The Murray Darling Basin Authority

Developing a Bayesian Network for Basin Water Resources Risk Assessment

Technical Report:

Risk Assessment Tool for Water Resource Plans

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Context

Impacts from overallocation and drought have caused a widespread decline in the ecological health of the Murray-Darling Basin (Davies et al. 2008). The Basin Plan, as described in the Water Act (2007) is being developed to redress issues of overallocation of water resources.

Section 22(1)3 of the Water Act (2007) requires an identification of the risks to the condition, or continued availability, of the water resources within the Murray-Darling Basin. The risks considered must include the risks to the availability of water resources that arise from:

a) The taking and use of water (including through interception activities);
b) The effects of climate change;
c) Changes to land use; and
d) The limitations on the state of knowledge on the basis of which estimates about matters relating to basin water resources are made.

Section 22(1)5 of the Water Act 2007 requires strategies to be adopted to manage, or address, the risks identified under item 3.

The Basin scale risk assessment was initiated by the Murray-Darling Basin Authority (MDBA) to fulfil the risk requirements of the Water Act (2007). Bayesian networks were selected by the MDBA as the risk analysis tool as they fulfil the following needs:

- Integration: Bayesian networks are able to integrate a range of data types and existing models. Where data does not exist, qualitative information can be used. When this evidence is assembled in concert, the overall weight from individual threads of evidence can be assessed.
- Prioritisation: Ranking of risks to water resources can be determined through analysis of Bayesian network models.
- Flexibility: Models can be modified to suit the context in which they are applied. Models can also be updated as new knowledge is obtained.
- Adaptability: Bayesian networks can be updated over time and extended (e.g. to incorporate risk management scenario planning) if required.

In collaboration with the University of Canberra and the University of Melbourne, the Australian National University developed the Risk Analysis models to fulfil the Water Act (2007) risk assessment requirements, and for use in developing response strategies. The project objectives were to:

- Develop and apply a Risk Analysis tool to undertake a Risk Assessment at the Basin Scale, to meet the needs of the Basin Plan.
- Develop a set of Risk Analysis tools and protocols for use by the Basin States and the Territory for undertaking Risk Assessments at the Water Resource Planning Area (WRP area) scale (documented in Pollino et al. 2010).

This document contains: an introduction to risk assessment; an introduction to Bayesian networks; documents the framework and reporting requirements for the WRP risk assessment; introduces the generic WRP Bayesian network models; and introduces the KEA Bayesian network models.

The WRP area-scale approach outlined in this document will focus assessors on risks to water resources in the Murray-Darling Basin, where water resources are defined in the context of water availability, water quantity and ecological health. The WRP area tool has been road tested in two WRP regions, the Eastern Mount Lofty Ranges and the Murrumbidgee (Pollino et al. 2010a).

The outcomes of the WRP area assessment include:

- A sound risk assessment tool for use as part of the WRP process;
- Documentation of data and uncertainties in the risk analysis;
- Documentation of findings of the risk assessment;
- A prioritized list of risks to water resources within the WRP area; and
- A tool that can be extended to risk management, where appropriate.

Introduction

Risk is the chance, within a time frame, of an adverse event with specific consequences (Burgman 2005).

Risk assessment is a process used to collect, organise, integrate and analyse information for use in a planning environment, where the outcomes is the analysis and prioritisation of risks or hazards to a stated objective. Risk assessment methods can help bring disparate data and information into a consistent, testable and updateable assessment framework.

Risk management (or risk treatment) involves the development of strategies to minimise, monitor, and control the probability and/or impact of adverse events.

In its most basic of form, risk assessment involves evaluating the likelihood that adverse ecological effects may occur, or are occurring, as a result of exposure to one or more hazards, and the consequences of such an exposure (Pollard et al. 2008). A recognised framework for assessing and managing risk is provided in AS/NZS:4360 and is shown in Figure 1. The AS/NZS: 4360 risk management framework was used to guide the development of procedural arrangements for the risk assessment. A brief description of the generic risk assessment framework is given in Box 1.

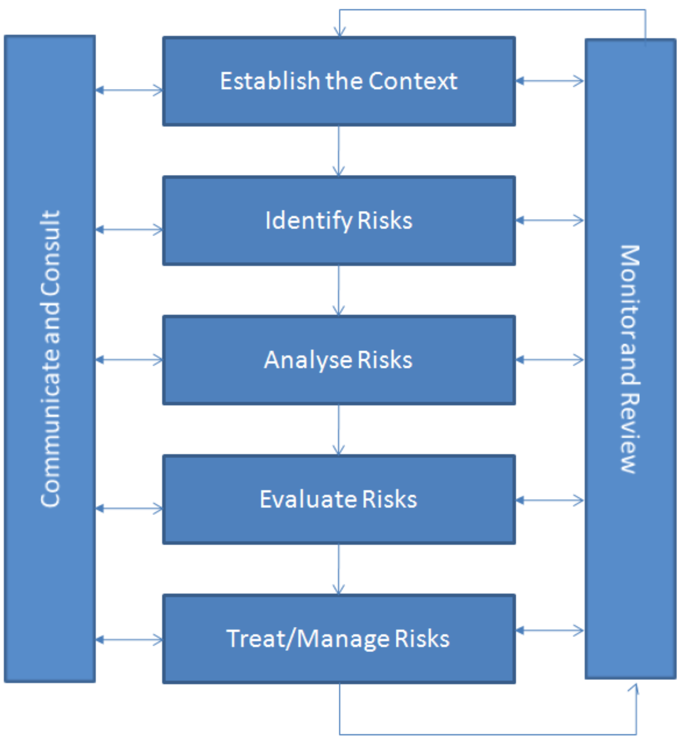

Figure 1: Risk management framework, modified from AS/NZS: 4360

The outcome of a risk assessment and risk management process is an improved understanding and prioritisation of risks for a given system, and guidance on the implementation of appropriate risk reduction strategies.

> Box 1: Description of the AS/NZS: 4360 risk management framework
>
> The context of the risk assessment is defined through specification of objectives and key elements and the scales of assessment. Risk identification is used to establish the relationships between the focus of the risk (e.g. risk objectives or system values) and existing and possible hazards or stressors. Typically, this involves the development of conceptual models. The risk analysis phase involves collection of data and other knowledge and (where possible) quantification of the relationship between stressor levels and ecological effects. The risk to the risk objectives or identified system values and the prioritisation of stressors are estimated in the risk evaluation step. These outcomes form the basis of the risk assessment findings. Treatment or management of risk occurs through the development of risk management scenarios, where alternative risk management options can be developed, and their effectiveness determined. Monitoring and acquisition of new data may occur in support of any of these phases. Communication and consultation throughout the process is highly recommended to strengthen assessment rigour.

Risk analysis techniques have progressed from single-point deterministic risk analyses (e.g. risk matrix) to allow probabilistic expressions of risk factors across a range of outcomes (Pollard et al. 2008). Such probabilistic expressions of risk can take a range of forms (Figure 2).

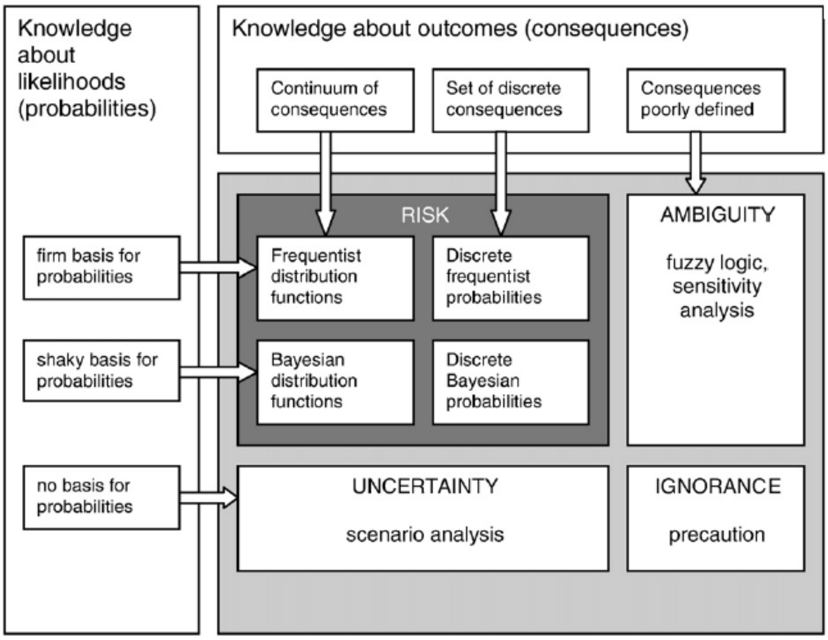

Figure 2: Categorising risks within environmental decision making (Pollard et al. 2008) after (Stirling 2001)

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Advances in the analysis of risk allows for greater complexity and better representation of uncertainties. This promotes transparency in decision-making and more realistic and testable outcomes. Evidence and institutional knowledge play a critical role in the success and implementation of risk assessment and management.[1]

Within the WRP area assessment process, the context of the assessment and factors included in the assessment have been defined within the context of the Water Act (2007) and the Basin Plan, in consultation with Commonwealth and State bodies and water resource experts. Generic Bayesian networks are provided for the risk analysis step. The process of how to undertake the risk assessment for a WRP area is outlined in further detail below.

Bayesian networks and Risk Assessment

Bayesian networks are probabilistic graphical models that are increasingly being applied in environmental and risk domains where considerable uncertainty exists (e.g. (Hart and Pollino 2008; Hart and Pollino 2009; Marcot et al. 2006; Newman and Evans 2002; Pollino and Hart 2008; Pollino et al. 2007a; Pollino et al. 2007b; Sikder et al. 2006; Varis 1997; Wooldridge and Done 2003)). As decision support tools, Bayesian networks can be used to analyse complex problems, prioritise hazards, and support decision-making in an adaptive process, where knowledge is incomplete (Hart and Pollino 2009). For a description and review of Bayesian networks in natural resource management and policy, see (Pollino and Henderson 2010).

Bayesian networks are ideal for assisting decision-making where evidence is incomplete, contradictory or disparate. Unlike many other risk analysis methods, they make use of a range of data types, concepts and assumptions for which a range of evidence of varying quality exists. When this evidence is assembled in concert, the overall weight from individual threads can support in prioritising, and where relevant, managing risks.

The risk assessment and management cycle and the process used to build a Bayesian network are highly complementary (Figure 3) where the outcome of each part of the risk assessment cycle can be formalised within a Bayesian network. Where appropriate, risk management strategies, and the probability of their success, can be built and tested within the Bayesian network (Pollino et al. 2008).

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[1] For more information on risk assessment in decision making environments, see Burgman M. 2005. Risks and decisions for conservation and environmental management. Melbourne: Cambridge University Press, Gouldson A, Morton A, Pollard SJT. 2009. Better environmental regulation -- contributions from risk-based decision-making. Science of the Total Environment 407(19):5283-5288, Pollard SJT, Davies GJ, Coley F, Lemon M. 2008. Better environmental decision making - Recent progress and future trends. Science of The Total Environment 400:20 - 31..

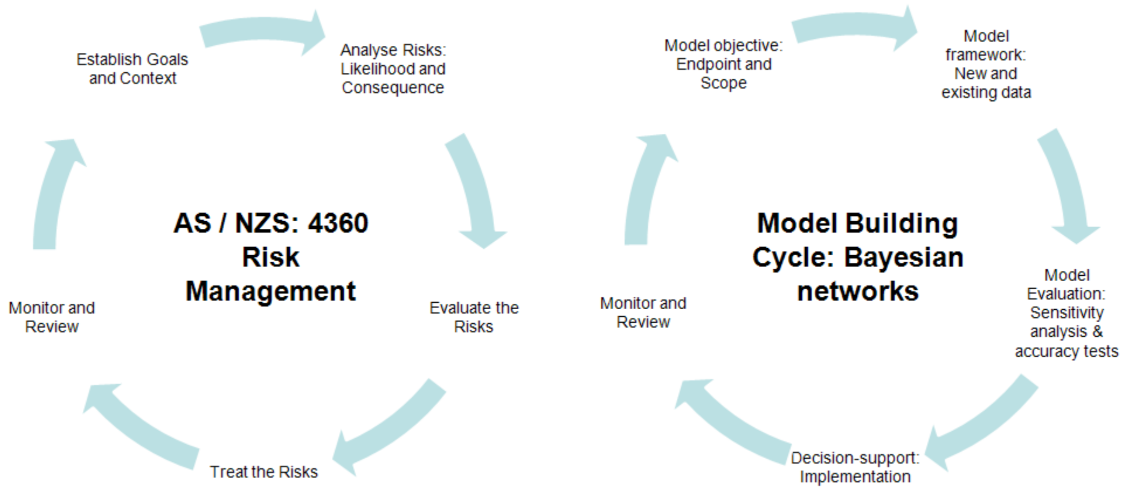


Figure 3: Cycle for Risk Management (Standards Australia / Standards New Zealand) and Bayesian network building cycle

The following section contains a description of Bayesian networks.

An Introduction to Bayesian networks

Bayesian networks are model-based decision support tools that are ideal for environments where considerable uncertainty exists, and for diverse problems of varying size and complexity, where disparate issues require consideration. The models are graphical, where the structure is used to describe the causal or correlative relationships between key factors and final outcomes. They maintain clarity by making causal assumptions explicit (Stow and Borsuk 2003) and are often used to model relationships not easily expressed using mathematical notation (Pearl 2000).

Being graphical, Bayesian networks are made up of a collection of variables (or nodes), which represent the relevant variables for analysis. Arrows (or arcs) describe relationships between variables (as in a conceptual model). To define the model structure, conceptual models, represented as influence diagrams, are used. Probabilities, which describe the strength of relationships between variables, can be defined using empirical data (observed data, monitoring data, modelled data, etc.), other 'parent' models, expert knowledge; or a combination of these. A conditional probability distribution (often defined as a conditional probability table or a CPT) is used to describe the relative likelihood of the state of each variable, conditional on every possible combination of parent variables.

Consultation, through workshops and via one-on-one meetings is an integral part of building a Bayesian network. Workshops can assist in developing or refining model structures, identifying and refining model inputs, and for reviewing model outputs.

Bayesian Probabilities

Bayesian probability interprets probability as "a measure of a state of knowledge", rather than as a frequency (as in Frequentist statistics). The Bayesian interpretation of probability is seen as an extension of logic that enables reasoning with uncertain statements. In order to evaluate the probability of a hypothesis, a prior probability (which can also be uninformative or 'flat') is used, which is updated with new relevant data.

Bayesian networks exploit the distributional simplifications of the network structure by calculating how probable certain events are, and how these probabilities can change given subsequent observations, or predict change given external interventions (Korb and Nicholson 2004). A prior (unconditional) probability represents the likelihood that an input parameter will be in a particular state; the conditional probability calculates the likelihood of the state of a parameter given the states of input parameters affecting it; and the posterior probability is the likelihood that a parameter will be in a particular state, given the input parameters, the conditional probabilities, and the rules governing how the probabilities combine. The network is solved when nodes have been updated using Bayes' Theorem:

$$P(A|B) = \frac{P(B|A)\,P(A)}{P(B)}$$

Where **P(A)** is the prior distribution of parameter **A**. After collection of data **B, P(A|B)** represents the posterior (new) distribution of **A** given the new knowledge **(B)**. **P(B|A)** is the likelihood function that links **A** and **B**.

Probabilities can be updated as new information becomes available, using Bayes' theorem. Being probabilistic, Bayesian networks readily incorporate uncertain information (Reckhow 2002), with uncertainties being reflected in the conditional probabilities defined for linkages (Rieman et al. 2001). When analysing risk, communication of uncertainties is essential. Sources of uncertainty can include imperfect understanding or incomplete knowledge of the state of a system, randomness in the mechanisms governing the behaviour of the system, or a combination of these factors. In ecology, modelling of processes using Bayesian networks is particularly useful as Bayesian inference provides a probability based approach that can update scientific knowledge when new information becomes available (Reckhow 2002).

Structure of a Bayesian network

The first step in constructing a Bayesian network is to develop a causal structure. Important criteria for inclusion of variables in Bayesian networks are that the variable is: (a) manageable, (b) predictable, or (c) observable at the scale of the management problem. This structure can be derived from conceptual models developed during the problem formulation phase.

The Bayesian network should represent interactions between hazards and the assessment endpoint(s) (Figure 4). The scales of interest can be linked to relevant variables. Interactions and interdependencies between variables can be captured in process nodes.

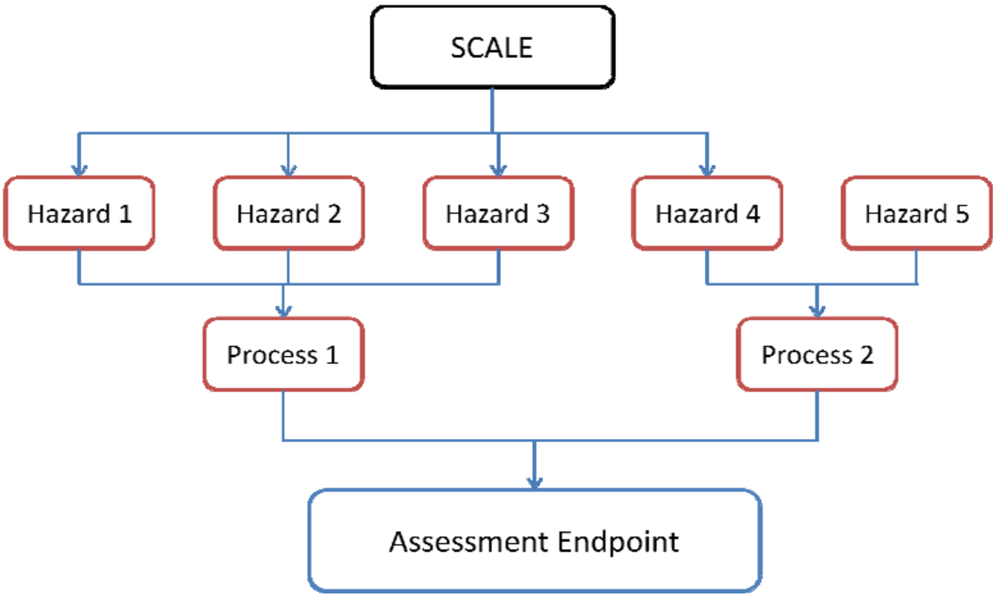


Figure 4: Basic layout of Risk Assessment Bayesian network models

The use of process nodes also simplifies the number of conditional probabilities to be estimated in the endpoint node. As each parent node is linked to a child node, the number of probabilities that need to be estimated increase exponentially.

Discretisation of Nodes: Assigning States

In order to represent continuous relationships in a Bayesian network, a continuous variable must be divided or discretised into a set of states. States can be qualitative or quantitative, categorical (e.g. Absent vs. Present; 0 vs 1) or continuous (represented as a set of discrete intervals), where numerical ranges are assigned (e.g. 0 to 3, 3 to 10). Nodes can be discretised according to guidelines, existing classifications or percentiles of data (Pollino and Henderson 2010). There is no limit on how many states can be defined, but it is important to note that as the number of states increase, so do the number of probabilities to be estimated.

Specification of Probabilities

After defining node states, the strength of relationships between nodes need to be described. A probability distribution is required to describe the relative likelihood of the state of each variable, conditional on every possible combination of parent variables (parent nodes lead into child nodes). This relationship is defined using a conditional probability tables (CPT). If a node has no parents, it can be described probabilistically by a marginal probability distribution.

The following example (Figure 5) shows how CPTs work within a simple Bayesian network, where nodes A and B (parent nodes) represent the causal factors of node C (child node). The example has been carried out using the Bayesian network programming shell Netica (http://www.norsys.com) (Norsys 2010).

In this example, all nodes are discretely binomial, with the states being defined as either true or false. A variable can be described by a finite number of states, which can be defined either qualitatively or quantitatively.

In the network shown in Figure 5, the probability distributions for each node have not yet been specified. Nodes A and B are described as parent nodes, and can be defined by marginal probabilities. Node C, however, is the child of A and B, and so the probabilities of the states of node C are conditional on how the states of A and B combine.

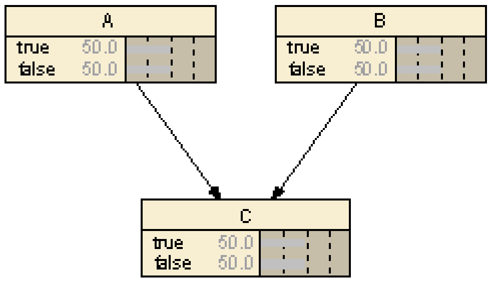
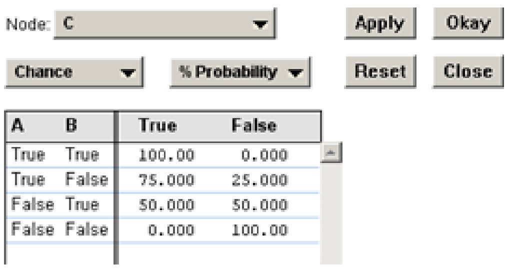


Figure 5: Example of a Bayesian network, showing variable states

The entries in a CPT can be 'parameterised' using a range of methods, including directly observed data (monitoring, research), probabilistic or empirical equations, results from model simulations, elicitation from expert knowledge, or a combination of these. The knowledge source should be documented for each variable.

In this example, direct expert elicitation is used. Elicitation often takes the form of scenarios, which are described as they appear in the table, e.g. given A is true and B is true, what is the probability that C is true (here 100%). The fully parameterised CPT is shown in Figure 6, shown here in the Netica (download: www.norsys.com) formatting. It is an important point to note, that the method used for probability generation must always be rigorously documented, including any assumptions and limitations.



A	B	True	False
True	True	100.00	0.000
True	False	75.000	25.000
False	True	50.000	50.000
False	False	0.000	100.00

Figure 6: Conditional Probability Table (CPT) for node C of the Bayesian network example

When the probability distributions of each node have been defined, the network is able to be 'solved', as shown in Figure 7 below. After evaluation tests, the Bayesian network is complete and can be used for scenario analysis.

A set of sub-models can be established within a Bayesian network. Sub-models can describe different processes (planning and implementation, physical or biological processes), relevant to the spatial scale specified. The impacts of these processes are aggregated into an output node, which relates directly to the outcome of interest (e.g. in the MDBA models, to the various water resource components of interest). Integration is done using CPTs, where weightings can also be applied.

Parameterisation using Datasets

Probabilistic relations can be specified from data (organised as case files). Data sources were entered into the network as a series of 'cases'. Cases can represent data collected during a monitoring program or as part of a research study. Data can be used to specify probability distributions, using learning algorithms in Netica (e.g. the Expectation Maximisation or EM algorithm function of Netica). The EM algorithm incorporates the Spiegelhalter Bayesian learning method (Spiegelhalter et al. 1993). Further details about parameterisation of Bayesian network models using data can be obtained from (Pollino and Henderson 2010).

Model evaluation

An important aspect in building a Bayesian network is evaluation. Evaluation of a Bayesian network requires assessing the model behaviour to determine if the model is representative of the system.

To evaluate the quantitative performance of the model three types of evaluation methods are discussed: sensitivity analysis, data-based evaluation and non-quantitative evaluation of model outputs using experts. Where possible, evaluation tests should be quantitative; however, this is not always possible. In cases where large data sets are not available (especially common in complex systems such as ecological and biological systems), a model review by an independent domain expert (e.g. an expert not engaged in constructing the model) can be used.

Bayesian networks can be evaluated using both empirical data and expert evaluation (Pollino et al. 2007b; Woodberry et al. 2004). Further, Bayesian methods can be used to test expert predictions against empirical data, assess expert bias, and to provide a framework for the efficient accumulation and use of evidence (Newman and Evans 2002; Pollino et al. 2007b).

Where empirical data is not available, model evaluation will be limited. Therefore the acquisition of empirical data, collected via adaptive management processes, should be seen as a crucial component of model evaluation (Sobehart et al. 2001).

Testing scenarios

To determine how probabilities change in response to external interventions (such as management actions) the simplest intervention is to enter evidence by assigning a fixed distribution to the parameter of interest. Thus, the original function is assigned a new function that specifies a value, with other variables being kept the same (Borsuk et al. 2004). The updated model represents the system's behaviour under the intervention and can be solved (through the propagation of probabilities) for the other variables to determine the net effect of the specified intervention. The effect of the scenario can be examined by its effect on other nodes, as illustrated in Figure 7. A scenario node can be used, which represents scenario options as variable states. For more information and examples using scenario nodes, see (Pollino and Henderson 2010).

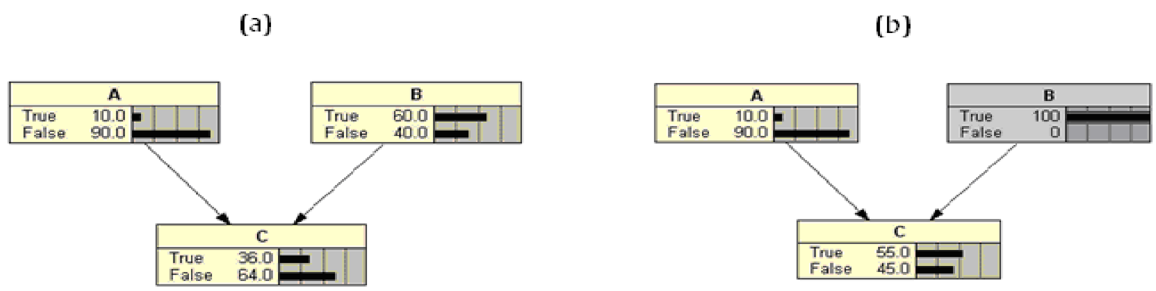


Figure 7: Bayesian network before (a) and after (b) the propagation of new information

Sensitivity Analysis: Prioritisation of Risks

Having established the structure of the model and the relationships used to drive the model, the key knowledge gaps and priority risks can be identified using sensitivity analysis. Sensitivity analysis can be used to investigate the uncertainties and inaccuracies in the model structure, relationships and outputs. Results can be represented using metrics such as mutual information or by plotting variation in a target node, where parent nodes are altered over probability ranges 0 to 1.

Analyses provide a ranking of the importance of variables, relative to the variable of interest (usually the output variable). This highlights where quantification of variables is particularly important and where knowledge gaps and data gaps exist. Based on these results, recommendations for targeted monitoring and future research can be made. As the results from sensitivity to findings can differ for different spatial areas or scenarios, key knowledge gaps and priority risks can also differ.

Using the WRP Area Risk Assessment Tool

The steps of the AS/NZS: 4360 risk assessment process (Figure 1) can be used to guide the risk assessor through the risk assessment process for the WRP. Associated with each of these steps is a reporting requirement, and in order for the risk assessment outcomes to be complete, these reporting requirements should be met.

Risk Assessment: Problem Formulation

The problem formulation step is used to establish the context for the risk assessment. To fulfil the problem formulation component of a risk assessment, the following need to be defined:

- Assessment endpoints;
- Scales of assessment; and
- Conceptual models.

When this part of the assessment is complete, risk assessors should have a clear focus for the assessment and a plan for the analysis phase.

Assessment endpoints

An assessment endpoint (or assessment objective) is an explicit expression of the environmental value that is to be protected, operationally defined by an ecological entity and its attributes (EPA 2008).

Section 22 of the Water Act outlines the following mandatory requirements for the Basin and WRP area scale risk assessments. The Water Act (2007) Section 22 (3), states that the assessment must include an identification of the risks to the condition, or continued availability, of the Basin water resources.

Water resources have been defined by the Act as:

(a) Surface or groundwater;
(b) A watercourse, lake, wetland or aquifer (whether or not it currently has water in it); and
(c) Includes all aspects of the water resource (including water, organisms and other components and ecosystems that contribute to the physical state and environmental value of the water resource).

Accordingly, the risk endpoints considered in this report are:

- Insufficient water available for the environment;
- Inadequate water quality to meet the needs of all uses; and
- Declining ecological health of water dependent ecosystems.

Considering the context of the Act and the Basin Plan, the risk assessment needs to consider: Sustainable Diversion Limits (SDLs) and the Environmental Watering Plan (EWP).

Associated with endpoints are a set of hazards, which include (but are not confined to) those outlined in the Water Act (2007). These hazards were defined by the MDBA, in consultation with Commonwealth, State and Regional bodies and water resource experts. The hazards that are to be assessed for the WRP area are documented within the descriptions of models. Each of these factors needs to be considered as part of the WRP area risk assessment; however, if a hazard is deemed irrelevant at the WRP area scale, it can be excluded. Documentary requirements within the tool require formal justifications where such decisions are made.

Scales of assessment

Clear definitions of scales, both spatial and temporal, are required to guide the data collection and aggregation process to measure assessment endpoints.

Understanding the basic characteristics of the WRP area is necessary as it provides the context for evaluating the risks of concern, and in determining which of the WRP area resources may be at risk. At a minimum, the risk assessment is to be undertaken at the whole of WRP area-scale. However, assessors can also undertake the risk assessment processes at sub-WRP area scales (to reflect scales of processes, different catchments or to reflect the scales of alternative risk management activities within different areas of the WRP area). Where multiple SDLs occur within a single WRP area, these can be considered explicitly in the model. This will simplify the preparation of data to inform the model. Where data has been referenced spatially, a spatial variable can be included in the risk analysis model. The scale of the assessment will also differ for groundwater and surface groundwater WRP areas defined within the Basin Plan.

Separate assessment tools are provided in this report, which focus on Type A Key Environmental Assets. These will need to be considered within their relevant WRP areas.

The timeframe for the assessment is from implementation of the WRP to the review of that WRP (i.e. Ten years).

Conceptual model

A conceptual model (also known as an influence diagram) is used to explicitly represent the interrelationships between resources, stressors and effects, and can assist in focusing the risk analysis phase. Conceptual models should be developed as part of a consultative process. Conceptual models include the ‘what can happen’ and ‘how can this happen’ aspects of the risk assessment, within the context defined above. The outcomes of this step should reflect appropriate scales, and language should be sufficiently specific so as to avoid ambiguity in the assessment.

For the WRP, conceptual models are required for:

- Risk 1: The risk of not meeting the sustainable diversion limit (SDL);
- Risk 2: Inadequate water quality to meet the needs of all uses; and
- Risk 3: The risk to water dependent ecosystems.

Refining the WRP conceptual models

Documented within this risk assessment tool are conceptual models (shown as Bayesian network structures) for each of the three risk components (water availability, water quality and water dependent ecosystems) making up the Basin water resources (Appendix 1). These conceptual models incorporate important factors that could impact on water resources at WRP scales across the Basin and can be modified based on specific knowledge of your WRP area. Factors that are not relevant at the WRP area scale can be removed; however, this should be documented and justified. It is highly recommended that a consultative exercise be undertaken within this step, to aid in maintaining the rigor and credibility of the assessment outcomes. A consultative process also ensures that existing, new and emerging issues are considered as part of the assessment.

The conceptual model should consolidate, in graphical form, relationships between activities and hazards and their effects on risk outcomes. In the conceptual models, causal relationships are assigned based on best professional judgment, and can be guided by existing models or other information. Evaluating available information will assist in identifying known and potential (unknown) relationships within conceptual models, and much of the assessment will focus on obtaining an improved understanding of these relationships. This step will help determine the types and extent of data and other knowledge required.

In this step, the available information for risk analysis (type, quantity and quality) is to be documented. This documentation will be updated throughout the subsequent steps in the assessment process. Gaps in knowledge and data may be identified; however, this variable or relationship in the risk analysis step.

Documenting outcomes: Problem formulation

A clear statement of the objectives and key elements of the WRP area risk assessment and the scales over which the assessment is being applied should be made. The context for the assessment must be consistent with, Section 22 of the Water Act (2007).

As stated above, additional factors can be included for consideration, and documented as part of the reporting process. Any factors that are considered irrelevant at the WRP area scale can also be removed with justification. Select variables in the conceptual models are mandatory (as defined in the Act), and must be included in the risk assessment; these are documented in the 'WRP Risk Assessment models' section.

On completion of the risk identification phase, documentation is required and must include:

- Refined WRP area conceptual models, showing relationships among hazards, ecological resources, and effects;
- Documentation of what factors have been added or removed from the generic conceptual models (Appendix 1: Bayesian network structures); and
- Documentation of what data and knowledge inputs are required to quantify risks.

Risk analysis

The risk analysis step should be guided by the outcomes of problem formulation, as follows: definition of assessment objectives, scope, conceptual models, available data and knowledge for the analysis, and knowledge gaps. This information will assist in determining which of the variables will be used in the Bayesian network risk analysis models. Using the Bayesian networks, the significance of each of the causal factors in the models will be assessed to give an overall description of risk.

The analysis phase includes characterisation of the hazard and the endpoint(s), as documented in the conceptual model. The steps in this phase are significantly more technical and quantitative than in the problem formulation phase, and require the use of data, model outputs, and expert opinion where data gaps exist.

