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

Simon Neville
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

Ecotones and Associates

Authors

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

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Disclaimer

The views expressed herein are not necessarily the views of the Commonwealth or NCCARF, and neither the Commonwealth nor NCCARF accept responsibility for information or advice contained herein.

Cover image: Low density peri-urban housing adjacent to Lake Powell, a freshwater wetland in Western Australia © Simon Neville, Ecotones and Associates.
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EXECUTIVE SUMMARY

This document reports on the provision of Geographic Information System (GIS) services to the NCCARF project – “Adapting to Climate Change: A Risk Assessment and Decision Making Framework for Managing Groundwater Dependent Ecosystems with Declining Water Levels”. There were two specific objectives:

- Incorporation of hydrological data on to GIS platform
- Incorporation of risk assessment framework on to GIS platform

Ultimately the work covered 6 main areas:

- Identifying and sourcing data from custodians in WA.
- Creation of new datasets from data provided.
- Incorporation of hydrological data on to GIS platform, and producing maps of exposure and vulnerability of GDEs in the study area.
- Integrating GIS data with Bayesian Belief Network (BBN) Models.
- Investigating ways of integrating environmental values with risk

Sourcing Datasets

This study focussed on three sites representing two groundwater dependent aquatic ecosystems (GDEs): Wetlands on the data-rich Gnangara Mound (Gnangara Study Area) and in the data-poor Blackwood catchment (Blackwood Study Area) and adjacent caves (Jewel and Lake Caves, Margaret River).

Figure A. The south west corner of Western Australia with the location of the three study areas: wetlands of the Gnangara Mound, river base-flow system in the Blackwood River and the Leeuwin Naturaliste Ridge Caves.

Main providers of datasets were:

- The CSIRO
- Western Australian Department of Water (DOW); and
Western Australian Department of Environment and Conservation (DEC)

The CSIRO-led South West Sustainable Yields Project (SWSY) provided a set of groundwater change projections for different climate scenarios out to the year 2030 (CSIRO, 2009A).

- Scenario A – This historical climate scenario was based on the climate of the historical past (28 years 1975 to 2007).
- Scenario B – The recent climate scenario based on the climate of the recent past (10 years 1997 to 2007).
- C Scenarios - Future climate. These were based on 15 global climate models with three estimates of temperature changes to give three alternative ~2030 climates:
  - Scenario CDry – Dry extreme
  - Scenario CMid - Median
  - Scenario CWet – Wet extreme
- Scenario D - The future climate with future development scenario used the same climate time series as CMid, but added future levels of development by increasing groundwater abstraction to full allocation limits.

The projections had been made using PRAMS (the Perth Regional Aquifer Modelling System) and SWAMS (the South West Regional Aquifer Modelling System).

All of the datasets received were organised within a GIS framework. Significant amounts of data were received in non-spatial form and were converted to spatial datasets.

Integrating GIS Data with Bayesian Models

The project required that the set of Bayesian Belief Network (BBN) models being developed could be provided with a range of data from the spatial datasets assembled. A brief review of the literature was carried out to identify examples of and methods for integration of GIS datasets and BBNs. The general process as adopted is adapted from the CRAFT process outlined in Hicks and Pierce 2009:21-23) and was in four stages: Stage 1: Location & Data Preparation; Stage 2: Data Combination and Export; Stage 3: Export Data from ArcMap and import into Netica; and Stage 4: Export Data from Netica and re-import into ArcMap. Some simple tools were written to automate processing tasks.

In all six separate models were produced in the project. Only three of these were run in a spatial form – the Gnangara Invertebrate Model, the Gnangara Vegetation Change Model, and the Blackwood River Fish Model - due to a lack of data availability or spatial unsuitability (Stygofauna model).

Spatial mapping of risk using GIS

GNANGARA VEGETATION MODEL

The Gnangara Vegetation Change Model is a broad-scale model that predicts vegetation change in areas where groundwater is less than 5.2m deep. The Gnangara Study area is extensive (228,000 ha), having 8870 PRAMS reporting cells on a 500m grid. However the limitation on groundwater depth means that results are reported from only 1503 cells, or just fewer than 17% of all cells.
The model uses three data inputs: Starting Groundwater depth, Groundwater decline and Rate of Groundwater decline. All of these are sourced from the PRAMS model monthly results tables, which report projected water table heights in meters for each month of the year at 2030. Data was extracted for each of the 6 CSIRO Scenarios at the year 2030.

The required data values were calculated from the files of monthly projected heights (AHD) for each model point as exported from PRAMS. Each PRAMS Scenario output was joined to the XY coordinates for each point, added into ArcGIS ArcMap GIS software, and a point file (Start GWD, GW Decline and Rate of decline values) created for each scenario.

The results for each scenario with returned to ArcMap and mapped. The output representation is in the form of single quantified legend for the Probability that the Risk of Change to Vegetation State is Large. Colours were chosen to make visual identification of this easy. Note that the probability for a large vegetation change does not drop below 65% for all scenarios.

**GNANGARA MACRO INVERTEBRATE MODEL**

The Gnangara Macro-Invertebrate Model is a site-specific model that predicts Risk of Change to Macro-Invertebrate Communities and Water Quality. The necessary data for the Invertebrate model were Lithology, Groundwater Depth and No. of dry days/year (or hydro-period). The model is applicable to any wetland area within the PRAMS SWSY area; however the necessary datasets are only currently available from 16 wetland sites. Some of these sites (eg Lake Wilgarup, Lexia 186B) have earlier finish dates due to the wetland drying. Each site provided a single case for the BBN.

Data was provided from each wetland for two times in the year, effectively a dry and wet point. So the purpose of modeling we selected just the first and last data point for each site – the ‘Start’ and ‘Finish’ point. This gave the opportunity to illustrate change over time.

Each wetland site was saved in a table; supplied with AWRC reference number to geo-reference it, and added into the GIS. An output file listed Lithology, Groundwater depth and No. of dry days/year for each site.

The results were added into ArcMap and represented in the form of single pie chart for each wetland, showing three Probabilities of ‘Overall Wetland Risk’ - Low, Moderate and High. Colours were chosen to make visual identification of this easy.

**BLACKWOOD RIVER FISH HEALTH MODEL**

Although the Blackwood study area covers some 280,000 ha, the area that this model applies to is only a small part of that. The model was developed by analysing groundwater-river level relationships that apply in a short length of the Blackwood River where groundwater has a significant effect on water quality in the summer months. 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. The total area of the buffer is 1501 ha.

The fish model uses a single data input – Depth to water table (m) in March, as this is the critical time when groundwater height influences water quality in the river. The data
is sourced from the SWAMS model, which reports projected water table heights in meters for each month of the year at 2030. Data was extracted for each of the 6 CSIRO Scenarios at the year 2030. Data extraction was carried out for each model point in the fish model area – a total of 191 points.

The final composite fish health index combines the results from two indicator fish, *Galaxias occidentalis* and *Nannatherina balstoni* as follows: GOOD (100%) – Both species Persist; INTERMEDIATE – Combinations of Species persistence and decline; and POOR (100%) – Both species Severe Decline.

**Cave Stygofauna Model**

Very limited cave GIS data was available for the project, and discrepancies were observed between datasets, so it was decided to re-created locations of caves from survey data. Outlines of caves had been surveyed manually in the past, and were available as graphics with scale and north point (from Eberhard, 2004), although not as geo-referenced datasets.

We therefore created cave outline shapefiles from hand-drawn outlines for Lake, Easter and Jewel Caves and the Labyrinth using a 3-stage geo-rectification process. The resulting cave outlines were checked against known features on the ground surface, and orientation & location corrected where required. Hand-drawn maps of estimated water levels were provided for each cave, identifying the approximate extent of water in the caves for two historical periods (1958-1982, 1995-2004) and the present (2010-2012). These were also converted to digital maps.

**Alternative Impact Assessment**

**Value assessment**

Risk is characterised as the *likelihood* that something will happen and the *consequence* suffered if it happens (McNeill et al 2006). The models listed above deal with the nature of the event, and the probability of it happening, but do not clearly evaluate consequences.

In order to further explore this, we carried out some simple *Value Assessments* for the Gnangara Wetlands, based on existing datasets, to illustrate the potential of value assessment, where the high probability of change to a high value asset indicates greater consequence. The technique used was very exploratory, and the results only intended as illustrations of the potential of such assessments.

The approach taken to assess wetland values mirrors a similar approach used to evaluate conservation value of remnant vegetation in the south west (Neville, 2009), using a series of simple criteria based on existing GIS data area used. The assessment criteria were based on the principles of diversity, rarity, naturalness and area.

The chosen modelling vehicle was MCAS-S (Multi Criteria Analysis Shell for Spatial Decision Support - ABARES, 2011), MCAS-S is a spatial software shell which can display spatial data but does not have full GIS functionality. This software is relatively easy to use and can easily be provided to 3rd parties for their use and modification. It allows rapid combination of spatial datasets & criteria specification, and thus allows real-time development with interested parties/experts etc.

**Simple Hydrological Impact Assessment**

4 Spatially representing the impacts of falling groundwater levels
An alternative technique to assess risk - using a simple assessment of the groundwater change projections in conjunction with groundwater depths – was presented. Previous studies in the Gnangara Mound (Sommer & Froend (2010)) as well as the analysis carried out in the current Project (SD2 Sommer et al 2013) have identified the importance of groundwater surface proximity in determining groundwater change sensitivity in the ecology. Proximity is a strong determinant of risk in both the Vegetation Change Model and the Macro-Invertebrate Model in this current project. The same studies identify that the amount (and by definition the rate) of groundwater change over time is also important. A technique was developed that combines these two factors – depth to groundwater and projected groundwater decline – in a simple weighted assessment.

A second stage of the process combined the risk maps with previously produced conservation value maps for the wetlands, to produce “consequence” maps. These maps provide a simple tool for identifying where wetland assets are under most threat, and where wetlands are most likely to survive under different future climate scenarios.

**Issues remaining**

The exposure and vulnerability mapping is all based on the results of the South West Sustainable Yield (SWSY) project run by CSIRO and using a series of large-scale groundwater models (PRAMS and SWAMS). The CSIRO SWSY project was designed to provide information on groundwater levels at regional scale, and project the impacts of climate-change related rainfall change and abstraction on both surface and confined aquifers. To use the same projections for predicting impacts at the surface is problematic, due to the fine scale of surface wetland features and surface topography. However they are the only available projections of groundwater change.

The Vegetation Change Model was successfully run for the CSIRO 2030 Scenarios for the entire Gnangara Area – PRAMS – although the model (in its current form) is only applicable to areas where the DWT <5.2m. The model suggests broad-scale vegetation change under all scenarios.

The scenario differentiation of the results is also not clear, with counter-intuitive results, which can be traced to the model’s inconsistent output under certain input conditions. This is probably due to:

- the training datasets having missing combinations of input variables, or
- individual cases in some groups having unusual external influences (such as high levels of vegetation change due to weed invasion).

With further work these issues could be corrected.

This Blackwood Fish Model was run for the six CSIRO 2030 Scenarios, and provides a prognosis for 6 fish species [persist, likely decline, severe decline], as well as for the general fish health [poor, intermediate, good] based on 2 fish sp.

The model has a very limited area of application, but the approach has real promise for similar situations elsewhere. In its current form it identifies limited small refugia, with the situation under Scenarios CDry & D the least optimistic.

The Gnangara Invertebrate Model varies from the previous two in that each site is a survey wetland with real data. At this stage, the model has only been run for beginning
and end survey years, however a 2030 projection is being attempted and may be
finalised in order to run the model for the future scenarios. Some changes that the
model predicts are verifiable from historical survey data.

