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Adapting to climate change: A risk assessment and decision making framework for managing groundwater dependent ecosystems with declining water levels

Supporting Document 6: Development of Bayesian Belief Networks for modelling the impacts of falling groundwater due to climate change on groundwater dependent ecosystems

Peter Speldewinde

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SUPPORTING DOCUMENT 6:

Development of Bayesian Belief Networks for modelling the impacts of falling groundwater due to climate change on groundwater dependent ecosystems

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The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision-makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

Cover image: Quin Brook is located on the northern Gnangara Mound, Western Australia. This photo was taken in 2008 when there still used to be water in it © Dr Bea Sommer, Edith Cowan University, Centre for Ecosystem Management

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EXECUTIVE SUMMARY

Bayesian Belief Networks (BBNs) are an excellent tool for assessing the impact of climate change on groundwater dependent ecosystems. Due to its visual nature BBNs present a tool for communicating the environmental issues and processes and also a means of gathering additional information to feed into models or develop new models. BBNs are based on Bayesian probability which states that for any two events, A and B, the probability of event B occurring given that event A has happen ($p(B|A)$ can be determined using the formula

$$p(B|A) = p(A|B) \times p(B)/p(A)$$

where $p(A|B)$ is the probability of event A occurring given B, $p(B)$ is the probability of event B and $p(A)$ is the probability of event A. A BBN is composed of nodes (or variables) which have causal links where changes in the state of one node may influence other nodes linked to it. The nature of these changes are defined by conditional probability tables which give the probability of an outcome given the change in the influencing nodes.

BBNs have a number of advantages (Jakeman, 2009)-

- Easily updated with new submodels and new information
- Spatial and landscape components can be included as separate nodes
- Easily used as a tool for communicating complex environmental problems among experts, managers and stakeholders
- Can integrate models of different types
- Can be used as a decision making tool
- Transparent.

Bayesian belief networks (BBNs) were developed to model the potential impacts of climate change on groundwater dependent ecosystems. Three systems were chosen as case studies (Gnangara Mound, Blackwood River and Margaret River Caves). Each system had varying degrees of data available, ranging from a data rich case study (Gnangara Mound (invertebrates and vegetation) through to a data poor case study (Margaret River Caves).

The development and testing of the BBNs followed the process of-

(1) Developing a conceptual model for each of the systems: In this stage the identification of important system variables and links between variables were established. In this case this was done at a workshop with experts defining variable and causal links.
(2) Parameterisation of the models with data: In this stage states and probabilities for each variable were assigned, with each variable being discreet. As the three systems varied in the quality and quantity of data available, ranging from a completely data driven approach for the data rich Gnangara Mound wetlands (invertebrates and vegetation) through to an expert opinion approach for the Margaret River Caves and Gnangara Mound frogs. For all case studies Netica^{TM} v4 (www.norsys.com) was used for the construction of the BBNs (there is a range of BBN software, such as Genie^{TM} (www.genie.sis.pitt.edu) and Hugin^{TM} (www.hugin.com), any of these could have been used).
(3) Evaluation of the models: Evaluation of models was undertaken in two forms, expert opinion and sensitivity analysis. Qualitative feedback was obtained through stakeholders and experts in workshops where the models were demonstrated. Sensitivity analysis identifies how sensitive a conclusion is to the evidence provided. Sensitivity analyses were conducted at different

groundwater levels (node set to 100% for a particular groundwater level) to determine major driving nodes.

(4) Analysis of the impacts of various climate change scenarios on the systems using the BBN: Analysis of the impacts of various climate change scenarios was conducted using GIS for the Gnangara Mound and Blackwood River study sites, where groundwater level projections under different climate change scenarios were modelled using the BBNs (see SD7 Neville 2013).

In the case of the Gnangara Mound wetland invertebrates and wetlands, which had an extensive data set, BBNs were constructed using only available data. In the case of the Blackwood River where data was less extensive a combination of data and expert opinion was utilised. In the case of the amphibians and Margaret River caves case studies, where there was not appropriate data, expert opinion was utilised. In all cases BBNs could be constructed and the networks were able to model the impacts on the systems examined due to changing groundwater levels.

The case studies demonstrate the use of BBN’s in modelling the impact of altered groundwater levels, due to climate change, on groundwater dependent ecosystems. The case studies used a variety of information from extensive datasets (Gnangara mound invertebrates and vegetation) through to expert opinion (Gnangara mound frogs and Margaret River caves). The models provided a visual representation of the systems examined and allowed the manipulation of starting conditions for the models for the testing of different scenarios.

1. INTRODUCTION

A Bayesian Belief Network (BBN) is a graphical model which can be used to establish the causal relationships between key factors and final outcomes (Hart, 2006). BBN's can provide effective decision support tools for problems involving uncertainty and probabilistic reasoning (Cain, 2001). The networks are models that represent the correlative and causal relationships between variables graphically and probabilistically (Cain, 2001). BBNs can model a situation where causality plays a role but our understanding of what is going on is incomplete.

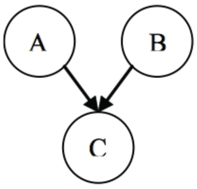
Bayesian Belief Networks are composed of a series of nodes, which represent a variable in the model. Each node has a number of states with an associated probability distribution. Where there is a casual link between nodes the nodes are linked, the relationship between the nodes is defined by a conditional probability table (Mo, 2010). The conditional probability table represents likelihoods based on prior information or past experience (Anon, 2008). The outcome of the BBN is a probability for the hypothesis, given the data or other evidence (Mo, 2010). For example, in Figure 1 an example of a simple network structure can be seen where nodes A and B represent causal factors influencing the probability of C (Figure 1a). The values of the nodes are defined in terms of states (Figure 1b). A conditional probability table (Figure 1c) defines the causal relationship between A,B and C. This results in the probability of the three outcomes of C (high, medium, low) occurring.

Bayesian Belief Networks are based on Bayesian probability theory. Bayes rule states that for any two events, A and B, the probability of event B occurring given that event A has happen $(p(B|A))$ can be determined using the formula

$$p(B|A) = p(A|B) \times p(B)/p(A)$$

where $p(A|B)$ is the probability of event A occurring given B, $p(B)$ is the probability of event B and $p(A)$ is the probability of event A (Jenson, 2007).

a)



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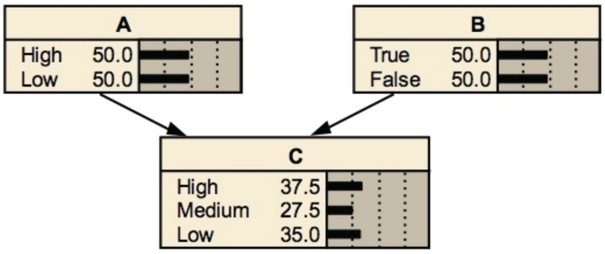

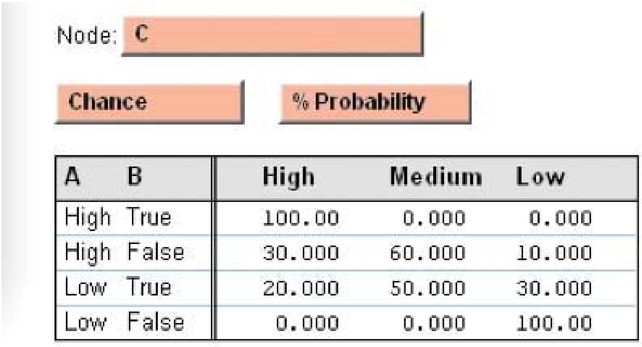

Node: C

A	B	High	Medium	Low
High	True	100.00	0.000	0.000
High	False	30.000	60.000	10.000
Low	True	20.000	50.000	30.000
Low	False	0.000	0.000	100.00

Figure 1: Example of a simple Bayesian Network structure (from (Kragt, 2009)).

Bayesian probability theory allows the modelling of uncertainty and outcomes by combining expert knowledge and observational evidence. The probability can be based on expert knowledge or data. When there is very little data the model will rely heavily on expert knowledge, where there is more data the model relies less on expert knowledge. One of the important features of BBNs is that the probabilities do not need to be exact to be useful. BBN’s are generally robust to imperfect knowledge and approximate probabilities (even educated guesses) very often give very good results.

BBNs have a number of advantages (Jakeman, 2009)-

- Easily updated with new submodels and new information
- Spatial and landscape components can be included as separate nodes
- Easily used as a tool for communicating complex environmental problems among experts, managers and stakeholders
- Can integrate models of different types
- Can be used as a decision making tool
- Transparent.

Disadvantages include (Jakeman, 2009)-

- Cannot be used as dynamic models (*e.g.* time step models)
- Cannot use feedback loops
- Variables must be discreet
- Not optimal for statistical inference
- Sometimes difficulty can be experienced in obtaining agreement on network structure.

Bayesian Belief networks have been used in a variety of fields including medicine, engineering, finance and ecology. BBN's have been used in a number of ecological and natural resource management contexts (Aguilera, 2011). An example of the use of Bayesian networks in natural resource management can be seen in Chan *et al.* (2012) where BBNs were used to assist decision-making on the environmental flow requirements for the Daly River in the Northern Territory. In this case BBNs were used to determine the impacts of altered flows on the abundance of two fish species. Due to the lack of data the majority of the relationships between flow and fish abundance were defined by expert opinion, with data being used where available. When the model was validated with field data prediction errors were between 20 and 30%. The models indicated that an increase in water extraction would deleteriously impact on the fish populations.

Marcot *et al.* (2001) used BBNs to evaluate fish and wildlife population viability under a number of land management alternatives. The BBN modelled the ecological causal web of a number of key environmental variables that influenced habitat capability, potential population response for each species and the influence of habitat planning alternatives. The probabilities within the model were obtained through a mixture of empirical data and expert opinion. The modelling allowed identification of planning decisions and key environmental variables that most impacted on species viability and therefore helped to prioritise management activities.

