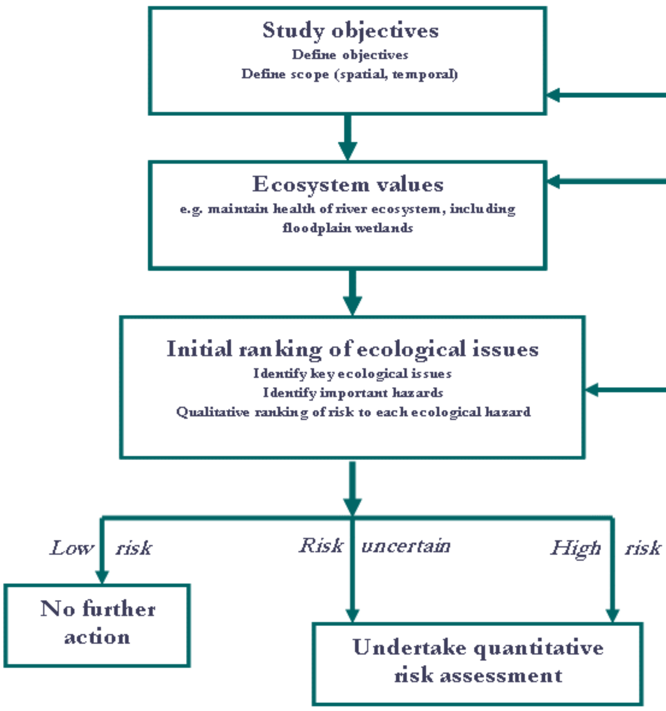


Figure 3 Flowchart for circumstances where a detailed quantitative risk assessment may be worth undertaking (Source: Hart *et al.* 2005).

The subjective risk assessment undertaken with staff involved in the Buntine-Marchagee recovery catchment provides an example of the protocol's application[2].

[2] A fuller description of the Buntine-Marchagee risk assessment is provided in Section 3.5 and Appendix B.

Four members of CALM staff involved in the Buntine-Marchagee recovery catchment were asked to assess the likelihood and consequence of a suite of hazards potentially impacting a wetland. Results for a subset of hazards are shown in Figure 4.

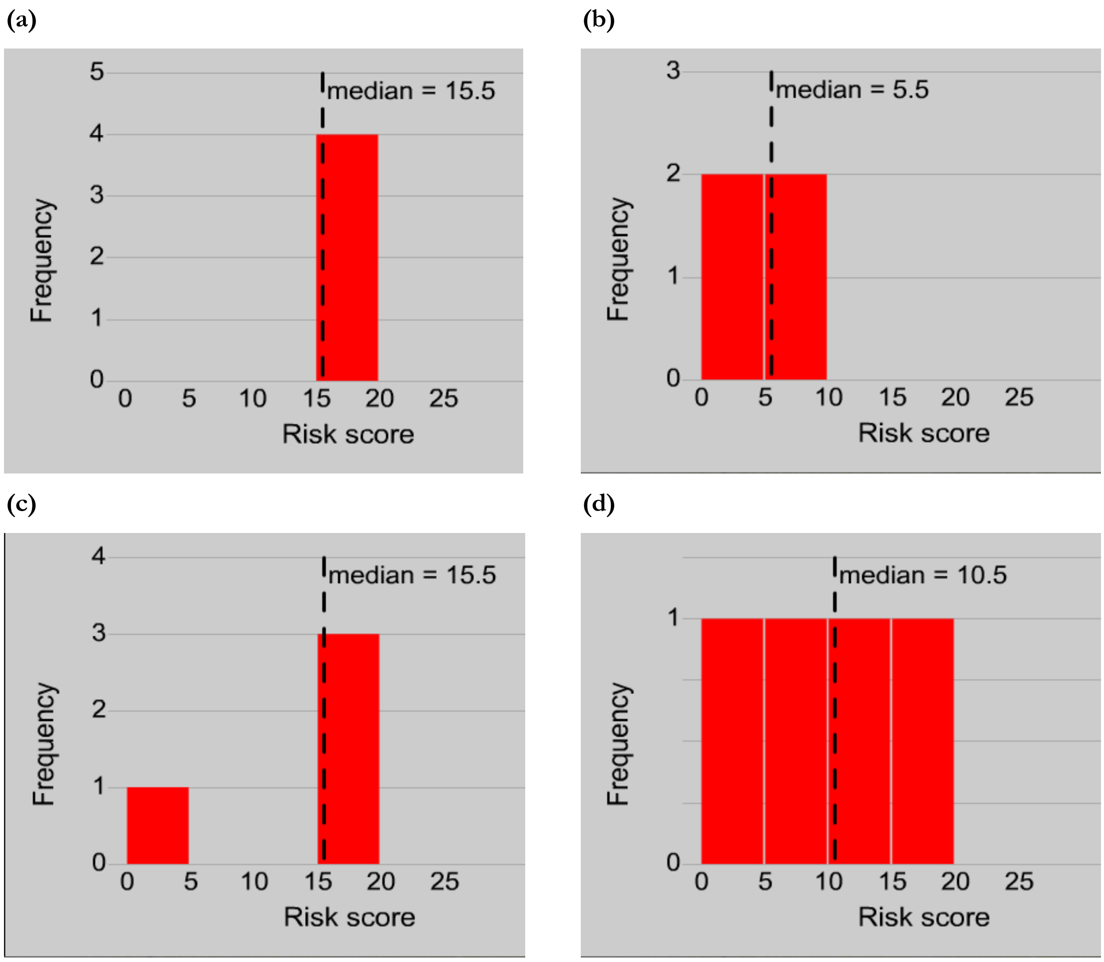


Figure 4. Examples of outcomes of a subjective risk assessment involving four participants for the representative sandy seep wetland within the Buntine-Marchagee recovery catchment. The graphs collate the risk scores from the four participants for four hazards; (a) groundwater salinity; (b) sedimentation via surface water; (c) inundation via surface water; and (d) eutrophication via surface water. Risk scores are the product of likelihood and consequence, derived from use of the matrix shown in Table 2. See text for details.

In Figure 4a, all four assessors agreed the hazard (groundwater salinity) represented a high risk. It is clear some form of management intervention is needed to mitigate the risk, but the best course of action is unlikely to be self-evident. Detailed description of the risk through conceptual cause-and effect-models and their quantitative extensions are likely to provide a sound and transparent basis for investing management resources under an adaptive management framework.

In Figure 4b all assessors considered sedimentation via surface water to be a low to medium risk. Unless a manager is distinctly risk-averse, this finding suggests management action is not warranted, nor is further assessment using quantitative ERA.

In Figure 4c, three of the four participants regarded inundation as a high hazard and one a low hazard. Discussion among the assessors may clarify the basis of the disagreement. Where the divergence of opinion is found to be substantial (rather than an arbitrary language-based misunderstanding) detailed risk assessment can identify areas for targeted investment in management action, research and monitoring.

Figure 4d shows the assessors had widely differing views on the importance of eutrophication as a degrading process in the wetland. Clearly, further work involving more detailed description of ideas on cause-and-effect is needed to disentangle the bases of alternative views and to promote robust cross-examination.

3.0 PRELIMINARY APPLICATION TO CURRENT RECOVERY CATCHMENTS

This section describes *preliminary* application of risk assessment and decision-support tools developed for facets of each of the six recovery catchments, in consultation with regional CALM staff. The principal aim of these consultations was to gauge the conceptual relevance and merit of risk-based approaches to decision support. The emphasis of applications presented below is on how the tools can be applied in varying contexts to provide insights of conceptual benefit to decision-making.

The findings presented here should *not* be used as a basis for weighing the benefits and costs of one or more specific management options. It is important to recognise that the development of user-ready tools and models was not a specific aim of this project. Time constraints meant that the structure and parameterisation of all quantitative tools failed to capture the full extent of available knowledge and expert opinion regarding the issues examined. Further work is required before these tools can be considered user-ready.

3.1 Muir-Unicup

Relative to the other five recovery catchments, Muir-Unicup is characterised by the high number of ecological assets it contains, a high level of complexity in surface and ground water interactions that drive hydrological dynamics, and a large number of secondary threatening processes that potentially impact assets. When faced with this complexity, it's difficult for a manager to know *what* management actions implemented *where* in the catchment might best represent a prudent expenditure of finite resources. The approach we adopted in this case study was to attempt to address this complexity through development of a coarse-filter protocol that sought to identify spatial and/or temporal clustering of high value assets, their threats, and their candidate management actions. For simplicity, only threats and management actions associated with the catchment's hydrology were considered.

A number of sub-catchments make up the Muir-Unicup recovery catchment. The proposed protocol comprises two elements to be employed for each asset in each subcatchment:
(a) an assessment of the significance of identified assets to establish relative priority; and
(b) a decision tree that identifies circumstances of 'hydrological threat' where one candidate management action may be preferred over another

A simple point-scoring procedure could be used for evaluation of asset significance, where a (weighted or unweighted) score is given to each of several criteria, such as:
- regional significance
- state significance
- presence (or number) of rare and threatened taxa
- presence (or number) of geographic outliers

Candidate actions considered in the decision tree were:
- Engineering structures to divert surface flows
- Dams to store water higher in the catchment
- Groundwater pumping in close proximity to the asset
- Revegetation with perennials at a local scale

- Revegetation with perennials at a catchment or regional scale
- Encourage agronomic change
- Do nothing

The circumstances of hydrological threat that might lead to the selection of any one of these management actions is shown in Figure 5.

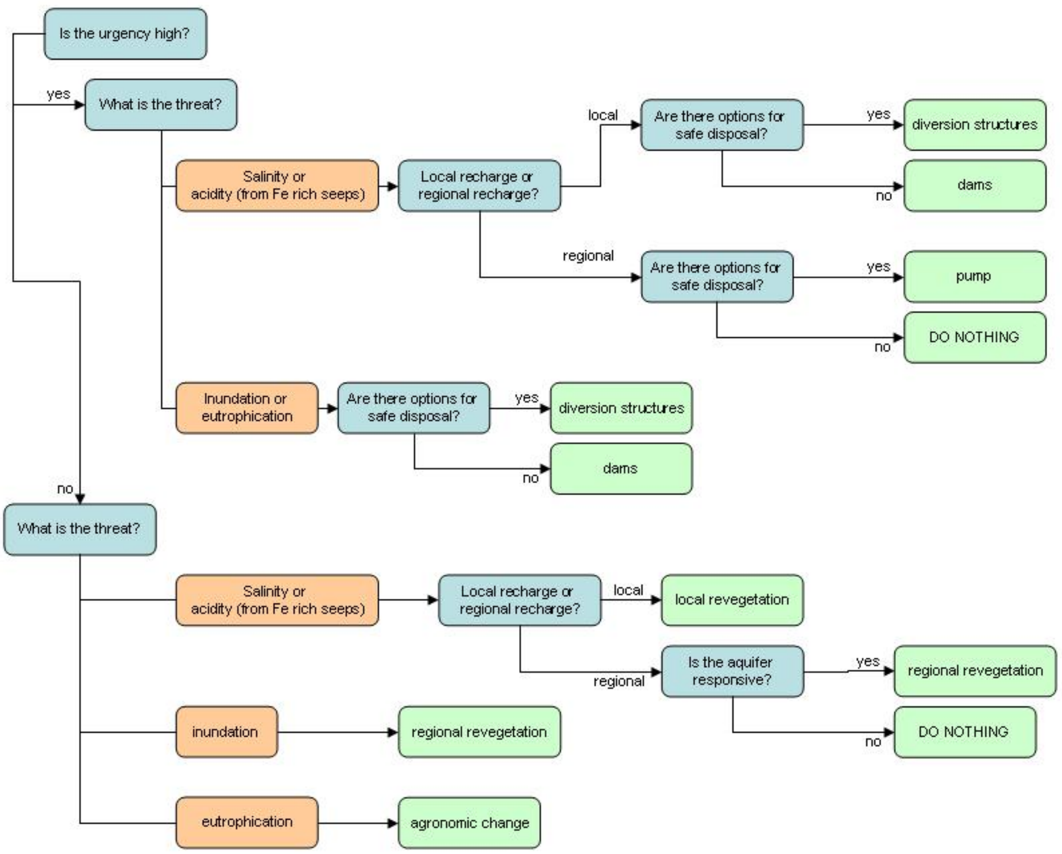


Figure 5. Decision tree for discriminating the hydrological circumstances in which alternative management actions may be most effective for any individual asset. Blue nodes represent points at which the user is required to make a decision, red nodes represent alternative threats to the asset being assessed, and the green nodes represent terminal branches describing the best management action among a list of candidates. Developed with Roger Hearn, Department of Conservation and Land Management.

The structure of the decision tree makes some fundamental assertions about how the Muir-Unicup recovery catchment system works and its responsiveness to management action. Specifically:

- For the Muir-Unicup recovery catchment, the management actions for salinity *or* acidity from iron rich seeps are the same, at least coarsely.
- Where the threat is immediate (i.e. urgency is high) such that the likelihood of unacceptable degradation is high over a short time horizon, the management actions for inundation and eutrophication are the same. But where the threat is low, inundation is best treated through regional revegetation and eutrophication through agronomic change.
- It is a waste of time and resources to invest in management intervention where the threat of salinity OR acidity is substantial AND groundwater is driven by regional recharge AND the groundwater aquifer's transmissivity means it is unlikely to respond to revegetation OR there are no options for safe disposal of groundwater. Do nothing, or undertake investigations to develop feasible management options.

The legitimacy of these assertions could (and should!) be challenged and cross-examined. This capacity for cross-examination is perhaps the best feature of the decision tree. After refining its structure through incorporation of the views of other experts and conservation managers, and when combined with an evaluation of the significance of ecological assets, the tool is likely to identify areas where management intervention is a greater priority and where it is a lesser priority.

It is worth noting that the decision tree shown in Figure 5 implies that the user knows the state of the system definitively. That is, the user can say without qualification whether the asset is urgently or non-urgently threatened, that they know the principal threats to the hazard, and they have a more or less complete hydrological understanding of the system. Of course, such knowledge is unlikely to be available. An extension of the decision tree can involve incorporation of a probabilistic approach whereby the user estimates probabilities for each branch of the tree subjectively. Section 3.6 of this report outlines a fault tree that has been extended to include probabilistic analysis.

3.2 Toolibin

This case study looks at hydrological drivers of water volume in Toolibin Lake using a Bayesian Belief Network (BBN). In particular, we were interested in describing the mean expectation for the length of time between successive higher flow events that would result in Toolibin Lake being filled. Ecological assets of Toolibin Lake include a threatened ecological community and waterbirds. There is some concern that under current management, present and future rainfall patterns (Figure 6) will fail to deliver sufficient water to the lake to maintain these ecological values. A related aim of management is to phase out reliance on groundwater pumping as a means of addressing salinisation of the lake bed.

