



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

## Guidelines for use

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## EXECUTIVE SUMMARY

This document provides guidance on how to use a risk assessment and decision making framework (referred to hereafter as 'the framework') to manage groundwater dependent ecosystems (GDEs) with declining groundwater levels due to climate change, anthropogenic extraction, land use and land management.

The framework integrates a standard risk assessment protocol enabling the approach to be easily transferred to sites within Australia and internationally. The framework is based around the construction of a conceptual model which identifies the interrelationships between climate, hydrology, water quality and/or biotic resources and the biota in an ecosystem. It is a problem solving framework that provides a transparent outline of the cause and effects of change to an ecosystem, highlighting key drivers that provide the focus for management and climate change adaptation. The framework is designed for declining water levels within the ecosystem, so it can readily be adapted to address surface water ecosystems by substituting, or adding, surface water inputs into the conceptual model (Figure A).

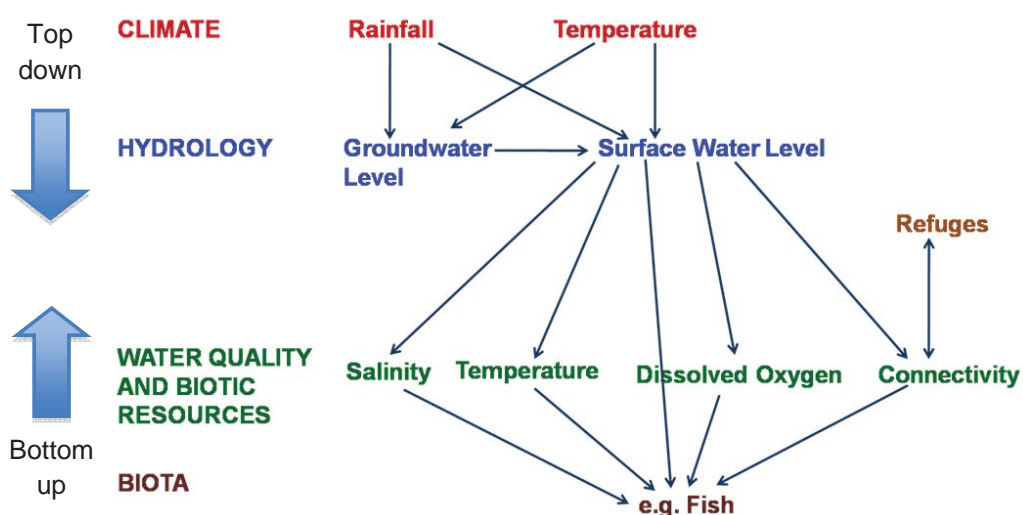


Figure A: An example of a conceptual model designed for the Blackwood River groundwater intrusion zone, showing top down and bottom up management approaches.

The document is in two parts. In *Part 1) Identifying your Management Issue and the Nature of your Ecosystem* we outline steps to identify the management issue of concern, determine if your ecosystem is groundwater dependent, construct a hydrogeological model that identifies the inputs and outputs of water in the GDE, determine the spatial boundaries of the system and prioritise assets within these boundaries. In *Part 2) the Risk Assessment and Decision-Making Framework* we outline how to incorporate information in a series of five steps that creates a model relevant to your ecosystem and management/adaptation needs. The five steps are:

**Step 1: Identify the hazard** – the framework is designed to manage the hazard of declining groundwater levels. This step identifies the primary and secondary hazards and the cause of declining groundwater levels.

**Step 2: Determine exposure and vulnerability** – the magnitude and rate of groundwater decline is determined spatially and temporally (historically, currently and projected to the future). The dynamics of hydrological change, such as changes in seasonality and/or the number and frequency of dry periods, are also considered.

**Step 3: Assess effects** – a conceptual model of ecosystem function is developed describing the cause and effect interrelationships between climate, hydrology, water quality, required biotic resources and biotic response. The key drivers that cause ecosystem change are identified.

**Step 4: Characterise risk** – A number of techniques (expert opinion, using presence/absence data and statistical analysis) are described to determine the tolerance limits or *thresholds* of the key drivers that drive change in the biota. The conceptual model, with key drivers now quantified by thresholds, are now incorporated into Bayesian Belief Networks (BBNs) that can be easily modified to show changes in probability of risk resulting from these interactions. The outputs of the BBNs or other risk models can then be mapped spatially using geographic information systems (GIS).

**Step 5: Manage risk** – The use of a conceptual model provides the framework with a high degree of adaptability. The framework can be used to determine the effects of groundwater decline (whether through climate change, groundwater extraction, other cause, or a combination of these) on GDEs. This would be a top down approach using the conceptual model (Figure A) to test a number of scenarios of differing levels of groundwater decline. It can equally be used to determine the tolerance limits of GDEs or specific biota within them. This ‘bottom up’ approach would define the limits of unacceptable change that could inform management targets.

The framework was developed by a multidisciplinary team of ecologists, modellers and hydrogeologists in south-western Australia, a biodiversity hotspot that has already suffered three decades of below average rainfall and consequently declining groundwater levels due to increased groundwater abstraction and land use change. This has provided a ‘living experiment’ providing validation of the framework against observed changes (not just modeled projections). The combination of this research together with input from a suite of end-users, other scientists and experts from across Australia has provided a robust and adaptable framework.

The guide is supported by a companion document – Development and Case Studies - outlining how the framework was developed and tested in the three case studies (Chambers *et al.* 2013). The framework was developed in ecosystems that contain surface expression of groundwater in wetlands and rivers and the subterranean expression of groundwater in caves but could be adapted to any type of GDE or surface water system. The Development and Case Studies document showcases the three case studies to provide first hand examples and variations of how the framework can be used. The first case study investigated both the risk to entire wetland

ecosystems and to different guilds of amphibians on the Gnangara Groundwater System, a key water resource for the capital city of Perth, with large available dataset. The second investigated the likelihood of survival of a suite of endemic freshwater fish threatened by salinity and lack of connectivity caused by reduced groundwater intrusion into the Blackwood River. The third the potential extinction of Threatened Ecological Communities (EPB Act 1999) of stygofauna in the Leeuwin Naturaliste Ridge Cave system due to declining groundwater levels. The latter two case studies had little data available, increasing the flexibility of the framework to data poor situations. Examples of these case studies are used throughout this guide to illustrate techniques used.

Further detail can be obtained in a series of seven documents supporting the Development and Case Study report. To determine how these supporting documents fit into the overall study refer to Table 2 in the Development and Case Studies report (Chambers *et al.* 2013).

## **1. PART 1: IDENTIFYING YOUR MANAGEMENT ISSUE AND THE NATURE OF YOUR ECOSYSTEM**

### ***1.1 Identifying your Management Issue***

It is vital to have a clear objective in carrying out the risk assessment and decision-making framework. What is the management issue you wish to address with this framework?

The framework can be used to determine the effects of groundwater decline (whether through climate change, groundwater extraction, other cause, or a combination of these) on GDEs. This would be a top down approach using the conceptual model (Figure A) to test a number of scenarios of differing levels of groundwater decline. It can equally be used to determine the tolerance limits of GDEs or specific biota within them. This 'bottom up' approach would define the limits of unacceptable change that could inform management targets.

Both types of scenario testing can be done with the same conceptual model but the answers you are seeking will define the information you need to collect. Having a clear statement of your goals will save time and resources and will result in a better outcome.

### ***1.2 Do you have a GDE (or a surface water system)? Developing a Hydrogeological Conceptual Model***

There are a number of resources online that can guide you to identify the nature of your ecosystem. The GDE toolbox (Richardson et al. 2011) provides a valuable resource to identify and conceptualise the hydrogeology of your GDE. The toolbox "presents a suite of practical and technically robust tools and approaches that will allow water resource, catchment and ecosystem managers to identify GDEs, determine the reliance of those ecosystems on groundwater, and determine possible changes to ecosystem state or function due to changes in the groundwater environment" (Richardson et al. 2011 p.2).

This involves using a three-stage assessment framework for determining the Ecological Water Requirements (EWR) of GDEs (Figure 1). Stage 1 involves a basic assessment of the type of GDE and requires the development of a conceptual model of the GDE. Stage 2 determines how reliant the ecosystem is on groundwater and Stage 3 characterises the ecological response of GDEs to change. An important component of the GDE toolbox describes developing conceptual models of GDEs and examples are given for wetlands (Lexia Wetlands, Western Australia), Caves (Mole Creek Karst, Tasmania), Mound Springs (Great Artesian Basin) and a Monsoon Vine Thicket.

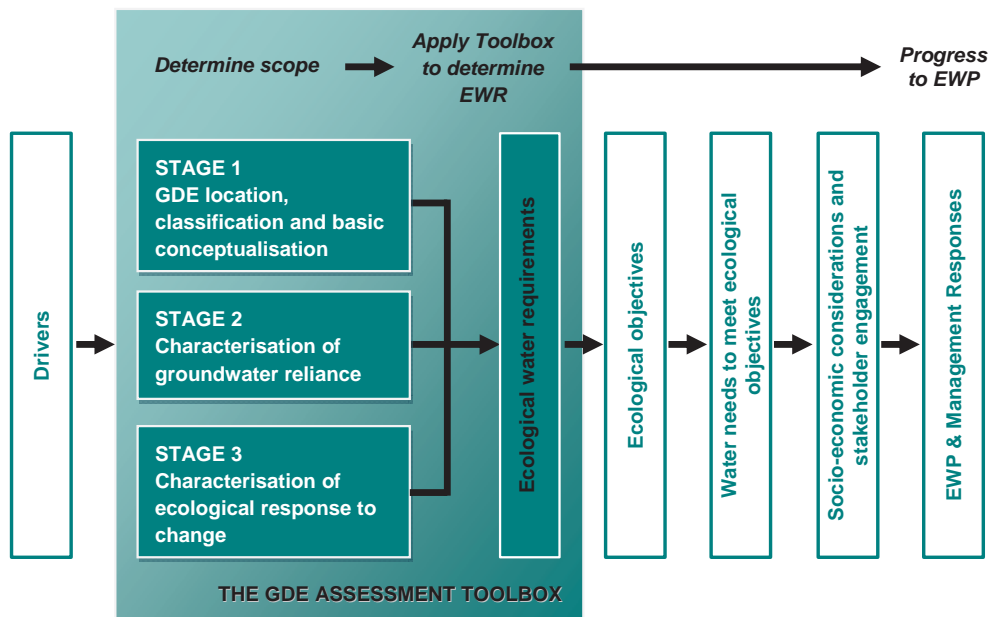


Figure 1: The three stage process for determining the EWRs of GDEs. The shaded section outlines the methodology outlined in the GDE toolbox (Richardson *et al.* 2011 p.18).

Other resources described in the GDE toolbox include Eamus (2009) which provides guidelines for land and water managers on how to identify GDEs and ‘The Atlas of Groundwater Dependent Ecosystems of Australia’ funded by the National Water Commission and led by Sinclair Knight Merz. The GDE Atlas is an interactive atlas which maps the position of ecosystems that potentially access groundwater and classifies them into three categories: ecosystems that rely on the surface expression of groundwater, ecosystems that rely on the subsurface expression of groundwater and subterranean ecosystems (SKM 2012). The GDE Atlas is hosted on the Bureau of Meteorology website and can be found at the link below.

URLs for these resources:

- GDE toolbox (Richardson *et al.* 2011)  
[http://nwc.gov.au/\\_data/assets/pdf\\_file/0006/19905/GDE-toolbox-part-1.pdf](http://nwc.gov.au/_data/assets/pdf_file/0006/19905/GDE-toolbox-part-1.pdf)
- Identifying GDEs (Eamus 2009):  
[http://lwa.gov.au/files/products/innovation/pn30129/pn30129\\_1.pdf](http://lwa.gov.au/files/products/innovation/pn30129/pn30129_1.pdf)
- GDE Atlas: <http://www.bom.gov.au/water/groundwater/gde/map.shtml>

## **1.3 Identifying Spatial Boundaries and Assets within your System**

### **1.3.1 Spatial Boundaries**

The spatial boundaries considered for the risk assessment framework should be determined by the groundwater aquifers impacted by climate or human-induced changes in storage and reductions in historical or future rainfall. Rising temperatures are also likely to result in increased potential evaporation from GDEs. It is important to consider the entire groundwater system that supports the GDEs rather than just the surface expressions (i.e. groundwater dependent wetlands themselves). It is also important to understand that some lakes may be perched (e.g. Ramsar-listed Lake Forestdale), being underlain by sediments that partially separate the lake from the underlying aquifer or by high water retention soils such as biogenic silica (diatomaceous earth). In the case studies outlined in the Development and Case Studies document (Chambers *et al.* 2013), an entire groundwater mound, or the region of groundwater expression into a river or a cave system together with the area of the supporting groundwater aquifer were included.

### **1.3.2 Assets**

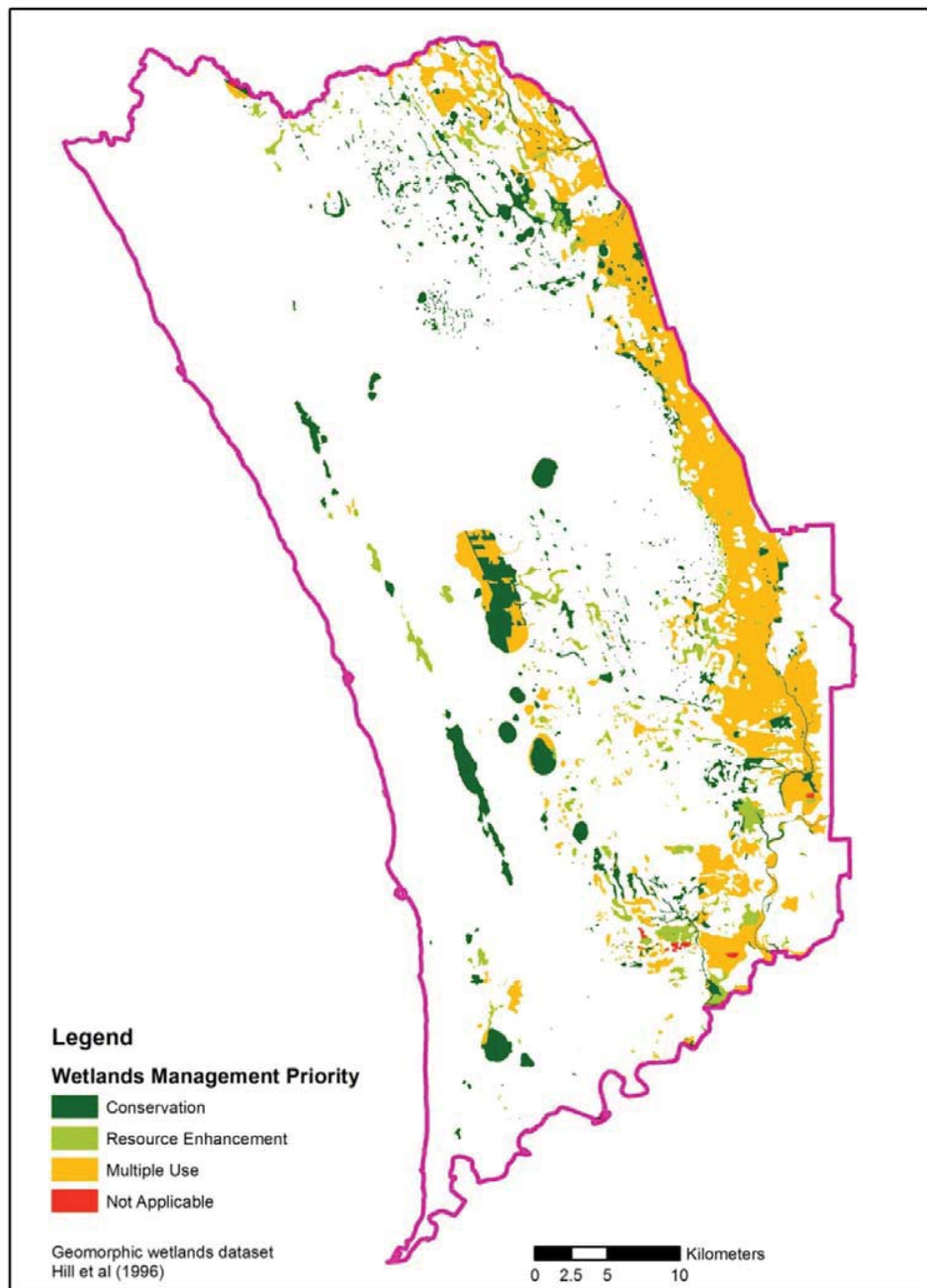
Once you have determined what GDEs are in your study area any information about them (e.g. their condition, connectivity, conservation status etc) is valuable in decision-making. Temporally the condition of areas where new GDEs might emerge is also of value as this can inform future planning and policy. It is possible to identify the location of high value assets within the study area based on existing datasets (Example 1).

#### **EXAMPLE 1: Existing Asset Valuation in the Gngangara study area**

In the Gngangara study area, wetland asset identification was available in the Geomorphic Wetlands dataset which has a Wetland Management Category - a form of valuation aimed at management (Hill *et al.* 1996). It identifies three management priorities:

- Conservation (to preserve wetland (natural attributes and functions)
- Resource enhancement (to restore wetlands through maintenance and enhancement of natural attributes and functions); and
- Multiple use (to use, develop and manage in the context of water, town and environmental planning).

Figure 3 encapsulates these management priorities to identify wetlands with high management priority.



**Figure 2: Three management priorities – conservation, resource enhancement and multiple use – are considered to prioritise wetland management on the Gnamptara study area.**

Should such pre-existing work be unavailable, it is possible to do such assessment based on existing datasets, using a set of criteria developed at the local scale, but based on generic assessment processes (e.g. Margules and Usher (1981), Margules *et al.* (1982) and Margules and Nicholl (1988)). A good example of wetland value assessment is shown for the Swan Coastal Plain, Western Australia in Hill *et al.* (1996;

section 5.6). A range of studies have taken such starting criteria and further developed and quantified their relative importance (Boteva *et al.* (2004), Panitsa *et al.* (2011), to end up with lists such as the following from Panitsa *et al.* (2011):

- Diversity (30% or total importance)
- Rarity (33%)
- Naturalness (26%)
- Area
- Threat/replaceability (9%)

Normal practice would be to carry out a series of workshops to establish the assessment criteria, the relative weights of each criterion and the classification and rating for each criterion (Voinov and Bousquet 2010). Conducting a series of workshops allows for the first cut assessment to be carried out and presented back to the stakeholders in an iterative process to refine the assessment model.

Identifying new assets has been developed for the Gngangara study area in Example 2 below. Further information on assessing assets is provided in SD7 (Neville, 2013).

**EXAMPLE 2: Identifying new assets** – a wetland value assessment (also known as the *indicative conservation model*) for the Gngangara study area (Figure 4).

