Groundwater methods used in the South-West Western Australia Sustainable Yields Project

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December, 2010

A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project
South-West Western Australia Sustainable Yields Project acknowledgments

The South-West Western Australia Sustainable Yields project was undertaken by CSIRO under the direction of the Australian Government Department of the Environment, Water, Heritage and the Arts. Important aspects of the work were undertaken by the Department of Water Western Australia. The Water Corporation and the Western Australia Department of Agriculture and Food provided expert advice and data. A contract to develop a groundwater model for part of the region was undertaken by URS Australia Pty Ltd. Additional technical input was provided by CyMod Systems, Jim Davies and Associates, Resource Economics Unit and Geographic Information Analysis. Valuable feedback was received during the review process from Tony Jakeman, Andy Pitman, Don Armstrong.

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Executive Summary

The South-west Western Australia (SWWA) Sustainable Yields Project determined the currently available surface and groundwater resources in south-west Western Australia and projected how these may change under future climate scenarios. These projections were used to estimate future surface and groundwater yields and the implications for meeting consumptive and environmental demands. Three main reports were produced from the project giving the findings for projections of surface water; groundwater; and water yields and demands. Additionally three summary reports, four fact sheets and an overall methods report were produced and are available from the web (http://www.csiro.au/partnerships/SWSY.html).

This report presents details on groundwater methods that were either not covered or only briefly covered in the main report and actual methods report. The methods are covered in sufficient detail that they may be repeated by anyone not familiar with the project in future if required.

This report contains five chapters describing methods used for the groundwater modelling and assessment part of the SWWA Sustainable Yields Project. Chapter 1 provides a general introduction of the SWWA Sustainable Yields Project and methodological framework of this report. Chapter 2 gives description of the actual methods used for the groundwater modelling and assessment under a range of climate change scenarios and current and future extraction regimes.

Chapter 3 provides a detailed land cover mapping methodology for the whole project area. The land cover mapping was required to provide inputs into the surface and groundwater models. For the groundwater part of the project the land cover mapping was used as input in the Vertical Flux Models (VFM) or WAVES (Water, Atmosphere, vegetation, Energy, Solute) model. These models estimates recharge rates or deep drainage based on soil type, climate, land cover and watertable depth. This chapter describes the development of an ArcGIS-based model for mapping the historical and current land cover for the project area which is a modification of the land cover methodology previously developed for the PRAMS area. The developed model was then used to process historical Landsat 5 Thematic Mapper (TM) data to produce land cover maps at two-yearly intervals from 1988 to 2002 and yearly intervals from 2003 to 2008. The areas of native vegetation, pine plantation, dryland agriculture, summer wet areas, urban and bare soil areas, commercial and industrial areas, and open water and wetland were classified as land cover classes on each map. In addition a number of subclasses within native vegetation and pine plantation classes were mapped to reflect vegetation densities that affect recharge rates.

Groundwater prioritisation approaches used to prioritise Groundwater Management Areas (GWAs) of the SWWA are described in Chapter 4. Three prioritisation approaches were used to prioritise the GWAs that make up the groundwater modelling and assessment project area. These include the: Murray-Darling basin prioritisation approach; National Land and Water Resources Audit/Department of Water prioritisation method; and tier-based prioritisation approach. The prioritisation results obtained using each of the three approaches are also part of this chapter.

The last chapter (5) of this report outlines detailed methodology for estimating groundwater levels using the Hydrograph Analysis and Rainfall Time Trends (HARTT) program. The HARTT method is an automated derivation of a statistical technique called Cumulative Deviation From the Mean (CDFM) for the prediction of groundwater levels from rainfall data. The CDFM method is based on the assumption that rainfall, or cumulative departure from mean rainfall, at a groundwater monitoring site explains changes in groundwater levels of unconfined aquifers. This analysis was used to project future groundwater levels in various regions of project area based on the relationships between rainfall and changes in watertable depth. These results were compared with model projections in the groundwater modelled areas for independent checks and validation.