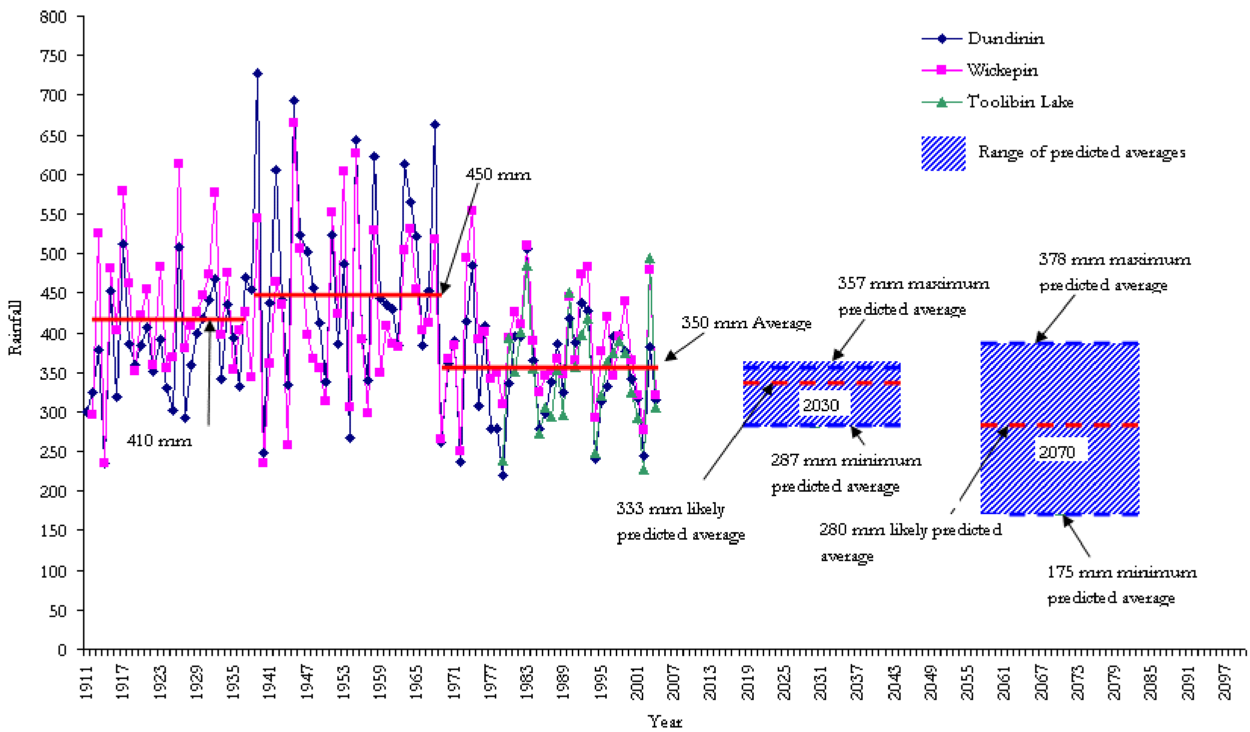


Figure 6 Past, present and predicted rainfall for Toolibin Lake. Past rainfall data comprise three observation points – Dudinin, Wickepin and more recently, Toolibin Lake. Rainfall predictions include point estimates and upper and lower bounds of regional climate change modelling. Data and graph collated by Peter Lacey, Department of Conservation and Land Management.

To increase the likelihood of the lake filling in any one year, we were interested in documenting intuition and knowledge regarding the effectiveness of the following management actions:

- Improve flow through construction of drains in valley floor *flats* and immediate surrounds (as proposed by Cattlin *et al.* 2004)
- Improve flow through construction of drains on catchment *slopes* (as proposed by Cattlin *et al.* 2004)
- Cease pumping groundwater at Toolibin Lake
- Replace annuals with perennial vegetation on the bottom third of the catchment (i.e. the flats, generally where slope is < 1%) to improve water quality to a point where saline flows no longer need to be diverted around Toolibin Lake.

Conventionally, the relative merit of these management options could be explored using an extended mass balance model of catchment hydrology. We employed a BBN because this approach to modelling is better adapted to dealing with uncertainty and can more readily accommodate expert opinion.

BBNs consist of a graphical structure and a probabilistic description of the relationships among variables of a system. The graphical component is akin to a conceptual model of cause and effect, where system variables are represented as nodes, and arcs between nodes imply that the state of a 'child' variable is in some way dependent on the state of one or more 'parent' variables. A BBN allows complex causal chains linking actions to outcomes to be factored into an articulated series of conditional relationships (Borsuk *et al.* 2004). The capacity of BBNs to incorporate empirical observations, system sub-models, and expert opinion makes their application in complex systems appealing. Their basis in Bayesian inference also means BBNs can be readily updated as new information from research and monitoring becomes available.

Advantages of BBNs include (Hart *et al.* 2005):

- BBNs are useful when scant data is available
- They can synthesize scientific data, existing models and expert opinion
- They can be used to formalize understanding
- They can identify and prioritize important variables (sensitivity analysis)
- They can be used to explore the effect of different management actions (predictive)
- They can be updated easily in the light of new information
- They provide a probability estimate for the likelihood of complying with endpoints identified in an Ecological Risk Assessment.

Software packages for building BBNs are readily available and include *Winbugs*, *Netica* and *Hugin*. In all applications presented in this report, we used Netica (Norsys 1997).

Bayesian Belief Networks (BBNs) can be viewed as a way of quantifying conceptual cause-and effect-models. Our understanding of hydrological cause-and-effect in relation to the management actions listed above is summarized in Figure 7. In Figure 8a, the same conceptual model is shown as a BBN through the Netica graphical-user-interface.

The BBN requires that each variable or node in the conceptual model is described by discrete states. So, for example, 'perennials flat' refers to the management option of perennial revegetation on the lower parts of the catchment and comprises two states – true (the action is implemented) or false (the action is not implemented). 'Volume in' is a continuous variable describing the volume of water that flows in to Toolibin Lake. It has three states – low, medium and high. A BBN requires the user to specify thresholds for the state space of continuous variables. For 'volume in', we described 'low volume' as less than 1 GL (in any one year), 'medium' as being between 1 and 3 GL (Figure 8b) and 'high' as greater than 3 GL.

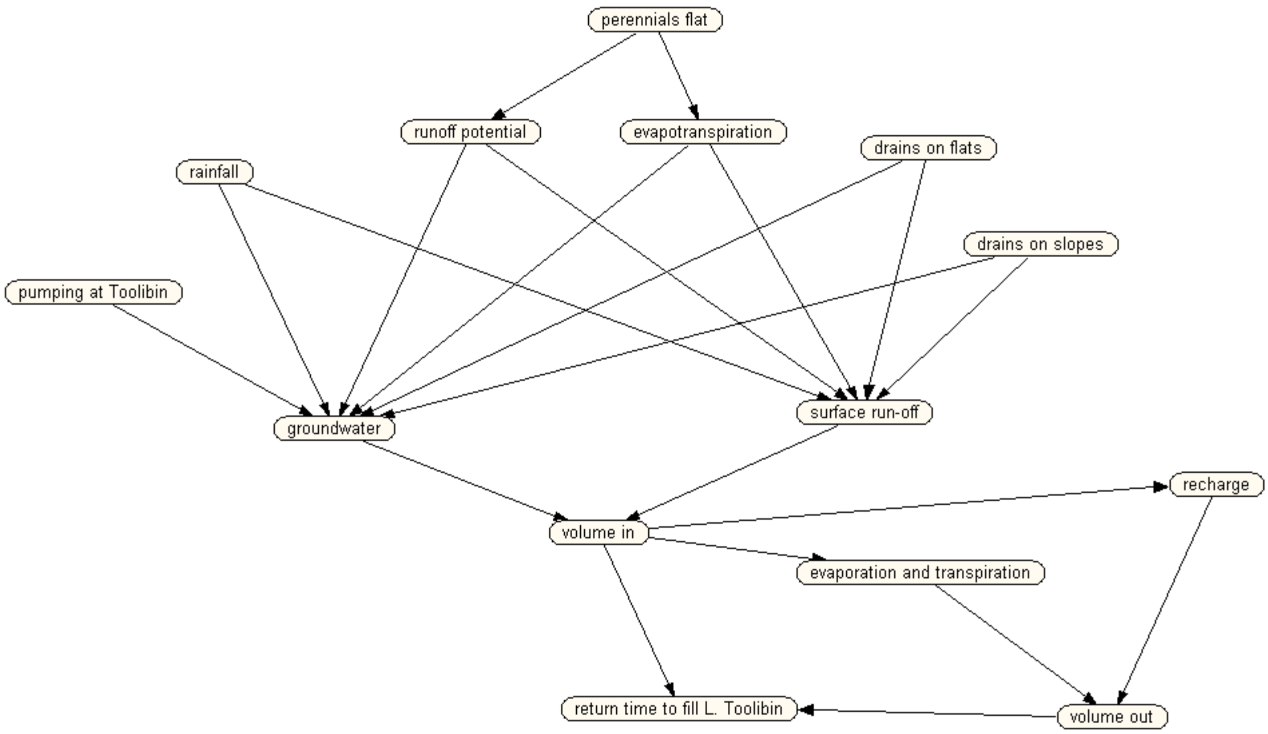
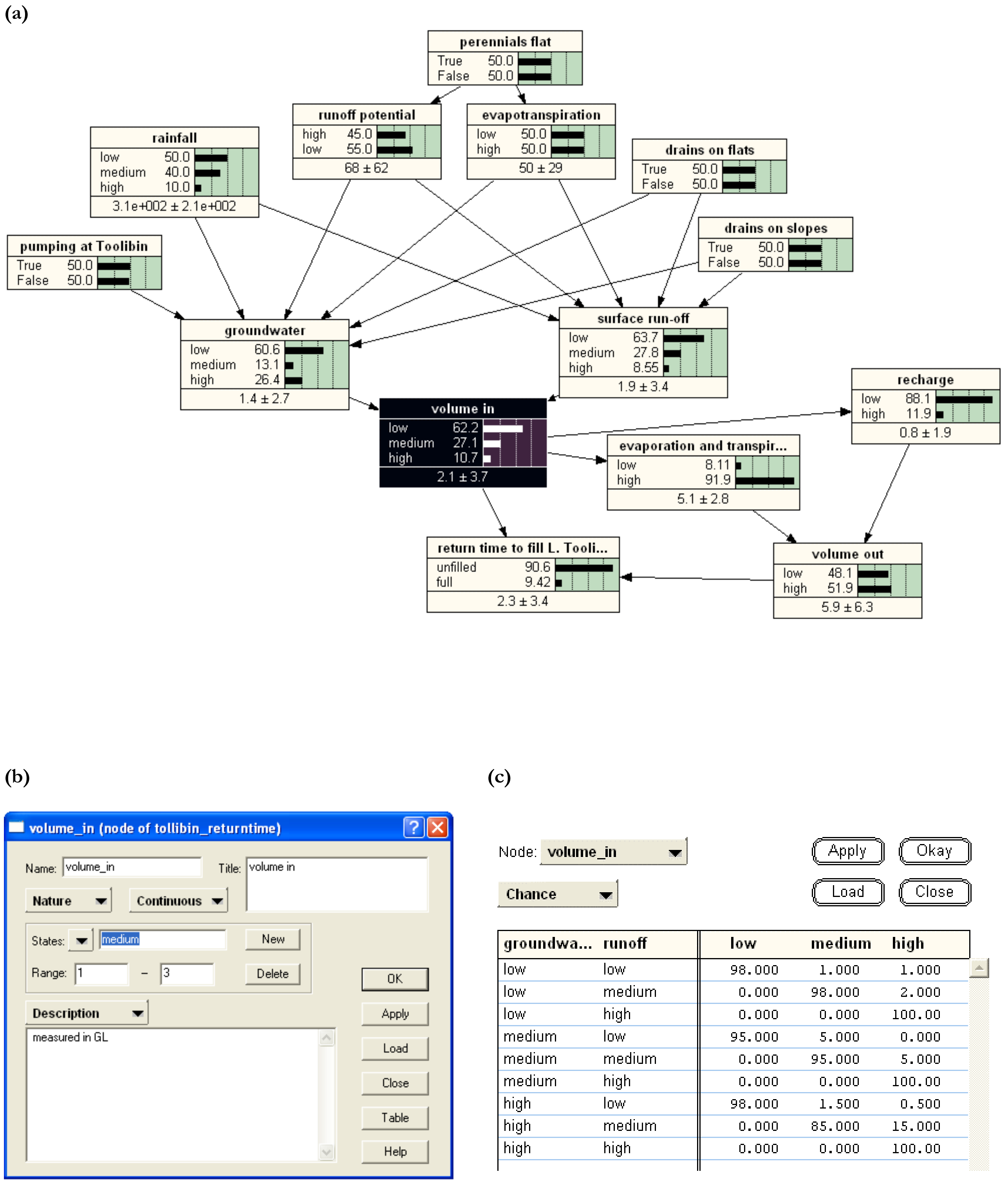


Figure 7 Conceptual model for the return time to fill Toolibin Lake. Developed with Peter Lacey, Department of Conservation and Land Management.

Defining the state space of A BBN is somewhat arbitrary. However, insights from a diligently constructed model should be reasonably insensitive to the exact state space specified. More important is description of conditional probabilities that describe the likelihood a 'child' variable will be in any one state, depending on the state of 'parent' variables. That is, conditional probabilities describe the relative importance of the causal chains that link events and predisposing factors to an endpoint. Figure 8c shows the conditional probability table for the variable 'volume in', which has two parents, 'groundwater' and 'surface runoff'. Because each parent variable has three states, there are nine combinations of states that require description for the child state. In the example shown in Figure 8c, it can be seen that the user's *belief* is that the volume of water flowing into Toolibin Lake is overwhelmingly dictated by surface water flows, with groundwater discharge having only a minor effect.

The conditional probability table may be filled in using empirical observations, output from an independent model, or expert opinion. In all case studies presented in this report conditional probabilities were always assigned using expert opinion and intuition.