Ideally, in a risk assessment, the risk analysis step would be wholly quantitative. However, this is rarely possible for complex systems such as WRP areas, which are affected by multiple hazards, and where quantitative information for describing hazards and their effects are incomplete. Consequently, best professional judgment and a "weight of scientific evidence" approach are required to address information gaps. However, the associated limitations of this approach should be noted.

Bayesian network models

The risk analysis step involves quantifying the likelihood of a variable being in a particular state, and the likely outcome to risk objectives, given this distribution across states. As outlined above, conceptual models form the basis for defining the causal linkages in the Bayesian network structure. Documented within this tool are generic Bayesian network structures (Appendix 1) that describe the three risk assessment endpoints. These networks have been developed in consultation with Commonwealth and State bodies and water resource experts. They have also been tested in two WRP area regions (documented in (Pollino et al. 2010a)). These networks can be refined to better focus on the issues relevant to the WRP area.

Defining variable states

The Bayesian networks provided within this tool have default variable states. States vary from being qualitative (e.g. Low, Medium, High) to quantitative (thresholds). For some models, these states will need to be modified for WRP areas, and in some cases, within WRPs. For example, water quality thresholds vary across WRP areas and within WRP areas. Default states, and the process for refining states, is documented within each model.

Defining causal relationships

The Bayesian networks provided within this tool also have default conditional probability distributions (describing relationships between nodes) defined using equations or equal weighting of variables. In risks 1 and 3, select variables also have differential (unequal) weightings. Where changes are made to the structure, these default distributions and weightings will require adjustment (as documented within the descriptions of each model). These changes also need to be documented.

Building evidence to evaluate causality is an area of active research. Hill (1965) developed criteria for assessing causality in epidemiological studies (Hill 1965), and such an approach is also being explored for ecological situations. The Causal Criteria tool developed by the eWater Cooperative Research Centre (Norris et al. 2008) can be used to build an evidence base for causality using Hill's criteria.

Data input variables

Each Bayesian network model has an associated set of input variables, where information or data specific to the WRP area is required to be entered by the risk assessor. Recommended sources for inputs are varied. These are documented within the descriptions of each model.

Quality assessment of inputs

Risk implies uncertainty and uncertainty comes from a range of sources, including variability in natural systems and lack of knowledge. The quality of knowledge can also vary and this has implications on the robustness of an assessment. For example, a risk assessor may use statistical techniques or mathematical models to quantify the relationship between a hazard and an ecological resource. To do this, extrapolations (e.g. across scales) may be required; and synthesis of different sources of literature may also play an important role. Representation of uncertainties ensures that the credibility and transparency of the risk assessment is upheld. The way in which these data sources vary in the quality of the input they can provide is illustrated in Table 1.

An evaluation of the quality of inputs to the risk analysis model needs to be completed by the risk assessor for select data input nodes in risk models. The level of uncertainty associated with the knowledge quality will be used as input to models for quantifying risk. The schema (Table 1) used to assess the quality (Low, Medium, and High) of knowledge in the risk analysis models was derived using (Bowden 2004; Marsh et al. 2007). The quality assessment assists in determining the rigour and credibility of the assessment outcomes, and assists in the next assessment step, risk evaluation, where priority risks are identified.

Table 1: Quality ranking for different inputs to the risk analysis Bayesian networks

Rank	Statistical analyses	Process-based model	Database	Literature	Expert
High	High calibration with data (≥95%)	Comprehensive validation using independent data set	Large sample, Multiple sites & times. Best practice design and collection methods	Published in peer reviewed forum	Multiple experts – high consensus
Medium	Moderately well calibrated with data (90 – <95%)	Some validation using independent data set	Limited sampling. Accepted design and collection methods	Non-peer reviewed publication	Multiple experts – partial consensus
Low	Poor calibration with data (< 90%)	No validation presented	Small sample, single site & time. Poor design and collection methods	Unreviewed publication	Single expert

Documenting outcomes: Risk analysis

Documentation of risk analysis outcomes should include:

- The Bayesian network structures being used for risk analysis;
- A record of where changes (structural, in the probabilities, or any other modifications) were made to the risk analysis models provided in the WRP area risk assessment tool, and a justification for these changes;
- A list of information sources used as inputs to the networks;
- A quality rating for each input to the risk analysis models;
- Documentation for limitations of the Bayesian networks not described above; and
- Useful additional analyses that could improve the assessment's certainty.

Outcomes of risk analysis: Risk evaluation

Risk evaluation involves identifying the relative importance of each risk to the risk outcome (risk prioritisation); and analysing the patterns of hazards, how they change over space and time, and what this means in terms of adverse effects. This analysis assists in improving our understanding of the strength of the associations between hazards and the risk outcomes. In the best case, there will be sufficient evidence in the Bayesian network to have a well established cause-and-effect relationship; however, given data limitations, this will not always be the case.

The outcomes of risk evaluation can be used to identify hazards that:

- Pose a risk to meeting Basin Plan objectives;
- Require ctive Risk management (as done for the Basin Plan risk management plan (Pollino and Glendining 2010)); and
- Identify what factors in the assessment can be removed from further consideration.

Risk outcomes

The risk outcomes need to be expressed as the percentage probability of being at Low, Moderate or High risk.

The risk estimates from the Bayesian network risk analysis need to be clearly communicated as a set of statements. The following are examples of such statements:

- There is a 20% chance of water availability not meeting the needs of key environmental assets within the WRP area, given the current state of knowledge of water requirements, predicted climate variability, and existing planning arrangements for water delivery.
- The likelihood of recreational water quality objectives for nutrients being exceeded is 30%, given predicted climate variability and existing land use within the WRP area.

Interpreting the significance of the risk translates possible risk estimates into a discussion of their consequences for the WRP area. This step may address the nature and magnitude of effects, spatial and temporal patterns of effects, and the potential for ecosystem recovery. The significance of predicted effects may vary considerably in their consequences for different types of ecological systems. For example, the loss of a small wetland area may be highly significant if it represents the only habitat available in an area for migratory birds, but negligible if it occurs among a number of small-sized wetlands.

Risk ranking

The description of each model outlines how sensitivity analysis can be used to assist in evaluating the important pathways within the Bayesian network. Sensitivity analysis can be used to explore the behaviour of complex models, and it allows us to study how the variation (or uncertainty) in the output of a model can be apportioned to different sources of variation in the input of a model. Through sensitivity analysis, we can begin to identify which variables in our models have the greatest influence on our model endpoints, as well as ordering the importance, strength and relevance of the inputs in determining the variation of the output.

Important pathways identified in the model can be the consequence of two types of outcomes: where an important causal pathway exists, and good evidence is available to support this, or where a gap in knowledge (i.e. uncertainty) exists. This type of output needs to be determined using the judgment of the risk assessor, using the sensitivity analysis results and the documentation of inputs from the risk analysis step.

Associated with the sensitivity results should be a discussion on the relative importance of attributes to the assessment endpoint, noting where sources of uncertainty in the model inputs are significant (i.e. were based on judgement of the risk assessor). Sources of uncertainty in Bayesian network models that require documentation include measurement error (e.g. inappropriate, imprecise or too few measurements), conditions of observation (e.g. extrapolation across scales), or limitations of input models (e.g. oversimplification of complex processes, limited calibration data, poor model fits to observed data, lack of representation of land use activities). Nested sensitivity analysis can also assist in determining the relative importance of parent variables to a child node within a sub-model of the Bayesian network.

The major outcome of this step is a better understanding of the stressor-response relationships, evaluating evidence for causality, and, when necessary, linking the effects that can be measured back to the effects of greatest interest (identified in problem formulation). These three components can be developed in any order, and the emphasis may be different depending on whether the objective of the assessment is to predict the effects associated with future change, or retrospectively analyse the causal factors influencing current state of ecological resources.

Documenting outcomes: Risk evaluation

The outcomes of the risk evaluation step need to be considered within the context established at the commencement of the assessment. The assessment needs to:

- Consider what the risks to water resources are over the life of the WRP
- Make as assessment against the risks in Section 22 (3) of the Water Act (2007) (this is mandatory);
- Rank the importance of risks to the risk objectives; and

- Identify the major sources of risk to the risks objectives, including knowledge uncertainty.

Outcomes need to be expressed as the percentage probability of being at Low, Moderate or High risk. For example:

- There is a 20% chance of water availability not meeting the needs of key environmental assets within the WRP area, given the current state of knowledge of water requirements, predicted climate variability, and existing planning arrangements for water delivery.
- The likelihood of recreational water quality objectives for nutrients being exceeded is 30%, given predicted climate variability and existing land use within the WRP area.

Assigning the significance or level of that risk for each assessment endpoint can be guided by the scheme used in the Basin Plan:

Risk Level	Low	Moderate	High
Based on Likelihood of the Risk Occurring	<40%	40–80%	>80%

Sensitivity analyses are used to identify the key factors contributing to the risk assessment endpoint. Examples of how to present and discuss this are provided in the documentation of the risk models. Associated with the sensitivity results should be a discussion on the relative importance of attributes to the assessment endpoint, noting where sources of uncertainty in the model inputs are significant (i.e. were based on judgement of the risk assessor). Nested sensitivity analysis can assist in determining the relative importance of parent variables to a child node within a sub-model of the Bayesian network.

Risk Management

Risk management (also referred to as Risk Treatment) is a process used to determine what actions are required to respond to the identified risks, so that the risk assessment outcomes directly inform the risk management strategy. It is possible to extend Bayesian networks (developed for risk analysis) to explicitly consider risk management options. Incorporating risk management options into a Bayesian network (as in Figure 8) allows the testing of risk management scenarios, e.g. the likely outcome of preventative versus reactive risk management.

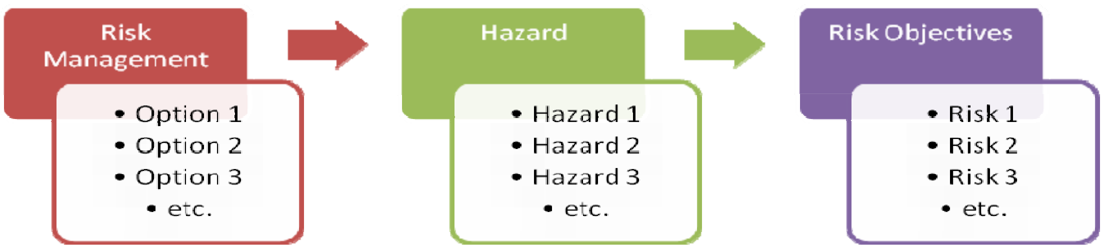


Figure 8: Representing risk management scenarios in Bayesian networks

Outcomes of the Bayesian network can also be used to explore prioritisation of risk management options, using prioritisation indices, such as those in (Cox 2009; Pollard et al. 2008). The following is an example of what a prioritisation index may look:

$$\text{Priority Index} = \frac{\text{Expected benefit of activity}^{2} \times \text{Likely success of activity}}{\text{Expected cost of activity}}$$

Finally, the risk must include the range of risk management options considered and evidence supporting the choice of the preferred option. Such evidence can include the breadth and quality of knowledge, the availability of corroborating information and any other supporting evidence of causality.

Monitor and review

The outputs of each of the risk assessment stages should be reviewed throughout and after the risk assessment process. Changes within the system, either physically or in the policy environment, or acquisition of new knowledge (e.g. literature review, field data, peer review or new analyses) should be considered throughout the assessment. Where changes do occur, the risk assessment process should be robust enough to be brought up to date. However, if the change is particularly significant, the whole process may need to be revisited.

The need for additional data acquisition can also occur during any phase in support of the assessment. Monitoring may provide data needed to improve estimation of hazard-response relationships, track patterns and changes in hazards, and to determine whether predicted effects are realised with time. Continued monitoring also provides a key feedback loop within the risk management process, in that detection of continued adverse effects after risk management actions will indicate the need for more effective action.

[2] Whether the outcome is private or public benefit may weight this outcome

Documenting outcomes of the WRP Risk Assessment

Documentation of outcomes is required for each risk assessment model:

- Risk 1: The risk of not meeting the sustainable diversion limit (SDL);
- Risk 2: Inadequate water quality to meet the needs of all uses; and
- Risk 3: The risks to water dependent ecosystems.

After risk characterisation is complete, assessors should have a better understanding of the risks at hand and a report that provides:

- A description of the WRP area risk assessment context;
- The refined WRP area conceptual models, with documented changes;
- Documentation of the major data and knowledge sources;
- Documentation on the quality of evidence;
- Documentation of assumptions used to bridge information gaps, and the basis for these assumptions;
- Model documentation (below); and
- Documentation of assessment findings.

For reporting WRP risk models, you should include:

- Documentations showing the definition of all model variables, including where changes to the generic Bayesian networks have been made;
- The state names and/or values, with reasoning and referencing, including where changes to the generic Bayesian networks have been made;
- The knowledge (data, literature, expert) inputs, with reasoning and references;
- The parameterization methods used (data, equation, expert) and the necessary information to recreate these (equations, CPTs);
- Outcomes of any model evaluation tests;
- The predictions of risk for the baseline and any scenarios tested;
- Sensitivity analysis, showing risk priorities; and
- Model discussion, including model limitations.

Examples of documentation are available in the Basin Plan risk assessment reports (Pollino et al. 2010b; Pollino et al. 2010c).

WRP Risk Assessment Models

Bayesian networks have been constructed for the following:

- The risk of not meeting the sustainable diversion limit (SDL);
- Inadequate water quality to meet the needs of all uses; and
- The risk to water dependent ecosystems.

The description of each model includes: an objective; the model structure; scales; required inputs; default nodes states; default weightings (if relevant); modification of the model (if relevant) and requirements for reporting outputs.

Note: all Bayesian networks for download are Netica files (available from: www.norsys.com).

Risk 1: The risk of not meeting the sustainable diversion limits (SDL)

Objective

The objective of this model is to assess risks to the Sustainable Diversion Limits in both the surface water and groundwater SDL areas within a Water Resource Planning Area. The model incorporates information to assess the quality of the knowledge base, current levels of planning and the level of public acceptance of the rules and regulations governing consumptive water use. It is not a hydrologic tool to assist with water accounting. The Risk 1 output is an input to Risk 3, recognizing that not meeting SDLs is likely to increase risks to meeting environmental watering requirement of water dependent ecosystems.

Model structure

The risk model takes into account:

- The quality of knowledge and capacity to quantify the various components of the water balance within each WRP area, both under current and future scenarios;
- The adequacy of existing management plans to provide for environmental water; and
- Public compliance factors.

While not easy to quantify, it is assumed that the following factors pose a risk to meeting the SDLs within a WRP area: a poor knowledge base, lack of a precautionary response to knowledge uncertainty within the existing water sharing plan and/or lack of a regulatory framework which promotes compliance.

Figure 9 shows the broad structure of the risk assessment model. The knowledge elements of the Bayesian network have been separated into surface water and groundwater components, but each includes an assessment of the knowledge of resource availability, consumptive use, and capacity to model alternative scenarios. Knowledge is assessed in terms of quality of data for quantifying the water balance component, as well as the significance of each form of take within the SDL area. Thus if knowledge of a particular form of take is poor, but that form of take does not occur within the SDL area, the assumed risk from lack of knowledge is considered to be minimal.

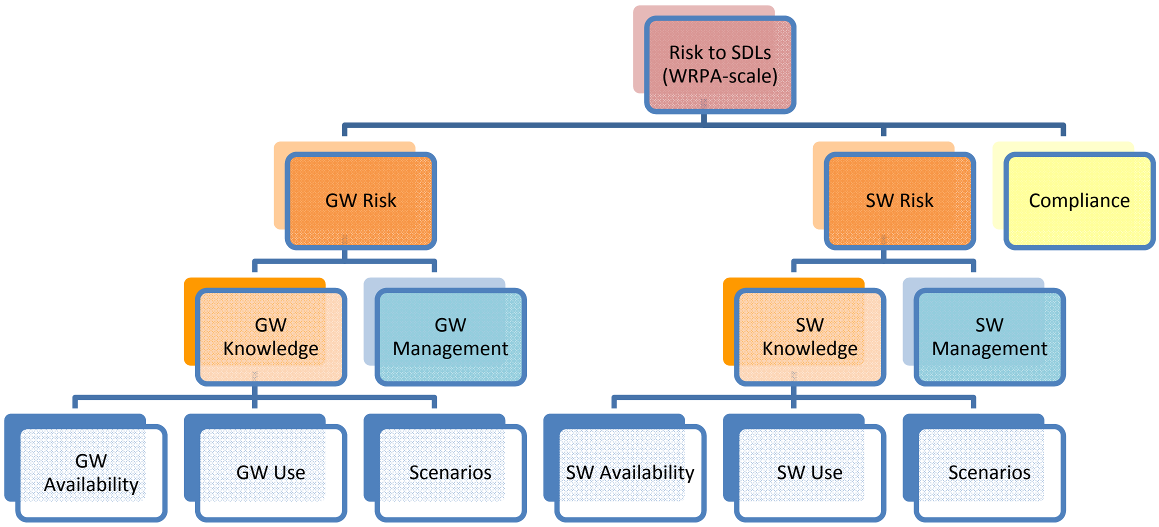


Figure 9 The key risk assessment components of the WRP area-scale Risk 1 Model.

Management of water resources, via existing water sharing plans, is included in the risk assessment, even though this involves a blurring of the distinction between a risk assessment and the risk management strategy that would normally flow on from it. The purpose here is to reflect the fact that water sharing plans already exist in the WRP areas that have been informed by the available information on water availability, consumption and projected changes in supply and demand. The model assumes that where the water sharing plan adopts a precautionary approach, which appropriately reflects the uncertainties arising from incomplete knowledge of the various components of the water balance, then the risk to the SDL will be lower than where the water sharing arrangements reflect an overly optimistic assessment of the supply-demand relationship.

The compliance section takes into account the risk to meeting the SDL from illegal take. It is assumed that climatic conditions, the existing regulatory and enforcement arrangements and the magnitude of the adjustment from existing extraction caps to new SDLs under the Basin Plan could all influence the public response to compliance. Practical constraints are included since the opportunity to access water is a prerequisite for any form of take. For example, the opportunity to pump water from a stream ceases, if the stream ceases to flow.

The compliance component also includes a node to represent the risk that the governing State suspends the WRP, as has occurred with the existing water sharing plans in New South Wales in recent years. How significant this risk will really be under the Basin Plan is likely to depend on the contingency planning within the Basin Plan. At the time of road-testing the WRP area scale models, this information was not available.

The risk from water trading was not included in the road test models, as it was not obvious that water trading poses a risk to the SDLs. If the rules governing water trading are regarded as a threat to SDLs being met, this risk would need to be incorporated into the risk assessment framework.

Scales

The WRP area-scale risk assessments need to take account of all the SDLs that have been set within the WRP area. This varies from WRP area to WRP area, but each will have at least one surface water SDL and one groundwater SDL.

Model inputs

The key elements of the risk assessment are identified in Figure 9, with detail shown in Figure 10. The recommended inputs are summarised in Table 2.

It should be noted that the input nodes listed in Table 2 are recommended because they demonstrate consideration of the various criteria which will be considered by the MDBA as part of the accreditation of water resource plans under the Basin Plan.

Generic Model Node States

The states adopted for each node in the generic model are summarised in Tables 3 and 4, and are based on states defined for the pilot models. These can be altered, as required, to better reflect the available data. The number of states used to classify input data should be appropriate for representing the relative differences in risk, and providing sufficient information about the input data to enhance interpretation of the model.

One model road test represented multiple surface water and groundwater WRP areas in the same framework. Consequently, the model needed to be tailored to enable selection of individual WRP areas. This meant including a 'None' state in the SW and GW WRP area nodes to 'switch' WRParea areas off. A consequence of this was that all input nodes that have SDL area specific data have an additional state 'Not_applicable' in the selection of possible states. This state has not been included for each node in Table 3 because its purpose is not to summarise SDL area information, but rather to allow a WRP area to be deactivated.

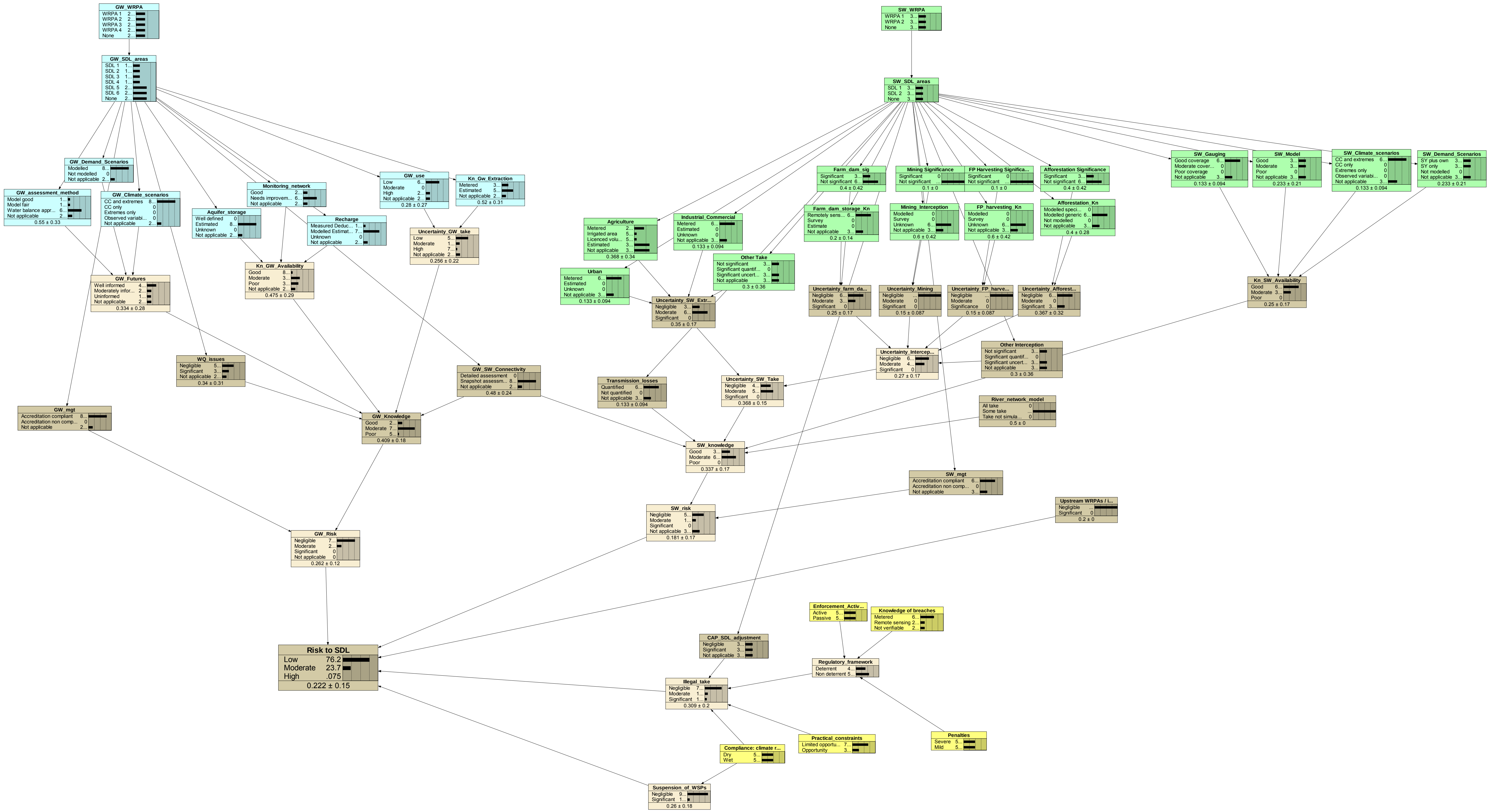


Figure 10: Risk 1 Bayesian network, showing data entry requirements for groundwater (blue), surface water (green) and compliance (yellow).

Table 2. Model inputs to the Risk of Not Meeting SDLs (column 3), grouped according to the main components shown in Figure 9

Main Component	Sub-grouping	Input Node	Description
Groundwater Knowledge	GW Availability	Aquifer Storage	Knowledge of water stored in developed aquifers
		Recharge	Knowledge of recharge rates to developed aquifers
		Monitoring Network	Extent to which developed aquifers are monitored
	GW Use	GW Extraction	Knowledge of extraction
		GW Use	To reflect the priority (significance) of extraction in the groundwater management zone.
	Scenarios	GW Assessment Method	Method and quality of model – calibration, validation and representation of processes
		Climate Scenarios	Water resource planning has included modelling of alternative climate regimes
		Demand Scenarios	Water resource planning has included modelling of alternative demand scenarios
	Other GW	Water Quality Issues	Risk that water quality issues could impact assessment of water availability
		GW-SW Connectivity	Knowledge of GW-SW interactions[3]
Surface Water Knowledge	SW Availability	Inflows Gauging	Coverage of gauging network – proportion of tributary inflows that are metered. Note presumption that gauging is reliable.
		SW Model	Quality of rainfall-runoff modelling – calibration, validation, representation of processes
	Scenarios	Climate Scenarios	Water resource planning has included modelling of alternative climate regimes
		Demand Scenarios	Water resource planning has included modelling of alternative demand scenarios
	SW Use - Take	Agriculture	Source (quality) of data informing estimates of water extraction for agriculture
		Industrial/Commercial	Source (quality) of data informing estimates of water extraction for industry/commerce
		Urban	Source (quality) of data informing estimates of water extraction for town water supply
		Other	Source (quality) of data informing

[3] Not a risk to the SDL *per se*, but assumption is that knowledge of connectivity will mean better planning and management of surface and groundwater systems.

			estimates of water extraction for other uses (fire-fighting, road construction…)
	SW Use - Interception	Afforestation	1. Source (quality) of data informing estimates of water intercepted by plantations 2. Significance of plantation forestry
		Farm Dams	1. Source (quality) of data informing estimates of water interception by farm dams 2. Significance of farm dams
		Floodplain Harvesting	1. Source (quality) of data informing estimates of flood waters intercepted on floodplains 2. Significance of floodplain harvesting
		Mining	1. Source (quality) of data informing estimates of water intercepted by mines 2. Significance of mining interception
		Other	1. Source (quality) of data informing estimates of other intercepted water 2. Significance of other forms of interception (NRM plantings; bushfires…)
Instream Routing		River Network Model	Capacity to model all inflows and outflows to river – i.e. extent to which impacts of extractions and interceptions are incorporated into the river model and propagated through the river system
		Transmission losses	Knowledge of transmission losses
		Upstream WRP areas	Risk from upstream WRP area(s) not meeting their SDLs**[4]
Management		Groundwater mgt	Is management of groundwater compliant with accreditation criteria? Assumes that the management plan takes account of knowledge uncertainty through adoption of precautionary approach – e.g. setting annual allocations conservatively
		Surface water mgt	Is management of surface water compliant with accreditation criteria? Assumes that the management plan takes account of knowledge uncertainty through adoption of precautionary approach – e.g. setting annual allocations conservatively

[4] Not clear how this is being handled - likely to be negligible if inflows from upstream WRP area are measured and assessment is based only on what happens within the WRP area. But this assumes that measurement of inflows is accurate.

Compliance		CAP-SDL adjustment	Risk from the change in take allowable under the SDL, relative to that under the Cap. Assumes that in WRP areas where the SDL involves a large reduction in the consumptive pool, there is a greater risk of illegal take (at least during some initial adjustment period).
		Climate regime	Assumes that the prevailing climate regime will influence the risk of illegal take – i.e. extended periods of drought will lead to more illegal take
		Practical constraints	Takes account of whether the opportunity exists to take water illegally – assumes that illegal take can only occur where a person has access to perennial river flows or groundwater during dry times
		Prosecutability	Knowledge of breaches – assumes that offences have a low probability of being prosecuted if the crime cannot be proven. So capacity to quantify illegal take and identify offenders is assumed to reduce risk of illegal take
		Penalties	Assumes that if penalties are set too low – i.e. are not commensurate with the crime – there is a greater risk of illegal take. Irrigators will more likely steal some water to finish a crop if the returns from the crop are significantly greater than the fine for stealing.
		Enforcement Activity	Assumes that if breaches of licence conditions are seen to be actively enforced, then there will be lower risk of illegal take than if there is little to no active enforcement.
		Suspension of WRPs	Recent experience indicates that States will exercise their right to suspend water sharing plans if the prevailing climate conditions pose a risk to basic water needs.

Table 3. States (and values) used for each input node in the default Risk of Not Meeting the SDL risk assessment model

Input Node	States (and values)
Aquifer Storage	Well_defined / Estimated / Unknown
Recharge	Measured_Deduced / Modelled_Estimated / Unknown
Monitoring Network	Good / Needs_Improvement
GW Extraction	Multiple_Sources / Metered / Irrigation Reports / Water Use Surveys (0.2 / 0.5 / 0.5 / 0.5)
GW Use	Low / Moderate / High (0.2 / 0.5 / 0.8)
GW Assessment Method	Model_good / Model_fair / Water_balance_approach
Climate Scenarios	CC_and_extremes / CC_only / Extremes_only / Observed_variability
Demand Scenarios	Modelled / Not_modelled
Water Quality Issues	Negligible / Significant (0.2 / 0.8)
GW-SW Connectivity	Detailed_assessment / Snapshot_assessment (0.2 / 0.6)
Inflows Gauging	Good_coverage / Moderate_coverage / Poor_coverage (0.2 / 0.5 / 0.8)
SW Model	Good / Moderate / Poor (0.2 / 0.5 / 0.8)
SW Climate Scenarios	CC_and_extremes / CC_only / Extremes_only / Observed_variability (0.2 / 0.4 / 0.3 / 0.6)
Demand Scenarios	SY_plus_own / SY_only / Not_modelled (0.2 / 0.5 / 0.8)
Agriculture - Knowledge	Metered / Irrigated_Area / Licensed_volume / Estimated (0.2 / 0.4 / 0.6 / 0.8)
Industrial/Commercial - Knowledge	Metered / Estimated / Unknown (0.2 / 0.4 / 0.8)
Urban - Knowledge	Metered / Estimated / Unknown (0.2 / 0.4 / 0.8)
Other Take - Knowledge	Not_significant /Significant_quantified / Significant_uncertain (0.1 / 0.3 / 0.8)
Afforestation - Knowledge	Modelled_specific / Modelled_generic / Not_modelled (0.3 / 0.6 / 0.9)
Afforestation - Significance	Significant / Not_significant (1.0 / 0.1)
Farm Dams - Knowledge	Remotely_sensed / Survey / Estimate (0.3 / 0.6 / 0.8)
Farm Dams - Significance	Significant / Not_significant (1.0 / 0.1)
Floodplain Harvesting - Knowledge	Modelled / Survey / Unknown (0.4 / 0.5 / 0.9)
Floodplain Harvesting - Significance	Significant / Not_significant (1.0 / 0.1)
Mining - Knowledge	Modelled / Survey / Unknown (0.4 / 0.5 / 0.9)

Mining - Significance	Significant / Not_significant (1.0 / 0.1)
Other Interception-Knowledge	Quantified / Not_quantified (0.2 / 0.8)
River Network Model	All_take / Some_take / Take_not_simulated (0.2 / 0.5 / 0.8)
Transmission Losses	Quantified / Not_quantified (0.2 / 0.8)
Upstream WRP areas	Negligible / Significant (0.2 / 0.8)
Groundwater mgt	Accreditation_compliant / Accreditation_non_compliant
Surface water mgt	Accreditation_compliant / Accreditation_non_compliant
CAP-SDL adjustment	Negligible / Significant
Climate regime	Dry / Wet
Practical constraints	Limited_opportunity / Opportunity
Knowledge of breaches (Prosecutability)	Metered / Remote_sensing / Not_verifiable
Penalties	Severe / Mild
Enforcement Activity	Active / Passive
Suspension of WSPs	Negligible / Significant (0.2 / 0.8)

Table 4. Variables, descriptions and states (and values) used for each aggregation variable (nodes with CPTs) in the default Risk of Not Meeting the SDL risk assessment model

Aggregation variable	Description	States (and values)
Kn_GW_Availability	Summary of knowledge of groundwater availability	Good / Moderate / Poor (0.2 / 0.5 / 0.8)
GW_Futures	Knowledge of groundwater futures (sustainable yield)	Well_Informed / Moderately_Informed / Uninformed (0.2 / 0.5 / 0.8)
Uncertainty_GW_take	Uncertainty in the knowledge of groundwater take	Low / Moderate / High (0.2 / 0.5 / 0.8)
GW_Knowledge	Summary description of the knowledge of groundwater	Good / Moderate / Poor (0-0.3 / 0.3-0.7 / 0.7-1.0)
GW_Risk	Risks to groundwater given status of knowledge and management	Negligible / Moderate / Significant (0.2 / 0.5 / 0.8)
Kn_SW_Availability	Summary of knowledge of surface water availability	Good / Moderate / Poor (0-0.3 / 0.3-0.6 / 0.6-1.0)
Uncertainty_Afforestation	Uncertainty in modelling of interception: Afforestation	Negligible / Moderate / Significant (0-0.3 / 0.3-0.6 / 0.6-1.0)
Uncertainty_FP_harvesting	Uncertainty in modelling of floodplain harvesting	Negligible / Moderate / Significant (0-0.3 / 0.3-0.6 / 0.6-1.0)
Uncertainty_Mining	Uncertainty in modelling of take and interception: Mining	Negligible / Moderate / Significant (0-0.3 / 0.3-0.6 / 0.6-1.0)
Uncertainty_farm_dams	Uncertainty in modelling of take and non-modelled take of farm dams	Negligible / Moderate / Significant (0-0.3 / 0.3-0.6 / 0.6-1.0)
Uncertainty_Interception	Uncertainty in interceptions not considered elsewhere in the Risk 1 model	Negligible / Moderate / Significant (0-0.3 / 0.3-0.6 / 0.6-1.0)
Uncertainty_SW_Extraction	ummary of uncertainty in knowledge and modelling of surface water extractions	Negligible / Moderate / Significant (0.8-1.2 / 1.2-1.7 / 1.7-1.9)
Uncertainty_SW_Take	Summary of uncertainty in knowledge and modelling of surface water take	Negligible / Moderate / Significant (0.2 / 0.5 / 0.8)

SW_knowledge	Summary of uncertainty in knowledge and modelling of surface water	Good / Moderate / Poor (0-0.3 / 0.3-0.6 / 0.6-1.0)
SW_risk	Risks to surface water given status of knowledge and management	Negligible / Moderate / Significant (0.2 / 0.5 / 0.8)
Regulatory_framework	Summary description of enforcement, given knowledge of breaches, enforcement activities and penalties	Deterrent / Non_deterrent
Illegal_take	Likelihood of illegal take, given climate period, practical constraints, adjustment between the Cap and SDl, and the regulatory framework	Negligible / Moderate / Significant (0.2 / 0.5 / 0.8)
Risk	Risk to SDL	Negligible / Moderate / Significant (0-0.3 / 0.3-0.6 / 0.6-1.0)

Generic Model Relationships

Relationships between variables can be derived a number of different ways:

1. Assigning values (or weights) to each state within a node;
2. Use of nodes specifically to reflect significance;
3. Weights incorporated into equations, used to combine inputs from multiple nodes into a single node; or
4. Manually populating conditional probability tables to capture the relative significance of different input nodes.