Appendix A in this report displays statistical hydrographs from the Central Perth Basin, the Southern Perth Basin; and the Northern Perth Basin. These statistical hydrographs were prepared using methods outlined in Chapter 5 of this report.
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1 Introduction

This report is one of a series of technical reports from the South-west Western Australia (SWWA) Sustainable Yields Project. The project determined the currently available surface and groundwater resources in south-west Western Australia and projected how these may change under future climate scenarios. These projections were used to assess future yields and demands and environmental implications. Three main reports were produced from the project giving the findings for projections of groundwater (CSIRO, 2009a), surface water (CSIRO, 2009b) and water yields and demands (CSIRO, 2009c). Three summary reports (CSIRO, 2009d; 2009e; and 2009f), four factsheets (CSIRO, 2009g; 2009h; 2009i and 2009j) and three technical reports (Charles et al., 2010; Silberstein et al., 2010 (in review); and Ali et al., 2010 (this report) were produced as well. All these reports are available from http://www.csiro.au/partnerships/SWSY.html.

A report of the proposed methods for the project was produced in 2008 (CSIRO, 2008). As the project was carried out the methods were adapted and often expanded to include additional analyses. A summary report on the methods used in the project was written (CSIRO, 2010) to replace the earlier methods report (CSIRO 2008).

This report presents further details of the groundwater modelling and assessment methods that were either not covered or only briefly covered in the main groundwater report (CSIRO 2009a) and actual methods report (CSIRO 2010). The structure of this report is given in Section 1.5.

The SWWA Sustainable Yield project developed a new regional groundwater flow model and two local area solute models through an external contract with URS. The model called Peel-Harvey Regional Aquifer Modelling System (PHRAMS) covers the area between Bunbury and Mandurah. The two local area solute models were: Myalup – Preston Local Solute Model and Peel Inlet, WA Local Solute Model. The following reports were produced by URS on these three models - URS, 2009a; 2009b; 2009c; 2009d; 2009e; 2009f and 2009g.

The SWWA Sustainable Yields Project, through an external contract with CyMod Systems Pty Ltd, linked the South West Aquifer Modelling System (SWAMS) and Collie groundwater model with the Vertical Flux Model (VFM) and updated their calibration. The reports produced by the CyMod Systems Pty Ltd were: Calibration of the Collie Groundwater Model with the VFM (CyMod Systems Pty Ltd, 2009a); and Calibration of the South West Yarragadee Aquifer Model with the VFM (CyMod Systems Pty Ltd, 2009b).

1.1 Background

In 2007 and 2008, CSIRO produced a series of reports examining the likely water yield of surface and groundwater catchments in the Murray-Darling Basin under future climate and development scenarios. Development included possible land management changes such as afforestation and farm dams.

On 26 March 2008, the Council of Australian Governments (COAG) agreed to expand this assessment of ‘sustainable yield’ to northern Australia, Tasmania and south-west Western Australia (SWWA) so that for the first time Australia would have a comprehensive scientific assessment of water yield in the major water systems across the country, allowing a consistent analytical framework for water policy decisions across the nation. The reports from these sustainable yields projects are available at:

Northern Australia: http://www.csiro.au/partnerships/NASY.html
Tasmania: http://www.csiro.au/partnerships/TasSY.html

The information collected and analysed in this project addressed water resources in SWWA which will assist water managers and users in the region to incorporate the effects of climate change and development in their estimates of future water yields.

The project aimed to:

- provide scientific information to improve the reliability of water allocation plans and reduce the likelihood of over-allocation, which could result in reduced water allocations threatening businesses, communities and industries that depend on a reliable supply of water for their survival;
• help managers identify and manage water dependent ecosystems that are under threat from a drying climate and growing water demands that threaten their ecological function;
• highlight the areas of SWWA which could develop significant gaps between water yields and demands between 2008 and 2030 so that management priorities may be better identified; and
• identify areas that may be less sensitive to climate change and areas that may allow more development of water resources than are currently planned.

1.2 Geographic scope of the project

The geographic extent of the South-West Western Australia Sustainable Yields Project was chosen to include all fresh (<500 mg/L) and brackish (500 to 1500 mg/L) surface and groundwater resources between the northern extent of the Perth Basin, north-east of Geraldton, and Albany in the south-east (Figure 1-1). This area covers all current and anticipated future water resources in SWWA suitable for irrigation, domestic water supplies and industries that require low salinity water. The SWWA region also supplies reticulated fresh water to much of the Wheatbelt, Great Southern and Goldfields regions because inland water resources are either limited or too saline for these uses. Therefore SWWA water resources support almost two million people and many important industries.