The output or endpoint of the model is a description of the likelihood the lake is filled or not filled, which can be used to infer the return time to filling. When the network is compiled for any management scenario (as it is in Figure 9) the likelihood each variable is in each state is shown by the belief bars. In the scenario shown in Figure 9, drains are constructed on the catchment's flats and slopes as proposed by Cattlin *et al.* (2004), groundwater pumping is discontinued, but no perennials are planted. The endpoint shows that our belief is that under such circumstances there is a 14.9% chance the lake will be filled in any one year, corresponding to a mean expectation for the return time of filling of 1/0.149 = 6.7 years.



groundwa...	runoff	low	medium	high
low	low	98.000	1.000	1.000
low	medium	0.000	98.000	2.000
low	high	0.000	0.000	100.00
medium	low	95.000	5.000	0.000
medium	medium	0.000	95.000	5.000
medium	high	0.000	0.000	100.00
high	low	98.000	1.500	0.500
high	medium	0.000	85.000	15.000
high	high	0.000	0.000	100.00

Figure 8 (a) A Bayesian Belief Network for the return time to fill Toolibin Lake. The numbers below the belief bars (eg. 2.1 ± 3.7) refer to the mean and standard deviation for the distribution of continuous variables (Norsys 1997). These values should be ignored in interpreting output because the distributions involved are highly skewed. (b) An example of defining the state space using the Netica graphical-user-interface. (c) An example of a conditional probability table. Developed with Peter Lacey, Department of Conservation and Land Management. See text for details.

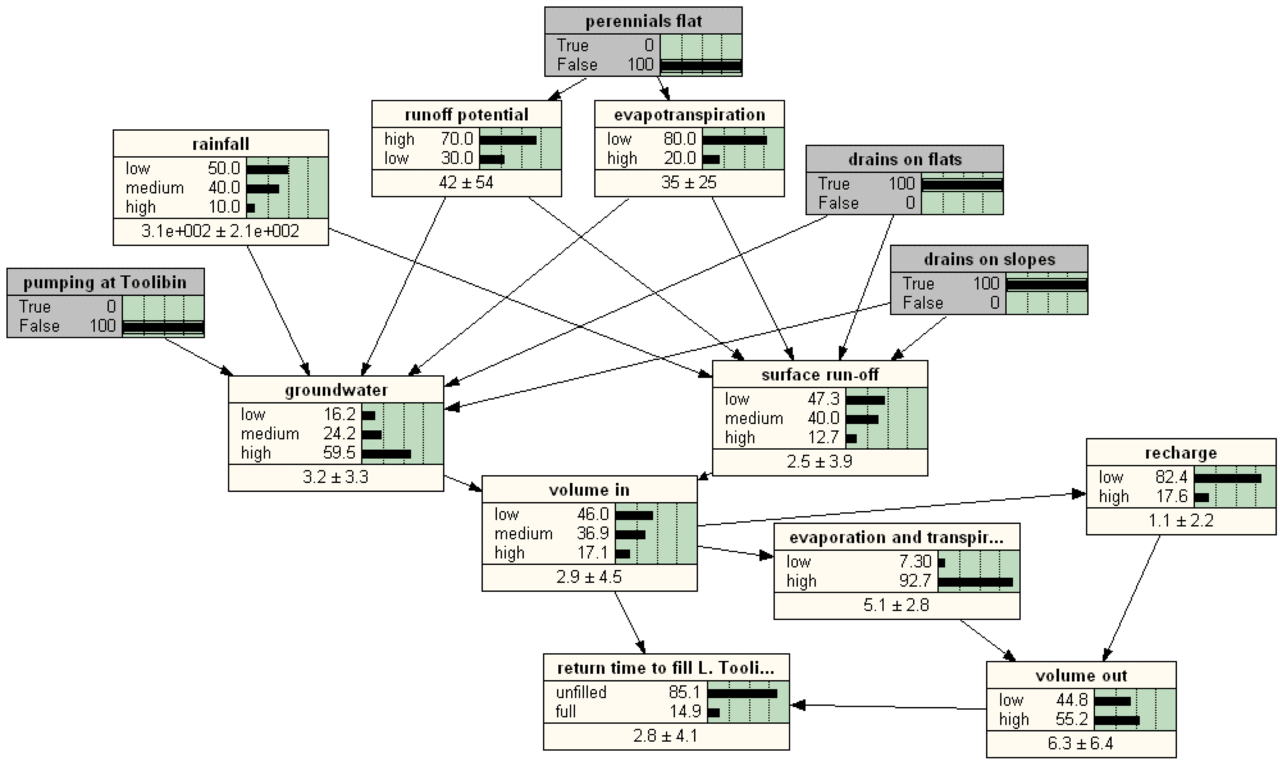


Figure 9 An example of outcomes from a 'what-if' scenario explored using a Bayesian belief Network. See text for details.

A range of scenarios for alternative management interventions were examined using the model and results are presented in Table 3. Scenarios where rainfall is fixed as being 'low' (less than 300 mm per annum), medium (300 – 500 mm) and 'high' (> 500mm) are presented to demonstrate the sensitivity of the model output to this variable. Of the more realistic scenarios where rainfall is 'unknown', the shortest return time (6.7 years) was associated with discontinued pumping, drains on flats and slopes and no perennial revegetation. The model does not include any consideration of water quality, and while the absence of perennials may result in a greater volume of water in Toolibin Lake, the salt concentration or load of that water may result in a net attrition of ecological values. Where revegetation with perennials is also included in the scenario, the return time to filling reported by the model is 10.3 years. This scenario is essentially the same as estimates made for the status quo (10.4 years).

Table 3. Results of selected scenarios for hydrological management of Toolibin Lake. * For a given scenario, the model quantifies the likelihood Toolibin Lake will fill in any one year. The mean expectation for the return time to filling can be derived from the reciprocal of the per annum likelihood of filling.

SCENARIO					**Return time to filling***
Status quo					
Rainfall - unknown	Pumping ✓	Drain flats ✕	Drain slopes ✕	Perennials on flats ✕	10.4 years (9.6%)
Drainage					
Rainfall - unknown	Pumping ✓	Drain flats ✓	Drain slopes ✕	Perennials on flats ✕	9.3 years (10.7%)
Rainfall - unknown	Pumping ✓	Drain flats ✓	Drain slopes ✓	Perennials on flats ✕	8.1 years (12.3%)
Drainage without pumping					
Rainfall - unknown	Pumping ✕	Drain flats ✓	Drain slopes ✕	Perennials on flats ✕	7.8 years (12.9%)
Rainfall - unknown	Pumping ✕	Drain flats ✓	Drain slopes ✓	Perennials on flats ✕	6.7 years (14.9%)
Drainage without pumping and with perennials on flats					
Rainfall - unknown	Pumping ✕	Drain flats ✓	Drain slopes ✕	Perennials on flats ✓	14.3 years (7.0%)
Rainfall - unknown	Pumping ✕	Drain flats ✓	Drain slopes ✓	Perennials on flats ✓	10.3 years (9.7%)
Influence of rainfall - drainage without pumping and with perennials on flats					
Rainfall - low	Pumping ✕	Drain flats ✓	Drain slopes ✓	Perennials on flats ✓	52.6 years (1.9%)
Rainfall - medium	Pumping ✕	Drain flats ✓	Drain slopes ✓	Perennials on flats ✓	7.8 years (12.9%)
Rainfall - high	Pumping ✕	Drain flats ✓	Drain slopes ✓	Perennials on flats ✓	2.7 years (36.4%)

In the absence of a parallel model dealing with water quality, it is difficult to make any meaningful judgment on whether investment in drains and perennial revegetation is worth the benefits associated with discontinued pumping. Nevertheless, in constructing and parameterising the BBN and running various scenarios, a better appreciation is gained of the magnitude of hydrological change that might be expected from management actions implemented individually or collectively.

It is important to recognise that the results presented in Table 3 simply represent our beliefs or intuitions. They are by no means 'scientifically' robust. They do, however, allow managers and stakeholders to see the logic of our ideas and cross-examine their legitimacy. Upon cross-examination, a proposal for investment in any management action may be unsupported because:

- There is disagreement on the structure of the cause-and-effect model (Figure 7)
- There is disagreement on the relative or absolute emphases of causal pathways that make up a cause-and-effect model (i.e. the conditional probabilities underpinning a BBN, Figure 8c)
- There is a perception that the chances of success are not sufficiently large to outweigh the risks of failure and/or the costs of implementation.

A central theme of this report is that the process of structured cross-examination promoted by formal documentation and quantification of ideas of cause and effect is a cornerstone of effective resource allocation.

3.3 Drummond

The Drummond Nature Reserve within the Drummond Recovery Catchment contains the last two claypan wetlands in the wheatbelt that occur in a matrix of uncleared land. The wetlands are associated with a distinctive biota that includes rare and threatened taxa.

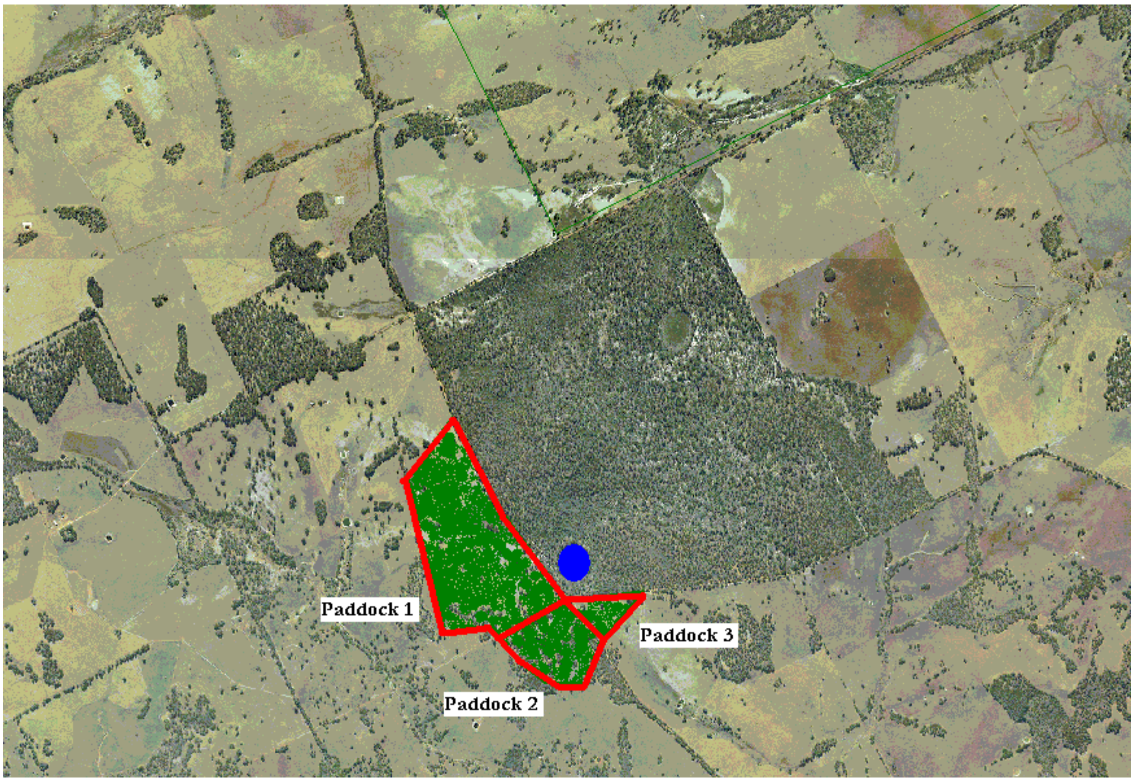


Figure 10. A scenario for management intervention aimed at mitigating hydrological risks to the southern clay pan wetland occurring in Drummond Nature Reserve. Proposed management intervention involves acquisition and revegetation of any or all of three parcels of land, currently owned by three separate landholders. Paddock 1~ 35 ha, Paddock 2 ~ 14 ha, and Paddock 3 ~ 7 ha. The asset, a claypan wetland, is marked blue. See text for details.

There is some evidence the ecological values of the southern wetland are threatened by salinisation. To address this threat, we could propose that agricultural land immediately adjacent and upslope of the asset be revegetated (Figure 10). Local landholders are unlikely to forgo productive land, so we assume that the costs of implementation include both land acquisition costs and revegetation costs. The area of the three paddocks for which revegetation is earmarked (Figure 10) is approximately 35 ha for Paddock 1, 14 ha for Paddock 2 and 7 ha for Paddock 3. Assuming land purchase costs $2,750 per ha and revegetation costs $3,000 per ha, total costs for acquisition and revegetation are estimated to be:

- Paddock 1 - $201,250
- Paddock 2 – $80,500
- Paddock 3 - $ 40,250

The effectiveness of this proposal is somewhat speculative. The current extent and future trends in salinisation are largely undescribed, and the degree to which discharge from adjacent agricultural land is impacting the claypan's biota is uncertain. Nevertheless, we have access to reasonable intuitions based on field observations that could, perhaps, guide management decisions. To explore the matter further, we developed a simple BBN to 'unpack' the intuition underlying our notions of cause-and-effect regarding the effectiveness of revegetating nearby agricultural land (Figure 11).

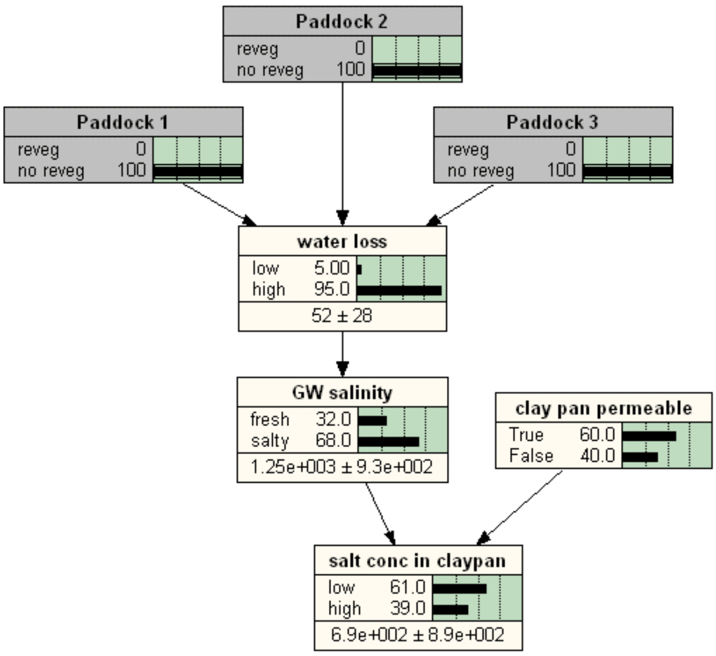


Figure 11. BBN for salt concentration in the southern claypan, Drummond Nature Reserve, in response to revegetating parts of three nearby paddocks. Developed with Bob Huston, Department of Conservation and Land Management. See text for details.