The choice of method might be influenced by the number of nodes and states being combined (e.g. it is time-consuming to manually populate conditional probability tables with large number of combinations of states, so using an equation to generate the CPT is more expedient), by a desire to provide transparency in the structure of the risk model, and/or because a standard relationship between input nodes exists. In the generic model, all of these approaches have been used. Table 5 summarises the method for combining nodes for each of the child nodes of the Risk 1 model. The associated CPTs for each of the nodes of the generic model can be accessed from the model file (Risk1_Generic.neta), in Appendix 1.

In the first approach, the value is used to reflect the level of risk associated with a particular state. Thus, a well-calibrated model is assumed to carry a lower risk, in terms of water accounting, than a poorly-calibrated model. Thus in the SW_model node, the risk values have been set at 0.2 for a Good model and 0.8 for a Poor model. Table 3 and 4 provide the values that have been assigned to each node for input nodes and CPT nodes, respectively.

In the second approach, a node can be incorporated into the risk assessment framework specifically to indicate significance of another node. This is a very transparent way of introducing weightings. In the generic model, this approach has been used to represent each of the interception activities – e.g. there is a node for knowledge of water intercepted by floodplain harvesting (FP_harvesting_Kn) and there is a separate node which represents the significance of floodplain harvesting in the WRP area (FP_Harvesting_Significance). While the first node reflects the quality of information available to quantify water intercepted via floodplain harvesting, the second node simply reflects whether floodplain harvesting is a significant activity in the WRP area: if significant, a value of 1 has been assigned to the state; if not significant, a value of 0.1 has been assigned. When the uncertainty associated with floodplain harvesting is computed (Uncertainty_FP_harvesting), the equation adopted is simply FP_Harvesting_Significance * FP_harvesting_Kn.

When an equation is used to combine the values from multiple input nodes into a single value, weights can be used to put greater emphasis on some nodes relative to others, as in Table 5 and Table 6. In an unweighted combination, a simple sum or average of the input values can be used. In a weighted combination, such as the Knowledge of surface water availability node (Kn_SW_availability) in the generic model, the quality of gauging and modelling have been accorded greater significance (0.35 each) than the modelling of alternative climate futures (0.2) and alternative demand futures (0.1). In other words, the model assumes that a WRP area that does not having good monitoring of inflows and/or a well calibrated rainfall-runoff models is at greater risk of not meeting its SDLs than if the WRP area has not undertaken alternate climate and demand future modelling.

Table 5. Method used to combine nodes to generate conditional probability tables (CPT), and the weights assigned (as appropriate).

CPT	Input Nodes	Parametrisation Method	Weights
Kn_GW_Availability	Aquifer_storage Monitoring_network Recharge	Manual	
GW_Futures	GW_Climate_scenarios GW_Demand_Scenarios GW_model	Manual	
Uncertainty_GW_take	Kn_GW_Extraction GW_use	Manual	
GW_Knowledge	GW_Futures GW_SW_Connectivity Kn_GW_Availability Uncertainty_GW_take WQ_issues	Equation (weighted)	0.2 0.1 0.3 0.3 0.1
GW_Risk	GW_Knowledge GW_mgt	Manual	
Kn_SW_Availability	SW_Climate_scenarios SW_Demand_Scenarios SW_Gauging SW_Model	Equation (weighted)	0.2 0.1 0.35 0.35
Uncertainty_Afforestation	Afforestation_Kn Afforestation_sig	Significance node	
Uncertainty_FP_harvesting	FP_harvesting_Kn FP_harvesting_sig	Significance node	
Uncertainty_Mining	Mining_Kn Mining_sig	Significance node	
Uncertainty_farm_dams	Farm_dam_sig Farm_dam_storage_Kn	Significance node	
Uncertainty_Interception	Misc_Interception Uncertainty_Afforestation Uncertainty_FP_harvesting Uncertainty_Mining Uncertainty_farm_dams	Equation (average)	
Uncertainty_SW_Extraction	Agriculture Industrial_Commercial Other_Take Urban	Equation (sum)	
Uncertainty_SW_Take	Uncertainty_Interception Uncertainty_SW_Extraction	Manual	
SW_knowledge	GW_SW_Connectivity Kn_SW_Availability River_network_model	Equation (weighted)	0.1 0.35 0.1

	Transmission_losses Uncertainty_SW_Take		0.1 0.35
SW_risk	SW_knowledge SW_mgt	Manual	
Regulatory_framework	Enforcement_Activity Penalties Prosecutability	Manual	
Illegal_take	CAP_SDL_adjustment Climate_regime Practical_constraints Regulatory_framework	Manual	
Risk	GW_Risk Illegal_take SW_risk Other_WRPAs Suspension of WSPs	Equation (weights)	0.2 0.3 0.2 0.1 0.2

In the fourth approach, the relative significance of individual nodes can be set via manual population of the conditional probability tables (CPT). This method is particularly useful, where one variable has the potential to override all other variables in the combination, such as in the case of the Illegal_Take node in the generic model. In this case, the model assumes that if the prevailing climate regime is wet, then the risk of illegal take is low regardless of the states of the other input nodes. If the prevailing climate regime is dry, then the states of the other nodes (practical constraints, regulatory framework and SDL-CAP adjustment) become influential.

Tailoring the Risk Model

The generic WRP area Risk 1 model provides a basic model for undertaking a risk assessment and should be viewed as a bare minimum. Individual WRP area models will benefit from being tailored to better reflect the specifics of each region. It is recommended that no nodes are removed from the tailored model, but new nodes can be added to capture more information or the state names varied within nodes to better represent the available data and associated risks.

For water balance nodes (i.e. nodes which summarise the quality of information about each water balance term – e.g. inflow, extraction and interception nodes), it is assumed that the uncertainty associated with metered (gauged) data is less than that for modelled data (assumed to require the use of empirical relationships or regionalisation techniques or other means of extrapolating data to estimate unmetered quantities), which, in turn, is slightly less than that for survey data. These assumptions do not necessarily hold true in every area, and there might well be situations where the quality of information obtained from surveys should be treated as better than that from modelling estimates, or indeed where it is known that the metered data is unreliable and alternative means of quantifying water balance terms are required. In cases like these, the weights assigned to the states can be varied to reflect the different assumption, with justification for varying the weights documented in the accompanying risk assessment report.

Table 6. State names for describing quality of information underpinning estimates of water balance terms. Weightings are those from the generic risk model.

States (and variations)	Assumptions	Risk Weighting
Metered Measured	Estimate is based on measured data. Modelling might also have been done, but calibrated/informed by observed data.	0.2
Modelled	Estimate is based on extrapolation or regionalisation or empirical relationships.	0.4
Modelled_specific Model_good	Model parameterised according to site specific information. Knowledge is based on a well calibrated and validated model.	0.3
Modelled_generic Generic Model_fair	Generic relationship, empirical relationship – does not take account of site specifics. Knowledge is based on a model, which does not necessarily have a good calibration and/or validation, or may not adequately represent the system drivers.	0.6
Specific_and_generic	Information is based on combination of site specific or calibrated models and generic relationships.	0.4
Irrigated_area Irrigation_Reports Licensed _volume Survey Water_Use_Survey	Method assumes that water use has been based on area of land irrigated. Method assumes that estimates of take are based on what the licence permits, rather than what might actually have been taken A sub-sample of population have been asked questions about consumption – quality will depend on size and representativeness of sample and survey design.	0.4 0.6 0.5
Extrapolation	Estimate is based on extrapolation from other data.	0.6
Multiple_sources	Various lines of evidence have been used to inform estimate.	0.2
Not Modelled Unquantified Unknown	No attempt has been made to estimate the water balance term.	0.9

Table 6 summarizes the range of state names that have been used in the generic Bayesian network and what is assumed by each state. The variations in state names serve to illustrate different options for characterising the quality of input data, but the WRP area risk assessor is not constrained by these. The risk weightings assigned in the generic Bayesian network are included, but can be varied to reflect local knowledge of the quality of the data source.

In the generic model, the quality of surface water models and groundwater models are each represented by a single node, with states relating to the quality of model calibration. It is assumed that a good calibration reflects both the ability of the model to reproduce observed data, as well as its representation of the key processes within the system. These indicators of model quality can be represented as two separate nodes (e.g. model performance and model conceptualisation) for greater transparency of information. Furthermore, surface water model performance could be characterised by more than one node to reflect performance in terms of reproducing high flows and/or low flows and/or the flow regime more generally.

The weightings in the generic model were based on the Bayesian network developer's assessment of the relative risk from the different factors, and it is acknowledged that not everyone is going to come up with the same set of weighting or the same choices about where and how to incorporate weightings. As stated in the section on Generic Model weightings (above), there are several ways to incorporate weightings (relative significance of risk) into a Bayesian network. The main issue to be aware of is double-weighting. For example, if you have specific nodes to define the significance of a particular variable, such as the significance nodes for the various forms of interception in the generic model, then there is no need to apply weights to the equation that is used to determine the combined risk from all forms of interception. Conversely, you do not need nodes to reflect significance, if your equation for combining variables incorporates weights to reflect each node's significance.

Reporting outcomes

The prediction of risk to the outcome should be reported as a probability. For example, there is a 30% probability that the risk of not meeting the SDL is high.

Using sensitivity analysis, a ranked list of variables can be obtained in decreasing order of sensitivity. Sensitivity analysis can assist in ranking of risks, for example, to meeting the SDLs within a WRP area (as in Figure 11), or for nested components of the model, for example, a groundwater WRP area only.

For example, in Figure 11, illegal take is contributing most to the risk to not meeting SDLs, followed by suspension of WRPs by jurisdictions (as set out in the Water Act (2007)) due to the climate regime. The discussion should continue so on and so forth.

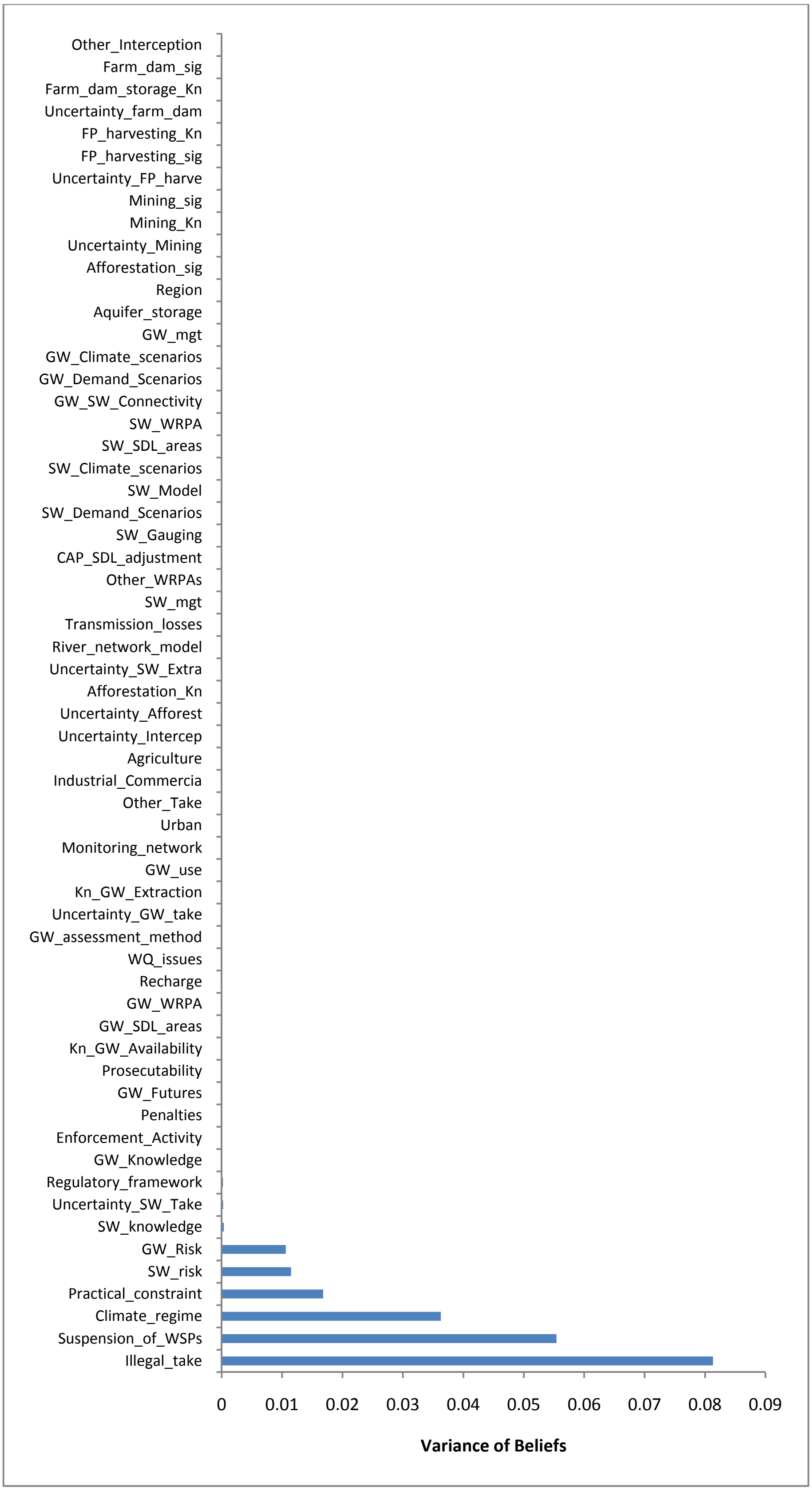


Figure 11: Global sensitivity analysis of the Risk 1 model (Example only).

Risk 2: Inadequate water quality to meet the needs of all uses

Objective

The objective of this model is to assess the risk that the quality of the water within a WRP area is not adequate to meet the needs of all uses. The model considers the physical, chemical and biological attributes of water that affect its ability to sustain environmental values ((ANZECC/ARMCANZ 2000). The model makes use of water quality data to assess the probability of exceeding threshold or trigger values and can use both historical or modeled water quality data to perform the assessment. The Risk 2 output is an input to Risk 3, recognizing that water quality will have a significant effect on water dependent ecosystems.

Model structure

Water quality drivers, processes and outcomes vary spatially, being influenced by a complex set of interacting factors. At a landscape scale, both the drivers of water quality and the processes that contribute to changes in water quality are well understood (e.g., (Stendera and Johnson 2006)); however, the complexity of responses caused by interacting factors means that considerable effort is required to model water quality outcomes (Heathwaite 2010) and such models are not widely available.

The assessment gives a broad indication of how water quality parameters change, given variations in landscape characteristics, land use, riparian zone and climate variation. The risk model (the overarching structure of which is shown in Figure 12) links a suite of landscape scale drivers of water quality (geology and groundwater flow systems, landuse and riparian character) to either monitoring stations or defined sub-catchment areas. These large scale drivers of water quality are linked to the water quality record and climate measures. The records for each water quality parameter are combined to model outcomes for each of the four uses of the basins water resource, where the outcomes are defined as the water quality being above or below pre-defined thresholds of adequacy for use.

Uses are defined in terms of the six environmental value categories adopted by the Australian Water Quality Guidelines for Fresh and Marine Waters (ANZECC/ARMCANZ 2000):

- Aquatic ecosystems
- Primary Industries (irrigation and general water uses, stock drinking water, aquaculture and human consumers of aquatic food)
- Recreation and aesthetics
- Drinking water
- Industrial water
- Cultural and spiritual values

At the time of writing, thresholds for cultural and spiritual values had not been defined and assessing water quality for industrial water use was not considered to be relevant because of the wide range of potential uses and the capacity for industrial users to treat water on-site. In addition, the adequacy of water for use in primary industries is dependent on the industry involved (e.g. sheep grazing will have different water quality requirements from poultry farming, which is different from rice growing). Consequently the MDBA only requires as assessment of these four uses:

- Aquatic ecosystems;
- Water for Primary Industries (irrigation)
- Recreation and aesthetics; and
- Drinking water.

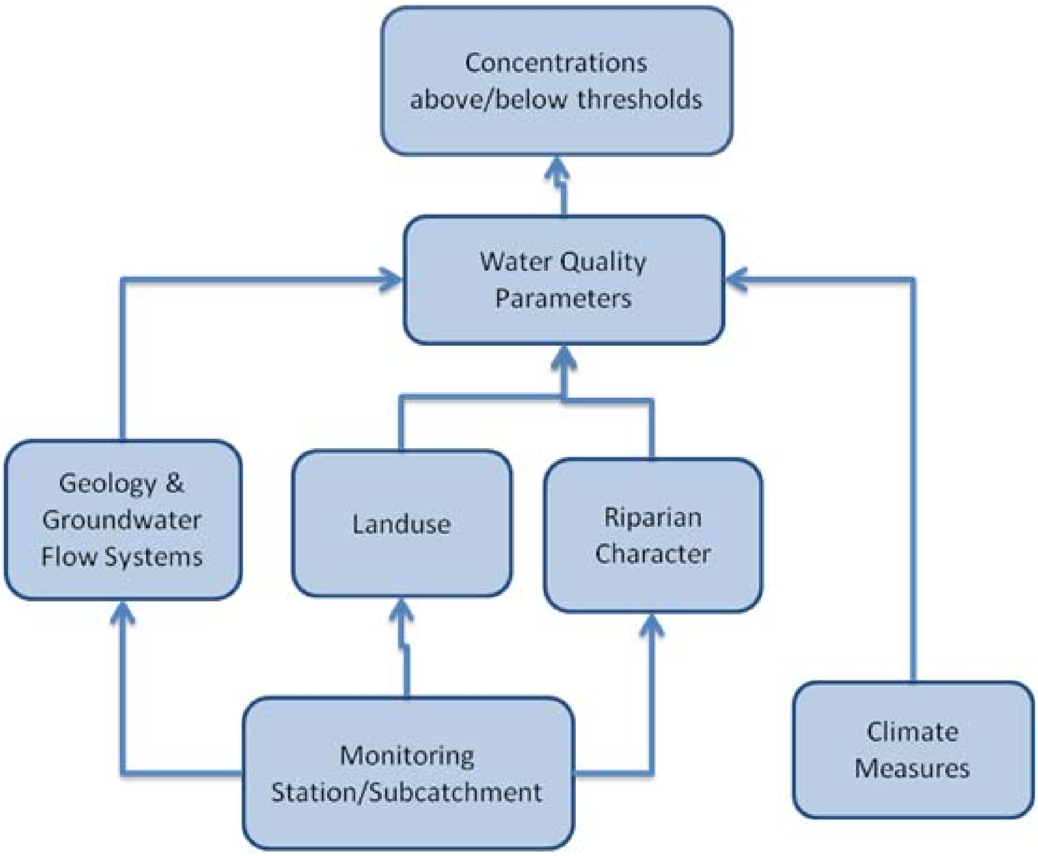


Figure 12: Basic structure of model for Risk 2.

Depending on the size of the datasets being used within the model, four different models (one for each of the four uses defined above) may need to be constructed and the results of each model then combined to give an overall assessment.

Scales

Water quality is typically measured at a point within a water body. Large scale assessments of water quality, (e.g. (Norris *et al.* 2001)) generally rely on data from individual reaches or at the end point of catchments and aggregate to a larger scale. The WRP area scale assessments need to take into account data and processes from the total WRP area and need to ensure that all areas of the catchment are represented by the data used.

Model inputs

The variables requiring inputs are shown in Figure 13 and coloured according to the groupings in Table 7. These are based on the generic model defined for the WRP area assessment trials and can be altered to reflect the available data and requirements of the

WRP area being assessed. Some guidance to the types of data/information that can be used is included in the comments section of Table 7.

Table 7: Inputs to the model used to assess the risk that the quality of the water resource is not adequate for use. The nodes are grouped according to the sections of the model defined in

Section	Input Node	Description	Comments
Location	Weighting	Used to aggregate data from the monitoring stations or subcatchments to the WRP area scale	Options trialed are to weight evenly or by either catchment area or mean annual flow.
	Subcatchments/ Monitoring Stations	Subcatchment from which water quality data are sourced	If there are a limited number of monitoring stations, individual monitoring stations can be used instead of subcatchments.
	Upland/Lowland	Used to differentiate between sites which may be subject to different threshold/trigger values for water quality parameters	If locally derived thresholds exist for some water quality parameters the location of these should be included in this node.
Landscape Characteristics	Groundwater Unit	The relative proportion of each groundwater unit within the subcatchment	Where a large number of groundwater units exist within the catchment it may be helpful to use a groundwater index. A similarity index such as the Euclidean distance (Washington 1984) has been used in trials
Landuse	Landuse index	An index representing the landuse within each subcatchment	Calculated externally to the Bayesian network as the Euclidean distance between the origin and the point described in n-dimensional space by the relative proportions of each landuse.
	Dryland Cropping	Proportion of dryland cropping (0 to 1) within each subcatchment.	Used to calculate landuse index
	Dryland Pasture	Proportion of dryland pasture (0 to 1) within each subcatchment.	Used to calculate landuse index
	Irrigated Crops	Proportion of irrigated crops (0 to 1) within each subcatchment.	Used to calculate landuse index
	Irrigated Pasture	Proportion of irrigated pasture (0 to 1) within each subcatchment.	Used to calculate landuse index
	Plantation Forest	Proportion of plantation forest (0 to 1) within each subcatchment.	Used to calculate landuse index
	Native	Proportion of native	Used to calculate landuse index

Section	Input Node	Description	Comments
	Vegetation	vegetation (0 to 1) within each subcatchment.	
	Urban	Proportion of urban areas (0 to 1) within each subcatchment.	Used to calculate landuse index
	Waterbodies	Proportion of waterbodies (0 to 1) within each subcatchment.	Used to calculate landuse index
Riparian Condition	Riparian Cover	Value representing the riparian tree cover in the subcatchment.	Where actual percent tree cover for the subcatchment is not available it is possible to use the riparian vegetation index from the National Land and Water Resources Audit (Norris *et al.* 2001).
Climate period	Year (period)	Year in which water quality data point collected	Used as a surrogate for different climate/water use scenarios where flow percentiles (refer Flow Percentile node) not available. Assists in prediction of water quality associated with different climate scenarios.
	Flow Percentile	The corresponding flow percentile for each water quality data point	Used for predictions of water quality risk associated with different climate scenarios and therefore different flow distribution. Data may not be available and network can function without node.
Water Quality Parameters	Salinity	Salinity (Electrical Conductivity) time series data from monitoring sites	
	pH	pH time series from monitoring sites	
	DO	Dissolved Oxygen (% sat) time series data from monitoring sites	Thresholds are specified as percent saturation, however, these can be adjusted if only concentration (mg/L) data available
	TP	Total phosphorus concentration (mgL^{-1}) from monitoring sites	
	TN	Total nitrogen concentration mgL^{-1} from monitoring sites	
	Turbidity	Turbidity (NTU) from monitoring sites	
	Transparency	Sechhi distances from	Often not available.

Section	Input Node	Description	Comments
		monitoring sites	Unfortunately no widely applicable correlation between Secchi depth and turbidity.
	Water Temperature	Temperature time series from monitoring sites	
	Metals	Metal concentrations (mgL^{-1}) from monitoring sites	Metals selected for assessment must contribute to the adequacy of the water resource for use (thresholds must be available). The trials used a selection of the following metals depending on the availability of data. Arsenic, Cadmium, Chromium, Copper, Iron, Lead, Manganese, Mercury, Nickel, Zinc
	Pesticides	Pesticide concentrations ($\mu g^{-1)}$ from monitoring sites	Pesticides selected for assessment must contribute to the adequacy of the water resource for use (thresholds must be available). The trials used a selection of the following pesticides: 2,4,5-T, 2,4-D, Atrazine, Benthiocarb, Bromacil, Chlorpyrifos, Demeton-S-methyl, Diazinon, Diuron, Endosulfan, Malathion, Mealochlor, Molinate, Parathion, Profenofos, Simazine, Trifluralin
	Blue Green Algae	Cell counts ($cells.ml^{-1}$) from monitoring sites.	Algal data is rarely available. Where algal data are not available or not available for sufficient long periods of record to make assessments meaningful the Blue Green Algae Susceptibility sub-model can be used.

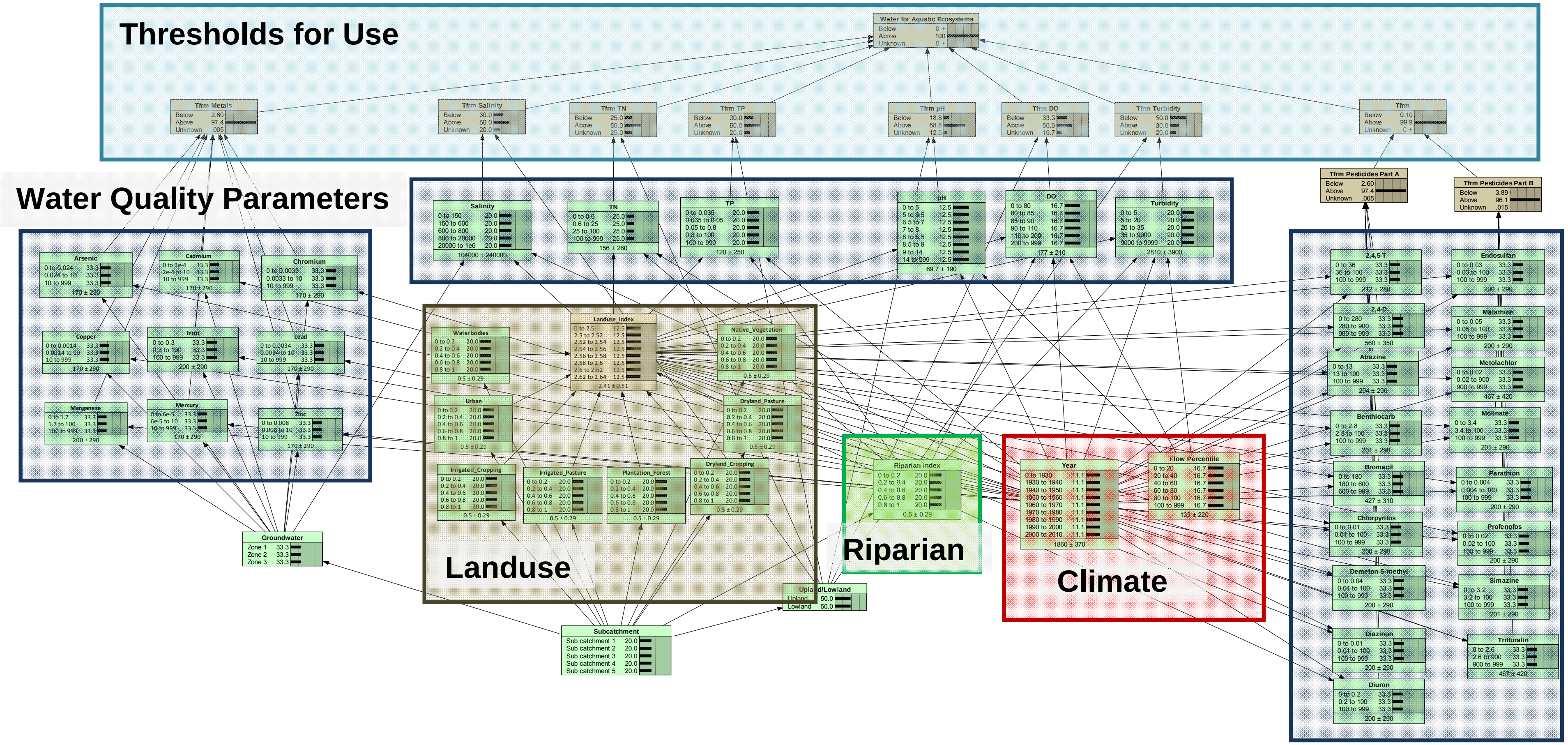


Figure 13: Risk 2 model, showing input variables coloured according to groupings in Table 7.

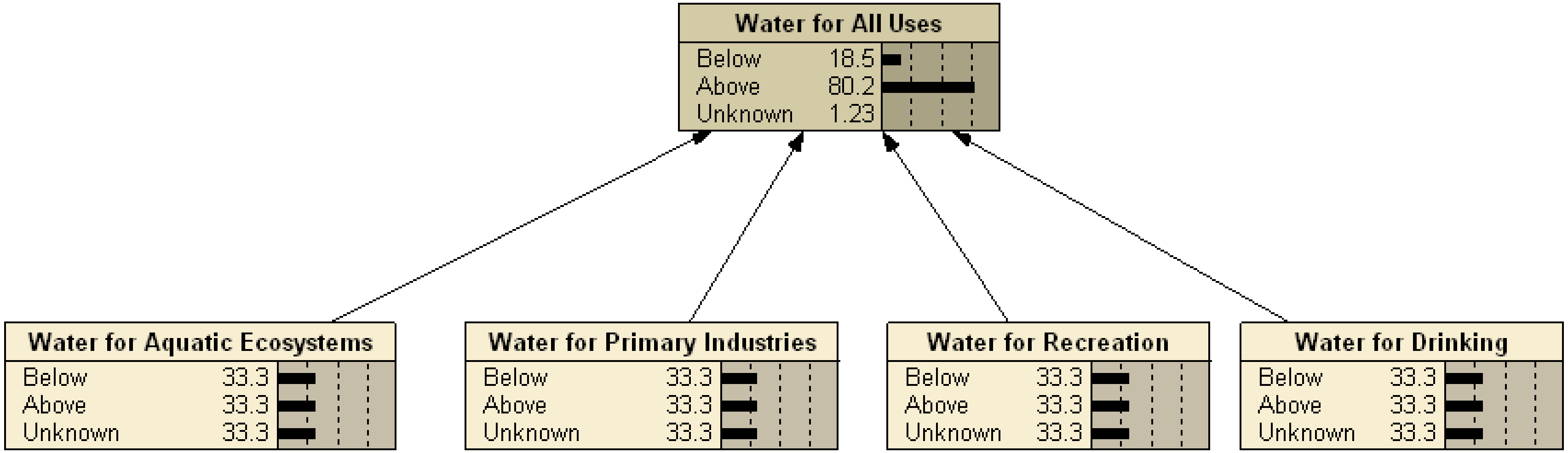


Figure 14: Model used for combining the outcomes from assessing the risk to each use.

