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

Supporting Document 3: Identifying thresholds for responses of amphibians to groundwater and rainfall decline

Nicola Mitchell, Bea Sommer and Peter Speldewinde

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SUPPORTING DOCUMENT 3:
Identifying thresholds for responses of amphibians to groundwater and rainfall decline

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Cover image: A male crawling frog, *Pseudophryne guentheri* calling from a terrestrial nest in Lake Pinjar on the Gnangara mound, Western Australia © Dr Nicola Mitchell, the University of Western Australia, School of Animal Biology

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ABSTRACT

Amphibians are key indicators of wetland health and under conditions of hydrological change it is important to be able to predict changes in their diversity and abundance. Here we develop a methodology for predicting how nine amphibian species with different life histories could potentially respond to declining groundwater, and declining rainfall – both of which are occurring on the Gnangara Mound north of Perth in south-western Australia. This example can be considered as 'data-poor' because although we had access to data on amphibian assemblages and relative abundance from systematic surveys, we could derive few insights into the environmental drivers of such patterns using multivariate analysis. Instead we turned to amphibian biologists with relevant expertise on Gnangara Mound amphibians to derive conceptual models of the most important factors explaining whether populations would persist or decline under anticipated environmental change. These models were constructed as Bayesian Belief Networks (BBNs) and were developed for each of three reproductive guilds: amphibians that breed in water, amphibians that breed in terrestrial nests that are later flooded, and one entirely terrestrial-breeding species. The models showed that aquatic breeding species were most sensitive to changes in the hydroperiods, but were unable to demonstrate an impact of groundwater level because we lacked the information to derive an empirical link between groundwater and hydroperiods. The terrestrial-aquatic breeding species were also sensitive to hydroperiod length, with declines in autumn and winter rainfall further decreasing the probabilities of population persistence. The BBN developed for the Turtle frog – the terrestrial-breeding species – assumed that groundwater levels would influence soil moisture and that this species would experience population declines if groundwater levels were either high or very low. Hence, situations where groundwater-dependent wetlands transition to terrestrial ecosystems under groundwater decline could potentially suit Turtle frogs provided that an appropriate vegetation community develops. While the BBNs developed here are largely conceptual, and thus preliminary, they demonstrate a promising approach for anticipating the impacts of groundwater decline on amphibians, provided that the links between hydrological processes and amphibian thresholds can be determined empirically or mechanistically. Our models also demonstrate the key role that seasonal rainfall events play in triggering reproduction, and suggest that the drier climates projected for south-western Australia will place additional stress on amphibian communities.

EXECUTIVE SUMMARY

In this project we developed Bayesian Belief Networks (BBNs) that described the responses of each of three reproductive guilds of amphibians to groundwater decline and weather variables. While the distribution of amphibian species occurring within our study region (the Gnangara mound) had been systematically surveyed for a previous project since 1999, the dataset was not well suited to multivariate analysis of the environmental drivers that explained presence or absence at breeding sites. These analyses were designed to feed into the 'effects assessment' and 'risk characterization' components of the risk assessment process. Although spatial patterns were evident in the data, particularly with regard to species assemblages on the Bassendean and Spearwood soil complexes, multivariate regression tree (MRT) analyses designed to identify hydrological (and other) thresholds could not be applied because the data did not meet the requirements for this type of analysis, particularly in relation to number of observations and the relatively short time frame over which the data were collected. Similarly, there was an absence of empirical data on environmental tolerance thresholds of embryonic, larval and adult life stages for the nine species currently occurring on the Gnangara mound.

In this 'data poor' situation we used the opinions of four experts on amphibian biology to derive separate BBNs for three groups of amphibians based on differences in their reproductive modes. The first group consisted of six species that deposit eggs in water (the Myobatrachid frogs *Crinia glauerti, C. georgiana, C. insignifera* and *Limnodynastes dorsalsis,* and the Hylid species *Litoria adelaidensis* and *Litoria moorei*). The second group consisted of two species with terrestrial embryos and aquatic larva (*Heleiporus eyrei* and *Pseudophryne guentheri*), and a final network was constructed for a terrestrial species that breeds underground (the turtle frog *Myobatrachus gouldii*). In all cases, a reduction in seasonal rainfalls that trigger breeding activity (or other key events such as flooding of nest sites) were viewed as important drivers of population declines. Similarly, a reduction in the hydroperiod (potentially due to declining groundwater, reduced rainfall or alteration to the catchment) and water quality (due to salinization) was considered to jeopardise recruitment to metamorphosis.

In a previous study of amphibians on the Gnangara Mound, five species (*H. eyrei, C. georgiana, L. dorsalis, L. adelaidensis* and *L. moorei*) were considered to be reasonably robust to hydrological decline due to either their longevity or because they favoured large water bodies with capacity for contraction. In contrast, three species (*C. glauerti, C. insignifera* and *P. guentheri*) were viewed as being sensitive to hydrological change due to their relatively short life cycles and specific breeding requirements. We tested whether our networks captured these different expectations of species vulnerability by driving our BBNs with similar thresholds and filters, and examining probabilities of population persistence or decline. We found that the terrestrial-aquatic breeding group were the most vulnerable to population decline, with the *P. guentheri* being more vulnerable than *H. eyrei*, in keeping with the earlier assessment. All aquatic breeding frogs were predicted to persist unless the hydroperiod was less than a critical threshold (determined by expert opinion) that would allow time for each species to reach metamorphosis. The probability of persistence of the turtle frog (a fossorial species) was sensitive to groundwater levels, and depended on intermediate groundwater levels that moderated suitable soil moisture at the underground retreat sites and nest sites of this species. This species could potentially benefit from hydrological change if former wetlands become terrestrial ecosystems, but turtle frogs depend on functioning Banksia woodlands which are vulnerable to over-abstraction of groundwater.

1. INTRODUCTION

Amphibians are highly susceptible to any process that threatens the quality and periodicity of wetland habitats (Bradford 2002; Bunnell and Ciraolo 2010). Breeding sites are diverse, and include seepages, watercourses, floodplains or wetlands, and in some regions these water bodies are groundwater-dependent. While most species of amphibians utilise aquatic breeding sites, many species have terrestrial embryos that develop in nest sites adjacent to water bodies. Embryos are subsequently flooded when the water table rises following seasonal rainfall, triggering hatching. The initiation of breeding activity in terrestrial-breeding species is critically dependent on moist soils that prevent the dehydration of males calling from nest sites, and that are wet enough to prevent the desiccation of eggs that develop in the nest (Andrewartha et al. 2008; Mitchell 2001; 2002). Hence, the wetting of surface soils at the break of season is a key driver of breeding events in terrestrial-breeding amphibians.

Typically, soil wetting is a top-down process that is dependent on rainfall, but groundwater levels and vegetation dynamics can also affect soil moisture profiles, and hence the distance to groundwater can potentially moderate the suitability of breeding sites of amphibians that nest in underground burrows. For example, the Western Australian Turtle frog, *Myobatrachus gouldii* is a species with direct developing eggs that are deposited up to 1.5 m underground in sandy soils (Roberts 1981). This species depends on moderately wet soils, as waterlogged soils dramatically reduce the ambient oxygen available for the developing embryos. Hence this species tends to occupy terrestrial habitats that are not subject to groundwater intrusion (Bamford 1992) and could potentially benefit from groundwater decline as wetlands transition to terrestrial ecosystems.

Abstraction of groundwater for domestic and industrial purposes has led to the decline of amphibian populations in other regions of the world, notably in North America (Bradford 2002; Bunnell and Ciraolo 2010). This is largely because decreasing groundwater connectivity has led to declining hydroperiods in ephemeral water bodies, or has led to the transition of permanent water bodies to ephemeral systems. This in turn affects the capacity of amphibian species to complete the larval (tadpole) phase of the lifecycle, with premature drying of water bodies leading to failed recruitment. Declining rainfall, and shifts in the seasonality of rainfall is an additional stressor to amphibian populations, not only because rainfall recharges groundwater, but because these events often trigger reproduction (Walls et al. 2013). Regions of south-western Australia are currently faced with both groundwater decline and rainfall decline (Refer to Section 3.1.1 of the Development and Case Studies document), and the purpose of this technical report is to develop a methodology for assessing how environmental variables such as groundwater, hydroperiods and rainfall influence population trends in amphibians, and to apply the methodology using future groundwater and climate scenarios.

2. METHODS

2.1 Study location and species dataset

The amphibian case study developed for this project was based on the species assemblage occurring on the Gnangara Mound. Details of the study location and climate are described in Section 3.1 of the Development and Case Studies Report (Chambers *et al*. 2013). Thirteen species of amphibians have been recorded on the Gnangara Mound, of which four are occasional vagrants that have not been recorded in recent decades (Bamford and Huang 2009). The nine species that currently occur on the mound fall into three broadly defined breeding guilds: six species that have aquatic embryos and larvae (tadpoles), two species with terrestrial embryos and aquatic larvae, and a single fossorial species that breeds in Banksia woodlands (Figure 1). This latter species, the Turtle frog (*Myobatrachus gouldii*) has direct-developing eggs that develop 0.8 -1.5 m underground and hatch as fully formed frogs. This breeding strategy is highly unusual, but is shared by two other western Australian amphibians (the northern and southern sandhill frog, *Arenophryne rotunda* and *Arenophryne xiphorhyncha;* Doughty and Edwards 2008).