The Conservation Value mapping, Simple Risk Assessment and Consequence
mapping provide examples of simpler risk techniques, and contextualise the risk model
outputs in terms of assets. The approach recognises that management agencies may
be called upon to make choices in a drying environment, and so some form of ordering
of assets will be required. However the work presented is only illustrative of the
technique, and the outputs are not intended to be definitive. Importantly, the process
has the potential to identify high-value assets, to allow refinement of the outputs in real
time (due to the use of highly adaptable software in MCAS-S) and is entirely
transparent in that all the contributory data and criteria are explicit.
1. OBJECTIVES OF THE RESEARCH

To provide Geographic Information System (GIS) services to the NCCARF project – “Adapting to Climate Change: A Risk Assessment and Decision Making Framework for Managing Groundwater Dependent Ecosystems with Declining Water Levels”. Specific objective were:

- Incorporation of hydrological data on to GIS platform
- Incorporation of risk assessment framework on to GIS platform

Within this report, these tasks have been reported on under the following headings:

**Project area definition**
Provision of defined area outlines that were required for the project study areas.

**Dataset provision**
Accessing of data for modeling and general project mapping requirements.

**Exposure & Vulnerability Mapping**
The incorporation of the following hydrological data onto the GIS platform:

- CSIRO Mapping of change
- CSIRO Projections
- Department of Water (DOW) survey data relating to water assets
- Cave water level change

Development of new (derived) datasets.

**Risk Characterisation**
Incorporate the risk assessment framework onto a GIS platform, and provide of spatial outputs from risk models.

Assess appropriate datasets, data scale, and methods for extracting data from GIS data and integrating with models.
2. RESEARCH ACTIVITIES AND METHODS

Simon Neville from Ecotones & Associates was contracted to provide GIS support to the NCCARF project – “Adapting to Climate Change: A Risk Assessment and Decision Making Framework for Managing Groundwater Dependent Ecosystems with Declining Water Levels”. This support was to cover four main areas:

- Identifying and sourcing data from custodians in WA.
- Incorporation of hydrological data on to GIS platform, and producing maps of exposure and vulnerability of GDEs in the study area.
- Creating new datasets from data provided.
- Integrating GIS data with Bayesian Belief Network (BBN) Models.

Additional work emerged through the project, including

- Definition of project areas
- Investigating ways of integrating environmental values with risk

2.1 Assemble Datasets for Project Areas

2.1.1 Define Project Areas

This study focussed on three sites representing two groundwater dependent aquatic ecosystems (GDEs): Wetlands on the data-rich Gnangara Mound and in the data-poor Blackwood catchment and caves (Jewel and Lake Caves, Margaret River). The sites were of sufficient size (landscape and subcatchment scale) to test the framework but remain manageable within the project timeframe.

Project areas were defined in consultation with the project team, and a call was sent out to the team to identify any potential datasets that would be required. The two main project areas were the Gnangara Study Area and the Blackwood Study Area.

The Gnangara area has been identified in many previous studies, and the actual outline used here was sourced from the Gnangara Mound Eco-Hydrological Study (Sommer & Froend, 2010). The area is 228,800ha approx.

The Blackwood study area did not have a specific pre-cursor, so the group decided to modify a number DWAI Groundwater SubAreas as supplied by DOW (notably the Blackwood-Yarragadee, Scott, Beenup, Rosa and Jasper areas) to create a shape covering the areas of interest. This area is 282,600ha approx. Note that the actual final modelling covered a smaller area within this (Yarragadee surface-expression) of approx 11,000 ha.

The Cave study area was defined as the cave extents. Note that the caves are very small in relation to the other study areas, as shown in Table 1:

<table>
<thead>
<tr>
<th>Name</th>
<th>area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easter Cave</td>
<td>6.16</td>
</tr>
<tr>
<td>Labyrinth Cave</td>
<td>1.34</td>
</tr>
<tr>
<td>Jewel Cave</td>
<td>1.63</td>
</tr>
<tr>
<td>Lake Cave</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table 1 – Cave Areas
These three study areas are outlined in Error! Reference source not found..
2.2 Datasets Assembled

Our project focus was mainly on GIS datasets. In addition, GIS data providers were contacted at an early stage to elicit a series of base GIS datasets. This was done well before the BBNs were developed to try to ensure data provision did not delay the project. Main providers of datasets were:

- The CSIRO
- Western Australian Department of Water (DOW)
- Western Australian Department of Environment and Conservation (DEC)

Some datasets provided in this way were from external custodians, and were licensed through the above providers.

2.2.1 Hydrological Datasets

A large amount of data was supplied by DOW. Some of this data was not subsequently either mapped or used in the spatial models, in particular large amounts of water quality data (both surface and bore data, water quality and stage heights) for the Blackwood Study Area from DOW. However the data was converted from spreadsheets into spatial locations and supplied to the fish modelling team to assist in model development. The following table lists some of the most significant hydrological datasets accessed.

<table>
<thead>
<tr>
<th>Name</th>
<th>Area</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DWAID_Groundwater_Areas &amp; subareas</td>
<td>WA</td>
<td>Groundwater Areas</td>
</tr>
<tr>
<td>HydroHierarchy &amp; HydroLinear</td>
<td>Gnangara &amp; Blackwood</td>
<td>Major streams &amp; All Streams</td>
</tr>
<tr>
<td><strong>Hydro Point datasets</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stream Gauging station locations</td>
<td></td>
<td>Locations</td>
</tr>
<tr>
<td>Stream Stage height Data</td>
<td></td>
<td>min, max, mean or total; annual, monthly, daily; Continuously recorded surface water sites.</td>
</tr>
<tr>
<td>Stream Discharge Data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Water Quality Data</td>
<td>Blackwood</td>
<td>Surface water SGS sites Data for 10 sites to 1999 &amp; for 22 sites 2000 – 2012</td>
</tr>
<tr>
<td>Groundwater site locations</td>
<td></td>
<td>Location, ID, construction details for 573 boreholes or wells</td>
</tr>
<tr>
<td>Groundwater levels</td>
<td></td>
<td>14325 water level readings from 401 separate sites</td>
</tr>
<tr>
<td>Groundwater Quality Sampling Data</td>
<td></td>
<td>573 boreholes or wells. 15581 WQ readings</td>
</tr>
<tr>
<td>Rainfall Data</td>
<td></td>
<td>min, max, mean or total; annual, monthly, daily; 13 continuously recorded rainfall sites</td>
</tr>
<tr>
<td>WIN Sites GN &amp; BW</td>
<td>SW WA (also clipped for Gnangara &amp; Blackwood)</td>
<td>Water Information network sites (bores, wetlands etc)</td>
</tr>
<tr>
<td><strong>Hydrogeology &amp; related</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrology State wide</td>
<td>Gnangara &amp; Blackwood</td>
<td>Surface Geology</td>
</tr>
<tr>
<td>250K Hydrogeology</td>
<td>Blackwood</td>
<td>1:250k map series hydrology</td>
</tr>
<tr>
<td>Soil_c_subsystem</td>
<td>Central Region &amp; Southern Region - (clipped for Gnangara &amp; Blackwood)</td>
<td>Soil Subsystem Mapping</td>
</tr>
</tbody>
</table>
A full list of all GIS datasets accessed in this way is provided in Appendix 1.
At later stages in the project additional data (such as Wetland Survey data) was
provided in tabular form and geo-referenced.

2.2.2 Geomorphic Wetlands dataset

The Geomorphic Wetland files supplied from DEC had incomplete (Swan Coastal
Plain) or no (Augusta-Walpole) Consanguineous Suite attribution. As it was considered
that this would be a useful classification for modelling, the information was updated
from the respective reports covering the development of this mapping (Hill, et al., 1996)
(V & C Semenuik Research Group, 1997).

For the Swan Coastal Plain, the Natural Wetlands Groups map (Figure 3, p10 from(Hill,
et al., 1996)) was rectified and digitised, and used to update any wetland polygons
without consanguineous suite attributes (about 37% of the total). For the south coast,
the map of preliminary descriptions of consanguineous wetlands suites (Fig 6, p22)
was used in the same way to indicate consanguineous suites for polygons in the area
covered by the suite mapping. This mapping only covers about 50% of the mapped
wetlands in the Blackwood study area.

2.3 Exposure & Vulnerability

2.3.1 CSIRO mapping of change

2.3.1.1 Datasets from CSIRO

The South West Sustainable Yields Project (SWSY) is one of a number of groundwater
change modeling projects around Australia being run through the CSIRO. It provided a
set of groundwater change projections for different climate scenarios out to the year
2030 (CSIRO, 2009A).

- Scenario A – This historical climate scenario was based on the climate of
  the historical past (28 years 1975 to 2007).
- Scenario B – The recent climate scenario based on the climate of the recent
  past (10 years 1997 to 2007).

C Scenarios - Future climate. These were based on 15 global climate models with
three estimates of temperature changes to give three alternative ~2030 climates:

- Scenario CDry – Dry extreme
- Scenario CMid - Median
- Scenario CWet – Wet extreme

In all the above scenarios, current levels of surface water and groundwater
development were used.

- Scenario D - The future climate with future development scenario used
  the same climate time series as CMid, but added future levels of
development by increasing groundwater abstraction to full allocation limits.

The CSIRO project partners provided an extensive set of data for the project, for both
the Central Perth Basin (using PRAMS: the Perth Regional Aquifer Modelling System)
and the Southern Perth Basin (using SWAMS: South West Regional Aquifer Modelling System), summarised below.

### 2.3.1.1.1 Datasets provided as classified grids

Much of these datasets were provided as classified grids, where the results were aggregated into a small number of classes (less than 10). This was done in order to respect the nature of the results – being projections, which are best regarded in terms of relative change rather than as absolute values. The list of data so provided is in Table 3 – SWSY Scenario Datasets provided as Grids. These data were classified rather than raw results.

In providing the actual model output, CSIRO were careful to point out that while it is possible to calculate the GW levels from the spreadsheets they “caution against basing results on actual projected levels given the uncertainties and errors in the models.” (G Hodgson, pers comm. Jan 2012.) For this reason their reports mainly look at the relative differences between scenarios. They do not claim to know exactly where the watertable will be in 2030 but can assess the relative impacts of climate change compared to a base case.

This is very important in the context of this project – the models developed here are based on actual model values, not relative values, and so are pushing the data beyond what the provider feels is appropriate.

**Table 3 – SWSY Scenario Datasets provided as Grids. These data were classified rather than raw results.**

<table>
<thead>
<tr>
<th>SWSY Scenario Projections</th>
<th>Area</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in Groundwater Levels 2008-2030</td>
<td>PRAMS &amp; SWAMS</td>
<td>Projected Change in Groundwater Levels from 2008 to 2030 – 500m classified Grid</td>
</tr>
<tr>
<td>Change in Groundwater Levels 2008-2030 relative to Scenario A</td>
<td>PRAMS &amp; SWAMS</td>
<td>Projected Change in Groundwater Levels from 2008 to 2030 compared to Scenario A – 500m classified Grid</td>
</tr>
<tr>
<td>Projected Groundwater Levels in 2030</td>
<td>PRAMS &amp; SWAMS</td>
<td>Projected Groundwater Levels in 2030 – 500m classified Grid</td>
</tr>
</tbody>
</table>

**Risk Scenarios**

| Risk to Groundwater Dependant Ecosystems 2008 - 2030 | PRAMS & SWAMS | Risk category associated with groundwater dependant ecosystems: |
| Changes in Area of Groundwater Dependant Ecosystems 2008 - 2030 | PRAMS & SWAMS | Change in area of groundwater dependant ecosystems: |
| Risk to Groundwater Dependant Ecosystems 1984 – 2007. Actual Groundwater change | PRAMS | Risk category associated with groundwater dependant ecosystems: |

### 2.3.1.1.2 Data provided as point files (ascii or excel)

Notwithstanding the preference to use the data as classified values, the NCCARF team requested that the raw projection data be provided, as this was what the BBN models would require. Initially this was done to provide the actually 2030 projected groundwater values for each scenario, and then further detail was provided as monthly projected values for the year 2030 to allow the use of max/min values in BBNs. These data are listed in Table 4.
Table 4 – SWSY Scenario Datasets – provided as point files. These data were the raw model output.