Criteria are weighted as follows:

- RARITY – Wetland Proportion of Consanguineous Suite – 1 (15%)
- RARITY - Consanguineous Suite Area (total) – 0.5 (8%)
- RARITY - Wetland - Proportion of Class – 0.5 (8%)
- DIVERSITY - Wetland Class – 1.5 (23%)
- NATURALNESS/AREA - Wetland Area (by class) – 1 (15%)
- NATURALNESS - Evaluation (Wetland Zoning) – 2 (31%)



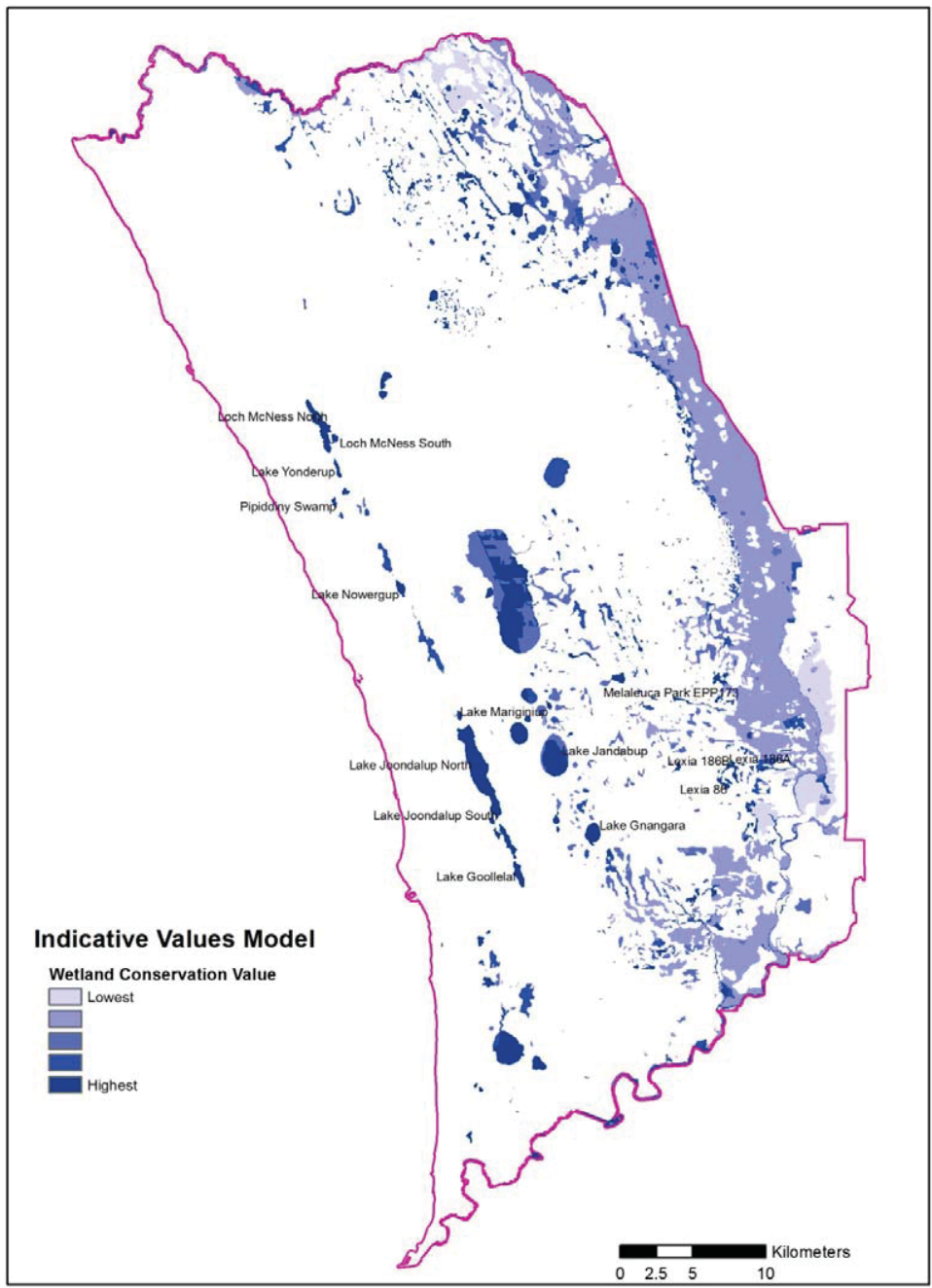


Figure 3: Identifying new assets – a wetland value assessment for the Gngangara study area (also referred to as the *indicative values model*).

## PART 2: THE RISK ASSESSMENT AND DECISION-MAKING FRAMEWORK

The framework presented here has been modified from a standard Risk Assessment Framework (Asante-Duah 1998) which consists of five steps (Figure 5).

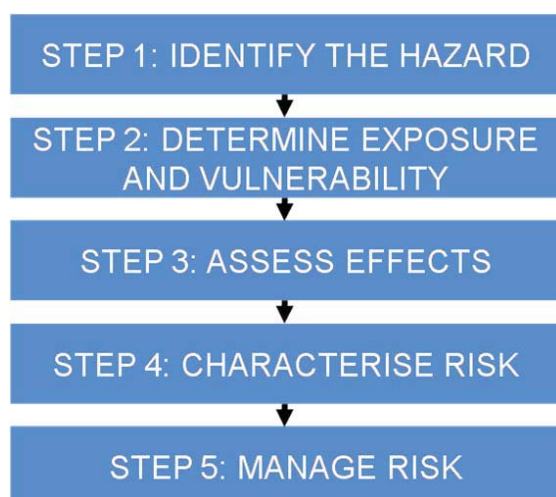


Figure 4: The Risk Assessment and Decision Making Framework consists of five steps (based on a standard risk assessment framework developed by Assante-Duah (1998)).

### 1. Step 1: Identify the hazard

It is important to understand the difference between hazards and risks. **Hazards** are any source of potential damage, harm or adverse health effects on the GDE under certain conditions. These are also called *sources* of risk. **Risk** is the chance or probability that a GDE will be harmed, or experience an adverse health effect, if exposed to a hazard.

This framework is designed to address the primary hazard of declining groundwater levels that cause lower surface water levels or reduced frequency and/or duration of the surface expression of groundwater. However, the framework can be adapted to suit a number of purposes including addressing different hazards e.g. declining water levels due to surface water inputs. To enable this we have clearly outlined a step-wise methodology (Figure 5). This is:

**Step 1.1:** identify the primary and, if necessary, secondary hazards that are a cause of harm to the ecosystem;

**Step 1.2:** determine the time frame for the framework and

**Step 1.3:** identify the cause(s) of the hazard(s)

It is also useful to consider what measures are going to be most helpful in categorising risk (probability and consequence of the hazard occurring).

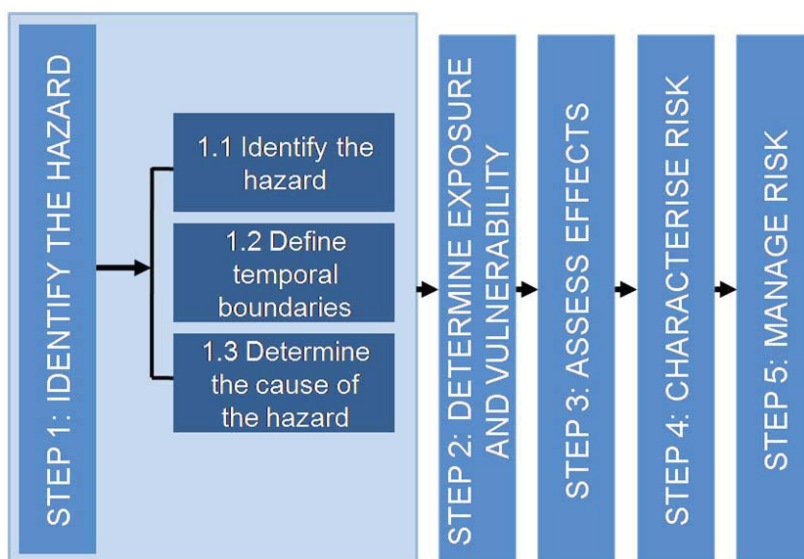


Figure 5: The Risk Assessment Framework with the steps involved in identifying the hazard.

## 1.1 Identify the Hazard

### 1.1.1 Primary Hazard

This framework has been designed for the hazard of declining water levels in GDEs due to declining groundwater levels. While several impacts may be affecting the system, the framework is designed to assess only one primary hazard at a time. If desired the framework can be adapted by considering a different primary hazard. Other primary hazards could include the impact of changing dynamics (e.g. seasonality, changed hydroperiods) or rising groundwater levels on GDE values.

Declining groundwater levels can result from groundwater abstraction, drainage, declining rainfall, recharge being impacted by land uses on the intake area (e.g. commercial plantations) or changes to land management (fire frequency, plantation thinning regimes) or changes to runoff, due to climate change (decreased rainfall, increased temperature, evapotranspiration) or a combination of these factors.

### 1.1.2 Secondary Hazard

A secondary hazard is a change in other parameters that affect the GDE, as a consequence of the primary hazard. The most likely secondary hazards resulting from declining water levels are changes in physicochemical parameters (water quality) in the GDE or other resources required for ecosystem function e.g. hydrological and/or biotic connectivity. Changes in community interactions (e.g. increased predation) could also be a secondary hazard. An example is given below (Example 3) relevant to wetlands on the Gngangara Mound (the superficial aquifer of the Gngangara Groundwater System, where the groundwater influences the GDEs). The secondary hazard can be determined through looking at historical monitoring data, previous scientific studies, talking to experts such as landholders, consultancies etc. and field surveys.

### EXAMPLE 3: Secondary hazards identified for the Gngangara Mound

Declining groundwater levels can result in reduced water availability to freshwater ecosystems and often decreased flushing and the evapo-concentration of nutrients, salts and pollutants (Figure 6). A shallower or smaller area of surface water may also increase the temperature of the water body and expose sediments, which decreases soil moisture and may expose pyritic sediments to oxygen, resulting in the production of actual acid sulfate soils (Figure 6). Altered water quality parameters can lead to shifts in faunal assemblages and a reduction in biodiversity and productivity in the GDEs. Reduced groundwater, relative to surface water input, can also cause poor water quality as surface water can often have greater loads of nutrients and pollutants than groundwater.

Increasing groundwater levels can result in salinisation in both dryland and irrigated systems. They can also increase flushing of nutrients into receiving bodies. Therefore the relationships shown in Figure 6 are site specific.

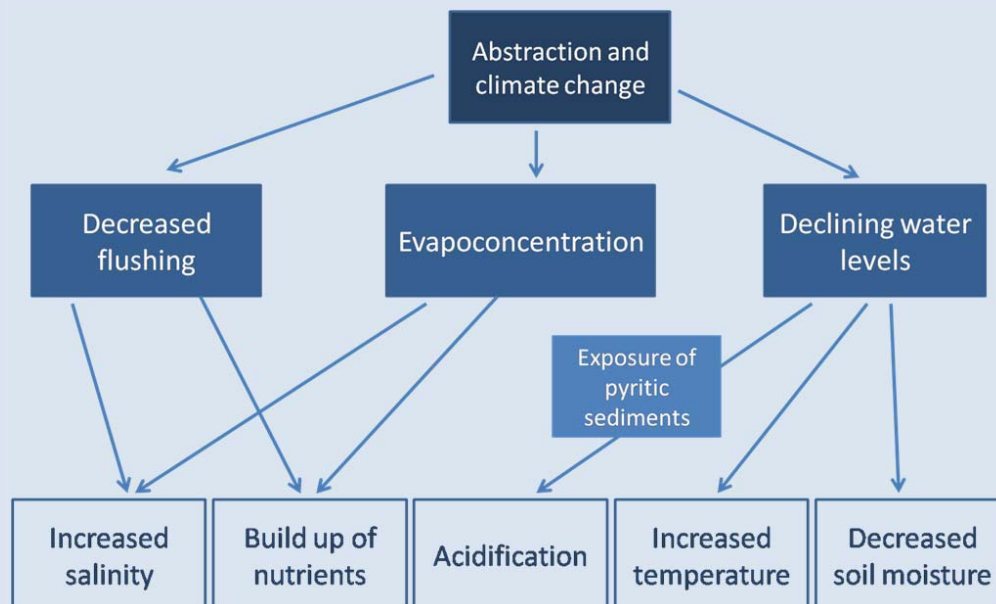


Figure 6: Secondary impacts of abstraction and climate change can lead to decreased flushing, evapo-concentration and declining water levels, which in turn can alter water quality parameters and the soil moisture content of the system. This example is for the wetlands of the Gngangara Mound Perth, WA, other systems may have different drivers.

## 1.2 Define Temporal Boundaries

The temporal boundaries of the framework are largely determined by the management question. For example, the time period would be different for scenario testing of groundwater extraction compared to climate change projection. Where possible, the temporal boundaries should include a period before the occurrence of the hazard to provide baseline data, a period after the onset of the hazard to determine effects and a future period where effects can be extrapolated based on the conditions outlined by

future climate scenarios. Where the hazard has not yet occurred, it can be assessed through scenario development (see later for scenario development). Temporal boundaries need also to align with available data and resources. Example 4 outlines the temporal boundaries used in the Development and Case Studies document.

**EXAMPLE 4: In the Development and Case Studies** (Chambers *et al.* 2013) document we chose three temporal scenarios:

1. **Historical climate:** assumed the climate of 1975-2007 continued until 2030
2. **Recent climate:** assumed the recent drier climate of 1997-2007 continued until 2030
3. **Future climate:** Projections to 2030 under a range of climate change scenarios.

The historical and recent time periods were chosen due to observed changes in the climate and the availability of data. The projections to 2030 used 15 Global Climate Models (GCMs) to modify the historical climate to produce wet, median and dry 2030 climate scenarios based on CSIRO's South West Sustainable Yields Project. More details on the above five climate scenarios and the impact on surface water resources, GDEs and divertible yields can be found in CSIRO (2009a, b and c), Silberstein *et al.* (2012), Ali *et al.* (2012a), Barron *et al.* (2012) and McFarlane *et al.* (2012). Sustainable yields projects have also been carried out in the Murray Darling Basin, Tasmania, Northern Australia and the Great Artesian Basin but not all included future projections of groundwater levels.

### **1.3 Cause of the Hazard**

Identifying the cause of the hazard is an important step for management as it identifies opportunities to remedy the problem. This is especially true of secondary hazards, which may not have been recognised as part of the problem, but where they are alleviated can reduce stress on the GDE and provide greater resilience to climate change.

#### **1.3.1 Primary Hazard**

The main causes of groundwater level decline are climate change, human use of water e.g. groundwater extraction, land use and land management changes (Example 5). It is likely that a combination of these factors is responsible but in many instances anthropogenic effects can be the main driver.

Example 6 shows how cumulative rainfall departure from the mean analysis can be used to determine causality of groundwater decline. Where extraction, land use and/or land management are the main cause of groundwater decline, direct intervention can reduce the impact of the hazard on GDEs. This in turn will reduce the vulnerability of the ecosystems to climate change.

**EXAMPLE 5: Cause of groundwater decline in the Gngangara Groundwater System (GSS), Western Australia.**

The Gngangara Groundwater System (GGS) is a complex, multi-layered system which consists of three different aquifers (Figure 8). The Gngangara Mound or the superficial aquifer is the unconfined surface layer, which supports the GDEs. Underlying the superficial aquifer are two confined aquifers - the Leederville and Yarragadee. The northern region of the GGS is the main source of groundwater recharge to these confined aquifers because there is no confining bed between the superficial aquifer and the underlying aquifers. The GGS is an important water source for human use. It supplies water to the Perth metropolitan region and is used for irrigation, mainly in agriculture. It is also an important resource to groundwater dependent wetlands and their associated biota. Wetland and groundwater levels have declined in the region since 1974 (Gngangara Sustainability Strategy 2007). To quantify and determine the main causes of groundwater decline, groundwater hydrographs were compared with cumulative deviation from mean rainfall (CDFM –see Example 6 below for more detail). From this analysis three main causes of groundwater decline were identified: reduced rainfall, groundwater extraction and pine plantations (Yesertener 2008).

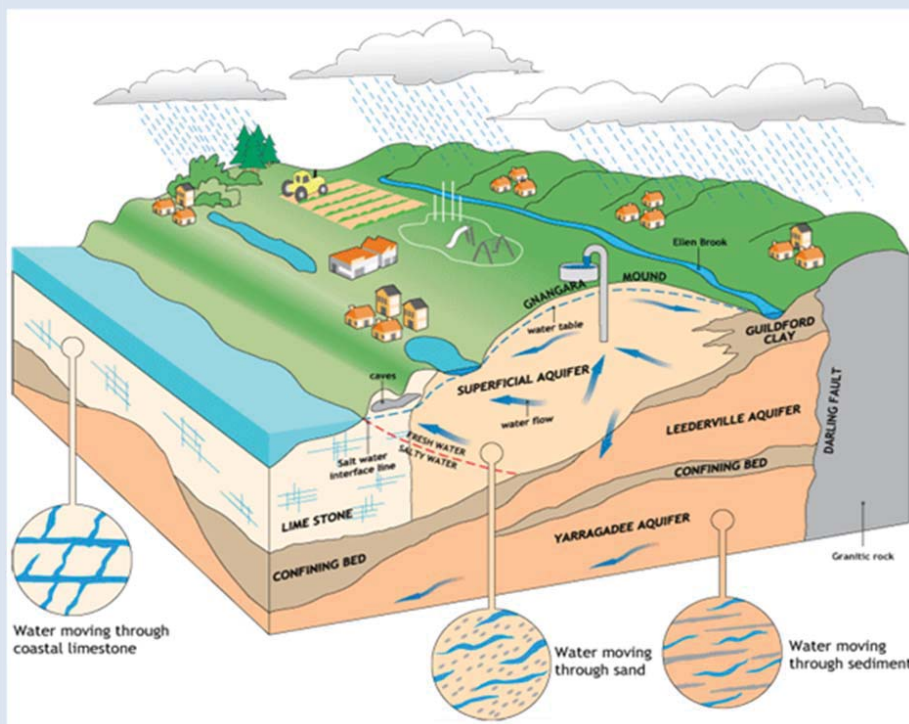


Figure 7: The Gngangara groundwater system in south Western Australia, with the hydrogeology, land-use types and groundwater abstraction illustrated. It is a complex, multi-layered system which consists of three different aquifers - the Gngangara Mound, the Leederville and the Yarragadee aquifers. Source: Gngangara Sustainability Strategy (2007).

**Reduced rainfall:** two periods of rainfall were identified, a wet period from 1915-1968 and a dry period from 1969-2001. A 10-16% decline in rainfall and consequently recharge was observed during the dry period. This was identified as the main cause of groundwater decline in the Gngangara Mound and resulted in reduced groundwater levels of up to 4m from 1979–2005 (Yesertener 2008).

**Groundwater extraction:** The Gngangara groundwater system contributes a significant water resource to the Perth Metropolitan water supply. Declining groundwater levels within the Gngangara Mound were due to direct extraction of groundwater from the superficial aquifer as well as abstraction from the underlying Leederville and Yarragadee Aquifers. The cumulative impact of extraction from the superficial aquifer and the confined aquifer was determined to be a groundwater decline of up to 3m from 1997-2005 and in some areas contributed to ~60% of the overall groundwater decline. The impact on groundwater levels can extend as far as 6kms from the abstraction point (Yesertener 2008).

**Land-use and management changes:** The primary land use change that impacted the Gngangara Mound was due to planting of pines for forestry products. Initially pine plantations resulted in a rise in groundwater levels due to the clearing of native vegetation. Once the plantations began maturing, they caused reduced groundwater recharge through evapotranspiration and interception of rainfall. The impact that they had on groundwater levels depended on the density of the stands. In areas managed at high density there was a moderate to high impact on groundwater levels, resulting in declines of 3.5m from 1979-2005. In areas where there was low density there was no impact on groundwater levels when compared with the native vegetation control area. Removal of pine plantations was shown to cause up to a 2m rise in groundwater levels in some areas (Yesertener 2008).

### EXAMPLE 6: Identifying the cause of the hazard in the Leeuwin Naturaliste Ridge Cave System, Western Australia.

In the Leeuwin Naturaliste Ridge Cave System, the cause of groundwater decline was investigated through Cumulative Rainfall Departure (CRD) analysis (Figure 8). This provides an excellent analysis of whether the declining groundwater is due to declining rainfall (climate change) or another cause. In this instance, the simulated groundwater level (based on the relationship between rainfall and groundwater level) shows a different pattern to what has actually been measured/exhibited in Jewel Cave. When compared to changes in land use and management in the Jewel-Easter catchment and cave system between 1958-present, it is evident that land use changes are likely to be the main cause of groundwater drawdown. This provides an excellent prognosis for managing the system as anthropogenic changes such as land use are far more easily rectified than changes due to climate change.