Nationally, very few long-term datasets exist on the diversity and distributions of amphibians in groundwater dependent wetlands. However, due to concern about the impacts of groundwater abstraction on the biota of the Gnangara Mound, the Western Australian Department of Water (formerly Water and Rivers Commission) commissioned the monitoring of amphibians across this region in 1999, and monitoring has continued under various initiatives up until 2011. This monitoring data was compiled and made available to the current project by Bamford Consulting Ecologists. The data consisted of estimates of the abundance of each species from aural surveys (listening for calling males and night during the autumn and spring during the typical breeding seasons), and was initially conducted by staff from the Department of Terrestrial Vertebrates at the Museum of Western Australia (Aplin et al. 2001). In 2002, the project was transferred to Bamford Consulting Ecologists (Davis and Bamford 2004). Following the 2002 survey, changes were implemented so that the project focussed more intensely on a smaller number of wetlands than was the case in the original study, and this approach was used annually from 2003 to 2009. In 2008, additional aural survey sites were included in the program as part of the Gnangara Sustainability Strategy (GSS) project with 59 sites located across the Gnangara Mound (Bamford and Huang 2009). In 2010 and 2011, additional pitfall trapping sites were added to the program as it was considered important to examine the recruitment success of a representative species (in this case, the terrestrial-breeding Moaning Frog, *Heleioporus eyrei*) as a measure of the impact of changes in groundwater levels. Two of the nine species were not adequately surveyed across the Gnangara Mound: the motorbike frog which calls in late spring and summer and hence was detected rarely in the aural surveys conducted in early spring, and the turtle frog, which calls on only a few nights each year (Mitchell 2011) and was only detected in the trapping surveys. This species was also trapped extensively during the GSS project, but these data were not sought for this study. A summary of data types and sources is shown in Table 1 and their distribution across the Gnangara Mound is shown in Figure 2.
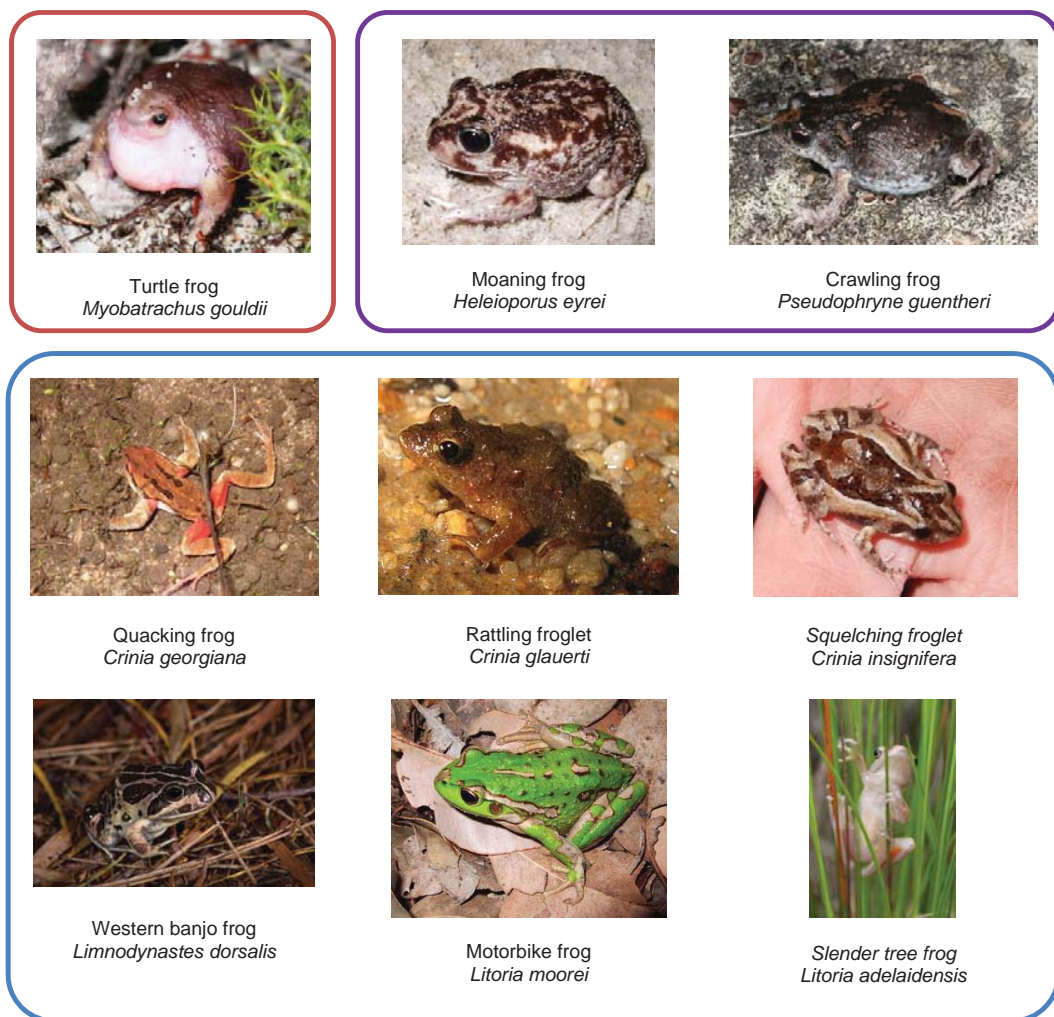
Figure 1. Amphibian species occurring in the study area, arranged by breeding guild (red = terrestrial; purple = terrestrial-aquatic; blue = aquatic). The motorbike frog are slender tree frog are in the Family Hylidae, while the remaining species are all ground frogs in the family Myobatrachidae. All photographs by Nicola Mitchell, except *Limnodynastes dorsalis* (Mike Brown) and *Crinia glauerti* (Evan Pickett).

Two of the nine species were not adequately surveyed across the Gnangara Mound: the motorbike frog which calls in late spring and summer and hence was detected rarely in the aural surveys conducted in early spring, and the turtle frog, which calls on only a few nights each year (Mitchell 2011) and was only detected in the trapping surveys. This species was also trapped extensively during the GSS project, but these data were not sought for this study. A summary of data types and sources is shown in Table 1 and their distribution across the Gnangara Mound is shown in Figure 2.

Table 1. Summary of amphibian survey sites and sampling periods on the Gnangara Mound

Monitoring Series	East Lexia Wetlands	GSS short term	GSS long term	Whiteman Park
Number of sites	6	59	20	18
Date initiated	1999	2008	2010	2007
Date of last data	2011	2010	2011	2007
Survey type	Aural and trapping (2 sites)	Aural	Aural and trapping (4 sites)	Aural

The vegetation and hydrological changes at two trapping sites that had the largest amounts of data (East Lexia Wetland sites LEX86 and EPP173) are described below.

LEX86 (31°45'13''S, 115°57'29''E)
LEX86 contains dense *Baumea articulata* and *Typha orientalis* stands and a riparian fringe of large Melaleuca trees. In 2003, the wetland basin was dry in May but the wetland was extensively flooded in October. In 2004, the wetland basin was damp in May but almost dry by October. Water levels were higher in 2005, with the wetland flooded in both early June and October/November. In 2006, the wetland did not flood but contained temporary pools in late winter. The failure of this wetland to contain water in 2006 was due to very poor winter rainfall. In 2007 and 2008, Lexia 86 wetland was dry in June and October. It was damp with pools in May 2009 but was dry by October of the same year

EPP173 (31°42'19''S, 115°57'45''E)
This wetland is largely undisturbed and heavily vegetated with dense stand of *Baumea articulata* and *Typha* species, emergent shrubs and a dense riparian fringe of Melaleuca and other species. The wetland appears to be permanent and flows into adjacent paddocks when water levels are high. Water levels peak in spring and in some years (2004 and 2005) the wetland overflows into adjacent paddocks and there is extensive flooding of riparian vegetation. In 2003, 2006, 2007, 2008 and 2009, however, the overflow did not occur and flooding of the riparian vegetation was limited.

2.2   Multivariate analysis of species abundance related to environmental drivers

While our amphibian dataset was not species rich in comparison to datasets for aquatic macroinvertebrates and wetland vegetation (SD2 Sommer *et al.* 2013), there was considerable overlap in the monitoring sites and years over which these three datasets were collected. We therefore attempted to define thresholds that defined each species' response to groundwater and other environmental variables using an identical process to that described for the Gnangara Mound macroinvertebrates and vegetation (SD2 Sommer *et al.* 2013). Any thresholds identified that related to groundwater levels could then be incorporated in to a Bayesian Belief Network (BBN) and potentially analysed on a GIS platform.

All amphibian datasets were split into 'trapping' and 'aural' datasets, and then in to spring and autumn observation periods. Aural abundance categories (e.g. 1-10, 11-30, >30, >100) were converted to absolute values (5, 22, 35 and 120 respectively) and sites that had missing data (e.g. not sampled in some years, or where no species were detected) were excluded. Amphibian data were log (x+1) transformed before PCoA and db-RDA were carried out using the Primer Permanova v. 6 software package (SD2 Sommer *et al.* 2012).
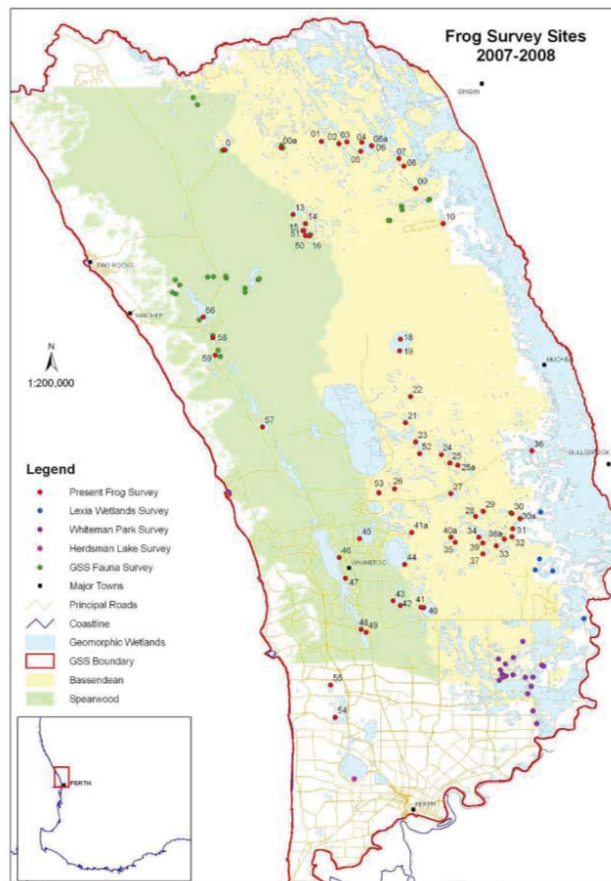
Figure 2. Locations of frog aural survey sites in the 'short-term' Gnangara Sustainability Strategy project (red circles with site codes), in addition to other locations where data were available on frogs. Figure from Bamford and Huang 2009 (Copyright the Government of Western Australia, the Department of Environment and Coservation).

2.3   Use of expert opinion to define thresholds

Given the limited insights we ultimately derived from the multivariate analysis, we turned to using expert opinion to decide on the thresholds and structure of our BBNs, as is often necessary in data poor situations (Hosack, Hays, and Dambacher, 2008). 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. Expert opinion has several roles in BBN networks (Cain, 2001): 1) the development of the model structure, including the identification of nodes and linkages between nodes, 2) the population of conditional probability tables for nodes, and 3) review of BBN models.

In the example reported here, we took the approach of dividing the nine amphibian species currently occurring in the GSS into three functional groups: 1) frogs requiring permanent water, 2) frogs with terrestrial embryos and aquatic larvae, and 3) the entirely terrestrial Turtle Frog. This approach had the advantage of producing fewer BBNs than had we had produced networks for individual species, but allowed us to compare how each functional 'group' responded to declining rainfall and groundwater levels. For each group, a conceptual model was first derived by one expert (Mitchell) indicating how major environmental variables influenced the survival of these species.

A half-day workshop was then convened with experts on Gnangara Mound frogs. Six local scientists were invited to participate in the workshop, and four accepted. All four participating experts had doctoral degrees in herpetology and recent experience working on amphibians in the Gnangara study system, and the experts included one of the scientists who collected data provided by Bamford Consulting ecologists (Table 2). Experts were first asked if they agreed with the conceptual models and given the opportunity to modify the models, on the proviso that the preference was for a simple model over a more complex one. 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.