<table>
<thead>
<tr>
<th>SWSY Scenario Projections</th>
<th>Area</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projected Groundwater Levels in 2030</td>
<td>PRAMS &amp; SWAMS</td>
<td>Projected Groundwater Levels in 2030 – Model results, 500m cell values, xlsx spreadsheets.</td>
</tr>
<tr>
<td>Projected Groundwater Levels in for each month 2030</td>
<td>PRAMS</td>
<td>Projected Groundwater Levels in 2030 by month – Model results, 500m cell values, xlsx spreadsheets.</td>
</tr>
<tr>
<td>Projected Groundwater Levels in for each month 2030</td>
<td>SWAMS</td>
<td>Projected Groundwater Levels in 2030 by month – Model results, 500m cell values. Supplied as xyz ascii files.</td>
</tr>
</tbody>
</table>

**Bore Projections**

<table>
<thead>
<tr>
<th>PRAMS_super_bores_statistical_hydrographs_v1 PRAMS</th>
<th>PRAMS</th>
<th>PRAMS Bore sites – GW levels extracted from PRAMS model. 28 bores in PRAMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRAMS_bores_for_statistical_hydrographs.shp PRAMS</td>
<td>PRAMS</td>
<td>HARTT – statistical hydrograph analysis locations: separate analysis to compare to PRAMS model. (5 bores)</td>
</tr>
</tbody>
</table>

2.3.1.2 Datasets derived from CSIRO Projections

Two additional datasets were derived from the CSIRO projections, based on the model results, listed in Table 5 – SWSY Scenario Data derived from Grids. Only one of these (Rate of Change) was used in modelling, but the other is implicit in the vegetation change model. Rate of change was calculated as Projected Change / 23 (years 2007-2030). Change as a % of depth was calculated as Projected Change / Depth to Water Table (2007) as supplied by CSIRO.

Table 5 – SWSY Scenario Data derived from Grids

<table>
<thead>
<tr>
<th>SWSY Scenario Projections</th>
<th>Area</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projected Groundwater Levels in 2030 – Rate of Change</td>
<td>PRAMS &amp; SWAMS</td>
<td>Projected Change in Groundwater Levels to 2030 as m/yr</td>
</tr>
<tr>
<td>Projected Groundwater Levels in 2030 – Change as a % of Depth</td>
<td>PRAMS &amp; SWAMS</td>
<td>Projected Change in Groundwater Levels to 2030 as a % of the original depth to groundwater</td>
</tr>
</tbody>
</table>

2.3.2 Cave water level change

2.3.2.1 Cave Outlines

Very limited cave GIS data was available for the project, and discrepancies were observed between datasets, so it was decided to re-created locations of caves from survey data. Outlines of caves had been surveyed manually in the past, and were available as graphics with scale and north point (from Eberhard, 2004), although not as geo-referenced datasets.
We therefore created cave outline shapefiles from hand-drawn outlines for Lake, Easter and Jewel Caves and the Labyrinth using the following process:

- Cave outlines were scanned and geo-rectified in 3 stages:
  - Each cave outline had a metric scale which allowed the scanned image to be scaled;
  - entrance point locations allowed surface locations to be established; and
  - each map file was rotated to align north points on the scanned image with map north.
- The resulting cave outlines were checked against known features on the ground surface, and orientation & location corrected where required.

The final results were considered to be as accurate as possible (Eberhard, S pers com 2012) given the manual nature of the original surveys, and adequate for the purpose of cave visualisation.

### 2.3.2.2 Cave Water Levels

Hand-drawn maps of estimated water levels were provided for each cave, identifying the approximate extent of water in the caves for two historical periods (1958-1982, 1995-2004) and the present (2010-2012). These outlines were converted to solid shapes and rasterised using the ArcScan extension of ArcGIS. These were then used to clip the outline of each cave to create three separate shapefiles for each cave, one for each time period, as shown below for Jewel cave.

![Figure 2 – Hand-drawn maps have been converted to digital datasets (shapefiles). These illustrate declining Water Level in Jewel Cave. Severe groundwater decline over time has seen most water leave the cave.](image)

For the purposes of visualisation, 2.5D maps were produced of the four caves, to assess if these would assist in understanding of the cave structure and processes contributing to cave water decline. The maps were produced using the 3D Analyst extension of ArcGIS, and while not true 3D (where floor and roof topography would be accurately rendered), provided a simple outline of the cave structure. For Lake Cave this was made more realistic by creating a floor surface based on inferred levels; for the other caves, a single floor height was used for each cave, and rendered in the same scale as the surface topography, as shown in Figure 3.
Figure 3 – Representation of Leeuwin Caves in 2.5D. The cave representation is not true 3D, as it lacks interior topography.

Figure 4 – Representation of Lake Cave in 3D (floor). Rotating the point of view shows the cave as a 3D object.

2.4 Integrating GIS Data with Bayesian Models

2.4.1 Current literature

The project required that the set of Bayesian Belief Network (BBN) models being developed (SD6 Speldewinde 2013) could be provided with a range of data from the spatial datasets assembled. A brief review of the literature was carried out to identify examples of and methods for integration of GIS datasets and BBNs.

Integration of spatial data with spatial modelling, risk assessment frameworks and Bayesian networks has been carried out in very broad variety of ways for the last 30 years. Early work in spatial environmental modelling was carried out for conservation assessment reserves in the 1980’s (Margules and Usher, 1981; Margules and Nicholls, 1988; Margules, 1989). With the development of GIS techniques, more complex tools
were created, and by the 2000’s a very wide range of tools and techniques were being used. For example: Ortigosa et al (2000) developed a program (VVF) to integrate a range of suitability models into GIS; Heidtke and Auer (1993) created a GIS-Based Nonpoint Source Nutrient Loading Model; Boteva et al (2004) used multi-criteria evaluation to determine conservation significance of vegetation communities; Panitsa et al (2011) integrate species and habitat-based approaches to conservation value assessment within GIS. The large range of approaches use both built-in tools and customised tools for a very broad range of applications – from conservation value investigations to modelling of nutrient risk (Neville et al 2008) to modelling of ecological risk (Bartolo et al 2012). As part of these, GIS has been used as a base for a wide range of environmental models.

Analysis can be run from 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 modeling software such as MCAS-S (ABARES 2011), or by writing entire stand-alone programs. Or a combination of these approaches - Plant & Vayssieres (2000) combine a purpose-built package (QTIP) for qualitative modelling with the Idrisi GIS platform.

Modelling of risk has expanded greatly since initial single point analysis in the 1990’s: Pollino et al (2012) introduce a collection of risk assessment approaches by noting that models, “whether they be qualitative, quantitative, or a combination of both, play a fundamental role in risk assessment” (p13). They observe that ecological risk assessment has progressed from simple assessment to consider multi-stressor and multi-outcome assessments in dynamic environments, and has demanded a great increase in the sophistication of the models in order to meet users’ requirements of greater realism and transparency decision-making processes.

Many recent papers discuss the use of BBNs, which has developed as Bayesian modelling software has become popular. However few detail the use of GIS specifically to provide data to BBNs. Hart and Pollino (2009) carried out a detailed review of the potential application of two Bayesian modelling approaches (Bayesian hierarchical models and Bayesian network models) in the determination and management of environmental flow allocations. They conclude that Bayesian models “could play an important role in environmental flow assessment and decision-making in Australia” (pvi) but do not investigate the links between such networks and GIS for data provision or risk characterisation.

Gibbs (2007) outlines the use of a BBN to assess risk of aquaculture development on shore birds, but has no GIS component. Pollino et al (2007) describe the parameterisation and evaluation of a Bayesian network for use in ecological risk assessment, and note that parameterisation can be difficult in a knowledge situation and detail a process for combining data and knowledge. They use data sourced from databases but do not link the BBN with spatial data, and do not output results spatially. Glendining and Pollino (2012) discuss the use of BBN support tools in river rehabilitation works, and while there is a spatial component to this work, reporting on any linkage with, or outputs from the GIS is absent.

Dlamini (2010) developed a BBN from a range of variable to determine factors that influence wildfire activity in Swaziland. Satellite-sourced wildfire data were geospatially
integrated using the (GIS) software ArcView and BBN software Netica. However actual details on the integration with the GIS is sparse:

“The geographical database of all the variables was integrated using the ArcView 3.3 software (ESRI, 2002). All the explanatory variables were extracted at each point using ArcView’s geoprocessing functions and exported into a Microsoft Excel file for generating a case file of all the fire and no-fire points... for input into the BBN software Netica 4.02 (Norsys Software Corporation, 2007).” (Dlamini, 2012:201)

Based on different inputs, Smith et al (2007) use GIS data to both populate BBN Conditional Probability Tables and to map the results. They provide only a very brief outline of the process, which uses entirely polygon-based data rather than rasters. They initially intersected all their environmental variables into a single polygon layer, and exported the attribute table as a case file for all unique polygons. The case file was then run through their suitability model using the ‘Process Case’ function of Netica, and the output joined back to the attribute table. While Smith et al provide an overview of the process, no detail is provided. It has the advantage of using existing GIS tools and techniques, and requires no additional coding, but the approach is not suitable for raster data.

Hicks and Pierce (2009) outline a project where a purpose-built approach called CRAFT – the Comparative Risk Assessment Framework and Tools – was developed by the US Forest Service. This tool uses raster rather than polygon datasets. In searching for current solutions to integrate BBNs and GIS, researchers found nothing that was suitable for in-depth analysis of risk or was suitably generic. They therefore wrote their own tool using the ArcGIS application ArcMap and Netica, the BBN software from Norsys Software Corp. This paper (Hicks & Pierce) outlines an approach to the integration, which although lacking in actual code (or offering up online sources for same) gives a detailed outline of the process for the integration.

2.4.2 Study Approach

The general process as adopted is adapted from the CRAFT process outlined in Hicks and Pierce 2009:21-23) and can be summarised as follows:

Stage 1: Location & Data Preparation
1. Obtain necessary data.
2. Define Study areas
3. Prepare location data so all data have the same projection and resolution and that raster cells snap to the same grid.
4. Reclassify all data to appropriate classes.
5. Clip all data to study area boundaries.

Stage 2: Data Combination and Export
1. Use a custom tool to collect & classify input rasters and create an aggregate pointfile (Prep_Part_1).
2. Use a second custom tool to export this dataset as a case file (Prep_Part_2): Script defines a comma-delimited text file where every cell/point in the study
area is a single row, also selects export fields. Each variable—location IDnum and data—has a single column.

3. Where BBN uses discrete variables, open text files in Excel classify output values. Value_replacement.xlsx – converts classified raster values (integer) to model input values (text input values). Uses a modifiable lookup table.

Stage 3: Export Data from ArcMap and Import It into Netica

1. Write Control file for each model to identify input and output columns in the model input values dataset.

2. Open each export ascii file in Process_outfile_files.xlsx to convert headings to conform to database standards and export as .txt file.

3. Run the control file to import the comma-delimited text file into Netica as a case file: Cases>Process cases. This runs each case through the BBN without affecting it (as it would if a set of findings).

4. Define the BBN output file.

5. Open all scenario output files in single excel spreadsheet, name ranges for each scenario output.

Stage 4: Export Data from Netica and Import It Back into ArcMap

1. Add BBN export data from excel spreadsheet.

2. Run tool (BWF_Return_to_Pointfile) to add data and join to pointfile of model locations.

3. Symbolise output data.

The basic process was subsequently varied when point files rather than grids were used as input data; variations are noted below.