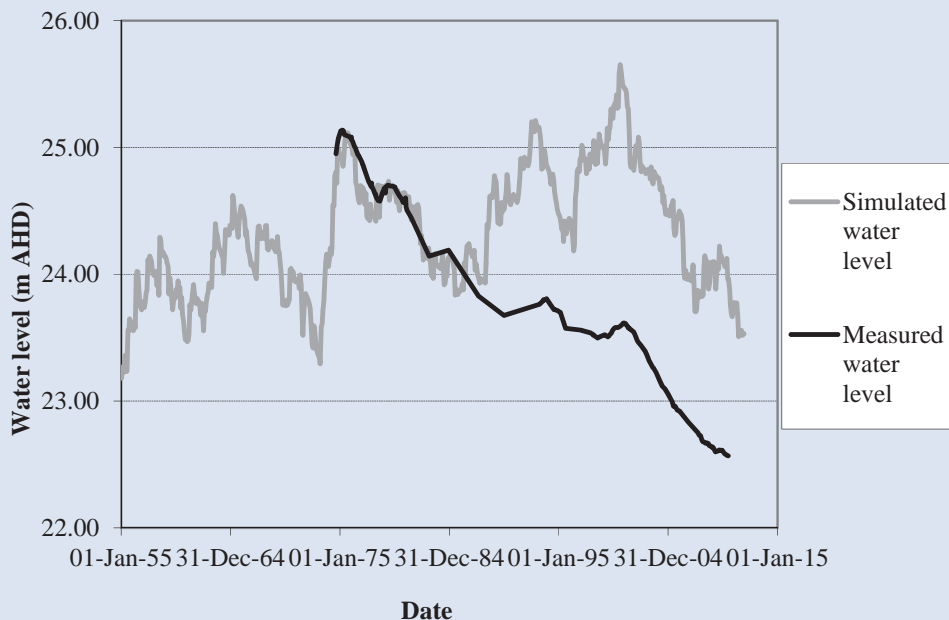


Figure 8: Jewel Cave Cumulative Rainfall Departure (CRD) diagrams displays measured groundwater levels in Jewel Cave compared with simulated levels according to climatic data (Data source courtesy, Steve Appleyard).

#### 1.3.2 Secondary Hazard

By definition, the cause of the secondary hazard is the primary hazard (see Example 3 for cause and effect relationships). However once the secondary hazards have been identified it is frequently the case that human factors exacerbate the problem. For example, reduced water levels may cause an increase in nutrient concentrations through evapoconcentration but nutrients might also be sourced through surface water runoff from surrounding urban or agricultural land use. Identifying other sources that contribute to the secondary hazard provide an opportunity to alleviate the secondary hazards through reducing the anthropogenic stressors.



## 2. Step 2: Determine exposure and vulnerability

Having identified the hazard, this step quantifies the likely distribution and level of impact of groundwater level decline on GDEs in the study area (Figure 9). To ascertain exposure and vulnerability of GDEs the spatial and temporal change of groundwater levels will need to be determined e.g. the magnitude and rate of groundwater decline. The dynamics of hydrological change, such as changes in seasonality and/or the number and frequency of dry periods, are also considered.

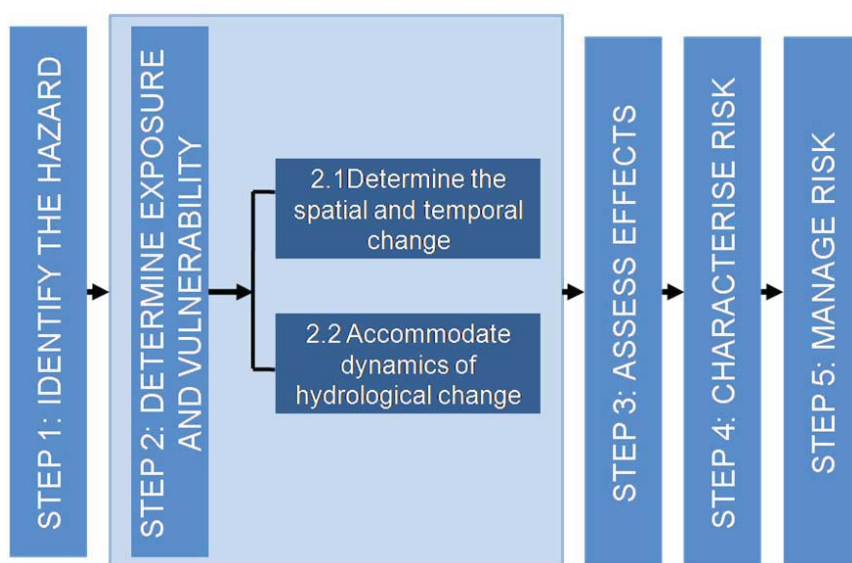


Figure 9: The steps involved to determine the exposure and vulnerability of the study area to groundwater decline.

### 2.1 Determine the Spatial and Temporal Extent of Change

From your understanding of the inputs and outputs of water developed in the hydrogeological conceptual model created in Part 1, the spatial and temporal changes in water level in your GDE can be determined. Where GDEs are a surface or sub-surface expression of groundwater, this can be determined through measurement of changes in groundwater level.

What evidence do you have of changes to groundwater levels? Past and current data indicating change may be available from groundwater bores or may be inferred from changes in groundwater expression in GDEs (e.g. maximum water level marks on remnant vegetation in wetlands, inundated tree trunks) as well as groundwater levels stored in state water manager's databases (e.g. Department of Water's Water Information (WIN) database in WA). Collate the evidence you have of groundwater change both spatially and temporally in your study area. Changes in rainfall and temperature (relevant to assessing rates of evapotranspiration) are available from the Bureau of Meteorology website.

Future changes to groundwater levels are more difficult to determine. In the south-west of Western Australia (and the Great Artesian Basin) CSIRO have conducted

Sustainable Yields Projects which discuss current trends in surface water (CSIRO 2009a) and groundwater yields (CSIRO 2009b) and project future yields. Sustainable Yields projects have also been carried out in other regions of Australia to varying extents. An example of the scenarios available from the CSIRO Sustainable Yields Projects can be seen below (Example 7). Where these are not available estimating future groundwater levels can be done by several methods:

1. Where data exists that enables a groundwater hydrograph to be drawn, simple extrapolation of past trends may be possible. This assumes that the future climate and extraction will be similar to that in the past, which may be optimistic given that most systems are coming under increasing development pressure and future climates are likely to be warmer, even if future rainfalls are less well known.
2. If both rainfall and groundwater level data are available a relationship between them can be established using the HARRT technique (Ferdowsian *et al.* 2001; Ferdowsian and McCarron 2001). This method is useful where rainfall is the only factor affecting levels (i.e. pumping and land uses are stable) and there is an annual response to rainfall (i.e. it is unsuited to confined aquifer systems or ones where recharge is lost to drainage or significant evaporation). Once a relationship has been established for a historical period, it is possible to apply future wetter or drier rainfalls to assess how they may affect future levels (e.g. CSIRO 2009b).
3. Groundwater models use data on aquifer properties, rainfall, potential evaporation, abstraction and drainage to reproduce water fluxes and storages (levels) for aquifer systems over time. These are most suited to estimating future levels by imposing different future climate conditions, including those generated from Global Climate Models. This is the system that was used in the Gngangara and Blackwood River case studies in this framework.

#### **EXAMPLE 7: CSIRO Sustainable Yields Project in the south west of Western Australia**

Estimates for south west Western Australia were made under six climate and development scenarios, using existing groundwater flow models – Perth Regional Aquifer Modelling Systems (PRAMS) and the South West Aquifer Modelling Systems (SWAMS) (CSIRO 2009b). These climate change and development scenarios were:

- Scenario A: 2030 projections based on extension of the 1975-2007 period and current development (i.e. abstraction and landuse unless known to change).
- Scenario B: 2030 projections based on extension of the 1997-2007 record and current development.
- Scenario C: 2030 projections using wet, median (mid) and dry global climate model climate change scenarios and current development.
- Scenario D: Projections into 2030 under the CMid climate change scenario and abstraction taken out to the maximum limit

Change in groundwater levels can be mapped using GIS to give a spatial distribution. Where there is sufficient data and knowledge of the groundwater system, temporal change can be shown by a series of maps for different years and discrete time intervals with projections into the future, as shown in Example 8. A number of parameters can be used to characterise spatial and temporal change including the extent (or magnitude) of groundwater decline over time, the rate at which this decline occurs and the dynamics of hydrological change, such as changes in seasonality and/or the number and frequency of dry periods.

### ***2.1.1 Determine the Magnitude of Groundwater Decline***

Mapping of the magnitude of groundwater decline over time will indicate the level of risk to GDEs in your study area (Example 8). The magnitude of groundwater decline needs to be considered in relation to the depth at which groundwater and surface water interact. Groundwater level declines below this level will mean surface expression of groundwater (the type of GDE encompassed by this framework) will cease. Adaptation at this point will mean assessing whether rainfall, surface water inputs or modifications to the ecosystem (e.g. artificial perching) can retain the ecosystem.

Alternatively, if you cannot project changes to groundwater then the framework can use scenarios based on groundwater levels e.g. what would happen to the ecosystem if the groundwater declined 1m or 2m?

**EXAMPLE 8: The magnitude of groundwater decline** was projected into 2030 under a range of climate change and land use scenarios for the Gnangara Mound, Western Australia (Figure 10). These projections were made in the South West Sustainable Yields Project and are based on the PRAMS groundwater model (CSIRO 2009b).

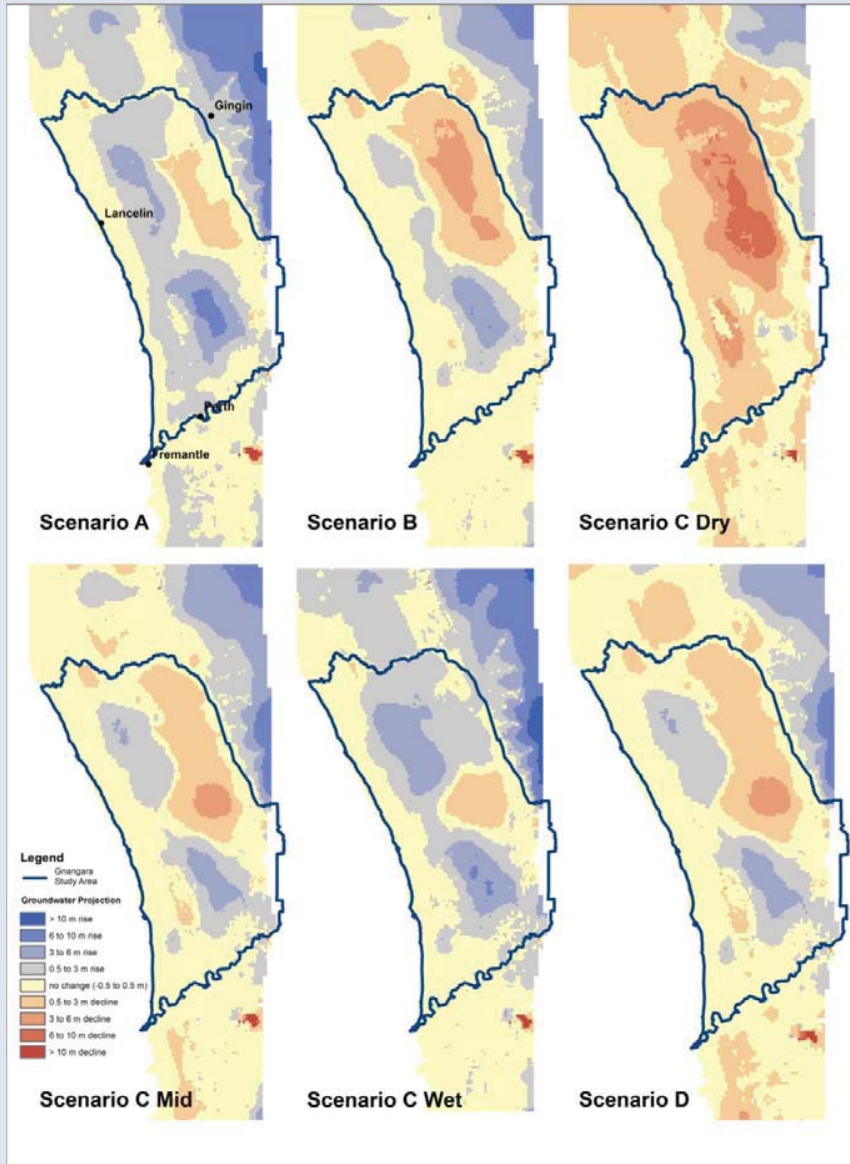


Figure 10: An example of magnitude of groundwater level change. The magnitude of groundwater decline has been projected into 2030 under a range of climate change and land use scenarios for the Gnangara Mound, Western Australia. These projections were made in the South West Sustainable Yields Project and are based on the PRAMS groundwater model. Scenario A: 2030 projections based on extension of the 1975-2007 period and current development (i.e. abstraction and land use unless known to change). Scenario B: 2030 projections based on extension of the 1997-2007 record and current development. Scenario C: 2030 projections using wet, median (mid) and dry GCM climate change scenarios and current development. Scenario D: Projections into 2030 under the CMid climate change scenario and abstraction taken out to the maximum limit (CSIRO 2009b). Note: groundwater level declines in some areas and rises in others.

### **2.1.2 Combine Groundwater Decline and Surface Proximity**

An alternative technique to assess risk is to undertake simple assessment of the groundwater level change projections based on existing groundwater levels. Previous studies in the Gngangara Mound (Froend and Loomes, 2004, Sommer and Froend 2010) as well as the analysis carried out in the current project (SD2 Sommer *et al.* 2013) have identified the importance of the proximity of the groundwater level to the surface in determining the sensitivity of the GDE to groundwater level changes (Example 9). The same studies identify that the amount (and by definition the rate) of groundwater change over time is also important.

Neither the rate of change or the depth of the groundwater level by itself will be a good indicator of risk: high levels of change in deep groundwater levels are unlikely to impact on GDEs, if the groundwater is beyond any rooting depth or surface or subterranean hydrological impact. Alternatively, shallow water tables are not an issue if there is no projected decline into the future.

It is possible to combine these two factors – depth to groundwater and projected groundwater decline – in a simple weighted assessment. The assessment has been called the Simple Risk Assessment (SRA) (SD7 Neville 2013) and is an adaptation of a technique developed by Froend and Loomes (2004) to estimate risk of groundwater decline on vegetation.

The technique requires that existing values for depth to water table or projected change to be classified, and each class rated in terms of its perceived contribution to risk of change.

**Example 9: A simple impact assessment** for combining surface proximity (Table 1) and groundwater decline (Table 2) for the Gngangara Mound projected into 2030 under a range of climate change and land use scenarios for the Gngangara Mound, Western Australia (Figure 11). These projections were made in the South West Sustainable Yields Project and are based on the PRAMS groundwater model (CSIRO 2009b).

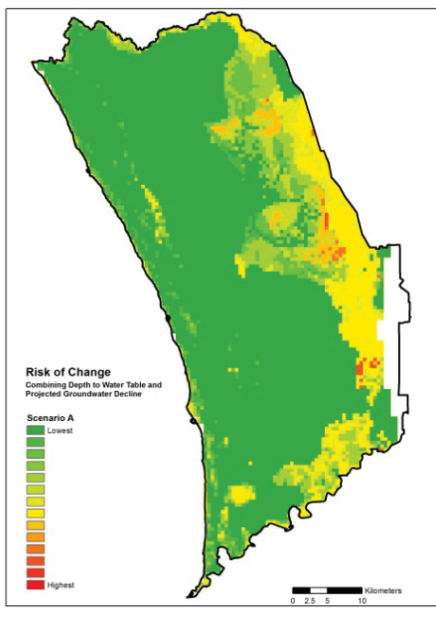
In this example (SD7 Neville 2013), groundwater depths less than 5m are rated as having the highest contribution (8-10) to impact, and depths below 20m rated with no contribution (Figure 11). A projected groundwater decline of more than 0.5m is rated as having the highest contribution (8-10) and a rise of more than 0.5m rated as having no contribution (Figure 11). The example shows ratings that are indicative and illustrative only.

**Table 1: An example of giving depth to water table contributions of impact (ratings are indicative and illustrative only) on the Gngangara Mound.**

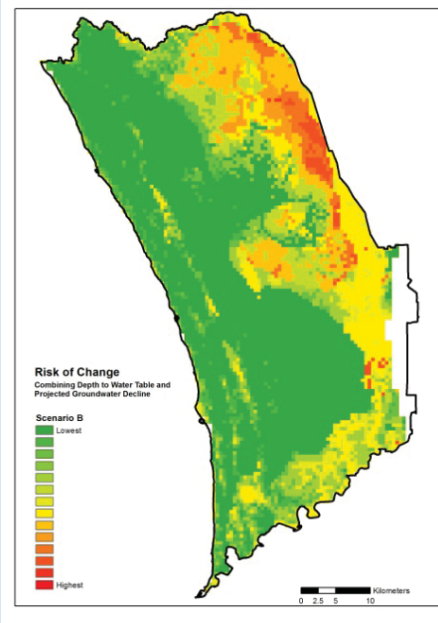
Input raster	
PRAMS 2007 DWT Max Ht	
Reclass field	
Value	
Reclassification	
Old values	New values
-149.824 - 0	10
0 - 2.5	10
2.5 - 5	9
5 - 10	5
10 - 15	2
15 - 20	1
20 - 30	0
30 - 50	0

**Table 2: Projected groundwater change for the Gngangara study area.**

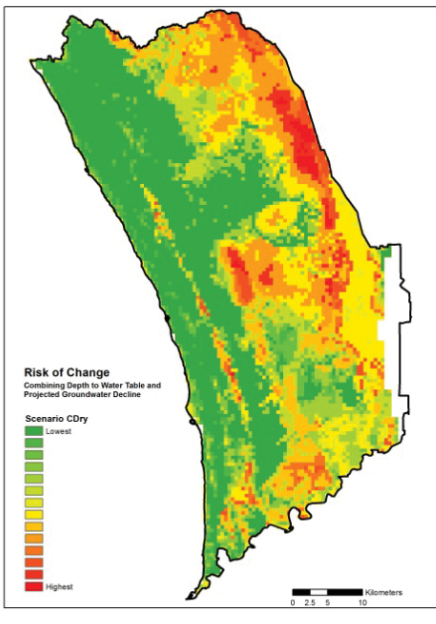
Input raster	
Input GWchange2030 Scenario	
Reclass field	
Value	
Reclassification	
Old values	New values
-17.486 - -10	10
-10 - -6	10
-6 - -3	10
-3 - -0.5	8
-0.5 - 0.5	2
0.5 - 3	0
3 - 6	0
6 - 10	0



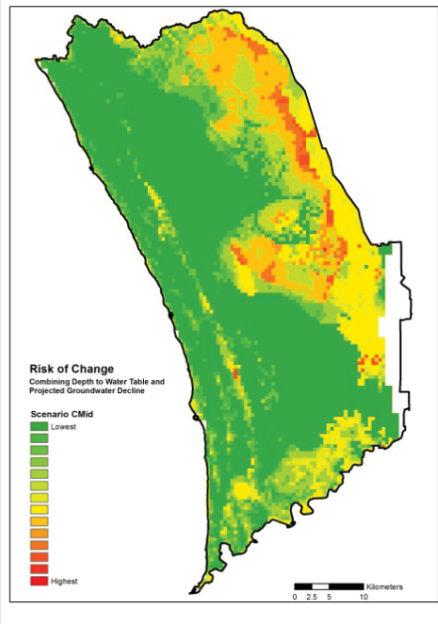
Scenario A



Scenario B



Scenario CDry



Scenario CMid

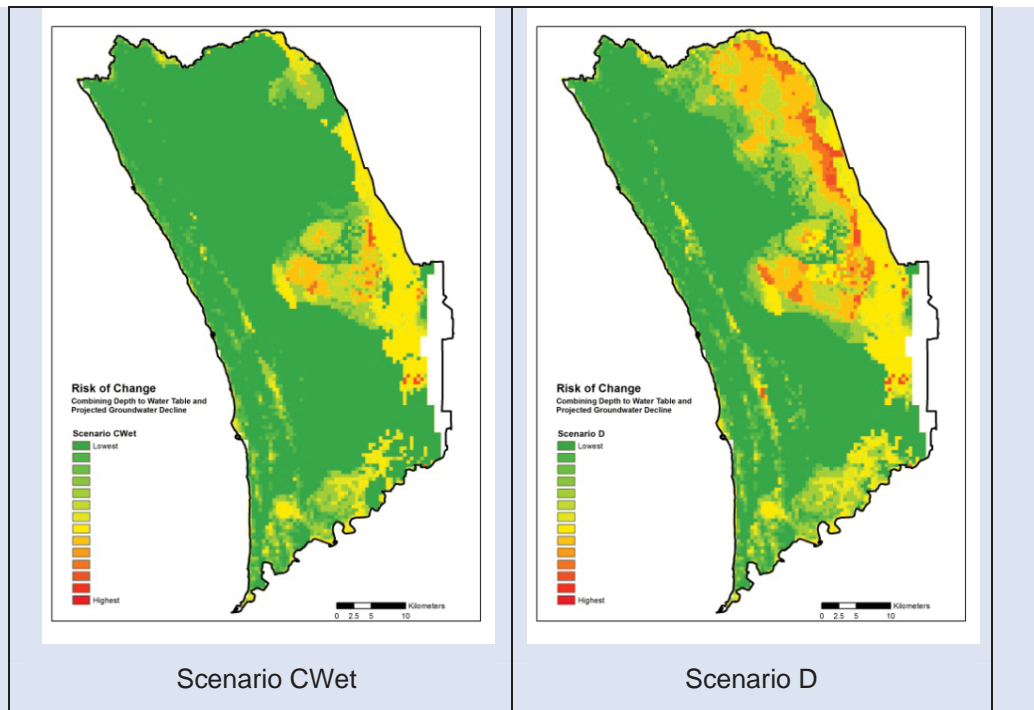


Figure 11: An example of Simple Impact Assessment maps, combining groundwater decline and surface proximity for the Gngangara Mound Study Area. The maps identify areas that may be expected to suffer the greatest impacts from groundwater decline. The projections were made in the South West Sustainable Yields Project and are based on the PRAMS groundwater model. Scenario A: 2030 projections based on extension of the 1975-2007 period and current development (i.e. abstraction and landuse unless known to change). Scenario B: 2030 projections based on extension of the 1997-2007 record and current development. Scenario C: 2030 projections using wet, median (mid) and dry GCM climate change scenarios and current development. Scenario D: Projections into 2030 under the CMid climate change scenario and abstraction taken out to the maximum limit (CSIRO 2009b).