In general, experts relied on a combination of their knowledge of relevant life history publications, unpublished data, and personal experience to decide on the structure of the conceptual model and the probability values. For completeness, a table of life history parameters and relevant sources of data are included in Table 3, but note that this information was not provided to the expert panel.

2.4   Worked examples of scenarios

We ran a complete range of scenarios for each BBN, with a focus on presenting the interactions between the groundwater node and other parent nodes in the model (usually hydroperiods and seasonal rainfall nodes). A detailed description of the nodes in each BBN are included in SD6 (Speldewinde 2013), along with a sensitivity analysis relating to groundwater levels.
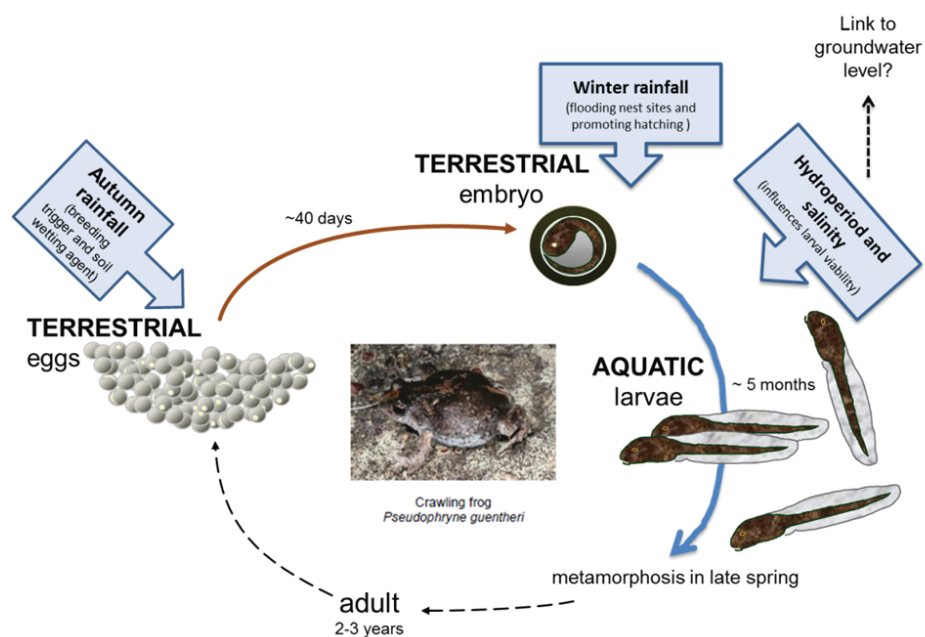
Figure 3. Life history diagram for the Crawling frog, showing key nodes (in blue) incorporated in to the BBN as thresholds for population responses in the terrestrial-aquatic breeding guild.

Table 2. List of experts providing input in to the BBNs

Expert	Institution	Relevant background
Professor J Dale Roberts	School of Animal Biology, University of Western Australia	Conducted research and published widely on Western Australian amphibians since 1978. Familiar with the Gnangara study area.
Dr Nicola Mitchell	School of Animal Biology, University of Western Australia	Conducted research on terrestrial-breeding amphibians in the Gnangara study area since 2005, and published widely on terrestrial-breeding species.
Dr Leonie Valentine	School of Plant Biology, University of Western Australia	Worked for the Gnangara Sustainability Strategy Taskforce since 2008; survey work included trapping amphibians in the Gnangara study area.
Dr Wes Bancroft	Bamford Consulting Ecologists	Works for the consultants who produced the 2009 report 'The occurrence and status of frogs in the Gnangara Sustainability Strategy study area' and generated some of the amphibian datasets.

Table 3. Life history* of the amphibian species on the Gnangara mound

Common name and reproductive guild	Scientific name	Relevant life history information	Embryonic lifespan (d)	Larval lifespan (d)	Require flooding?	References
Terrestrial						
Turtle frog	*Myobatrachus gouldii*	Direct-developing fossorial species. Emerge to feed after rainfall (primarily in winter) and for late spring/early summer courtship. Mate 0.8- 1.5m underground at the end of summer. Eggs hatch and metamorphs emerge after the break of season in autumn.	60	n/a	No	Roberts 1981, Mitchell 2011
Terrestrial-aquatic						
Crawling frog	*Pseudophryne guentheri*	Terrestrial breeding species with breeding peak in late May once soils wet up after autumn rainfall. Embryos can survive long periods on land, but flooding of nest sites is required to trigger hatching and larval development	40-60	60	Yes	Main 1965; Eads *et al.* 2012
Moaning frog	*Heleioporus eyrei*	Terrestrial breeding species with breeding peak in April/May; males begin calling before break of season and travel large distances to wetlands. Foam nests deposited at the base of burrows up to 0.5 m deep. Flooding of burrows required to trigger hatching and larval development.	30	150	Yes	Bamford 1992, Lee 1967, Main 1965
Aquatic						
Quacking frog	*Crinia georgiana*	Breed in winter, typically in shallow seepages. Eggs deposited in depressions and larvae washed out following rainfalls	5	30-45	n/a	Main 1965, Seymour & Roberts 1995
Squelching froglet	*Crinia insignifera*	Breed from May-July, typically in shallow water in ephemeral wetlands or at the margins of permanent wetlands	2	Up to 150	n/a	Main 1957, 1968
Rattling froglet	*Crinia glauerti*	Breeds from July -October, typically in swamps and streams.	3	100	n/a	Main 1965, 1968, Littlejohn 1959
Western Banjo frog	*Limnodynastes dorsalis*	Breed in winter and early spring, foam nests deposited amongst vegetation in permanent water	3	4	n/a	Main 1965, Martin 1972
Slender tree frog	*Litoria adelaidensis*	Breed in winter and spring, eggs typically attached to submerged vegetation in permanent water	3	100	n/a	Main 1965
Motorbike frog	*Litoria moorei*	Breed in late spring and summer, typically in permanent water	3	120-365	n/a	Main 1965

* Additional information on habitat types and historical prevalence on the Gnangara Mound can be found in Bamford and Huang (2009).

10   Identifying thresholds for responses of amphibians to groundwater and rainfall decline

3. RESULTS

3.1 Overview

Because the multivariate analyses were not satisfactory in terms of identifying practical hydrological (and other) thresholds, and thereby assessing risk, the Bayesian Belief networks we ultimately developed were based on expert opinion. For completeness, we present the basic multivariate analyses below in Section 3.2, and present more detailed outputs from the BBNs developed using expert opinion in Section 3.3.

3.2 Is the spatio-temporal distribution of amphibian assemblages related to habitat characteristics?

3.2.1 Trapping data

All nine of the amphibian species known to currently occur on the Gnangara Mound were trapped from at least one of the two survey sites at the East Lexia Wetlands (LEX86 and ESS173). A principal coordinate analysis (PCoA) of all trapping datacoded by the survey period (Autumn or Spring) shows the seasonal distribution of observations (Figure 4. As the spring trapping data tended to be more species rich (Bamford and Huang 2009) we restricted the remainder of our analyses to the spring dataset only. A canonical analysis of Principal Coordinates (CAP) showed a weak association between the composition of amphibian species trapped at each site in spring and the basin moisture classification (Figure 5), whereas other habitat variables could not be analysed using CAP due to only having two categories. Instead, a PCoA of the spring data coded by lithology is presented (Figure 6) but a PCoA coded into vegetation groups is not shown as there were only two groups (most wetlands had trees/shrubs/sedges and rushes, while two wetlands, 36-11s and 5-10 had only tree and shrubs).
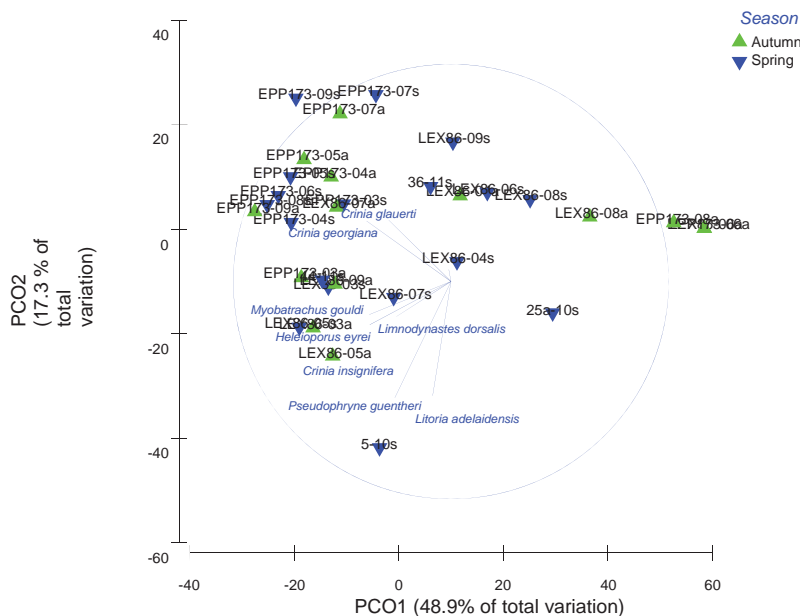
Figure 4. PCoA ordination showing the trapping data coded by season (autumn or winter) with sites coded into season, overlain with frog species.

Figure 5. CAP plot for spring trapping data of 32 sites covering the timeframe 2003-2011 with sites colour-coded by basin moisture. Squared canonical correlations were CAP1 = 0.51 and CAP2 = 0.24. The two canonical test statistics were significant (*P* = 0.024 and 0.034 respectively, using 999 permutations). Species overlain in blue show which species tended to be associated with each site but show no convincing patterns with regard to the basin moisture classifications.

Figure 6. PCoA plot coded by lithology overlain with amphibian species.

A distance-based redundancy analysis (dbRDA) showed that only rainfall (pseudo-F 2.21, P< 0.05) and mean minimum temperature (pseudo-F 2.26, P< 0.05) significantly explained the distribution of observations (Figure 7).
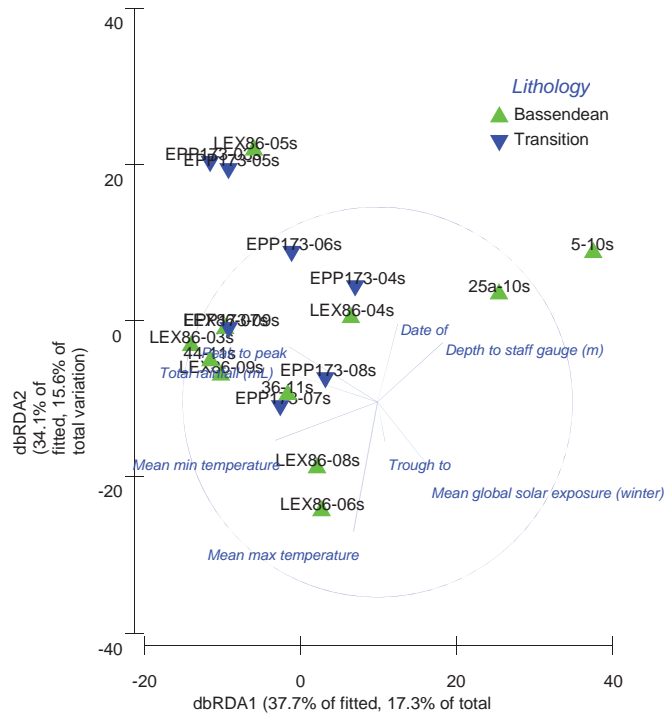
Figure 7. dbRDA of spring trapping data coded by lithology.