The output we are interested in is how much the likelihood of 'low' salt concentration increases with various combinations of paddock revegetation. In the model, 'low' salt concentration refers to surface water and is defined as concentrations below 200 mS/m, measured at peak annual volume (say July). Consistent with the time horizon of management planning for the Drummond Recovery Catchment, the time horizon for scenarios is 50 years.

The conceptual links in the model shown in Figure 11 involve paddock revegetation affecting the volume of water discharging into the aquifer beneath the claypan (the variable 'water loss'), which in turn affects the salt concentration of the groundwater. The reasoning behind this link is that the source of salinisation is thought to be soil-stored salt. Ultimately, the model asserts that salt concentration of surface water in the claypan is determined by the salt concentration of groundwater and the permeability of the clay pan.

Results of our beliefs in the effectiveness of revegetating some or all of the paddocks are presented in Figure 12. In short, results reflect our lack of conviction regarding the value of the proposed management intervention. Even where no revegetation is undertaken, our uncertainty in the system's dynamics translates to a reasonable chance of low salt concentration (61%). Of the three paddocks, the best value for money based on our limited hydrological understanding is clearly Paddock 2. Where all three paddocks are revegetated, our expectation is that the chance of low salt concentration improves substantially (79%) but this level of improvement may not justify the outlay of some $322,000.

Table 4 Results of scenarios for the predicted effect of revegetation of various combinations of paddocks immediately adjacent to the southern boundary of Drummond Nature Reserve on salt concentration of surface water in the nearby claypan wetland.

Paddocks revegetated	Chance of 'low' salt concentration	Cost
none	61 %	nil
1	73 %	$ 201,250
2	72 %	$ 80,500
3	62 %	$ 40,250
1 and 2	78 %	$ 281,750
1 and 3	74 %	$ 241,500
2 and 3	73 %	$ 120,750
1 and 2 and 3	79 %	$ 322,000

After developing the BBN, we suggest that our current understanding is insufficient to justify substantial investment in the proposed management intervention at this time. Preparation of the BBN, however, was instructive in informing priorities for future research and field investigations. These priorities include:

- Better description of the permeability of the clay pan
- Greater precision in estimating the salt concentration of groundwater below the wetland
- Improved predictive accuracy in the capacity of planted vegetation to reduce discharge.

Clearer understanding in any or all of these aspects may make the case for investment in revegetation more compelling than that suggested by results shown in Table 4. For example, using a linear scale from 0 to 100, where 0 represents totally impermeable and 100 represents totally permeable, the results in Table 4 assume permeability of the clay pan is 60. If field investigations reveal a permeability rating of 90, the chance of low salt concentration in the clay pan is reduced to 42% without revegetation. With revegetation of all three paddocks, the chance is increased to 69%. In the context of the unique ecological values occurring in the wetland, the merit of investment in management intervention in these circumstances may be considered relatively greater.

3.4 Warden

The Warden recovery catchment includes a western, central and eastern suite of wetlands. The case study presented here is restricted to the western suite, which comprises Pink Lake and Lake Warden. Studies and observations of the western suite suggest that the seasonal abundance of migratory wader waterbirds have declined over recent decades as a consequence of excessive water depths in the lakes.

Candidate management actions to address excessive water volumes include revegetation of hydrologically responsive elements of the landscape with perennials and/or engineering approaches to dewatering. Figure 12 coarsely illustrates preliminary ideas for dewatering through engineering.

Because these ideas include disposal of water into Bandy Creek, a potentially important trade-off associated with any improvement in waterbird habitat in the lakes is the magnitude of any adverse impact on the marine environment.

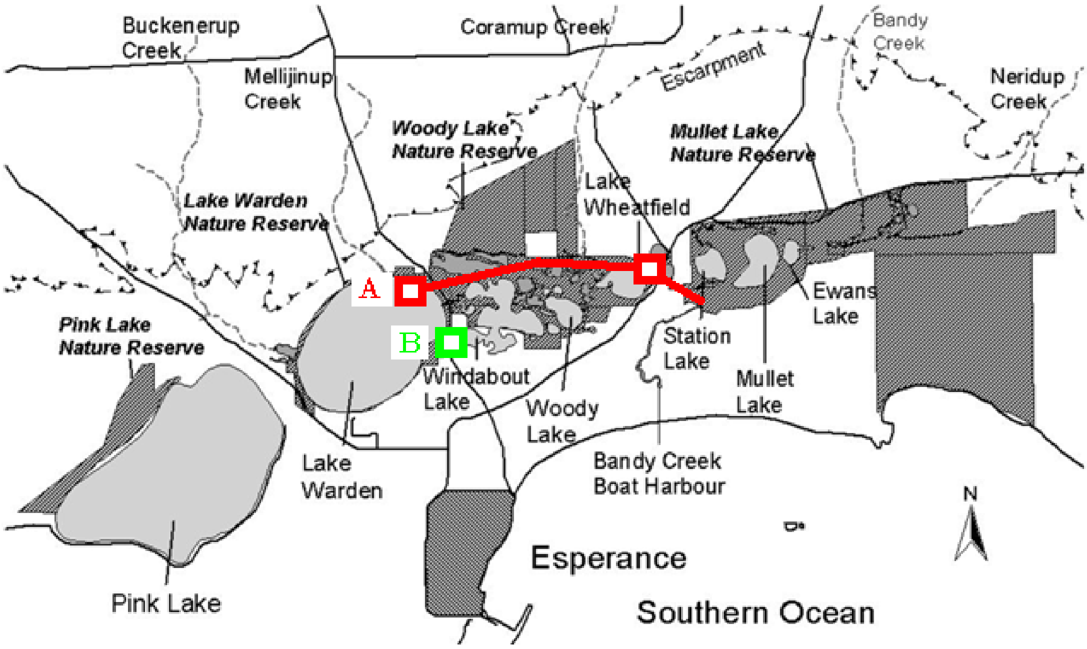


Figure 12 A scenario for engineering management intervention aimed at manipulating lake depths to create more favourable habitat for wader waterbirds. (A) Pumping surface water from L. Warden and disposing into a drain that outflows to Bandy Creek Boat Harbour. The disposal system would include sediment traps in the Lake Wheatfield/Bandy Creek outflow structure. (B) Managing culvert flows from L Windabout to L Warden

Consistent with the protocol outlined in Section 2.2 of this report, we sought to better document our understanding of the trade-off between environmental benefits and costs under uncertainty using a subjective risk assessment and a BBN. The subjective risk assessment used wader waterbird abundances as its ecological endpoint, considered over a time horizon of 25 years. Results are shown in Table 5. Because we relied on the insights of just one expert in estimating the consequence and likelihood of each hazard, we also included a qualitative descriptor of uncertainty in the assessment as a very rough substitute for canvassing the views of multiple experts.

The risk assessment summarised in Table 5 refers to risks to wader waterbirds in the absence of any further management intervention. We also listed aspects that may require the attention of management should the management actions outlined above be implemented:

- Eutrophication of the marine environment
- Sedimentation of the marine environment
- Increased acidity through soil disturbance
- Increased *Phytophthora* through soil disturbance
- Aesthetic nuisance (H_2S) from seasonal decomposition of lake biomass
- Increased salt concentration via less diluting water volume
- Increased nutrient concentration via less diluting water volume
- Increased risk of drought-induced water stress

Table 5 Subjective risk assessment for wader waterbird abundances at Lake Warden and Pink Lake, Warden recovery catchment. Risks are assessed over a 25 year time horizon (to 2030) under a scenario where no further management intervention is undertaken. Hazards beyond the immediate capacity of the recovery catchment program are not included (eg. avian bird flu, loss of international habitat, and climate change). For uncertainty, H = high, M = medium, L = low. Prepared with the assistance of Tilo Massenbauer, Department of Conservation & Land Management.

Hazard	**likelihood × consequence = risk**	**uncertainty**
Water quality of the lakes		
Excessive inundation	5 × 5 = 25	L
Sedimentation and eutrophication	1 × 4 = 4	M
Increased acidity through acid sulfate soil exposure	1 × 1 = 1	H
Increased acidity through agricultural acidification	1 × 2 = 2	M
Salinity impacts on invertebrate food source	2 × 3 = 6	M
Riparian vegetation degradation		
Inundation	5 × 4 = 20	L
Salinity	3 × 4 = 12	M
pH	1 × 2 = 2	H
Phytophthora	4 × 3 = 12	M
Fire	3 × 3 = 9	M
Drought	5 × 2 = 10	L
Other hazards		
Predation	5 × 3 = 15	M
Drought	1 × 3 = 3	L

Key elements of the risks to wader waterbirds revealed in the subjective risk assessment were captured in a conceptual model and translated to a BBN as shown in Figure 13a. The two 'levers' under management control are perennial revegetation ('perennials') and the engineering approaches to dewatering illustrated in Figure 12 ('engineering'). To communicate our understanding of the effect these management actions may have on the marine environment, we also included these variables in a parallel BBN that had seagrass cover as its ecological endpoint (Figure 13b).

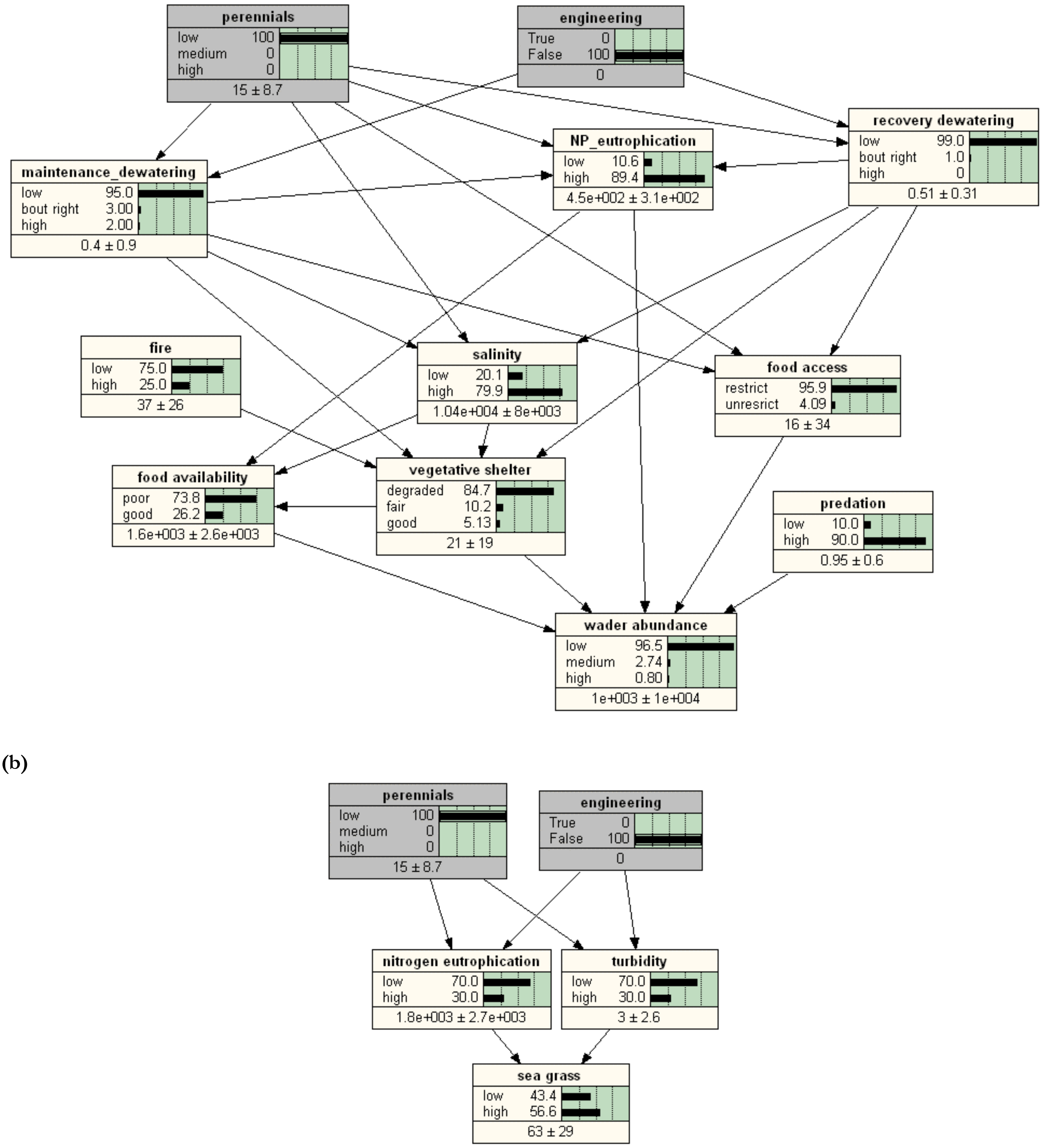
Results of scenarios explored using the BBNs are shown in Table 6. The status quo essentially equates to the scenario where engineering is absent and establishment of perennials is low, corresponding to a 1% chance of high wader bird abundance and a 43% chance of low seagrass cover. Our understanding of the system suggests that the chances of observing greater than 5000 wader birds in any one season are poor in the absence of engineering dewatering. Where engineering works are undertaken without concomitant establishment of perennial vegetation, the beliefs embedded in the networks suggest the chance of a consequential decline in sea grass cover are substantial.

Table 6 The predicted impact of various management scenarios on wader bird abundance in Lake Warden and Pink Lake and sea grass cover immediately adjacent to Bandy Creek Boat harbour. See text for details.

		Chance of 'high' wader abundance	**Chance of 'low' seagrass cover**
Engineering ✗	Perennials - low	1%	43%
	Perennials - medium	1%	36%
	Perennials - high	6%	29%
Engineering ✓	Perennials - low	41%	66%
	Perennials - medium	49%	62%
	Perennials - high	59%	55%

If the models are regarded as reasonable approximations of the real-world after cross-examination from other experts, robust and transparent management decisions can be made. Together with the costs of implementation, the extent to which a manager values sea grass over waterbirds or vice-versa, and the extent to which they are risk averse, will largely inform a preferred course of action among the scenarios shown in Table 6.

(a)



(b)

Figure 13 BBNs for exploring the trade-off between (a) improved wader waterbird abundance in lake Warden and Pink Lake and (b) decline in seagrass cover in the area immediately adjacent to Bandy Creek Boat Harbour (i.e. excluding Esperance Port). Wader abundance refers to the number of birds observed in any one season and thresholds for the state space are low = less than 500, medium = 500 to 5000, high = greater than 5000. A 'low' seagrass cover was defined as being less than 70% and 'high' greater than 70%. Models developed with Tilo Massenbauer, Department of Conservation & Land Management.