### 2.1.3 Determine the Rate of Groundwater Decline

While the magnitude of groundwater level decline is important, so too is the rate of decline. Slow changes provide time for the ecosystem to adapt, while rapid decline may exceed the plants' and animals' ability to respond and result in the death of organisms. Rapid groundwater level decline can also result in rapid changes to water quality e.g. increasing temperature, concentration of salts.

Rate of decline can simplistically be measured by dividing the magnitude of decline by the time period it is observed or projected. Once again, if information is not available to do this you may use 'what if scenarios' of different rates to determine potential ecosystem outcomes. Below is an example of spatially displaying the rate of groundwater decline (Example 10).



**Example 10: The rate of groundwater decline** was projected into 2030 under a range of climate change and land use scenarios for the Gnamagara Mound, Western Australia (Figure 12). These projections were made in the South West Sustainable Yields Project and are based on the PRAMS groundwater model (CSIRO 2009b).

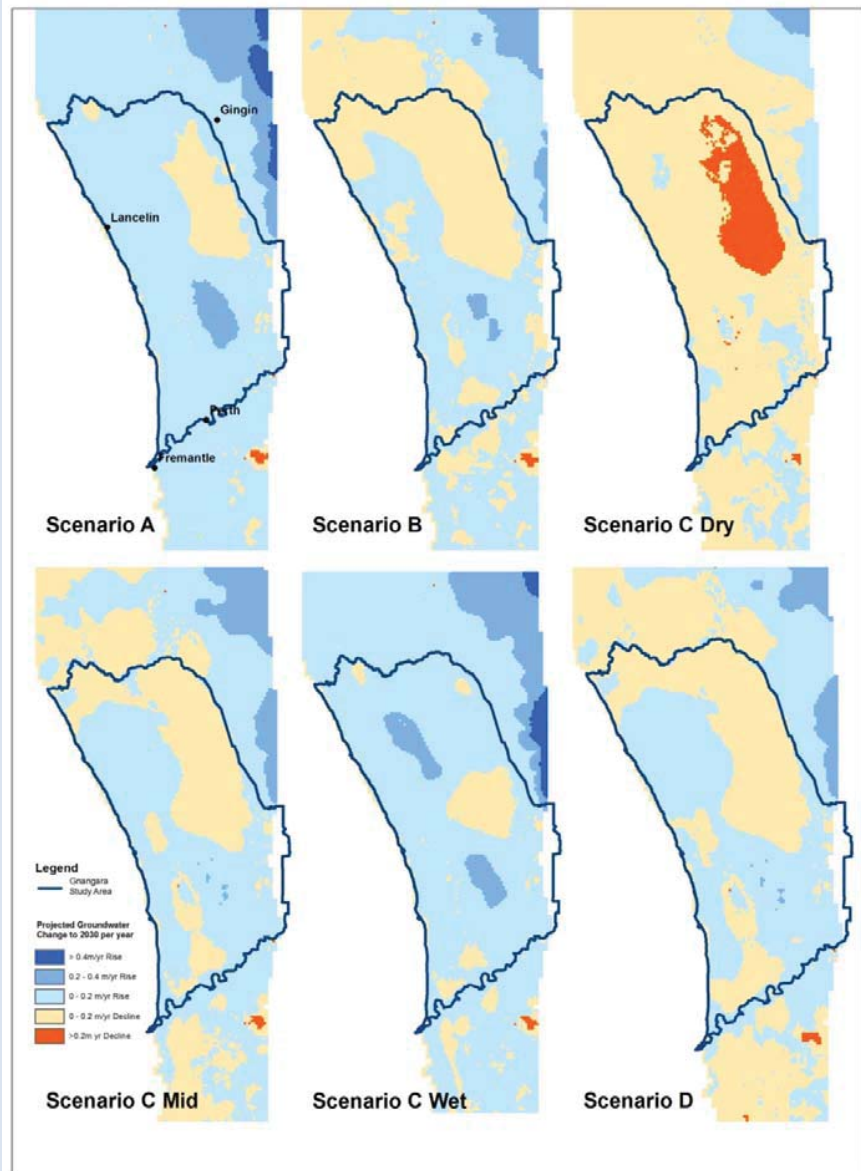


Figure 12: An example of rate of groundwater decline (m/year), projected into 2030 under a range of climate change and land use scenarios for the Gnamagara Mound, Western Australia. These projections were made in the South West Sustainable Yields Project and are based on the PRAMS groundwater model (CSIRO 2009b). Scenario A: 2030 projections based on extension of the 1975-2007 period and current development (i.e. abstraction and land use unless known to change). Scenario B: 2030 projections based on extension of the 1997-2007 record and current development. Scenario C: 2030 projections using wet, median (mid) and dry GCM climate change scenarios and current development. Scenario D: Projections into 2030 under the CMid climate change scenario and abstraction taken out to the maximum limit. Note: groundwater level declines in some areas and rises in others.

## **2.2 Accommodate Dynamics of Hydrological Change**

It is important to consider that the drying trend we note for declining groundwater levels is often calculated as the mean of a variable system. The experienced change into the future is not likely to be steady. As occurs now, there will be wet and dry years and episodic events. These events may have a greater individual impact than the mean decline and must be considered (see SD3 Nugent *et al.* 2013). Biotic response to change is often not linear but can take the form of a threshold, hysteresis or irreversible change (see SD3 Nugent *et al.* 2013 pp.22-25).

While it is not possible to predict timing or the magnitude of these events, one way in which it can be accommodated is to consider the response to the longevity and/or frequency of drying events in a GDE (days, months, years) and/or the number of days a GDE is dry (has no surface water) in a year. As noted in the effects assessment below, this is primarily tied to the capacity of the plants and animals to fulfil their life cycle requirements during the period of available water, the persistence of resting stages (such as seeds, eggs and cysts) under dry conditions and the capacity of biota in nearby refuges to recolonise the area.

Where groundwater levels are at the surface and groundwater dependent lakes and rivers have surface water expression, rainfall may be lost through drainage and evapotranspiration rather than recharge the aquifer. This is often called 'rejected recharge'. It is possible for annual rainfalls to decline and for groundwater levels to remain high, provided annual rainfall is enough to recharge the aquifer and maintain surface water expression. The reduction in rainfall is offset by less drainage and evapotranspiration. Once rainfall fails to recharge the aquifer, groundwater levels will decline. The further they decline below the soil surface, the less the drainage and evapotranspiration losses will become and any reduction in rainfall will be directly reflected in a declining groundwater level. Thus a full aquifer system may appear buffered against initial declines in rainfall but be sensitive once levels have fallen, especially when they fall below the root zone of phreatophytic plants. Therefore the status of the aquifer system can determine how it will respond to a change in rainfall and/or a rise in temperatures in a non-linear manner.

One of the most common parameters monitored in GDEs with a surface water expression is water level. These data can be used to create a hydrograph to determine past drying events and their frequency, to which the biota have adapted (illustrating the hydroperiod of the system – the frequency and duration of inundation). An example for this is given in two wetlands in Western Australia (Example 11).

**EXAMPLE 11: Using hydrographs to accommodate dynamics of hydrological change**

Figure 13 illustrates a hydrograph for Thomson and Forrestdale Lakes. This figure illustrates the frequency and variability of past drying periods. Projections of groundwater levels might be used to assess the likely change to this hydroperiod, based on the relationship between surface and groundwater levels determined for a GDE. A graph such as this can be used to determine the frequency and/or longevity of periods when the wetland is dry (no surface water expression). This can provide information on the number of dry days in the conceptual model for the Gngangara Mound wetlands shown in Example 14. This can later be related to biotic temporal requirements for surface water e.g. getting through stages of a life cycle.

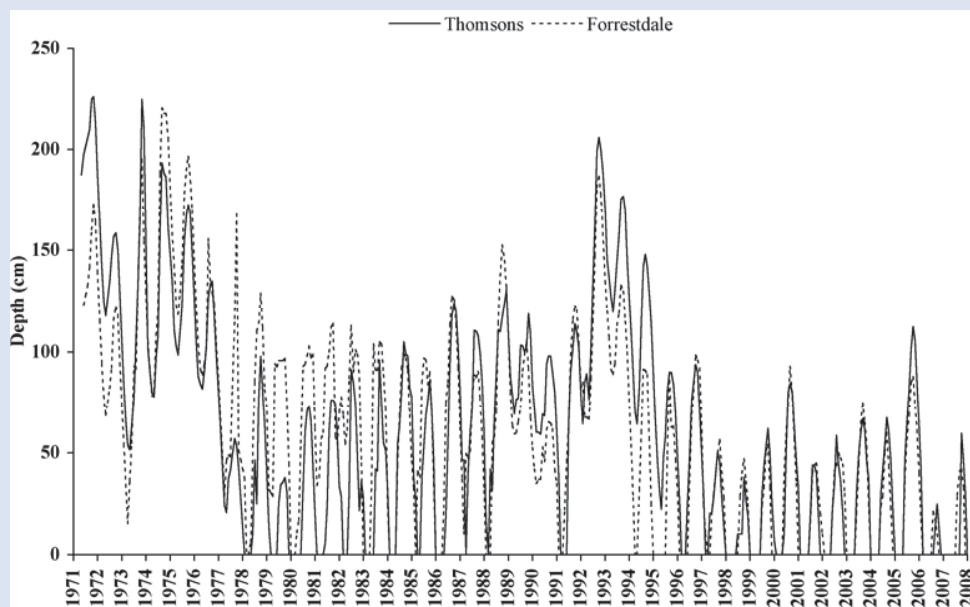
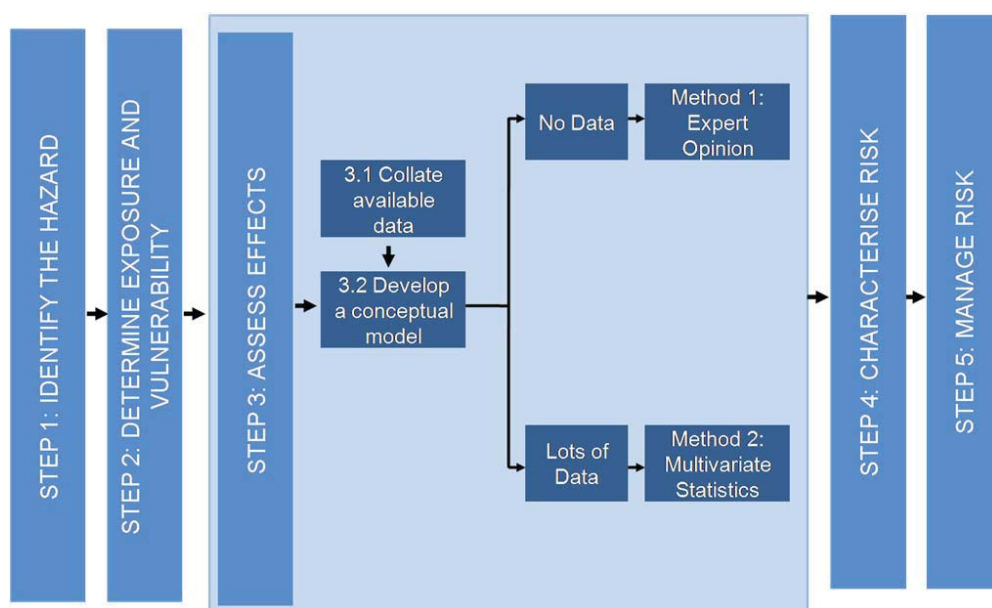


Figure 13: Hydrograph for Thomson and Forrestdale Lakes from January 1971 to January 2008 (source: WA Department of Water).

### 3. STEP 3: ASSESS EFFECTS

This step of the framework determines the effect of declining groundwater levels and associated water quality on biota (Figure 14). To determine risk, it is essential to understand the relationships between hydrology, water quality and the resource requirements of biota under conditions of declining groundwater level. This can be done through developing a conceptual model. To determine the nodes of the conceptual model, the key parameters that drive ecosystem change need to be identified. This is done using two methods 1) expert opinion and 2) multivariate statistics, depending on the level of data available (Figure 14).



**Figure 14:** To assess the effects that declining water levels and associated water quality decline have on the biota of your study area a conceptual model will need to be developed. The conceptual model is based on the ecosystem drivers that affect the biota. The method for determining the key drivers depends on the availability of data - Method 1 requires no data and Method 2 requires lots of data. A combination of the two methods can be used if a moderate level of data is available.

#### 3.1 Develop a Conceptual Model

Conceptual models are a useful tool for visualising how an ecosystem works and provide a synthesised diagram of the major ecosystem components and their interactions. They are useful for showing likely ecological responses to multiple anthropogenic and natural stressors and can be used to predict the consequences of future change such as management intervention or climate change. They ensure that all parties managing a system have the same level of understanding of ecosystem structure and function. Through the construction of conceptual models managers and researchers can identify knowledge gaps that need to be addressed (Richardson *et al.* 2011).

The type of conceptual model you choose depends on the management question. If your focus is on a species or a group of species with similar requirements for survival, then the focus of the conceptual model will be on the key climatic, hydrological,

physiochemical and other resource requirements of the biota (Example 12 and 13). If the management focus is on determining how an entire ecosystem is likely to be impacted by climate change then the same elements (climatic, hydrological, physiochemical and other resource requirements) are considered for the whole ecosystem (Example 14).

**Example 12: Conceptual model developed for species of biota**

This conceptual model of a base-flow river GDE was developed to determine how declining groundwater levels will impact freshwater fish in the Blackwood River GDE (Figure 15). To develop this conceptual model we consulted Dr Stephen Beatty who is familiar with the seasonal fluctuations of groundwater, the key drivers that effect the Blackwood River fish and their required water quality and biotic resources.

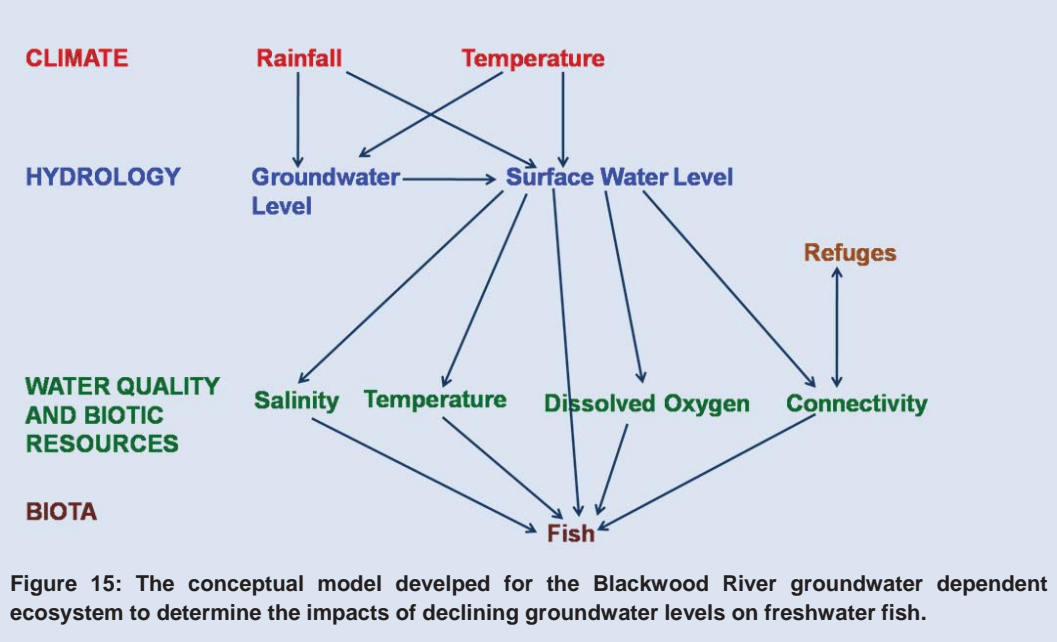


Figure 15: The conceptual model developed for the Blackwood River groundwater dependent ecosystem to determine the impacts of declining groundwater levels on freshwater fish.

**3.1.1 Collate Available Data**

To populate the conceptual model you need information on climate, hydrology, water quality, biotic resources and biota. Data can be sourced from published studies, experts, local landholders and organisations (e.g. consultants, universities, government departments).

Relevant data includes:

- Previous information from Step 2: Exposure and Vulnerability
- General information: soil type, position of open water, vegetation, land-use
- Physicochemical parameters: pH, nutrients, dissolved oxygen, conductivity, soil moisture etc.
- Biota: presence/absence, diversity, abundance

### **3.1.2 Methodologies Based on Different Data Availability**

Conceptual models can be developed in different ways depending on the amount and type of data available. Conceptual models can become very complex. It is important to keep the models simple and identify only the key drivers that effect ecosystem change. We have identified two methods to do this. Method 1 was developed where little data was available to undertake statistical analysis. It uses a species of interest or guild of organisms (eg organisms that require free water in their life cycle) or key, indicator or vulnerable species that will indicate levels of unacceptable change in your ecosystem. As outlined in example 13, expert opinion, information from the literature and available data can be used to determine key life cycle attributes necessary for a species to reproduce and sustain a population.

These attributes are incorporated as the key drivers in the conceptual model. The reliability of this approach is dependent on the quality of the information and/or data and the confidence in the experts available. Expert opinion can be obtained from 1 or more experts in a discussion format (as was done for Example 3.2) or a group of experts can give their opinions without discussion with others. In this case a consensus can be arrived at for each probability in each node and a standard deviation for this consensus arrived at. This provides a measure of the error involved in the estimation.

#### **Example 13: A case study using method 1**

Where limited data is available a conceptual model can be developed based on expert opinion. The life cycle of the Crawling Frog - *Pseudophryne guentheri* – was used by experts to determine the most important factors to the species survival (Figure 16). The key drivers included seasonal autumn rainfall that triggers breeding activity, winter rainfall which promotes hatching of the embryo and the wetland hydroperiod and salinity which were considered to threaten recruitment to metamorphosis in the aquatic breeding guild. These key parameters will make up the nodes of the conceptual model (Figure 17). The initial conceptual model was developed by Dr Nicola Mitchell and was workshopped by a group of people with doctoral degrees in herpetology and experience working with amphibians on the Gngangara Mound (Refer to SD 3 Mitchell *et al.* 2013, Table 2).