Figure 8. PCoA ordination showing trajectory of change in the amphibian assemblage detected from spring trapping surveys for the Lexia EPP173 site from 2003-2009.

A (PCoA) was used to show a trajectory of change for the Lexia wetland site EPP173. In 2003, 2006, 2007, 2008 and 2009 the flooding of riparian vegetation was limited, whereas vegetation was flooded in 2004 and 2005.

3.2.2 Aural data

Eight of the nine amphibian species were detected from the aural surveys, but one of these eight - the Motorbike frog – was considered to have been inadequately surveyed as the timing of the surveys did not coincide with the peak in the breeding season (Bamford and Huang 2009). The undetected species was the Turtle frog, which only calls on a few nights each year, usually in late spring and summer (Mitchell 2011).

In spite of significant test statistics, the CAP analysis showed no clear associations between frog species aural data and lithology (Figure 9). This is in contrast to the littoral vegetation and macroinvertebrates on the Gnangara mound which showed very strong associations (SD2 Sommer et al. 2013). However, there was clear separation between spring and autumn surveys, a reflection of the fact that most species call in spring (Figure 10). A dbRDA analysis showed that of the environmental drivers tested, only the mean maximum and the mean minimum winter/spring temperature (pseudo-F 4.52 and 5.49 respectively, both $P< 0.01$) and the solar exposure in winter (pseudo-F 2.92, $P< 0.05$) significantly explained the distribution of the observations from the aural surveys (Figure 11). The dbRDA further shows that the 2010 observations (all to the left of the x-axis) were particularly associated with higher winter/spring minimum temperatures. The PCoA in Figure 12 shows that there appears to be a directional change in species composition at EPP173, particularly from 2004 onwards. What exactly this change constitutes would have to be investigated in more detail, however it appears the site was experiencing higher numbers of *L. adelaidensis, C. glauerti* and *C. insignifera* (based on calls) towards 2011.
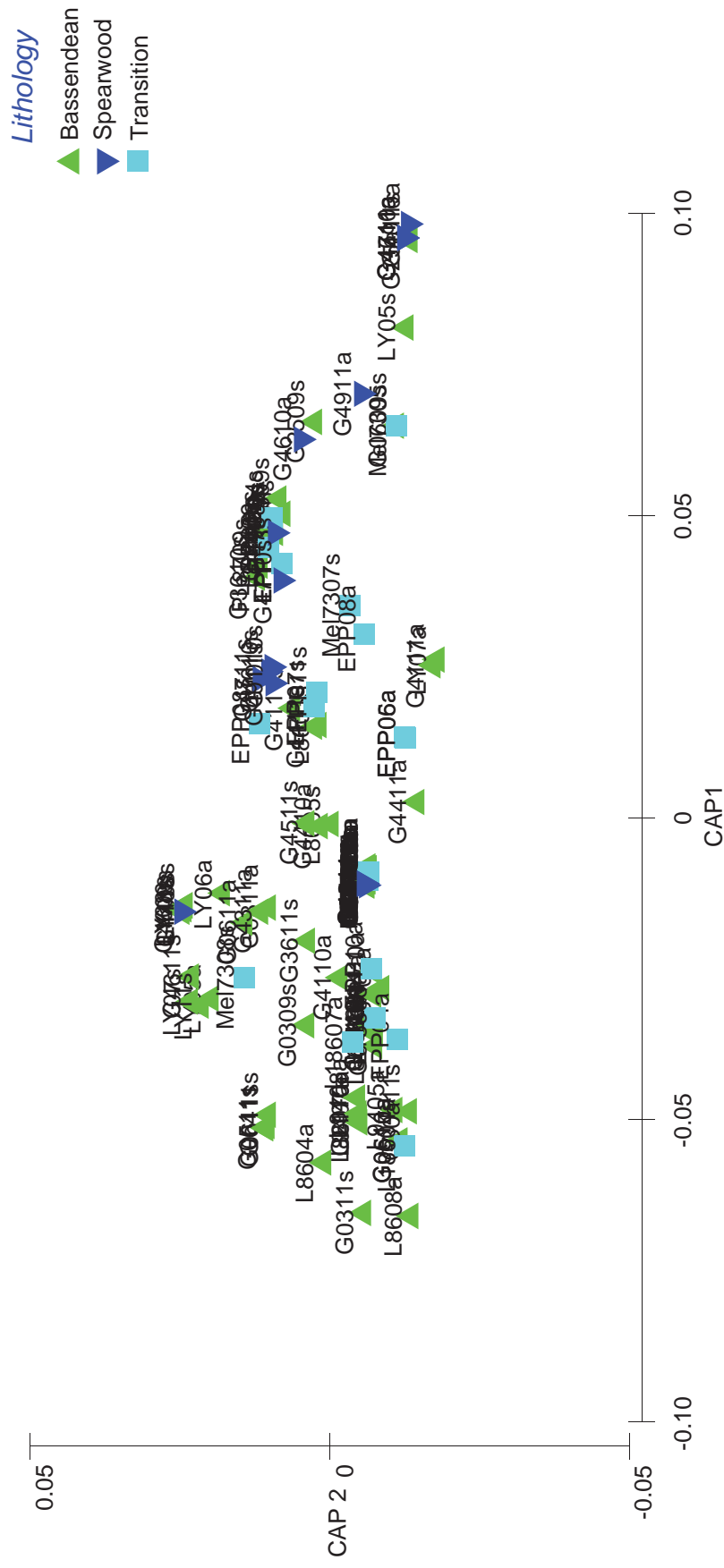
Figure 9. CAP plot for spring and autumn aural survey data of 122 sites covering the timeframe 1999-2011 with sites colour-coded by lithology. Squared canonical correlations were CAP1 = 0.18 and CAP2 = 0.13. The two canonical test statistics were significant (both *P* = 0.004, using 999 permutations), and overall 60% of sites were correctly allocated. Most misclassifications occurred for the Transition group (20% correct, versus 72.8% classified correctly for the Bassendean group and 56% classified correctly for the Spearwood group).
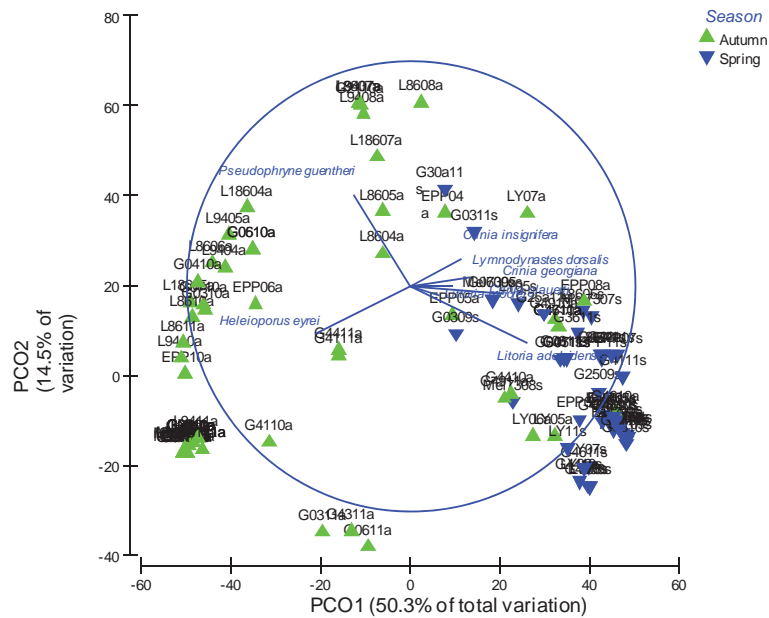
Figure 10. PCO sites from the aural surveys of amphibians, coded into season.
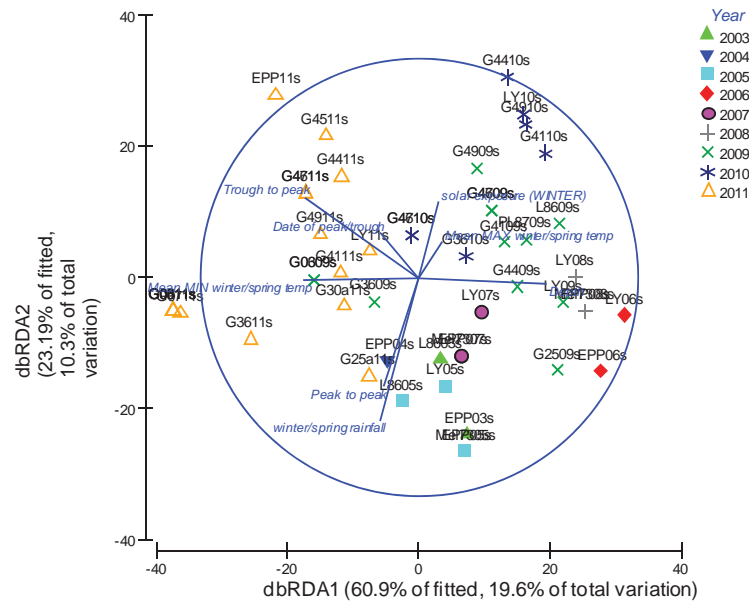
Figure 11. dbRDA of the spring aural surveys, with sites coded by year.