2.4.3 Tools produced

Three simple tools were created for this project to partially automate repetitive data processing tasks:

**BBN_Prep_Part 1** – ArcGIS Tool created in Modelbuilder. User selects one of more raster files, and re-classifies them to a preset set of classes. User also selects a point file (corresponding to the raster centroids), and extracts values from the rasters at the points for output as a point shapefile.
Figure 5 – BBN_PreP_Part 1 schematic diagram

**BBN_PreP_Part 2** - ArcGIS Tool created in Modelbuilder. Extracts selected field values from a point shapefile and exports them as an output ascii file. Uses a modification of the ArcGIS tool [Export Feature Attribute to ASCII] which does not export XY coordinates.

Figure 6 – BBN_PreP_Part 2 schematic diagram

**BBN_Return_to_PointFile**. ArcGIS Tool created in Modelbuilder. A simple tool which joins the output from BBN to a point file to allow display of the model results.
2.5 Risk Characterisation

In all six separate models were produced in the project (see SD6 Speldewinde 2013). They are shown in Error! Reference source not found. below, which lists the types of model and data requirements in each case. Only three of these have been run in a spatial form – the Gnangara Invertebrate Model, the Gnangara Vegetation Change Model, and the Blackwood River Fish Model - due to a lack of data availability or spatial unsuitability (Stygofauna model).
<table>
<thead>
<tr>
<th>Model</th>
<th>Gnaragra Invertebrate Model</th>
<th>Gnaragra Vegetation Change Model</th>
<th>Integrated Wetland Health Model</th>
<th>WA Frog Model</th>
<th>Blackwood River Fish Model</th>
<th>Cave Stygofauna Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Combo_macinvs_flters2.BBN</td>
<td>VegChange.BBN</td>
<td>Asstd.</td>
<td>final_blackwood_model.dne</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Source</td>
<td>Analysis of invertebrate collections in 16 wetlands over 14 years.</td>
<td>Analysis of transect data for x transects over x years.</td>
<td>Combination of GIM &amp; VCM</td>
<td>Expert opinion on Frogs</td>
<td>analysis of fish records</td>
<td>analysis of fauna records, water quality data, expert opinion</td>
</tr>
<tr>
<td>Input Data</td>
<td>Lithology, # Dry days/year, groundwater depth (m).</td>
<td>Starting DWT, GW change, GW rate of change from CSIRO Projections</td>
<td>Groundwater?, soil moisture, ?</td>
<td>Fish Health [poor, intermediate, good]</td>
<td>based on probability of outcome for 6 fish sp [persist, likely decline, severe decline]</td>
<td>Groundwater level</td>
</tr>
<tr>
<td>Output</td>
<td>Probability of adverse change in proportion, abundance, probability of risk of change to Vegetation State</td>
<td>Wetland Health [Good, Intermediate, Poor]</td>
<td>Stygofauna health</td>
<td>Water level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Scale</td>
<td>Wetland PRAMS model 500m cell</td>
<td>Wetland with modifications single wetland or cell</td>
<td>SWAMS model 250m cell</td>
<td>Per cave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Scenario Options</td>
<td>Start / finish of surveying (nominally 1996 &amp; 2010), &amp; [6 CSIRO Scenarios]*</td>
<td>6 CSIRO Scenarios</td>
<td>Not available currently</td>
<td>6 CSIRO Scenarios</td>
<td>Not available currently</td>
<td></td>
</tr>
<tr>
<td>Model Run Date</td>
<td>1996, 2010, [2030]*</td>
<td>2030</td>
<td>[2030]*</td>
<td>n/a</td>
<td>2030</td>
<td></td>
</tr>
<tr>
<td>Status</td>
<td>Partial</td>
<td>Complete</td>
<td>awaiting data*</td>
<td>Un-run</td>
<td>Complete</td>
<td>Un-run</td>
</tr>
</tbody>
</table>
2.5.1 Gnangara Vegetation Change Model

2.5.1.1 Area definition & mapping

The Gnangara Vegetation Change Model (SD2 Sommer et al 2013) is a broad-scale model that predicts vegetation change in areas where groundwater is less than 5.2m from the surface. These are areas where groundwater has a significant effect on water availability to vegetation, ranging from Aquatic through Sub-littoral, Littoral, Supralittoral and Phreatophytic vegetation EH states (Sommer and Froend, 2010). The Gnangara Study area is extensive (228,000 ha), having 8870 PRAMS reporting cells on a 500m grid, and this model can be run over the entire area.

The model was developed by analysing vegetation change in relation to groundwater decline along transects at 17 locations in the Study Area, during the years 1996-2008 (Wetland vegetation) and 1975-2008 (Terrestrial Vegetation) (Sommer & Froend, 2010). The limitation on groundwater depth arises as the model training dataset only contained sites where groundwater was within 5.2m of the surface. Such areas (at the model start year 2007) cover 1503 cells, or just fewer than 17% of all cells, as shown in Figure 8 below.

![Figure 8 - Gnangara Vegetation Change Model reporting points](image.png)
2.5.1.2 Base dataset source

The model uses three data inputs: Starting Groundwater depth, Groundwater decline and Rate of Groundwater decline. All of these are sourced from the PRAMS model monthly results tables, which report projected water table heights in M for each month of the year at 2030. The PRAMS model outputs projected values on a constant sized cell basis of 500x500m, cover almost the entire Gnangara mound study area.

2.5.1.3 Base datasets extraction

Data extraction was carried out for each PRAMS point in the Gnangara Study Area – a total of 8870 points. As the model requires the decline and rate to be calculated from the maximum height in the end year (2030), the max height (m AHD) was subtracted from the model base height (m AHD) for each cell in the area of interest to give groundwater decline, and divided by 23 (number of years) to give the rate of decline. This data was extracted for each of the 6 CSIRO Scenarios for the year 2030.

2.5.1.4 Model Process

1. Derivation of groundwater decline and rate was carried out in the Excel files as exported from PRAMS. Each PRAMS Scenario output was joined to the XY coordinates for each point, and the output identified as a ‘Named Range’ in Excel. The tables were added into ArcMap, and a point file was created for each scenario by using the ‘Display XY Data’ command, and then saving the result as a new point file.

2. We used BWF_PreP_Part2 to export field values from each point file as a comma delimited ascii file.

   Inputs: Extraction point file; Value fields required; delimiter
   Output: Point file with Start GWD, GW Decline and Rate of decline values.

3. Because it was developed with real data, the Veg Change model was set up to use continuous values. However it was necessary to truncate input values to match the extents used in the model, as shown in Figure 9.

   The outputs were copied into PRAMS_create_modeldata.xlsx, which was used to truncate PRAMS values to match model input ranges. These values were created for each SWSY Scenario, and the results saved as a .cas (case) file for Netica.
Spatially representing the impacts of falling groundwater levels

Start Groundwater depth was left unchanged. Values greater than 5.2m were simply excluded from final reporting. GWD < -0.8 is treated as -0.8.

Groundwater decline values were truncated:
=IF(GW Decline<0,0, IF(GW Decline>5,5)
Values between 0 and 5 remained unchanged.

Rate of decline values were also truncated:
=IF(Rate<0,0,IF(Rate>0.6,0.6,H3))
Values between 0 and 0.6 remained unchanged.

<table>
<thead>
<tr>
<th>Start_GWD</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.8 to 0.5</td>
</tr>
<tr>
<td>0.5 to 2</td>
</tr>
<tr>
<td>2 to 3.5</td>
</tr>
<tr>
<td>3.5 to 5.2</td>
</tr>
<tr>
<td>5.25 ± 0.43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GW_decl</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 0.3</td>
</tr>
<tr>
<td>0.3 to 0.45</td>
</tr>
<tr>
<td>0.45 to 1</td>
</tr>
<tr>
<td>1 to 5</td>
</tr>
<tr>
<td>0.725 ± 0.16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rate_decl</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 0.03</td>
</tr>
<tr>
<td>0.03 to 0.1</td>
</tr>
<tr>
<td>0.1 to 0.6</td>
</tr>
<tr>
<td>0.065 ± 0.02</td>
</tr>
</tbody>
</table>

Figure 9 – Vegetation Change Model Input Values

4. We ran each case file through Netica using the function Cases>Process cases.

A Netica Control File was written to export the required findings: a finding for Risk of Change to Vegetation State (P of Small or Large), a finding for Adverse Change in Proportion Risk (P of Small or Large), and a finding for Adverse Change in Abundance Risk (P of Small or Large). The Netica model must be compiled. Inputs must not be set to single case input. The Netica control file used was as follows:

```plaintext
IDnum()
finding (Start_GWD)
bel (Risk, Small)
bel (Risk, Large)
bel (Prop_change, Small)
bel (Prop_change, Large)
bel (Abund_change, Small)
bel (Abund_change, Large)
```

The output was a text file of results for each scenario.

5. We used a single Excel file [VegChange_results.xlsx] to process each Netica output file – multiple worksheets were used to rename headings to conform to database standards, and to name each results table (as a named range) for use in ArcMap.

6. These results tables were added into ArcMap, and a point file was created for each new scenario using the ‘Display XY Data’ command, and then saving the result as a new point file.

7. Finally, we ran BWF_Return_to_Pointfile to provide a pointfile with appended BBN results which can be displayed in ArcMap.

2.5.1.5 Output Representation

The output representation is in the form of single quantified legend for the Probability that the Risk of Change to Vegetation State is Large. The colours chosen make visual identification of this easy, and are all in the orange-red spectrum to reinforce that the
probability for a large vegetation change does not drop below 65% for all scenario, as shown below:

- 65 - 75%
- 75 - 85%
- 85 - 90%

**Figure 10 – Output Representation for Gnangara Vegetation Change Model**

### 2.5.2 Blackwood Fish Model

#### 2.5.2.1 Area definition & mapping

The Blackwood Fish Model (SD6 Speldewinde 2013) is a very area-specific model that predicts fish survival along a length of the Blackwood River where groundwater has a significant effect on water quality in the summer months. A long term survey program has provided the datasets that the fish model is based on, and the sites for this are shown in Figure 11.

**Figure 11 – Blackwood Fish Survey Sites**

Although the Blackwood study area as defined covers some 280,000 ha, the area that this model applies to is only a small part. The model was developed by analysing groundwater-river level relationships that apply in 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. The total area of the buffer is 1501 ha, shown below.

Figure 12 – Blackwood River (Yarragadee) Fish Health Model Area

2.5.2.2 Base dataset source

The fish model uses a single data input – Depth to water table (m). This input was sourced from the SWAMS model, which reports projected water table heights in M for each month of the year at 2030.

The model required a height 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 SWAMS model outputs projected values on a variable sized cell basis – varying from 1000x500m spacing along the western edge to 250x250m spacing along the Blackwood river in the area of interest for this project – the Blackwood River Fish Health Model (Yarragadee Aquifer area). The points are shown in Figure 13, where it can be seen that the area covered by the Fish Health model is one of two high density areas in the model.
Figure 13 - SWAMS Model reporting points
Data was extracted for each of the 6 CSIRO Scenarios at the year 2030.

2.5.2.3 Base datasets extraction
The Fish Model Area buffer – a 400m buffer either side of the river – was used define data points – a total of 191 points, as shown in Figure 14. Data extraction was carried out for each model point in the fish model area. Each model point provided a single DWT value for the model.
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Figure 14 - Blackwood River Fish Health Model reporting points

2.5.2.4 Model Process

1. Initially BWF_Prep_Part1 was used to classify the input raster and extract point values. However for the final runs we sourced the DWT (mar) values directly from the point files as exported from SWAMS. Each SWAMS Scenario output was joined to the XY coordinates for each point in Excel, and the output identified as a "Named Range" in Excel. The tables were added into ArcMap, and a point file was created for each scenario by using the ‘Display XY Data’ command, and then saving the result as a new point file.

2. We used BWF_Prep_Part2 to export field values from each pointfile as a comma delimited ascii file.
   - Inputs: Extraction point file
   - Value fields required
   - delimiter
   - Output: Point file with March DWT values.