For the modelling of the impacts of climate change on groundwater dependent ecosystems BBN's were considered an appropriate tool as

- Knowledge of the interactions involved in groundwater dependent ecosystems is incomplete therefore some of the processes have to be modelled using expert opinion on top of the available data, BBNs are very robust to the use of imperfect knowledge
- Much of the data on groundwater dependent ecosystems had spatial components, BBNs are composed of nodes which can incorporate separate spatial components
- This project aims to develop a framework for use in assessing the impact of climate change on groundwater dependent ecosystems. Due to its visual nature BBNs present an excellent tool not only for communicating the environmental issues and processes but also a means of gathering additional information to feed into models or develop new models
- BBNs are composed of nodes which allow the manipulation of starting conditions for the model, they therefore present a useful management tool to test different scenarios.

2. METHODS

2.1 Definition of model objectives systems and scales

Bayesian belief networks (BBNs) were developed to model the potential impacts of climate change on groundwater dependent ecosystems. Three systems were chosen as case studies (Gnangara Mound, Blackwood River and Margaret River Caves). Each system had varying degrees of data available, ranging from a data rich case study (Gnangara Mound (invertebrates and vegetation) through to a data poor case study (Margaret River Caves). The Blackwood River system had data available for the species present but not necessarily available from the system. The development and testing of the BBNs followed the process of (1) developing a conceptual model for each of the systems, (2) parameterisation of the models with data, (3) evaluation of the models and (4) analysis of the impacts various climate change scenarios on the systems using the BBN. Points 1-3 are the subject of this section, analysis of impacts of climate change scenarios can be found in SD7 Neville 2013.

2.2 Development of a conceptual model for each of the systems

There are two important steps in the initial construction of the conceptual model of a Bayesian Belief Network (BBN). Firstly, the identification of important system variables and secondly, establishing links between variables (Kragt, 2009). The initial conceptual models were developed for all three systems being examined (Gnangara mound, Blackwood River and Margaret River Caves) at a workshop attended by experts on the three systems. The workshop involved experts identifying the key components of the ecosystem relating to groundwater level change. Participants in the workshops were asked to identify possible variables, relating to either climate change and/or groundwater levels which would impact on the biota of each system. A facilitator constructed the conceptual model during the workshop under direction of the experts present. The conceptual models were simple representations of the systems where links between relevant variables were made, with the direction of the impact noted. These conceptual models were used as the first step in the development of the BBNs.

2.3 Parameterisation of the models with data

To parameterise the model, states and probabilities for each variable needed to be assigned, with each variable being discreet. The conditional probability tables then needed to be populated. As the three systems varied in the quality and quantity of data available, ranging from a completely data driven approach for the data rich Gnangara Mound wetlands (invertebrates and vegetation) through to an expert opinion approach for the Margaret River Caves and Gnangara Mound frogs. The process for each of the cases are outlined below. For all case studies Netica^{TM} v4 (www.norsys.com) was used for the construction of the BBNs (there is a range of BBN software, such as Genie^{TM} (www.genie.sis.pitt.edu) and Hugin^{TM} (www.hugin.com), any of these could have been used).

2.3.1 Gnangara Mound

The Gnangara mound study area had a large data set covering a number of years for the response of macroinvertebrates and vegetation to changing groundwater levels. This dataset was used to create two BBNs (one for macroinvertebrates and one for vegetation) based solely on data. Development of these models is detailed in SD2 Sommer *et al.* 2013.

To develop an overall risk of wetland health based on both macroinvertebrates and vegetation the two models were joined, with their final outputs being used to populate a wetland health index conditional probability table. The two outputs were combined into a wetland health conditional probability table where if both inputs were 100% low risk then wetland health was rated 100% low risk, if both inputs were 100% high risk then wetland health was rated high risk (Table 1). Risk between the two extremes was determined by expert opinion.

Table 1: Conditional probability table for overall wetland health using risk to wetland vegetation and wetland macroinvertebrates. Showing the percentage probability of low, medium and high risk to wetland health.

Vegetation risk	Marcoinvertebrate risk	Low	Moderate	High
Low	Low	100	0	0
Low	Moderate	50	50	0
Low	High	25	75	0
Low	Very high	0	100	0
Moderate	Low	50	50	0
Moderate	Moderate	0	100	0
Moderate	High	0	75	25
Moderate	Very high	0	50	50
High	Low	25	75	0
High	Moderate	0	75	25
High	High	0	25	75
High	Very high	0	10	90
Very high	Low	0	100	0
Very high	Moderate	0	50	50
Very high	High	0	10	90
Very high	Very high	0	0	100

In addition to the risk to wetland vegetation and macro invertebrates models, BBNs were constructed for the frog species present in the wetlands. Initially an attempt was made to construct a BBN in a similar method to the methods used for the vegetation and macroinvertebrates (see SD2 Sommer *et al.* 2013 and SD3 Mitchell, Sommer and Speldewinde 2013). Due to the lack of appropriate data this was not possible, therefore networks were developed for the amphibians using expert opinion. The use of expert opinion in ecological decision making has been gaining use in recent years (Kuhnert, 2010). Martin *et al.* (2011) suggests five steps for the elicitation of expert knowledge:

1. Deciding on how the information will be used,

2. Determining what to elicit,
3. Designing the elicitation process,
4. Performing the elicitation, and
5. Translating the elicited information into quantitative statements which can be used in a model.

In the case of amphibians as part of the Gnangara mound groundwater dependent ecosystem the information was to be used to construct a BBN for modeling the impact of changes in groundwater levels on amphibians. Prior to consulting an expert panel, the species of interest were divided into three reproductive guilds by an expert on amphibians of the area (aquatic-breeding species (*Crinia glauerti, C. georgiana, C. insignifera, Limnodynastes dorsalsis, Litoria adelaidensis, Litoria moorei*), species with terrestrial embryos and aquatic larva (*Heleiporus eyrei* and *Pseudophryne guentheri*), and an entirely terrestrial species that breeds underground (*Myobatrachus gouldii*) (see SD3 Mitchell, Sommer and Speldewinde 2013). For each of the guilds a conceptual model was derived indicating the major variables relating to the survival of these species. A workshop was then convened with four experts on Gnangara Mound frogs. Experts were first asked if they agreed with the conceptual models and given the opportunity to modify the models. Once agreement on model structure was reached, expert opinion was then used to populate the conditional probability tables of the BBN. This process consisted of showing the group the model and then working through each node in the model and allowing experts to discuss their opinions on the probability of outcomes before reaching a consensus. This method was chosen given that the expert panel was small (four people) and the models were not overly complex (five nodes in the case of the Turtle Frog model). Once conditional probability tables for each node were completed, experts were given the opportunity to alter the tables if required and simple scenarios were run through the model to check if model outcomes matched with the expected outcome predicted by the expert panel.

The amphibian BBN's we not included in the wetland health model so that it could remain an example of a completely data driven BBN.

2.3.2 Blackwood River

The Blackwood study site was not as data rich as the Gnangara Mound study site, therefore a mixture of data and expert opinion was utilized to develop the BBN for fish in the Blackwood River. The relationship between groundwater levels (GWL) and surface water levels (SWL)(summer groundwater dependent flows) was derived using data from Department of Water gauging station on the Blackwood River (DOW gauge 609041). Using gauging station data and SWAMS groundwater levels the relationship was determined using regression (note only summer flows were used in the regression) (SWL=-4.4+(0.5× GWL)).

The relationship between surface water levels and water quality was derived using water quality and surface water level data from DOW gauging station 609041 (

Table 2). For each of the four water quality variables (temperature, salinity, dissolved oxygen and pH) the relationship was only determined for the summer months when groundwater inflow was the main contribution to surface water levels. For salinity and dissolved oxygen there was not a significant relationship to surface water levels although there was a general trend. The general trend for these two variables were used to determine salinity and dissolved oxygen values in the model.

Table 2: Relationships between variables used in the Blackwood River BBN and surface water level.

Variable	Relationship to surface water level(SWL)
Temperature	Temp=237.9-(21.2× SWL)
Dissolved oxygen (mg/L)	DO=-263.7+(32.4× SWL)
pH	pH=-13.0+(1.9× SWL)
Salinity (conductivity)	Sal=-58657.3+(5902.8× SWL)

The thresholds for the environmental variables were based on data (see SD4 Beatty *et al.* 2013) but were derived by expert opinion. Three possible outcomes were defined for the threshold, population 'persist', population 'likely decline' and population 'extreme decline'. For an outcome to fall into the population 'extreme decline' outcome one or more of the environmental thresholds had to fall outside of the known range for that species (the exceptions being if the salinity and dissolved oxygen, it was considered that salinity levels below recorded values or DO levels above recorded levels were still within the species thresholds). Population 'likely decline' was defined as three or more of the environmental variables being recorded in the 0-25 percentile or 75-100 percentile. If all of the variables fell in the 25-75 percentile the outcome was defined as population persist (the exceptions being salinity and DO, it was considered that salinity below the 25th percentile or DO levels above the 75th percentile were within the species thresholds).

To develop an overall index of fish health in the Blackwood study area, two indicator species were chosen to contribute to the index (*Nannatherina balstoni* and *Galaxias occidentallis*). *N.balstoni* only occurs over a narrow range of environmental conditions while *G.occidentalis* occurs over a wide range of environmental conditions (SD4 Beatty *et al.* 2013). A measure of fish community health node was therefore constructed in the model based on the characteristics of these two species (the thresholds of the remaining species lie between the two extremes of *N.balstoni* and *G.occidentalis*). If both species were found to persist in the the system was defined as 100% healthy, if both species were classified as 'severe decline' then the system was defined as 100% unhealthy. Various combinations in-between these two extremes were given probabilities by the expert panel (

Table 3).

Table 3: Conditional probability table for fish health in the Blackwood River based on outcomes from *N.bastoni* and *G.occidentalis*. Showing the percentage probability of low, medium and high risk to fish health.

N.balstoni	*G.occidentalis*	Good	Intermediate	Poor
Severe decline	Severe decline	0	0	100
Severe decline	Likely decline	0	25	75
Severe decline	Persist	0	50	50
Likely decline	Severe decline	0	25	75
Likely decline	Likely decline	0	50	50
Likely decline	Persist	25	50	25
Persist	Severe decline	0	25	75
Persist	Likely decline	0	50	50
Persist	Persist	100	0	0

2.3.3 Margaret River Caves

Very little data on the behaviour of these systems was available therefore the BBN was constructed purely on expert opinion. The basic outline of how networks are formed using expert opinion is described above for amphibians. In the case of the Margaret River Caves, two experts on the systems (Stefan Eberhard and Stacey Chilcott) working from the initial conceptual model derived a basic network structure based solely on groundwater level inputs and populated the conditional probability tables for each node based on their experience with the caves.