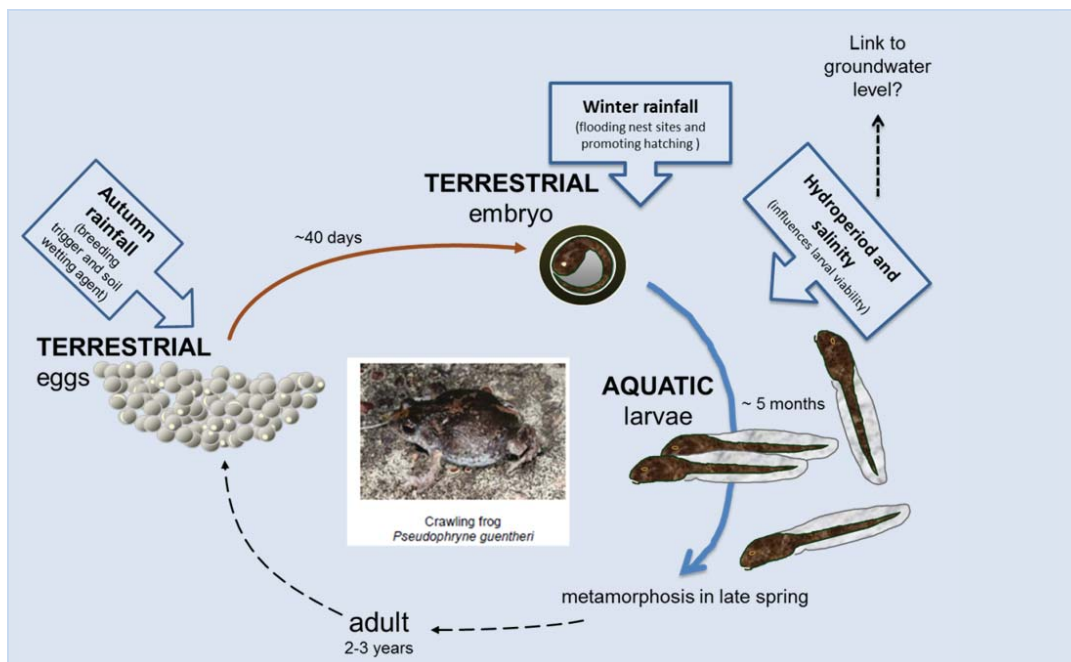


Figure 16: The life-cycle of *Pseudophryne guentheri* or the Crawling Frog was used to consider the factors most important to the species survival.

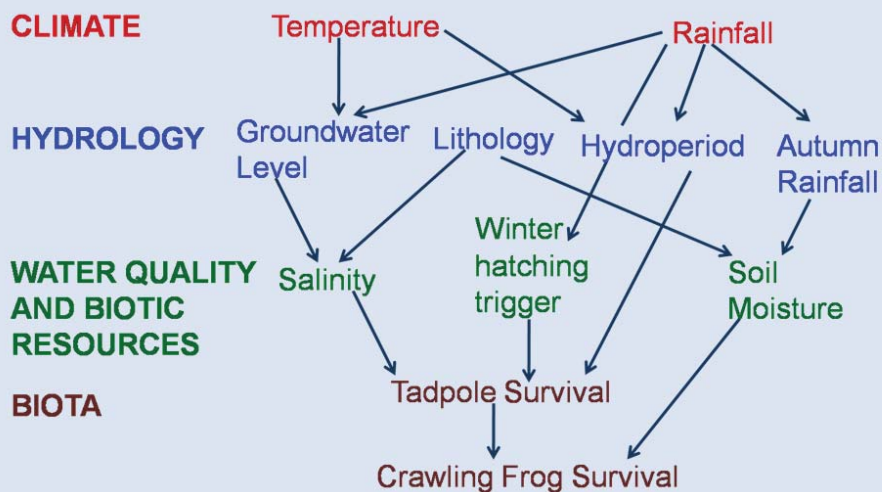


Figure 17: The conceptual model developed for the survival of the crawling frog, where the key drivers were determined through expert opinion based on the species life cycle.

Method 2 can be used where large datasets are available on hydrological, water quality and biotic components and where change has already occurred. This enables the effects of change to be identified. In Example 14 multivariate statistics are used to identify the key drivers responsible for change in the community composition of macroinvertebrates in groundwater dependent wetlands undergoing water level decline. A detailed explanation of this methodology, the suite of statistics that can be used and examples for its use on wetland macroinvertebrate and plant communities is provided in SD2 (Sommer *et al.* 2013).

These two methods are examples of appropriate methodologies at the two ends of the spectrum of data availability. They are suggested methods only and do not preclude other alternatives for assessing effects.

### Example 14: A case study using method 2

Because there was a lot of data available on the macroinvertebrates in the Gngangara Mound wetlands, multivariate analysis could be undertaken. The db-RDA analysis indicated that pH, annual maximum depth, ammonium and the number of dry days were the most important drivers of macroinvertebrate composition in Gngangara Mound wetlands (Figure 18). The key parameters identified will make up the nodes in our conceptual model (Figure 19).

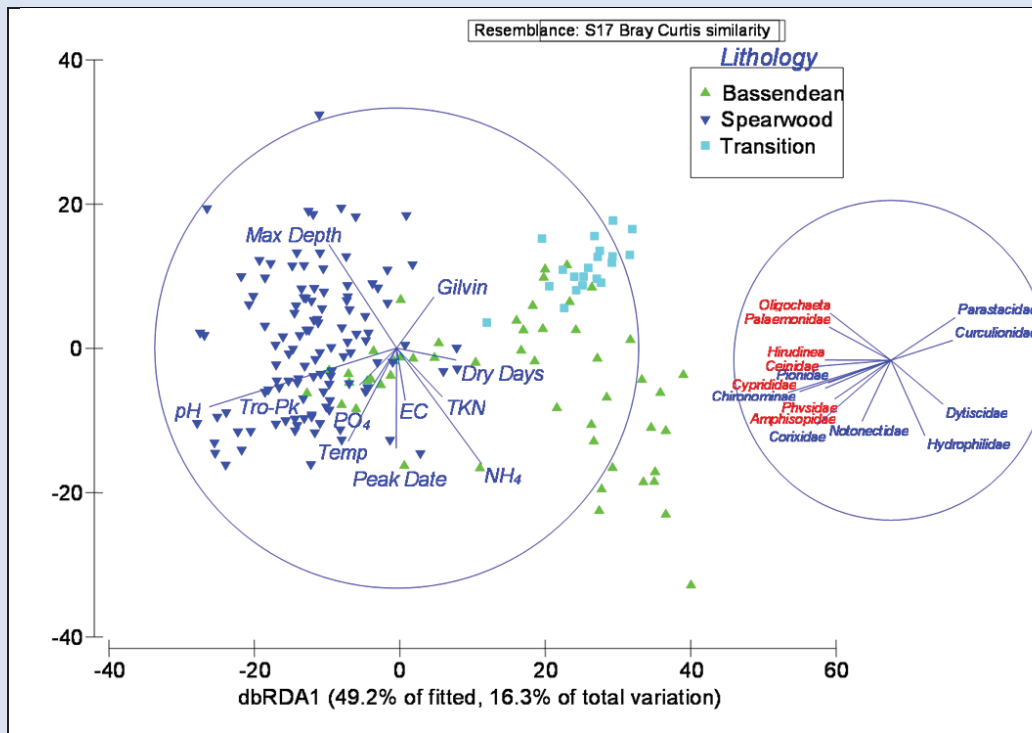
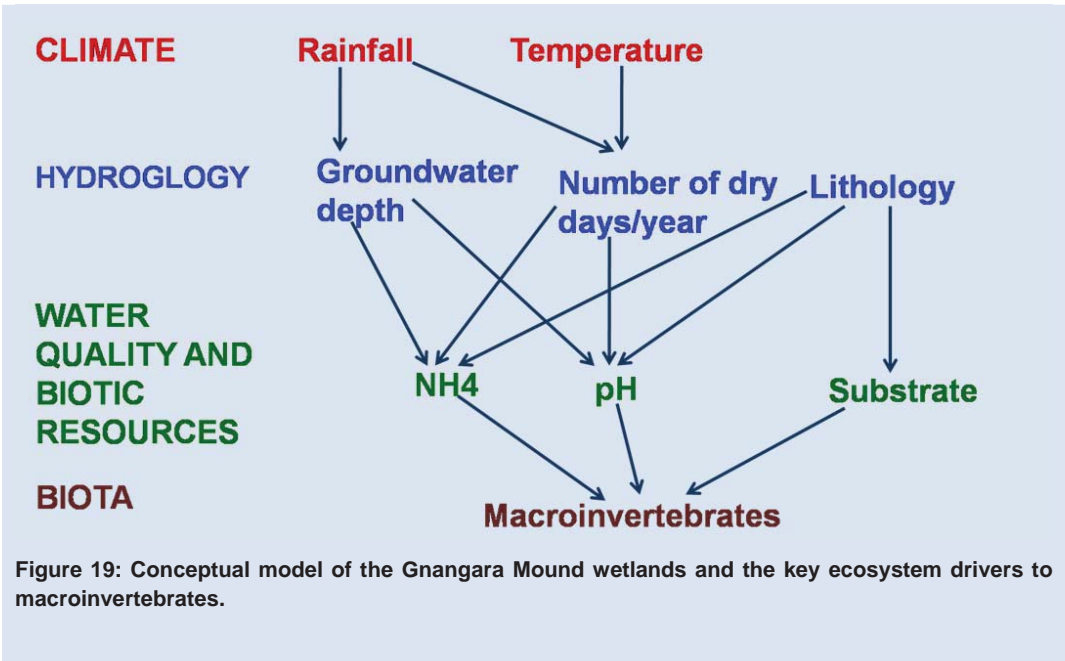


Figure 18: db-RDA biplot for spring macroinvertebrate data and hydrological and physico-chemical factors on the Gngangara Mound.





## 4. STEP 4: CHARACTERISING RISK

Risk is the chance or probability that a GDE will be harmed, or experience an adverse health effect, if exposed to a hazard. An excellent way of assessing whether the biota will be harmed is to determine their thresholds to environmental parameters that were identified as the key drivers of change (Step 3) resulting from groundwater decline. These thresholds define the boundaries of the “comfort zone” in which organisms exist. Outside these thresholds the likelihood that an adverse effect on the organism will occur increases. So the first stage in characterising risk is to identify these thresholds (Figure 20). Secondly, we need to know how the climate, hydrology, physicochemical and biotic resource requirements and the biota interact to result in change to the GDE. The conceptual model we derived in Step 3 captures these inter-relationships but now we have to quantify these interactions to see how change can affect risk to the GDEs. This is done using a Bayesian Belief Network (BBN). Finally where we have adequate data the results from the Bayesian Analysis can be represented spatially using GIS to provide a spatial risk assessment map.

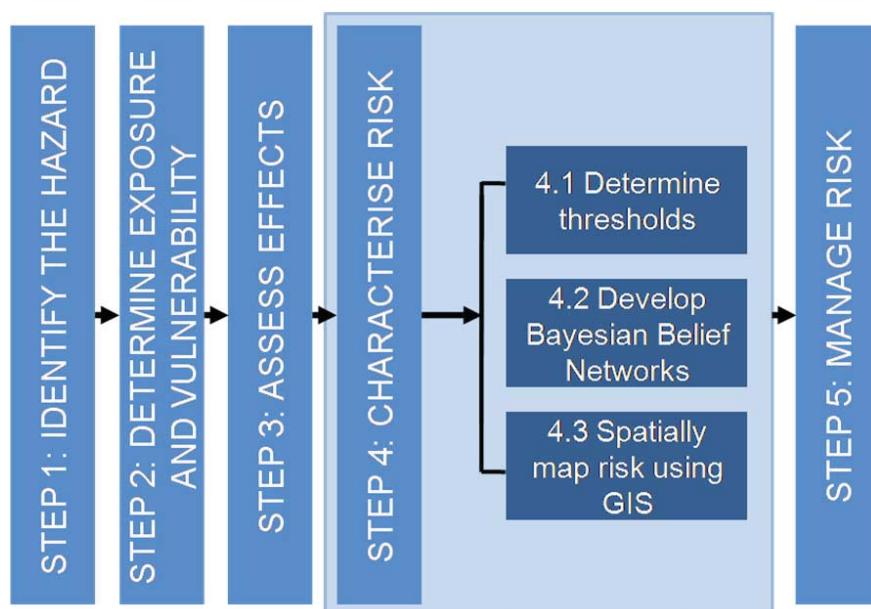


Figure 20: The steps involved in characterising risk that declining groundwater levels and associated water quality decline will have on the biota of your study area.

### 4.1 Determine Thresholds

The methodology for determining thresholds will depend on the amount and type of data available to your study area (Table 3). In this section examples are given of the various methodologies undertaken to determine thresholds based on the conceptual models derived in Step 3: Assessing Effects. Identifying thresholds may be difficult and thresholds may change in both space and time (Daily *et al.* 2012), so it is important conceptual models are kept up to date as new data becomes available.

**Table 3: The approach for determining the thresholds depends on the amount and type of available data. Brief examples of the approaches developed by the research team are given.**

Available Data	Approach	Examples	
		Approach	Study Area
None/Inadequate data	Expert opinion	Expert opinion and amphibian life cycles were used to identify resource requirements	Gnangara Mound, Western Australia Example 15
Limited data	Population distributions to identify resource requirements	Freshwater fish tolerance curves were used to determine percentiles, which can be used as surrogates for thresholds	Blackwood River, Western Australia Example 16
	Population changes over time to determine resource requirements	Using relationships between change in species community composition and hydrological parameters to determine stygofauna requirements	Leeuwin Naturaliste Ridge Caves, Western Australia . Example 17
Lots of data	Multivariate analysis	The relationship between change in species community composition and hydrological/water quality parameters were used to determine thresholds for macroinvertebrates and littoral/sub-littoral vegetation	Gnangara Mound, Western Australia Example 17.

#### **Example 15 – using life cycles to identify resource requirements**

While there may be no or inadequate empirical data on the plant and animal species in your GDE, it is likely that there is information on the life history of key species or functional groups of species. Using expert opinion, a life history diagram can identify key triggers or resources that enable a species or group to complete its life cycle (see Example 13). The biotic tolerance limits of these key variables can be used in identification of thresholds. This can be done for individual species (in the case of a threatened, keystone and/or indicator species) or for functional groups. A functional group is where species have similar hydrological or life history requirements (eg the need for open water) or a guild of species (eg fish, macroinvertebrates etc). An example of this is shown using expert opinion to determine thresholds for Amphibians on the Gnangara Mound in the Development and Case Studies document (Chambers *et al.* 2013) and further detail is outlined in the supporting document SD 3: Mitchell *et al.* (2013).

### **Example 16 – using population distributions to identify resource requirements**

In some cases, the distribution of species and/or their habitat is known. If hydrological and water quality data is available for some or all of these known locations then presence /absence can be related to hydrological and water quality variables. A review of available literature on the distribution and water quality, together with data in government, university and/or consultancies can be used to investigate this relationship. For each species, the number of occupied sites can be graphed against each hydrological or water quality parameter. This will describe the tolerance curve for the species. The median, mean, maximum, minimum for each parameter (e.g. conductivity, pH) for occupied sites can be calculated. Comparison of these tolerance curves can determine which are the key variables that influence distribution. To identify risk (Step 4.1) 5th, 25th, 75th and 95th percentiles on these graphs can be used as thresholds. An example of this is shown for fish in the Blackwood River in the Development and Case Studies document (Chambers *et al.* 2013) and further detail is outlined in the supporting document SD 4: Beatty *et al.* (2013).

### **Example 17 – using relationships between change in species community composition and hydrological/water quality parameters**

Another technique is to compare hydrological parameters with species community composition using ordination techniques (eg: Primer E Version 6). Regressions between key parameters and species diversity can also be used. A simple example of this is shown for stygofauna in the Leeuwin Naturaliste Ridge Caves in the Development and Case Studies document (Chambers *et al.* 2013) and further detail is outlined in Supporting Document 5 (Chilcott 2013).

Many multivariate statistics can be used to identify these changes including Canonical Analyses of Principal Coordinates (CAP), Distance-based Redundancy Analyses (db-RDA), Principal Component analysis (PCA) and Multivariate Regression Tree Analyses (MRT). An example of the use of these analyses is shown for fringing (emergent and dampland) vegetation and macroinvertebrates in wetlands on the Gngangara Mound: refer to the Development and Case Studies document (Chambers *et al.* 2013) and further detail is outlined in the supporting document SD 2: Sommer *et al.* (2013).

In these examples, the process of developing the conceptual model, identifying key drivers and defining the thresholds for these drivers has quantified the interrelationships responsible for ecosystem/species/community composition change. For example, in our Amphibian case study the key drivers were timing of rainfall triggers, soil moisture, hydroperiod and appropriate water quality (especially salinity). This enabled the range of tolerance of the organism(s) to these variables and identification of thresholds that could be used to describe when a species/organism/community was outside its range of tolerance. The thresholds could be used to describe the interaction between the ecosystem parameters and the target organisms. Thresholds determine the level of acceptable change and can be used to define the boundaries of tolerance. Going outside these levels of tolerance incurs a risk

that the organism/species/community will be lost. This enables us to develop a probability of risk based on the interaction of one or more variables with our target biota. An ideal framework for doing this is to turn the conceptual model into a Bayesian Belief Network.

## **4.2 Determining Probabilities of Risk: Bayesian Belief Networks**

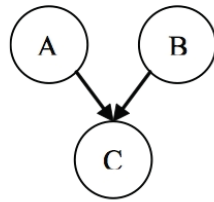
Bayesian Belief Networks (BBNs) are an excellent tool for determining the probabilities of risk to GDEs as a consequence of declining groundwater levels. BBNS were chosen because, unlike most decision support tools, they are able to incorporate both qualitative and quantitative information. They are also a useful tool for communicating the environmental issues and processes due to their visual nature. BBNs are also a valuable means of gathering additional information to feed into models or develop new models.

### **4.2.1 General Information about Bayesian Belief Networks**

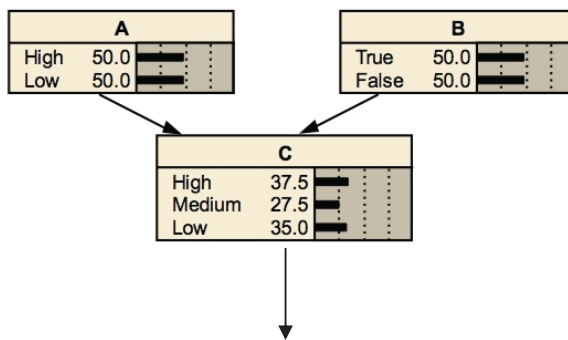
A Bayesian Belief Network is a graphical model, which can be used to establish the causal relationships between key factors and final outcomes (Hart and Pollino 2006). BBNs can provide effective decision support tools for problems involving uncertainty and probabilistic reasoning (Cain 2001). The networks 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 (Moe 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 (Moe 2010). For example in Figure 22 an example of a simple network structure can be seen where nodes A and B represent causal factors influencing the probability of C (Figure 22a). The values of the nodes are defined in terms of states (Figure 22b). A conditional probability table (Figure 22c) defines the causal relationship between A, B and C. This results in the probability of the three outcomes of C (high, medium, low) occurring.

a)



b)



c)

Node: **C**

		Chance	% Probability		
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 21: Example of a simple Bayesian Network structure (Kragt 2009).**

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 ( $p(B | A)$ ) 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 (Jensen and Nielsen 2007).

Bayesian probability theory allows the modelling of uncertainty and outcomes by combining expert knowledge and observational evidence. The probability is based on expert knowledge and 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. BBNs are generally robust to imperfect knowledge and approximate probabilities (even educated guesses) very often give very good results. However, imperfect data will have an impact on the final outcome from the model. The level of confidence in the outcome will always depend on the quality and amount of data that is used to develop the model. It is also necessary to update the BBN as new data becomes available as this may alter probabilities, which can result in major change to the structure and outcomes from BBNs.

BBNs have a number of advantages (Jakeman *et al.* 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 *et al.* 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

For the modelling of the impacts of climate change on GDEs, BBN's are an appropriate tool because:

- Knowledge of the interactions involved in GDEs is incomplete, therefore some of the processes have to be modeled using expert opinion on top of the available data, BBNs are very robust to the use of imperfect knowledge
- Much of the data on GDEs has spatial components, BBNs are composed of nodes which can incorporate separate spatial components
- 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.