3.5 Buntine-Marchagee

The Buntine-Marchagee recovery catchment includes more than 100 individual wetlands occurring in an extensively cleared agricultural landscape. To focus management effort and resources, the approach of the recovery team to date has been to identify a single exemplar of five different wetland types threatened by salinity. (Although wetlands have been the focus of management attention to date, it is anticipated that selected terrestrial ecosystems will be included as priorities in the future). The wetland typology includes those characterised as valley floor wetlands, freshwater seeps on sandy soils, granite rock pools, gypsum lakes and bentonite wetlands. The location of each selected representative wetland within the recovery catchment is shown in Figure 14.

The case study for this recovery catchment involved two exercises: (a) a subjective risk assessment for four of the five representative wetlands (an assessment for the granite rock pool was not undertaken because hydrological risks were considered to be insignificant); and (b) preparation of a BBN for the sandy seep wetland to explore the relative merit of alternative management options.

The subjective risk assessment involved four members of the recovery catchment team. The hazards elicited and the range of risk scores derived from estimates of consequence and likelihood (Table 2) made by the four members for the four wetlands are provided in Appendix B. In general, the lack of commonality in perceptions of the magnitude of risk posed by various hazards suggests patchy or poor understanding of system dynamics. This observation tentatively suggests that greater proportional investment in improved understanding rather than management action may be preferable at this point in time. However, it should be noted that a substantial reason for the poor consensus among the group may be related to variable interpretation of what is entailed in each hazard. Further discussion and a repeat of the exercise may have suggested clearer priorities for management intervention, but time constraints precluded further work.

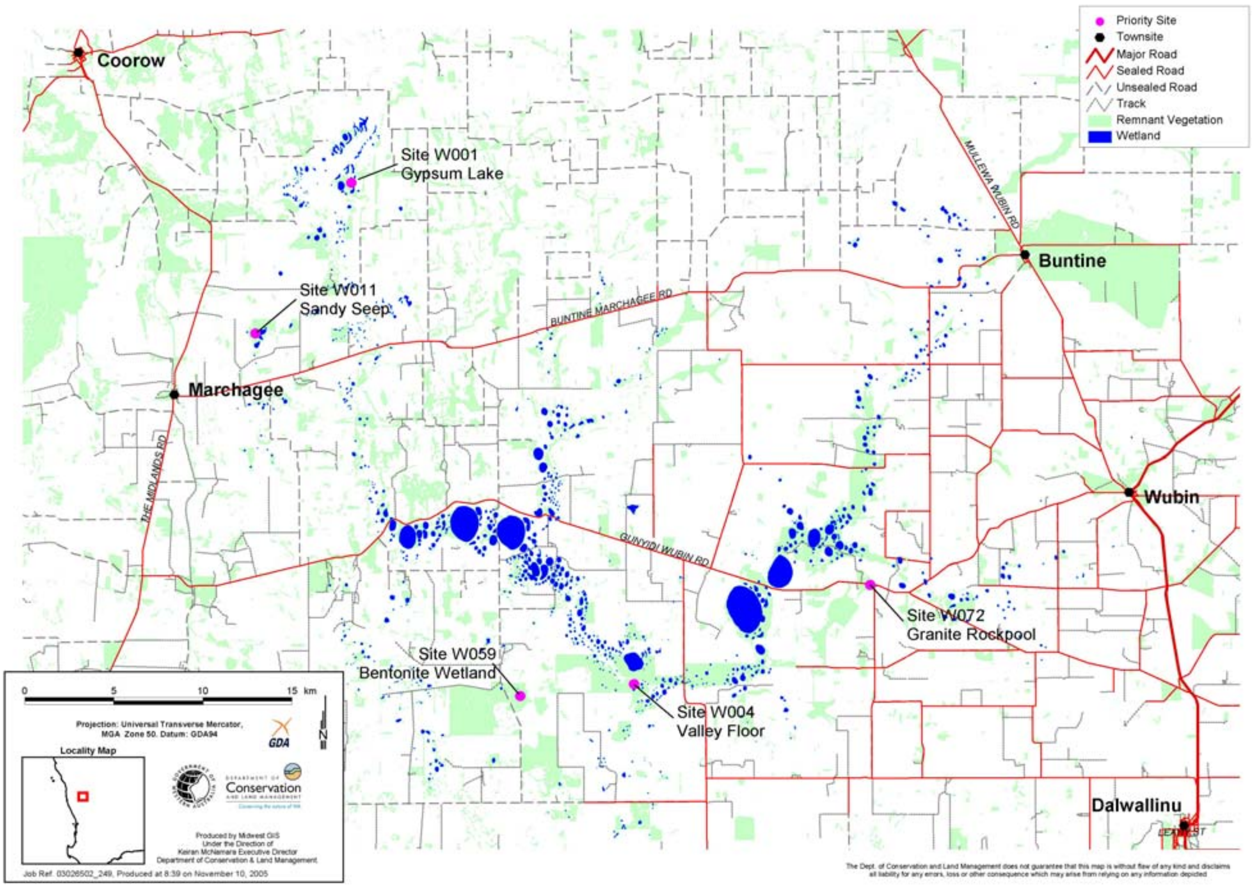


Figure 14 The location of representative wetlands in the Buntine-Marchagee Recovery catchment. Image prepared by Glen Daniel, Department of Conservation and Land Management

Informal discussion arising from the subjective risk assessment suggested that the magnitude and urgency of hydrological-related threats associated with the sandy seep wetland implied that some form of management intervention may be needed in the near future. The sandy seep wetland is notable for the richness of its aquatic invertebrate fauna and this attribute was chosen as the endpoint in development of a conceptual model and BBN. Three management options were considered in development of the model (see Figure 15) and cost estimates were made for each option. Although there is scope for cost-sharing with local landholders for each of the three options, the estimates made below assume CALM incurs full costs.

- Option 1 – engineering
  Install sub-surface drainage immediately upslope of the asset.
  Estimated cost: $300 000
- Option 2 – buy land and revegetate with native cover
  Estimated cost: $450 000
- Option 3 – alley farming involving 20% cover of mallee species
  Estimated cost: $136 000

The BBN linking the management options to our hydrological understanding, and ultimately to aquatic species richness in the wetland, is depicted in Figure 16. Essentially, the management options are aimed at increasing the likelihood of annual drying of the wetland, which in turn is thought to diminish the chances of high concentrations of salt that would lead to direct or indirect lethal or sub-lethal effects on invertebrates.

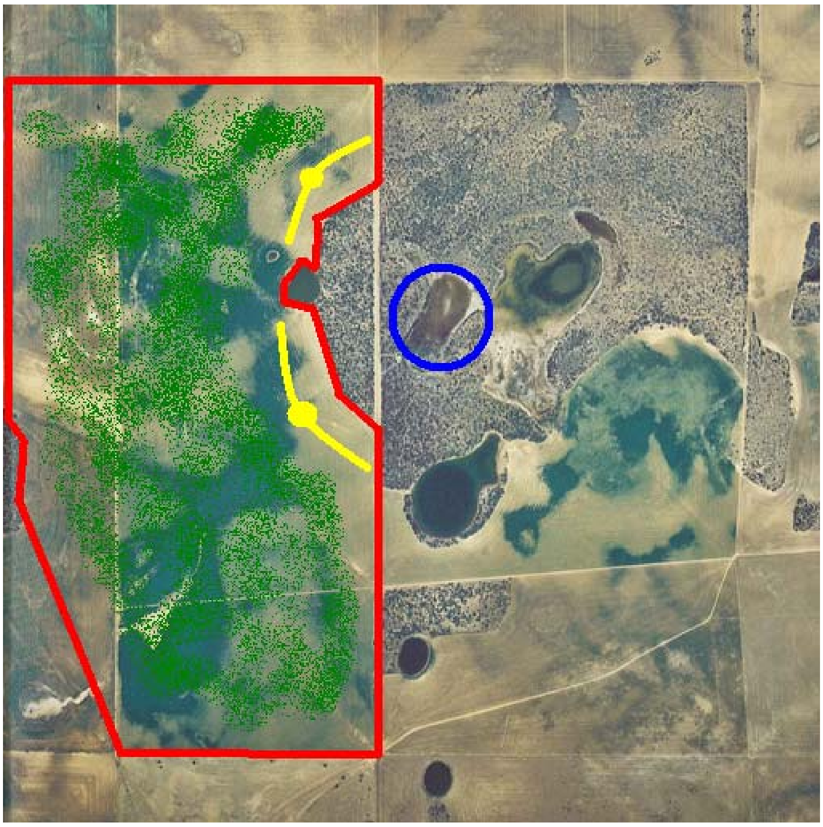


Figure 15 Management options for the representative sandy seep wetland within the Buntine-Marchagee recovery catchment. The wetland asset is circled in blue. Yellow lines indicate the approximate location of proposed sub-surface drains upslope of the asset. The red polygon indicates the area proposed for either full revegetation with native species, or, alley farming involving 20% cover of mallee species. Thanks to Lindsay Bourke, Department of Conservation and Land Management for providing the aerial photo image. Management options developed with Lindsay Bourke and Gavan Mullan, Department of Conservation and Land Management.

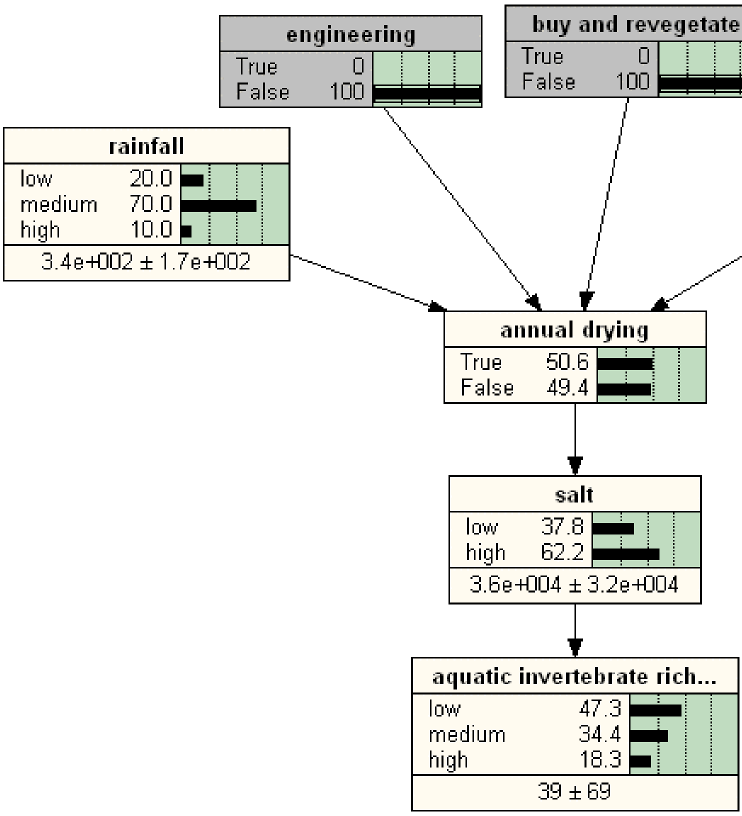


Figure 16 BBN for the effect of alternative management options on aquatic invertebrate richness in the sandy seep representative wetland. The particular scenario shown involves a prediction that the introduction of alley farming will result in a 47% chance of low species richness (< 10 species), a 34% chance of medium richness (10 – 30 species) and an 18% chance of high richness (> 30 species), where measurements of species richness involves standard sampling effort described by Storey *et al* (2004). Note that the uncertainty in the model is somewhat understated because it was assumed that 80% of the wetland's water volume under current conditions is sourced from the area proposed for revegetation or alley farming.

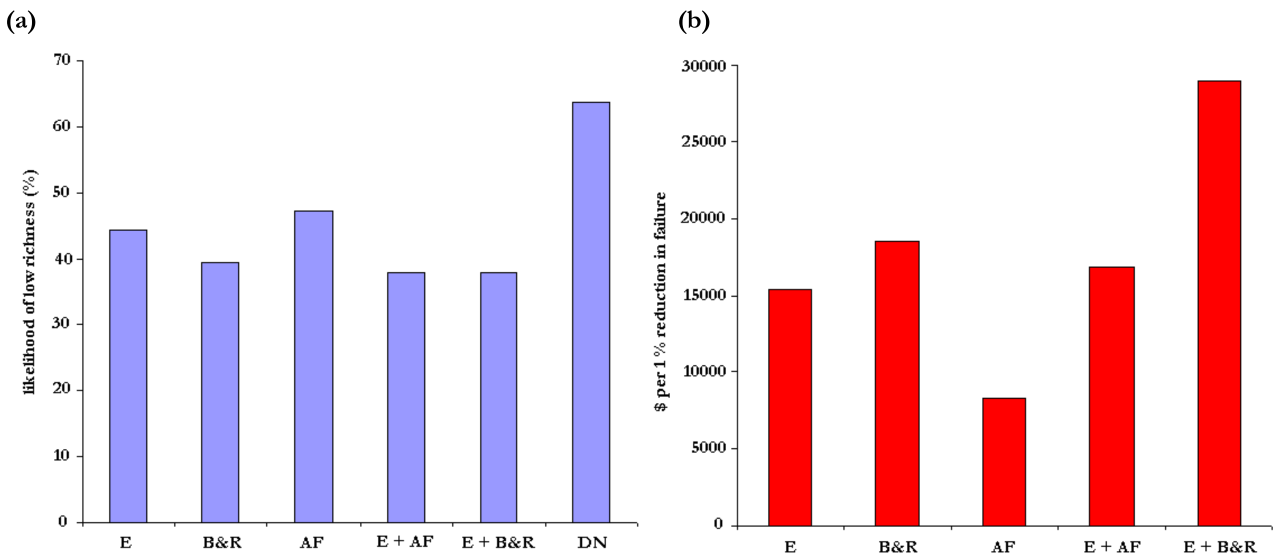


Figure 17 Results of BBN scenarios exploring the relative merit of three management options for mitigating hydrological risks to invertebrate richness. (a) The chance of observing low species richness (< 10 species) for scenarios involving engineering drains (E), buying land and revegetating (B&R), alley farming (AF) or do nothing (DN). (b) The cost per 1% reduction in the chance of low species richness for each scenario.

Results of BBN scenarios are shown in Figure 17a. Our belief is that the option of doing nothing will result in about a 64% chance of failure, where we define failure as species richness less than 10. There is little variation in the reduction in risks of failure among the management options, ranging from 38% to 47%. In Figure 17b, the per unit reduction in risk of failure associated with each management option is couched in terms of cost. It is clear that when cost is considered concurrently with risk reduction, the most attractive option to management is alley farming.