2.4 Evaluation of models

Evaluation of models was undertaken in two forms, expert opinion and sensitivity analysis. Qualitative feedback was obtained through stakeholders and experts in workshops where the models were demonstrated. Experts and stakeholder were asked to confirm if the model structure reflected their perception of how the system functioned and if the outputs derived from the models were what would be expected.

Sensitivity analysis was performed on each model. Sensitivity analysis identifies how sensitive a conclusion is to the evidence provided (Jenson, 2007). Sensitivity analysis also allows the identification of key nodes in the model, which play a significant role in the outcome of the model. The higher the value for a node the more that node influences the target, in this case outcome, node. Sensitivity analyses were conducted at different groundwater levels (node set to 100% for a particular groundwater level) to determine major driving nodes.

2.5 Analysis of impacts of various climate change scenarios on systems using the BBNs

Analysis of the impacts of various climate change scenarios was conducted using GIS for the Gnangara Mound and Blackwood River study sites, where groundwater level projections under different climate change scenarios were modelled using the BBNs (see SD7 Neville 2013).

3. RESULTS

3.1 Gnangara Mound

A conceptual model was derived during a workshop with a panel of experts (Figure 2). The initial conceptual model highlighted the importance of water quality, soil moisture, vegetation and soil type on this groundwater dependent ecosystem. With the exception of soil type, all these variables were dependent on the amount of water in the system. This conceptual model was refined to a number of separate BBNs (macroinvertebrates (see SD2 Sommer *et al.* 2013), vegetation (see SD2 Sommer *et al.* 2013), an overall wetland health model (Figure 1, Table 4 and Table 5). Results for the macroinvertebrate and vegetation models are discussed in SD2 Sommer *et al.* 2013.

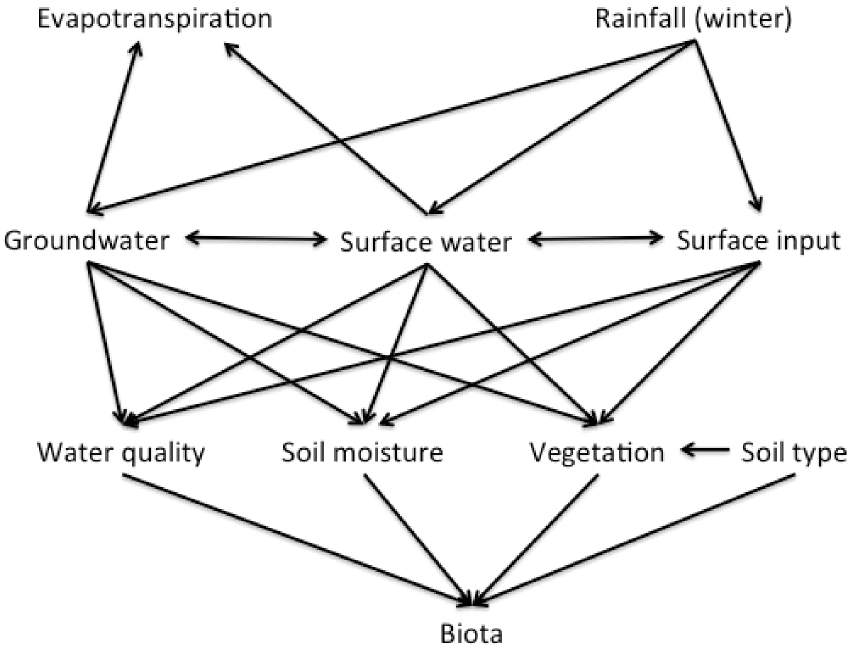

Figure 2: Conceptual model of the Gnangara Mound groundwater dependent ecosystem.

For the macroinvertebrates, the greatest contributing variable to risk to water quality and macroinvertebrate risk was changes in water chemistry (Table 6). Most nodes had slightly altered entropy reduction with changing groundwater depth, indicating that as groundwater levels the relative importance of these nodes changed. Depending on the lithology, changes in the number of dry days per year and groundwater depth impacted on both pH and NH4 (Table 6 and see also SD2 Sommer *et al.* 2013). For the vegetation model, a similar effect was observed with the entropy reduction altering slightly for most variables (Table 7). The slight changes in entropy reduction with changes in groundwater level for both models would seem to indicate that the response of each node is similar at the differing groundwater levels i.e. groundwater changes impact on the outcome of the model but each node does not change the way it responds when groundwater level changes.

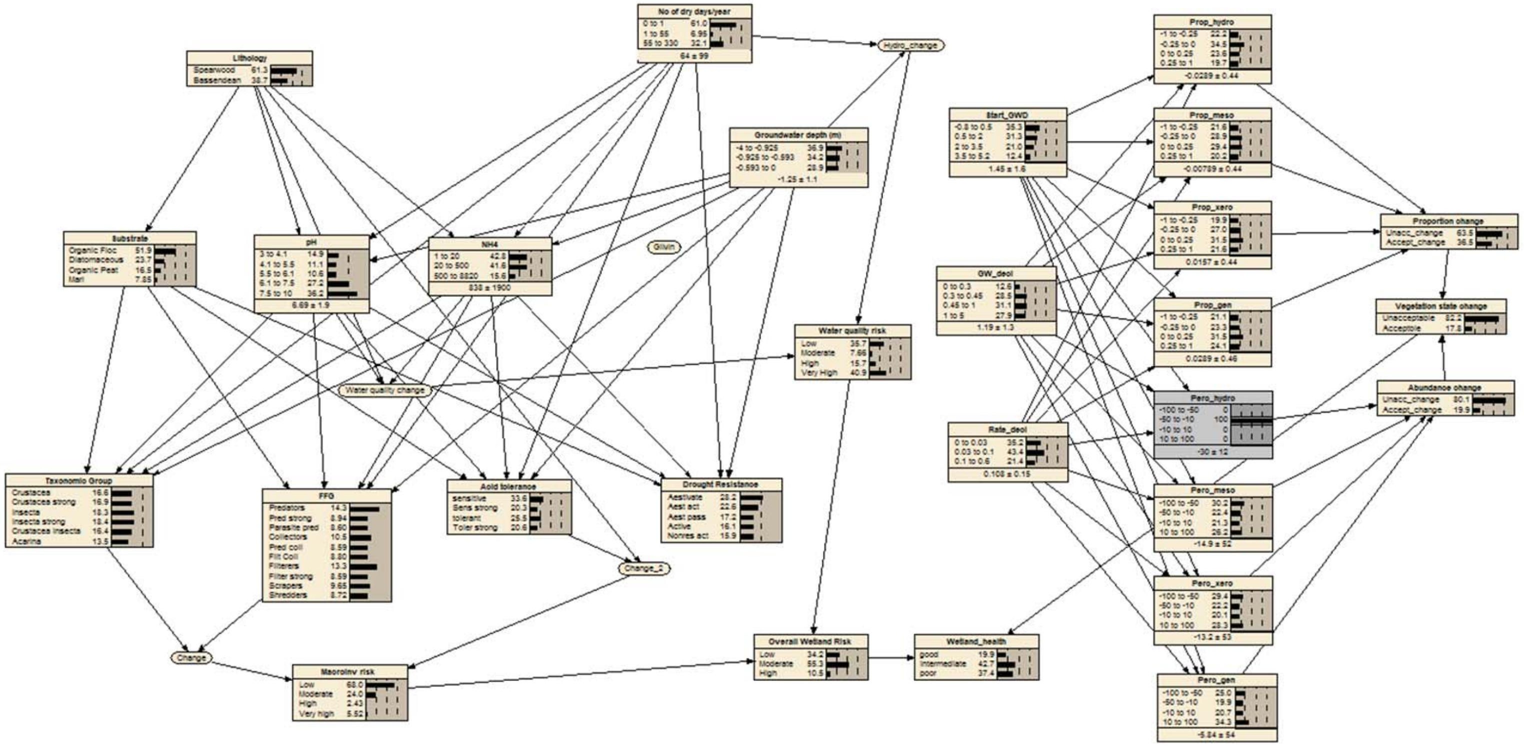

Figure 3: Combined macroinvertebrate and vegatation BBNs into an overall wetland health BBN.

Table 4: Description of nodes in invertebrate BBN.

Node	Description	Possible Node States
Lithology	Lithology	Spearwood Bassendean
No of dry days/year	The number of dry days/year	3 intervals taken from MRT threshold analyses
Groundwater depth (m)	Groundwater depth (m)	3 intervals taken from MRT threshold analyses
Hydro_change	Filter node for No of dry days and Groundwater depth	Acceptable Unacceptable
Substrate	Substrate	Organic Floc Datomaceous Organic Peat Marl
pH	pH	4 intervals taken from MRT threshold analyses
NH4	Ammonium concentration in µg/L	3 intervals taken from MRT threshold analyses
Water quality change	Filter node for lithology, pH and NH4	Acceptable Unacceptable
Water quality risk	Water quality risk	Low Moderate High Very high
Taxonomic group	Dominant macroinvertebrate taxonomic group	6 possible states
FFG	Dominant macroinvertebrate functional feeding group	10 possible states
Acid tolerance	Macroinvertebrate tolerance to acidity	Sensitive Sens strong Tolerant Toler strong
Drought resistance	Macroinvertebrate drought resistance	Aestivate Aest act Aest pass Active Nonres act
Change	Filter node for Taxonomic Group and FFG	Acceptable Unacceptable
Change_2	Filter node for Acid tolerance and lithology	Acceptable Unacceptable
Macroinv risk	Risk that macroinvertebrate functional character will change	Low Moderate High Very high
Overall Wetland Risk	Risk that ecological character of the wetland will change	Low Moderate High

Table 5: Description of nodes in the vegetation BBN and their output states.