Generic Model Node States

The states adopted for each node in the default model are summarised in Table 8, and are based on states defined for WRP area pilot models (Pollino et al. 2010a). These can be altered, as required, to better reflect the available data. The number of states used to classify input data should be appropriate for representing the relative differences in risk, and providing sufficient information about the input data to enhance interpretation of the model. Node states have been defined qualitatively, quantitatively or both.

Note, in the Generic models provided in Appendix 1, default states are for the Murrumbidgee.

Table 8. States (and values where appropriate) used for each input node in the default model for assessing risk that the quality of the water resource is not adequate for use.

Input Node	States (and values)
Weighting	Flat: equal weighting of regions Area: regions weighted according to proportional area
Subcatchments/ Monitoring Stations	Listed according to station or sub-catchment
Upland/Lowland	Upland; Lowland
Groundwater Unit	Proportion of each groundwater units within the sub- catchment
Landuse index	Equally spaced discretisation of data for the range of the index
Dryland Cropping	0 to 0.2; 0.2 to 0.4; 0.4 to 0.6; 0.6 to 0.8; 0.8 to 1.0
Dryland Pasture	0 to 0.2; 0.2 to 0.4; 0.4 to 0.6; 0.6 to 0.8; 0.8 to 1.0
Irrigated Crops	0 to 0.2; 0.2 to 0.4; 0.4 to 0.6; 0.6 to 0.8; 0.8 to 1.0
Irrigated Pasture	0 to 0.2; 0.2 to 0.4; 0.4 to 0.6; 0.6 to 0.8; 0.8 to 1.0
Plantation Forest	0 to 0.2; 0.2 to 0.4; 0.4 to 0.6; 0.6 to 0.8; 0.8 to 1.0
Native Vegetation	0 to 0.2; 0.2 to 0.4; 0.4 to 0.6; 0.6 to 0.8; 0.8 to 1.0
Urban	0 to 0.2; 0.2 to 0.4; 0.4 to 0.6; 0.6 to 0.8; 0.8 to 1.0
Waterbodies	0 to 0.2; 0.2 to 0.4; 0.4 to 0.6; 0.6 to 0.8; 0.8 to 1.0
Riparian Cover	0 to 0.2; 0.2 to 0.4; 0.4 to 0.6; 0.6 to 0.8; 0.8 to 1.0
Year (period)[5]	0 to 1960; 1960 to 1970; 1970 to 1980; 1980 to 1990; 1990 to 2000; 2000 to 2010
Flow Percentile	0 to 20; 20 to 40; 40 to 60; 60 to 80; 80 to 100; 100 to 999
Salinity	Discretisation based on thresholds for different uses 0 to 600 µscm^{-1}; 600 to 800 µscm^{-1}; 800 to 1500 µscm^{-1}; 1500 to 19000 µscm^{-1}; 19000 to 9.99999e5 µscm^{-1}
pH	Discretisation based on thresholds for different uses See Basin Plan for thresholds specific to your region
DO	Discretisation based on thresholds for different uses See Basin Plan for thresholds specific to your region
TP	Discretisation based on thresholds for different uses

[5] Distribution of years will depend on available data and known climate/water use periods.

Input Node	States (and values)
	See Basin Plan for thresholds specific to your region
TN	Discretisation based on thresholds for different uses See Basin Plan for thresholds specific to your region
Turbidity	Discretisation based on thresholds for different uses See Basin Plan for thresholds specific to your region
Transparency	Discretisation based on thresholds for different uses 0 to 1.6m; 1.6 to 10m; 10 to 999m
Water Temperature	Discretisation based on thresholds for different uses 0 to 15 °C; 15 to 20 °C; 20 to 25°C; 25 to 50 °C; 50 to 999 °C
Metals	States used will be dependent upon the concentrations of each metal and thresholds
Pesticides	States used will be dependent upon the concentrations of each Pesticide and thresholds
Blue Green Algae	Discretisation based on thresholds for different uses 0 to 6500 cells.ml^{-1}; 6500 to 15000 cells.ml^{-1}; 15000 to 300000 cells.ml^{-1}; 300000 to 999999 cells.ml^{-1}

Table 9. States (and values where appropriate) used for each input node in the default model for combining the assessment of the risk that the quality of the water resource is not adequate for each use (refer to Figure 14)

Input Node	States (and values)	Comments
Water for Drinking	Below/Above/Unknown	Values defined from model used to assess risk to drinking water
Water for Recreation	Below/Above/Unknown	Values defined from model used to assess risk to drinking water
Water for Primary Industries	Below/Above/Unknown	Values defined from model used to assess risk to drinking water
Water for Aquatic Ecosystems	Below/Above/Unknown	Values defined from model used to assess risk to drinking water

Generic Model Relationships

As described in the Risk 1 model description, relationships between variables can be derived a number of different ways. The methods used for combining variables in the generic Risk 2 model(s) are shown in Table 10 and Table 11. The associated CPTs for each of the nodes of the generic model can be accessed from the model files in Appendix 1.

Table 10: Method used to combine nodes to generate conditions probability tables (CPTs) in the default model for assessing risk that the quality of the water resource is not adequate for use

Node	Parameterisation Method	Description
Tfrm Parameter[6]	Manual (deterministic)	Simplification of parent node concentration distribution to above/below/unknown Below: Concentration range is below threshold/trigger value Above: Concentration range is above threshold/trigger value Unknown: Concentration data are not available
Tfrm Metals	Manual (deterministic)	Aggregation of parent node concentration distributions to above/below/unknown states. If any of the input metal concentrations states are above the threshold/trigger value, the Tfrm Metals state is set to Above. Below: Concentration range is below threshold/trigger value Above: Concentration range is above threshold/trigger value Unknown: Concentration data are not available
Tfrm Pesticides	Manual (deterministic)	Aggregation of parent node concentration distributions to above/below/unknown states. If any of the input pesticide concentrations states are above the threshold/trigger value, the Tfrm Pesticides state is set to Above. Below: Concentration range is below threshold/trigger value Above: Concentration range is above threshold/trigger value Unknown: data are not available
Water for Use[7]	Manual (deterministic)	Below: all input nodes below threshold/trigger value Above: at least one input node is above threshold/trigger value Unknown: data are not available

[6] Generic node used for all water quality parameters. Only provided once in this table as the nodes are the same for all water quality parameter.

[7] Generic node used for all uses. Only provided once in this table as the nodes are the same for all uses.

Table 11: Description of the assessment endpoint variable in the default model, which is used to combine the assessment outcomes of individual water use models (refer to Figure 14)

Node	Parameterisation Method	Description
Water for All Uses	Manual (deterministic)	Below: all input nodes below threshold/trigger value Above: at least one input node is above threshold/trigger value Unknown: data are not available

Tailoring the Risk Model

The generic WRP area Risk 2 model provides a basic model for undertaking a risk assessment and, because of the nature of the input data, will need to be tailored to reflect the data availability and thresholds of each region. It is recommended that the basic structure of the generic model are maintained, but nodes can be added (or removed with caution) to better represent the available data and risks (both realized and potential).

Some considerations for tailoring the risk model are provided in the following sections.

Water Quality Thresholds/Trigger Values

The Water Quality Salinity Management Plan within the Basin Plan should be used to define thresholds in the models. Thresholds have been defined lowland and upland regions throughout the Basin. Regionally specific thresholds have been established for pH, turbidity, dissolved oxygen, total phosphorous and total nitrogen.

For all remaining parameters (e.g. salinity[8], metals, pesticides, blue green algae), the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC/ARMCANZ 2000), or 'The Guidelines' should be used. These provide a guide to setting water quality objectives for a range of uses. The Guidelines do not specify mandatory water quality thresholds, rather provide a framework for setting thresholds locally or regionally depending on the use of the water and the level of protection required.

Selection of Water Quality Parameters

As with the selection of thresholds, the wide range of environmental conditions and water use across the basin means that it is not appropriate to define a single set of water quality parameters that must be included in the assessment. The water quality parameters considered within the generic model will provide a starting point, but should be reviewed by local experts in water quality to define those parameters relevant to the WRP area.

Blue Green Algal Blooms

The assessment of the risk associated with Blue Green Algal blooms is problematic because of a lack of widespread data (providing information about cell counts and species) and a lack

[8] Requires clarification by MDBA

of specific thresholds for some uses. Indicative threshold values for microsystins (which are produced by a number of species of algae) are defined by (NHMRC and NRMMC 2004). Two approaches are available to assessing the risk associated with Blue Green Algal blooms. Where cell count data are available, the generic assessment approach described above can be used. Where cell count data are not available it is possible to use a simple model of bloom susceptibility based on phosphorus concentrations, water temperature, historical occurrences of blooms and thermal stratification. The details of this model are described in Appendix 2.

Data

Data are precompiled as text files and the distributions learnt by Netica. Water quality data sets tend to be large, in a variety of formats and are time consuming to work with. It is not a trivial exercise to compile the data into the text files required for the model. Sufficient time and resources should be allocated to this task. In compiling the data sets the following points should be considered.

Uncertainty: If no data exists for a particular parent node combination, Netica automatically applies an even distribution across states which can result in an inappropriate assessment of the risk. To prevent this occurring and provide a direct assessment of the degree of uncertainty associated with a lack of data, a set of 'dummy' data need to be included. These set concentrations to 999 (or 999999 in the case of algal cell counts) for each parent node combination. A state is then created within each water quality parameter that will capture these data points (typically 900 to 999). When Netica learns the probability it assigns a probability to missing data and the assessment defines this as Unknown.

Length of record: The trial assessments (Pollino et al. 2010a) demonstrated that small data sets have the potential to significantly skew the assessments, particularly if data are collected at only a few locations and at a few points in time. Typically monitoring stations with fewer than 30 data points (across all parameters) should be excluded as should any parameter with fewer than 20 data points. Care should be taken with small data sets (particularly for metals and pesticides) that single data points are not exerting undue influence on the outcome.

Improving the interpretive capacity of the models

Water quality varies both spatially and temporally and is influenced by a complex set of interacting factors which can be both nonlinear and dynamic (Heathwaite 2010). This assessment of water quality does not include such complexity, and only gives a broad indication of how water quality parameters change given landscape characteristics, land use, riparian character and historic climate variation. There are a number of potential improvements that could be made to the models for future assessments that will improve the predictive capacity of the assessments.

Links to landuse and riparian data sets

The assessment used the historical water quality record which was linked to data sets describing landuse and riparian condition from a single point in time. As a consequence, the model's capacity to interpret temporal variations in water quality in relation to landuse or riparian condition is limited and future iterations of the Bayesian network should explore the availability of landuse and riparian data over the period for which water quality data are available.

Links to water quality models

This assessment provides a broad indication of how water quality parameters change given certain landscape characteristics, land use, riparian character and historic climate variation. Water quality models, such as BigMod or IQQM, could assist in refining the relationships in the Bayesian network and future iterations should explore this link. The models use water quality data sets which are compiled externally to the model and therefore it is possible to use either historical data or modeled data sets.

Water quality models such as WaterCAST (Cook et al, 2009) may be used in the future but at present, WaterCAST provides long term loads rather than concentrations and is therefore not useful in identifying if concentration thresholds have been exceeded.

Reporting outputs

The prediction of risk to the outcome should be reported as a probability. For example, there is an 80% probability that the water resources will not be adequate for all uses.

Using sensitivity analysis, a ranked list of variables can be obtained in decreasing order of sensitivity. Sensitivity analysis can assist in ranking of risks, for example, to Water for Primary Industries within a WRP area (as in Figure 15). In this example, the risk to water for primary industries is driven by salinity concentrations.

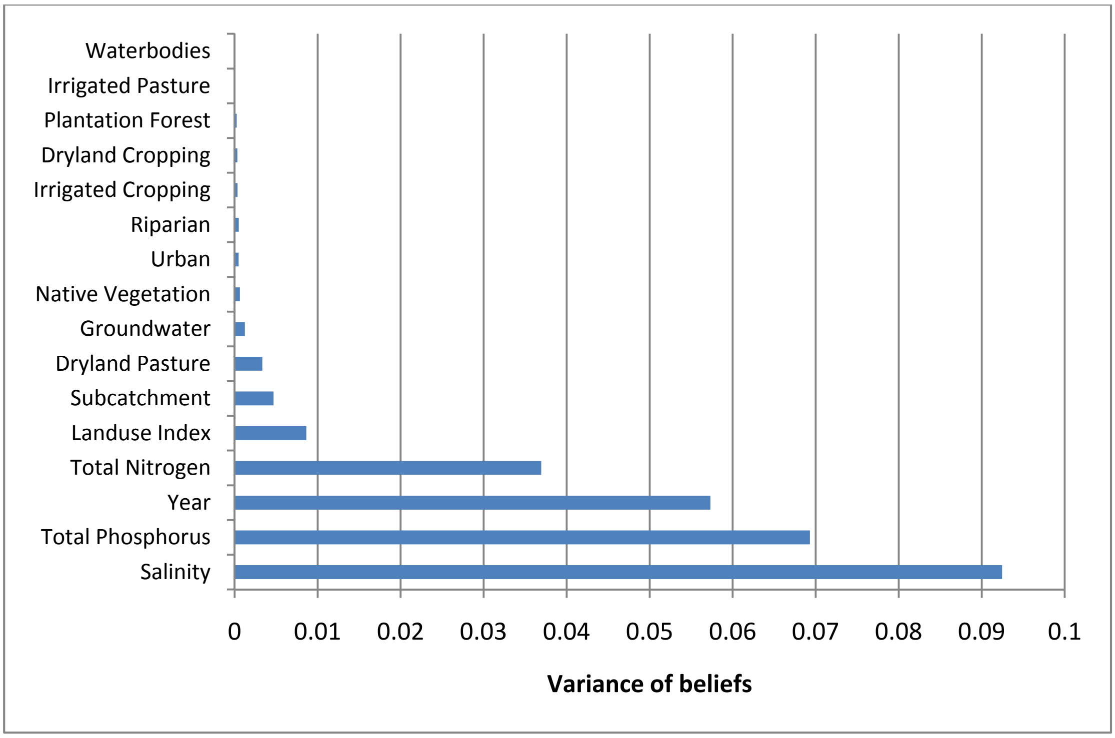


Figure 15: An example of sensitivity analysis.

Risk 3: The risk to water dependent ecosystems

Objective

The objective of this model is to assess risks to water dependent ecosystems (WDEs) within a WRP area. The model is developed in the context of the Basin Plan[9], being consistent with SDLs and the Environmental Watering Plan (EWP), while incorporating other factors that could compromise WDEs in the Basin. Risk 3 requires inputs from Risks 1 and 2.

Model structure

The risk model takes into account:

- The WRP area SDLs, and the risks they pose to planned and held environmental water (PEW and HEW);
- The quality of knowledge, change from natural icondition and prioritization steps used for setting of environmental watering requirements of WDEs;
- Planning and biophysical perversities; and
- Direct impacts on WDEs from land use and management activities.

The model combines inputs from water resource planning, including SDL and environmental watering planning. Other aspects of the model include planning requirements and physical activities within the WRP area. Figure 16 shows the major components of the model.

The risk to reduced water availability to the environment is quantified through a linkage to the outputs of the Risk 1 model. In the model, it is assumed that not meeting an SDL is going to put environmental water (the remaining 'portion' of the water resource) at risk. Environmental water is made up of two components, PEW and HEW (as above). PEW is considered to be of higher security than HEW, which is described as adaptive environmental water. This is consistent with their definitions in the Water Act (2007), and reflected in the model.

The ecosystem function component of the model incorporates a physical and a knowledge component. As documented in the EWP, select components of the flow regime are required to be assessed, dependent on the functional zone the WRP area occurs in within the Basin. The assessment component is the 'change in the natural flow' for the flow regime component. The risk assessment requires the percent change of each flow component from natural, as well as the knowledge type (data, models, expert opinion) used to quantify change.

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[9] Note: Only a draft of the EWP was available when this report was written. Specifics in the Plan may have changed since completing this report.

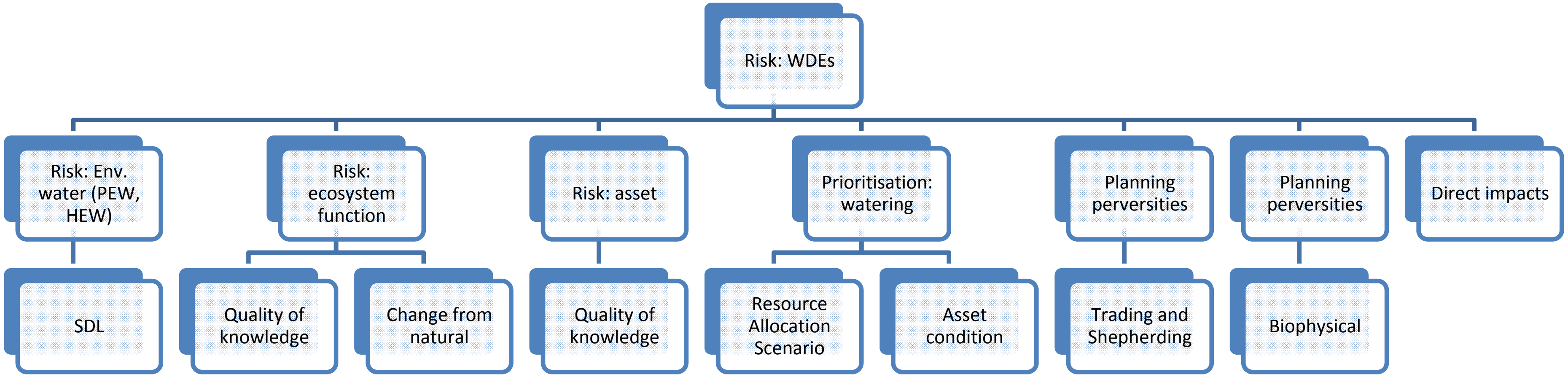

Figure 16: Key components for the Risk 3 WRP model.

The assets component of the model considers WDE assets (documented in the Basin Plan), not just indicator or key (Type A) assets[10], where assets are defined by the Act to include: water-dependent ecosystems; sites with ecological significance; and ecosystem services.

In the Basin Plan, an asset must meet one of the following criteria:

Criterion 1 — The water-dependent ecosystem is formally recognised in, and/or is capable of supporting species listed in, international agreements.
Criterion 2 — The water-dependent ecosystem is natural or near-natural, rare or unique.
Criterion 3 — The water-dependent ecosystem provides vital habitat.
Criterion 4 — The water-dependent ecosystem supports Commonwealth-, state or territory-listed threatened species and/or ecological communities.
Criterion 5 — The water-dependent ecosystem supports or is capable of supporting significant biodiversity.

For all assets defined within a jurisdiction, the environmental water requirements need to be defined. To do this, a range of knowledge types are used. The quality of this knowledge is variable. The risk component for assets assesses the quality of the knowledge used to derive the watering requirements, and the knowledge type used to identify assets and their location. The model also incorporates a component for prioritization of environmental watering, based on the condition of assets, and the resource allocation scenario (as defined in the EWP).

Planning perversities (or opportunities) are likely to arise in WRP areas with significant water trading or shepherding activities. The model incorporates the significance of the volume and the timing of the activity, to determine whether this is likely to increase or reduce the risk to WDEs. Physical perversities, due to salinity, pest (e.g. carp), blackwater events or acid sulfate soils are also considered, with separate assessment tools provided to assist in the assessing the significance of these hazards (Appendix 3).

Other 'local' scale hazards that require consideration in the model include water quality (link to Risk 2), physical barriers to connectivity (lateral and longitudinal), quality of physical habitat, grazing activities and riparian zone condition.

Scales

The WRP area-scale risk assessments need to take into account the total WRP area, and all the relevant assets (surface and groundwater, as defined in the Basin Plan) and functions that are contained within that area.

Model inputs

The variables requiring inputs are shown in Figure 17. Table 12 describes input variables. Input nodes are consistent with the requirements for WRPs.

[10] Separate assessment models are described in a latter part of this document for assessing Type A assets

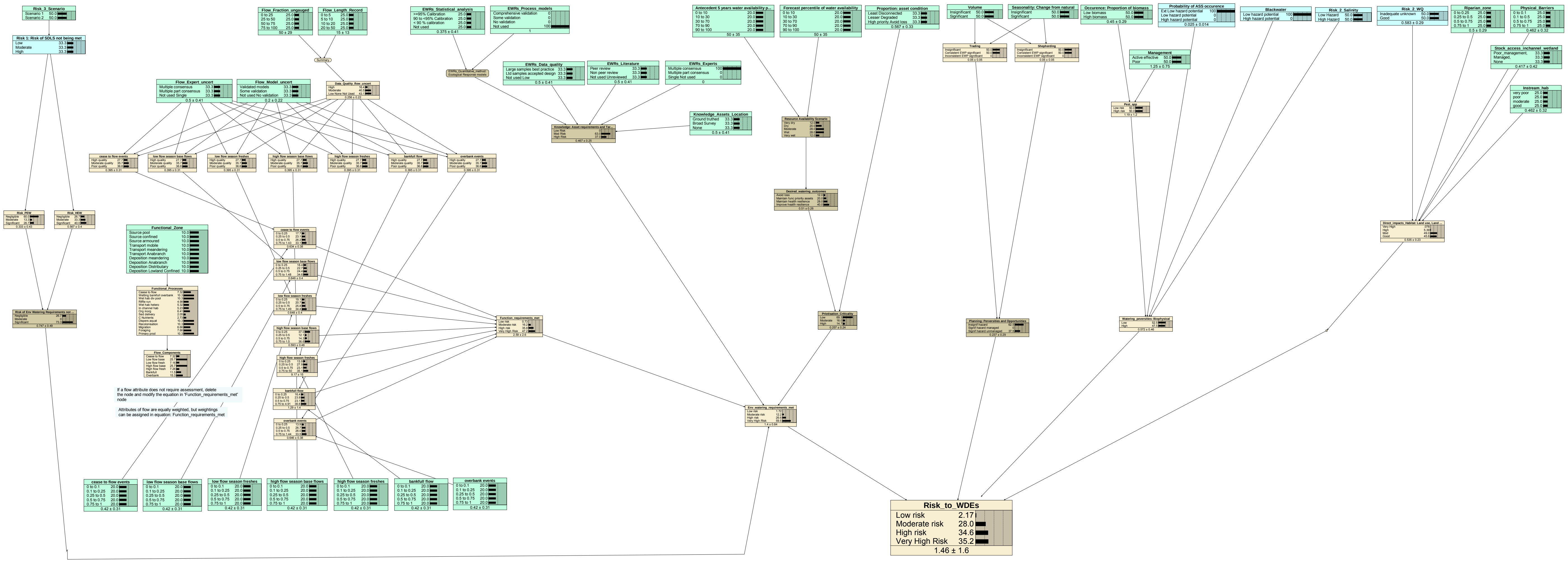

Figure 17: Risk 3 model, with input variables in green, and nodes that link to outputs from other risk models in blue.

Table 12: Model inputs for the Risk to WDEs (column 3), grouped according to the main components shown in Figure 16

Model component	Sub-grouping	Input node	Description
Risk_1	Risk_1	Risk_1	Link to Risk 1 - Risk to not meeting SDLs
Ecosystem Function	Functional Process zone	Functional_Zone	What Functional process zones occur in your WRP? The outcome will determine what flow attributes need to be assessed
	Knowledge for defining Ecosystem Function watering requirements	Flow_Length_Record	Length of flow record
		Flow_Fraction_ungauged	Fraction of WRP ungauged
		Flow_Model_uncert	Quality of flow model, based on calibration data or validation
		Flow_Expert_uncert	Quality of expert input, based on engagement type
	Change from natural for flow attribute	overbank_change	Overbank: proportional change in natural (as assessed in EWP)
		bankfull_change	Bankfull: proportional change in natural (as assessed in EWP)
		high_fresh_change	High flow period freshes: proportional change in natural (as assessed in EWP)
		high_flow_base_change	High flow period base: proportional change in natural (as assessed in EWP)
		low_fresh_change	Low flow period freshes: proportional change in natural (as assessed in EWP)
		Low_base_change	Low flow period base: proportional change in natural (as assessed in EWP)
		cease to flow_change	Cease to flow: proportional change in natural (as assessed in EWP)
Assets	Knowledge for defining Asset watering requirements	EWRs_Statistical_analysis	Quality of statistical models used for defining watering, based on calibration
		EWRs_Process_models	Quality of mechanistic models used for defining watering, based on validation
		EWRs_Data_quality	Quality of data, based on collection method
		EWRs_Literature	Quality of literature, based on publication type
		EWRs_Experts	Quality of expert input, based on engagement type
	Asset location	Knowledge_Assets_Location	Knowledge of asset location, given different survey methods

Prioritisation	Prioritisation of environmental water (EWP)	Antecedent_climate	Antecedent (5 years) percentage water availability
		Forecast_Climate	Forecast percentage water availability
		Condition_assets	Current condition of assets across the WRP area
Perversities	Planning perversities (or opportunity)	Volume: Trading and Shepherding	Significance of volume for trading or water shepherding
		Timing: Trading and Shepherding	Timing of water trading or water shepherding
	Physical perversities	Occurrence_pests	Is environmental watering likely to exacerbate pests (e.g. carp)? See Appendix 3 for Carp assessment model.
		Management_pests	Is management in place to manage pest problem (e.g. carp screens)? See Appendix 3 for Carp assessment model.
		ASS_Event	Is watering likely to inundate an active acid sulfate soils zone? See Appendix 3 for ASS assessment model.
		Blackwater	Is watering likely to lead to a backwater event? See Appendix 3 for Blackwater assessment model.
		Risk_2_Salinity	Is watering likely to mobilise salts? See Appendix 3 for Salinity assessment model.
Direct impacts: Land use and Land management	Direct impacts: Land use and Land management	Risk_2	Link to Risk 2 - Risk to not meeting water quality guidelines (aquatic ecosystems only)
		Riparian_zone	What is the condition of the riparian zone in the WRP area?
		Physical_Barriers	Are barriers (lateral and longitudinal) compromising connectivity in the WRP area?
		Grazing_inchannel_wetland	Is there access to streams and wetlands by grazers (i.e. cattle)?
		Instream_hab	What is the condition of instream habitat in the WRP area?

Generic Model Node States

The states adopted for each node in the default model are summarised in Table 13 and Table 14, and are based on states defined for WRP area road tests. These can be altered, as required, to better reflect the available data. The number of states used to classify input data should be appropriate for representing the relative differences in risk, and providing sufficient information about the input data to enhance interpretation of the model. Node states have been defined qualitatively, quantitatively or both.

Table 13. States (and values) used for each input node in the default Risk WDEs risk assessment model

Input node	States (and values)
Scenario	Scenario_1; Scenario_2
Risk_1	Low; Moderate; High
Functional_Zone	Source_pool; Source_confined; Source_armoured; Transport_mobile; Transport_meandering; Transport_Anabranch; Deposition_meandering; Deposition_Anabranch; Deposition_Distributary; Deposition_Lowland_Confined
Flow_Length_Record	0-5; 5-10; 10-20; 20-50
Flow_Fraction_ungauged	0-25; 25-50; 50-75; 75-100
Flow_Model_uncert	Validated_models (0); Some_validation (0.1); Not_used_No_validation (0.5)
Flow_Expert_uncert	Multiple_consensus (0); Multiple_part_consensus(0.5); Not_used_Single (1)
overbank_change	High_quality (0-0.1); Moderate_quality (0.1-0.5); Poor_quality (0.5-1)
bankfull_change	High_quality (0-0.1); Moderate_quality (0.1-0.5); Poor_quality (0.5-1)
high_fresh_change	High_quality (0-0.1); Moderate_quality (0.1-0.5); Poor_quality (0.5-1)
high_flow_base_change	High_quality (0-0.1); Moderate_quality (0.1-0.5); Poor_quality (0.5-1)
low_fresh_change	High_quality (0-0.1); Moderate_quality (0.1-0.5); Poor_quality (0.5-1)
Low_base_change	High_quality (0-0.1); Moderate_quality (0.1-0.5); Poor_quality (0.5-1)
cease to flow_change	High_quality (0-0.1); Moderate_quality (0.1-0.5); Poor_quality (0.5-1)
EWRs_Statistical_analysis	High_calib (0); Moderate_calib (0); Poor_calib (0.5); None (1)
EWRs_Process_models	Comprehensive_validation (0); Some_validation (0); No_validation (0.5); Not_used (1)
EWRs_Data_quality	Large_samples_best_practice (0); Ltd_samples_accepted_design (0.5); Not_used_Low (1)
EWRs_Literature	Peer_review (0); Non_peer_review (0.5); Not_used_Unreviewed (1)
EWRs_Experts	Multiple_consensus(0);Multiple_part_consensus (0.5); Single_Not_used(1)
Knowledge_Assets_Location	Ground_truthed (0); Broad_Survey (0.5); None (1)
Antecedent_climate	0-10; 10-30; 30-70; 70-90; 90-100

Forecast_Climate	0-10; 10-30; 30-70; 70-90; 90-100
Condition_assets	High_priority_Avoid_loss (1); Lesser_Degraded (0.5); Least_Disconnected (0.2)
Volume: Trading and Shepherding	Insignificant; Significant
Timing: Trading and Shepherding	Insignificant; Significant
Occurrence_pests	Low_risk (0-0.4); High_risk (0.4 - 4)
Management_pests	Active_effective (0.5); Poor (2)
ASS_Event	Low_hazard_potential; High_hazard_potential
Blackwater	Low_hazard_potential; High_hazard_potential
Risk_2_Salinity	Poor_unknown (0-0.666) / Good (0.666-1)
Risk_2	Poor (0-0.333); Moderate (0.333-0.666); Good (0.666-1)
Riparian_zone	0-0.2; 0.2-0.4; 0.4-0.6; 0.6-0.8; 0.8-1
Physical_Barriers	0-0.1; 0.1-0.5; 0.5-0.75; 0.75-1
Grazing_inchannel_wetland	Poor_management (0); Managed (0.25); None (1)
Instream_hab	very_poor (0-0.1); poor (0.1-0.5); moderate (0.5-0.75); good (0.75-1)

Table 14. Variables, descriptions and states (and values) used for each aggregation variable (nodes with CPTs) in the default Risk of Not Meeting the SDL risk assessment model

Name	Description	States
Risk_PEW	Risk to PEW from not meeting the SDL	Negligible; Moderate; Significant
Risk_HEW	Risk to HEW from not meeting the SDL	Negligible; Moderate; Significant
Flow_requirements	Risk of environmental watering requirements not being met	Negligible (0-0.1); Moderate(0.1-0.5); Significant (0.5-1.5)
Functional_Processes	Functional process zone(s) of WRP	Cease_to_flow; Wetting_bankfull_overbank; Wet_hab_div_pool; Riffle_run; Wet_hab_hetero; In_channel_hab; Org_inorg; Sed_delivery; C_Nutrients
Flow_Components	Flow components needing assessment, given functional process zone	Cease_to_flow; Low_flow_base; Low_flow_fresh; High_flow_base; High_flow_fresh; Bankfull; Overbank
Flow_data_summary	Summary of quality of flow data for assessing flow attributes	0-25; 25-50; 50-75; 75-100
quality_ctf_summary	Summary of cease to flow events	0-0.25; 0.25-0.5; 0.5-0.75; 0.75-1.5
Low_base_summary	Summary of low flow season base flows	0-0.25; 0.25-0.5; 0.5-0.75; 0.75-1.5
low_fresh_summary	Summary of low flow season freshes	0-0.25; 0.25-0.5; 0.5-0.75; 0.75-1.5
high_flow_base_summary	Summary of high flow season base flows	0-0.25; 0.25-0.5; 0.5-0.75; 0.75-1.5
high_fresh_summary	Summary of high flow season freshes	0-0.25; 0.25-0.5; 0.5-0.75; 0.75-1.5
bankfull_summary	Summary of bankfull flow	0-0.25; 0.25-0.5; 0.5-0.75; 0.75-1.5

overbank_summary	Summary of overbank events	0-0.25; 0.25-0.5; 0.5-0.75; 0.75-1.5
Function_requirements_met	Risk to function requirements being met	Low_risk (0-0.25); Moderate_risk (0.25-0.5); High_risk (0.5-0.9); Very_High_Risk (0.9-8.73162122263342)
EWRs_Quantitative method	Summary of quality of quantitative method (e.g. ecological response models)	High(0-0.1); Moderate (0.1-0.5); Low_Not_used (0.5-1)
Asset_Requirements targets	Summary of knowledge: Asset requirements and Targets	Low_Risk (0-0.1); Mod_Risk (0.1-0.5); High_Risk (0.5-1)
Env_requirements_met	Risk to asset requirements being met	Low_risk (0-0.25); Moderate_risk (0.25-0.5); High_risk (0.5-0.9); Very_High_Risk (0.9 - 3.02423808321908)
Climate_priority	Climate priority based on Resource Availability Scenario (see EWP) [11]	Very_dry; Dry; Moderate; Wet; Very_wet
Desired_watering outcomes	Desired watering outcomes based on climate priority (see EWP) [12]	Avoid_loss (1); Maintain_func_priority_assets (0.75); Maintain_health_resilience (0.5); Improve_health_resilience (0.25)
Priotisation_Criticality	Description of risk to environment with changes in resource availability	Low (0-0.25); Moderate (0.25-0.5); High (0.5-1)
Trading	Inter valley and Intra valley transfer water trading	Insignificant (0); Consistent_EWP_significant (0.1); Inconsistent_EWP_significant (1)
Shepherding	Inter valley and Intra valley transfer water shepherding	Insignificant (0); Consistent_EWP_significant (0.1); Inconsistent_EWP_significant (1)

[11] Note: Only a draft of the EWP was available when this report was written. Specifics in the Plan may have changed since completing this report.