Of course, there is no justification for assuming that other managers and stakeholders will accept the rationale we used to suggest that alley farming has greater merit than the other options in this circumstance. People may disagree with the structure of our model, its conditional probabilities, or the cost estimates we made for the alternative management actions. Or, it may be agreed that alley farming is clearly the best option, but that the reduction in risk associated with its implementation is insufficiently large to justify any expenditure on active protection of the asset. The most important feature of the work presented here is that more robust decisions can be arrived at through structured cross-examination of the rationale communicated in the BBN.

3.6 Lake Bryde

Among the major ecological assets of the Lake Bryde recovery catchment are the valley floor communities of the North and South Lakelands Nature Reserves. There is reasonable evidence to suggest that the viability of these communities is seriously threatened by increased inundation associated with greater surface flows reaching the valley on account of poor water use on farms. To address this threat, a shallow drain or ‘waterway’ is proposed to carry excess flow to disposal wetlands at the downstream northern end of the valley (see Figure 18).

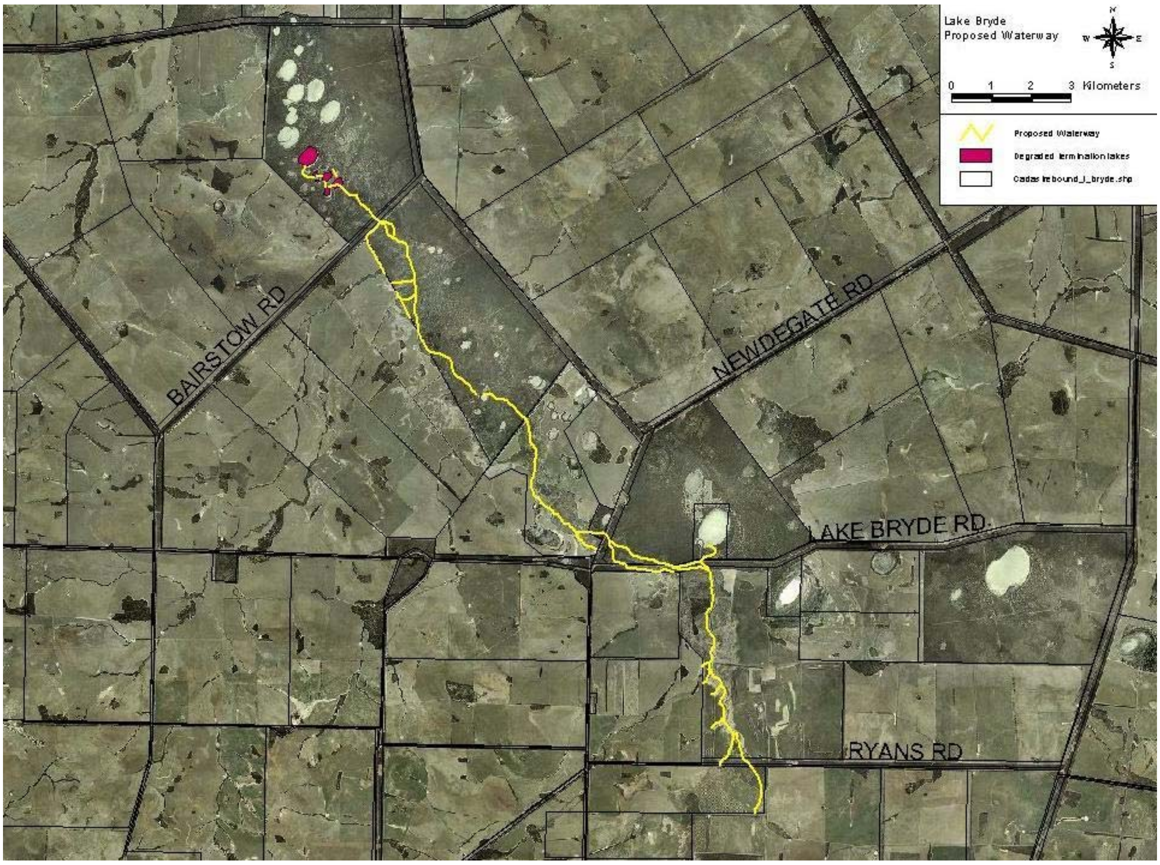


Figure 18 Proposed alignment of the waterway for the Lake Bryde recovery catchment valley floor. In addition to the waterway itself, additional works aimed at decreasing ponding around roads are proposed (Source: Darren Coulson, Department of Conservation and Land Management).

The waterway's focus on the threat of inundation may distract management away from other important hazards or threats. To coarsely canvass the suite of hazards associated with valley floor communities we initially conducted a subjective risk assessment, as described in Section 2.2 of this report. In undertaking the risk assessment, we sought to identify an endpoint for the valley floor community that was:

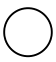
- Ecologically important
- Socially relevant, and
- Amenable to measurement.

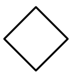
After some consideration we chose the cover of Melaleuca species on the valley floors as our endpoint and made an assessment of risks over a time horizon of 20 years. Results of the subjective risk assessment are shown in Table 7. To get a better appreciation of the nature and magnitude of risks posed by hazards, which the subjective assessment suggested were high risk or medium to high uncertainty, we then developed a conceptual model of cause-and-effect.

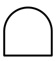
Table 7 Subjective risk assessment for Melaleuca cover in the valley floor of the Lakelands Nature Reserves, Bryde recovery catchment. Risks are assessed over a 20 year time horizon (to 2025) under a scenario where no further management intervention is undertaken. For uncertainty, H = high, M = medium, L = low. Prepared with the assistance of Darren Coulson, Department of Conservation & Land Management. Asterisks denote hazards considered high risk or medium to high uncertainty, requiring greater detail in their description.

Hazard	likelihood × consequence = risk	uncertainty
Waterlogging from excess run-off *	4 × 5 = 20	L
Surface saline flows *	2 × 4 = 8	M
Sub-surface saline flows *	3 × 4 = 12	M
Local salinity through recharge associated with inundation *	4 × 4 = 16	L
Acidity *	1 × 4 = 4	L-M
Heavy metal contamination *	1 × 3 = 3	M
Biocides in run-off	1 × 3 = 3	L
Weeds	2 × 2 = 4	L
Drought related water stress *	1 × 4 = 4	M
Fire *	3 × 3 = 9	M
Phytophthora *	1 × 3 = 3	H
Introduced species - herbivory	2 × 1 = 2	L
Introduced species – soil compaction and disturbance	2 × 1 = 2	L

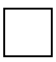
An alternative to a BBN is translation of a conceptual cause-and-effect model into a fault tree. Fault trees are a versatile tool for mapping causal links between system components (Burgman 2005). They use some standard symbols, including (Hayes 2002):

 Basic event: events that indicate the limit of resolution of the fault tree.

 Underdeveloped event: indicating the level of detail could be greater.

 AND gate: output occurs only if all inputs are true (or occur simultaneously).

 OR gate: output occurs if any input is true.

 Event: an event or condition within a fault tree.

If an expert or manager can estimate the likelihood of observing basic events in a fault tree, the various AND and OR statements that make up the tree can be subjected to ordinary probabilistic calculus to estimate the likelihood of all events. Events may be mutually exclusive or independent. If they are mutually exclusive, then the probability that one or the other will occur is given by

$$p(A \cup B) = p(A) + p(B)$$

and the chance that both will occur is, by definition

$$p(A \cap B) = 0$$

If two events are independent, then the chance that either one or the other, or both, will occur, is

$$p(A \cup B) = p(A) + p(B) - p(A \cap B)$$

where

$$p(A \cap B) = p(A)p(B)$$

For three events, A, B, and C, the chance of (A, B or C) is given by

$$p(A \cup B \cup C) = p(A) + p(B) + p(C) - p(A \cap B) - p(A \cap C) - p(B \cap C) + p(A \cap B \cap C)$$

We constructed probabilistic fault trees for a pre-waterway scenario and a post-waterway scenario (Figure 19). There are several insights worth highlighting:

- The probability of failure due to waterlogging is estimated to decrease from 1.00 to 0.18 with construction of the waterway.
- Although construction of the waterway is expected to result in escalated risks of failure due to *Phytophthora*, drought, heavy metal toxicity, fire and acidity, the individual and collective probability of these failure modes are much smaller than the principal threats of waterlogging and salinity.
- The waterway is unlikely to successfully maintain Melaleuca cover in the absence of complementary management intervention addressing salinity.

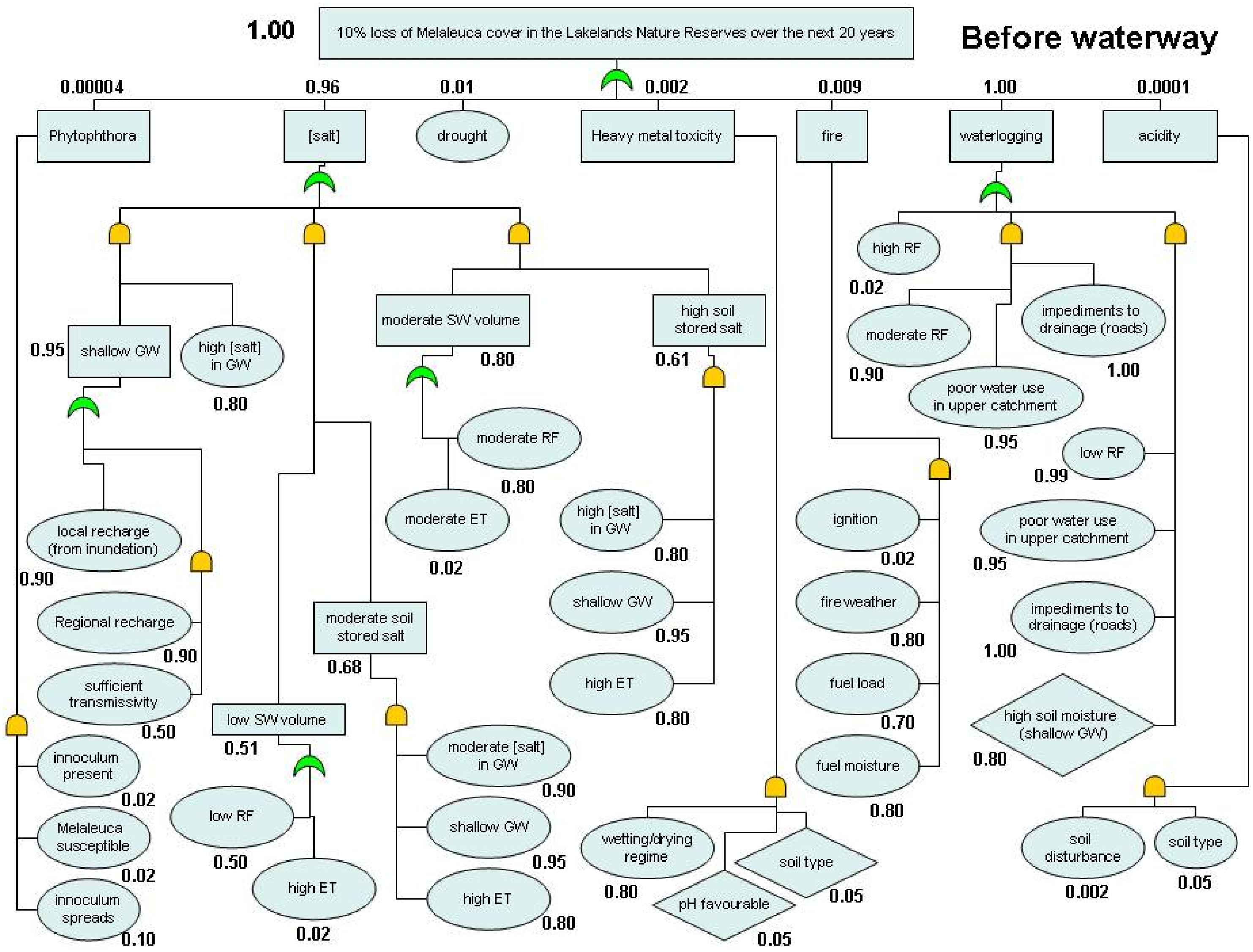
Calculation of the probability of the various failure pathways depicted in Figure 19 rely on point estimates of the probability of basic events, which themselves are subject to uncertainty. To better describe this uncertainty, upper and lower bounds for basic events can be included and the probabilistic calculus described above applied to intervals rather than point estimates (Neumaier 1990). Table 8 shows calculations made for the probability of each failure mode pre-and post-waterway using point (or 'best') estimates and lower and upper bounds. Although the best estimates shown in Figure 19 suggest a 92% chance of failure post-waterway construction, the bounds of uncertainty described by the intervals indicate the risk of failure may be as low as 31% and as high as 100%.

As for case studies using BBNs, the degree to which these risks and opportunities are accepted or embraced depend largely on (a) the extent to which management concurs with the model underlying the fault tree and its probabilistic calculations, (b) whether management has an appetite for risk or is risk-averse, and (c) the costs of implementation.

Overleaf

Figure 19 Probabilistic fault trees describing the relative importance of various pathways by which a goal of maintaining Melaleuca cover in the valley floors of Lakelands Nature Reserves may fail. (a) Before implementation of the proposed waterway (b) After implementation of the proposed waterway. All values for the probability of basic events were derived using subjective estimates. Developed with Darren Coulson, Department of Conservation and Land Management.