For more detail the following references are available online:

- Anon: <https://www.cra.com/pdf/bnetbuilderbackground.pdf>.
- Cain 2001: <http://nora.nerc.ac.uk/9461/1/N009461BO.pdf>
- Hart and Pollino 2006:  
[http://ns1.mrcmekong.org/download/programmes/ep/Bayesian\\_Network\\_Reading1.pdf](http://ns1.mrcmekong.org/download/programmes/ep/Bayesian_Network_Reading1.pdf).

- Kragt 2009:  
[http://www.landscapelogicproducts.org.au/site/system/files/32/original/No\\_9\\_BNs\\_for\\_Integrated\\_Catchment\\_Management.pdf?1275581173](http://www.landscapelogicproducts.org.au/site/system/files/32/original/No_9_BNs_for_Integrated_Catchment_Management.pdf?1275581173)
- Marcot *et al.* 2001:  
<http://planet.botany.uwc.ac.za/NISL/Gwen's%20Files/Conservation%20Biology/Chapters/Info%20to%20Use/Chapter7/evaluateviabilityMarcot.pdf>

#### 4.2.2 How to Develop a Bayesian Belief Networks

The conceptual model of your ecosystem (developed in Part 2, section 3.1) makes up the basis of your Bayesian Belief Network. This is modified as follows:

- The key drivers identified in Step 3: Assessing Effects (Part 2, Section 3.2) will determine which nodes should be in the BBN.
- The relationship between the nodes is determined by the threshold analysis undertaken in section 4.1 (Part 2). BBNs require that the effect of each driver is compartmentalised into discrete categories, even if the natural response is continual (Example 18). This is done using the thresholds. This information can then be fed into the probability distribution table.

#### Example 18 – Using the thresholds to populate the Bayesian Belief Network probability distribution tables.

The temperature thresholds (determined through the 25<sup>th</sup> and 75<sup>th</sup> percentile of population distribution along a continuum of temperature) (Figure 22) for the Western minnow (*Galaxias occidentalis*) in south-western Australia are used to populate the BBN probability distribution table. The green bar represents favourable conditions (= low risk) while <13°C or >19°C represent unfavourable conditions (= higher risk).

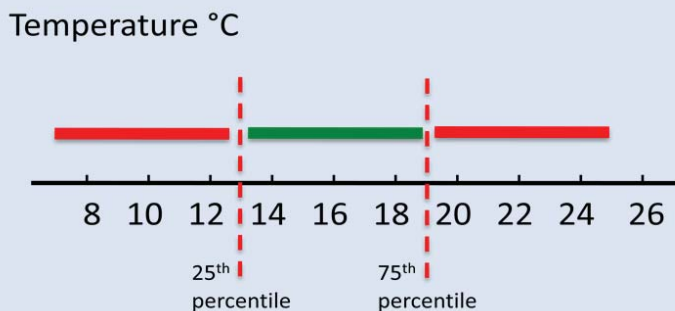


Figure 22: Discretisation of temperature using thresholds defined by the 25<sup>th</sup> and 75<sup>th</sup> percentile of population distribution along a continuum of temperature for Western minnow (*Galaxias occidentalis*) in south-western Australia. The green bar represents favourable conditions (= low risk) while <13°C or >19°C represent unfavourable conditions (= higher risk).



The Netica™ Application is the most common BBN development software. A limited version can be obtained free of charge through Norsys Software Corp (<https://www.norsys.com/download.htm>). Other BBN development software, such as Genie™ (<http://www.genie.sis.pitt.edu>) or Hugin™ (<http://www.hugin.com>) could be used.

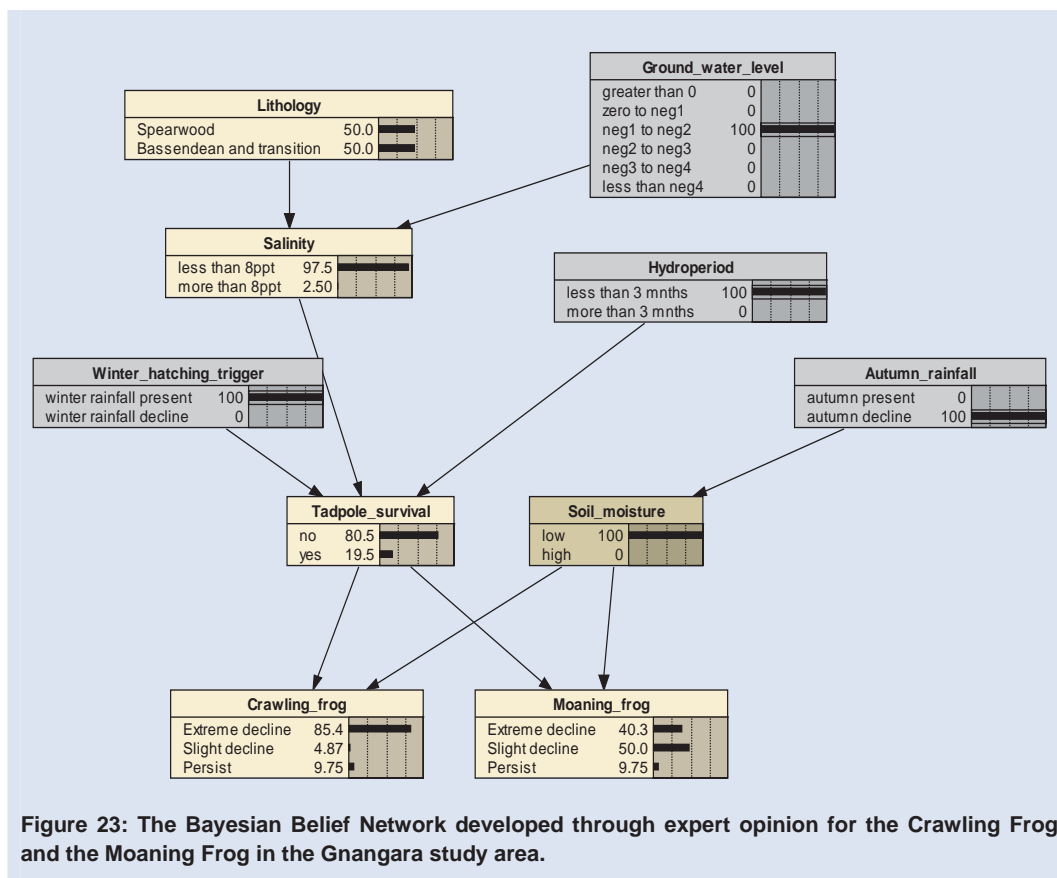
It is advised when developing BBNs to obtain advice from a BBN specialist. Once BBNs are created they are relatively simple to use and update, but correct procedure is necessary in their development to ensure meaningful outcomes. Further information on BBN development is given in Supporting Document 6 (SD6: Speldewinde 2013)

#### **4.2.3 Interpreting a Bayesian Belief Network**

An example of a BBN developed for the Amphibian conceptual model is shown in Example 19 below. Comparison of the Amphibian conceptual model (Example 13) with the BBN below shows that the same drivers are displayed at each node. However in the BBN the interrelationships have been quantified to indicate the probability of risk to amphibian survival based on whether the key drivers fall outside the limits of tolerance set by the thresholds. The grey nodes are the input variables that, through information contained in the probability distribution table, determine the likely values of dependent variable and the probability of risk to the Amphibians. A key benefit of BBNs is that the input variables can be changed at will to test different scenarios and determine the probability of risk to the organism or ecosystem of interest.

#### **Example 19: The Bayesian Belief Network developed for the Amphibians in the Gngangara Mound**

The BBN for the crawling (*Pseudophryne guentheri*) and the moaning frog (*Heleioporus eyrei*) (Figure 23) was developed by experts and was based on the key drivers which enable the Amphibians to carry out their life cycle. The thresholds for the BBN were also determined by expert opinion and were used to populate the probability distribution table.



While our framework uses BBNs as a decision support tool to determine risk, it does not preclude the use of other techniques if they are more suitable to your needs.

### 4.3 Spatial Mapping of Risk

Ecosystem management can be carried out at different scales, depending on the management objectives. Maintaining resources such as biological diversity and water quality require a regional or landscape scale, however, all management decisions lead to activities which alter landscape patterns. Consequently, managers require tools for visualising ecosystem dynamics of the entire landscape to determine the impact of local and regional management decisions (Turner *et al.* 1995, Plant and Vayssières 2000).

Appropriate management practices can be determined at the landscape level by testing 'what if' scenarios (Turner *et al.* 1995, Plant and Vayssières 2000) such as the effect of no management, alternative management strategies and natural events (Turner *et al.* 1995).

Risk can be mapped in a wide variety of ways, including:

- mapping past or projected future landscape change;
- mapping risk models based on BBNs; or
- mapping risk models based on other techniques.

The mapping of risk based on projected changes or using other modelling tools has been demonstrated in Section 2.1 (Part 2). Mapping the outputs of Bayesian network-based risk models developed in this project is one way of representing the results spatially. In most cases the BBN will use spatial information held in a GIS; these need to be imported into the BBN, and then the output of the BBN needs to be imported back into the GIS to give a spatial representation of the likelihood of risk. Note that any complex mapping work, especially linking models to GIS, will almost certainly require a GIS specialist.

It is possible to map risk and the results of Bayesian network risk models in a range of ways, using a wide range of tools and techniques. The literature covers a large range of approaches using both built-in tools and customised tools for a range of applications. See Supporting Document 7 for more details (SD7 Neville 2013).

Mapping is possible from within ArcGIS – the industry standard GIS program – or using other packages such as Idrisi. Risk analysis can be run with a GIS platform, such as by using Modelbuilder within the ArcGIS environment; through writing additional tools for the ArcGIS software in Python (Python Software Foundation 2007); by using existing modelling software such as MCAS-S (ABARES 2011), or by writing entire stand-alone programs.

BBNs are becoming increasingly common in modelling and management as Bayesian modelling software has become popular. There are significant differences in the basis for the BBNs - some projects use entirely polygon-based data, others use raster (grid) data. The basic process will vary depending on the GIS used, the type of data (points or grids) and the number and type of additional tools created to assist with processing. Supporting Document 7 provides some details on processing approaches (SD7 Neville 2013).

The general process for the integration of GIS with BBNs is as follows:

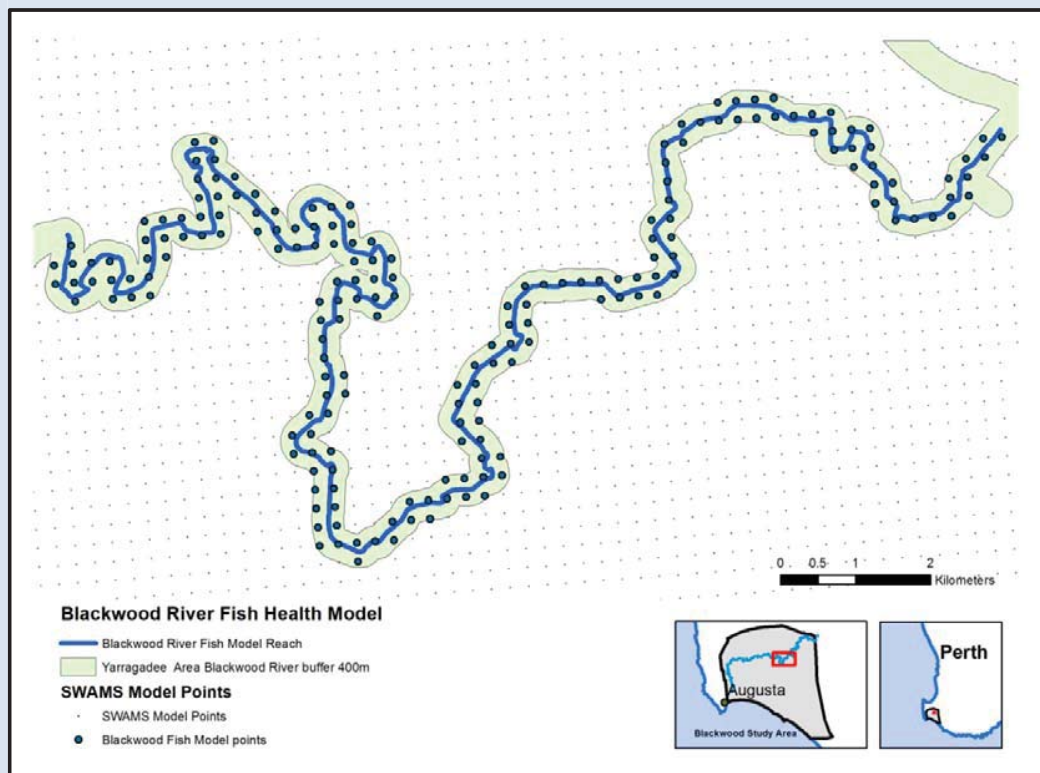
- Stage 1: Data acquisition and preparation in GIS
- Stage 2: Combine the data required by the BBN and export from GIS
- Stage 3: Import data into Netica, and run the model using cases
- Stage 4: Export data from Netica and import back into GIS for spatial representation

The basic process will vary depending on the GIS used, the type of data (points or grids) and the number and type of additional tools created to assist with processing. Example 20 below shows how the 'Blackwood River fish model' spatially mapped the outputs of the BBN to show the likelihood of risk for the Blackwood River freshwater fish.

**Example 20: Mapping risk using the *Blackwood River fish health model***

The *Blackwood River fish health model* applies to a short length of the Blackwood River. A 400m buffer – the fish model area - was created along this river reach, which runs for 33.4 km within a straight-line distance of 12.5 km (Figure 24).

The *fish health model* uses a single data input – depth to water table. This input was sourced from the South West Aquifer Modelling System (SWAMS), which reports projected water table heights in metres for each month of the year at 2030. Data was extracted for each of the 6 CSIRO Scenarios at the year 2030, for each model point in the fish model area – a total of 191 points (Figure 24). Each model point provided a single depth to water table value for the model.



**Figure 24: The area and reporting points (the South West Aquifer Modelling System (SWAMS) reporting points) of the *Blackwood River fish health model*.**

The model used the value for March, the end of summer, as this is the critical time when groundwater height influences water quality in the river. The March height (m AHD) was subtracted from the model base height (m AHD) for each cell in the area of interest to give a depth to watertable.

The depth to water table (March) values came from the point files as exported from SWAMS. Each South West Sustainable Yields Project Scenario output point was joined to the X,Y coordinates for the point in Excel, and the output plotted as a new point shapefile in ArcGIS.

Field values were exported from each pointfile as a comma delimited ascii file. The SWAMS values (real) were converted to model input values (text input values). This

was done with a modifiable lookup table to match a range of real values to a discrete model input class (shown in Table 8 of SD7 Neville 2013). The output was a case file for Netica with March depth to water table values in 'model classes' for each South West Sustainable Yields Scenario (CSIRO 2009b).

Each case file was run through Netica using the function Cases>Process cases. A Netica Control File must be written for this process, which lists the required findings (outputs). The output from this was a text file of the results for each scenario.

Each Netica output file was added into ArcMap as a new point shapefile which could be displayed in ArcMap.

The final fish health index combines the results from two indicator fish, *Galaxias occidentalis* and *Nannatherina balstoni* (Figure 25). These have been mapped individually, although only a single example of each is given in the results. The composite Fish Health index was created as follows:

- GOOD (100%) – Both species Persist.
- INTERMEDIATE – Combinations of Species persistence and decline
- POOR (100%) – Both species Severe Decline.

See the SD6 Speldewinde (2013) and SD7 Neville (2013) for more detail.

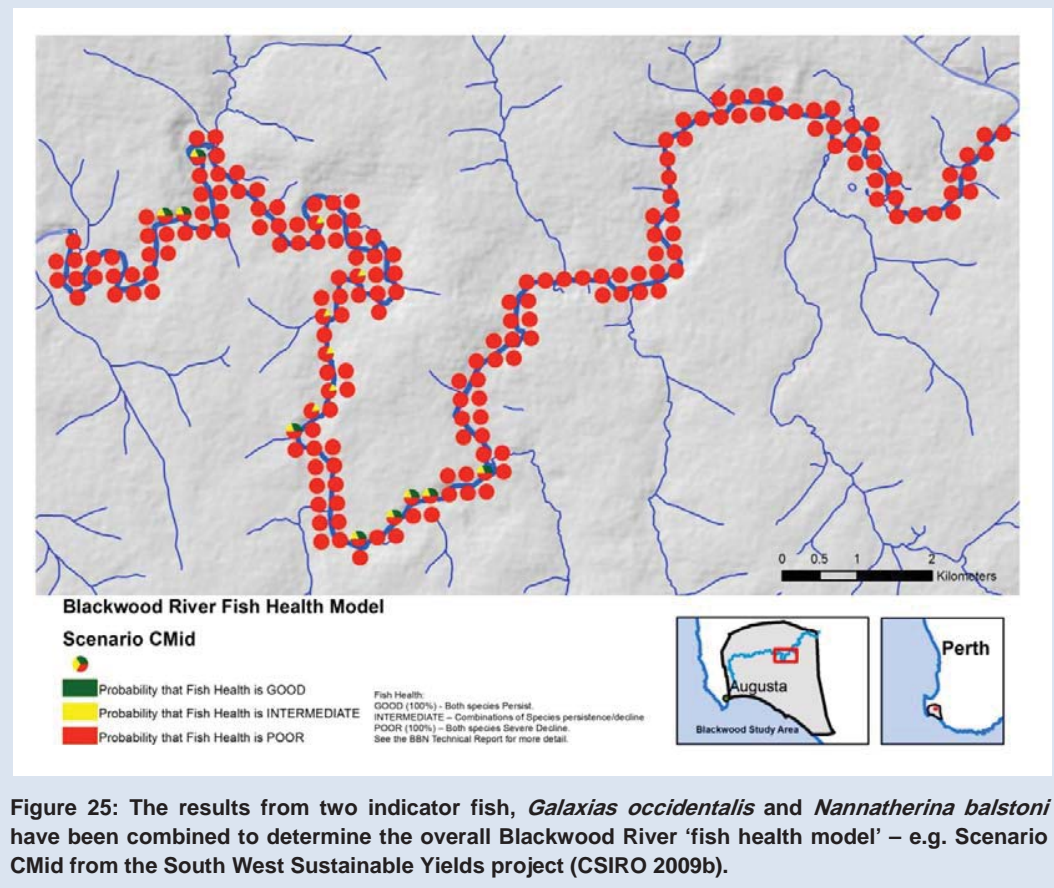


Figure 25: The results from two indicator fish, *Galaxias occidentalis* and *Nannatherina balstoni* have been combined to determine the overall Blackwood River 'fish health model' – e.g. Scenario CMid from the South West Sustainable Yields project (CSIRO 2009b).

## 5. STEP 5: MANAGE RISK

### 5.1 Using the Framework for Adaptation and Management

The nature of the framework means that information to support climate adaptation and management decisions are provided at each step (Figure 26).

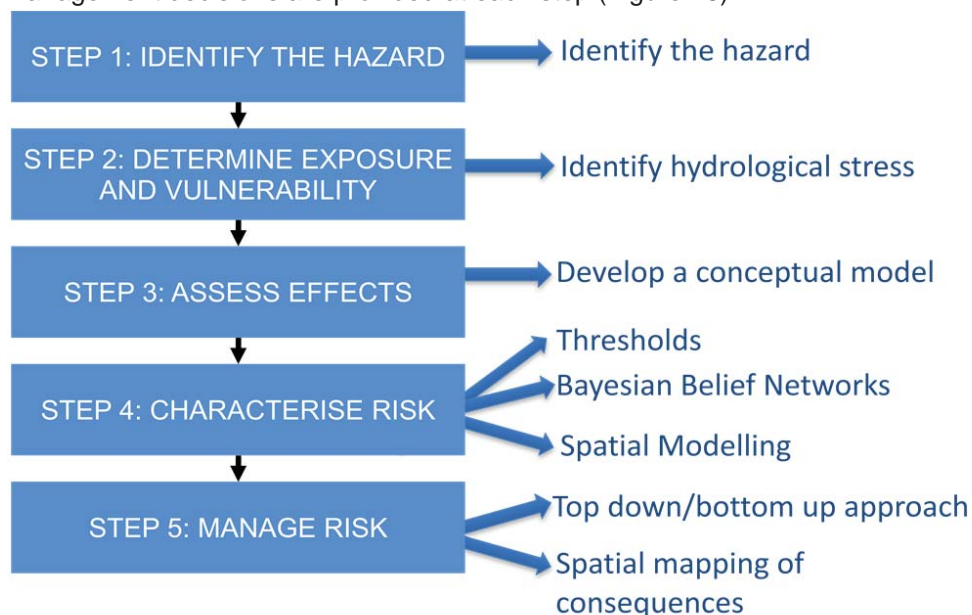


Figure 26: The management implications at each step of the Risk Assessment and Decision Making Framework.