[12] Note: Only a draft of the EWP was available when this report was written. Specifics in the Plan may have changed since completing this report.

Planning_Perversities	Summary of planning perversities and opportunities given trading and water shepherding	Insignif_hazard (0-0.1); Signif_hazard_managed (0.1-0.1); Signif_hazard_unmanaged (0.1-1)
Watering_peversities	Summary of watering perversities: Biophysical	Low (0-0.4); High (0.4-1)
Direct_impacts_Habitat	Summary of direct impacts on WDEs: Land use, Land management	Very_High (0-0.1); High (0.1-0.25); Mod (0.25-0.5); Good (0.5-1)
Risk_to_WDEs	Risk to WDEs	Low_risk (0-0.25); Moderate_risk (0.25-0.5); High_risk (0.5-0.75); Very_High_Risk (0.75 - 6)

Generic Model Relationships

As described in the Risk 1 model description, relationships between variables can be derived a number of different ways. The methods used for combining variables in the generic Risk 3 model are shown in Table 15. The associated CPTs for each of the nodes of the generic model can be accessed from the model file (Risk3_Generic.neta), in Appendix 1.

Tailoring the Risk Model

The generic WRP Risk 3 model provides a basic model for undertaking a risk assessment and describes the minimum requirements of what should be considered. Individual WRP area models will benefit from being tailored to better reflect the specifics of each region. It is recommended that the basic structure and content of the generic model be retained, but with additional nodes added to better represent the available data and risks (both realized and potential).

Recommendations for tailoring the risk model are below:

- A scenario node can be added to the model. This can be used to test alternative scenarios within this model (e.g. flow planning and how this links to change in flow attributes for ecosystem function) or can be used to link to model scenarios tested in Risk 1 (as in (Pollino et al. 2010a)) or Risk 2 models.
- Ecosystem function: Not all flow attributes need to be assessed within WRP areas. Flow attributes are specific to the functional processes and functional zone in which the WRP occurs within the Basin. This is documented in the EWP, and can be assessed as a sub-component of the Risk 3 model. If flow attributes are not assessed, they need to be deleted from the model, and the equations of summary flow attribute nodes need to be changed to reflect this.
- Assets: The assets section only includes variables for 'knowledge quality of location of assets' and 'environmental watering requirements of the asset.' Although not required as part of the EWP, an assessment on change in inundation (floodplain or wetland) from natural (or baseline) can be included in the analysis (as with the KEA assessment models).
- Assets: A parent node can be added to which identified individual assets or asset types in a WRP area. This can be linked to the asset knowledge nodes, to indicate the variability in the quality of the knowledge used across different assets or asset types.
- The prioritization of environmental water is based on resource availability and condition of the asset. Other aspects, or explanatory variables describing condition (e.g. physical perversity nodes), could be included in the analysis.
- Planning perversities could be expanded to consider other aspects of water planning. These could include State or regional planning.
- Physical perversities could be expanded to include specific pests, and their behavioural or reproductive responses to inundation. Specific management action could also be explicitly included in the model.
- The landuse-land management activities (direct impacts) could be tailored to better reflect the local activities that could compromise meeting environmental watering objectives.

Table 15. Method used to combine nodes to generate conditional probability tables (CPT), and the equations used (as appropriate).

Name	Parameterisation method	Equation
Risk_PEW	Manual	-
Risk_HEW	Manual	-
Flow_requirements	Equation (average)	Flow_requirements (Risk_HEW, Risk_PEW) = ((Risk_HEW*2)+Risk_PEW)/2
Flow_data_summary	Equation (weighted)	Summary (Flow_Fraction_ungauged, Flow_Length_Record) = (Flow_Fraction_ungauged+(Flow_Length_Record*2))/2
Functional_Processes	EWP	-
Flow_Components	EWP	-
quality_ctf_summary	Equation (weighted)	quality_ctf_summary (quality_ctf_uncert, ctf_change) = (quality_ctf_uncert+(ctf_change*2))/2
Low_base_summary	Equation (weighted)	Low_base_summary (Low_base_uncert, Low_base_change) = (Low_base_uncert+(Low_base_change*2))/2
low_fresh_summary	Equation (weighted)	low_fresh_summary (low_fresh_uncert, low_fresh_change) = (low_fresh_uncert+(low_fresh_change*2))/2
high_flow_base_summary	Equation (weighted)	high_flow_base_summary (high_flow_base_uncert, high_flow_base_change) = (high_flow_base_uncert+(high_flow_base_uncert*2))/2
high_fresh_summary	Equation (weighted)	high_fresh_summary (high_fresh_change, high_fresh_uncert) = ((high_fresh_change*2)+ high_fresh_uncert)/2
bankfull_summary	Equation (weighted)	bankfull_summary (bankfull_uncert, bankfull_change) = (bankfull_uncert+(bankfull_change*2))/2
overbank_summary	Equation (weighted)	overbank_summary (overbank_uncert, overbank_change) = (overbank_uncert+(overbank_change*2))/2
Function requirements met	Equation (average)	Function_requirements_met (quality_ctf_summary, Low_base_summary, low_fresh_summary, high_flow_base_summary, high_fresh_summary, bankfull_summary, overbank_summary) = (quality_ctf_summary+Low_base_summary+low_fresh_summary+high_flow_base_summary+high_fresh_summary+bankfull_summary+overbank_summary)/7
EWRs_Quantitative method	Equation (average)	EWRs_Quantitative_method (EWRs_Process_models, EWRs_Statistical_analysis) = (EWRs_Process_models+EWRs_Statistical_analysis)/2

Asset_Requirements targets	Equation (average)	Asset_Requirements_targets (EWRs_Quantitative_method, EWRs_Data_quality, EWRs_Literature, EWRs_Experts, Knowledge_Assets_Location) = (EWRs_Quantitative_method+EWRs_Data_quality+EWRs_Literature+EWRs_Experts+Knowledge_Assets_Location)/5
Env_requirements metEnv_watering requirements_met	Equation (weighted)	Env_requirements_met (Asset_Requirements_targets, Flow_requirements, Function_requirements_met, Priotisation_Criticality) = (Priotisation_Criticality+Asset_Requirements_targets+(2*Flow_requirements)+Function_requirements_met)/4
Climate_priority	EWP	-
Desired_watering outcomes	EWP	-
Priotisation_Criticality	Manual	-
Trading	Manual	-
Shepherding	Manual	-
Planning_Perversities	Equation (average)	Planning_Perversities (Trading, Shepherding) = (Trading+Shepherding)/2
Watering_peversities	Equation (average)	Watering_peversities (Pest_spp, Risk_2_Salinity, Blackwater, ASS_Event) = (Pest_spp+Risk_2_Salinity+Blackwater+ASS_Event)/4
Direct_impacts Habitat	Equation (average)	Direct_impacts_Habitat (Instream_hab, Grazing_inchannel_wetland, Riparian_zone, Physical_Barriers, Risk_2_WQ) = (Instream_hab+Grazing_inchannel_wetland+Riparian_zone+Physical_Barriers+Risk_2_WQ)/5
Risk_to_WDEs	Equation (average)	Risk_to_WDEs (Watering_peversities, Planning_Perversities, Env_requirements_met, Hab_tfrm) = (Watering_peversities+Planning_Perversities+Hab_tfrm+ Env_requirements_met)/4

Reporting outputs

The prediction of risk to the outcome should be reported as a probability. For example, "there is a 80% probability that the risk to WDEs is high."

Using sensitivity analysis, a ranked list of variables can be obtained in decreasing order of sensitivity. Sensitivity analysis can assist in ranking of risks, (e.g. to WDEs within a WRP area, as in Figure 18), or for nested components of the model (e.g. attributes of ecosystem function only).

For example, in Figure 18, the variable contributing most to the risk of decline in WDEs is the likelihood of environmental water requirements not being. Changes in flow metrics for functional requirements are contributing to this outcome. The discussion should continue so on and so forth.

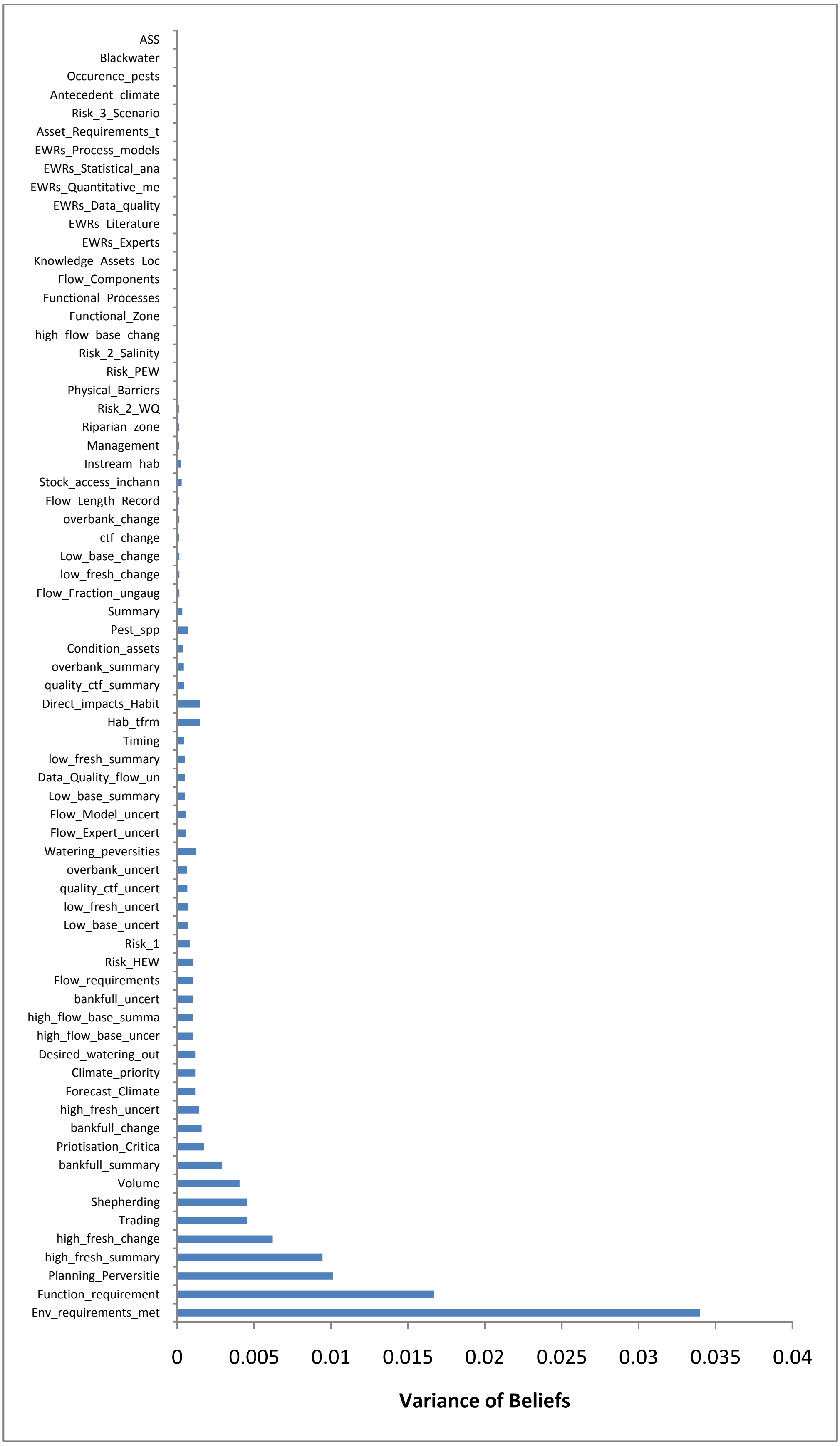

Figure 18: Global sensitivity analysis of the generic Risk 3 model (Example only).

Key Environmental Asset Assessment Models

A requirement of the Basin Plan is that all Type A (or Key) environmental assets require a risk assessment. Using the watering requirements of 16 key assets[13] in the Basin Plan,[14] a set of Bayesian network assessment tools have been constructed. These models only consider watering requirements, with inputs (e.g. flow volumes, duration of inundation) represented as independent processes, though in reality they are dependent on each other. This pragmatic approach is consistent with the information presented within the Basin Plan. Flow-hydrology-ecology models were not available for deriving asset models in this report. An example of this type of modelling approach can be found in (Merritt et al. 2010).

The models provided can assist in flow planning, where distributions of flows over a planning period and the seasonality of flows can be entered into the flow components of the models. The outcomes of this would be the likelihood of meeting flow requirements (or compromising flow requirements) in the Basin Plan.

The asset models, documented below and available in Appendix 1, focus on environmental watering requirements only. To extend the model to consider other hazards, components in the Risk 3 model can be used. This extension of the asset models is shown in Figure 19, using the Lower Darling as an example (Appendix 1: KEA_Extension_Lower_Darl_e.g..neta). The same principles used can be applied for the other asset models.

All individual models are found in Appendix 4.

[13] Watering requirements for only 16 of the 18 assets were listed in the EWP draft available at the time this report was written.

[14] Note: Only a draft of the EWP was available when this report was written. Specifics in the Plan may have changed since completing this report.

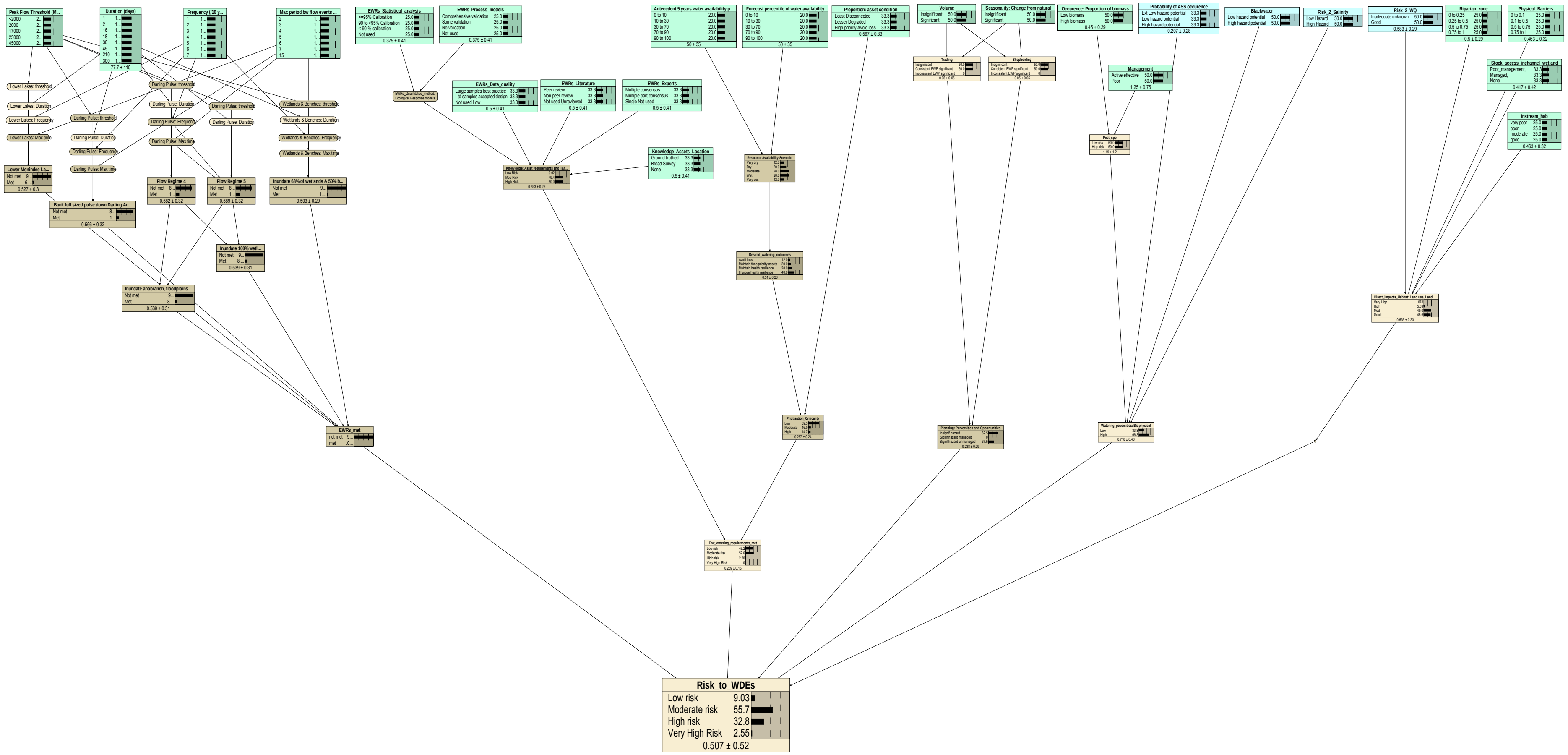

Figure 19: Extension of a Key Environmental Asset model (Lower Darling) to consider other risks, such as those in the Risk 3 model.

BARMAH-MILLEWA FOREST: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Barmah-Millewa group of forests and floodplains.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Barmah-Millewa forests, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Barmah-Millewa forests (see Figure 20) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow threshold: The threshold volume of flow required for each target (ML/day). If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node), then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (expressed in weeks). If the required duration of flow (or an amount of time above this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met' (when the duration is less than what is required for that target the node will indicate that the target is 'not met').

Timing: This node indicates whether the flow required for a target is seasonally dependent, and if so the season that the flows should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over the 10 year time frame of the Basin Plan, expressed as a 'preferred' and the 'minimum' frequency required. If flows occur at the 'preferred' frequency (or greater) then the frequency node for that target is 'met.' If the 'minimum' frequency is entered into the Bayesian network (via the frequency

node) then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met at the minimum frequency is less than at the higher, preferred frequency. If the frequency is less than the minimum requirement the frequency node for that target will indicate that it is 'not met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets, expressed as a 'preferred' and the 'maximum' number of years. If flows occur within the 'preferred' maximum time then the 'max time' node for that target indicates that it is 'met.' If the 'minimum' time is entered into the Bayesian network (via the max time node) then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met is higher when the time between events is shorter and lower when the time between events is longer. If the time between events is greater than the 'maximum' number of years the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

There are six ecological targets outlined in the EWP for the Barmah-Millewa forests, they are as follows:

- Maintain 100% of freshwater meadows or shallow freshwater marshes in healthy condition.
- Maintain 100% of Moira Grass plains in healthy condition.
- Maintain 100% of Red Gum forest in healthy condition. Note: this ecological target has a requirement for two distinct hydrological regimes, which differ in their volume, timing, frequency and the maximum time between events. This is reflected in the Bayesian network.
- Maintain 100% of Red Gum woodland in healthy condition.
- Maintain 100% of Black Box in healthy condition.
- Provide conditions conducive to successful breeding of thousands of colonial nesting waterbirds. Note: the hydrological requirements for this ecological target have two components: a high flow event within which there is a period of higher 'peak' flow. This is reflected in the Bayesian network.

Each of the ecological targets has a node for each of the flow regime components. If the flow regime is such that any of these components (threshold, duration, timing, frequency, max time) is 'not met' then the ecological target is also 'not met.'

Application to management

The ecological targets for the Barmah-Millewa forests each have a specified hydrological regime; a combination of hydrological requirements that, based on our current knowledge, will ensure that they are maintained in a good condition. These regimes differ in the required threshold volumes, the duration of flows above this threshold, the timing of flows, the preferred and minimum frequency of flows, and the preferred and maximum tolerable period between flow events. Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets, without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (see Figure 20) can be used to explore the outcome of different flow regimes, as it will predict the effect of changing each of the flow regime components on the different ecological components of the system. Different flow regimes can be entered into the Bayesian network (as 'findings' for threshold volume, duration, timing, frequency, period between events), and the outcomes can be identified for each of the ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

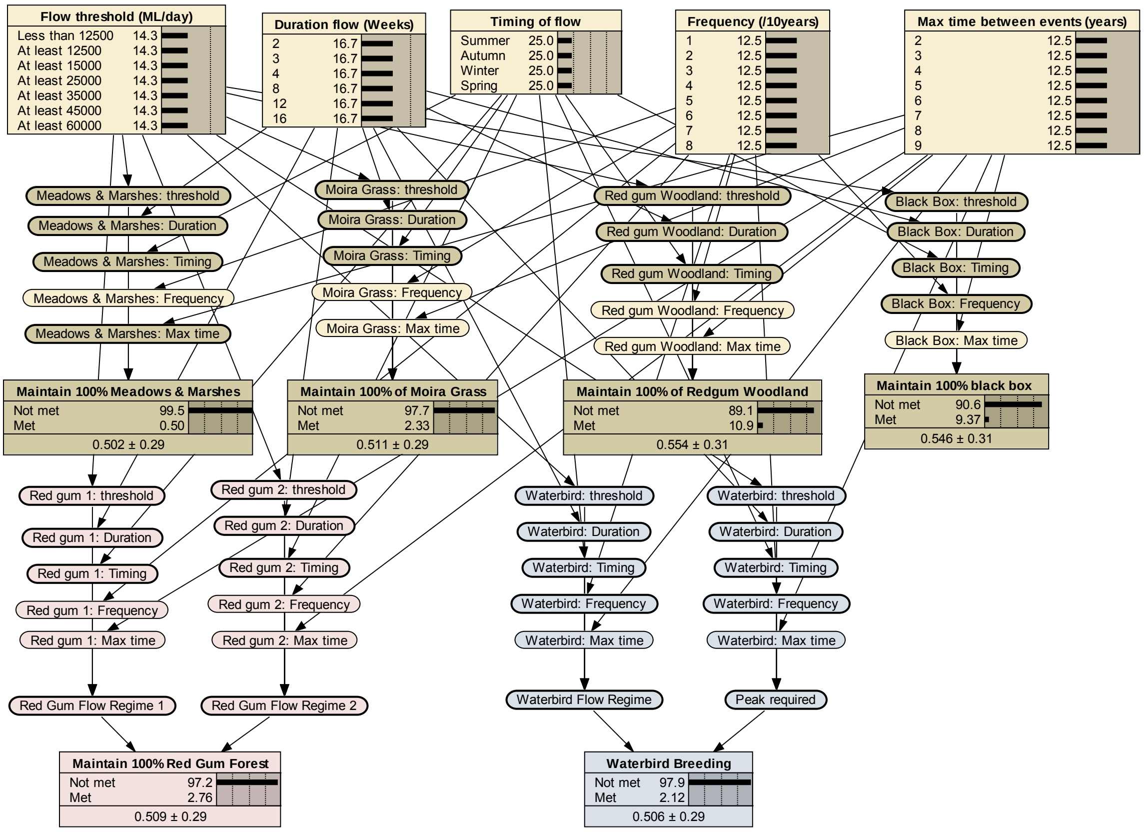

Figure 20: The Bayesian network model for the Barmah-Millewa group of forests, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

BOOLIGAL WETLANDS: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Booligal wetlands.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Booligal wetlands, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Booligal wetlands (see Figure 21) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow threshold: The threshold volume of flow required for each target (ML/day). If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node) then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (expressed in weeks). If the required duration of flow (or an amount of time above this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met' (when the duration is less than what is required for that target the node will indicate that the target is 'not met').

Timing: This node indicates whether the flow required for a target is seasonally dependent, and if so the season that the flows should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over the 10 year time frame of the Basin Plan, expressed as 'low risk' and 'high risk.' If flows occur at a frequency that is low risk then the frequency node for that target will indicate that it is 'met.' If flows occur at a frequency that is high risk then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met at the high risk frequency is less than at the low risk frequency. If the frequency is less than that indicated by the 'high risk' frequency then the frequency node for that target will indicate that it is 'not met.' If the frequency is higher than that indicated by the 'low risk' frequency then the frequency node for that target is 'met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets, expressed as 'low risk' and 'high risk.' If flows occur within the timeframe described as 'low risk' (the stated number of years or less) then the 'max time' node for that target will indicate that it is 'met.' If the number of years indicated by the high risk timeframe is entered into the Bayesian network (via the max time node) then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met is higher with 'low risk' timeframe than with the 'high risk' timeframe. If the time between events is greater than the number of years indicated as 'high risk' the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

There are six ecological targets outlined in the EWP for the Booligal wetlands, they are as follows:

- Maintain 100% of Red Gum forest and woodland currently in good condition.
- Restore to good condition and maintain 100% of Red Gum forest and woodland currently in poor condition.
- Maintain 100% of Lignum Shrubland currently in good condition.
- Restore 80% of Lignum Shrubland currently in poor condition.
- Provide flows to support moderate-large colonial waterbird breeding events.
- Restore to good condition and maintain 100% of open water lagoon.

Each of the ecological targets has a node for each of the flow regime components. If the flow regime is such that any of these components (threshold, duration, timing, frequency, max time) is 'not met' then the ecological target is also 'not met.'

Application to management

The ecological targets for the Booligal wetlands each have a specified hydrological regime; a combination of hydrological requirements that, based on our current knowledge, will ensure that they are maintained in (or restored to) good condition. These regimes differ in the required threshold volumes, the duration of flows above this threshold, the timing of flows, the frequency of flows (includes a low risk and high risk frequency), and the maximum tolerable period between flow events (includes low and high risk timeframe). Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets, without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (Figure 21) can be used to explore the outcome of different flow regimes, as it will predict the effect of changing each of the flow regime components on the different ecological components of the system. Different flow regimes can be entered into the Bayesian network (as 'findings' for threshold volume, duration, timing, frequency, period between events), and the outcomes can be identified for each of the ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

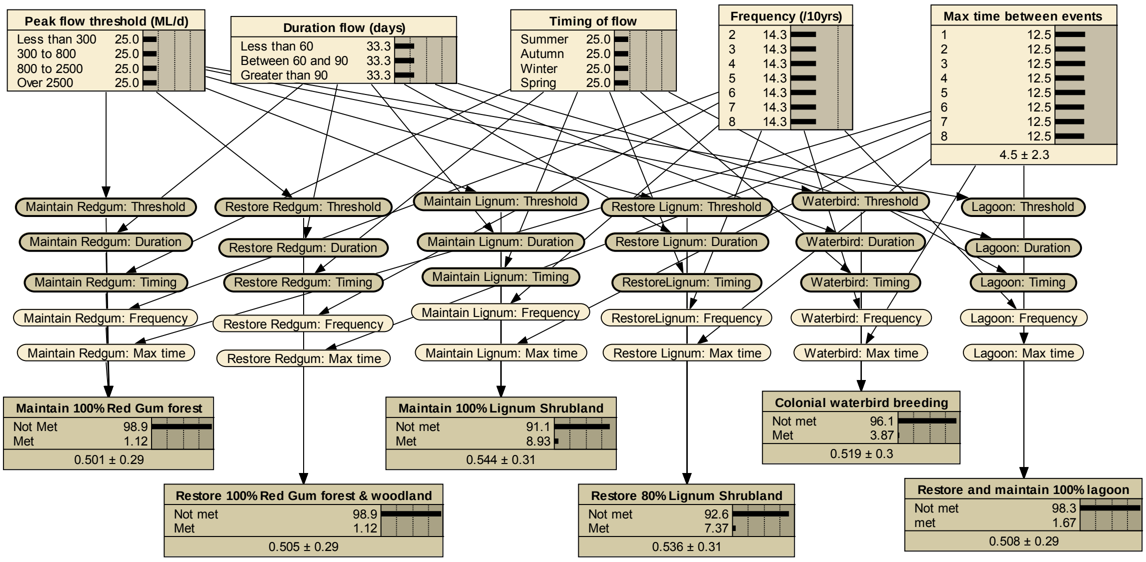

Figure 21: The Bayesian network model for the Booligal wetlands, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

CHOWILLA FLOODPLAINS & LINDSAY-WALLPOLLA ISLANDS: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Chowilla Floodplain and Lindsay-Wallpolla Islands.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Chowilla Floodplain and Lindsay-Wallpolla Islands, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Chowilla Floodplain and Lindsay-Wallpolla Islands (see Figure 22) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow threshold: The threshold volume of flow required for each target (ML/day). If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node), then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (expressed in days). If the required duration of flow (or an amount of time above this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met' (when the duration is less than what is required for that target the node will indicate that the target is 'not met').

Timing: This node indicates whether the flow required for a target is seasonally dependent, and if so the season that the flows should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over the 10 year time frame of the Basin Plan, expressed as a 'preferred' and the 'minimum' frequency required. If flows occur at the 'preferred' frequency (or greater) then the frequency node for that target is 'met.' If the 'minimum' frequency is entered into the Bayesian network (via the frequency

node) then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met at the minimum frequency is less than at the higher, preferred frequency. If the frequency is less than the minimum requirement the frequency node for that target will indicate that it is 'not met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets, expressed as a 'preferred' and the 'maximum' number of years. If flows occur within the 'preferred' maximum time then the 'max time' node for that target indicates that it is 'met.' If the 'minimum' time is entered into the Bayesian network (via the max time node) then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met is higher when the time between events is shorter and lower when the time between events is longer. If the time between events is greater than the 'maximum' number of years the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

There are four ecological targets outlined in the EWP for the Chowilla Floodplain and Lindsay-Wallpolla Islands, they are as follows:

- Maintain 80% of wetlands in healthy condition.
- Maintain 80% of Red Gum forest in healthy condition. Note: this ecological target has a requirement for two distinct hydrological regimes, which differ in their volume, duration, timing, frequency and the maximum time between events. This is reflected in the Bayesian network.
- Maintain 80% of Red Gum woodland in healthy condition.
- Maintain 80% of Black Box in healthy condition. Note: this ecological target has a requirement for two distinct hydrological regimes, which differ in their volume, duration, frequency and the maximum time between events. This is reflected in the Bayesian network.

Each of the ecological targets has a node for each of the flow regime components. If the flow regime is such that any of these components (threshold, duration, timing, frequency, max time) is 'not met' then the ecological target is also 'not met.'

Application to management

The ecological targets for the Chowilla Floodplain and Lindsay-Wallpolla Islands each have a specified hydrological regime; a combination of hydrological requirements that, based on our current knowledge, will ensure that they are maintained in a good condition. These regimes differ in the required threshold volumes, the duration of flows above this threshold, the timing of flows, the preferred and minimum frequency of flows, and the preferred and maximum tolerable period between flow events. Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets, without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (Figure 22) can be used to explore the outcome of different flow regimes, as it will predict the effect of changing each of the flow regime components on the different ecological components of the system. Different flow regimes can be entered into the Bayesian network (as 'findings' for threshold volume, duration, timing, frequency, period between events), and the outcomes can be identified for each of the ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

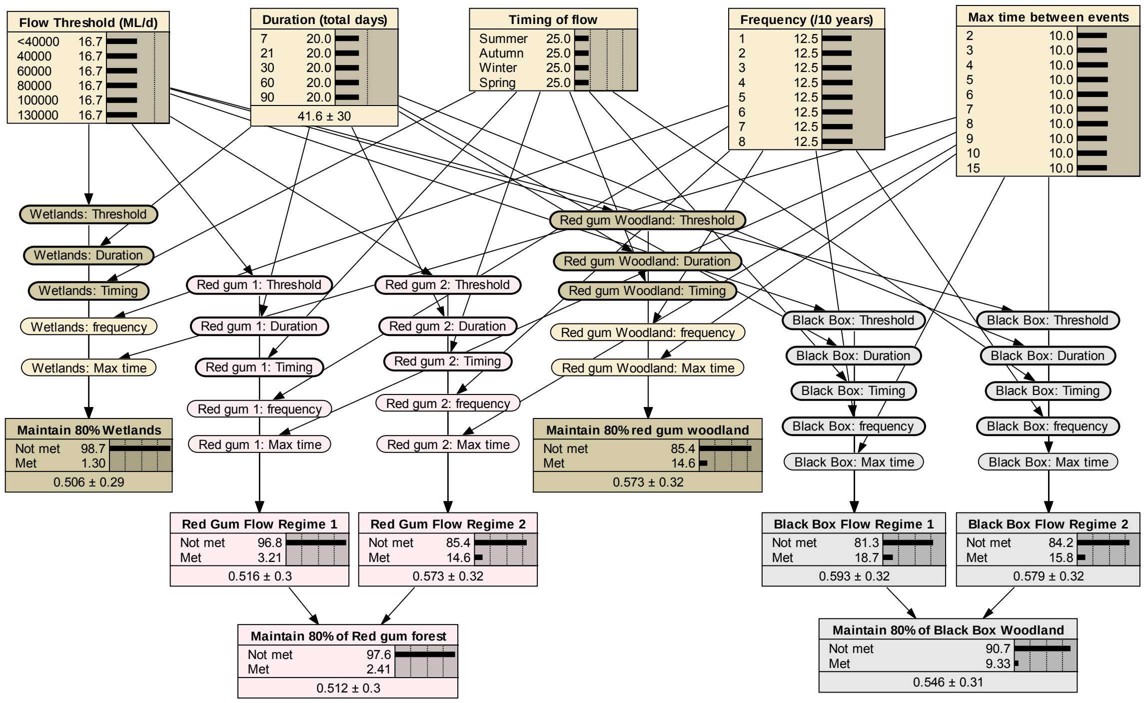

Figure 22: The Bayesian network model for the Chowilla Floodplains and Lindsay-Wallpolla Islands, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

THE GREAT CUMBUNG SWAMP: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Great Cumbung Swamp.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Great Cumbung Swamp, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Cumbung Swamp (see Figure 23) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow threshold: The threshold volume of flow required for each target (ML/day). If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node) then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (expressed in weeks). If the required duration of flow (or an amount of time above this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met' (when the duration is less than what is required for that target the node will indicate that the target is 'not met').