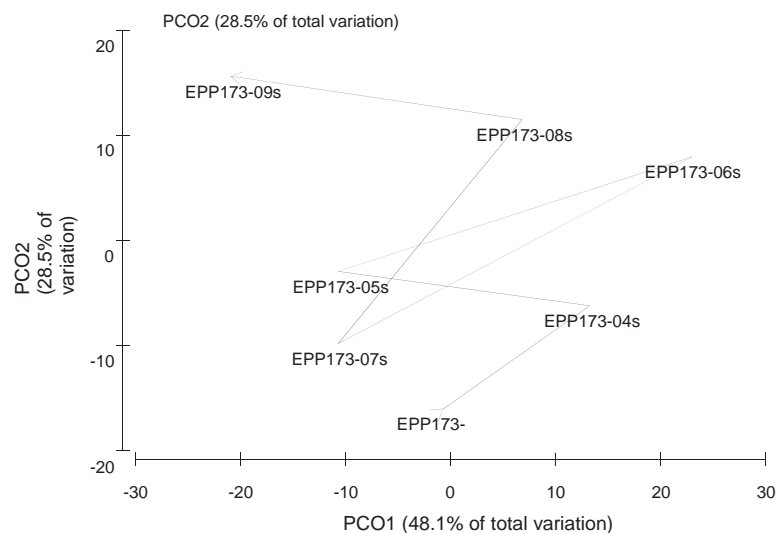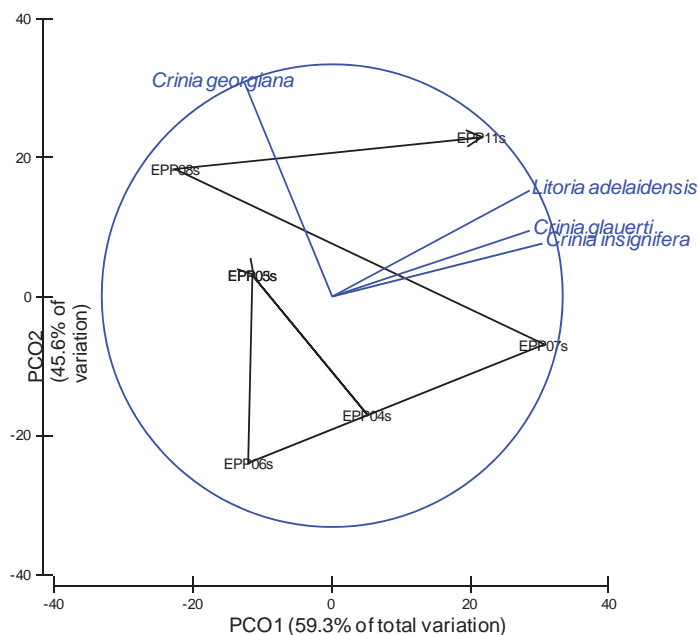**Figure 12. PCoA ordination showing trajectory of change in the amphibian assemblage detected from spring aural surveys for the site EPP173 from 2003-2009.**

3.3 Bayesian Belief Networks developed by expert opinion

3.3.1 Aquatic-breeding guild

The amphibian experts concurred that a key driver of population persistence for the six species in the aquatic reproductive guild was the hydroperiod of the wetland (or other waterbody), as this parameter is critical for larvae having sufficient time to complete metamorphosis and to disperse from wetlands. While hydroperiods are almost certainly dependent on groundwater in many wetlands on the Gnangara Mound, we had no means of deriving an empirical link between groundwater level and surface water expression. Hence, hydroperiod was set as an independent node with defined monthly increments (see SD6; Speldewinde 2013). Groundwater level did contribute to the network through a salinity node, as there was empirical data relating groundwater levels to electrical conductivity for each lithology class in the GSS (see SD2 Sommers et al. 2012), and evidence from other Australian species of amphibian that salinity above a threshold of 8ppt leads to high levels of deformity and morbidity in tadpoles (e.g. Kearney *et al.* 2012). However, based on this empirical data, the probability of salinity above the 8ppt threshold were always very small.

The four tadpole survival filters estimated the probabilities of 'extreme decline', 'slight decline' or 'persist' under different combinations of salinity and hydroperiod. The species that required a minimum 1-month hydroperiod (the Quacking frog) was influenced by Tadpole survival 1, whereas species requiring a minimum 2, 3 and 4-month hydroperiod were influenced by Tadpole survival 2,3 and 4 respectively.
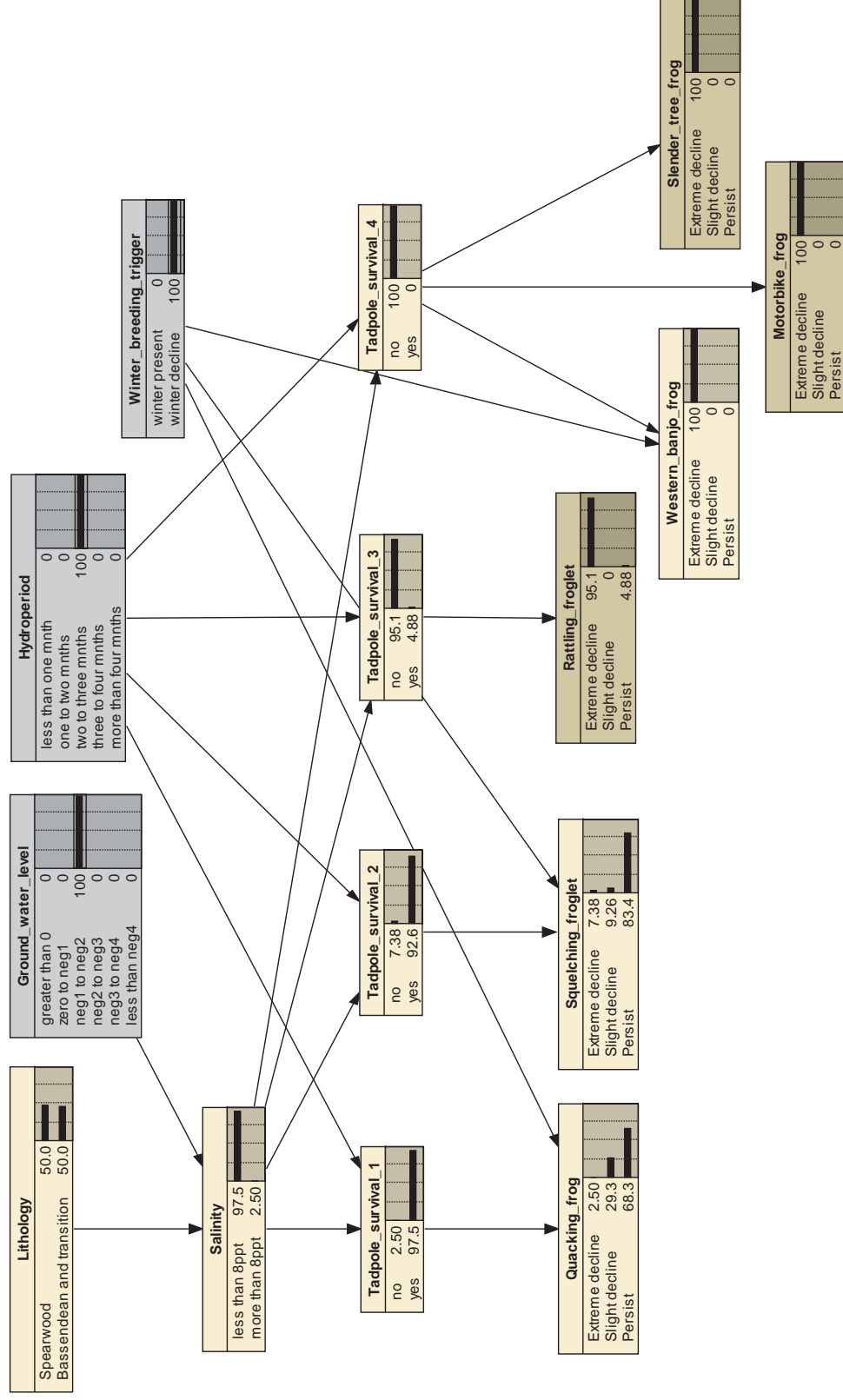
Figure 13. BBN for aquatic breeding amphibians, illustrating the impact of groundwater between 1-2 m from the surface, a 2-3 month hydroperiod, and a decline in the winter breeding trigger.

18   Identifying thresholds for responses of amphibians to groundwater and rainfall decline
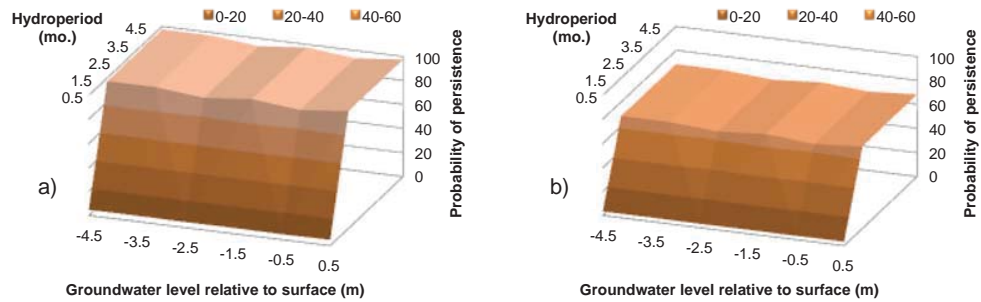
Figure 14. The influence of groundwater and the hydroperiod on the probability of population persistence for the Quacking frog, with a) the winter-breeding trigger present, or b) in decline.
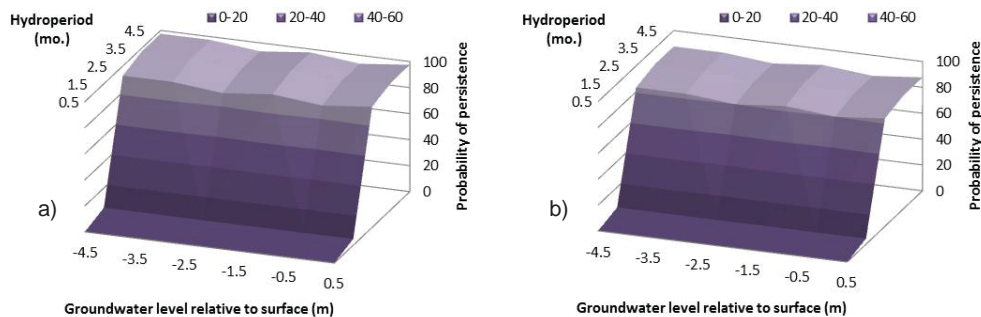
Figure 15. The influence of groundwater and the hydroperiod on the probability of population persistence for the Squelching frog, with a) the winter-breeding trigger present, or b) in decline.

Three of the six aquatic breeding amphibians were viewed as requiring a winter rainfall trigger to initiate breeding, hence the BBN was structured to cause a reduction in the probability of population persistence under a scenario of winter rainfall decline. Figures 14, 15 and 17 show examples of scenarios run with and without a decline in winter rainfall, but in general, the influence of this node was very small (see sensitivity analysis in SD6; Speldewinde 2013).