(a)


1.00
10% loss of Melaleuca cover in the Lakelands Nature Reserves over the next 20 years
Before waterway
0.00004
Phytophthora
0.96
[salt]
0.01
drought
0.002
Heavy metal toxicity
0.009
fire
1.00
waterlogging
0.0001
acidity
0.95
shallow GW
high [salt] in GW
0.80
local recharge (from inundation)
0.90
Regional recharge
0.90
sufficient transmissivity
0.50
innoculum present
0.02
Melaleuca susceptible
0.02
innoculum spreads
0.10
moderate SW volume
0.80
moderate RF
0.80
moderate ET
0.02
moderate soil stored salt
0.68
low SW volume
0.51
low RF
0.50
high ET
0.02
moderate [salt] in GW
0.90
shallow GW
0.95
high ET
0.80
high soil stored salt
0.61
high [salt] in GW
0.80
shallow GW
0.95
high ET
0.80
wetting/drying regime
0.80
soil type
0.05
pH favourable
0.05
ignition
0.02
fire weather
0.80
fuel load
0.70
fuel moisture
0.80
high RF
0.02
moderate RF
0.90
impediments to drainage (roads)
1.00
poor water use in upper catchment
0.95
low RF
0.99
poor water use in upper catchment
0.95
impediments to drainage (roads)
1.00
high soil moisture (shallow GW)
0.80
soil disturbance
0.002
soil type
0.05

(b)

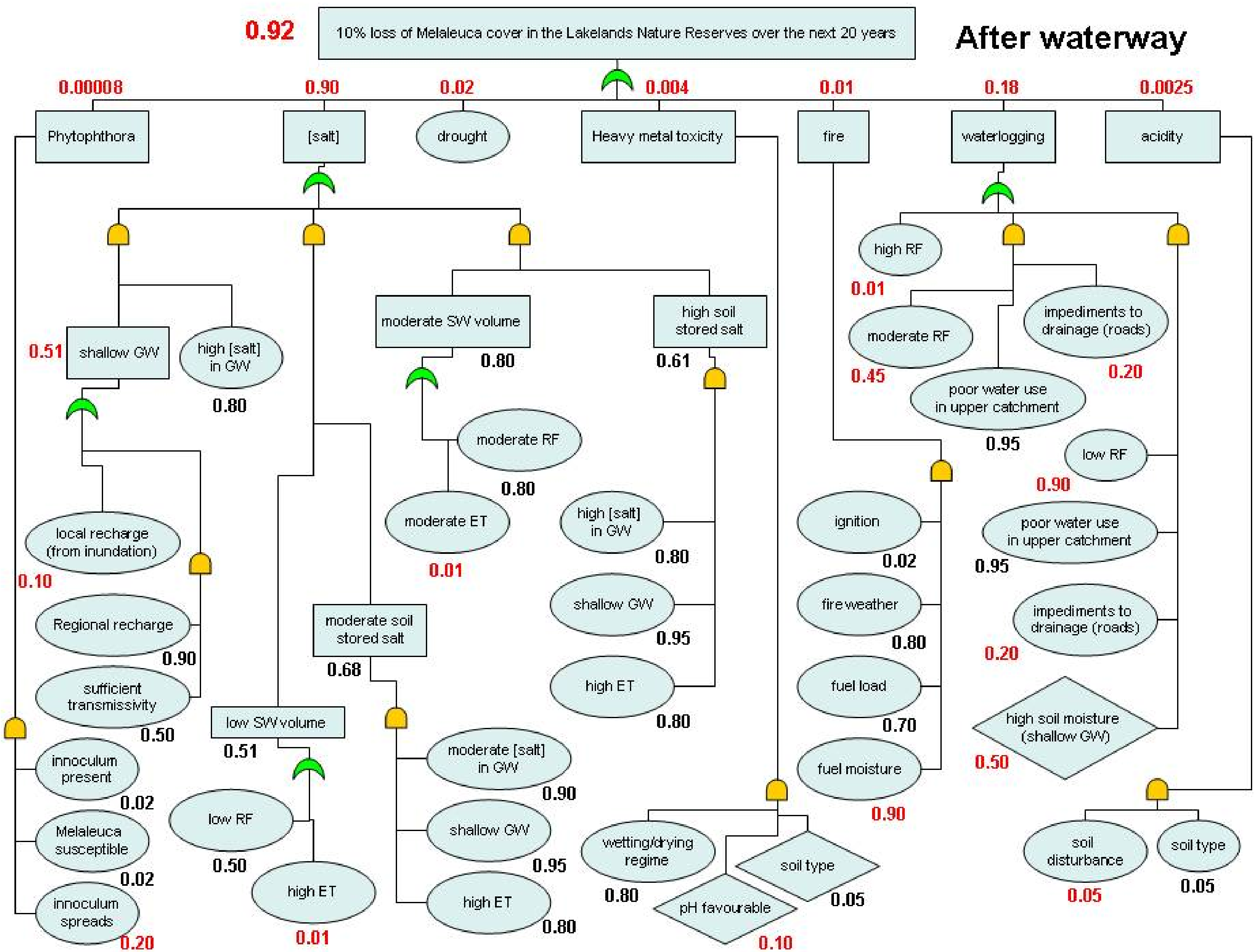

0.92
10% loss of Melaleuca cover in the Lakelands Nature Reserves over the next 20 years
After waterway
0.00008
Phytophthora
0.90
[salt]
0.02
drought
0.004
Heavy metal toxicity
0.01
fire
0.18
waterlogging
0.0025
acidity
0.51
shallow GW
high [salt] in GW
0.80
local recharge (from inundation)
0.10
Regional recharge
0.90
sufficient transmissivity
0.50
innoculum present
0.02
Melaleuca susceptible
0.02
innoculum spreads
0.20
moderate SW volume
0.80
moderate RF
0.80
moderate ET
0.01
moderate soil stored salt
0.68
low SW volume
0.51
low RF
0.50
high ET
0.01
moderate [salt] in GW
0.90
shallow GW
0.95
high ET
0.80
high soil stored salt
0.61
high [salt] in GW
0.80
shallow GW
0.95
high ET
0.80
wetting/drying regime
0.80
soil type
0.05
pH favourable
0.10
ignition
0.02
fire weather
0.80
fuel load
0.70
fuel moisture
0.90
high RF
0.01
moderate RF
0.45
impediments to drainage (roads)
0.20
poor water use in upper catchment
0.95
low RF
0.90
poor water use in upper catchment
0.95
impediments to drainage (roads)
0.20
high soil moisture (shallow GW)
0.50
soil disturbance
0.05
soil type
0.05

Table 8 The predicted probability of a 10% loss of Melaleuca cover in the Lakelands Nature Reserves through various failure modes. Predictions include best estimates and lower and upper bounds derived using subjective intervals for the basic events shown in Figure 19.

Hazard	Best estimate	Lower bounds	Upper bounds
Pre-waterway			
Phytophthora	0.00004	0.00	0.09
[salt]	0.96	0.61	1.00
Drought	0.01	0.005	0.05
Heavy metal toxicity	0.002	0.00005	0.04
Fire	0.009	0.002	0.09
Waterlogging	1.00	1.00	1.00
Acidity	0.001	0.00001	0.002
Overall	1.00	1.00	1.00
Post-waterway			
Phytophthora	0.00008	0.00	0.09
[salt]	0.90	0.28	1.00
Drought	0.02	0.005	0.05
Heavy metal toxicity	0.004	0.0001	0.04
Fire	0.01	0.002	0.09
Waterlogging	0.18	0.03	0.90
Acidity	0.0025	0.0001	0.02
Overall	0.92	0.31	1.00

4.0 DISCUSSION

When combined with a tendency for overconfidence, the failure to deal with uncertainty at a policy level tends toward unrealistic goals. Unwittingly, high aspiration goals can lead to inefficient use of resources because decision-makers avoid the blame of failure through accumulating knowledge rather than investing in action. That is, high aspirations are highly vulnerable to uncertainty relative to modest aspirations (Ben-Haim 2001), and on-ground managers will tend toward allocating resources to improving knowledge or will be inclined to manage by benign neglect.

The scale of salinisation and flooding as threatening processes throughout the wheatbelt and the prevalence of uncertainty in our scientific understanding demand improved approaches to the allocation of management resources. Uncertainty can tend toward decision-making paralysis or the allocation of scarce conservation resources to ineffective management interventions. Although the concepts underpinning adaptive management (Walters 1986) and triage (Hobbs *et al.* 2003) seek to overcome these limitations, their practical application requires specific tools to be tested in on-ground applications.

Defining a decision problem involves specifying the possible states of a system, identifying alternative management actions, and predicting the outcomes of those actions under different system states. A standard application of decision-theory under uncertainty involves ascribing probabilities to describe the likelihood the system is in each possible state and describing predicted outcomes for each action as utilities. The problem can then be solved by maximising expected utility.

For example, in Table 9 the elements of a hypothetical decision problem for addressing decline in the condition of a wetland's fringing vegetation are presented. The example is restricted to three threats associated only with the hydrology of the system and three candidate management actions. Management actions include (1) revegetation of part of the catchment using woody perennial species, (2) constructing diversion channels to direct surface water away from the receiving wetland, and (3) pumping groundwater from the immediate environment of the wetland. The predicted effectiveness of these management actions varies according to what is assumed to be the state of the system. If waterlogging is the principal stressor, then diversion structures will be the best action (predicted 50% improvement in vegetation condition). Groundwater pumping is predicted to be most effective if salt concentration is responsible for decline in vegetation condition. The management decision is to select the best action for implementation among the three candidates, acknowledging that understanding of the state of the system is incomplete. Using standard approaches to maximising utility, Action 2 (surface water diversion structures) would be selected.

Table 9 Hypothetical decision table (utilities and probabilities) for addressing degradation in the condition of a wetland's fringing vegetation, involving three management actions and three states. The likelihood of each state is a subjective probability that waterlogging, or salinity, or both, are the primary cause of degradation. For each action and each state, the utility is described by a point estimate of the percentage improvement in vegetation condition. The overall expected utility for each action is the sum of products of the likelihood of each state and its corresponding utility.

System state (cause of degradation)	**Likelihood of each state**	**Action 1** (revegetate with woody perennials)	**Action 2** (diversion structures)	**Action 3** (groundwater pumping)
Waterlogging	0.3	10%	50%	5%
Salt concentration	0.2	10%	-5%	15%
Waterlogging and salt	0.5	20%	20%	20%
	Expected utility	**15%**	**24%**	**14.5%**

The example is simplified for illustrative purposes. Additional aspects of the decision problem include threatening processes other than those associated with hydrology and salinity, and consideration of the costs and feasibility of implementing alternative management actions. Despite these complexities, the example highlights a number of limitations to standard applications of decision theory that only coarsely treat uncertainty.

The summed expected utilities for each action ignore the possibility of negative outcomes. Although the construction of diversion channels is predicted to lead to a 50% improvement in vegetation condition if waterlogging is the cause of decline, there is a possibility of exacerbating degradation if the cause is physiological sensitivity to salt concentrations. Such a scenario may arise if surface water flows act to dilute the wetland's salt load. When presented with a fuller account of uncertainty, a risk-averse manager may prefer to forgo the possibility of sweeping success to avoid the possibility of disastrous outcomes.

A fuller account of uncertainty needs to acknowledge ignorance and environmental variation in (a) the state of the system and (b) predicted outcomes of implementing alternative actions. Although Table 9 offers an estimate of the likelihood the system is in a given state, the probability that the system is in that state is unrealistically assumed to be known with certainty. Likewise, it is implied that predicted utilities describing percent improvement in vegetation condition are known without error. Among other things, uncertainty in states and predicted outcomes will be associated with environmental variability and incomplete knowledge regarding the absolute and relative volumes and salt concentrations of surface water versus groundwater entering the wetland, their interactions with rainfall and evapotranspiration, and the ecological and physiological sensitivity of the biota to these interactions.

Collectively, these shortcomings tend toward misinformed management strategies because the magnitude of uncertainty and risk is poorly described. Methods and tools exist to address these limitations, but there are few examples of their application natural resource management (Morgan and Henrion 1990, Hart *et al.* 2003, Burgman 2005).

Building on the experience outlined in this report, further research is needed to test tools that:

1. Describe the hydrological-based risks to defined conservation values;
2. Allow integration with other threatening processes;
3. Provides a method for synthesizing outputs from hydrological models, field observations and expert judgments;
4. Allows the impact and risks of various management options to be compared;
5. Place assumptions regarding system understanding in plain view; and
6. Are able to be readily used by recovery catchment managers.

This report has used Bayesian Belief Networks (BBNs) extensively to illustrate the conceptual appeal of documenting ideas of cause-and-effect and uncertainty. However, the capacity of BBNs to convey the full extent and nature of uncertainty is limited. Once the nodes and links of a network are defined, the outputs from BBNs fail to account for structural uncertainty in system understanding. The conditional probability tables that underpin causal chains depicted in BBNs are essentially point estimates (although the sensitivity of the output to these estimates can be explored). The conditional probabilities relating two or more nodes in a BBN often make unjustified assumptions about the nature of the dependency between variables. And although uncertainty is communicated in the output of a BBN, that output does not convey the relative contributions of poor scientific understanding and environmental variability. These criticisms of BBNs do not detract substantially from their strengths, but they do suggest that other tools that illuminate different aspects of the decision problem are worth exploring.

Together with Bayesian Belief Networks, probability bounds analysis and Info-gap theory represent promising developments in risk-based decision support. p-bounds can accommodate the range of plausible dependencies that link two or more variables (Ferson *et al.* 2004). The method is appropriate where there is more information than a simple interval comprising upper and lower bounds and less information than that required to specify distributional parameters needed for Monte Carlo techniques (Burgman 2005). p-bounds can faithfully represent what is known and what is unknown about variable dependencies, and in so doing, avoid the costs of hyper-conservatism associated with sure bounds and the overconfidence commonly encountered in Monte Carlo methods.

BBNs and p-bounds are useful tools in characterising risk and uncertainty, but they do not directly inform decision-making. Info-gap theory provides a framework for decision-making under severe uncertainty (Ben-Haim 2001). The central basis of info-gap is the trade-off between the aspirations of a decision-maker and immunity to uncertainty. That is, high aspirations are more vulnerable than low aspirations when models and data are uncertain or erroneous. The theory accommodates both probabilistic uncertainty in model dependencies and structural uncertainty in system understanding. Recognising that uncertainty can lead to either outright failure or sweeping success, the decision-problem under info-gap theory can be described as a robustness function or an opportunity function. A risk-averse manager is interested in the robustness function, which describes immunity to failure. That is, it answers the question, how wrong can the model be without causing failure? The decision-maker can then trade robustness for higher aspirations. The opportunity function describes immunity to sweeping success and may be of interest to the manager with an appetite for risk. It answers the question, how much should the model be changed to allow a 'windfall' in aspiration.

This report recommends that further work be undertaken to explore the utility and merit of a number of risk-based decision support tools to guide public investment of scarce conservation resources.

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Appendix A

Assessing Biophysical Threats to Biodiversity and Water Assets (Source: Wallace *et al.* 2003)

Biodiversity/Water Asset: Asset name/description.

Asset Goal: For biodiversity assets the goal will be "to maintain the existing (2003) natural species richness of the wetlands and associated habitats at Asset X in a natural or near natural ecosystem for the next 50 years." Goal for Water Resources assets will be defined once technical and economic aspects have been assessed.