Timing: This node indicates whether the flow required for a target is seasonally dependent, and if so the season that the flows should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over the 10 year time frame of the Basin Plan, expressed as 'low risk' and 'high risk.' If flows occur at a frequency that is low risk (or a frequency greater than this) then the frequency node for that target will indicate that it is 'met.' If flows occur at a frequency that is high risk then there is a 50%

chance of the target being 'met.' This reflects the fact that the likelihood of the target being met at the high risk frequency is less than at the low risk frequency. If the frequency is less than that indicated by the 'high risk' frequency then the frequency node for that target will indicate that it is 'not met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets, expressed as 'low risk' and 'high risk.' If flows occur within the timeframe described as 'low risk' (the stated number of years or less) then the 'max time' node for that target will indicate that it is 'met.' If the number of years indicated by the high risk timeframe is entered into the Bayesian network (via the max time node) then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met is higher with 'low risk' timeframe than with the 'high risk' timeframe. If the time between events is greater than the number of years indicated as 'high risk' the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

There are seven ecological targets outlined in the EWP for the Cumbung Swamp, they are as follows:

- Maintain 100% of Red Gum forest and woodland currently in good condition.
- Restore to good condition and maintain 100% of Red Gum forest and woodland currently in poor condition.
- Maintain 100% of Reed Bed currently in good condition.
- Restore 80% of Reed Bed currently in poor condition.
- Maintain 100% of Black Box Woodland currently in good condition.
- Restore 80% of Lignum Shrubland currently in poor condition.
- Provide flows to support moderate-large colonial waterbird breeding events.
- Restore to good condition and maintain 100% of open water lagoon.

Each of the ecological targets has a node for each of the flow regime components. If the flow regime is such that any of these components (threshold, duration, timing, frequency, max time) is 'not met' then the ecological target is also 'not met.'

Application to management

The ecological targets for the Great Cumbung Swamp each have a specified hydrological regime; a combination of hydrological requirements that, based on our current knowledge, will ensure that they are maintained in (or restored to) good condition. These regimes differ in the required threshold volumes, the duration of flows above this threshold, the timing of flows, the frequency of flows (includes a low risk and high risk frequency), and the maximum tolerable period between flow events (includes low and high risk timeframe). Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets, without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (Figure 23) can be used to explore the outcome of different flow regimes, as it will predict the effect of changing each of the flow regime components on the different ecological components of the system. Different flow regimes can be entered into the Bayesian network (as 'findings' for threshold volume, duration, timing, frequency, period between events), and the outcomes can be identified for each of the ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

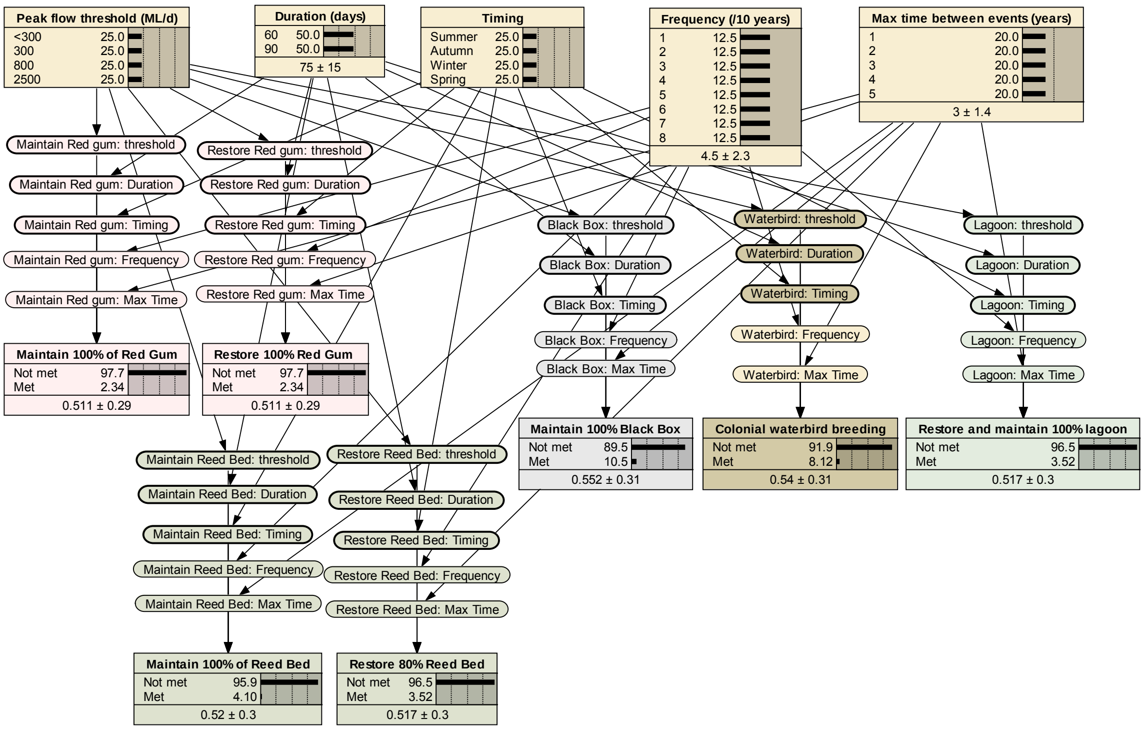

Figure 23: The Bayesian network model for the Great Cumbung Swamp, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

EDWARD-WAKOOL RIVER SYSTEM: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Edward-Wakool River system.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Edward-Wakool River system, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Edward-Wakool River system (Figure 24) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Area of inundation: The area of inundation required for each target (Ha). If the required area (or larger) is entered into the Bayesian network (via the 'Area of Inundation' node), then the node for that target will indicate that it has been 'met' (when areas are entered that are below the required area the threshold will indicate that the target is 'not met'). The area of inundation estimated for the first target is the length of stream required (>1000km) to maintain fish habitat, this has been converted into an area of 400 Ha (this estimate assumed an average stream width of 4 metres).

Flow threshold: The threshold volume of flow required for each target (ML/day). If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node), then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met'). Note: for some targets there are multiple flow thresholds provided (for different locations), where this occurs the threshold for Deniliquin has been used.

Duration: The duration for which that flow volume is required for each target (expressed in weeks). If the required duration of flow (or an amount of time above this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met' (when the duration is less than what is required for that target the node will indicate that the target is 'not met').

Timing: This node indicates whether the flow required for a target is seasonally dependent, and if so the season that the flows should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over the 10 year time frame of the Basin Plan. If flows occur at the threshold frequency (or greater) then the frequency node for that target is 'met.' If the frequency is less than the minimum requirement the frequency node for that target will indicate that it is 'not met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets is expressed in years. If flows occur within the maximum time threshold then the 'max time' node for that target indicates that it is 'met.' If the time between events is greater than the 'maximum' number of years the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

There are six ecological targets outlined in the EWP for the Edward-Wakool River system, they are as follows:

- Maintain vital fish habitats in permanent and semi-permanent regulated rivers and creeks (particularly as a drought refuge during dry years).
- Maintain Reed Bed wetlands in Werai forest (to support waterbird breeding events).
- Provide conditions suitable for waterbird breeding in Werai forest.
- Maintain a high proportion of Red Gum forest in healthy condition.
- Maintain a high proportion of ephemeral wetlands and watercourses in healthy condition. Note: this ecological target has a requirement for two distinct hydrological regimes (one for wetlands and one for watercourses), which differ in their required volume, area inundated, duration, frequency and the maximum time between events. Note also that the requirements for ephemeral wetlands are the same (except for the area inundated) as those for maintaining Red Gum forest. This is reflected in the structure of the Bayesian network.
- Maintain a high proportion of Black Box in healthy condition. Note: This target has the same flow requirements as the target for ephemeral watercourses; this is reflected in the structure of the Bayesian network.

Each of the ecological targets has a node for each of the flow regime components. If the flow regime is such that any of these components (area, threshold, duration, timing, frequency, max time) is 'not met' then the ecological target is also 'not met.'

Application to management

The ecological targets for the Edward-Wakool River system each have a specified hydrological regime; a combination of hydrological requirements that, based on our current knowledge, will ensure that they are maintained in a good condition. These regimes differ in the required area inundated, threshold volumes, the duration of flows above this threshold, the timing of flows, the frequency of flows, and the maximum tolerable period between flow events. Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets, without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (Figure 24) can be used to explore the outcome of different flow regimes, as it will predict the effect of changing each of the flow regime components on the different ecological components of the system. Different flow regimes can be entered into the Bayesian network (as 'findings' for area inundated, threshold volume, duration, timing, frequency, period between events), and the outcomes can be identified for each of the ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

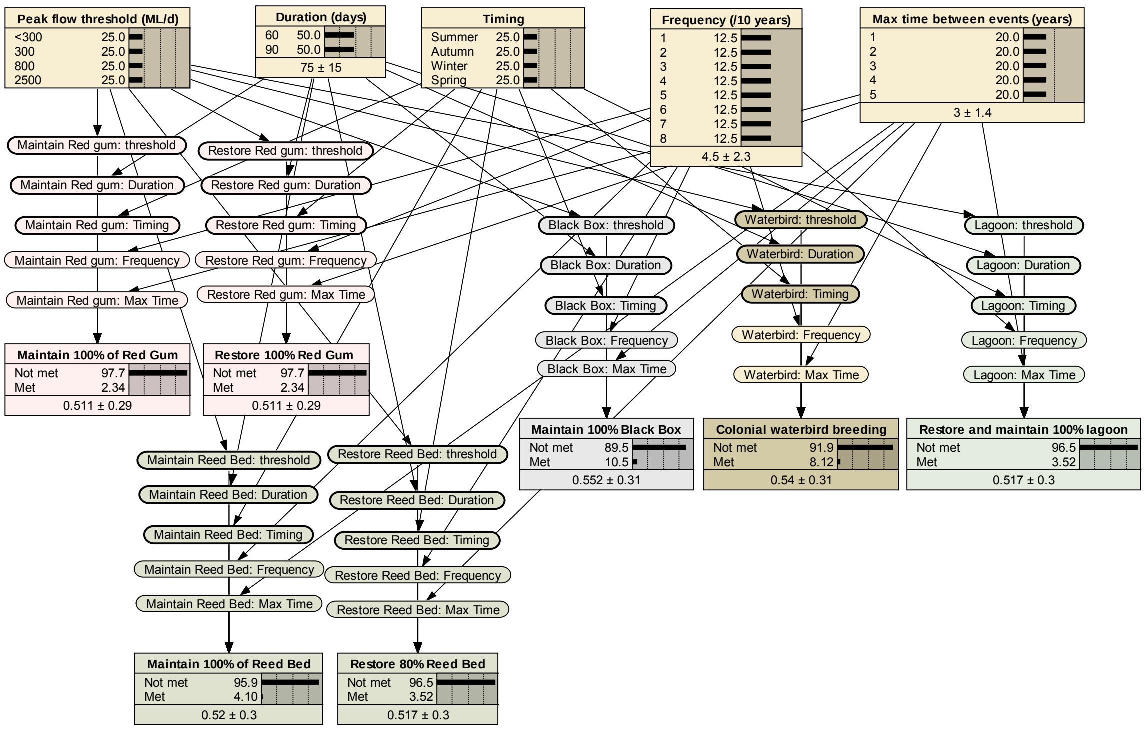

Figure 24: The Bayesian network model for the Edward-Wakool River system, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

GUNBOWER KOONDROOK-PERRICOOTA FORESTS: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Gunbower Koondrook-Perricoota forests.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Gunbower Koondrook-Perricoota forests, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Gunbower Koondrook-Perricoota forests (Figure 25) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow threshold: The threshold volume of flow required for each target (ML/day). If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node), then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (expressed in months). If the required duration of flow (or an amount of time above this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met' (when the duration is less than what is required for that target the node will indicate that the target is 'not met').

Timing: This node indicates whether the flow required for a target is seasonally dependent, and if so the season that the flows should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over the 10 year time frame of the Basin Plan, expressed as a 'preferred' and the 'minimum' frequency required. If flows occur at the 'preferred' frequency (or greater) then the frequency node for that target is 'met.' If the 'minimum' frequency is entered into the Bayesian network (via the frequency

node) then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met at the minimum frequency is less than at the higher, preferred frequency. If the frequency is less than the minimum requirement the frequency node for that target will indicate that it is 'not met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets, expressed as the 'preferred' and the 'maximum' number of years. If flows occur within the 'preferred' maximum time then the 'max time' node for that target indicates that it is 'met.' If the 'minimum' time is entered into the Bayesian network (via the max time node) then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met is higher when the time between events is shorter and lower when the time between events is longer. If the time between events is greater than the 'maximum' number of years the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

There are six ecological targets outlined in the EWP for the Gunbower Koondrook-Perricoota, they are as follows:

- Maintain 100% of permanent wetlands in healthy condition.
- Maintain 100% of semi-permanent wetlands in healthy condition.
- Maintain 100% of Red Gum forest in healthy condition.
- Maintain 100% of Red Gum woodland in healthy condition.
- Maintain 100% of Black Box in healthy condition.

Provide conditions conducive to successful breeding of thousands of colonial nesting waterbirds at least 3 years in 10. Note: the hydrological requirements for this ecological target have two components: a high flow event within which there is a period of higher 'peak' flow. This is reflected in the Bayesian network.

Each of the ecological targets has a node for each of the flow regime components. If the flow regime is such that any of these components (threshold, duration, timing, frequency, max time) is 'not met' then the ecological target is also 'not met.'

Application to management

The ecological targets for the Gunbower Koondrook-Perricoota forests each have a specified hydrological regime; a combination of hydrological requirements that, based on our current knowledge, will ensure that they are maintained in a good condition. These regimes differ in the required threshold volumes, the duration of flows above this threshold, the timing of flows, the preferred and minimum frequency of flows, and the preferred and maximum tolerable period between flow events. Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets, without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (Figure 25) can be used to explore the outcome of different flow regimes, as it will predict the effect of changing each of the flow regime components on the different ecological components of the system. Different flow regimes can be entered into the Bayesian network (as 'findings' for threshold volume, duration, timing, frequency, period between events), and the outcomes can be identified for each of the ecological targets.

Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

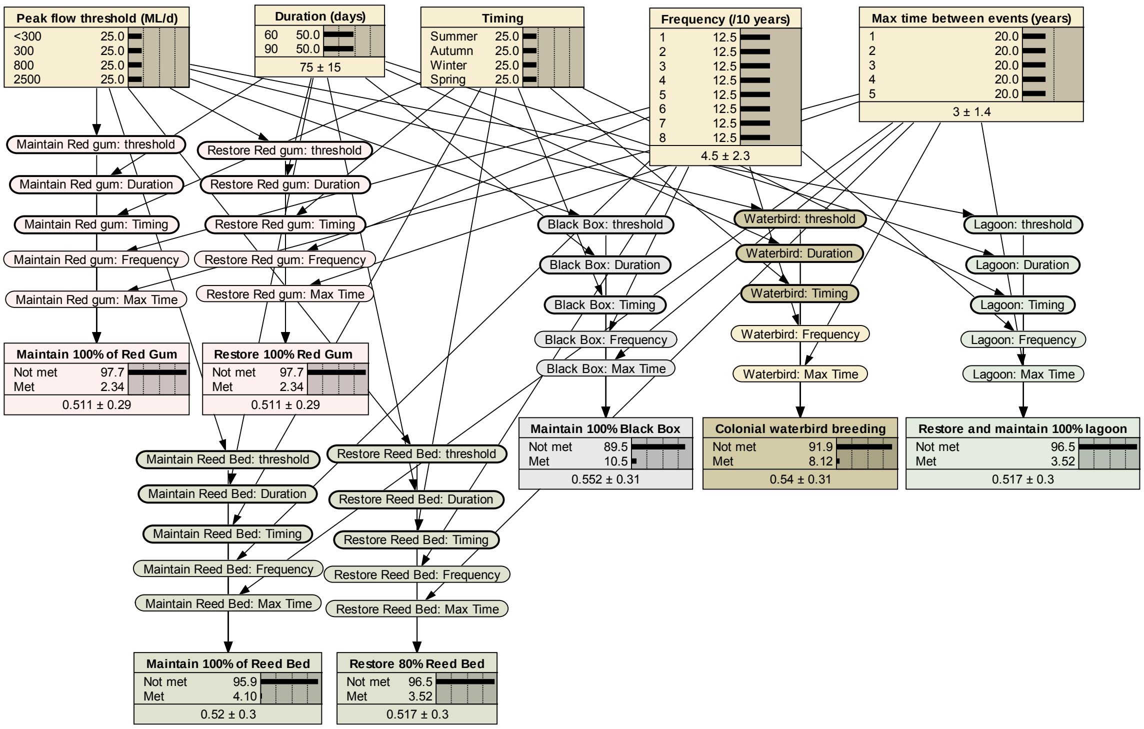

Figure 25: The Bayesian network model for the Gunbower Koondrook-Perricoota forests, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

GWYDIR WETLANDS: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Gwydir wetlands.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Gwydir wetlands, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Gwydir wetlands (Figure 26) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow threshold: The threshold volume of flow required for each target (ML/day). If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node) then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (in days), expressed as 'low risk' and 'high risk.' If the 'low risk' flow duration (or an amount of time greater than this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met.' If the 'high risk' flow duration is entered then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met at the high risk flow duration is less than at the low risk flow duration. If the duration is for a period less than that indicated by the 'high risk' flow duration then the duration node for that target will indicate that it is 'not met.'

Timing: This node indicates whether the flow required for a target is dependent on the time of year, and if so the months during which the flow should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over a 10 year timeframe for each target. The information for this node was supplied as the interval of time between flow events ('Return Period'); these were converted into an estimate of the number of times the flow event should occur in a 10 year period (to coincide with the timeframe of the Basin Plan). If flows occur at a frequency that is less than that required for a target the frequency node for that target will indicate that it is 'not met.' If flows occur at a frequency that is higher than the threshold for a target then the frequency node for that target is 'met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets. If flows occur within the timeframe described (the stated number of years or less) then the 'max time' node for that target will indicate that it is 'met.' If the time between events is greater than the number of years indicated the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

There are seven ecological targets outlined in the EWP for the Gwydir wetlands, they are as follows:

- Stimulate breeding and provide stable post flows to fish spawning success (Maintenance Target 1). Note: this ecological target has a requirement for two distinct hydrological regimes (Flow Rule 1 and 2), which differ in their volume, duration and timing of flows. This is reflected in the Bayesian network.
- Core wetland in good condition (Maintenance Target 2). Note: this ecological target has a requirement for two distinct hydrological regimes (Flow Rule 3 and 4), which differ in their volume, frequency and the maximum time between events, as reflected in the Bayesian network.
- Core wetland and surrounding Floodplain communities in good condition (Maintenance Targets 3 and 4). Note: this ecological target has a requirement for two distinct hydrological regimes (Flow Rule 5 and 6), which differ in their volume, timing and the maximum time between events, as reflected in the Bayesian network.
- Provide conditions to support resident waterbird population (Waterbird Target). Note: same requirements as for Flow Rule 3.
- Provide conditions to support large scale colonial nesting waterbird breeding 3 years in 10 (Colonial Waterbird Target). Note: this ecological target has a requirement for two distinct hydrological regimes (Flow Rule 3 and 8), which differ in their volume, duration, timing, frequency and maximum time between events. This is reflected in the Bayesian network.
- Restoration Target 1: 14,000 ha of SPW in good condition. Note: this ecological target has a requirement for two distinct hydrological regimes (Flow Rule 3 and 7), which differ in their volume, frequency and maximum time between events. This is reflected in the Bayesian network.
- Restoration Target 2: 35,000 ha of Gwydir wetlands in good condition (Flow Rule 8).

Each of the ecological targets has a node for each of the flow regime components. If the flow regime is such that any of these components (threshold, duration, timing, frequency, max time) is 'not met' then the ecological target is also 'not met.'

Application to management

Each of the ecological targets of the Gwydir wetlands has one or two specified hydrological regimes. This combination of hydrological requirements, based on best available knowledge, will ensure that the ecological targets are either maintained in a good condition or restored to good condition (as described in the EWP). These regimes differ in the required threshold volumes, the duration of flows above this threshold (with a low risk and high risk duration), the timing of flows, the frequency of flows and the maximum tolerable period between flow events. Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets, without the benefit of decision support tools, is made very difficult.

The Bayesian network presented here (Figure 26) can be used to explore the outcome of different flow regimes, as it will predict the effect of changing each of the flow regime components on the different ecological components of the system. Different flow regimes can be entered into the Bayesian network (as 'findings' for threshold volume, duration, timing, frequency, period between events), and the outcomes can be identified for each of the ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

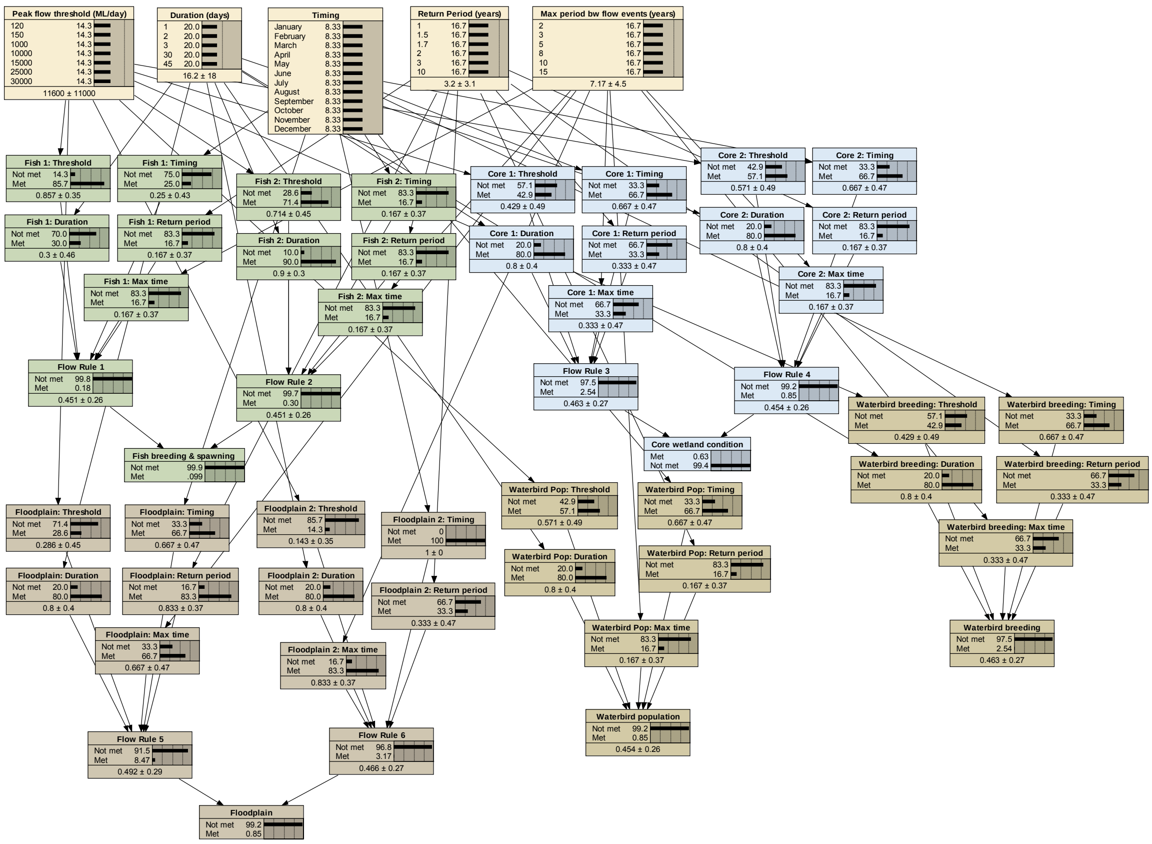

Figure 26: The Bayesian network model for the Gwydir wetlands, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

HATTAH LAKES: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Hattah Lakes.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Hattah Lakes, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Hattah Lakes (Figure 27) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow threshold: The threshold volume of flow required for each target (ML/day). If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node) then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (expressed in weeks). If the required duration of flow (or an amount of time above this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met' (when the duration is less than what is required for that target the node will indicate that the target is 'not met').

Timing: This node indicates whether the flow required for a target is seasonally dependent, and if so the season that the flows should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over the 10 year time frame of the Basin Plan, expressed as 'low risk' and 'high risk.' If flows occur at a frequency that is low risk (or a frequency greater than this) then the frequency node for that target will indicate that it is 'met.' If flows occur at a frequency that is high risk then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met at the high risk frequency is less than at the low risk frequency. If the frequency is less than that indicated by the 'high risk' frequency then the frequency node for that target will indicate that it is 'not met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets, expressed as 'low risk' and 'high risk.' If flows occur within the timeframe described as 'low risk' (the stated number of years or less) then the 'max time' node for that target will indicate that it is 'met.' If the number of years indicated by the high risk timeframe is entered into the Bayesian network (via the max time node) then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met is higher with 'low risk' timeframe than with the 'high risk' timeframe. If the time between events is greater than the number of years indicated as 'high risk' the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

There are six ecological targets outlined in the EWP for the Hattah Lakes, they are as follows:

- Maintain 100% of semi-permanent and persistent temporary wetlands in good condition. Note: this target has a requirement for three distinct hydrological regimes, as reflected in the Bayesian network.
- Maintain 50% of temporary wetlands in good condition. Note: as above, this target has a requirement for three distinct hydrological regimes.
- Maintain 100% of fringing Red Gum and Red Gum forest in good condition.
- Maintain 80% of Red Gum Woodland with flood tolerant understorey in good condition.
- Maintain 50% episodic wetlands in good condition.
- Maintain 60% Black Box Woodland in good condition. Note: this target has the same requirements as the target for episodic wetlands (above).

Each of the ecological targets has a node for each of the flow regime components. If the flow regime is such that any of these components (threshold, duration, timing, frequency, max time) is 'not met' then the ecological target is also 'not met.'

Application to management

The ecological targets for the Hattah Lakes each has one, or more, specified hydrological regimes; a combination of hydrological requirements that, based on our current knowledge, will ensure that they are maintained in good condition. These regimes differ in the required threshold volumes, the duration of flows above this threshold, the timing of flows, the frequency of flows (includes a low risk and high risk frequency), and the maximum tolerable period between flow events (includes low and high risk timeframe). Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets, without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (Figure 27) can be used to explore the outcome of different flow regimes, as it will predict the effect of changing each of the flow regime components on the different ecological components of the system. Different flow regimes can be entered into the Bayesian network (as 'findings' for threshold volume, duration, timing, frequency, period between events), and the outcomes can be identified for each of the ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

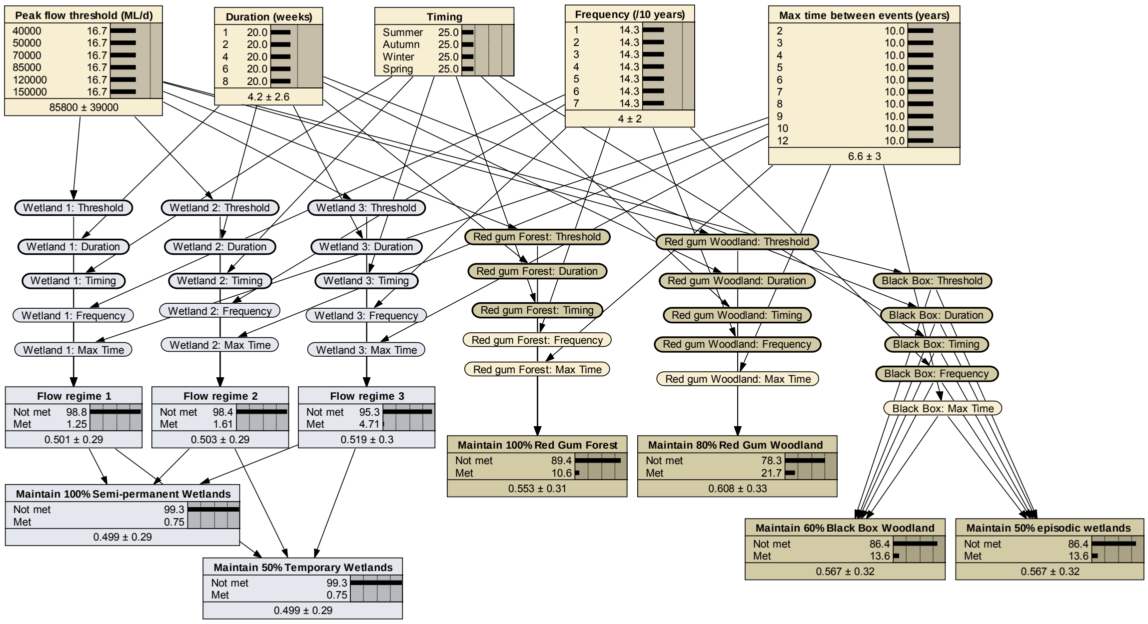

Figure 27: The Bayesian network model for the Hattah Lakes, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

LACHLAN SWAMP: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Lachlan Swamp.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Lachlan Swamp, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Lachlan Swamp (Figure 28) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow threshold: The threshold volume of flow required for each target (ML/day). If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node) then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (expressed in days). If the required duration of flow (or an amount of time above this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met' (when the duration is less than what is required for that target the node will indicate that the target is 'not met').

Timing: This node indicates whether the flow required for a target is seasonally dependent, and if so the season that the flows should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over the 10 year time frame of the Basin Plan, expressed as 'low risk' and 'high risk.' If flows occur at a frequency that is low risk then the frequency node for that target will indicate that it is 'met.' If flows occur at a frequency that is high risk then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met at the high risk frequency is less than at the low risk frequency. If the frequency is less than that indicated by the 'high risk' frequency then the frequency node for that target will indicate that it is 'not met.' If the frequency is higher than that indicated by the 'low risk' frequency then the frequency node for that target is 'met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets, expressed as 'low risk' and 'high risk.' If flows occur within the timeframe described as 'low risk' (the stated number of years or less) then the 'max time' node for that target will indicate that it is 'met.' If the number of years indicated by the high risk timeframe is entered into the Bayesian network (via the max time node) then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met is higher with 'low risk' timeframe than with the 'high risk' timeframe. If the time between events is greater than the number of years indicated as 'high risk' the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

There are six ecological targets outlined in the EWP for the Lachlan Swamp, they are as follows:

- Maintain 100% of Red Gum forest and woodland currently in good condition.
- Restore to good condition and maintain 70% of Red Gum forest and woodland currently in poor condition.
- Maintain 100% of Lignum Shrubland currently in good condition.
- Restore 80% of Lignum Shrubland currently in poor condition.
- Provide flows to support moderate-large colonial waterbird breeding events.
- Restore to good condition and maintain 100% of open water lagoon.

Each of the ecological targets has a node for each of the flow regime components. If the flow regime is such that any of these components (threshold, duration, timing, frequency, max time) is 'not met' then the ecological target is also 'not met.'