Node	Description	Possible Node States
Start_GWD	Groundwater depth at commencement of monitoring	4 possible ranges taken from MRT threshold analyses
GW_decl	Magnitude of groundwater decline in meters	4 possible ranges taken from MRT threshold analyses
Rate_decl	Rate of groundwater decline in meters/year	3 possible ranges taken from MRT threshold analyses
Prop_hydro	Change in the proportion of hydrophytes	4 intervals
Prop_meso	Change in the proportion of mesophytes	4 intervals
Prop_xero	Change in the proportion of xerophytes	4 intervals
Prop_gen	Change in the proportion of generalists	4 intervals
Perc_hydro	Percentage change in hydrophyte abundance	4 intervals
Perc_meso	Percentage change in mesophyte abundance	4 intervals
Perc_xero	Percentage change in xerophyte abundance	4 intervals
Perc_gen	Percentage change in generalists abundance	4 intervals
Adverse change in proportion	Adverse change in the proportion of hydrotypes (filter node)	Unacc_change Accept_change
Adverse change in abundance	Adverse change in the percentage change of hydrotypes (filter node)	Unacc_change Accept_change
Risk of change to vegetation state	Risk of change to vegetation state	Unacceptable Acceptable

Table 6: Sensitivity analysis showing percentage entropy reduction for overall wetland risk (macroinvertebate model) at different groundwater levels.

Influencing node	**Groundwater depth -4 to -0.925**	**Groundwater depth -0.925 to -0.593**	**Groundwater depth -0.593 to 0**
Water quality risk	34.8%	32.3%	32.2%
Macro invertebrate risk	23.0%	22.4%	22.0%
Chem_change	25.8%	19.9%	19.7%
Change_2	10.4%	9.8%	9.5%
Change	5.5%	5.4%	5.3%
pH	5.8%	5.7%	4.7%
Hydro_change	4.5%	5.9%	2.8%
Acid_Tol	4.6%	3.8%	3.3%
NH4	3.8%	3.5%	2.7%
Dry_days	4.5%	3.8%	0.5%
Lithology	2.0%	1.4%	1.9%
Substrate	1.9%	1.2%	1.7%
FFG	1.6%	1.0%	0.8%
Taxa_group	1.0%	0.9%	0.6%
Drought_res	0.9%	0.7%	0.2%

Table 7: Sensitivity analysis showing percentage entropy reduction for overall risk of change to ecological character (vegetation) at different levels of groundwater decline.

Influencing node	**GW_decl 0 to 0.3**	**GW_decl 0.3 to 0.45**	**GW_decl 0.45 to 1**	**GW_decl 1 to 5**
Proportion change	21.0%	20.3%	21%	20.5%
Abundance change	23.5%	19.9%	20.6%	20.6%
Start_GWD	0.1%	1.2%	0.7%	0.2%
Rate_decl	1.5%	0.5%	1.8%	0.8%
Perc_xero	2.1%	2.0%	2.0%	1.3%
Perc_hydro	8.8%	8.8%	9.4%	8.0%
Prop_hydro	7.7%	6.7%	7.9%	7.6%
Perc_meso	0.5%	0.3%	0.4%	0.2%
Prop_meso	0.2%	0.3%	0.1%	0.1%
Perc_gen	2.1%	1.6%	2.6%	2.6%
Prop_gen	2.6%	2.3%	2.6%	2.3%
Prop_xero	1.6%	2.0%	1.1%	1.8%

Three BBNs were developed for the Gnangara mound frogs, one for each reproduction guild (

Figure 4, Table 8, Figure 5, Table 10, Figure 6 and

Table 13). Sensitivity analysis of the Turtle frog BBN (

Figure 4 and Table 9) shows no entropy reduction when the groundwater depth is zero and below 4m. At these depths the soil moisture is 100% unsuitable for the Turtle Frog and therefore the rainfall trigger nodes become irrelevant in the model. In between these two extremes soil moisture was still a highly relevant influence on the output node.

Sensitivity analysis of the BBN for aquatic breeding frogs (Figure 5 and Table 10) showed a similar pattern for all species where entropy reduction for each node was unchanged with changes in groundwater level. The only influence of the changes in groundwater level are through the salinity node. Within the groundwater levels modelled the salinity levels do not exceed the salinity threshold and therefore do not influence any of the output nodes.

With the terrestrial-aquatic frog BBN a similar situation was found with the sensitivity analysis (Figure 6 and Table 14). For the terrestrial aquatic frogs the salinity threshold was never exceeded in the model with the groundwater levels tested therefore altering the groundwater level did not alter the sensitivity analysis.

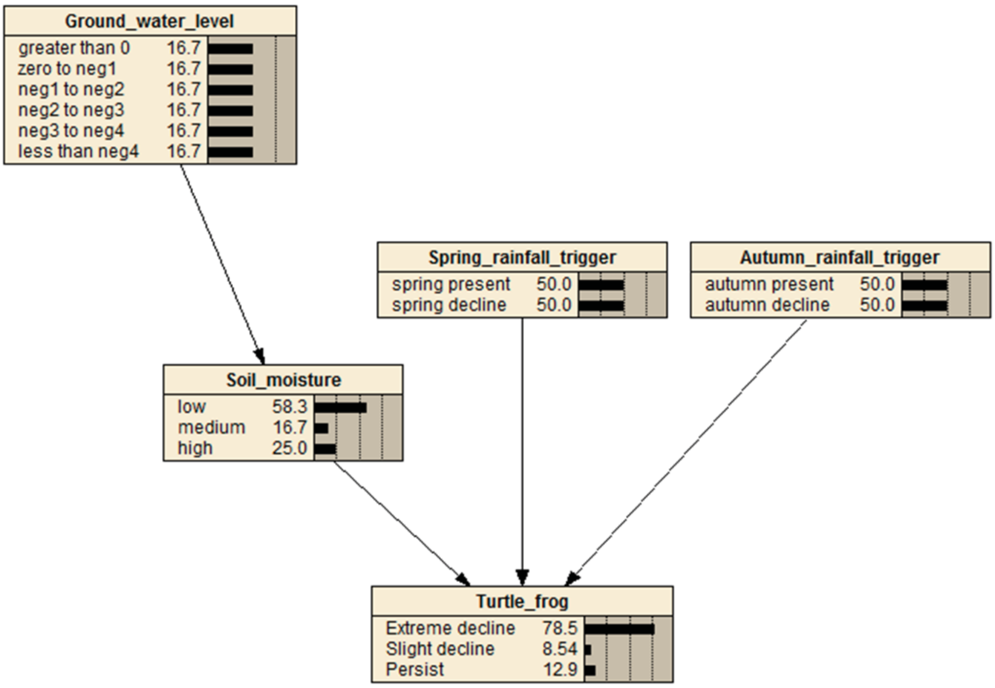

Figure 4: BBN for the Turtle Frog.

Table 8: Description of nodes in the Turtle frog BBN.

Node	**Description**	**Possible node states**
Ground_water_level	Height of water table relative to surface	6 groundwater levels
Soil_moisture	Amount of moisture in soil	Low/medium/high
Spring_rainfall_trigger	Rainfall in spring to trigger courship	Present/decline
Autumn_rainfall_trigger	Rainfall in autumn to trigger emergence of metamorphs	Present/decline

Table 9: Sensitivity analysis for the Turtle Frog BBN showing percentage entropy reduction at differing groundwater levels (assuming 50% chance of spring and autumn rainfall triggers).

Node	Greater than 0m	-1m to -2m	Less than -4m
Soil_moisture		32.8%	
Max_depth			
Autumn_rainfall_trigger		0.2%	
Spring_rainfall_trigger		0.1%	

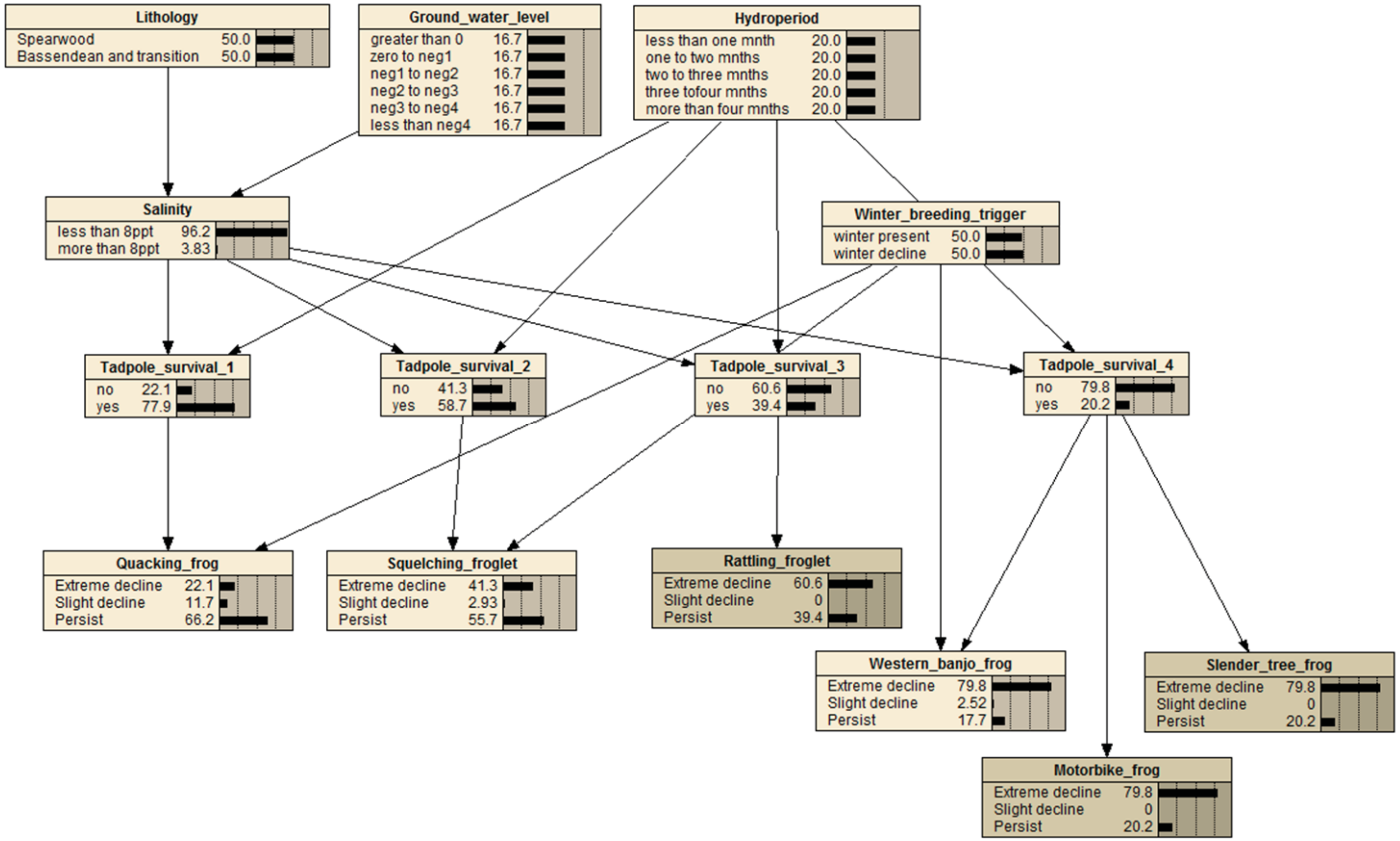

Figure 5: BBN for aquatic breeding frogs on the Gnangara Mound.