The probabilities of persistence for the remaining three species (Figures 16 and 18) were influenced primarily by the hydroperiod node, with very little influence from the groundwater node that modified salinity according to the underlying lithology. The direct influence of the lithology parent node was not examined as a sensitivity analysis (Table 11; SD6; Speldewinde et al.) showed that this node was relatively unimportant. This was because empirical data showed that the probability of salinity increase was very low, and therefore lithology (which impacts on salinity) was inconsequential.
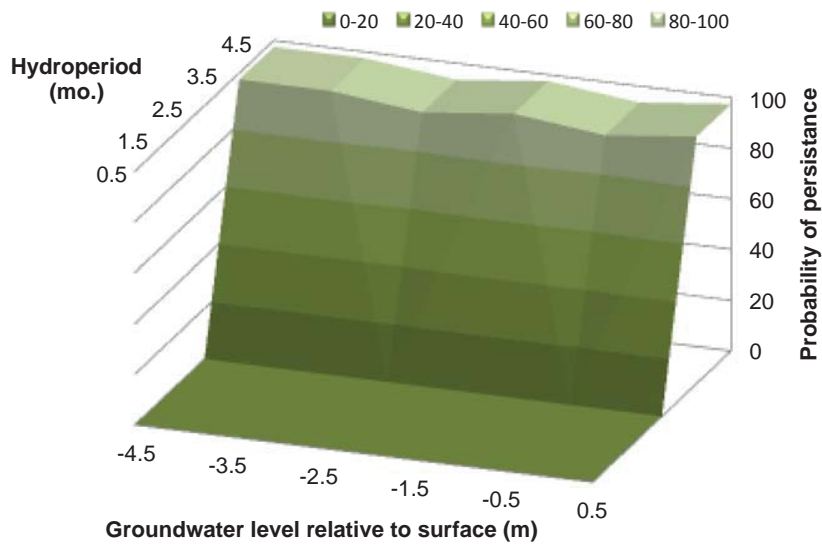
Figure 16. The influence of groundwater and the hydroperiod on the probability of population persistence for the Rattling froglet. This species breeds opportunistically after rainfall, except during summer months.
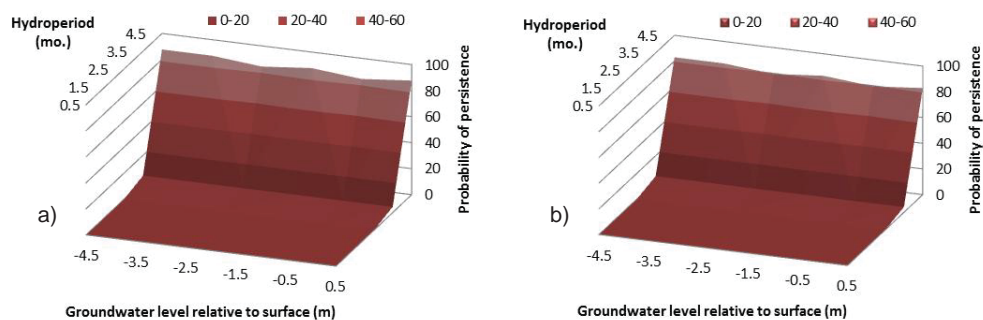
Figure 17. The influence of groundwater and the hydroperiod on the probability of population persistence for the Western Banjo frog, with a) the winter-breeding trigger present, or b) in decline.
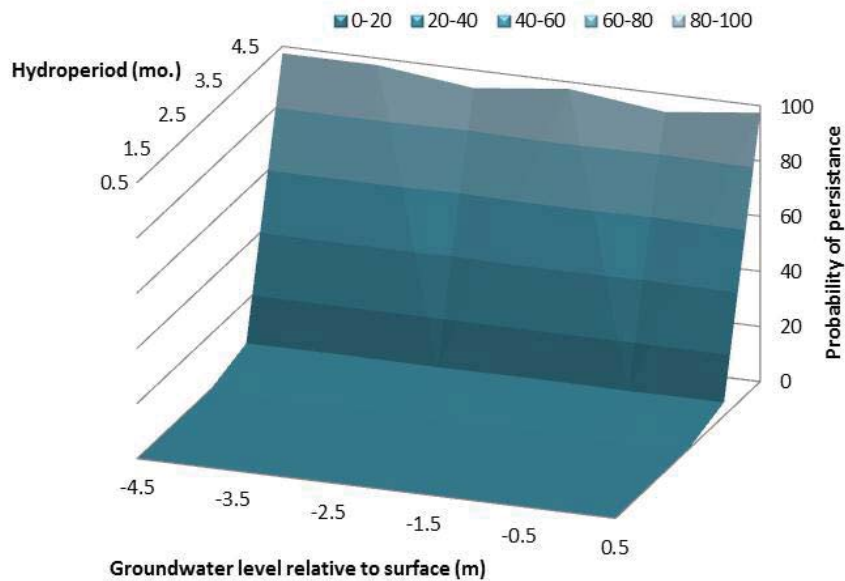
Figure 18. The influence of groundwater and the hydroperiod on the probability of population persistence for the Motorbike frog and the Slender tree frog. These species were both influenced by the same tadpole survival node in the BBN, and hence their probabilities of persistence were identical.

3.3.2   Terrestrial-aquatic breeding guild

Only two species were incorporated in to the BBN for the terrestrial-aquatic breeding guild, and although these species were both autumn breeders they depended to different extents on seasonal rainfalls to initiate breeding (Figure 19). The Moaning frog - a larger, species than the Crawling frog that burrows deeper underground, can begin calling before the break in season, but peak breeding occurs at the break of season. In contrast, the Crawling frog begins calling at the break of season but peak breeding is delayed for several weeks as the shallow surface soils where nests are constructed increase in water content. The BBN was structured to reflect this link between autumn rain and soil moisture, where it was assumed that a decline in autumn rainfall would result in sub optimal soil moisture for reproductive activity (Figure 19). Unpublished data on the crawling frog conducted during a record dry year in 2006 (N. Mitchell) supports this relationship. The expert panel introduced a second rainfall node to denote winter rainfall, which prevents the cue for hatching when nest sites flood (Bradford and Seymour 1985).

Like the BBN for the aquatic breeding guild, the aquatic larvae of these species depend on a suitable hydroperiod to allow metamorphosis, and are vulnerable to salinity (Davis and Roberts 2011). The relationships between the Lithology, Ground water level and Salinity nodes were therefore constructed from the same empirical data as was used in the BBN for the aquatic-breeding amphibians. Similarly, a tadpole survival filter was constructed by estimating the probabilities of extreme decline, slight decline and persistence under different combinations of salinity and hydroperiod. An analysis of the interrelationships between groundwater levels, the hydroperiod, and the presence of decline of seasonal rainfall is shown for each species in Figures 20 and 21.

Ground_water_level

greater than 0	0
zero to neg1	0
neg1 to neg2	100
neg2 to neg3	0
neg3 to neg4	0
less than neg4	0

Hydroperiod

| less than 3 mnths | 100 |
| more than 3 mnths | 0 |

Autumn_rainfall

| autumn present | 0 |
| autumn decline | 100 |

Lithology

| Spearwood | 50.0 |
| Bassendean and transition | 50.0 |

Salinity

| less than 8ppt | 97.5 |
| more than 8ppt | 2.50 |

Soil_moisture

| low | 100 |
| high | 0 |

Winter_hatching_trigger

| winter rainfall present | 100 |
| winter rainfall decline | 0 |

Tadpole_survival

| no | 80.5 |
| yes | 19.5 |

Moaning_frog

Extreme decline	40.3
Slight decline	50.0
Persist	9.75

Crawling_frog

Extreme decline	85.4
Slight decline	4.87
Persist	9.75

Figure 19. A BBN for terrestrial-breeding amphibians with aquatic larvae, illustrating the impact of groundwater between 1-2 m from the surface, a hydroperiod less than three month, and a decline in the autumn breeding trigger. The difference in dependence on the autumn rainfall trigger is primarily driving the different responses between the two species.