Application to management

The ecological targets for the Lachlan Swamp each have a specified hydrological regime; a combination of hydrological requirements that, based on our current knowledge, will ensure that they are maintained in (or restored to) good condition. These regimes differ in the required threshold volumes, the duration of flows above this threshold, the timing of flows, the frequency of flows (includes a low risk and high risk frequency), and the maximum tolerable period between flow events (includes low and high risk timeframe). Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets, without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (Figure 28) can be used to explore the outcome of different flow regimes, as it will predict the effect of changing each of the flow regime components on the different ecological components of the system. Different flow regimes can be entered into the Bayesian network (as 'findings' for threshold volume, duration, timing, frequency, period between events), and the outcomes can be identified for each of the ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

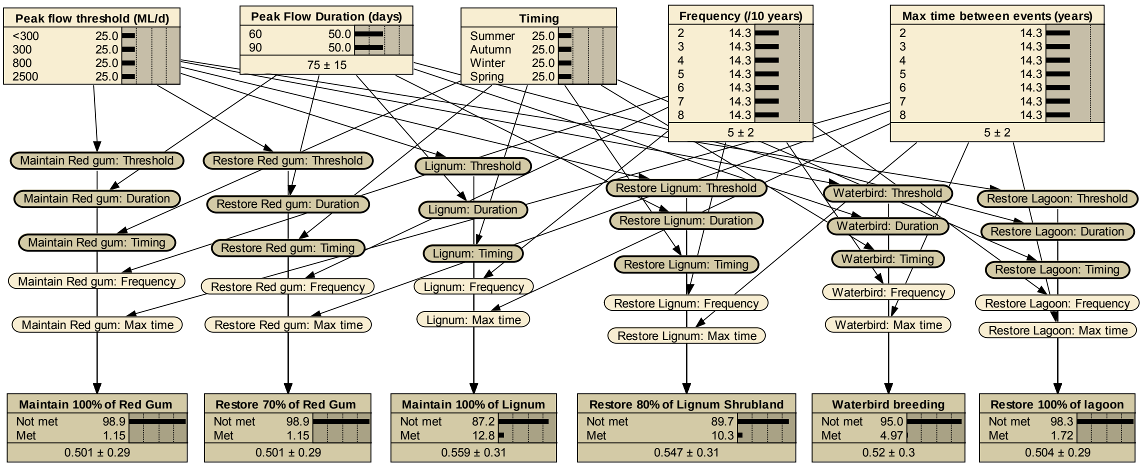

Figure 28: The Bayesian network model for the Lachlan Swamp, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

LOWER BALONNE FLOODPLAIN: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Lower Balonne Floodplain.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Lower Balonne Floodplain, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Lower Balonne Floodplain (Figure 29) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow threshold: The threshold volume of flow required for each target (ML/day). If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node) then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (expressed in months). If the required duration of flow (or an amount of time above this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met' (when the duration is less than what is required for that target the node will indicate that the target is 'not met'). The duration of flow required for some of the ecological targets is unknown; this is reflected in the Bayesian network (where the conditional probabilities for these cases are entered as 'unknown').

Timing: This node indicates whether the flow required for a target is dependent on the time of year, and if so the months during which the flow should be delivered. The information supplied for this node indicates that there is no seasonal dependence of flow for any of the ecological targets; therefore this variable has been omitted from the Bayesian network.

There are six ecological targets outlined in the EWP for the Lower Balonne Floodplain, they are as follows:

- Maintain 100% of grassland in good condition.
- Maintain 100% of Coolibah in good condition.
- Maintain 100% of Red Gum in good condition.
- Maintain 100% of Lignum in good condition.
- Maintain 100% of Black Box in good condition.

Restore small floods to ensure longitudinal hydrological connections and maintain refugia.

Each of the ecological targets has a node for each of the flow regime components. If the flow regime is such that one of these components (threshold or duration) is 'not met' then the ecological target is also 'not met.' There are two ecological targets for which the duration of flow required is unknown (Grasslands and Coolibah). Because of this, even at the highest flow thresholds, the uncertainty around whether these targets are met (or not) is high.

Application to management

Each of the ecological targets for the Lower Balonne Floodplain have a number of specified hydrological regimes; a combination of hydrological requirements that, based on our current knowledge, will ensure that they are maintained in good condition. These regimes differ in the required threshold volume and the duration of flow. Predicting the outcome of any particular schedule of water flows on each of the flow regimes and in turn each of the individual ecological targets, without the benefit of decision support tools, is made difficult. The Bayesian network presented here (Figure 29) can be used to explore the outcome of different flow volumes and durations, as it will indicate whether the flow regimes are met and in turn predict the effect on the ecological components of the system. Different flow regimes can be entered into the Bayesian network (as 'findings' for threshold volume and duration), and the outcomes can be identified for each of the ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

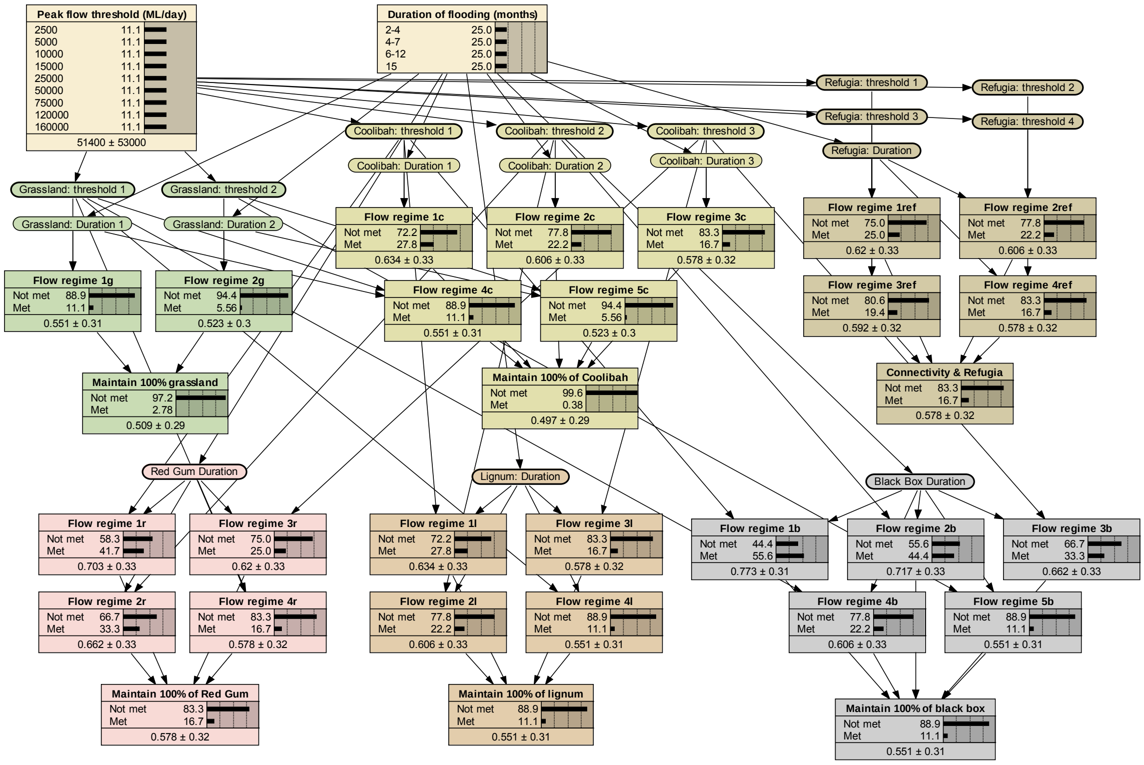

Figure 29: The Bayesian network model for the Lower Balonne

LOWER DARLING RIVER: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Lower Darling River.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Lower Darling River, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Lower Darling River (Figure 30) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow threshold: The threshold volume of flow required for each target (ML/day). If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node) then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (in days), expressed as 'low risk' and 'high risk.' If the 'low risk' flow duration (or an amount of time greater than this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met.' If the 'high risk' flow duration is entered then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met at the high risk flow duration is less than at the low risk flow duration. If the duration is for a period less than that indicated by the 'high risk' flow duration then the duration node for that target will indicate that it is 'not met.'

Timing: This node indicates whether the flow required for a target is seasonally dependent, and if so the season that the flows should be delivered. The information supplied for this node indicates that there is no seasonal dependence of flow for any of the ecological targets; therefore this variable has been omitted from the Bayesian network.

Frequency: The frequency at which these flows are required over a 10 year timeframe for each target. The information for this node was supplied as the interval of time between flow events ('Return Period'); these were converted into an estimate of the number of times the flow event should occur in a 10 year period (to coincide with the timeframe of the Basin Plan). If flows occur at a frequency that is less than that required for a target the frequency node for that target will indicate that it is 'not met.' If flows occur at a frequency that is higher than the threshold for a target then the frequency node for that target is 'met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets. If flows occur within the timeframe described (the stated number of years or less) then the 'max time' node for that target will indicate that it is 'met.' If the time between events is greater than the number of years indicated the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

There are six ecological targets outlined in the EWP for the Lower Darling River, they are as follows:

- Menindee Lakes Target 1: the maintain Lake Wetherell and Pamamaroo Lakes as predominantly permanent water bodies to act as drought refugia. Note: The hydrological requirements were not supplied for this target; therefore it was not included in the Bayesian network.
- Menindee Lakes Target 2: Instigate a variable flow regime for the Lower Menindee Lakes (Menindee Lake and Lake Cawndilla) and ensure a flow event 1 in 4 years for duration of 7-10 months. Note: the flow requirement for this ecological target is a depth of the water at Menindee Lake and Lake Cawndilla; therefore this information was not be included in the Bayesian network.
- Darling Anabranch Target 1: Provide bank full sized pulse down the Darling Anabranch 3 years in 10.
- Darling Anabranch Target 2: Inundate anabranch, surrounding floodplains and lakes 1 year in 10. Note: this ecological target has a requirement for two distinct hydrological regimes, which differ in their volume and low and high risk duration. This is reflected in the Bayesian network.
- Darling River Target 1: Inundate 100% of wetlands along the Lower Darling River 1 year in 10. Note: this ecological target has a requirement for two distinct hydrological regimes, which differ in their volume and low and high risk duration. This is reflected in the Bayesian network.
- Darling River Target 2: Inundate 68% of wetlands and 50% of benches along the Lower Darling River 3 years in 5.

Each of the ecological targets has a node for each of the flow regime components. If the flow regime is such that one of these components (threshold or duration) is 'not met' then the ecological target is also 'not met.'

Application to management

Each of the ecological targets for the Lower Darling River has a specified hydrological regime (some have two); a combination of hydrological requirements that, based on our current knowledge, will ensure that the environmental water requirements for each of the ecological targets is met. These regimes differ in the required threshold volumes, the duration of flows above this threshold (includes a low risk and high risk duration), the frequency of flows, and the maximum tolerable period between flow events. Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets, without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (Figure 30) can be used to explore the outcome of different flow regimes, as it will predict the effect of changing each of the flow regime components on the different ecological components of the system. Different flow regimes can be entered into the Bayesian network (as 'findings' for threshold volume, duration, frequency, period between events), and the outcomes can be identified for each of the ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

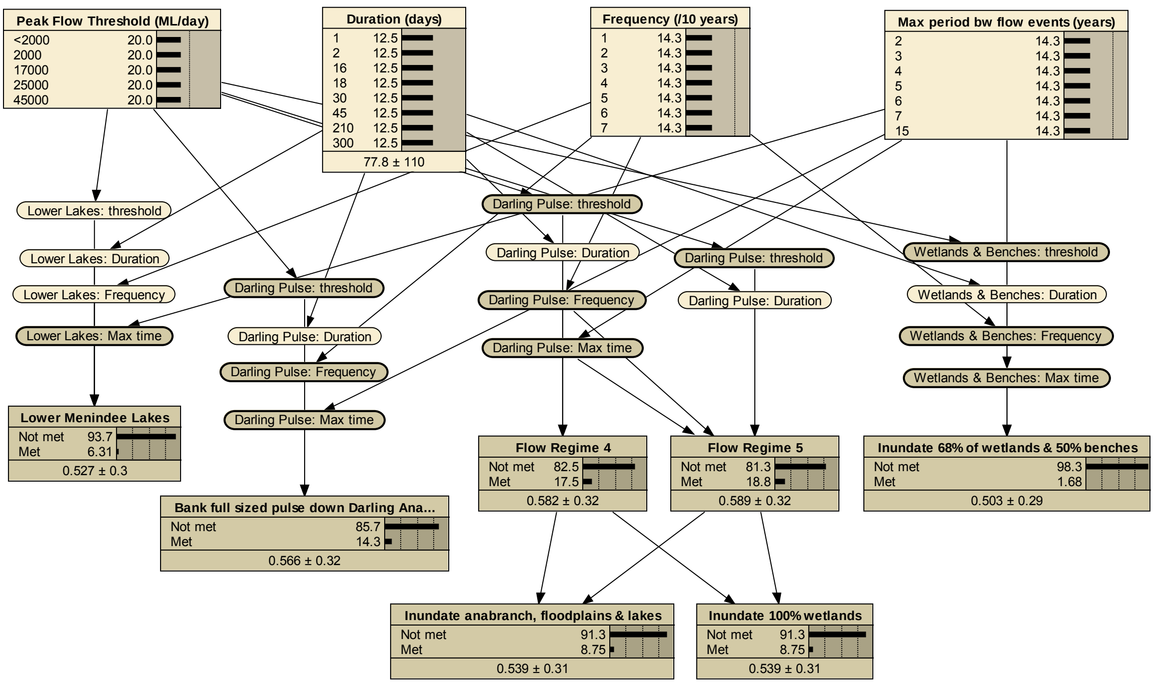

Figure 30: The Bayesian network model for the Lower Darling River, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

LOWER GOULBURN FLOODPLAIN: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Lower Goulburn Floodplain.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Lower Goulburn Floodplain, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Lower Goulburn Floodplain (**Figure 31**) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow threshold: The threshold volume of flow required for each target (ML/day). If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node) then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (expressed in days). If the required duration of flow (or an amount of time above this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met' (when the duration is less than what is required for that target the node will indicate that the target is 'not met').

Timing: This node indicates whether the flow required for a target is seasonally dependent, and if so the season that the flows should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over the 10 year time frame of the Basin Plan, expressed as a 'preferred' and the 'minimum' frequency required. If flows occur at the 'preferred' frequency (or greater) then the frequency node for that target is 'met.' If the 'minimum' frequency is entered into the Bayesian network (via the frequency

node) then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met at the minimum frequency is less than at the higher, preferred frequency. If the frequency is less than the minimum requirement the frequency node for that target will indicate that it is 'not met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets, expressed as a 'preferred' and the 'maximum' number of years. If flows occur within the 'preferred' maximum time then the 'max time' node for that target indicates that it is 'met.' If the 'minimum' time is entered into the Bayesian network (via the max time node) then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met is higher when the time between events is shorter and lower when the time between events is longer. If the time between events is greater than the 'maximum' number of years the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

There are three ecological targets outlined in the EWP for the Lower Goulburn Floodplain, they are as follows:

- Maintain 100% of wetlands in healthy condition. Note: this ecological target has a requirement for two distinct hydrological regimes, which differ in their volume, frequency and the maximum time between events. This is reflected in the Bayesian network.
- Maintain 100% of Red Gum forest and Red Gum woodland in healthy condition. Note: this ecological target has a requirement for two distinct hydrological regimes, which differ in their volume, duration, frequency and the maximum time between events. This is reflected in the Bayesian network.
- Provide conditions conducive to successful breeding of waterbirds at least 3 years in 10. Note: the hydrological requirements for this ecological target have two components: a high flow event within which there is a period of higher 'peak' flow. This is reflected in the Bayesian network.

Each of the flow regimes has a node for each of the hydrological components. If the hydrological regime is such that any of these components (threshold, duration, timing, frequency, max time) is 'not met' then the flow regime (and therefore the ecological target) is also 'not met.'

Application to management

The ecological targets for the Lower Goulburn Floodplain each have two specified hydrological regimes; a combination of hydrological requirements that, based on our current knowledge, will ensure that they are maintained in a healthy condition. These regimes differ in the required threshold volumes, the duration of flows above this threshold, the timing of flows, the frequency of flows (includes a preferred and minimum frequency), and the maximum tolerable period between flow events (includes preferred and maximum period). Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets, without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (**Figure 31**) can be used to explore the outcome of different hydrological regimes, as it will predict the effect of changing each of the hydrological regime components on the different flow regimes and therefore the ecological components of the system. Different hydrological regimes can be entered into the Bayesian network (as ‘findings’ for threshold volume, duration, timing, frequency, period between events), and the outcomes can be identified for each of the flow regimes and ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

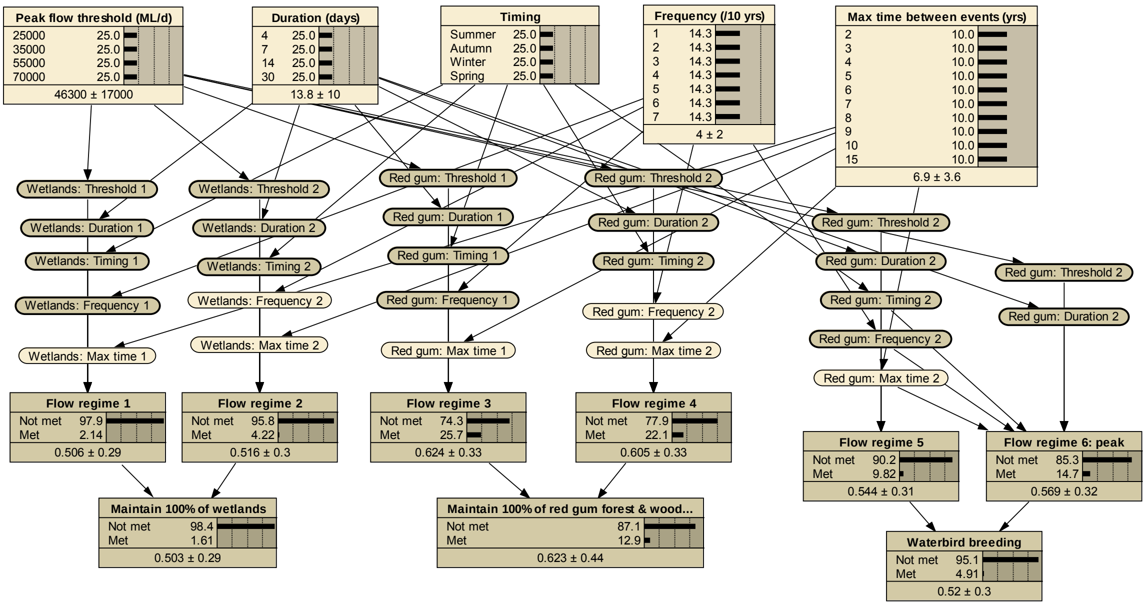

Figure 31: The Bayesian network model for the Lower Goulburn floodplain, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

LOWER MURRUMBIDGEE FLOODPLAIN: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Lower Murrumbidgee Floodplain.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Lower Murrumbidgee Floodplain, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Lower Murrumbidgee Floodplain (Figure 32) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Total Flow required: The total volume of flow required for each target (GL). If the required volume of flow (or a volume above this) is entered into the Bayesian network (via the 'Total Flow Required' node) then the flow node for that target will indicate that it has been 'met' (when volumes are entered below the flow required the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (in days). If the required duration of flow (or an amount of time above this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met' (when the duration is less than what is required for that target the node will indicate that the target is 'not met').

Timing: This node indicates whether the flow required for a target is seasonally dependent, and if so the season that the flows should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over a 10 year timeframe for each target. If flows occur at a frequency that is less than that required for a target the frequency node for that target will indicate that it is 'not met.' If flows occur at a frequency that is higher than the threshold for a target then the frequency node for that target is 'met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets (in years). If flows occur within the timeframe described (the stated number of years or less) then the 'max time' node for that target will indicate that it is 'met.' If the time between events is greater than the number of years indicated the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

There are fifteen ecological targets outlined in the EWP for the Lower Murrumbidgee Floodplain, grouped together in management units, they are as follows:

- Nimmie-Caira Management Unit
    - 100% of lignum in rookeries and floodways in good condition
    - 100% of red gum in rookeries, floodways and creeks in good condition
    - 100% of black box woodland in rookeries, floodways and creeks in good condition
- Redbank Management Unit
    - 100% of reed bed and rush wetlands and open lakes healthy condition
    - 100% of red gum forest in good condition
    - 70% of red gum woodland in good condition
    - 70% of black box woodland in good condition
- Murrumbidgee Management Unit
    - 100% of lignum in within identified Habitat Protection Areas in good condition
    - 100% of red gum in within identified Habitat Protection Areas in good condition
    - 100% of black box woodland within identified Habitat Protection Areas in good condition
- Fiddlers-Uara Management Unit
    - All water bodies identified as Southern Bell Frog sites in healthy condition.
    - 100% of remnant black box communities at Fingerboards in good condition (same requirements as 100% of black box within identified Habitat Protection Areas in good condition)
    - 100% of lignum in within identified Habitat Protection Areas in good condition
    - 100% of red gum within identified Habitat Protection Areas in good condition
- Across entire Lower Murrumbidgee Floodplain
    - Provide conditions conducive to successful breeding of thousands of colonial nesting waterbirds at least 3 years in 10

Each of the ecological targets has a node for each of the flow regime components. If the flow regime is such that any of these components (threshold, duration, timing, frequency, max time) is 'not met' then the ecological target is also 'not met.'

Application to management

The ecological targets for the Lower Murrumbidgee Floodplain each have a specified hydrological regime; a combination of hydrological requirements that, based on our current knowledge, will ensure that they are maintained in (or restored to) good condition. These regimes differ in the required threshold volumes, the duration, timing and frequency of flows, and the maximum tolerable period between flow events. Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets, without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (Figure 32) can be used to explore the outcome of different flow regimes, as it will predict the effect of changing each of the flow regime components on the different ecological components of the system. Different flow regimes can be entered into the Bayesian network (as 'findings' for total flow required, duration, timing, frequency, period between events), and the outcomes can be identified for each of the ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

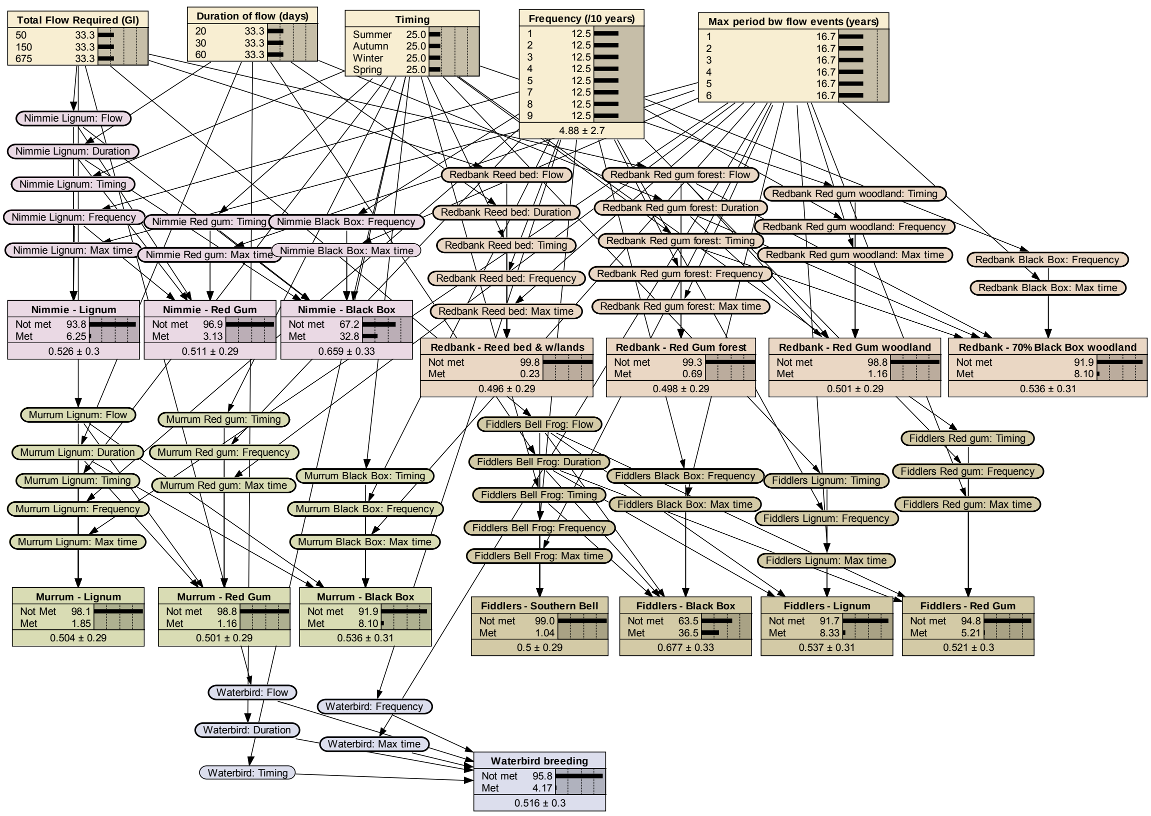

Figure 32: The Bayesian network model for the Lower Murrumbidgee Floodplain, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

MACQUARIE MARSHES: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Macquarie Marshes.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Macquarie Marshes, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Macquarie Marshes (Figure 33) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow volume: The total volume of flow required for each target (GL). If the required volume of flow (or a volume above this) is entered into the Bayesian network (via the 'Flow Volume' node) then the flow node for that target will indicate that it has been 'met' (when volumes are entered below the flow required the node will indicate that the target is 'not met').

Area of inundation: The area of inundation required for each target (ha). If the required area (or larger) is entered into the Bayesian network (via the 'Area of Inundation' node), then the node for that target will indicate that it has been 'met' (when areas are entered that are below the required area the threshold will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (in months). If the required duration of flow (or an amount of time above this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met' (when the duration is less than what is required for that target the node will indicate that the target is 'not met').

Timing: This node indicates whether the flow required for a target is dependent on the time of year, and if so the months during which the flow should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over a 10 year timeframe for each target. If flows occur at a frequency that is less than that required for a target the frequency node for that target will indicate that it is 'not met.' If flows occur at a frequency that is within the range specified (or higher frequency) for a target then the frequency node for that target is 'met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets (in years). If flows occur within the timeframe described (the stated number of years or less) then the 'max time' node for that target will indicate that it is 'met.' If the time between events is greater than the number of years indicated the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

Scenarios: Five of the ecological targets (2, 4, 5, 6 and 7 – see below) describe different flow regimes where there would be low, medium or high risk to reaching each of the ecological targets. The low risk flow regimes are those that are preferred (with a low risk of not reaching the target), the high risk regimes are the minimum requirements (with a high risk of not reaching the target). These flow regimes have been included in the Bayesian network in the 'Scenarios' node. To investigate the flow regime requirements for a particular target with a particular level of risk, that finding is entered into the Bayesian network.

For example, if one of the low risk scenarios for the water couch/mixed marsh communities is entered the Bayesian network shows which states each of the flow regime components (flow, area, duration, timing, frequency and the max. time between events) could possibly be in, and that the requirements for this target will be 'met.' If the medium risk scenario is entered there is a 75% chance that this target would be met, and if the high risk scenario is entered there is a 50% chance that this target would be met. In each case the Bayesian network indicates what state each of the flow regime components would be in under each scenario.

To investigate the effect of different flow regimes on the other targets (1, 3 and 8 – see below) the scenarios node should be set to 'none' and findings entered in each of the flow regime component nodes (flow, area, duration, timing, frequency and the max. time between events).

There are eight ecological targets outlined in the EWP for the Macquarie Marshes, they are as follows:

- Maintain 100% of current Common reed beds, water couch and mixed marsh in good condition.
- Restore 90% of water couch/mixed marsh and open water lagoons to good condition.
- Maintain 100% of current river red gum forest and woodland in good condition.
- Restore 90% of river red gum forest with semi-permanent wetland understorey currently to good condition.
- Restore 95% of river red gum forest with predominantly terrestrial species in the understorey currently to good condition.

- Maintain 100% of current River Cooba Woodland and lignum shrubland currently in good condition.
- Maintain 100% of current Coolibah, black box and Myall woodland in good condition.

Provide flows to support moderate-large colonial waterbird breeding events (2-3 in 10). Note: this ecological target has a requirement for three distinct hydrological regimes, which differ in their volume, duration, timing, frequency and the maximum time between events. This is reflected in the Bayesian network.

Each of the ecological targets 1, 3 and 8 has a node for each of the flow regime components. If the flow regime is such that any of these components (threshold, duration, timing, frequency, max time) is 'not met' then the ecological target is also 'not met.'

Application to management

The ecological targets for the Macquarie Marshes each have a specified hydrological regime; a combination of hydrological requirements that, based on our current knowledge, will ensure that they are maintained in (or restored to) good condition. These regimes differ in the required threshold volumes, areas of inundation, the duration, timing and frequency of flows, and the maximum tolerable period between flow events. In addition, some also differ in the likelihood of success of different flow regimes in meeting the ecological targets. Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets, without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (Figure 33) can be used to explore the outcome of different flow regimes, as it will predict the effect of changing each of the flow regime components on the different ecological components of the system. Different flow regimes can be entered into the Bayesian network (as 'findings' for total flow required, area, duration, timing, frequency, period between events), and the outcomes can be identified for each of the ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different flow regimes.

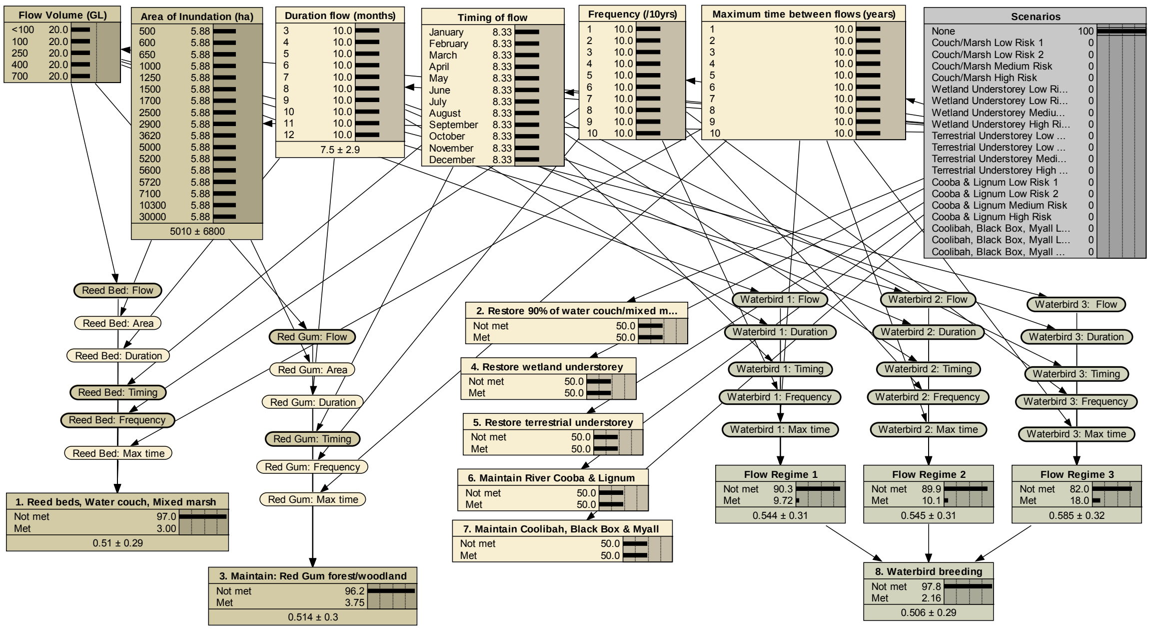

Figure 33: The Bayesian network model for the Macquarie Marshes, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

MID MURRUMBIDGEE WETLANDS: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Mid Murrumbidgee wetlands.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Mid Murrumbidgee wetlands, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Mid Murrumbidgee wetlands (Figure 34) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow threshold at Wagga: The threshold volume of flow required for each target (ML/day) at the Wagga Gauge. If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node) then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Flow threshold at Narrander: The threshold volume of flow required for each target (ML/day) the Narrander Gauge. If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow threshold' node) then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (in days), expressed as 'low risk' and 'high risk.' If the 'low risk' flow duration (or an amount of time greater than this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met.' If the 'high risk' flow duration is entered then there is a 50% chance of the target being 'met.' If the number of days entered is intermediate between high risk and low risk, then there is a 75% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met at the lower flow duration is less than at the higher flow duration.

Timing: This node indicates whether the flow required for a target is seasonally dependent, and if so the season that the flows should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over the 10 year time frame of the Basin Plan, expressed as 'low risk' and 'high risk.' If flows occur at a frequency that is low risk then the frequency node for that target will indicate that it is 'met.' If flows occur at a frequency that is high risk then there is a 50% chance of the target being 'met.' This reflects the fact that the likelihood of the target being met at the high risk frequency is less than at the low risk frequency. If the frequency is less than that indicated by the 'high risk' frequency then the frequency node for that target will indicate that it is 'not met.' If the frequency is higher than that indicated by the 'low risk' frequency then the frequency node for that target is 'met.'