Table 10: Description of nodes in BBN for aquatic breeding frogs.

Node	Description	Possible node states
Salinity	Salinity of water with 8ppt being the threshold for survival	Less than 8ppt Greater than 8ppt
Tadpole_survival_1	Salinity and hydroperiod suitable for survival of tadpoles requiring surface water for one month	Yes/no
Tadpole_survival_2	Salinity and hydroperiod suitable for survival of tadpoles requiring surface water for two months	Yes/no
Tadpole_survival_3	Salinity and hydroperiod suitable for survival of tadpoles requiring surface water for three months	Yes/no
Tadpole_survival_4	Salinity and hydroperiod suitable for survival of tadpoles requiring surface water for four months	Yes/no
Winter_breeding_trig	Sufficient winter rainfall to trigger breeding	Present/decline
Ground_water_level	Depth of groundwater relative to the surface	Six groundwater levels
Hydroperiod	Time surface water available	Five time periods
Lithology	Type of lithology	Spearwood or Bassendean

Table 11: Sensitivity analysis for BBN for aquatic breeding frogs (assuming correct hydroperiod for the species, 50% chance of winter breeding trigger present and lithology 50%) at three groundwater levels.

Influencing Node	Quacking frog			Squelching froglet			Rattling froglet		
	Greater than 0m	-1m to -2m	Less than -4m	Greater than 0m	-1m to -2m	Less than -4m	Greater than 0m	-1m to -2m	Less than -4m
Salinity	22.1%	22.1%	22.1%	15.6%	15.6%	15.6%	100%	100%	100%
Tadpole_survival_1	22.1%	22.1%	22.1%	15.6%	15.6%	15.6%	100%	100%	100%
Tadpole_survival_2	0.2%	0.2%	0.2%	58.9%	58.9%	58.9%	100%	100%	100%
Tadpole_survival_3				0.1%	0.1%	0.1%	100%	100%	100%
Tadpole_survival_4							1.1%	1.1%	1.1%
Winter_breeding_trig	21.6%	21.6%	21.6%	7.45%	7.45%	7.45%			
Ground_water_level									
Hydroperiod									
Lithology	3.34%	3.34%	3.34%	0.9%	0.9%	0.9%	15.1%	15.1%	15.1%

Table 12: Sensitivity analysis for BBN for aquatic breeding frogs (assuming correct hydroperiod for the species, 50% chance of winter breeding trigger present and lithology 50%) at three groundwater levels.

Influencing Node	Western Banjo Frog			Motorbike Frog			Slender Tree Frog		
	Greater than 0m	-1m to -2m	Less than -4m	Greater than 0m	-1m to -2m	Less than -4m	Greater than 0m	-1m to -2m	Less than -4m
Salinity	24.1%	24.1%	24.1%	100%	100%	100%	100%	100%	100%
Tadpole_survival_1	24.1%	24.1%	24.1%	100%	100%	100%	100%	100%	100%
Tadpole_survival_2	24.1%	24.1%	24.1%	100%	100%	100%	100%	100%	100%
Tadpole_survival_3	24.1%	24.1%	24.1%	100%	100%	100%	100%	100%	100%
Tadpole_survival_4	24.1%	24.1%	24.1%	100%	100%	100%	100%	100%	100%
Winter_breeding_trig	0.6%	0.6%	0.6%						
Ground_water_level									
Hydroperiod									
Lithology	3.6%	3.6%	3.6%	15.1%	15.1%	15.1%	15.1%	15.1%	15.1%

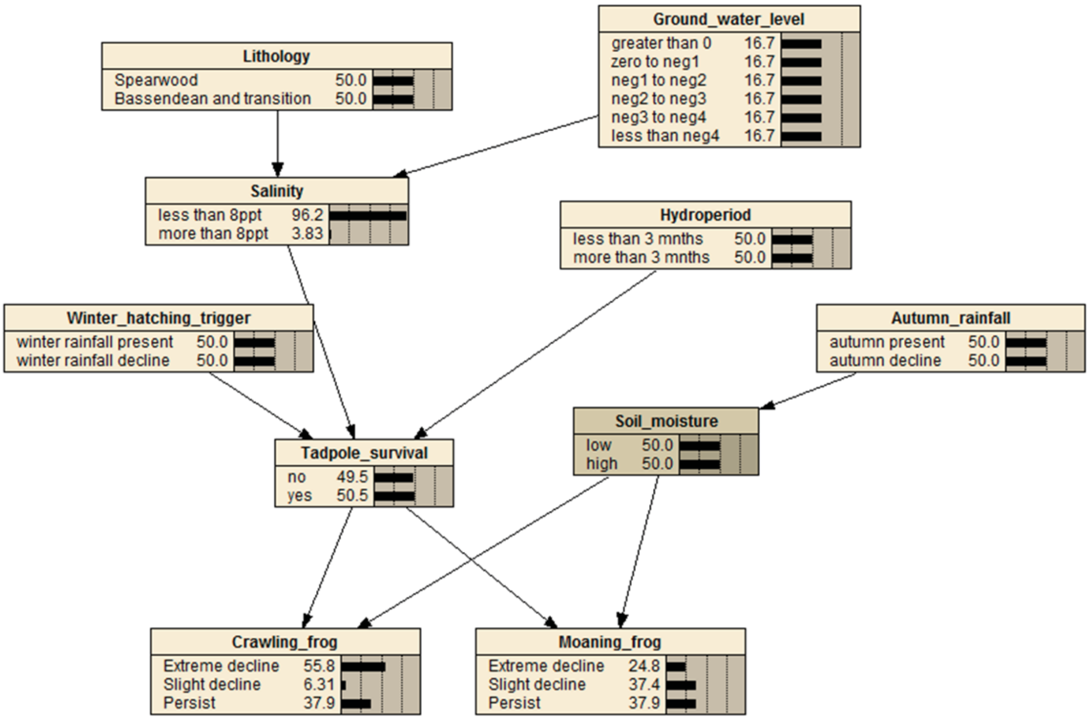

Figure 6: BBN for terrestrial-aquatic frogs.

Table 13: Description of nodes for terrestrial-aquatic frogs BBN.

Node	Description	Possible node states
tadpole_survival	Salinity and hydroperiod suitable for survival of tadpoles requiring surface water	Yes/no
Salinity	Salinity of water with 8ppt being the threshold for survival	Less than 8ppt Greater than 8ppt
Hydroperiod	Time surface water available	Less than 3 months More than 3 months
Soil_moisture	Amount of moisture in soil	Low/medium/high
autumn_rain	Sufficient autumn rainfall to trigger breeding	Present/decline
winter_rain	Sufficient winter rainfall to trigger hatching	Present/decline
Lithology	Type of lithology	Spearwood or Bassendean
GWL	Depth of groundwater relative to the surface	Six groundwater levels

Table 14: Sensitivity analysis for terrestrial-aquatic frogs (assuming 50% chance of winter hatching trigger, autumn rainfall trigger , lithology and correct hydroperiod).

Influencing node	Crawling frog			Moaning frog		
	Greater than 0m	-1m to -2m	Less than -4m	Greater than 0m	-1m to -2m	Less than -4m
tadpole_survival	56.8%	56.8%	56.8%	42.0%	42.0%	42.0%
Salinity	1.7%	1.7%	1.7%	1.2%	1.2%	1.2%
Hydroperiod	25.9%	25.9%	25.9%	18.2%	18.2%	18.2%
Soil_moisture	8.0%	8.0%	8.0%	4.1%	4.1%	4.1%
autumn_rain	8.0%	8.0%	8.0%	4.1%	4.1%	4.1%
winter_rain	1.0%	1.0%	1.0%	0.7%	0.7%	0.7%
Lithology	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GWL						

3.2 Blackwood River

The conceptual model for the Blackwood River system (Figure 7) highlighted the importance of summer groundwater flows into the system. Besides impacting on the water chemistry (particularly on maintaining low salinity levels) the groundwater inflows provide sufficient water depth to maintain connectivity.

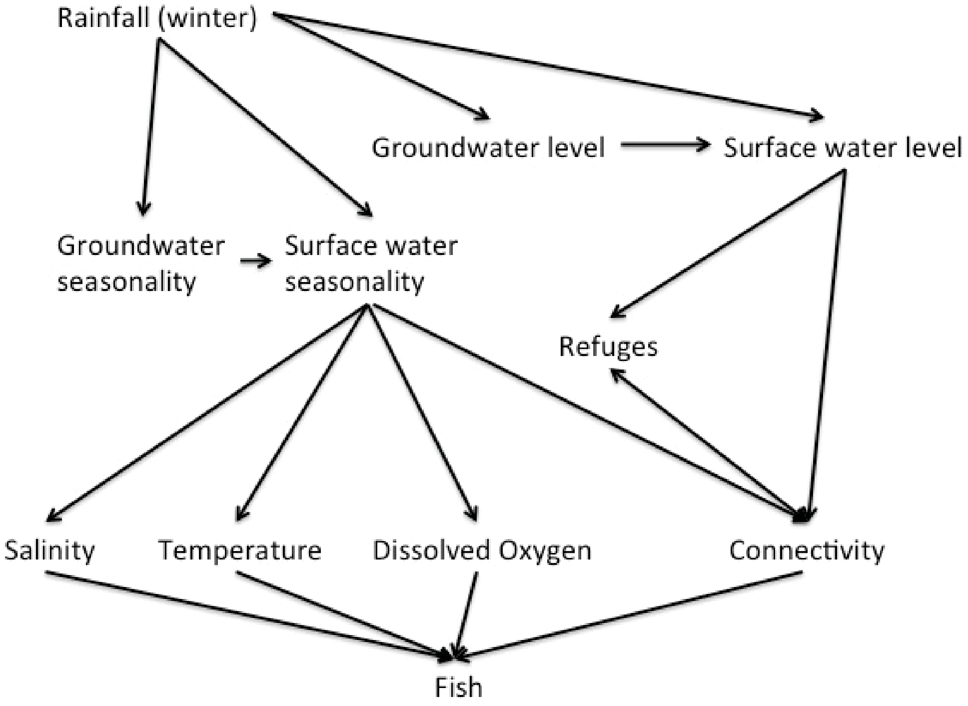

Figure 7: Conceptual model of the Blackwood River groundwater dependent ecosystem.