Almost all surface water diversions occur in catchments east of the Darling Scarp and on the Leeuwin–Naturaliste Ridge where the topography enables storage dams to be constructed. Almost all groundwater extractions occur on the flat Swan and Scott coastal plains (Perth Basin), the Collie Basin and the western Bremer Basin near Albany and where sedimentary aquifers are substantial and the water is usually fresh or brackish.

1.3 Groundwater regions

The South-West Western Australia Sustainable Yields Project covers an area of about 62,500 km², which includes about 38,800 km² of surface water catchments and about 37,200 km² of groundwater areas (GWAs), 13,500 km² of which overlap (Figure 1-1). The area extends from east of Geraldton, about 450 km north of Perth, to Albany, 410 km south-east of Perth.

A detailed overview of SWWA with respect to climate, geology, physiography, soil-landscapes, land use, demographics, water use, vegetation and water dependent environmental assets is given in the accompanying main reports (CSIRO, 2009a, b, c) and project technical reports (Ali et al., 2010; Silberstein et al., 2010; Charles et al., 2010; CSIRO, 2010).
Figure 1-1. Geographic scope of the South-West Western Australia Sustainable Yields Project
1.4 Subdivision of the project area for reporting

For the purposes of reporting, 24 GWAs were grouped into six groundwater regions, most of which align with groundwater model domains (CSIRO, 2009a). Likewise the surface water basins were grouped into three regions: the northern (Gingin to Murray); the central (Harvey to Preston) and the southern (Busselton Coast to Denmark). Within each surface water basin there are numerous catchments, many of which were used for surface water model calibration, and others for which projected surface water flows are assessed.

There are eight water demand regions within the project area which are aligned with statistical reporting regions such as local government and regional development authorities. Some demand regions extended outside the boundaries of the project area but these areas usually have very small water demands in comparison with the project area (CSIRO, 2009c). For comparison with surface and groundwater yields, these demand regions were broken into 45 sub-regions which align with surface water basins and GWAs.

1.5 Report structure

This report presents details on methods of the groundwater modelling and assessment that could be briefly covered in the main groundwater report of the South-West Western Australia Sustainable Yields project (CSIRO, 2009a). A companion report (Silberstein et al. 2010) gives similar details supporting the surface modelling results (CSIRO, 2009b).

This technical report is comprised of five chapters detailing methods for various parts of the groundwater modelling and assessment part of the SWWA Sustainable Yields Project. Chapter one (this chapter) introduced the SWWA Sustainable Yields Project and methodological framework. Chapter 2 describes the methods used to assess groundwater resource availability under a range of climate change scenarios and current and future extraction regimes. Chapter 3 gives detailed methods for the land cover mapping. The land cover mapping was required to provide inputs into various surface and groundwater models. Groundwater prioritisation approaches used to prioritise Groundwater Management Areas (GWAs) in SWWA are described in Chapter 4. The last chapter (5) of this report outlines detailed methods used in the hydrograph analysis techniques. This analysis was used to project future groundwater levels in various regions of project area based on the relationships between rainfall and changes in watertable depth. These results were compared with model projections in the groundwater modelled areas. Appendix A displays statistical hydrographs from the Central Perth Basin, the Southern Perth Basin and Northern Perth Basin. These statistical hydrographs were prepared using the methods outlined in Chapter 5.

Figure 1-2 shows the data processing steps and datasets created and archived from the groundwater modelling part of the SWWA Sustainable Yields Project.
Introduction

Shape definitions

Background reports and data

Results

Modelling or processing

Processed (figures, tables, maps)

Final product

Groundwater prioritisation

Groundwater levels

Hydrogeology data

Future land development (GW abstraction to allocation limits)

VFM linking and calibration of SWAMS and Collie models

Historical and future climate data (Scenarios A, B, Cdry, Cmid, and Cwet)

PHRAMS model development and calibration

WAVES recharge modelling

HARITT hydrograph analysis

Chloride balance method (CBM) and carbon-14 analysis

SW-Groundwater connectivity mapping and quantification

SWAMS scenario modelling

Collie scenario modelling

PHRAMS scenario modelling

Exit

Contextual info

Background reports and data

Groundwater management plans

GW management, allocation and use

ASRIS soil hydraulic properties

Land cover mapping

Climate zones

Hydrogeochemical data

Groundwater levels

Surface water flow data

GW bore monitoring data

Groundwater technical report

Groundwater main report

PRAMS, mxd, png, ArcMap

SWAMS, mxd, png, ArcMap

Collie model, mxd, png, ArcMap

PHRAMS, mxd, png, ArcMap

WAVES, tables, png

SW-GW interaction maps, figures, tables

PRAMS scenario outputs

SWAMS scenario outputs

Collie scenario outputs

PHRAMS scenario outputs

WAVES scenario outputs

Groundwater methods used in the SWWA Sustainable Yields Project 5

Figure 1-2. Audit trail of groundwater datasets and processing
1.6 References


CSIRO (2009b) Surface water yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia, 171+xx pp.