Max. time between events: The maximum time between high flow events that can be tolerated while still meeting ecological targets. If flows occur within the timeframe described (the stated number of years or less) then the 'max time' node for that target will indicate that it is 'met.' If the time between events is greater than the number of years indicated the 'max time' node for that target will indicate that this component of the hydrological regime is 'not met.'

There is one ecological target for the Mid Murrumbidgee wetlands, to 'Provide drought refuge for internationally significant waterbirds by improving the health and conservation value of 4000 ha of wetlands.' This target has four flow regimes; each of these has a node for each of the hydrological regime components. If the hydrological regime is such that any of these components (threshold at Wagga, threshold at Narrander, duration, timing, frequency, max time) is 'not met' then the flow regime (and hence the ecological target) is also 'not met.'

Application to management

The ecological target for the Mid Murrumbidgee wetlands has four specified flow regimes; a combination of hydrological requirements that, based on our current knowledge, will ensure that the wetlands are maintained in (or restored to) a healthy condition. These regimes differ in the required threshold volumes (at two gauge locations), the duration of flows above this threshold (includes a low risk and high risk duration), the frequency of flows (includes a low risk and high risk frequency), and the maximum tolerable period between flow events. Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual flow regimes, without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (Figure 34) can be used to explore the outcome of different hydrological regimes, as it will predict the effect of changing each of the hydrological regime components on the different flow regimes required to meet the ecological target. Different hydrological regimes can be entered into the Bayesian network (as 'findings' for threshold volume, duration, timing, frequency, period between events), and the outcomes can be identified for each of flow regimes and therefore the ecological target. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different hydrological regimes.

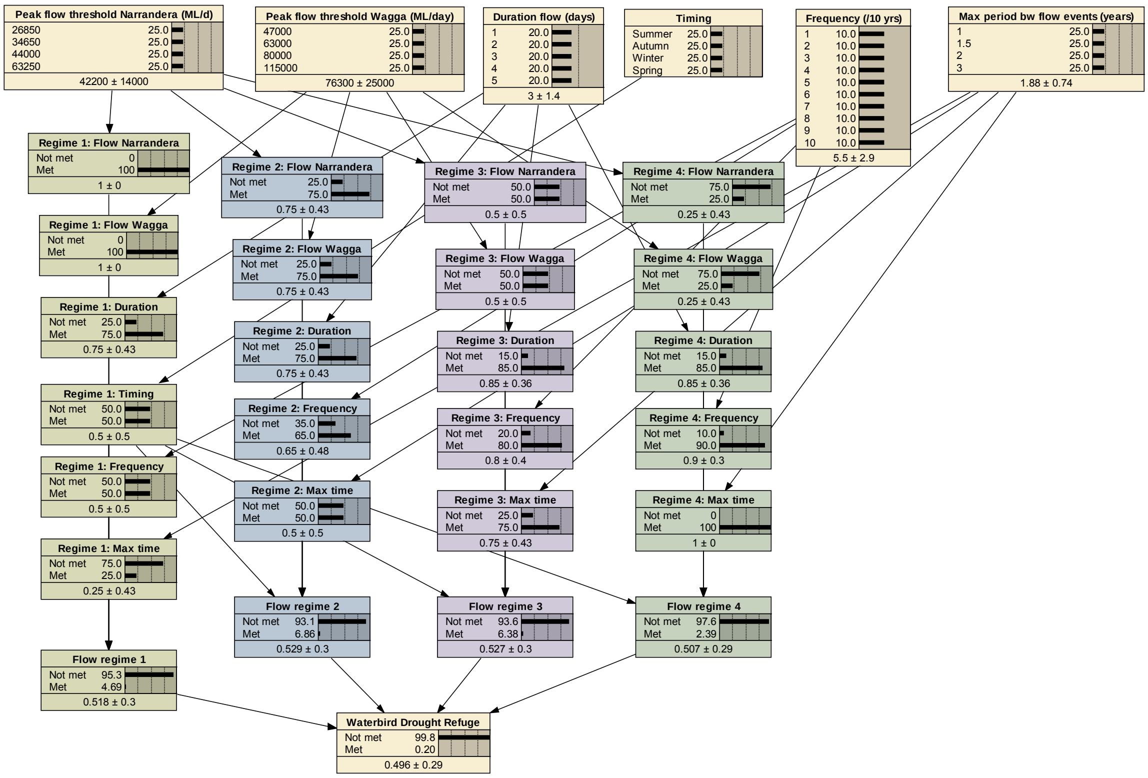

Figure 34: The Bayesian network model for the Mid Murrumbidgee wetlands, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

NARRAN LAKES: A Bayesian network model for Decision Support

Objectives

- To provide a model that can be used to aid in planning and decision-making for the Narran Lakes.
- To represent the information described in the *Environmental Watering Plan* (EWP), which outlines the environmental water requirements of the Narran Lakes, and the hydrologic targets that should be achieved to meet each of the environmental objectives.

Description

Bayesian decision support tools provide a modelling framework that can analyse complex problems and support decision-making in a risk assessment framework. A Bayesian network has been developed here to represent the hydrologic requirements for specific environmental objectives as set out in the EWP (Attachment C: Terminal asset hydrologic targets to measure progress towards meeting the environmental objectives for water dependent ecosystems over 2001-2019). Each 'box' (node) in the Bayesian network represents a component of the flow regime, or an ecological target, drawn from the EWP. These nodes are connected using arrows (arcs) which indicate the direction of causation, e.g. a particular flow threshold will cause each of the targets to either be 'met' or 'not met.'

The information used to parameterize the Bayesian network for the Narran Lakes (Figure 35) was drawn directly from Attachment C of the Environmental Watering Plan. The components of the hydrologic regime are as follows:

Flow threshold: The threshold volume of flow required for each target (ML/day). If the required threshold volume (or a volume above this) is entered into the Bayesian network (via the 'flow volume' node) then the threshold node for that target will indicate that it has been 'met' (when volumes are entered below the threshold the node will indicate that the target is 'not met').

Duration: The duration for which that flow volume is required for each target (in days). If the required duration of flow (or an amount of time above this) is entered into the Bayesian network, then the duration node for that target will indicate that it has been 'met' (when the duration is less than what is required for that target the node will indicate that the target is 'not met').

Timing: This node indicates whether the flow required for a target is seasonally dependent, and if so the season that the flows should be delivered. If a target is seasonally dependent and the flow is delivered at the wrong time of year the 'Timing' node will indicate that this component of the hydrologic regime is 'not met.'

Frequency: The frequency at which these flows are required over a 10 year timeframe for each target. The information for this node was supplied as the interval of time between flow events ('Return Period'); these were converted into an estimate of the number of times the flow event should occur in a 10 year period (to coincide with the timeframe of the Basin Plan). If flows occur at a frequency that is less than that required for a target the frequency node for that target will indicate that it is ‘not met.’ If flows occur at a frequency that is higher than the threshold for a target then the frequency node for that target is ‘met.’

There are six ecological targets outlined in the EWP for the Narran Lakes, they are as follows:

- Maintain and restore 100% of ecological character of the Narran Lakes Nature Reserve Ramsar site.
- Maintain 100% of lignum in the Narran Lakes Floodplain Wetland ecosystem.
- Maintain 100% of lignum and red gum woodland in the Clear/Back Lake Rookery.
- Maintain 100% of the Coolibah woodland.
- Inundate 100% of the Narran River Floodplain
- To provide environmental flows of >100,000 ML to the Narran Lakes Floodplain Wetland ecosystem.

Each of the targets (except for the final one) has a requirement for multiple flow regimes; each flow regime has a node for each hydrological component (flow volume, duration, timing and frequency). If the hydrological regime is such that any of these components (flow volume, duration, timing and frequency) is ‘not met’ then the flow regime (and hence the ecological target) is also ‘not met.’

Application to management

Each of the ecological targets for the Narran Lakes (apart from the final target) have multiple specified flow regimes; a combination of hydrological requirements that, based on our current knowledge, will ensure that they are maintained in (or restored to) a good condition. These regimes differ in the required threshold flow volumes, the duration of flows above this threshold, the timing of flows, and the minimum frequency of flows. Because of this, predicting the outcomes of any particular schedule of water flows on each of the individual ecological targets (or flow regimes), without the benefit of decision support tools, is made very difficult. The Bayesian network presented here (Figure 35) can be used to explore the outcome of different hydrological regimes, as it will predict the effect of changing each of the regime components on the different ecological components of the system. Different hydrological regimes can be entered into the Bayesian network (as ‘findings’ for threshold volume, duration, timing and frequency), and the outcomes can be identified for each of the flow regimes, and hence the ecological targets. Used in this way, the Bayesian network can help to weigh up the likely benefits and potential draw backs of different hydrological regimes.

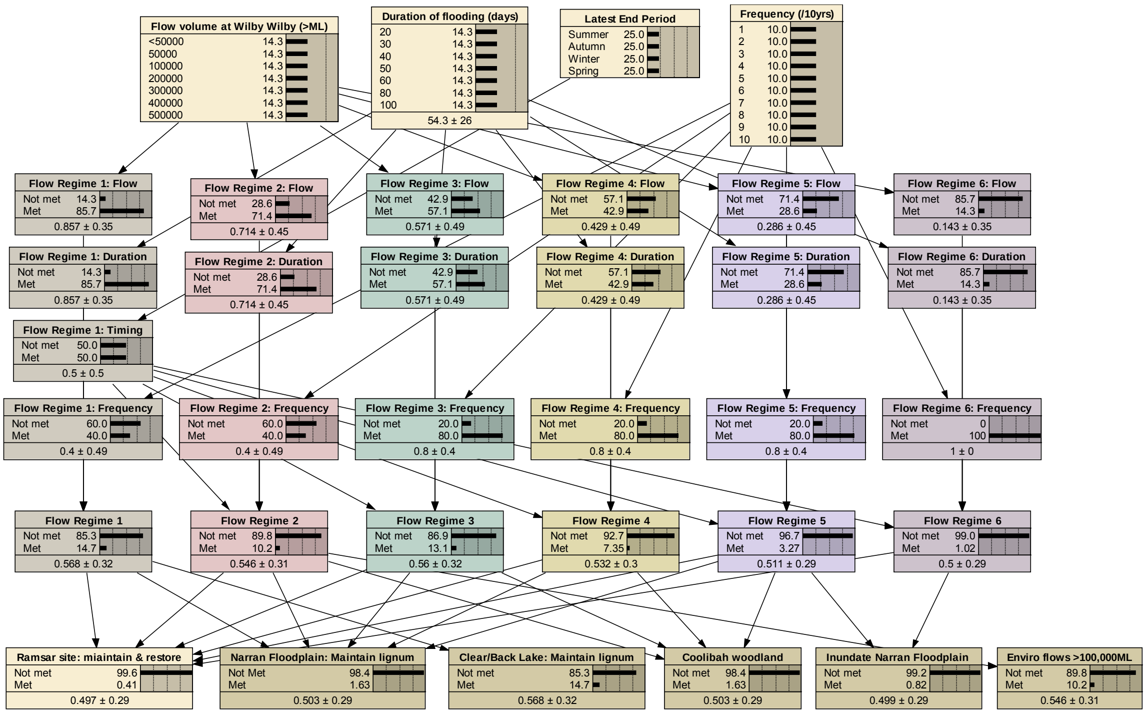

Figure 35: The Bayesian network model for the Narran Lakes, which includes flow regime components and the ecological targets for this system, as outlined in the EWP.

Definitions

Risk has two components, the likelihood of an adverse event occurring combined with the impact of that event.

Risk Assessment is a structured and systematic process, which includes an initial problem formulation phase (specifying the spatial, temporal and ecological limits of the assessment); conceptual modelling (describes system components, processes and causal links); hazard assessment (identifies threats to a system, the potential consequences and the nature of the undesirable effects); risk analysis (the relative likelihood of a hazard affecting a system); risk ranking; and scenario testing (predicting the consequences of likely future scenarios).

Risk Management uses the knowledge gained in the risk assessment to reduce the level of risk to the system under consideration and to aid in decision making. It should also include a monitoring component which estimates the effectiveness of the management strategy and can be used to recommend changes if necessary.

Hazards (also referred to as stressors or threats) are defined as any physical, chemical, or biological entity that can cause an adverse effect. Typically a wide range of stressors need to considered in the WRP area assessment. Sources of hazards can include human activities and natural processes.

Bayesian networks are a type of graphical probabilistic model, the basis of which is a diagram conceptualizing the ecological system to be managed; this diagram reflects how the system works as an integrated whole(Cain 2001). The variables in the system, each represented by a node, are linked to parent nodes, on which they are dependant. The arrows between the nodes represent causal dependencies based on understanding of process, statistical or other types of association; they represent the strength of the causal relationship between variables (Pollino et al. 2007b).

Acknowledgements

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Great Cumbung Swamp

Edward-Wakool River system

Gunbower Koondrook-Perricoota forests

Gwydir wetlands

Hattah Lakes

Lachlan Swamp

Lower Balonne Floodplain

Lower Darling River

Lower Goulburn Floodplain

Lower Murrumbidgee Floodplain

Macquarie Marshes

Mid Murrumbidgee wetlands

Narran Lakes

Appendix 1

Risk 1 model:

Risk1_Generic.neta

Risk 2 models:

Risk2_Drinking_Generic.neta

Risk2_Recreation_Generic.neta

Risk2_Primary_Industries_Generic.neta

Risk2_Aquatic_Ecosystems_Generic.neta

Risk2_All_uses_Generic.neta

Risk 3 model:

Risk3_Generic.neta

KEA extension model:

KEA_Extension_Lower_Darl_e.g..neta

Appendix 2

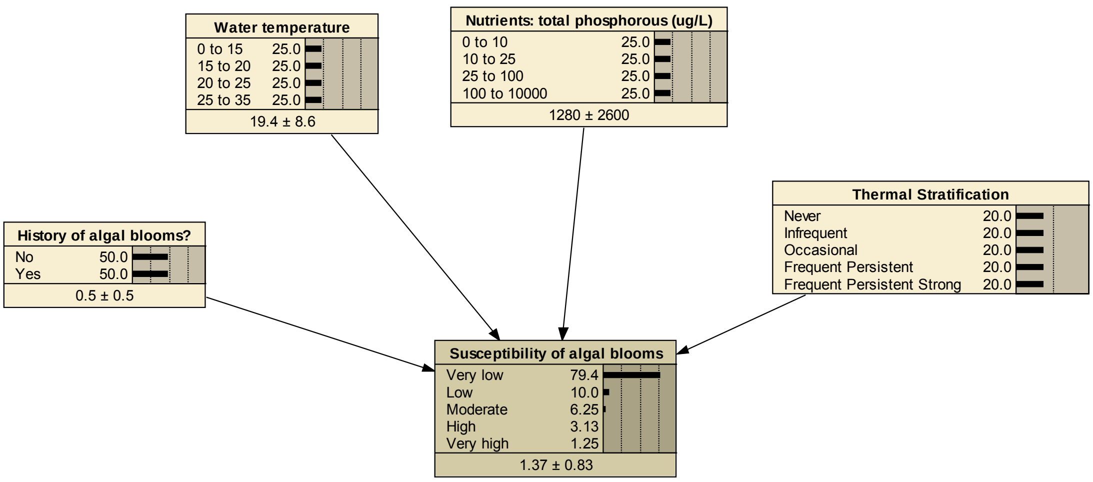
Blue Green Algae Alternative Assessment Model

This method assess the susceptibility to algal blooms based on water temperature, total phosphorus concentration, thermal stratification and a history of algal blooms at the site. It is sourced from a model by (Tighe et al. 2008) and is based on a relationship derived from information in the NHMRC guidelines (NHMRC 2006):

Environmental factors (singly or in combination)			
Water temperature (^{o}C)	Nutrients: total phosphorous (µg/L)	Thermal stratification	Susceptibility category
< 15	< 10	Never present	Very low
15 – 20	<10	Infrequent	Low
20 – 25	10 – 25	Occasional	Moderate
> 25	25 – 100	Frequent and persistent	High
> 25	> 100	Frequent and persistent / strong	Very high

The model assumes that:

- The susceptibility of the river to blue green algal blooms conforms to the relationships documented in the NHMRC guidelines (NHMRC 2006).
- The past history of algal blooms is indicative of possible future problems.
- The limiting nutrient is phosphorous.
- The specified thresholds used in the model are correct.

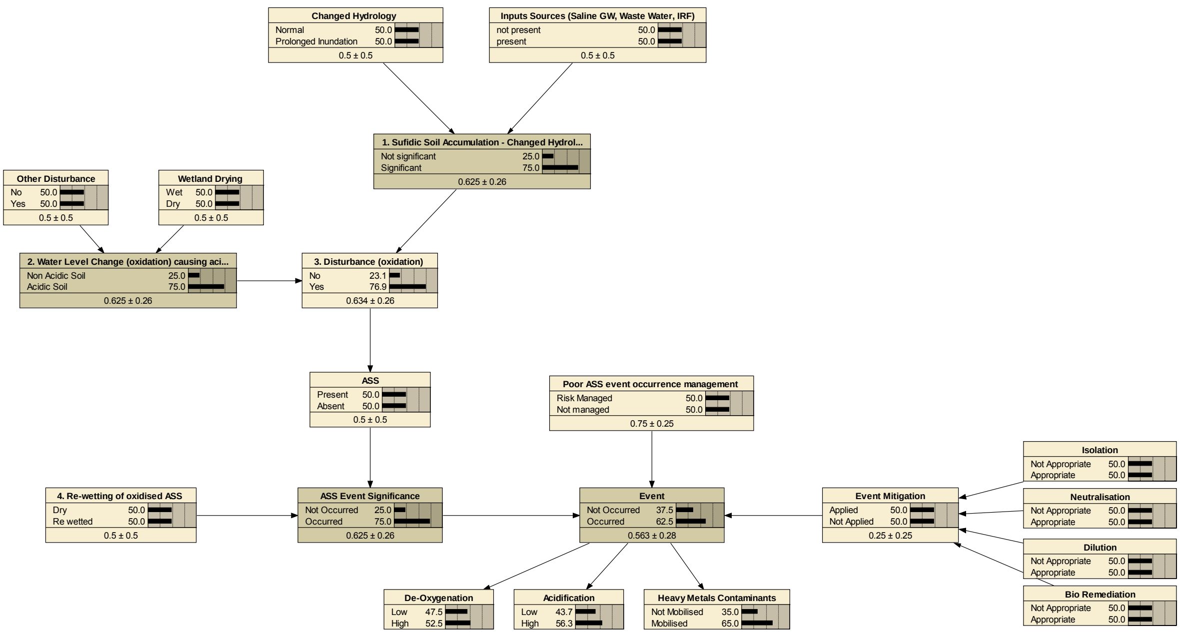


Appendix 3

Acid Sulphate Soils: ASS.neta

Acid sulfate soils (ASS) are becoming increasingly prevalent in the Murray Darling Basin (MDB) as a result of the drying of a number of wetlands, rivers and lakes due to a combination of changes in the hydrology in regulated sections of the system and drought. The low river levels and inflows have allowed the accumulation of sulfidic material in subaqueous and marginal soils (Fitzpatrick *et al* 2009). Acid sulfate soils in the MDB pose risks to water quality, human and animal health, agriculture and the environment. Potential impacts include: soils becoming so acidic that nutrients becoming less available to plants; increasing likelihood of salinity and waterlogging; grazing animals taking in too much aluminium and iron; and fish and aquatic species kills, accumulating in environmental degradation and the loss of agricultural productivity. Some areas of ASS concern in the MDB include the Mount Lofty Ranges, the Lower Lakes (Lake Alexandria to Lake Albert), Goolwa Channel, Finniss River and Currency Creek.

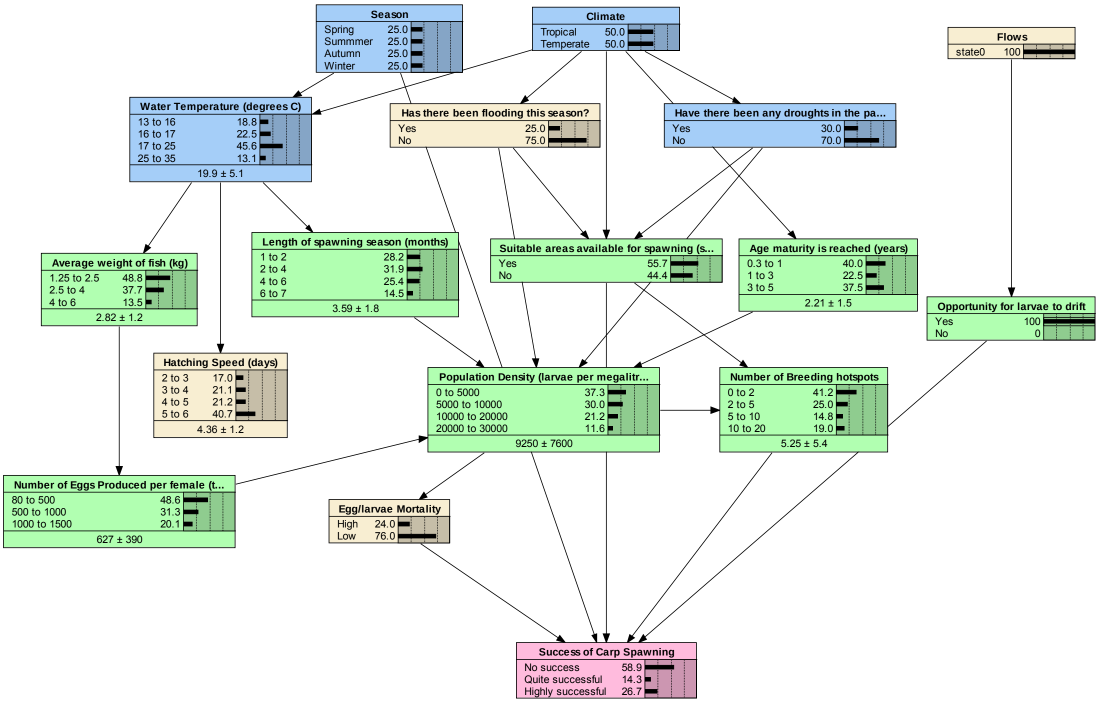
The ASS Bayesian network will assist land managers with predicting the likelihood of an ASS in a given landscape, and the likely levels of de-oxygentation, acidification and heavy metal contaminants. The Bayesian network can be used to assess the impact different mitigation methods will have on the likelihood of an ASS event, and the resulting implications. The network is designed to be used in conjunction with, and to support, a full program of ASS management, which should involve steps to: control and treat existing acidity (through isolation, neutralisation and dilution); maintain conditions for natural bioremediation processes; and prevent further acidity (ensuring ASS are permanently submerged/saturated).



Carp: Carp.neta

Carp were released into the wild in Australia in the 1800s and 1900s, and survived without causing much problem, until the 'Boolara' strain was released in the middle of the 20th century, which have been dominating the waterways of the Murray Darling Basin since. Widespread flooding in 1974 and 1975 is believed to have significantly contributed to the populations rapid spread. Recent surveys have found that carp represent 'more than 90% of fish biomass in some rivers, and have reached densities of up to one fish per square metre of water surface' (DAFF 2009).

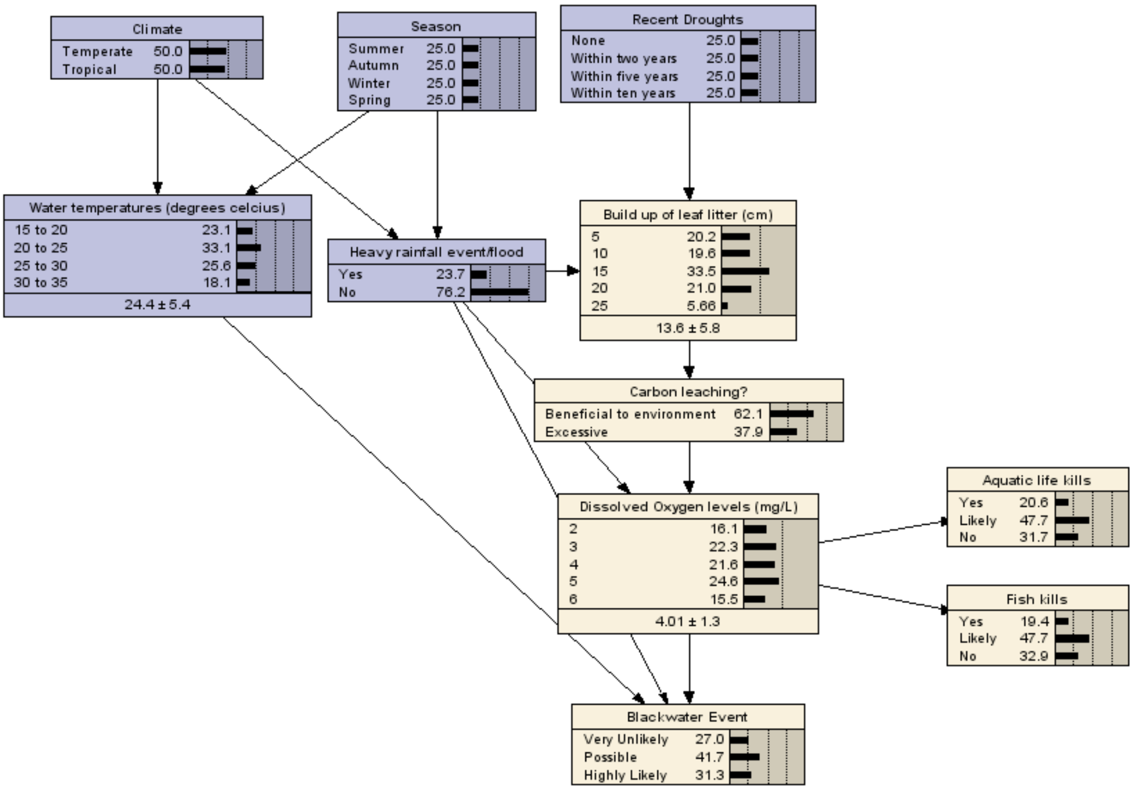
The Carp Bayesian network has been created to assist managers with predicting the likelihood of carp spawning given a series of conditions, and accordingly assist with managing carp populations. The network can be adapted for varying climates within the Basin (tropical or temperate, depending on ones location), and can be used in any season. The network should be used in conjunction with management plans, such as targeting spawning hotspots and inhibiting larvae drift. The network will assist with allocation of funds to eradication of higher density spawning sights at appropriate times, rather than exerting time and money on management options with a lower impact.



Blackwater events: Blackwater.neta

Blackwater events are caused by a combination of: high levels of carbon; low levels of dissolved oxygen; water temperature; flooding; and droughts. In a blackwater event, the water colour turns to that of black tea, and is also defined by a dramatic change in water quality. Blackwater events are considered a natural part of the ecology of lowland river systems (MDFRC 2009). Carbon is released from leaf litter that builds up on riverbeds, with increasing levels as leaf litter ages. Carbon plays as important role in the function of a river system, but elevated levels can change water quality. If there are elevated levels of carbon released, microrganisms consume some (about 1/3) of the dissolved carbon, and as they do so they use up the oxygen in the water - often at a faster rate than it can be replenished. Consequently, blackwater events are often linked to fish and aquatic life kills (caused by the lack of dissolved oxygen). Blackwater events are more likely to occur in warmer waters.

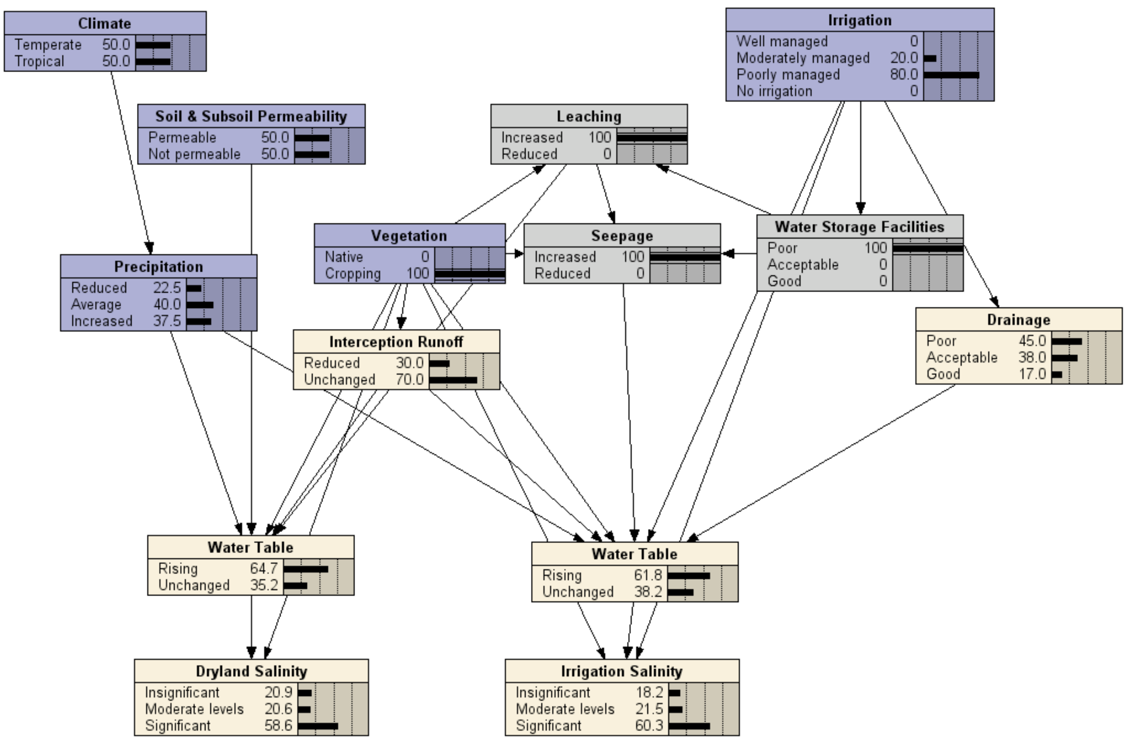
The Blackwater Bayesian network is designed to assist with predicting the likelihood of blackwater events, and taking necessary measures to avoid its occurrence, or minimise its impacts. Planning for blackwater needs to be long term, as once the factors are all in place for a blackwater event, it is then difficult to avoid. River managers must ensure that floodplains are regularly inundated to release the stores of carbon and nutrients, but must also ensure an inundated isn't going to release toxic levels of stores. The Bayesian network will assist river managers with assessing the risk of having a blackwater event.



Salinity: Salinity.neta

There are two types of salinity that affect Australian landscapes, dryland salinity and irrigation salinity. Dryland salinity is caused by a rising water table, which brings natural salts to the surface, and becomes progressively concentrated as water evaporates and is used by plants. Irrigation salinity occurs when water soaks through the soil where the plant roots grow, adding to the water table below, and bringing salt to the surface. The key impact of salinity on farm are a loss of production, which results in a loss of income. Additionally there is a decline in the value of land, damage to infrastructure, loss of shelter and shade, and the list goes on. If these affects are assessed at the regional scale, they are magnified to having a substantial impact on public resources such as biodiversity, water supplies, and infrastructure (ANRA 2009).

The salinity Bayesian network predicts both dryland and irrigation salinity levels, and is designed to be used by dryland and irrigation farmers and land managers as a tool to assist with salinity assessment and management. It is adaptable to areas throughout the Murray Darling Basin, whether they are irrigators with large water storage facilities, farmers on clay soils or tropical farmers in Queensland. A key function of the Bayesian network is the ability to assess how much of an impact management actions, such as a change from cropping to native vegetation, will have on the salinity levels in different areas. Salinity is a significant problem in the Murray Darling Basin, and results from management actions will be slow. Dramatic changes in farming practices are required, and the Salinity Bayesian network can be used to target those changes towards the most effective actions and spending.



Appendix 4

KEA Risk Assessment models

Barmah-Millewa Forest: Barmah Millewa.neta

Booligal Wetlands: Booligal.neta

Chowilla Floodplain and Lindsay-Wallpolla Islands: Chowill and Lindsay Wallpolla.neta

Great Cumbung Swamp: Cumbung swamp.neta

Edward-Wakool River system: Edward Wakool.neta

Gunbower Koondrook-Perricoota forests: Gunbower Koondrook-Perricoota.neta

Gwydir wetlands: Gwydir.neta

Hattah Lakes: Hattah.neta

Lachlan Swamp: Lachlan.neta

Lower Balonne Floodplain: Lower Balonne.neta

Lower Darling River: Lower Darling.neta

Lower Goulburn Floodplain: Lower Goulburn.neta

Lower Murrumbidgee Floodplain: Lower Murrmunbidgee.neta

Macquarie Marshes: Macquarie Marshes.neta

Mid Murrumbidgee wetlands:Mid Murrumbidgee.neta

Narran Lakes: Narran Lakes.neta