The BBN for fish in the Blackwood River consisted of four water chemistry variables (pH, dissolved oxygen, temperature and salinity) and a connectivity variable. All of which are directly linked to surface water depth, which in summer is directly driven by groundwater levels (Figure 8, Figure 9 & Table 15). Note: Figure 9 is BBN for the two species connected to the fish health node included to show the basic structure of the more complex Figure 8.

Changes to the nodes relating to *G.occidentalis* were the main influences on the fish health node (Table 16). The sensitivity analysis highlighted that the relative importance of various nodes altered with changes in depth to groundwater, for example, main channel connectivity entropy reduction was 52.9% at 1.5m depth to groundwater but reduces to 2.6% at -2.5m and back up to 17.6 at -8.5m.

For the fish health node for the BBN shown in Figure 8 a depth to groundwater of 4.5m was the optimal level for fish health (Figure 10) (note negative value indicates groundwater level is above surface). A decline in fish health with excess groundwater was due to the parameterization of the surface water node, where if surface water rises too high it is considered by the model to be water flow from surface flow upstream rather than groundwater and therefore is saline rather than fresh.

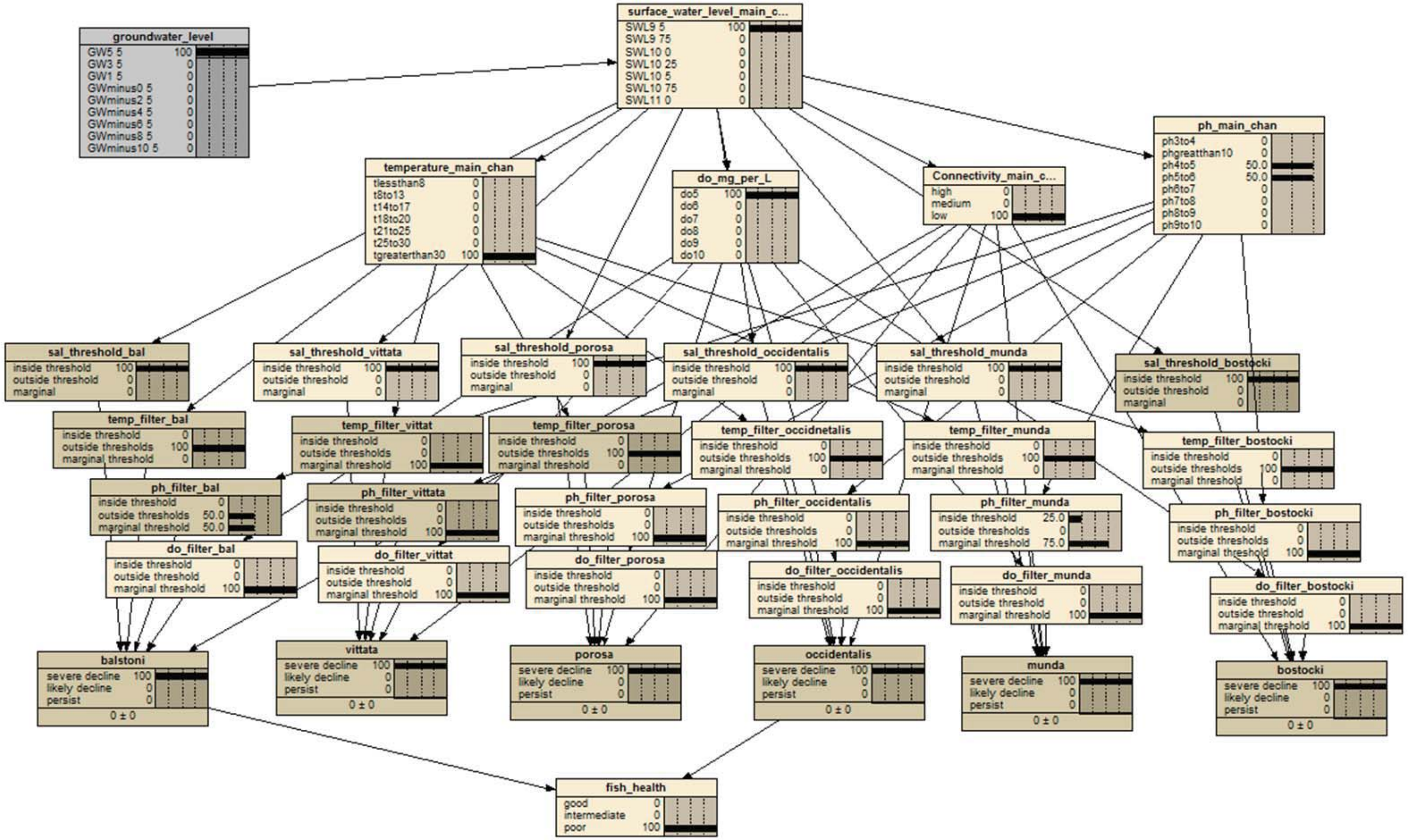

Figure 8: Complete BBN for Blackwood River incorporating all fish species and index of fish health. Note the model consists of six basic water parameter units repeated for each species specific threshold.

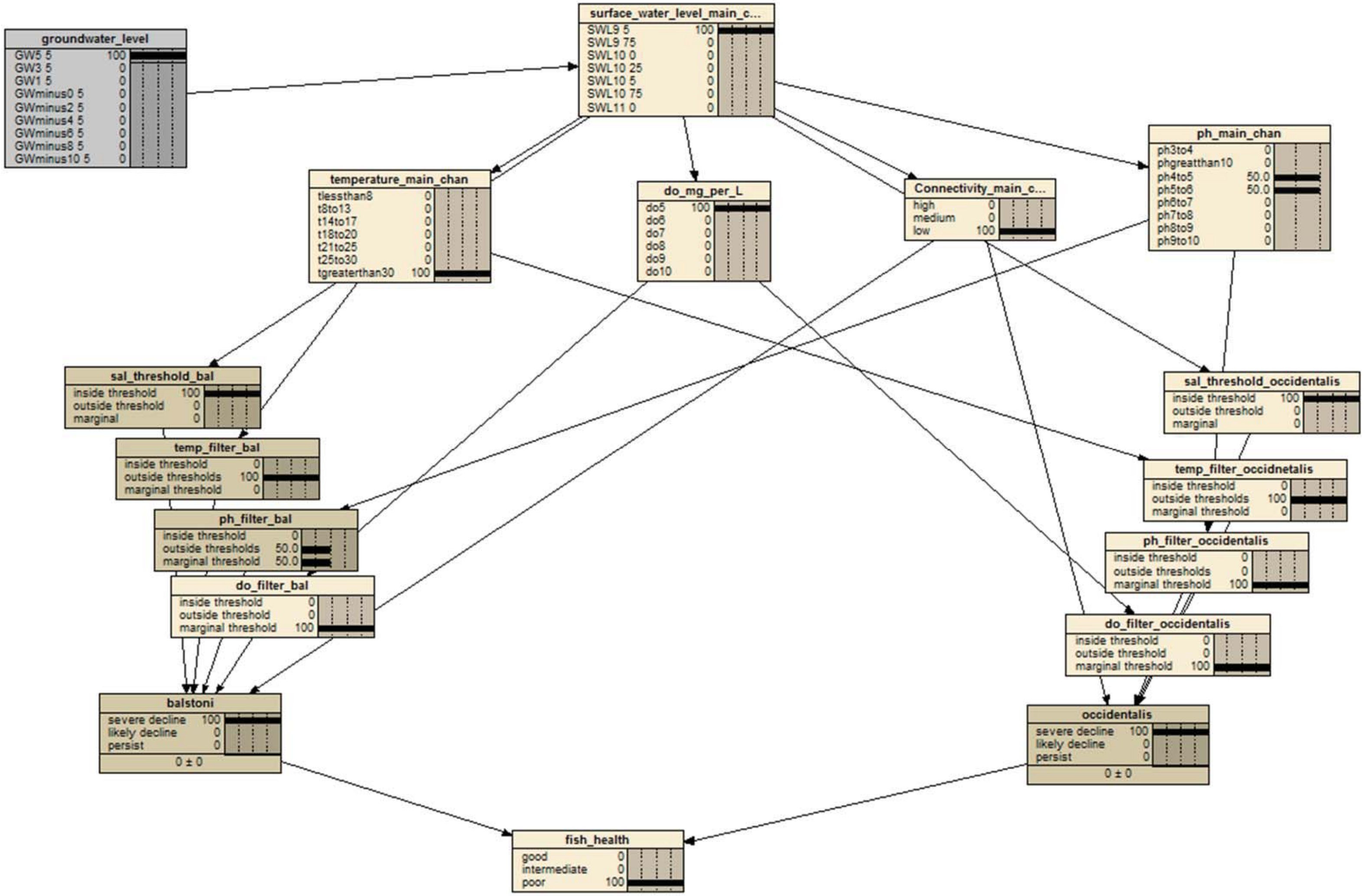

Figure 9: Simplified version of the Blackwood River BBN showing the impact of change in groundwater level on fish health.

Table 15: Description of nodes in the Blackwood River BBN and their output states.