3. The outputs were copied into Value_replacement.xlsx, and this Excel file was used to convert SWAMS values (real) 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 Error! Reference source not found..

   The output was a case (.cas) file for Netica with March DWT values in Model Classes; these were created for each SWSY Scenario.
Table 7 – Blackwood River Fish Health Model input class values

<table>
<thead>
<tr>
<th>Start</th>
<th>Finish</th>
<th>Input Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; - 8.5</td>
<td>-6.5</td>
<td>GWminus10_5</td>
</tr>
<tr>
<td>-8.5</td>
<td>-4.5</td>
<td>GWminus8_5</td>
</tr>
<tr>
<td>-6.5</td>
<td>-2.5</td>
<td>GWminus6_5</td>
</tr>
<tr>
<td>-4.5</td>
<td>-0.5</td>
<td>GWminus4_5</td>
</tr>
<tr>
<td>-2.5</td>
<td>1.5</td>
<td>GWminus2_5</td>
</tr>
<tr>
<td>-0.5</td>
<td>3.5</td>
<td>GWminus0_5</td>
</tr>
<tr>
<td>1.5</td>
<td>5.5</td>
<td>GW1_5</td>
</tr>
<tr>
<td>3.5</td>
<td>&gt;5.5</td>
<td>GW3_5</td>
</tr>
</tbody>
</table>

4. We ran each case file through Netica using the function Cases>Process cases.

A Netica Control File was written to export the required findings: a finding for Fish Health (P of Good, Intermediate or Poor), and findings for each of the 6 species involved (Persist, Likely Decline or Severe Decline). The control file used is listed below. The Netica model must be compiled, and Inputs must not be set to single case input.

```plaintext
IDnum()
  finding (groundwater_level)
  bel (fish_health, good)
  bel (fish_health, intermediate)
  bel (fish_health, poor)
  bel (balstoni, severe_decline)
  bel (balstoni, likely_decline)
  bel (balstoni, persist)
  bel (vittata, severe_decline)
  bel (vittata, likely_decline)
  bel (vittata, persist)
  bel (porosa, severe_decline)
  bel (porosa, likely_decline)
  bel (porosa, persist)
  bel (occidentalis, severe_decline)
  bel (occidentalis, likely_decline)
  bel (occidentalis, persist)
  bel (munda, severe_decline)
  bel (munda, likely_decline)
  bel (munda, persist)
  bel (bostocki, severe_decline)
  bel (bostocki, likely_decline)
  bel (bostocki, persist)
```

The output from this was a text file of the results for each scenario.

5. We used a single Excel file [Process_output_files.xlsx] to process each Netica output file – multiples worksheets were used to rename headings to conform to database standards, and to name each results table (as a named range) for use in ArcMap. These are the BBN Result tables.
6. These results tables were added into ArcMap, and a point file was created for each new scenario using the ‘Display XY Data’ command, and then saving the result as a new point file.

7. Finally, we ran BWF_Return_to_Pointfile to provide a pointfile with appended BBN results which could be displayed in ArcMap.

2.5.2.5 Output Representation

The output representation is in the form of a pie chart for each model point, each showing three values. These values represent the probability of the three output cases: Fish health = Good, Fish Health = Intermediate, and Fish Health = Poor. Colours were chosen to make visual identification of this easy:

- **Probability that Fish Health is GOOD**
- **Probability that Fish Health is INTERMEDIATE**
- **Probability that Fish Health is POOR**

**Figure 15 – Output Representation for Blackwood Fish Health Model**

The final fish health index combines the results from two indicator fish, *Galaxias occidentalis* and *Nannatherina balstoni*. 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 SD6 Speldewinde (2013) for more detail on the combinations making up the Intermediate class.

2.5.3 Gnangara Macro-Invertebrate Model

2.5.3.1 Area definition & mapping

The Gnangara Macro-Invertebrate Model (SD2 Sommer et al 2013) is a site-specific model that predicts Risk of Change to Macro-Invertebrate Communities. The necessary data for the Invertebrate model were Lithology (two options Spearwood or Bassendean sand); Groundwater depth and No. of dry days/year (or hydro-period). The model is applicable to any wetland area within the PRAMS SWSY area; however the necessary datasets are only currently available from 16 wetland sites.

2.5.3.2 Base dataset source

2.5.3.2.1 Wetland Surveys

The model was developed by analysing invertebrate collections for wetland sites at 16 locations in the Study Area, during the years 1996-2010. The sites and the years of data collection are shown below.
Table 8 – Wetland Sites and Data Collection

<table>
<thead>
<tr>
<th>Name</th>
<th>Start Year</th>
<th>Finish Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Gnangara</td>
<td>1996</td>
<td>2010</td>
</tr>
<tr>
<td>Lake Goolalal</td>
<td>1996</td>
<td>2010</td>
</tr>
<tr>
<td>Lake Jandabup</td>
<td>1996</td>
<td>2010</td>
</tr>
<tr>
<td>Lake Joondalup North</td>
<td>1996</td>
<td>2010</td>
</tr>
<tr>
<td>Lake Joondalup South</td>
<td>1998</td>
<td>2010</td>
</tr>
<tr>
<td>Lexia 186A</td>
<td>2000</td>
<td>2007</td>
</tr>
<tr>
<td>Lexia 186B</td>
<td>2003</td>
<td>2005</td>
</tr>
<tr>
<td>Lexia 86</td>
<td>2000</td>
<td>2007</td>
</tr>
<tr>
<td>Lake Mariginiup</td>
<td>1996</td>
<td>2009</td>
</tr>
<tr>
<td>Loch McNess North</td>
<td>1998</td>
<td>2010</td>
</tr>
<tr>
<td>Loch McNess South</td>
<td>1996</td>
<td>2010</td>
</tr>
<tr>
<td>Melaleuca Park EPP173</td>
<td>2000</td>
<td>2010</td>
</tr>
<tr>
<td>Lake Nowergup</td>
<td>1996</td>
<td>2010</td>
</tr>
<tr>
<td>Pipiddiny Swamp</td>
<td>1996</td>
<td>2008</td>
</tr>
<tr>
<td>Lake Wilgarup</td>
<td>1996</td>
<td>1998</td>
</tr>
<tr>
<td>Lake Yonderup</td>
<td>1996</td>
<td>2010</td>
</tr>
</tbody>
</table>

Some of these sites (eg Lake Wilgarup, Lexia 186B) have earlier finish dates due to the wetland drying. Each site provided a single potential case for the BBN.

2.5.3.2.2 Scenarios – Start/Finish

Data was provided from each wetland for two times in the year, effectively a dry and wet point. So the purpose of model run and visualisation, we selected just the first and last data point for each site – the ‘Start’ and “Finish” point. This gave the opportunity to illustrate change over time.

2.5.3.3 Base datasets extraction

Data was supplied as a single spreadsheet, and modified to provide two case files, one for the Start and one for the Finish point.

2.5.3.4 Model Process

1. Each wetland site was supplied with AWRC reference number as well as eastings & northings. A table was created for each Scenario (Start/Finish) in Excel, and identified as a ‘Named Range” in Excel. The tables were added into ArcMap, and a point file was created for each scenario by using the ‘Display XY Data’ command and then saving the result as a new point file.

2. We used BWF_Prep_Part2 to export field values from each pointfile as a comma delimited ascii file.

Output: Point file with Lithology, Groundwater depth and No. of dry days/year.

3. Other than Lithology (which was already categorical) the model was set up to use continuous values, so categorisation was not required. All input cases were within the model category bounds so no truncation was required.

These values were created for the two scenarios, and the results saved as a .cas (case) file for Netica.
4. We ran each case file through Netica using the function Cases>Process cases. A Netica Control File (listed below) was written to export the required findings: a finding for Overall Wetland Risk (P of Low, Moderate or High), a finding for Overall Macro-Invertebrate Risk (P of Low, Moderate or High), and a finding for water Quality Risk (P of Low, Moderate, High or Very High).

<table>
<thead>
<tr>
<th>IDnum()</th>
<th>bel (Overallr, Low)</th>
<th>bel (Overallr, Moderate)</th>
<th>bel (Overallr, High)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bel (Mac_Risk, Low)</td>
<td>bel (Mac_Risk, Moderate)</td>
<td>bel (Mac_Risk, High)</td>
<td></td>
</tr>
<tr>
<td>bel (Mac_Risk, Very_high)</td>
<td>bel (D, Low)</td>
<td>bel (D, Moderate)</td>
<td></td>
</tr>
<tr>
<td>bel (D, High)</td>
<td>bel (D, Very_High)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. We used a single Excel file [gn_wetland_cases.xlsx] to process each Netica output file. Multiple worksheets were used to rename headings to conform to database standards, and to name each results table (as a named range) for use in ArcGIS ArcMap. There were two result tables (Survey Start & Survey Finish).

6. These results tables were added into ArcMap, and a point file was created for each new scenario using the ‘Display XY Data’ command, and then saving the result as a new point file.

7. Finally, we ran BWF_Return_to_Pointfile to provide a pointfile with appended BBN results which can be displayed in ArcGIS ArcMap.

2.5.3.5 Output Representation

The output representation is in the form of single pie chart for each wetland, showing three Probabilities of ‘Overall Wetland Risk’ - Low, Moderate and High. Colours were chosen to make visual identification of this easy.

- Probability that Risk is LOW
- Probability that Risk is MODERATE
- Probability that Risk is HIGH

Figure 16 - Output Representation for Gnangara Macro-Invertebrate Model

2.6 Impact (Consequence) Assessment

2.6.1 Background

Risk is characterised as the likelihood that something will happen and the consequence suffered if it happens (McNeill et al 2006). In the context of the models being developed here, the event may be the change in existing aspects of the environment. The models deal with the nature of the event, and the probability (likelihood) of it happening, but do...
not evaluate consequences. Yet numerous studies suggest the need to evaluate ecological values when assessing risk (Hart & Pollino, (2009), McNeil et al (2006)).

2.6.2 Existing Values

It is possible to conduct simple *Value Assessments* of GDEs, based on existing datasets, to identify high value assets where change may have greater consequence. The initial stage of the process would be to identify if asset valuation is in existing datasets. If such valuation is available already, it can be used in conjunction with projections of change to identify risk.

In this project, asset identification is limited to the Geomorphic Wetlands dataset for the Swan Coastal Plan, including the Gnangara Study area. This includes a Wetland Management Category – a form of valuation aimed at management – which 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).

This valuation is shown in Figure 17.
Figure 17 – Wetlands Management Priority – Gnangara Mound

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. A good example of wetland value assessment for the Swan coastal plain is found in Hill et al. (1996) in section 5.6. Criteria can be taken from basic conservation value assessments (Margules & Usher (1981), Margules et al. (1982), Austin (1983), Margules and Nicholl (1988)).
2.6.3 Value Assessment

In order to further explore this, we have carried out some simple Value Assessments for the Gnangara Wetlands, based on existing datasets, to illustrate the potential of value assessment, where the high probability of change to a high value asset indicates greater consequence. The technique used was very exploratory, and the results only intended as illustrations of the potential of such assessments.

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. Conducting a series of workshops allows for the first cut assessment to be carried out and presented back to the group in an iterative process to refine the assessment model.

2.6.3.1 Approach

The approach taken to assess wetland values mirrors a similar approach used to evaluate conservation value of remnant vegetation in the south west (Neville, 2009). A series of simple criteria based on existing GIS data area used. The criteria are taken from basic conservation value assessments, which emerged in the 1980’s (Margules & Usher (1981), Margules et al (1982), Austin (1983), Margules and Nicholl (1988)).

These have been further developed and their relative importance quantified (Boteva et al (2004), Panitsa et al (2011):

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

The three datasets used were:

- Geomorphic Wetlands: An assessment of wetlands by classification, values, and consanguineous (similar) suite, from Semenuik, (1988) and Hill et al (1996);
- Heddle vegetation: Vegetation classifications (mapping of vegetation over the Darling Range region, showing vegetation complexes characteristic of various combinations of landforms, soils and rainfall) for the System 6 area from Heddle et al (1980)
- In addition a recent vegetation coverage layer from the Department of Agriculture was used to identify current vegetation extent.