#### 5.1.1 Identifying the Hazard

Identification of the cause of groundwater decline, and its impact on water quality, enables appropriate targeting of management action. Determining the hazard is a critical step and must be carefully done, as this will reveal the cause(s) of the hazard, their interactions (synergistic or antagonistic) and which anthropogenic stressors have greatest effect on the ecosystem. Reducing the impact of the hazard will reduce the vulnerability of the ecosystem. For example, if nutrient enrichment is a key secondary hazard then other means to address this stressor can be investigated (e.g. reducing nutrient runoff from agricultural or urban areas), making the system more resilient to the effects of climate change.

#### 5.1.2 Identifying Hydrological Stress

Identification of the location and rate of groundwater decline or rise, together with rating of ecosystem assets, enables prioritisation of adaptation or management measures including where (or not) to extract groundwater, conservation or land use planning decisions. Identifying hydrological stress also highlights the opportunities for favourable outcomes. For example, if areas of rising groundwater are identified in the landscape (e.g. Figure 11) it may be possible to instigate appropriate measures to conserve wetland ecosystems in these areas or allow novel wetland ecosystems to develop.

### **5.1.3 Developing a Conceptual Model**

Developing a conceptual model provides a transparent outline of the cause and effects of change to an ecosystem, highlighting key drivers that provide the focus for management and adaptation. This enables the parameters to be targeted to address undesirable outcomes, before extreme impacts of climate change are evident. It is also valuable information when designing monitoring regimes and developing management plans. Designing a conceptual model is a valuable exercise in considering the linkages between the ecosystem and the landscape and provides an excellent communication tool for explaining the rationale behind management plans.

### **5.1.4 Defining Thresholds**

Thresholds can be determined for single species for conservation purposes (e.g. threatened or endemic biota), functional groups of biota (e.g. those requiring free water to complete their life cycle), or guilds of biota (e.g. plants, frogs), enabling the framework to be tailored to specific purposes. Identifying thresholds defines the boundaries in which the biota of the GDE is likely to survive. This information is valuable as targets for monitoring programs, management plans, to define acceptable limits of change and for use in conservation and restoration initiatives.

### **5.1.5 Bayesian Belief Networks**

Bayesian Belief Networks can be easily modified to show changes in probability of risk resulting from the interaction between climate, hydrology, water quality, biotic resources requirements and biotic response. This provides a transparent and interactive template for decision-making at a range of levels. It equally shows the impact of extracting water on biota (a top down scenario) as it does the capacity for biota to survive under different climate and/or land use scenarios (a bottom up approach).

BBNS can be used for prediction, show cause–effect relationships, decision-making, system understanding and social learning. BBNs are very adaptable. It is easy to change parameters to immediately see probable effects and they are easily updated with new submodels and new information. They also provide a tool for communicating complex environmental problems among experts, managers and stakeholders.

### **5.1.6 Spatial Modelling**

Understanding the landscape scale in which your system occurs provides a holistic view for management and adaptation. Observing where groundwater levels are rising and falling can inform a number of decisions such as where and where not to extract groundwater for human use, or in which regions surface water GDEs are likely to be at increased risk of drying for conservation, remediation or triage purposes. Where groundwater is rising, the novel concept of allowing new GDEs to form with appropriate management and conservation of areas can be identified. The size and distribution of areas of rising and declining groundwater can suggest the relative connectivity between future ecosystems. For example, an ecosystem in a small localised area of rising groundwater surrounded by declining levels is likely to be isolated and be less

resilient to disturbance effects due to its reduced capacity to be colonised from surrounding systems.

Spatial mapping of risk can identify refuge areas (locations where the probability of harm is lower) and promote connectivity (where GDEs with favourable risk outcomes are close together or where intervention can make this so), providing key information for the maintenance of freshwater biodiversity (e.g. Figure 25: the Blackwood River Fish Health model). Identification of changed conditions in GDEs can inform appropriate restoration. For example, plant species can be chosen that will best survive future conditions, improving the ecological success and financial efficiency of restoration projects.

### **5.1.7 Top Down, Bottom Up Approaches**

The benefit of this framework is that it can be equally used top down or bottom up (Figure 28). A top down approach might be where groundwater is projected to decline as a consequence of climate change, groundwater abstraction and/or land use. The framework allows the consequences of this to be identified throughout the ecosystem (to water level, water quality, connectivity and biotic response) allowing a transparent and multifaceted approach to adapting to the new condition, highlighting which are the key variables. This might be due to a known scenario e.g. withdrawing 45ML from an aquifer will reduce the groundwater level by x metres or groundwater levels are projected to fall x metres as a consequence of climate change by 2030. If it is not possible to predict how a change will impact groundwater levels then 'what if' scenarios can be run to identify when groundwater decline is likely to impact GDEs. This can be used to inform policy conditions (e.g. groundwater extraction licences) or planning decisions.

Equally the framework can be used bottom up. For example, if there is concern for a particular species (e.g. threatened or endemic), functional groups of biota (e.g. those requiring free water to complete their life cycle), or guilds of biota (e.g. plants, frogs) then the framework can identify the resource requirements or thresholds of environmental change that the biota can tolerate. These can be incorporated into a BBN and show at what point changes in climate and groundwater levels are likely to result in negative impacts on flora and/or fauna.



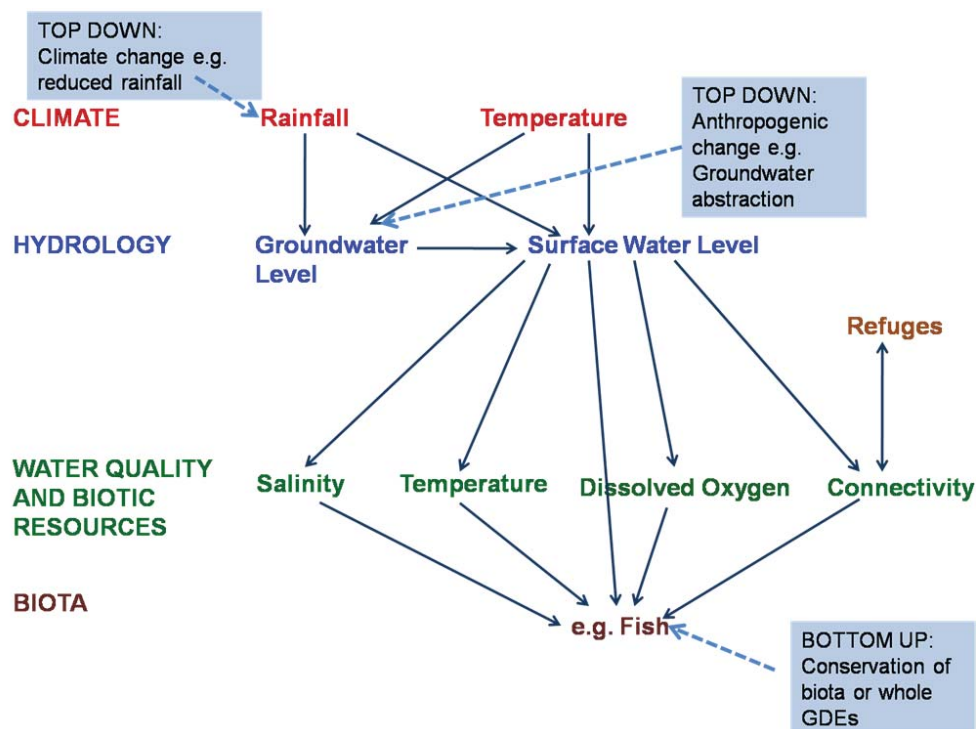


Figure 27: Using the conceptual model framework for top down or bottom up approaches to climate change adaptation.

### 5.1.8 Spatial Mapping of Consequence

Where adaptation or management requires spatial determination of consequence to GDEs within a landscape overlapping risk and asset/value determination can be an excellent tool. By overlapping risk with the asset and values mapping (described in Part 1, Section 1.3.2), we can identify areas where high risk will result in greater consequences – ecologically, and by extension, for management (see Example 21 and 22).

The risk can be identified through a modelling exercise using Bayesian models (Part 2, Section 4.2) or through using a simple risk assessment based on hydrology (Part 2, Section 2.1). The values (or assets) can be based on existing information or identified through a modelling exercise as shown in the *indicative conservation values* map (Figure 3).

Depending on the objectives, such mapping will help focus management attention. This could be relatively passive management (such as using zoning to indicate values) or active management (such as maintaining water levels by controlling extraction or even actively restoring the system through pumping water back into a wetland). Agencies may use consequence mapping to make decisions on triage – where some wetlands may be abandoned and management resources focussed on others that have a greater probability of maintenance of function and biota.

**EXAMPLE 21: Consequence of change** – a combination of *risk of change* and *conservation value* for the littoral and sub-littoral vegetation for the Gngangara study area, for the C Mid climate change scenario (CSIRO 2009b) (Figure 28). Refer to SD7: Neville (2013) for more detail.

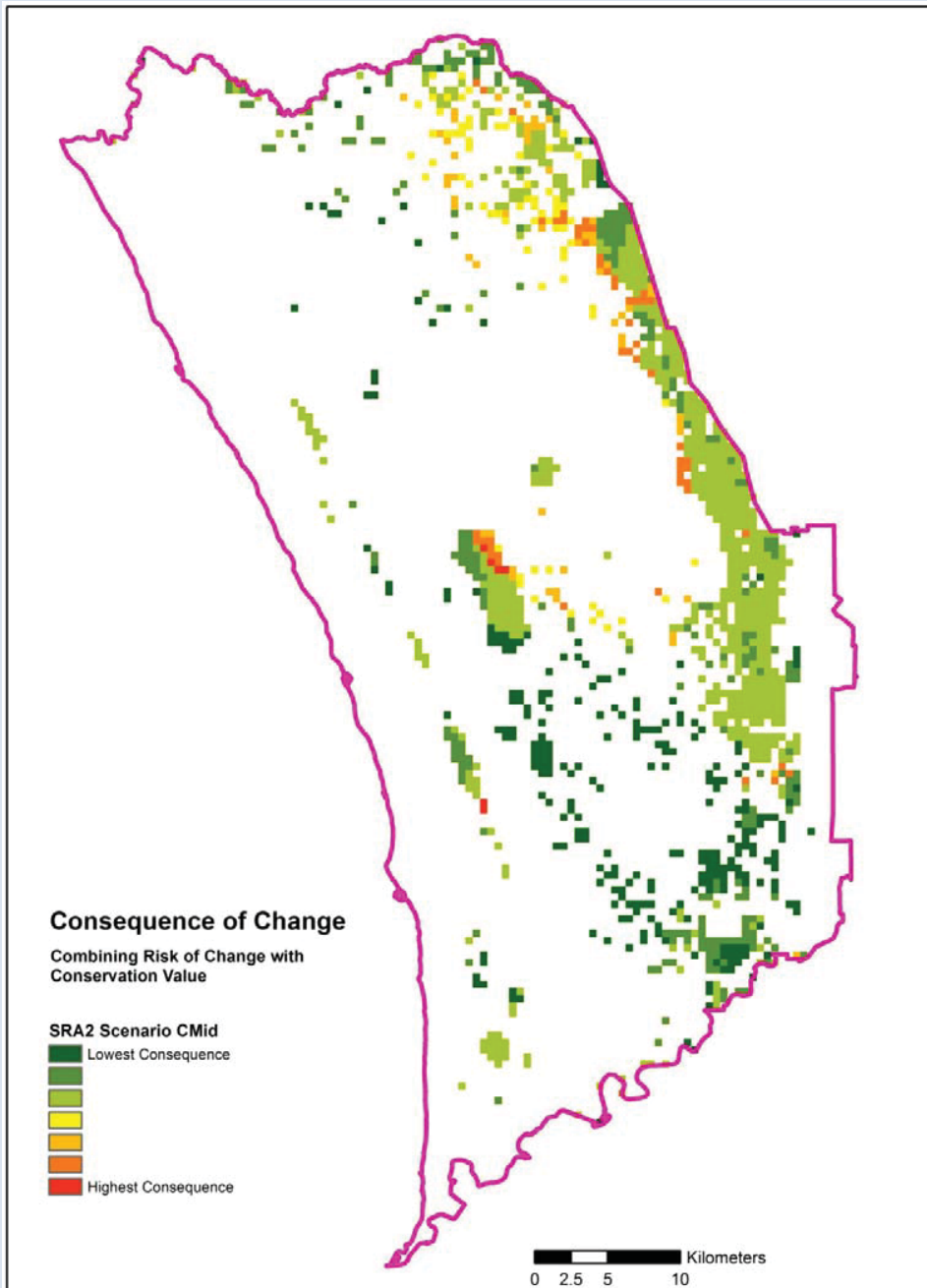


Figure 28: *Consequence of Change* – *risk of change* and *conservation value* combined for the littoral and sub-littoral vegetation on the Gngangara Mound, Scenario CMid from the South West Sustainable Yields Project (CSIRO 2009b).

**EXAMPLE 22: Implications of risk:** a combination of the overall wetland risk probability and the wetland conservation value for the Gngangara macroinvertebrates.

Combining the results of the overall wetland risk probability (that is probability of risk of change to the macroinvertebrates and the water quality) with the indicative wetland value mapping illustrates where the wetland survey sites coincide with high-value wetlands. The probability that wetland risk is moderate to high is significant in most of the high value wetlands, indicating severe consequences of change over the survey period (Figure 29). Refer to Supporting Document 7 for more information (SD 7 Neville 2013).

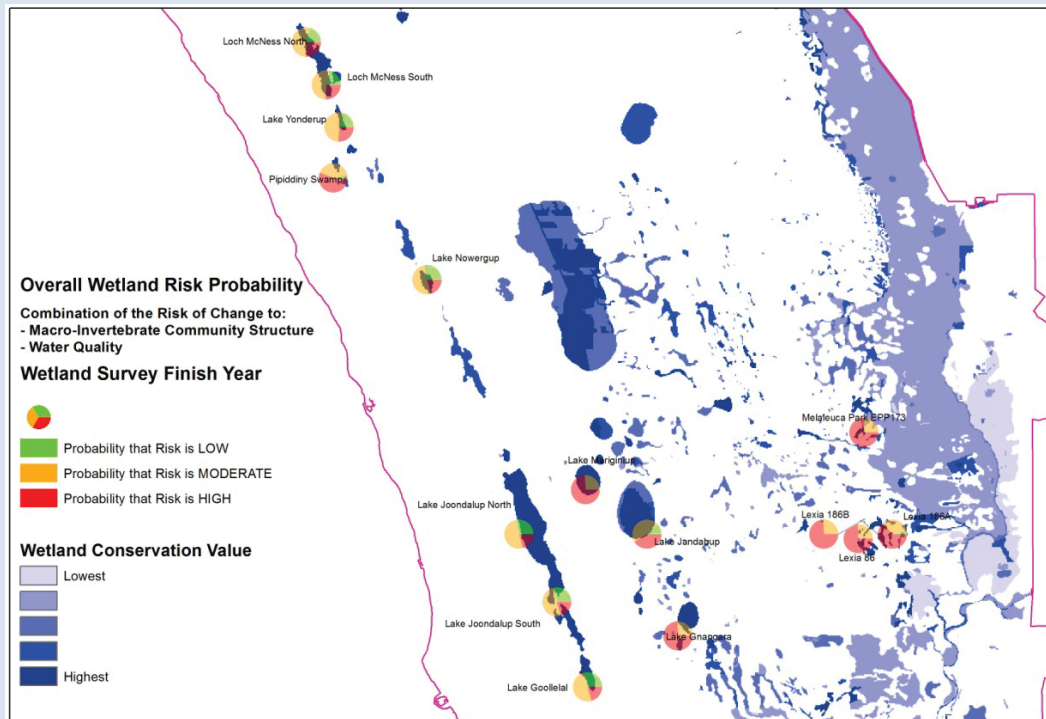


Figure 29: Implications of Risk: Mapping the overall wetland risk probability and the wetland conservation value for the macroinvertebrates in the Gngangara study area. (For more detail refer to SD7 Neville 2013).

## 6. ADAPTABILITY OF THE FRAMEWORK

While the framework has been developed for wetlands, rivers and cave ecosystems that are affected by **declining** groundwater levels, it can also be applied to the following situations if the necessary data and relationships are known:

1. Lake, river and cave ecosystems that may have **rising** groundwater levels. Whether species and ecosystem functions can return after being lost depends on factors that would need to be established. This application can help managers decide which groundwater dependent systems are more worthy of recovering after some functions have been lost. It is likely that there will be hysteresis in recovery processes in that the path back may not be the same as that which was followed when species or functions were lost after a threshold was exceeded.
2. Assessing risk to phreatophytic vegetation communities that depend on subsurface groundwater. This includes both obligate and facultative phreatophytes. In the southern Perth Basin, where two of the three case studies are located (Gnangara, Blackwood River), native vegetation can utilise groundwater when it is within ten metres of the soil surface, which is the case for 46 per cent of this area.
3. If groundwater-connected lakes, rivers and caves become disconnected from their supporting groundwater system, but can be managed so as to retain their levels or hydroperiods, then the framework is able to assess the likely impacts on important species for which data are available. However not all functions may be retained in perched systems, especially flushing. An example is where stormwater are added to groundwater throughflow lakes and are slowed from leakage through the lake bed by soil amendments such as clay or polymers.

This framework was tested through a number of workshops around Australia attended by a wide range of managers, researchers and community groups. As the framework is based on a conceptual model of the target ecosystem(s) and as it is based on a standard risk assessment framework, participants considered this would be an appropriate tool for assessing a wide range of ecosystem types. Case studies brought to these workshops included mound springs, wetland mosaics on floodplains, floodplain rivers receiving groundwater and surface water dependent systems (both wetlands and rivers).

A significant advantage of the framework is the ability to integrate people and data from many disciplines – climate, hydrology, botany, zoology, ecology, statistics and chemistry – into a decision support framework. Most studies are used in isolation and therefore have a limited, specialist application. The framework is also able to identify critical deficiencies in process understanding and data which may then be targeted in future work. Further refining aspects that are not sensitive in the framework or are already well defined may be wasteful use of scarce resources.

## **6.1 Scales, Limitation and Adaptation**

Climate change affects our ecosystem at the global scale. As such the imminent changes may not be able to overcome and we may need to accept that losses of ecosystems will occur and endeavour to retain maximum biodiversity in this changing landscape. This framework can assist identifying these changes so that we can plan and adapt accordingly.

Where groundwater systems are not highly over-allocated, it is normal for climate to have the greatest influence on groundwater trends at a **regional** scale. Management impacts are usually **local** and it is often difficult to influence long term trends to achieve management objectives. Therefore groundwater dependent lakes, rivers and caves may need intensive **local** management to be retained or recovered. This framework enables the most likely impacts on species of critical changes in levels or flows to be identified so that they can be managed in a targeted manner. Where assets have been lost because of low levels or inadequate hydroperiods, the framework may also assist in determining what assets and values may be returned were local management able to recover levels to a previous state.

The framework assumes that the lakes, rivers and caves are connected to aquifers that are usually unconfined but may be confined (e.g. mound springs, Blackwood River case study). As mentioned in the Introduction, it also has some applicability in perched systems and in evaluating the benefits that may be received by recovering levels through management or mitigation.

The benefits of landscape scale assessment is that regions of rising groundwater may be identified that can be used to improve the regional adaptation capability. Looking to conserve, restore or allow the emergence of new GDEs to mitigate for the loss in other areas.