Threat Category	Management Issue	Probability that threat will cause goal failure, existing management [1]	Probability that threat will cause goal failure, with extra management [2]	Assumptions Underlying Initial Probability Assessment [3]
Altered biogeochemical processes	Hydrological processes, particularly salinity			
	Nutrient cycles, including eutrophication			
	Carbon cycle and climate change			
Impacts of introduced plants and animals	Environmental weeds			
	Feral predators			
	Preventing new introductions of damaging species			
	Grazing by stock			
	Competition for food and shelter (other than as above, and includes habitat damage by pigs)			
Impacts of problem native species	Parrots			
	Defoliation by scarab beetles, lerps, etc.			
Impacts of disease	Dieback (*Phytophthora* spp)			
	Armillaria			
Detrimental regimes of physical disturbance events	Fire			
	Cyclones			
	Flood			
	Drought			
	Erosion (wind and water, includes sedimentation)			

Table continued from previous page.

Threat Category	Management Issue	Probability that threat will cause goal failure, existing management [1]	Probability that threat will cause goal failure, with extra management [2]	Assumptions Underlying Initial Probability Assessment [3]
Impacts of pollution	Herbicide/pesticide use and direct impacts			
	Pesticide surfactants and impacts			
	Oil, acid & other chemical spills			
	Secondary acidity (from drainage)			
Impacts of competing land uses	Recreation management			
	Agricultural impacts (other than as already dealt with above)			
	Forestry			
	Consumptive uses			
	Illegal activities (eg. rubbish dumping)			
	Mines and quarries			
An unsympathetic culture	Attitudes to saving assets from salinity threats, conservation values & their contribution to human quality of life			
Insufficient resources to maintain viable populations / asset value	Destruction of habitat (food, water, shelter, oxygen, access to mates)			
	Land clearing			
	Removing buffer / riparian vegetation			

Notes

(1) Probability that threat issue will cause goal failure with current management inputs: Spatial and temporal scales fixed as a basis for the probability analysis. The question being asked here is that, without additional management to that currently occurring, what is the probability that the specific threat-issue will result in non-achievement of the goal? It is proposed that probabilities of >0.25 need careful consideration with regard to the feasibility of their management.

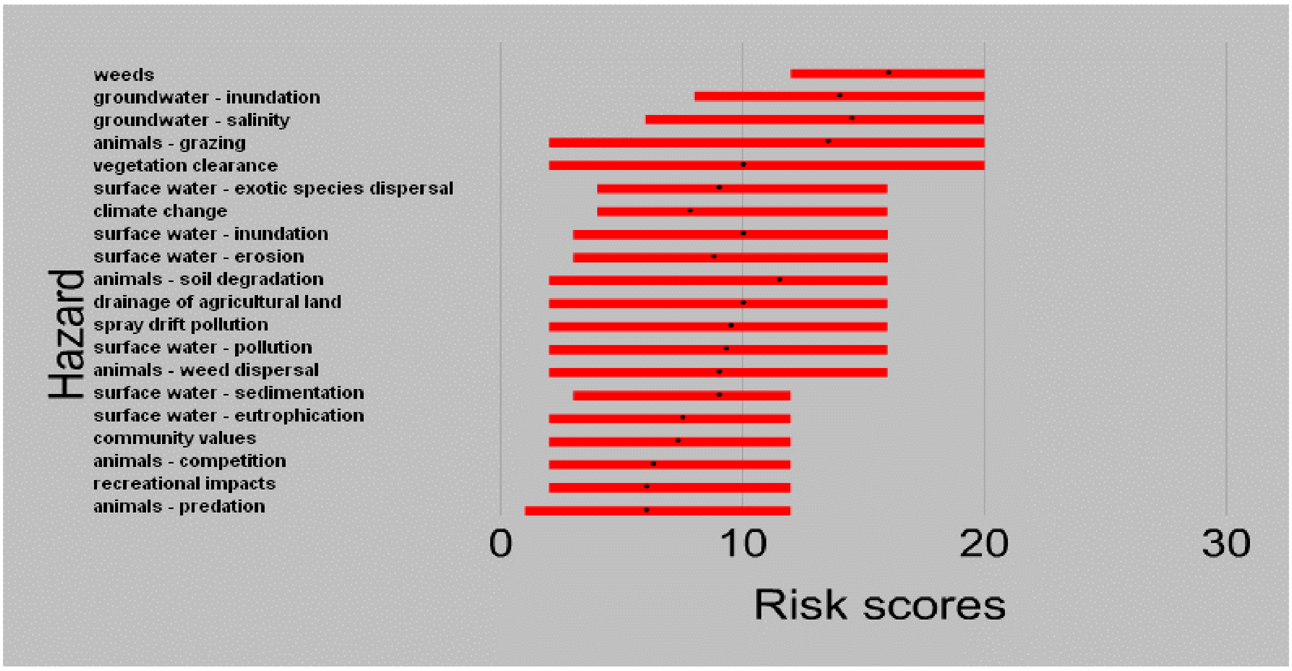
(2) Probability that threat issue will cause goal failure with additional management inputs: The question being asked here is what is the probability that, given a modest increase in management resources, the specific threat-issue will result in non-achievement of the goal? It is proposed here that probabilities of 0.2 or less represent a reasonable level of risk.

(3) It is essential that the assumptions or evidence underlying the assessment of each issue are described.

Appendix B

Subjective risk assessment for Buntine-Marchagee selected representative wetlands: (a) Bentonite (W059); (b) gypsum (W001); (c) sandy seep (W011); and (d) valley floor (W003). For each hazard, black dots indicate the average of four assessors' risk scores and red lines indicate the range of the scores. See section for 3.5 for further details.

(a)



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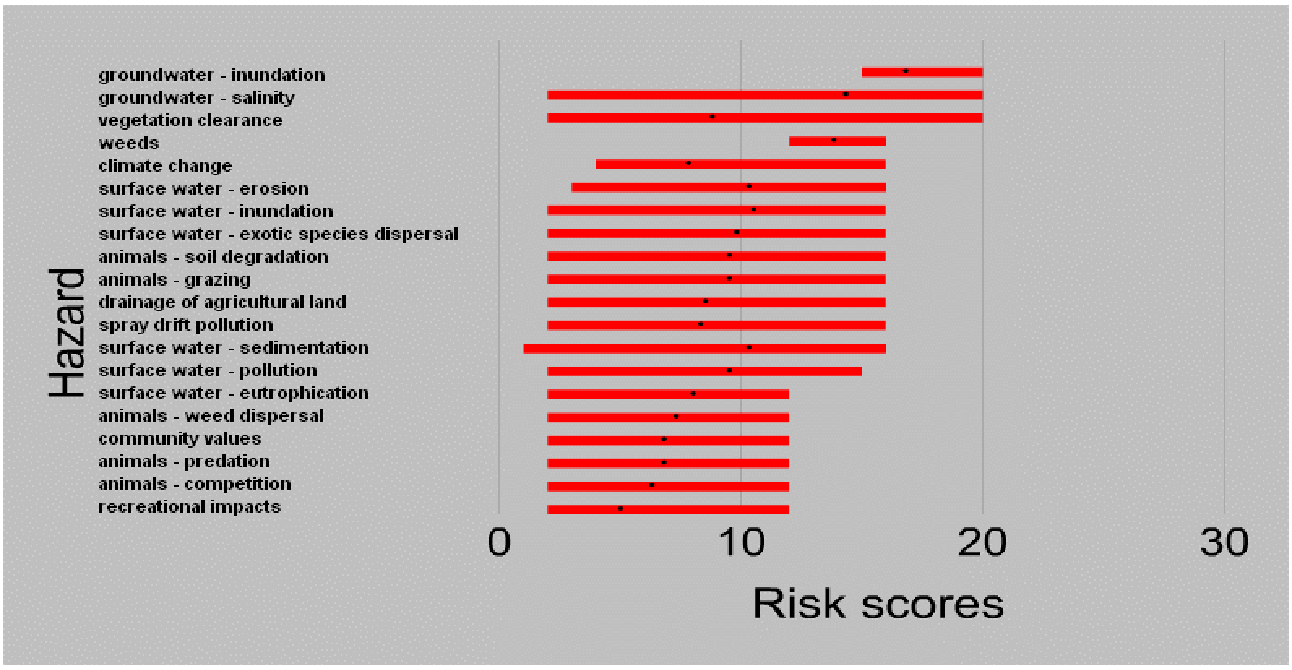

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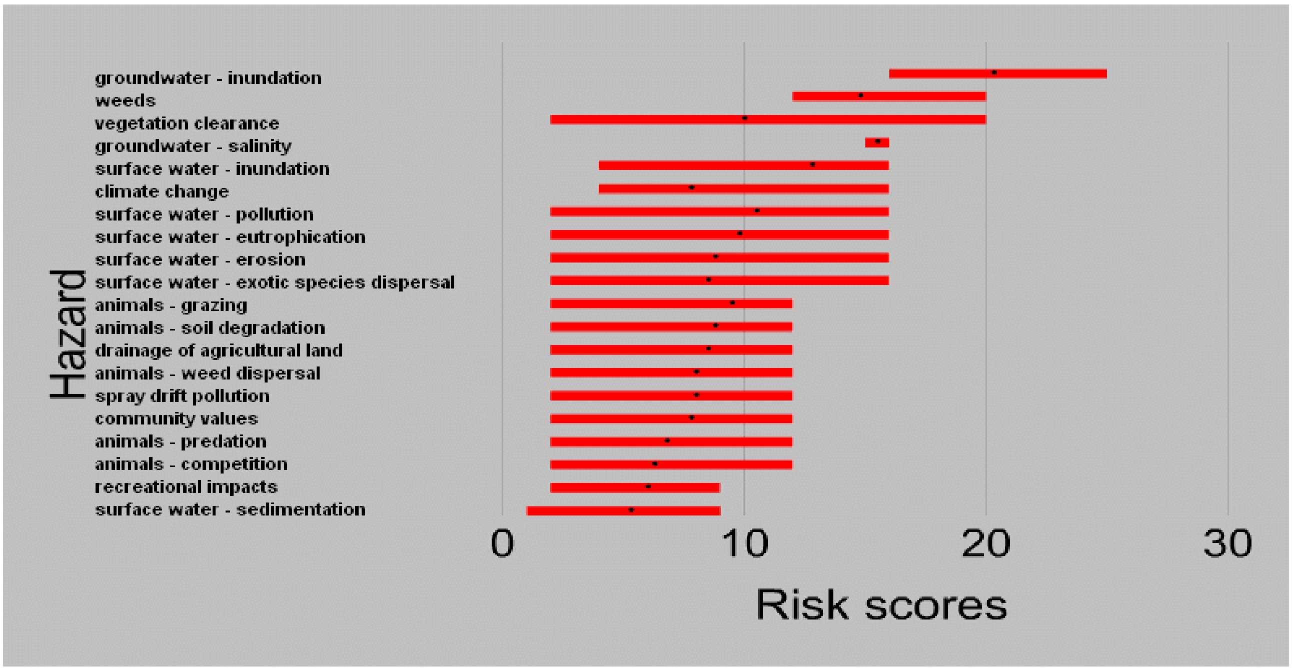
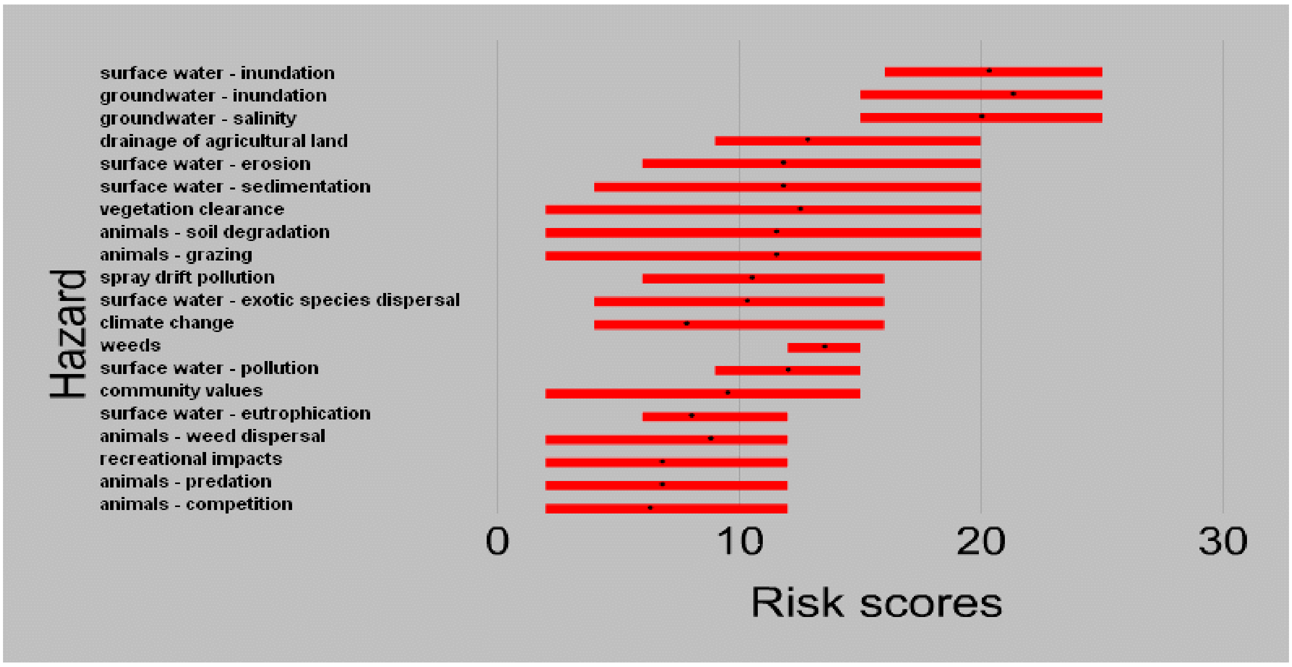

groundwater - inundation
weeds
vegetation clearance
groundwater - salinity
surface water - inundation
climate change
surface water - pollution
surface water - eutrophication
surface water - erosion
surface water - exotic species dispersal
animals - grazing
animals - soil degradation
drainage of agricultural land
animals - weed dispersal
spray drift pollution
community values
animals - predation
animals - competition
recreational impacts
surface water - sedimentation
Hazard
0
10
20
30
Risk scores

(d)


surface water - inundation
groundwater - inundation
groundwater - salinity
drainage of agricultural land
surface water - erosion
surface water - sedimentation
vegetation clearance
animals - soil degradation
animals - grazing
spray drift pollution
surface water - exotic species dispersal
climate change
weeds
surface water - pollution
community values
surface water - eutrophication
animals - weed dispersal
recreational impacts
animals - predation
animals - competition
Hazard
0
10
20
30
Risk scores