A much more detailed vegetation classification by Mattiske is available, but this does not cover the entire Gnangara Study area.

Based on the available datasets, and the literature-based common criteria, for the current project the assessment criteria were as follows:

- Diversity
  - Arbitrary - # Heddle veg types within 500m
  - Wetland class –more value given to those with wetter status (eg wetlands, sumplands)
Rarity
- Consanguineous Suite type area (total)
- % remaining of veg type
- Individual Patch as % of remaining type
- Individual Patch as a % of remaining class

Naturalness
- Wetland Evaluation (wetland zoning)
- Individual Wetland Area (ha)
- Area of contiguous vegetation

Area
- Wetland Area

Threat/replaceability, while sometimes used as a criterion, were not used due to lack of suitable data and time to develop.

2.6.3.2 Modeling method

The chosen modelling vehicle was MCAS-S (Multi Criteria Analysis Shell for Spatial Decision Support - ABARES, (2011)), MCAS-S is a spatial software shell which can display spatial data but does not have full GIS functionality. This software is relatively easy to use and can easily be provided to 3rd parties for their use and modification. In addition it allows rapid combination of spatial datasets & criteria specification, and thus allows real-time development with interested parties/experts etc.

Data held within MCAS-S must conform in spatial extent, resolution, and projection. Because of this the user of MCAS-S therefore still requires GIS software for data preparation, and ArcGIS is the recommended software for the conversion process. Datasets were prepared in ArcGIS ArcMap10 to reflect these various criteria, and exported as grids on a common 50m cell size for use in MCAS-S.

2.6.3.3 Workflow

There were a variety of ways in which datasets were processed to make them suitable for MCAS-S. The major components of the workflow are:

- Identify the dataset required
  - Identify the way in which it will be used – as continuous data or categorical data.

- Pre-Processing - Undertake any necessary initial processing, such as
  - Conversion from shapefile to raster.
  - Re-classification.
  - Euclidean distance for proximity features, or
  - Calculations on fields (such as area to create rasters of area).

- MCAS-S Processing
  - Sample or re-sample the dataset to the standard resolution and location,
  - Re-project the raster during re-sampling or export
  - Export the raster to the appropriate MCAS Folder.
The ArcGIS map document used had its ArcToolbox Environment Settings set up to ensure a standard set of output rasters. Settings pre-set for all MCAS-S analysis were:

- Output coordinates [GDA_1994_MGA_Zone_50]
- Processing extent [standard Gnangara study area shapefile, with a single snap raster to ensure exact coincidence of rasters in analysis]
- Raster Analysis [cell size fixed at 50m, and mask set for the study area].

2.6.3.4 Final Model

The final model was designed with two intermediate outputs: Wetland Conservation Value and (Wetland) Vegetation Conservation Value. These were combined to provide a Final Conservation Value, but are better used separately. The final design of the model is shown in Figure 18, where Red colour indicate highest value and dark blue is lowest value. Criteria weighting was assigned purely on the basis of the literature (with minor modifications to reflect the datasets used) but in practice should be the result of a proper consultative process (Voinov & Bousquet (2010)). *The outputs should be considered illustrative only.*

![Figure 18 – Wetland Conservation Value Model Diagram](image)

In preparing the model outputs for display, a buffer was created to mask all areas more that 100m from any wetland identified in the Geomorphic Wetlands Dataset.
2.6.3.4.1  Wetland Conservation Value Criteria

The wetland conservation value is a combination of six input criteria, and applies just to the actual wetland areas themselves. The criteria used cover

- Rarity;
- Diversity; and
- Naturalness.

Note that all are derived from the same wetland classification.

RARITY – Wetland Proportion of Consanguineous Suite

All wetlands in the Geomorphic Wetlands dataset are classified by consanguineous suite (see Figure 42). This criterion measures the area of each individual wetland polygon in relation to its consanguineous suite. The higher that proportion, the more representative it is of its suite and the higher the value given. Maximum values are for proportion >50%. The resulting values are shown in Figure 19.

![Figure 19 – Wetland Conservation Model: Rarity – Proportion of Consanguineous Suite](image)

RARITY - Consanguineous Suite Area (total)

This criterion measures the total area of each consanguineous suite type. The smaller the total area the rarer in general that suite is and the higher the value given. Values were ascribed on an ‘equal interval’ basis, so the value to size relationship is a straight line. Values are shown in Figure 20.
Spatially representing the impacts of falling groundwater levels

**Figure 20 - Wetland Conservation Model: Rarity – Consang Suite Area (total)**

**RARITY - Wetland - Proportion of Class**

All wetlands in the Geomorphic Wetlands dataset are classified by class (e.g., Wetland, Sumpland, Dampland, or Palusplain). This criterion measures the area of each individual wetland polygon in relation to its class area. The higher that proportion, the more representative it is of its class and the higher the value given. Maximum values are for proportion >50%, as shown in Figure 21.

**Figure 21 – Wetland Conservation Model: Rarity - Wetland - Proportion of Class**
**DIVERSITY - Wetland Class**

The criterion reflects the different water status of each class of wetland, and arbitrarily ascribes value on that basis (wetter and/or more natural is better) as follows, from highest value (most diverse) to least value:

- Lakes, Sumplands, Estuary-Waterbody;
- Dampland, Estuary-Peripheral;
- Flood Plain;
- Palusplain, Artificial Lake;
- Dryland, No Longer a wetland.

Values are shown in Figure 22.

**Figure 22 - Wetland Conservation Model: Diversity - Wetland Class**

**NATURALNESS/AREA - Wetland Area (by class)**

All wetlands as defined it the Geomorphic Wetlands dataset were groups into size classes, and values ascribed on the basis of class. Values were ascribed in a curved function: as shown below in Figure 23, with the highest values (mapped as black) in the 10-50ha size.
Figure 23 - Wetland Conservation Model: Naturalness/Area - Wetland Area (by class)

NATURALNESS - Evaluation (Wetland Zoning)

All wetlands in the Geomorphic Wetlands dataset have been evaluated as belonging to one of four wetland management zonings – Conservation, Resource Enhancement, Multiple Use and Not Applicable. These zonings are based on conservation values, and value was ascribed in that order as shown in Figure 24. Red values are highest.

Figure 24 – Wetland Conservation Model: Naturalness – Evaluation (Wetland Zoning)
2.6.3.4.2 **Wetland Conservation Value Overall**

Criteria are as follows, with weightings shown as a value and the percentage that each criterion represents of the total weight:

- RARITY – Wetland Proportion of Consanguineous Suite – 1 (15%)
- RARITY - Consang 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%)

The resulting map is shown in Figure 25, where red has the highest value.

2.6.3.4.3 **Vegetation Conservation Value Criteria**

The vegetation conservation value is a combination of four input criteria, and applies to all areas of vegetation (not just to the actual wetland areas themselves). The criteria used cover

- Diversity;
- Rarity;
- Representativeness; and
- Naturalness.

Note that most are derived from the same vegetation classification.
DIVERSITY - Vegetation Type Diversity (Heddle, 500m)

The measures the number of vegetation types within 500m of each cell as shown in Figure 26. As the Heddle classification is a broad bush approach to vegetation, the measure of diversity is quite crude. A much more complex vegetation classification exists in the Mattiske classification, but this does not cover the entire area and so was not used.

![Figure 26 – Wetland Conservation Model: Vegetation Type Diversity](image)

RARITY - % Remaining of VegType

The Heddle classification used above covers all vegetation past and remaining. The classification of % Remaining of Veg Type compares the remaining area of each vegetation type with the original area as a percentage. The lower the percentage the higher the proportion of that vegetation type that has been lost, and so the rarer and more valuable each remaining patch is taken as being (see Figure 27).
This criterion measures the area of each individual vegetation polygon in relation to the total area of that vegetation Type. The higher that proportion, the more representative it is of its type and the higher the value given. Maximum values are for proportion >50%, shown in red in Figure 28.

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**NATURALNESS Area of Contiguous Vegetation**

Connection to large areas of contiguous vegetation allows for the recruitment of individual and species from other areas. This criterion uses a calculation of the area of contiguous vegetation (where areas have been buffered out an additional 50m to allow for small gaps) to ascribe value. Below 10ha is given the lowest value, which increases to 100ha, 500ha, 40000ha and above. Highest values show in red in Figure 29.

![Figure 29 – Wetland Conservation Model: Naturalness - Area of Contiguous Vegetation](image)

### 2.6.3.4.4 Vegetation Conservation Value Overall

Criteria are as follows, with weightings shown as a value and the percentage that each criterion represents of the total weight:

- **DIVERSITY - Vegetation Type Diversity (Heddle, 500m)** – 3 (46%)
- **RARITY - % Remaining of VegType** – 3 (46%)
- **REPRESENTATIVENESS - Patch % Remaining of VegType** – 1 (15%)
- **NATURALNESS Area of Contiguous Vegetation** – 2 (31%)

The resulting map is shown in Figure 30, where red represents the highest value.
2.6.4 Simple Hydrological Impact Assessment

2.6.4.1 Background

An alternative technique to assess impact is to undertake simple assessment of the groundwater change projections in conjunction with groundwater depths. Previous studies in the Gnangara Mound (Froend & Loomes, 2004, Sommer & Froend 2010) as well as the analysis carried out in the current project (SD2 et al 2013) have identified the importance of groundwater surface proximity in determining groundwater change sensitivity in the ecology. Proximity is a strong determinant of risk in both the Vegetation Change Model and the Macro-Invertebrate Model in this current project. The same studies identify that the amount (and by definition the rate) of groundwater change over time is also important.

The following figure (Figure 31) shows the CSIRO projection of groundwater change for the C Mid scenario, alongside the base case (2007) depth to groundwater map. Neither factor by itself is necessarily a good indicator of risk: high levels of change at depth are less likely to impact on GDEs, as the groundwater is beyond most rooting depth or surface hydrological impact. Alternatively, shallow water tables are not an issue if there is no projected decline into the future.
2.6.4.2 Approach used

The technique used combines these two factors – depth to groundwater and projected groundwater decline – in a simple weighted assessment, using the Modelbuilder Extension of ArcGIS 10. The assessment has been called the Simple Impact Assessment (SIA), and is an adaptation of a technique developed by Froend & Loomes (2004) to estimate risk of groundwater decline on vegetation. Existing values for depth to water table or projected change are reclassified, and each class rated in terms of its perceived contribution to risk of change. These classifications are shown in Figure 32. As the figure shows, depths less than 5m are rated as having the highest contribution (8-10) to impacts, and depths below 20m rated with no value. A projected 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. Note that this may not be correct, as large levels of rise may have significant impacts; however the ratings set here are indicative and illustrative only. The ratings on the input rasters are currently set as shown in Figure 32. Such ratings can be changed if required.

The two input grids are combined in the weighted overlay with equal weights (50%) using the classified values, and produce a final output in the range of 1 to 50, where 50 is the highest hydrological impact.