CSIRO (2009c) Water yields and demands in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia, 276+xxvi pp.


CSIRO (2009e) Surface water yields in south-west Western Australia. Summary of a report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia, 12 pp.


CSIRO (2009g) Groundwater yields in south-west Western Australia. A Fact Sheet to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia, 4 pp.

CSIRO (2009h) Surface water yields in south-west Western Australia. A Fact Sheet to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia, 4 pp.

CSIRO (2009i) Water yields and demands in south-west Western Australia. A Fact Sheet to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia, 4 pp.

CSIRO (2009j) Water in south-west Western Australia. A Fact Sheet to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia, 4 pp.


CyMod Systems Pty Ltd (2009a) Calibration of the Collie Groundwater Model with the VFM, 23 pp


1 Introduction
2 Groundwater methods

To model groundwater systems, contextual information along with data about the geology, hydrogeology, hydrology, climate, land use and soils are required. For less developed groundwater systems this information is usually not available and groundwater modelling is less likely to provide meaningful insights into the state of groundwater systems. One of the important inputs into any groundwater model is the net recharge or discharge from the aquifer. For those groundwater systems where groundwater modelling is not carried out, the estimation of net recharge or discharge from the aquifer can be carried out to assess the rate of groundwater replenishment from rainfall. Recharge-discharge modelling is a prerequisite to any groundwater modelling and the main flux relating to the groundwater system, along with an assessment of storage (levels) over time and other key datasets such as rates of extraction and allocation.

Groundwater Management Areas (GWAs) were prioritised into first, second and third-tiers based on their level of exploitation. This was followed by the assembling of contextual information and its use in vertical flux modelling (VFM). Groundwater modelling was then carried out for first and second-tier GWAs. Vertical flux modelling was carried out for the three third-tier GWAs in the Northern Perth Basin and the Albany GWA where suitable groundwater models were not available. Hydrograph analyses were conducted on selected bores throughout the whole assessment area to project future groundwater levels and compare these with modelled values where available. Isotope and hydrogeochemical groundwater recharge assessments were carried out to check recharge estimates and groundwater modelling results. The methods are detailed in this Chapter in the following order:

- Prioritisation of Groundwater Management Areas (GWAs)
- Preparation of contextual information of the groundwater systems
- Rainfall-recharge estimation/modelling
- Groundwater modelling and assessment
- Hydrograph analysis
- Isotope and hydrogeochemical groundwater recharge assessments

2.1 Prioritisation of groundwater management areas

The basic unit used for prioritisation is the groundwater management area (GWA). A GWA (or unit) was defined by the 2000 National Land and Water Resources Audit as a ‘hydraulically connected groundwater system that is defined and recognised by Territory and State agencies’ (NLWRA, 2000). Groundwater extraction in many of the GWAs is controlled through a range of planning and regulatory mechanisms. The definition and extent of GWAs may change in time as the need and policy changes. GWAs are also three-dimensional in nature and are often associated with a particular geological formation or aquifer. They may overlie one another.

Twenty four GWAs varying in size, resource volumes and groundwater extraction were considered (Figure 2-1). Achieving a consistent level of modelling analysis across all GWAs was not possible within the time frame and resources of this project. An initial task was to prioritise GWAs to identify those to be considered in most detail. The prioritisation approach for GWAs was adopted from Richardson et al. (2008) as described below.
Figure 2-1. Groundwater management areas in SWWA
2.1.1 Murray-Darling Basin (MDB) prioritisation approach

GWAs were initially ranked according to an index \( I \), equation 2.1) based on normalised current groundwater extraction (2006/07), the fraction of groundwater allocation currently extracted (2006/07), the fraction of sustainable yield currently extracted (2006/07), a potential growth index and an index of the predicted future impact of groundwater extraction on surface water flow.