22   Identifying thresholds for responses of amphibians to groundwater and rainfall decline
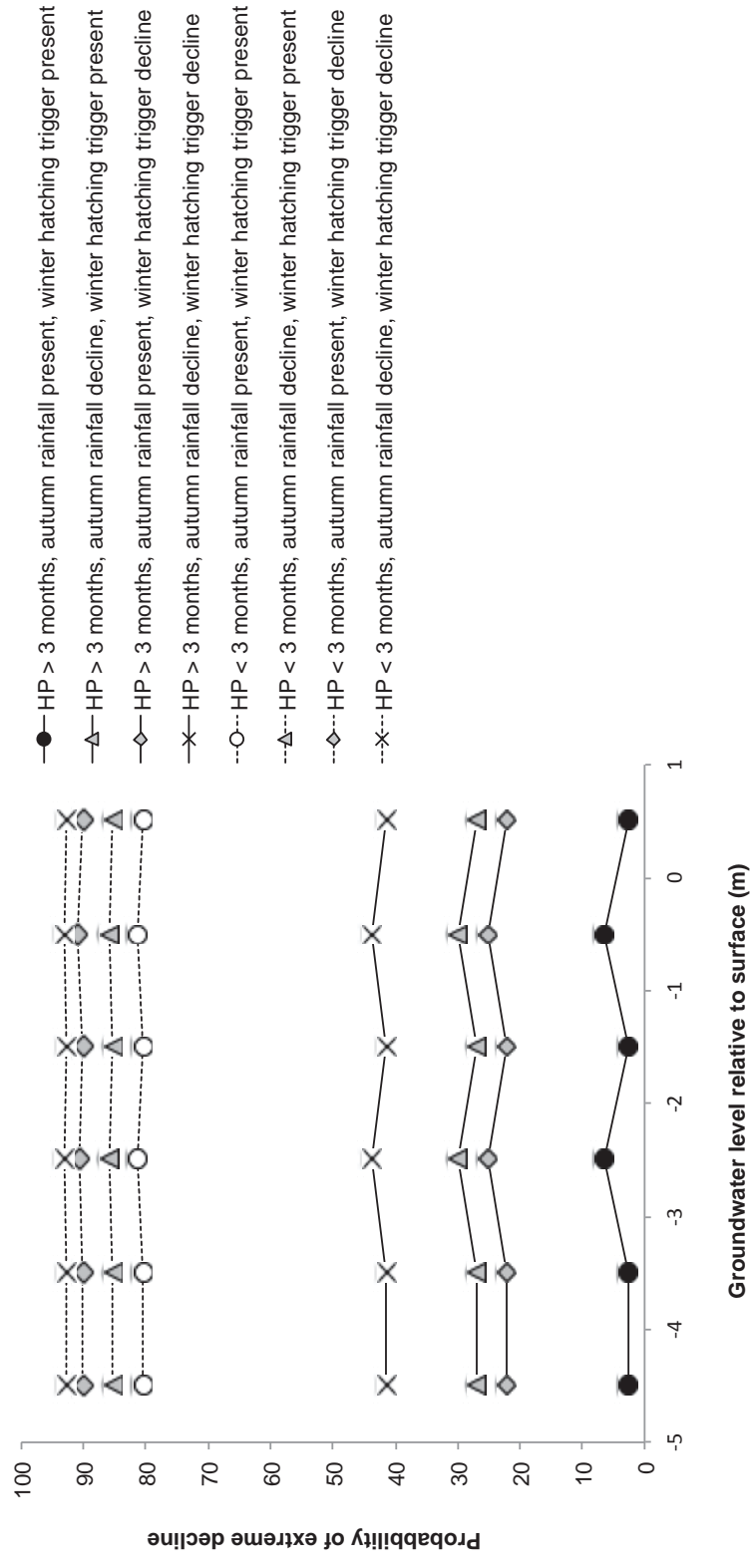
Figure 20. The relationship between groundwater levels and probability of 'extreme decline' for the Crawling frog, illustrating the influence the hydroperiods and seasonal rainfall triggers for key events in the species' lifecycle.
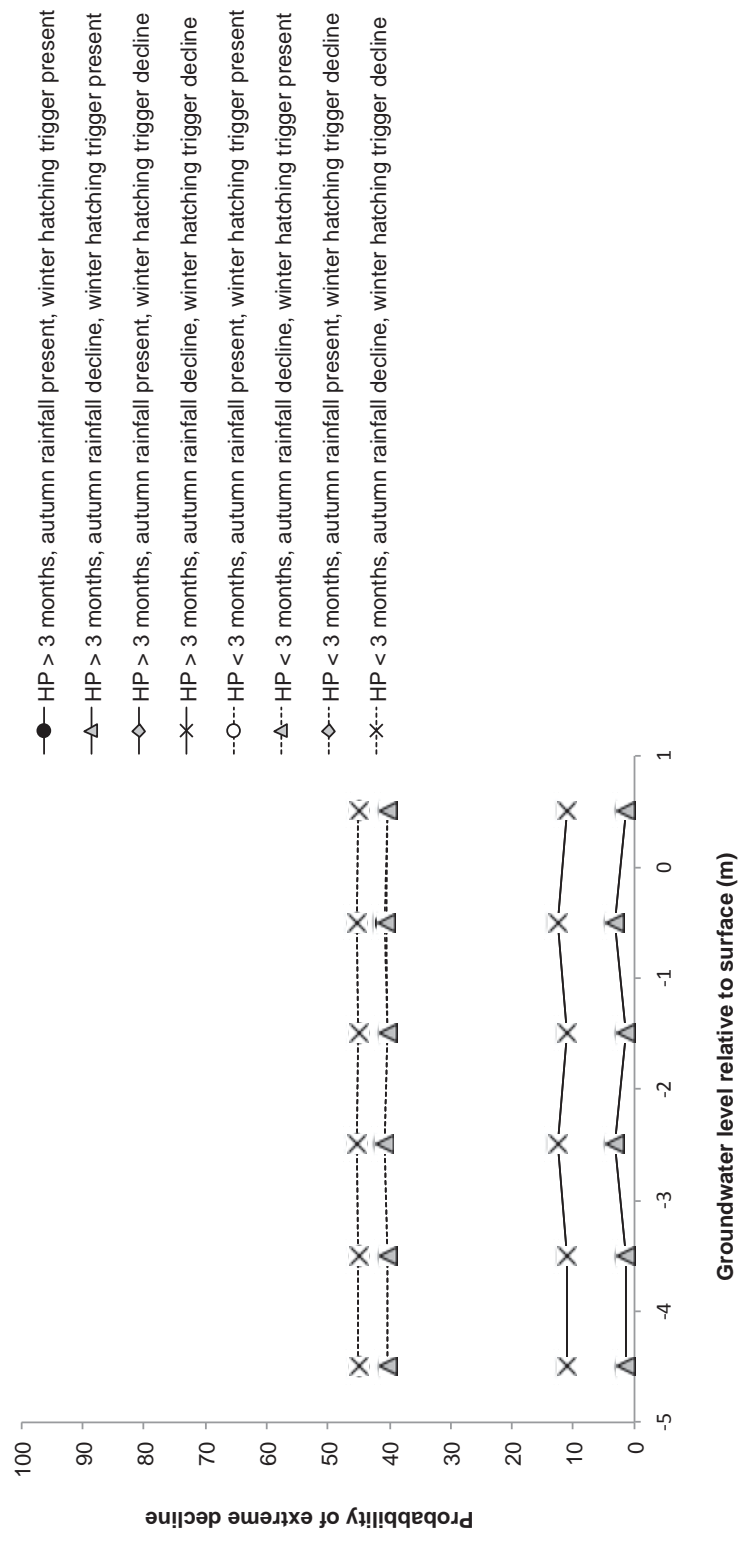
Figure 21. The relationship between groundwater levels and probability of 'extreme decline' for the Moaning frog, illustrating the influence of the hydroperiod and seasonal rainfall triggers for key events in the lifecycle

Legend (top to bottom):
- HP > 3 months, autumn rainfall present, winter hatching trigger present
- HP > 3 months, autumn rainfall decline, winter hatching trigger present
- HP > 3 months, autumn rainfall present, winter hatching trigger decline
- HP > 3 months, autumn rainfall decline, winter hatching trigger decline
- HP < 3 months, autumn rainfall present, winter hatching trigger present
- HP < 3 months, autumn rainfall decline, winter hatching trigger present
- HP < 3 months, autumn rainfall present, winter hatching trigger decline
- HP < 3 months, autumn rainfall decline, winter hatching trigger decline

Y-axis: Probability of extreme decline (0–100)

X-axis: Groundwater level relative to surface (m) (-5 to 1)

3.3.3 Terrestrial breeding guild

The single terrestrial-breeding species (the Turtle frog) was included in this case study as an interesting example of a species whose probability of persistence could potentially increase with groundwater decline. The relationship between groundwater level and population density is unknown for this species, but anecdotal evidence suggests that the species favours slightly elevated areas that are presumably more distant from the water table. Although soil moisture values at the underground retreat and breeding sites of this species have been measured (N. Mitchell, unpublished data) the influence of groundwater depth on soil moisture has not been determined in this habitat (primarily Banksia woodland), and is undoubtedly complex. Hence a conceptual link was developed between a groundwater node and a soil moisture node (Figure 22), the latter of which had three levels, with the 'medium' soil moisture being best suited to embryonic survival (dry soils would lead to embryonic desiccation, whereas wet soils would cause embryonic death due to hypoxia). It was assumed that the optimum 'medium' soil moisture conditions would be experienced when groundwater was relatively distant from the soil surface.

As for the other amphibian BBNs, two seasonal rainfall events were viewed as being important for population persistence: spring rainfall that promotes courtship at the soil surface (Roberts 1981; Mitchell 2011) and autumn rainfall that provides the trigger for the emergence of metamorphs from nest sites up to 1.5 m underground (Roberts 1981). The influence of groundwater level, and potential declines in these seasonal rainfall triggers is shown in Figure 23).

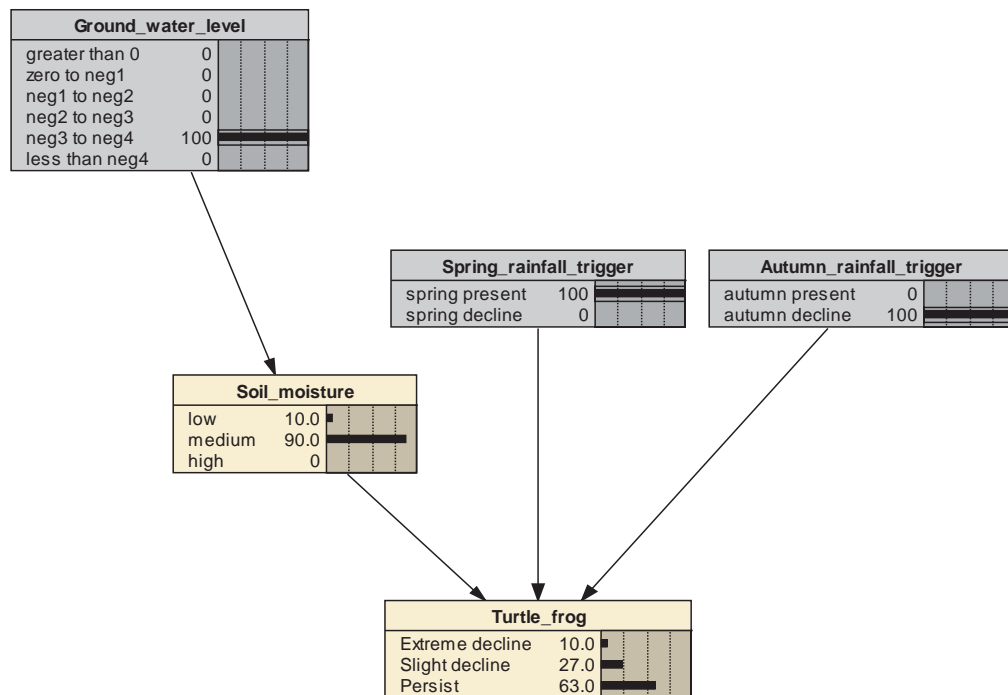**Figure 22. A simple BBN for the Turtle frog - a terrestrial-breeding amphibian**
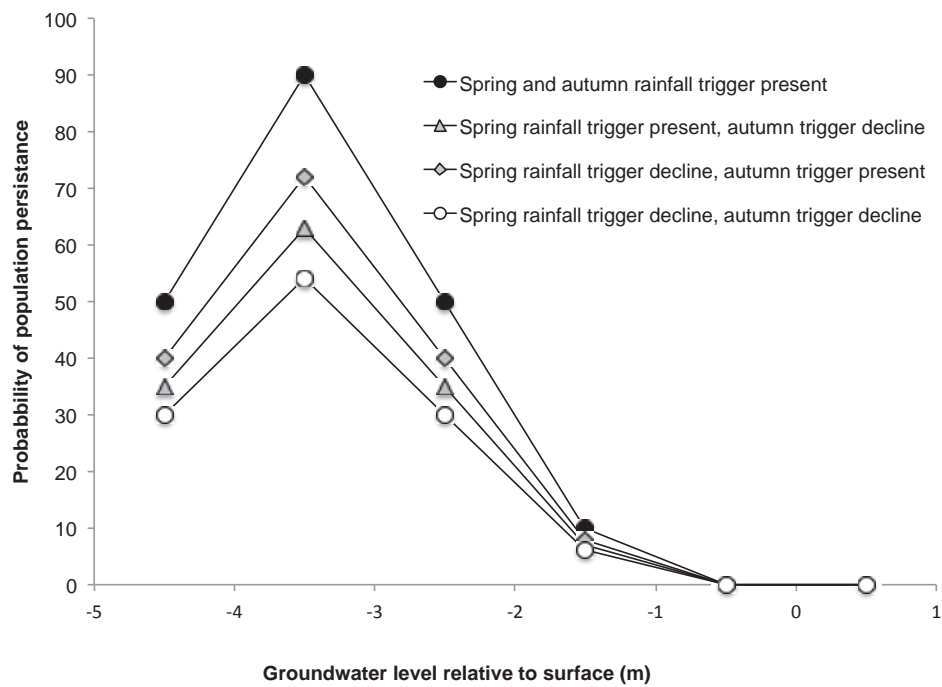
Figure 23. The relationship between groundwater levels and probability of population persistence for the Turtle frog, illustrating the influence of seasonal rainfall triggers for key events in the lifecycle.