Node	Description	Possible node states
groundwater_level	Groundwater level	Groundwater level at 2m intervals
surface_water_level_main_chan	Summer surface water flow as derived from groundwater level contributions	Surface water level at 0.25m intervals
Temperature_main_chan	Water temperature in the main channel derived from surface water level	8 possible temperature ranges
DO_mg_per_L	Disolved oxygen (mg/L) in the main channel derived from surface water level	Dissolved oxygen levels at 1mg/L intervals
pH_main_chan	pH in the main channel derived from surface water level	pH levels at 1unit intervals
temp_filter	Determines if water temperature is within the species threshold	Inside threshold Outside threshold Marginal threshold
sal_threshold	Determines if salinity is within the species threshold	Inside threshold Outside threshold Marginal threshold
do_filter	Determines if dissolved oxygen is within the species threshold	Inside threshold Outside threshold Marginal threshold
connectivity_main_chan	Depth of surface water high enough to permit movement of fish along channel	High Medium Low
ph_filter	Determines if pH is within the species threshold	Inside threshold Outside threshold Marginal threshold
fish_health	Index of fish population health based upon the states of the *N.balstoni* and *G.occidentalis* populations.	Good Intermediate Poor

Table 16: Sensitivity analysis of the simplified Blackwood BBN. Values are percentage entropy reduction under different groundwater levels. The greater the value the greater the influence on the parameter of interest. Note, null values indicate no entropy reduction.

Influencing node	GW5.5	GW3.5	GW1.5	GW-0.5	GW-2.5	GW-4.5	GW-6.5	GW-8.5	GW-10.5
occidentalis			80.5%	71%	27.5%	62.7%	44.3%	69.1%	
temp_filter_occidnet			8.2%	1.5%	0.4%	4.8%	16.9%	54.6%	
temp_filter_bal			4.7%	0.8%	3%	5.0%	16.9%	54.6%	
temperature_main_cha			9.8%	0.8%	3%	5.1%	16.9%	54.6%	
surface_water_level_			32.5%			1.9%	8.4%	48.8%	
do_mg_per_L			29.6%		0.5%	6.4%	1.4%	46.6%	
balstoni			7.6%	6.7%	18.1%	31.4%	29.3%	36.5%	
ph_filter_bal			54.9%	35.2%		1.3%	12.6%	20.7%	
ph_main_chan			54.9%	35.2%	2.4%	1.4%	12.6%	20.7%	
Connectivity_main_ch			52.9%	30.2%	12.7%	25.2%	2.3%	17.6%	
ph_filter_occidental			55.1%	35.7%	2.6%	3.7%	18.3%	11.3%	
do_filter_occidental					7.9%	13.5%	0.3%		
do_filter_bal					2.4%	3.8%	0.8%		
sal_threshold_occidentalis						0.1%	0.7%		
sal_threshold_bal							8.4%		

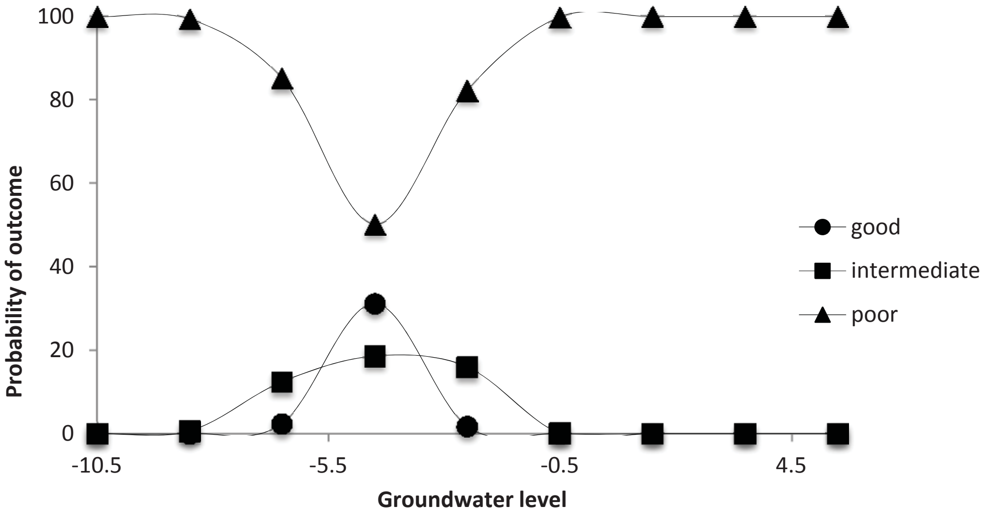

Figure 10: Probability of fish health outcomes under different groundwater levels.

3.3 Margaret River Caves

The initial conceptual model for the Margret River Caves was complex (Figure 11). As a number of variables could not be modelled in relation to climate change and groundwater decline (e.g. vegetation changes), the BBN was simplified to just model changes in cave fauna health in relation to changes in groundwater level (Figure 12 & Table 17). Running this simple model showed that as groundwater levels fall cave fauna health also falls (Figure 14), with changes in the root mat dependent fauna node being the main influence on the health of the system (Figure 13).

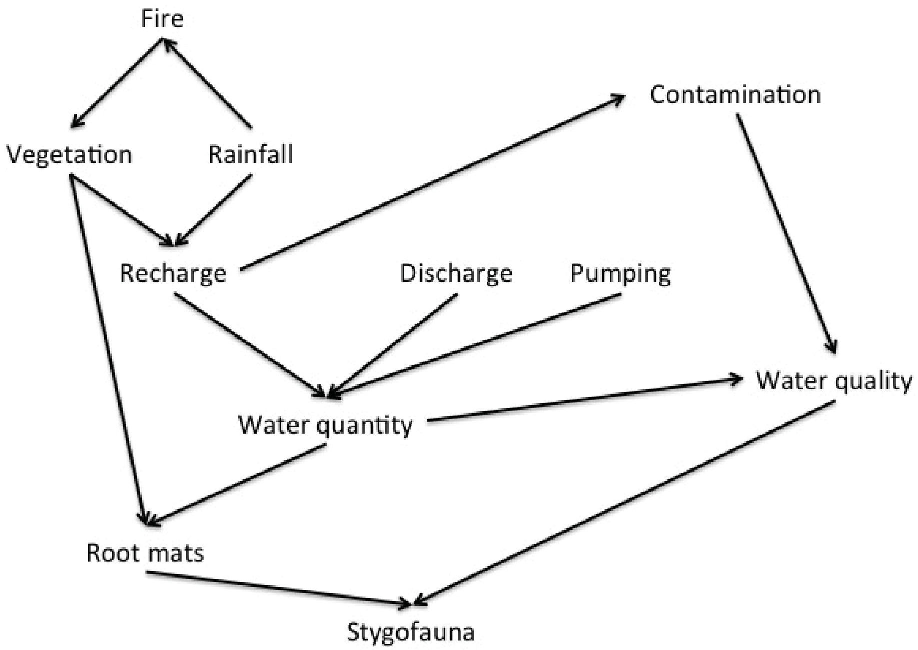

Figure 11: Conceptual model of the Margaret River Caves groundwater dependent ecosystem.

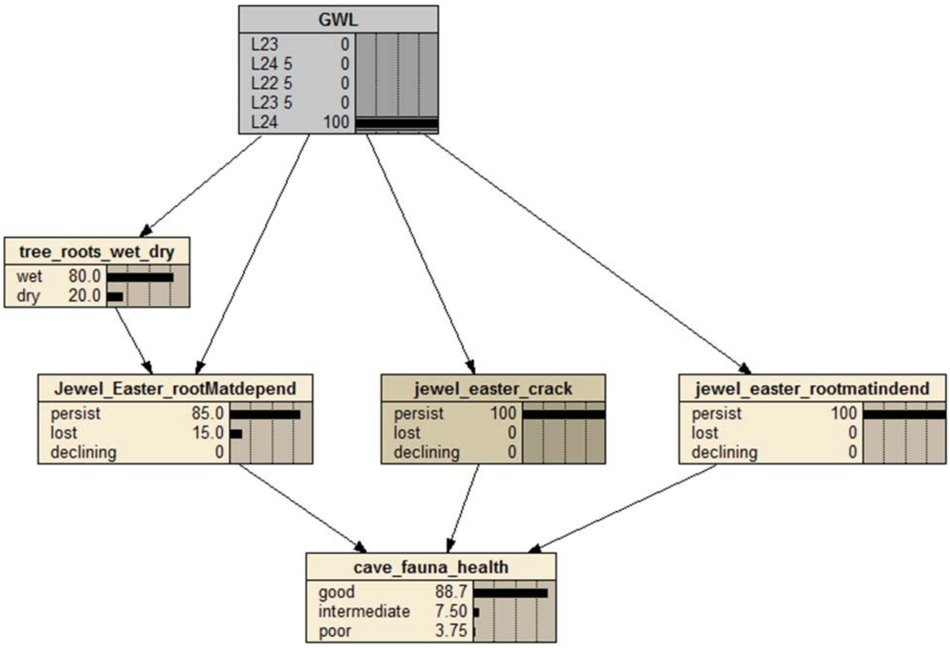

Figure 12: BBN for the Jewel and Easter Caves.

Table 17: Description of nodes in the Jewel and Easter caves BBN and their output states.