\[
I = \frac{E_c}{E_{c,\text{max}}} \times \frac{E_c}{A} \times \frac{E_c}{SY} \times \frac{E_f}{E_{c,\text{max}}} \times 0.2 \left[ 1 + 4 \left( \frac{E_f \times C}{E_{f,\text{max}} \times C} \right) \right] \tag{2.1}
\]

- \( E_c \) Current (2006/07) groundwater extraction for individual GWA [GL/year]
- \( E_f \) Predicted future (2054/55) groundwater extraction for individual GWA [GL/year]
- \( A \) Groundwater allocation for individual GWA [GL/year]
- \( SY \) Sustainable yield for individual GWA [GL/year]
- \( C \) Surface water – groundwater connectivity for individual GWA %
- \( E_{c,\text{max}} \) Maximum parameter across all south-west GWAs

Data from the South-West Western Australia Sustainable Yields Project was used to estimate these indices for GWAs of south-west Western Australia (SWWA). Five levels of priorities were assigned: very high, high, medium, low and very low as shown for the Murray-Darling Basin Sustainable Yields project ranking (Table 2-1.). For those GWAs where insufficient information was available to rank the GWAs these were categorised as low priority. For very high and high priority GWAs detailed groundwater modelling and assessment was conducted. Further details and results of GWA prioritisation using this approach are provided in Chapter 4 of this report.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Priority</th>
<th>Minimum assessment</th>
<th>Description of assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 7</td>
<td>Very high</td>
<td>Very thorough</td>
<td>Peer-reviewed model with good monitoring network and good assessment of connection to streams</td>
</tr>
<tr>
<td>8 to 12</td>
<td>High</td>
<td>Thorough</td>
<td>Numerical model with minimal peer review and adequate monitoring</td>
</tr>
<tr>
<td>13 to 20</td>
<td>Medium</td>
<td>Moderate</td>
<td>Minimally calibrated numerical model</td>
</tr>
<tr>
<td>21 to 89</td>
<td>Low</td>
<td>Simple</td>
<td>Simple water balance or analytical approach</td>
</tr>
<tr>
<td>90 to 123</td>
<td>Very low</td>
<td>Minimal</td>
<td>Description of hydrogeological setting and extraction rates</td>
</tr>
</tbody>
</table>

Table 2-1. Method for assigning minimum levels of assessment for MDB groundwater management units (source: Richardson et al., 2008)

2.1.2 NLWRA/DoW prioritisation approach

The level of utilisation as a proportion of the sustainable yield and required management inputs can be used to evaluate the level of confidence in the groundwater modelling and assessment (Johnson, 2005). This approach was used in this study. The level of utilisation as a proportion of the sustainable yield (\( C \)) defines the level at which the groundwater resource unit should be managed. The levels were based on a relative scale of management from 1 (low level of management) to 4 (high level of management), corresponding to each of the four categories of use listed in Table 2-2.
Table 2-2. Resource categories according to level of utilisation

<table>
<thead>
<tr>
<th>Utilisation as a percentage of sustainable yield</th>
<th>0-30 percent</th>
<th>30-70 percent</th>
<th>70-100 percent</th>
<th>&gt;100 percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of use category</td>
<td>C1</td>
<td>C2</td>
<td>C3</td>
<td>C4</td>
</tr>
<tr>
<td>Management response category</td>
<td>R1</td>
<td>R2</td>
<td>R3</td>
<td>R4</td>
</tr>
</tbody>
</table>

The resource assessment may be carried out at different levels ranging through reconnaissance, broad-scale and safe yield (WAWRC, 1991). These have been further defined as levels of management response (R1 to R4), broadly related to the level of groundwater allocation used in the NLWRA (WRC, 2000) and are summarised in Table 2-3.

Table 2-3. Actions required in groundwater management response

<table>
<thead>
<tr>
<th>R1 Reconnaissance Investigation</th>
<th>R2 Broad Scale Investigation</th>
<th>R3 Safe Yield and Environmental Hydrology</th>
<th>R4 Impact Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using hydrogeological mapping and existing drilling information from baseline investigations</td>
<td>Major borefields in environmentally sensitive areas</td>
<td>Test pumping</td>
<td>Groundwater model</td>
</tr>
<tr>
<td>Regional estimates of recharge based on existing data from baseline investigation programs</td>
<td>Move to R3 criteria</td>
<td>Recharge measurement</td>
<td>Regular/ongoing assessment</td>
</tr>
<tr>
<td></td>
<td>Targeted exploratory drilling</td>
<td>Groundwater age dating</td>
<td>Ecosystems hydrology</td>
</tr>
<tr>
<td></td>
<td>Recharge and throughflow estimates</td>
<td>Groundwater modelling</td>
<td>investigation and modelling</td>
</tr>
<tr>
<td></td>
<td>Preliminary assessment of safe yield</td>
<td>Ecosystems hydrology investigation and modelling</td>
<td></td>
</tr>
</tbody>
</table>