4. DISCUSSION

The influence of the groundwater node in two of the three BBNs developed for amphibians was negligible (Figures 14-18, 20-21). The sole influence of the changes in the groundwater level were mediated via the salinity node, and the range of groundwater levels that we modelled never predicted the critical salinity threshold of 8ppt and therefore did not influence any of the output nodes. Instead, the hydroperiod had the most appreciable influence on the probability of population persistence of these two guilds, as the expert panel had constructed the BBNs with a tadpole survival filter that reflected the combined influence of wetland hydroperiods and salinity.

Hydroperiod thresholds were based on best guesses of minimum larval lifespans. Further refinement of the larval lifespans of each species could increase the utility of the BBNs, but such basic life-history data is often unknown. Furthermore, temperature has an appreciate influence on embryonic and larval development rates (e.g. Mitchell 2000) and under a climate change scenario of warmer water temperatures, larval lifespans would be correspondingly shorter. Therefore quantification of the larval lifespans for the various species at current environmental temperatures would be valuable for accurately populating the thresholds for tadpole survival.

The apparent negligible influence of groundwater levels on amphibian species that require water to complete their lifecycle is unlikely to be realistic. The hydroperiod of any wetland or water body that is groundwater dependent will be directly affected by groundwater decline, but in this instance we lacked the empirical data from the multivariate analyses to link groundwater levels to hydroperiods. However, monitoring by the Western Australian Department of Water has shown a clear reduction in the expression of surface water (and therefore hydroperiods) associated with groundwater declines on the Gnangara Mound (Sonneman 2009), and terrestrial-aquatic breeding amphibians that breed in the sumplands have experienced several years of failed recruitment (N. Mitchell, unpublished observations).

To demonstrate a link between hydroperiods and groundwater levels in our BBNs we could have devised a hypothetical relationship (i.e. higher groundwater levels producing longer hydroperiods), but the disadvantage of this approach is that it would be misleading for perched or artificial water bodies. That is, amphibians could persist in perched wetlands provided that the hydroperiod is sufficient to allow recruitment of juveniles in to the population. An alternative approach to demonstrating a realistic relationship between groundwater levels and hydroperiods would be to use a hydrological model to predict hydroperiods from groundwater, rainfall, soil type/porosity and catchment inputs (e.g. Colletti et al. 2012). Modelled predictions can then be spatially explicit and driven by GIS (e.g. Mitchell at al. 2013), but modelled hydroperiods were well beyond the scope and timeframe of this study.

Aside from the wetland hydroperiod, the other nodes most influencing population persistence were declines in seasonal rainfall. Record low rainfalls in autumn and winter have been experienced in the south west of Australia in the past decade, and the trend is likely to continue (Bureau of Meteorology, 2012; Indian Ocean Climate Initiative 2012), hence seasonal rainfall declines pose a very real threat to the reproductive success of amphibians. For example, during a period of record low autumn rainfall in 2006, recruitment of the Crawling frog at a site on the Darling Escarpment failed, due to the combined effect of desiccation of embryos and failure of nest sites to flood (N. Mitchell, unpublished data). More subtle effects of desiccation stress have also been recorded in this species, including slower hatching times, smaller body sizes, increases asymmetry and reduced hatching success (Eads et al.

2012). Notwithstanding these effects, declines in seasonal rainfall will also directly reduce hydroperiods. Our BBNs could have been constructed to reflect such a dependency between nodes, but to improve tractability we limited the influence of declines in seasonal rainfall to their effects on triggering key events in amphibian lifecycles.

Overall, our BBNs suggested that the terrestrial-aquatic breeding amphibians had the highest probabilities of 'extreme decline' under the various constructs of the network (Figures 20 and 21). One of these species – the Crawling frog – was also viewed in a related study to be the species most vulnerable to population decline, partially due to its short lifespan and specific habitat requirements (Bamford and Huang 2009). Conversely, the other terrestrial-aquatic breeder was considered by the same authors to be reasonability robust to hydrological change, due to its longevity and high dispersal ability (Bamford 1991). This highlights one of the inadequacies of the existing BBNs, in that they do not account for differences in longevity, reproductive output or dispersal. While experts may have intuitively made allowances for such species' differences when populating the various conditional probability tables, these considerations are not tractable.

The BBN developed for the terrestrial breeding turtle frog (Figure 22) was the only model that demonstrated how changes in groundwater level could directly modify the probability of persistence (Figure 23). In this case, the groundwater level node controlled the soil moisture node. Sensitivity analysis of the Turtle frog BBN shows no entropy reduction when the groundwater depth is either < 1 m of higher (i.e. soil is saturated or flooded) or below 4m. At these depths the soil moisture is entirely unsuitable for the Turtle Frog and therefore the rainfall nodes become irrelevant in the model. In between these two extremes, soil moisture (and by inference groundwater level) was a highly relevant influence on the output node. Hence the predictions of the impact of declining groundwater at a wetland for a turtle frog would be an increasing probability of population persistence. There would, however, be a significant time lag before this could occur, as turtle frogs inhabit mature Banksia stands and feed on the associated invertebrate community (primarily termites). Because Banksia species could take decades to colonise and transform former wetland habitats it is unrealistic to assume that turtle frogs would replace other amphibian species in drying wetlands in the short term.

Seasonal rainfall triggers also modified the probabilities of population persistence for the Turtle frog, with a decline in the autumn rainfall trigger having a slightly greater influence than a decline in the spring rainfall trigger (Figure 23). This is because the experts viewed the rainfall trigger that initiates courtship as being fairly flexible in its timing (courtship behaviours have been recorded between September and February in this species; Roberts 1981). In contrast, a decline in autumn rainfall would lead the later emergence (and hence later opportunities for feeding) of metamorphs, which could potentially lead to reduced survival.

A key groundwater-dependent process that is likely to be highly influential in the persistence of turtle frogs on the Gnangara Mound is the health of the Banksia Woodlands. Over-abstraction of groundwater has led to the death of Banksia stands at long-term study sites (Groom et al. 2000) and recovery of these woodlands after groundwater recharge is slow. Again, there may be a time lag between the decline of a Banksia woodland and the associated turtle frog population, because termite abundance may remain high in dead trees. However, the impact of living Banksias on hydrological processes such as regulation of soil moisture is potentially profound. Largely due to uncertainties in the relationships between groundwater levels, Banksia health and soil moisture, a Banksia Health node was not incorporated into the BBN.

With improved understanding (and potentially modelling) of these interactions, a more complex BBN could be developed to investigate the response of this unique amphibian to hydrological change.
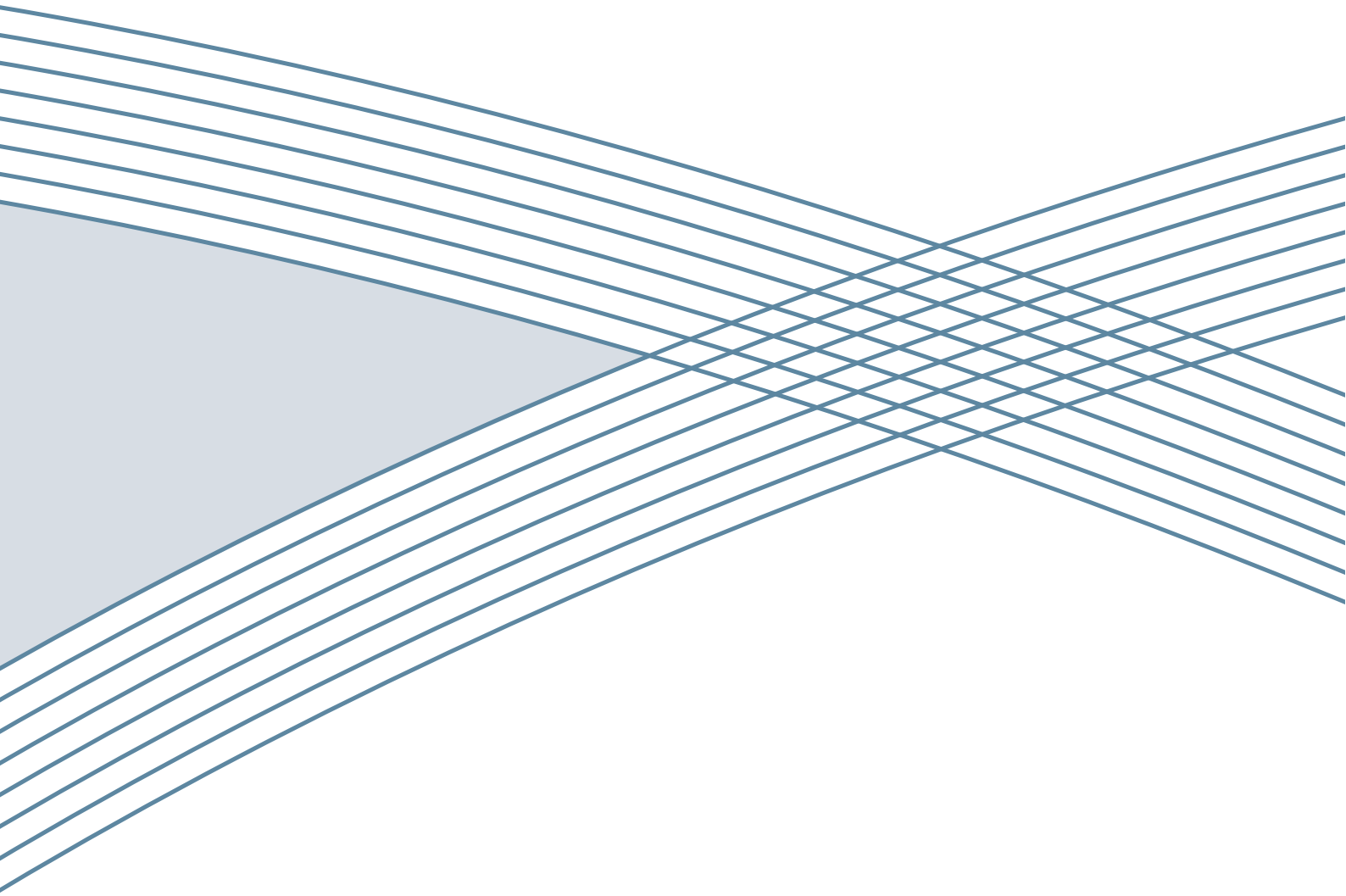
5. CONCLUSION

In data-poor situations such as the amphibian example developed here, we have demonstrated that Bayesian Belief networks constructed using expert opinion can provide insights into the responses to groundwater decline in a diverse range of species. Further, we demonstrate how weather variables that are important to recruitment can be incorporated into BBNs. In situations where parent nodes such as rainfall and groundwater levels could be projected in a spatially explicit manner, BBNs constructed using expert opinion can be used with greater utility. For example, they could be applied to particular wetlands where high-resolution data on depths to the water table are available, where hydroperiods can be modelled or derived empirically, and where future climate change scenarios have been projected at an appropriate scale. In this way, managers could anticipate the impact of groundwater abstraction at significant wetlands, and initiate appropriate responses to enhance the probability of the persistence of the amphibian community and the associated ecosystem services they convey.

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