Particularly where spatial risk assessment is carried out at regional scales, users of the framework are cautioned about the errors inherent in global climate model downscaling, the use of regional frameworks at local scales where the resolution of the data will not quantifiably support asset (GDE) scale decisions. In these instances it is likely that a first approximation or the relative change in groundwater levels (rising or falling, a lot or a little may be the best you can determine within the error margins of the data. It is necessary that users keep in mind the inherent limitations of the data they are using. Having said that, the application of the framework provides an excellent interrogation of the important factors that will impact GDEs. It will also highlight strengths and weaknesses in the data and show which key gaps need to be filled to improve understanding of the system.

In developing your conceptual, Bayesian and spatial risk assessment models it is vital that you consider the level of error or uncertainty at each stage and tally it through the process, so the final models are treated with due consideration of their limitations. What is the level of accuracy of your expert opinion? Can this be quantified? How do knowledge gaps increase your uncertainty? What is the level of uncertainty in the global climate change models you are using to predict climate change? What errors are involved in downscaling? What are the errors in any hydrological models you might be using? Some of these considerations are discussed in Section 4 of the Development and Case Studies document.

## **6.2 Transferability**

The framework was developed in south-western Australia, a biodiversity hotspot that has already suffered three decades of drying. The framework was tested using three GDE system types: wetlands, a river and caves and is appropriate for these ecosystem types across Australia. From our national workshops, the framework appears to be most suitable for GDEs including other types of groundwater systems (e.g. fractured rock rather than sand aquifer systems) and GDE types (e.g. mound springs). However the framework can be adapted to a wide range of management concerns and ecosystems including those relevant to surface water dependent systems. If you have used this framework the authors would be very interested in any feedback you have. Please contact Jane Chambers (email: [J.Chambers@murdoch.edu.au](mailto:J.Chambers@murdoch.edu.au)).

## REFERENCES

- ABARES (2011). Multi-Criteria Analysis Shell for Spatial Decision Support (MCAS-S): User Guide. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.  
[www.abares.gov.au](http://www.abares.gov.au)
- Aguilera, P.A., A. Fernández, R. Fernández, R. Rumí & A. Salmerón, (2011). Bayesian networks in environmental modeling. *Environmental Modelling & Software* 26,1376-1388.
- Ali, R., McFarlane, D., Varma, S., Dawes, W., Emelyanova, I., Hodgson, G. and Charles, S. (2012a). Potential climate change impacts on groundwater resources of south-western Australia. *Journal of Hydrology* 475, 456–472.  
<http://dx.doi.org/10.1016/j.jhydrol.2012.04.043>
- Ali, R., McFarlane, D., Varma, S., Dawes, W., Emelyanova, I. and Hodgson, G. (2012b). Potential climate change impacts on the water balance of regional unconfined aquifer systems in South-Western Australia. *Hydrology Earth Systems Science* 16, 4581–4601.  
[www.hydrol-earth-syst-sci.net/16/4581/2012/doi:10.5194/hess-16-4581-2012](http://www.hydrol-earth-syst-sci.net/16/4581/2012/doi:10.5194/hess-16-4581-2012)
- Anderson, M. J. and Willis, T. J. (2003). Canonical Analysis of Principal Coordinates: A Useful Method of Constrained Ordination for Ecology. *Ecology* 84, 511-525.
- Anon (2008). About Bayesian Belief Networks. Charles River Analytics Inc., USA, viewed 7 May 2012, <https://www.cra.com/pdf/bnetbuilderbackground.pdf>.
- Asante-Duah, D. K. (1998). *Risk assessment in environmental management*, John Wiley and Sons, Brisbane.
- Barnett, B., Townley, L. R., Post, V., Evans, R. E., Hunt, R. J., Peeters, L., Richardson, S., Werner, A. D., Knapton, A. & Boronkay, A. (2012 ). Australian groundwater modelling guidelines, Waterlines report. National Water Commission, Canberra. viewed 13 February 2012, [http://www.nwc.gov.au/\\_data/assets/pdf\\_file/0016/22840/Waterlines-82-Australian-groundwater-modelling-guidelines.pdf](http://www.nwc.gov.au/_data/assets/pdf_file/0016/22840/Waterlines-82-Australian-groundwater-modelling-guidelines.pdf).
- Barron, O., Silberstein, R., Ali, R., Donohue, R., McFarlane, D.J., Davies, P., Hodgson, G., Smart, N. and Donn, M. (2012). Climate change effects on water-dependent ecosystems in south-western Australia. *Journal of Hydrology*, 475, 95-109,  
<http://dx.doi.org/10.1016/j.jhydrol.2012.02.028>
- Bates, B. C., Chandler, R. E., Charles, S. P. & Campbell, E. P. (2010). Assessment of apparent nonstationarity in time series of annual inflow, daily precipitation, and atmospheric circulation indices: A case study from southwest Western Australia. *Water resources research* 46.
- Beatty S., Morgan D., Keleher J., Lymbery A., Close P., Speldewinde P., Storer, T., & Kitsios, A. (2013). Adapting to climate change: a risk assessment and decision making framework for managing groundwater dependent ecosystems with declining water levels. Supporting document 4: Environmental variables in the habitats of south-western Australian freshwater fishes: an approach for setting threshold indicator value. National Climate Change Adaptation Research Facility, Canberra, Australia.

- Boteva, D, Griffith, G. and Dimopoulos, P. (2004). Evaluation and mapping of the conservation significance of habitats using GIS: an example from Crete, Greece. *Journal for Nature Conservation* 12, 237—250.
- Cain, J. (2001). Planning improvements in natural resources management: guidelines for using Bayesian networks to support the planning and management of development programs in the water sector and beyond. Crowmarsh Gifford, Wallington, Oxon, UK, viewed 11 December 2011, <http://nora.nerc.ac.uk/9461/1/N009461BO.pdf>.
- Chan, T. U., Hart, B. T., Kennard, M. J., Pusey, B. J., Shenton, W., Douglas, M. M., Valentine, E. & Patel, S. (2012). Bayesian network models for environmental flow decision making in the Daly River, Northern Territory, Australia. *River Research and Applications* 28, 383-301.
- Chambers, J., Nugent, G., Sommer, B., Speldewinde, P., Neville, S., Beatty, S., Chilcott, S., Eberhard, S., Mitchell, N., D'Souza, F., Barron, O., McFarlane, D., Braimbridge, M., Robson, B., Close, P., Morgan, D., Pinder, A., Froend, R., Horwitz, P., Cook, B. & Davies, P. (2013). Adapting to climate change: a risk assessment and decision making framework for managing groundwater dependent ecosystems with declining water levels. Development and case studies. National Climate Change Adaptation Research Facility, Canberra, Australia.
- Chilcott, S. (2013). Adapting to climate change: a risk assessment and decision making framework for managing groundwater dependent ecosystems with declining water levels. Supporting document 5: The impact of declining groundwater levels on Stygofauna communities in the Leeuwin Naturaliste Ridge Cave systems, Western Australia. National Climate Change Adaptation Research Facility, Canberra, Australia.
- CSIRO (2009a). Water yields and demands in south-west Western Australia. A report to the Australian Government from the South-West Western Australia Sustainable Yields project. CSIRO Water for a Healthy Country Flagship, Australia.
- CSIRO (2009b). Groundwater yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.
- Daily J.P, Hitt, N.P, Smith, D.R and Snyder, C.D (2012). Experimental and environmental factors affect spurious detection of ecological thresholds. *Ecology* 93, 17-23.
- Gnangara Sustainability Strategy (2007). Gnangara Sustainability Strategy managing land and groundwater for the future, brochure, Department of Water, Western Australia.
- Eamus, D. (2009). Identifying groundwater dependent ecosystems, a guide for land and water managers. Land and Water Australia. viewed 11 June 2012, [http://lwa.gov.au/files/products/innovation/pn30129/pn30129\\_1.pdf](http://lwa.gov.au/files/products/innovation/pn30129/pn30129_1.pdf).
- Ferdowsian, R. and McCarron, C. (2001). HARTT-XLS Instruction Manual, Hydrograph Analysis: Rainfall and Time Trend. Department of Agriculture, Western Australia, and Lote-Tree Software.
- Ferdowsian, R., Pannell, D., McCarron, C., Ryder, A and Crossing, L. (2001). Explaining groundwater hydrographs: separating atypical rainfall events from time trends. *Australian Journal of Soil Research*, 39, 861-875.



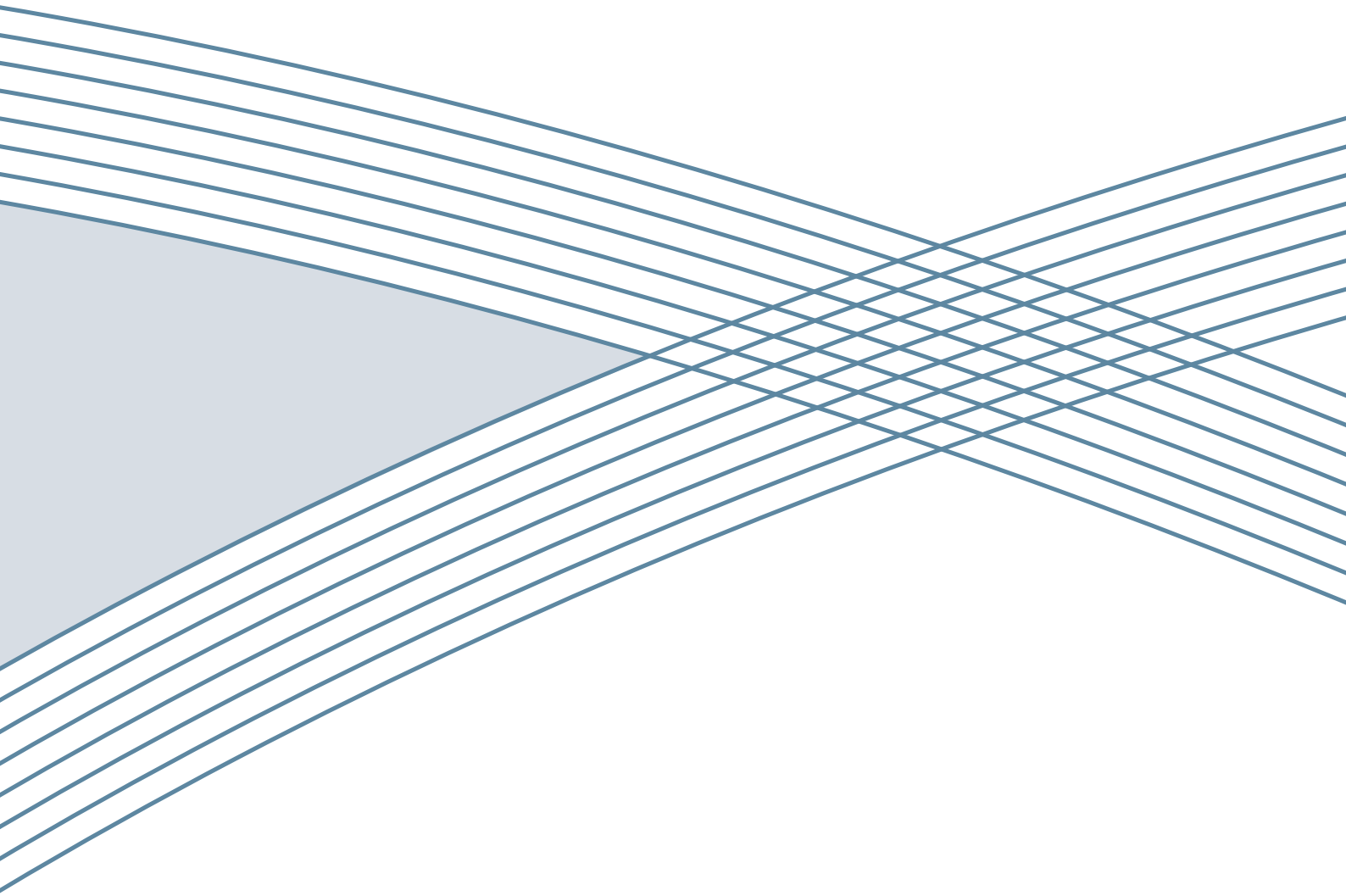
- Hart, B. T. & Pollino, C. (2006). Ecological risk assessment and Bayesian modeling. Water Studies Centre, Monash University, viewed 19 March 2012, [http://ns1.mrcmekong.org/download/programmes/ep/Bayesian\\_Network\\_Reading1.pdf](http://ns1.mrcmekong.org/download/programmes/ep/Bayesian_Network_Reading1.pdf).
- Hart, B. T. and Pollino, C. A. (2009). Bayesian modelling for risk-based environmental water allocation, Waterlines report. National Water Commission, Canberra.
- Hill, A.J., C.A. Semenuik, V Semenuik & A. Del Marco (1996). Wetlands of the Swan Coastal Plain Vol 2A: Wetland Mapping, Classification and Evaluation. Water Authority of WA.
- Jakeman, A., Chen, S. & Newham, L. (2009). 'Modelling and Adaptive Environmental Management', in C Allan & Stankey, GH (eds), *Adaptive Environmental Management: A Practitioner's Guide*, Springer, The Netherlands.
- Jensen, F. V. & Nielsen, T. D. (2007). Bayesian networks and decision graphs, Springer Science and Business Media, New York.
- Kragt, M. E. (2009). A beginners guide to Bayesian network modelling for integrated catchment management. Landscape Logic technical report no.9., Landscape Logic, Australia, viewed 11 December 2012, [http://www.landscapelogicproducts.org.au/site/system/files/32/original/No\\_9\\_BNs\\_for\\_Integrated\\_Catchment\\_Management.pdf?1275581173](http://www.landscapelogicproducts.org.au/site/system/files/32/original/No_9_BNs_for_Integrated_Catchment_Management.pdf?1275581173).
- Legendre, P. and Anderson, M. J. (1999). Distance-based redundancy analysis: testing multi-species responses in multi-factorial ecological experiments. *Ecological Monographs*, 69, 1-24.
- Legendre, P. and Legendre, L. (1998). *Numerical Ecology*, Amsterdam, The Netherlands, Elsevier.
- Legendre, P. & Gallagher, E. (2001). Ecologically meaningful transformations for ordination of species data. *Oecologia*, 129, 271-280.
- Lenat, D. R. (1993). A Biotic Index for the Southeastern United States: Derivation and List of Tolerance Values, with Criteria for Assigning Water-Quality Ratings. *Journal of the North American Benthological Society*, 12, 279-290.
- Marcot, B. G., Holtausen, R. S., Raphael, M. G., Rowland, M. M. & Wisdom, M. J. (2001). Using Bayesian belief networks to evaluate fish and wildlife population viability under land management alternatives from an environmental impact statement. *Forest Ecology and Management*, 153, 29-42.
- Margules, C. and Usher, M.B. (1981) Criteria used in assessing wildlife conservation potential: A Review. *Biological Conservation* 21, 79-109.
- Margules, C.R. and Nicholls, A.O. (1988) Selecting Networks of Reserves to Maximise Biological Diversity. *Biological Conservation* 43, 63-76.
- Margules, C.R., Higgs, A.J. and Rafe, R.W. (1982). Modern Biogeographic Theory: Are there any Lessons for Nature reserve Design? *Biological Conservation* 24, 115-128.

- McFarlane, D., Stone, R., Martens, S., Thomas, J., Silberstein, R., Ali, R. and Hodgson, G. (2012). Climate change impacts on water yields and demands in south-western Australia. *Journal of Hydrology* 475, 488-498  
<http://dx.doi.org/10.1016/j.jhydrol.2012.05.038>
- McNeill J, MacEwan R and Crawford D (2006), Using GIS and a land use impact model to assess risk of soil erosion in West Gippsland, *Applied GIS* 2,19.1 –19.16.
- Mitchell, N., Sommer, B. & Speldewinde, P. (2013). 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. National Climate Change Adaptation Research Facility, Canberra, Australia.
- Moe, S. J. (2010). 'Bayesian models in assessment and management', in LAL Kapustka, W. G. (ed.), *Environmental risk assessment from a landscape perspective*, John Wiley & Sons.
- Neville, S. (2013). Adapting to climate change: a risk assessment and decision making framework for managing groundwater dependent ecosystems with declining water levels. Supporting document 7: Spatially representing the impacts of falling groundwater due to climate change on groundwater dependent ecosystems. National Climate Change Adaptation Research Facility, Canberra, Australia.
- Nugent, G., Chambers, J. & Speldewinde, P. (2013). Adapting to climate change: a risk assessment and decision making framework for managing groundwater dependent ecosystems with declining water levels. Supporting document 1: Literature review. National Climate Change Adaptation Research Facility, Canberra, Australia.
- Panitsa, M, Koutsias, N, Tsiripidis, I, Zotos A. & , Dimopoulos, P. (2011). Species-based versus habitat-based evaluation for conservation status assessment of habitat types in the East Aegean islands (Greece). *Journal for Nature Conservation* 19, 269– 275.
- Plant, R. E. and M. P. Vayssieres. (2000). Combining expert system and GIS technology to implement a state-transition model of oak woodlands. *Computers and Electronics in Agriculture* 27, 33-52.
- Rassam, D., Jolly, I. & Pickett, T. (2012). Guidelines for modelling groundwater-surface water interactions in eWater source: Towards best practice model application. EWater Cooperative Research Centre, Canberra. Viewed 5 December 2012,  
[http://www.ewater.com.au/uploads/files/eWater-Modelling-Guidelines-GSWI-Source-\(v1-Mar-2012\).pdf](http://www.ewater.com.au/uploads/files/eWater-Modelling-Guidelines-GSWI-Source-(v1-Mar-2012).pdf).
- Richardson, S., Irvine, E., Froend, R., Boon, P., Barber, S. & Bonneville, B. (2011). Australian groundwater-dependent ecosystem toolbox part 1: assessment framework, Waterlines Report. National Water Commission, Canberra. Viewed 23 February 2012,  
[http://nwc.gov.au/\\_data/assets/pdf\\_file/0006/19905/GDE-toolbox-part-1.pdf](http://nwc.gov.au/_data/assets/pdf_file/0006/19905/GDE-toolbox-part-1.pdf).
- Silberstein, R.P. Aryal S.K., Durrant J., Pearcey, M. Braccia M., Charles S.P., Boniecka, L., Hodgson, G.A. Bari, M.A. and McFarlane, D.J. (2012). Climate change and runoff in south-western Australia. *Journal of Hydrology*, 475, 441-455.  
<http://dx.doi.org/10.1016/j.jhydrol.2012.02.009>

- SKM (2012). SKM Achieve Magazine, Issue 4. Viewed 10 November, 2012.  
[http://www.skmconsulting.com/SiteDocuments/Knowledge-andInsights/achieve/issue4\\_2012/SKMachieve\\_Issue4\\_2012\\_Online-groundwateratlas-safeguards-ecosystems.pdf](http://www.skmconsulting.com/SiteDocuments/Knowledge-andInsights/achieve/issue4_2012/SKMachieve_Issue4_2012_Online-groundwateratlas-safeguards-ecosystems.pdf).
- Sommer, B., McGuinness, S., Froend, R. & Horwitz, P. (2013). Adapting to climate change: a risk assessment and decision making framework for managing groundwater dependent ecosystems with declining water levels. Supporting document 2: Assessing risks to groundwater dependent wetland ecosystems in a drying climate: an approach to facilitate adaptation to climate change. National Climate Change Adaptation Research Facility, Canberra, Australia.
- Speldewinde, P. (2013). 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 modeling the impacts of falling groundwater due to climate change on groundwater dependent ecosystems. National Climate Change Adaptation Research Facility, Canberra, Australia.
- ter Braak, C. F. & Looman, C. N. (1986). Weighted averaging, logistic regression and the Gaussian response model. *Vegetation*, 65, pp. 3-11.
- Turner, MG, Arthaud, GJ, Engstrom, RT, Hejl, SJ, Liu, J, Loeb, S & McKelvey, K (1995). Usefulness of Spatially Explicit Population Models in Land Management. *Ecological Applications* 5, 12-16.
- Voinov, A. & F. Bousquet (2010). Modelling with stakeholders. *Environmental Modelling & Software* 25, 1268-1281
- Yesertener, C. (2008). Assessment of the declining groundwater levels in the Gnangara Groundwater Mound. Government of Western Australia, Department of Water, Perth, Western Australia. <http://www.water.wa.gov.au/PublicationStore/first/62920.pdf>.







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