Node	Description	Possible node states
GWL	Groundwater level	Groundwater level at 2m intervals
Tree_roots_wet_dry	Root mats on cave floor submerged or not submerged	Tree roots wet Tree roots dry
Jewel_Easter_rootMatdepend	Change in root mat dependent stygofauna population	Persist Lost Declining
Jewel_easter_crack	Change in stygofauna population living in wall cracks	Persist Lost Declining
Jewel_easter_rootmatindend	Change in root mat independent stygofauna population	Persist Lost Declining
Cave_fauna_health	Estimate of cave health based on the three stygofauna populations	Good Intermediate Poor

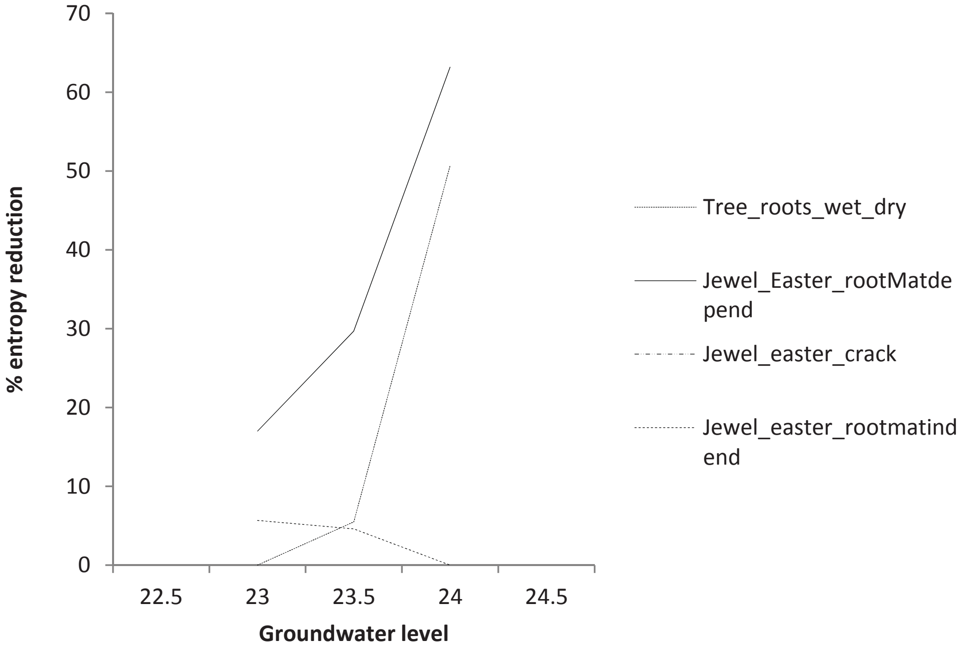

Figure 13: Entropy reduction in Margaret River Caves BBN nodes. Note Jewel_easter_crack node entropy reduction is 0% for all groundwater levels and at 22.5m and 24.5m entropy reduciton is 0% for all nodes.

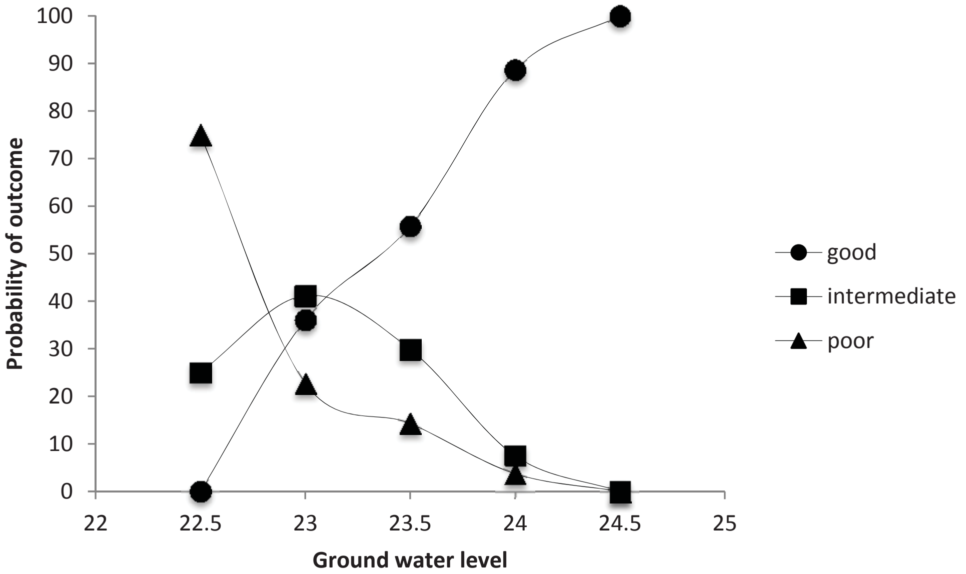

Figure 14: Probability of cave health outcome under different groundwater levels.

4. DISCUSSION

Bayesian Belief Networks (BBNs) were used to model potential impacts of changes in groundwater level (due to climate change) on ground water dependent ecosystems. Due to the range of quality and quantity of data available for the case studies BBNs provided a flexible modelling platform which was able to model situations with large amounts of data through to situations with little or inappropriate data which relied on expert opinion. For all case studies Netica^{TM} v4 (www.norsys.com) was used for the construction of the BBNs (there is a range of BBN software, such as Genie^{TM} (www.genie.sis.pitt.edu) and Hugin^{TM} (www.hugin.com), any of these could have been used).

For all the case studies examined conceptual models were developed prior to construction of the BBNs. This process identified potential variables to be included in the BBNs. In all cases the conceptual models were refined and reduced to a limited number of variables.

One of the limiting factors for constructing BBNs based on expert opinion can be the size of the conditional probability tables, if the tables are too large it can be difficult to complete the table. In the construction of BBNs the number of parent nodes feeding into a node should be kept to a minimum (Kragt, 2009). This is because as the number of parent nodes feeding into a node increases the size of the conditional probability table increases to allow for the increase number of possible combinations. For example in a simple case where a node only has parent nodes with two alternative states goes from four possible combinations with two parent nodes to eight possible combinations with three parent nodes (Figure 15 & Table 18). When the conditional probability tables need to be completed manually (such as in the case of expert opinion) the size of the tables can become too large to be completed effectively. An alternative to reducing the number of parent nodes is to limit the number of states in the parent node. In the case of the Blackwood model it was not possible to reduce the number of parent nodes feeding into the individual species health nodes, but to reduce the size of the conditional probability table the parent nodes had a limited number of states (inside threshold, outside threshold and marginal). Kragt (2009) suggests that most child nodes should not have more than three parent nodes, although there are no limitations restricting this apart from the size of the conditional probability table.

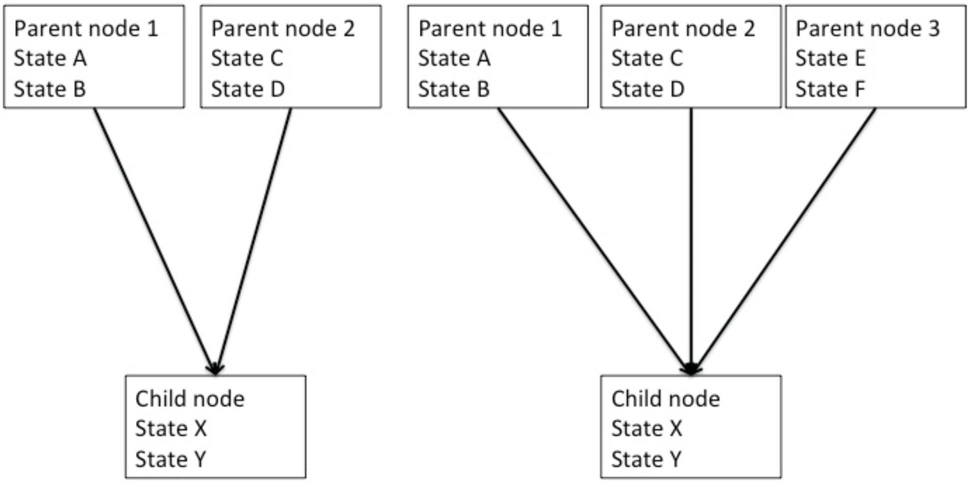

Figure 15: Simple BBN with two parent nodes and with three parent nodes.

Table 18: Possible combinations for a conditional probability table for a node with two parent nodes and three parent nodes.

Two parent nodes	Three parent nodes
AC AD BC BD	ACE ACF ADE ADF BCE BCF BDE BDF

Sensitivity analysis identifies how sensitive a conclusion is to the evidence it provides (Jenson, 2007). Sensitivity analysis essentially highlights the nodes which most influence the outcome node. In the Gnangara Mound models the sensitivity analysis found that the entropy reductions for each node was relatively constant across a range of groundwater levels. However, the Blackwood River model showed changes in the entropy reduction for each node across the range of groundwater levels. In the case of the Gnangara mound the response of the system (as modelled) was constant, therefore the entropy reduction stayed relatively constant for each node with changes in groundwater level. In the case of the Blackwood River model, the model was based around summer flows. During summer the river is groundwater fed and therefore fresh, whereas in winter the flows are saline due to land clearing in the upper catchment (WaterCorp, 2005). Therefore, the salinity of the system (as modelled) is high when groundwater level is low, as there is little freshwater entering the system. As the groundwater level rises, salinity falls until groundwater reaches approximately 4.5m above surface level, the model then treats this excess of water as surface water and therefore increases salinity.

One of the strengths of BBNs is their ability to use both data and expert opinion. Due to differences in the amount and applicability of data available for the case studies the methods used for parameterising the BBNs varied. In the case of the Gnangara Mound vegetation and invertebrates where there was many years data on the vegetation and invertebrate response to changes in groundwater a purely data driven approach was used. In the case of the Margaret River caves, the BBNs were based purely on expert opinion. Both methods produced realistic projections of potential impacts of groundwater changes on the groundwater dependent ecosystems.

Sensitivity analysis can also be used to eliminate nodes which may not be contributing to the model (Marcot, 2006). For example, in the Blackwood River model the salinity threshold node for *G.occidentalis* does not contribute significantly to the fish health node and could possibly be removed from the model. In this particular case the salinity threshold node for *G.occidentalis* does not contribute significantly to the model because the threshold is not exceeded for the species within the ranges tested in the model and other nodes, such as pH play a larger role in determining the outcome. This can also be seen in the terrestrial and terrestrial-aquatic models, sensitivity analysis showed that groundwater levels had no impact on the persistence of the frog species modelled as the salinity threshold was not exceeded, therefore the salinity, groundwater and lithology nodes are not required.

A number of good introductions to BBNs are readily available which discuss the potential uses, construction and use, such as the Netica^{TM} tutorial manual, Cain (2001), Kragt (2009) and Marcot et al. (2006). There is also a number of publications concerning the use of expert opinion, such as Kuhnert et al. (2010) and Martin et al. (2011). Publications such as these can provide a step by step guide to the production and analysis of BBNs.

The case studies demonstrate the use of BBN’s in modelling the impact of altered groundwater levels, due to climate change, on groundwater dependent ecosystems. The case studies used a variety of information from extensive datasets (Gnangara mound invertebrates and vegetation) through to expert opinion (Gnangara mound frogs and Margaret River caves). The models provided a visual representation of the systems examined and allowed the manipulation of starting conditions for the models for the testing of different scenarios.

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