Figure 31 – Depth to Groundwater (2007) and Groundwater Change Projection (Scenario C Mid). Areas with depths greater than 10m are unlikely to be GDEs.
Spatially representing the impacts of falling groundwater levels

Depth to Water Table (2007) | Projected groundwater change

<table>
<thead>
<tr>
<th>Input raster</th>
<th>Input raster</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRAMS 2007 DWT Max Ht</td>
<td>Input GW change 2090</td>
</tr>
<tr>
<td>Raster field</td>
<td>Scenario</td>
</tr>
<tr>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>Reclassification</td>
<td>Reclassification</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Old values</th>
<th>New values</th>
</tr>
</thead>
<tbody>
<tr>
<td>-149.524</td>
<td>0</td>
</tr>
<tr>
<td>0 – 2.5</td>
<td>10</td>
</tr>
<tr>
<td>2.5 – 5</td>
<td>9</td>
</tr>
<tr>
<td>5 – 10</td>
<td>5</td>
</tr>
<tr>
<td>10 – 15</td>
<td>2</td>
</tr>
<tr>
<td>15 – 20</td>
<td>1</td>
</tr>
<tr>
<td>20 – 30</td>
<td>0</td>
</tr>
<tr>
<td>30 – 50</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 32 – Input Value Ratings for Simple Hydrological Impact Model

Figure 33 – Simple Hydrological Impact Model Outline

Risk outputs were produced for each climate scenario groundwater projection. Note that this technique explicitly does not account for the hydro-geology of specific areas which will affect the risk. The maps use a coloured scale to indicate impact – the colours chosen are entirely subjective and should be calibrated against known impacts if possible.

A second stage of the SIA is possible by combining the risk maps with previously produced conservation value maps for the wetlands. This was done for each scenario, again using the Modelbuilder Extension of ArcGIS 10, and multiplying the values together for each cell. Outputs are only produced for the wetland areas, and the use of multiplication means high values indicate cells which have both high impact and high wetland values. Output values range from 0 – 50.

Figure 34 – SIA + Wetlands Risk Model Outline

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3. RESULTS AND OUTPUTS

A large number of spatial datasets have been accumulated or produced through this project, and the following section presents the most significant.

3.1 Study Areas

3.1.1 Gnangara Study Area

Figure 35 – Gnangara Study Area
3.1.2 Blackwood Study Area

Figure 36 - Blackwood Study Area

Spatially representing the impacts of falling groundwater levels
3.1.3 Caves Sites

Leeuwin Naturaliste Cave Systems

Figure 37 - Leeuwin Naturaliste Cave Systems. Reproduced by permission of Western Australian Land Information Authority, C/L28 –2013.
3.2 NRM datasets for project areas

3.2.1 Cave Outlines and Water Levels

Cave outlines and approximated water levels are present in the next four figures. In all cases, water levels have declined significantly; catastrophically in all but Lake Cave (eg no water remains in Labyrinth Cave by 2010-2012).

Figure 38 – Area of Water in Lake Cave. Significant decline between 1995-2004 and 2010-2012 is shown.
Figure 39 - Area of Water in Easter Cave. Severe decline in area of standing water is shown between 1958-1982 and 1995-2004; further severe decline between 1995-2002 and 2010-2012 has almost completely removed water from the cave.
Figure 40 - Area of Water in Labyrinth Cave. Extreme decline in area of standing water is shown between 1958-1982 and 1995-2004; by 2010-2012 there is no water in the cave.
Spatially representing the impacts of falling groundwater levels

Figure 41 - Area of Water in Jewel Cave. Severe decline in area of standing water is shown between 1958-1982 and 1995-2004; further severe decline between 1995-2002 and 2010-2012 has reduced water to a single small pool.
3.2.2 Geomorphic Wetland Classification Update

Figure 42 - Updated Consanguineous Suites - Gnangara Mound. The classification shows 23 separate wetland suites covering the study area.
3.3 Exposure & Vulnerability

3.3.1 Groundwater Level Change to 2030

The first series of maps in this section show Projected Groundwater Change for 2030 for each of the six scenarios. Whilst these maps are produced using the raw output from the PRAMS & SWAMS models (rather than classified), they are identical to the SWSY mapping (CSIRO 2009A).

The first figure (Figure 44) shows the entire PRAMS reporting area, subsequent maps are limited to the Gnangara or Blackwood study areas.
Figure 44 – SWSY Northern Perth Basin PRAMS Projection – Groundwater Change to 2030. Groundwater decline is generally less pronounced in the north and west of the PRAMS area, and most widespread under scenarios B, CMid, CDry and D.
Spatially representing the impacts of falling groundwater levels

Figure 45 – Gnangara Study Area PRAMS Projection – Groundwater Change to 2030. Groundwater decline is significant in the Gnangara Study area under scenarios B, CMid and D, and severe under scenario CDry, where the water tables are projected to decline over most the Gnangara Study area.
Figure 46 - Blackwood Study Area SWAMS Projection – Groundwater Change to 2030. Groundwater decline variation reflects a complex hydro-geological situation. Decline is indicated under all scenarios, more pronounced under future scenarios B, CMid and D, and severe under scenario CDry. Under Scenarios CDry and D significant areas of water table decline are located on the coastal plain along the south of the study area.
3.3.2 Rate of change for projected Groundwater Levels to 2030

Figure 47 - Gnangara Study Area SWSY SWAMS Projection – Rate of Groundwater Change to 2030. Scenario CDry produces the highest rates of decline.

Spatially representing the impacts of falling groundwater levels
Figure 48 - Blackwood Study Area SWSY SWAMS Projection – Rate of Groundwater Change to 2030. High projected rates of decline are evident across the study area under all future scenario projections; Under Scenarios CDry and D, moderate high rates of decline are evident along the coastal plain along the south of the study area.
3.3.3 Change as a % of initial GW depth

Figure 49 - Gnangara Study Area SWSY SWAMS Projection – Groundwater Change to 2030 as a % of Initial Depth. Highest % declines are evident under Scenarios B and CDry; only CWet projects limited areas of decline.
Figure 50 - Blackwood Study Area SWSY SWAMS Projection – Groundwater Change to 2030 as a % of Initial Depth. Area of large % declines are indicated under all scenarios, but especially future scenarios (CMid, CDry, D, and even CWet). Under Scenarios CDry and D areas of high % declines are located on the coastal plain along the south of the study area.
3.4 Risk Characterisation

Risk characterisation is the basic output of the three models completed.

3.4.1 Blackwood Fish Model

3.4.1.1 Individual Fish results

Examples of the mapping for two indicator species are given.

Figure 51 - Blackwood Fish Health Model results – Individual Fish Scenario A.
Figure 52 - Blackwood Fish Health Model results – Individual Fish Scenario C Dry

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3.4.1.2 Overall Fish Health results

Figure 53 – Blackwood Fish Health Model results – Scenarios A & B
Spatially representing the impacts of falling groundwater levels

Figure 54 - Blackwood Fish Health Model results – Scenarios C Dry and C Mid
Figure 55 - Blackwood Fish Health Model results – Scenarios C Wet and D

Spatially representing the impacts of falling groundwater levels
3.4.2 Gnangara Macro Invertebrate Model

Overall Wetland Risk Probability
Combination of the Risk of Change to:
- Macro-Invertebrate Community Structure
- Water Quality

Wetland Survey Start Year

- Probability that Risk is LOW
- Probability that Risk is MODERATE
- Probability that Risk is HIGH

Figure 56 – Gnangara Macro Invertebrate Model – Overall Wetland Risk: Survey Start

Spatially representing the impacts of falling groundwater levels
Overall Wetland Risk Probability
Combination of the Risk of Change to:
- Macro-Invertebrate Community Structure
- Water Quality

Wetland Survey Finish Year

Figure 57 - Gnangara Macro Invertebrate Model – Overall Wetland Risk: Survey Finish

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3.4.3 Gnangara Vegetation Change Model

3.4.3.1 Vegetation Change Risk Maps with SWSY GW Projections

The Vegetation Change model output for each groundwater scenario is provided in Figure 58 to Figure 63, placed over the corresponding projection for groundwater change to 2030. Comparing the C Dry results (Figure 60) with C Wet (Figure 62) illustrates problems in the model output, where inconsistencies in the training data set have lead to counter-intuitive indications. Areas are shown to have higher risk under the C Wet scenario that the C Dry, even though the latter leads to greater declines in groundwater levels that will stress vegetation more. Further examination of the model results show that this is not an error or inconsistency in the groundwater predictions; rather the model does not perform consistently in some input combinations. This is discussed in Section 4.2.2.
Figure 58 - Vegetation Change Risk & Groundwater Change - Scenario A
Figure 59 - Vegetation Change Risk & Groundwater Change - Scenario B
Figure 60 - Vegetation Change Risk & Groundwater Change - Scenario C Dry
Figure 61 - Vegetation Change Risk & Groundwater Change - Scenario C Mid
Figure 62 - Vegetation Change Risk & Groundwater Change - Scenario C Wet

Spatially representing the impacts of falling groundwater levels
Figure 63 - Vegetation Change Risk & Groundwater Change - Scenario D
3.5 Additional Risk Assessment

3.5.1 Indicative Conservation Value Maps

A number of approaches to identifying Risk/Consequences have been explored using value assessment mapping combined with various risk models.

The first two figures show the results of the conservation value mapping for wetlands as defined in the Geomorphic Wetlands dataset (Figure 64), and for existing vegetation in the areas defined as wetlands (Figure 65). The model identifies two series of high values wetlands running parallel with the coast, with the eastern wetland areas generally being of lesser value, except for a concentration of high value to the north east of the study area.

Wetland-associated high-value vegetation is spread much more broadly through the study area.
Spatially representing the impacts of falling groundwater levels

Figure 64 – Indicative Conservation Values – Gnangara Wetlands

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Spatially representing the impacts of falling groundwater levels

Figure 65 - Indicative Conservation Values – Gnangara Wetland Vegetation
3.5.2 Simple Impact Assessment

Results for the Simple Impact Assessment Model are given for the 6 CSIRO groundwater change Scenarios. These are indicative maps demonstrating the technique. Risk is indicated as being widespread in for Scenarios B and C Dry, less so for C Mid and D.

Note that due to the similarities in the input criteria of this technique and the Vegetation Risk BBN, the results of the Vegetation Change Model should correspond to the results of this technique to a large degree. This however is not the case, partly due to the inconsistencies noted previously, which are about relative results. For example the figure below shows the Veg Change model results over the SIA results for Scenarios A
Spatially representing the impacts of falling groundwater levels

The SIA underlay shows very significant differences for the two assessments – based entirely on the difference in groundwater projections. The Vegetation Change model values for the C Wet scenario are not only all in the same range (between 65 and 85% probability that risk is large) but some are actually higher than the corresponding value in the C Dry scenario – even though the indicated SIA risk is far lower.

**Figure 67 – Vegetation Change Risk Maps compared to SIA Assessments**

### 3.5.3 SIA + Wetland Maps: Combining Conservation Value and Impact Assessment

Overlaying the indicative wetland conservation values onto the Impact assessment map for the C Mid in Figure 68 shows that some of the larger high-value wetlands occur in areas not projected to have significant declines. Others (such as to the north of the study area) may be subject to large declines, but many of these are in areas with deep groundwater (>10m) and are unlikely to be groundwater dependant.
Using the second stage of the SIA, we have intersected these two components of Consequence – impact and value – into maps for each Scenario. Such maps would be useful in indicating areas of concern; also in providing a basis to make decisions of resource allocation – both for additional research and potentially for management. The six scenario maps are shown in Figure 69.
Spatially representing the impacts of falling groundwater levels

Figure 69 – SIA + Wetland – Consequence Maps – Gnangara Study Area
3.5.3.1 BBN Output overlays on Indicative Conservation Value Maps

3.5.3.1.1 Macro-Invertebrate Model

Combining the results of the Macro-Invertebrate Model with the indicative Wetland Value mapping illustrates the coincidence of the wetland survey sites with high-value wetlands. The probability that Wetland Risk is Moderate-High is significant in most of the high value wetlands, indicating severe consequences of change over the survey period.