The increasing level of management response from R1 to R4 requires a significant increase in the workload and amount of resources allocated to the assessment process. Below is a summary of the minimum level of understanding that is required at the different levels of assessment.

**R1 Outcome:**
- A basic knowledge of aquifers, including their approximate extent, thickness and salinity distribution
- Monitoring for baseline water level response

**R2 Outcome:**
- Detailed knowledge of aquifers in major borefields, supported by monitoring and modelling
- Broad understanding elsewhere
- Monitoring close to major abstraction centres

**R3 Outcome:**
- Detailed knowledge of aquifers
- Monitoring throughout the area
- Understanding of water balance supported by recharge measurement, age dating, etc.
- Determination of Groundwater Dependent Ecosystems (GDEs)
- Regional groundwater model, supported by pumping tests, to predict the effects of increased abstraction

**R4 Outcome:**
- Detailed understanding of hydrogeology
- Calibrated groundwater model that is able to predict the effects of abstraction
- Intensive water level monitoring, especially in environmentally sensitive areas
Groundwater resource assessment is a critical component in the water management process. As a consequence, the level of management (i.e. investigation) response should match increases in utilisation. For the larger, fully developed (C3, C4) GWAs, resource assessments that provide a high level of confidence are required (R3, R4) as shown in Figure 2-2. Conversely, when the level of development is low (C1, C2) and the available resource is small, a lower level of confidence in resource assessments is acceptable (R1, R2). Ultimately the measure that is required is the confidence that the right level of data and analysis has been matched to the appropriate level of development, i.e. the most developed GWA has the best analysis. The confidence assessment considers the appropriateness of the level of data and analysis given the size of the resource and the level of development. The development level and required management level criteria were used to classify GWAs in south-west Western Australia.

A measure of ‘management gap’ was assessed by comparing C and R classifications. For example, a R3 resource with a R2 response had a gap of 1; if the response was C1 then the gap would be 2 (Table 2-4). The results of this prioritisation approach are described in Chapter 4 of the Technical Report.

![Figure 2-2](image-url) Resource allocation and management response categories. Note the progressively better estimation of allocation limits as groundwater resources are more fully allocated and used.

<table>
<thead>
<tr>
<th>Use category</th>
<th>Management response</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R1</strong></td>
<td></td>
</tr>
<tr>
<td>C1 &lt;30 percent</td>
<td>0</td>
</tr>
<tr>
<td>C2 30–70 percent</td>
<td>−1</td>
</tr>
<tr>
<td>C3 70–100 percent</td>
<td>−3</td>
</tr>
<tr>
<td>C4 &gt;100 percent</td>
<td>−3</td>
</tr>
<tr>
<td><strong>R2</strong></td>
<td>+1</td>
</tr>
<tr>
<td><strong>R3</strong></td>
<td>+2</td>
</tr>
<tr>
<td><strong>R4</strong></td>
<td>+3</td>
</tr>
</tbody>
</table>

Table 2-4. Matrix showing the gaps between use and management response
2.1.3 Tier-based prioritisation approach

An initial prioritisation was done on the basis of use, level of groundwater development (ratio of use to extraction and predicted future groundwater extraction for individual GWAs considered for groundwater modelling and assessment (Figure 2-1), and whether there was a groundwater model for the GWA. This helped validate the above prioritisation approaches and provided priority rankings for those GWAs where the normalised index-based prioritisation approach could not be used due to unavailability of data or for other reasons.

This tier-based method was used along with consultation with experts in CSIRO and the West Australian Department of Water (DoW) to categorise GWAs into first and second-tier (higher priority), second-tier and third-tier (lower priority) GWAs as discussed in Chapter 4 of this report.

2.2 Preparation of contextual information

Assembling information relating to the groundwater system such as the nature and status of the resource and other datasets such as rates of extraction and allocation is a prerequisite to groundwater modelling and interpretation of the assessment and modelling results.