![Diagram of wetland risk and conservation value](image)

**Figure 70 – Wetland Risk and Wetland Conservation Value - Gnangara Study Area**

3.5.3.1.2 Vegetation Change Risk Model

At the broad scale, it is difficult to see clearly the intersection of Vegetation change model reporting and either the wetland conservation value (Figure 71) or (wetland) vegetation conservation value (Figure 72). But seen at a finer scale there is a high probability (>75%) that the risk of vegetation change is large for many high value wetlands along the coast (Figure 73).
Spatially representing the impacts of falling groundwater levels

Figure 71 – Vegetation Change Risk and Wetland Conservation Value – Gnangara Study Area
Figure 72 - Vegetation Change Risk and Wetland Vegetation Values
Figure 73 - Vegetation Change Risk and Wetland Values – Northern Coastal Plain, Scenario A
4. DISCUSSION

The main purpose of this report is to present the maps resulting from the application of the BBNs developed in the project, and describe the processes used.

4.1 Exposure & Vulnerability

The exposure and vulnerability mapping is all based on the results of the South West Sustainable Yield (SWSY) project run by CSIRO and using a series of large-scale groundwater models (PRAMS and SWAMS). The scale and purpose of the SWSY projection means that the datasets available are not ideal for the modelling uses that they have been put too. However they are the only projections of groundwater change into the future that we had access to. It is important to note that the SWSY project mainly refers the scenarios relative to the base case: they do not claim to know where the water table will be in 2030 but can assess the relative impacts of climate change compared to a base case.

The SWSY project characterises uncertainly of future estimates of groundwater levels as being ‘High’ or ‘Medium-High in both the Gnangara Study area and the Blackwood study area. This still allows for significant uncertainty in relation to the sensitivity of the models: average calibration error for PRAMS is 1.6m for the Superficial Aquifer, but this varies from 11.2m (max) to -16.0m (min). Average calibration error for SWAMS is 2.4m for the Superficial Aquifer, but this varies from 10.3m (max) to -6.6m (min). The average error is 3.0m for the Yarragadee Aquifer (20.5m Max and -99.1m min) (CSIRO 2009A:322). This error is significant in parts of the Gnangara Study area (shown in the following figure) where water levels are over-estimated by 2-5m (from CSIRO 2009A:311).

Figure 74 - PRAMS calibration error distribution in the Superficial Aquifer in 2003 (CSIRO 2009A:311)
4.2 Risk Characterisation

4.2.1 Use of regional groundwater model results.

Using the SWAMS or PRAMS results to project impacts of groundwater decline has significant issues. The CSIRO SWSY project was designed to provide information on groundwater levels at regional scale, and project the impacts of climate-change related rainfall change and abstraction on both surface and confined aquifers (CSIRO 2009a). Because of this focus, the use of a 500x500m grid (PRAMS) or a variable spacing grid (SWAMS – 250x250m up to 1000x500m) was acceptable and suitable. However trying to use the same grids for predicting impacts at the surface is problematic, due to the fine scale of surface wetland features and surface topography.

In this section we will outline just one aspect of these problems, noting that others are also significant (such as the margins for error in any results based on regional climate models and projected over 20 years into the future).

The map in Error! Reference source not found. below shows the variation in the surface topography (using a 10m DEM) compared to the model surface height (using the 500m DEM) for each SWAMS 500m grid cell. [Range of values for the 10m DEM using a 500m mesh as the zonal input]. Clearly the use of a 500m grid greatly simplifies the surface.

The groundwater values in the SWAMS/PRAMS output are given a single value over a large range of surface variation, meaning that inferring a specific depth to groundwater will produce errors according to the surface variation. Critical depths for GD plants are up to about 5.2m; therefore for much of the model the natural variation will be in excess of the critical value for ecological processes.
The way that this error propagates can be seen in the two figures below, one for the entire PRAMS area and the other a detail in the vicinity of Lake Joondalup. [PRAMS surface minus 10m DEM, 10m cell basis]. The differences between 10m cell heights and 500m cell heights vary from >30m below to 60m above.
Where the ground is flat, differences are low. But where the local relief is high, differences are evident, trending from positive to negative in the direction of the slope. These differences are significant in the context of the eco-hydrological models: for the vegetation change model, depths to groundwater of more than 5.2m are not considered, and yet variations of more than this are integral in the PRAMS model. We therefore have had to assume that the groundwater heights reported on a 500m grid basis are varying with the local relief, and maintaining a constant depth below surface regardless of surface terrain.

This mismatch in scale can also be seen with the vegetation change model, where the length of transects that the sampling was conducted with was generally no more than 40m – less than 10% of each PRAMS cells size.

For these and other reasons the results are presented as indications of how the data, techniques and models developed here can be used. The results should not be relied upon to provide actual indications of risk.

In order to overcome these issues a much finer scale dataset would be required. For the surface this already exists as high resolution digital elevations models on a pixel size of 10m or better. For groundwater levels there are a few options:
• Use finer scale models where these have been developed (eg in certain wetlands on the Gnangara Mound - Lake Bindiar, Lake Nowergup and the Lexia wetlands (SKM 2009a & b, 2010).)
• Project forward for single locations – eg using bore data where errors may be better controlled;
• Use the BBNs to model 'what-if' scenarios of potential future cases, rather than trying to create a future dataset under a specific scenario. E.g. "what if the water level falls 4m?"

4.2.2 Gnangara Vegetation Change Model

The Vegetation Change model was run for the CSIRO 2030 Scenarios for the entire Gnangara Area – PRAMS – although the model (in its current form) is only applicable to areas where the DWT <5.2m. The model uses the PRAMS data at the arguably inappropriate cell size (500m).

The model suggests broad-scale vegetation change under all scenarios. There is difficulty using coarse input data for such projections, given the level of potential error, relative to the sensitivity of the model. The margins of error in input data could shift model outputs very significantly.

The scenario differentiation of the results is also not clear, with counter-intuitive results, (as shown in Figure 67) which can be traced to the model’s inconsistent behaviour under certain input conditions. Figure 78 plots the probability of vegetation change risk being high under all input states, and shows, for example, the highest probability [of change risk being high] in two blocks where the starting groundwater depth between 0 and about 2.5m from the surface, and the magnitude of decline is between 0 and 1.5m. But between the two blocks, where magnitude of decline is between 0.5 and 1, the probability is at the second lowest level. This and other inconsistencies are probably due to either:

• the training datasets having missing combinations of input variables, or
• individual cases in some groups having unusual external influences (such as high levels of vegetation change due to weed invasion).
Figure 78 – Vegetation Change Model Results: Plot of Probability of Vegetation Change Risk being High under all input states

4.2.3 Blackwood Fish Model
This model was run for the six CSIRO 2030 Scenarios, and provides a prognosis for 6 fish species [persist, likely decline, severe decline], as well as for the general fish health [poor, intermediate, good] based on 2 fish species.

The model has a very limited area of application, but the approach has real promise for similar situations elsewhere. In its current form it identifies limited small refugia, with the situation under Scenarios C Dry & D the least optimistic. The latter is interesting as it suggests that the additional extraction under Scenario D will have an impact.

There are significant difficulties in using the SWAMS input data for such projections however, given a high level of potential error, and a very sensitive model. The likely margins of error in input data may be beyond the tolerance range of fish.

4.2.4 Gnangara Invertebrate Model
The model varies from the previous two in that each site is a survey wetland with real data, and thus is not subject to spatial uncertainty due to the scale of the model producing it. At this stage, the model has only been run for beginning and end survey years, however a 2030 projection is being attempted and may be finalised in order to run the model for the future scenarios.

Some changes that the model predicts are verifiable from historical survey data:

- Identifies refugia in Lakes Joondalup, Goollelal, Jandabup, Nowergup, McNess.
- Identifies increasing risk in eastern wetlands (Melaleuca Park, Lexia), Lakes Mariginiup, Gnangara, McNess.

These are very limited data sets, with surprisingly small number of sites considering the environmental values associated with wetlands. However each site represents significant investment over time. Generally we observe a lack of data required for such modelling.

4.2.5 Value/Impact/Consequence Mapping

Comprising the Conservation Value mapping, the Simple Impact Assessment and Consequence mapping, this work was undertaken to both provide examples of simpler risk techniques, and to contextualise the risk model outputs in terms of assets. It also recognises that management agencies may be called upon to make choices in a drying environment, and so some form of ordering of assets will be required.

As a simple example, we have combined a Consequence map (Scenario C Mid) with the map of natural wetland groups (from Hill et al 1996) in Figure 79. The indicates which wetland groups are likely to suffer significant decline, as well as if individual wetlands within a group are more likely to remain in good condition.

![Figure 79 – Wetlands Groups with Consequence of Change (Scenario C Mid).](image)

The criteria used in each section of the process are based on some literature and first principles, but would require significant work to be acceptable to management agencies or academia. However such work is entirely possible in the context of natural resource management in Western Australia and elsewhere. The use of experts in...
developing such assessments is both common and appropriate given the limited resources available and short timeframes involved in the change to hydrological assets [see Margules & Usher (1981), Neville (2009), Hart & Polino (2009), Sandker et al. (2010), Lombard et al. (2010), Voinov & Bousquet (2010), Gobbi et al. (2012) for a range of approaches to this].

The results of the process are supported by Vegetation Change Results to a degree, although the issues with the Vegetation Change Model suggest that the coincidence of the two techniques could be greater than the maps show.

Importantly, the process has the potential to identify high-value assets, to allow refinement of the outputs in real time (due to the use of highly adaptable software in MCAS-S) and is entirely transparent in that all the contributory data and criteria are explicit.
5. GAPS AND FUTURE RESEARCH DIRECTIONS

5.1 Refinement of existing Vegetation Change Model
Currently this model contains inconsistent Conditional Probability Tables (CPT’s) which have resulted in issues with outputs. Such tables are very large and require significant work to correct for inconsistency in the original (real) data they are based in. Such smoothing would provide a more suitable model for wider application.

5.2 Further Spatial Modelling Options
Sourcing of finer scale groundwater projections, such as may be available from more localised groundwater models. Such models have been developed for a small number of key wetlands in the Gnangara mound, including Lake Bindiar, Lake Nowergup and the Lexia wetlands (SKM 2009a & b, 2010). Future work could extract this data on much finer scales and use this to run the Gnangara models. Alternatively, development of downscaling methods to use projections at a coarse scale with existing finer scale groundwater mapping may provide more appropriate datasets for spatial models.

5.3 Develop additional modeling Datasets
Future projections of Wetland survey data would allow the Invertebrate model to be projected into the future, and to allow the full wetland model to be run.

5.4 Refine Spatial Impact Models
The Value/Impact/Consequence work here is just the beginning – a process to involve management agencies in developing the assessment criteria could produce a valuable management tool. Indeed, this could find immediate applications in areas where conservation assessment of wetlands is currently needed, in areas where declining water tables are already affecting wetlands.
REFERENCES

Reports associated with this project


Spatially representing the impacts of falling groundwater levels

Reference list

(Includes items collected through this project but not referenced in the report.)


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## APPENDIX 1 – GIS DATASETS COLLECTED.

### GIS Datasets Collected – NCCARF Groundwater Project

**Table 9 – Data sourced and licensed from CSIRO**

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Spatially representing the impacts of falling groundwater levels

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<th>Bore Projections</th>
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<th>PRAMS Bore sites – GW levels extracted from PRAMS model. 28 bores in PRAMS</th>
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<td>PRAMS_super_bores_statistical_hydrographs_v1</td>
<td>PRAMS</td>
<td>HARTT – statistical hydrograph analysis locations: separate analysis to compare to PRAMS model. (5 bores)</td>
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Ecosystems: Wetlands & Vegetation (0-3m GW depth), Vegetation (3-6m), Vegetation (6-10m)
Risk categories (Severe, high, moderate, low, none) from Froend & Loomes 2004, 500m classified Grid
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<td>Pre-European Vegetation</td>
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<td>Vegetation Associations pre-European clearing</td>
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<td>Location, boundary and geomorphic classification (wetland type) of wetlands. Source: Mapping and classification of wetlands from Augusta to Walpole in the South West of Western Australia (V &amp; C Semeniuk Research Group 1997)</td>
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<td>Waterbodies</td>
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Hydrogeology etc
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