Method

1. The background reports on hydrogeology, water sharing plans, groundwater extraction, extraction limits, entitlement data and information on groundwater status were sourced from the DoW, West Australian Water Corporation, West Australian Department of Agriculture and Food, GHD, URS, regional water service providers and private irrigation companies.

2. Summary description of the hydrogeological setting, surface–groundwater interactions and trends in groundwater levels was provided for six groundwater basins/areas: Northern Perth Basin, Central Perth Basin, Peel-Harvey Area, Southern Perth Basin, Collie Basin and the Albany Area.

3. Water management regimes including the pattern of historical groundwater extraction were summarised. A strategic picture of the groundwater resources for the next 23 years was provided using projected groundwater demands at 2030.

4. All the above information was collated within the groundwater main report and a summary report.

2.3 Rainfall-recharge modelling

2.3.1 Introduction

Climate change results in changes to rainfall and potential evapotranspiration. These result in changes to recharge and the need to develop climate-recharge relationships for recharge estimation and use, either independently or by linking it with groundwater models. The three main recharge mechanisms are: (i) diffuse dryland recharge; (ii) irrigation recharge; and (iii) stream recharge (surface-groundwater interactions).

Groundwater models often include relatively simple recharge relationships such as a percentage of rainfall or similar linear relationship – sometimes with a threshold. The combination of the choice of recharge and hydrogeological parameters is required to match groundwater levels. The partitioning of the varying forms of recharge can be difficult and so the application of the rainfall data directly into the embedded relationships can be questionable.

Climate change also affects temperature, relative humidity and rainfall and has a flow-on effect throughout the hydrological cycle (Loáiciga et al., 1996). In European studies, Lasch et al. (2002) showed that a 10 to 20 percent decrease in rainfall could lead to a 60 percent decrease in recharge. Conversely, however, Eckhardt and Ulbrich (2003) showed that in an area where rainfall is predicted not to change while CO₂ and temperatures increased as a result of climate change, recharge was also predicted not to change. This lack of change in recharge was attributed to decreased
stomatal conductance limiting transpiration being balanced by the increased atmospheric demand, thus leaving overall evapotranspiration almost unchanged.

A Vertical Flux Model (VFM) was used for rainfall-recharge estimation in all of the GWAs covered by three of the groundwater models: the Perth Regional Aquifer Modelling System (PRAMS) used in the Central Perth Basin; the South West Aquifer Modelling System (SWAMS) used in the Southern Perth Basin; and the Collie Basin groundwater model used in the Collie Basin. The PRAMS groundwater model already had a directly coupled VFM utilising the WAVES model (Zhang and Dawes, 1998) and other empirical equations for estimating recharge rates. By being directly coupled, the model was able to estimate the depth of the watertable after a simulation period and this new depth was used to estimate subsequent recharge and discharge amounts. This project also coupled the VFM with the SWAMS and Collie models. For these ‘first-tier’ GWAs covered by the PRAMS, SWAMS, and Collie models, rainfall-recharge modelling was carried out according to the procedure described in Barr et al. (2003) and summarised and reported as a by-product of the groundwater modelling. For the second-tier GWAs, a new groundwater model called Peel-Harvey Regional Aquifer Modelling System (PHRAMS) was developed and the rainfall-recharge modelling was done using a linked but not dynamically coupled VFM. The WAVES model was used to estimate recharge rates in third-tier GWAs. In addition to WAVES, other recharge estimation and validation methods such as hydrograph analysis and chloride balance were used.

2.3.2 Vertical Flux Modelling (VFM)

The VFM calculates recharge to, and discharge from, an aquifer system. ‘VFM Manager’ incorporates a number of different recharge models such as WAVES, which is used for the vegetated areas covered by pasture, pine plantations and Banksia woodlands. Simple recharge models are used for urban areas, market gardens, wetlands and areas where watertables are close to the ground surface. The VFM performs five key tasks:

1. Manages the generation of Recharge Response Units (RRUs) from raw cell attributes
2. Manages the spatial selection of which recharge model to run in each cell or grid
3. Manages data input to the recharge models
4. Runs the recharge models
5. Passes the calculated recharge to the groundwater model or output file

The VFM estimates aquifer recharge or deep drainage based on the following four factors.

1. Climate
2. Land cover
3. Soil type
4. Watertable depth

It can estimate the deep drainage for each cell depending on the above factors. However, due to time constraints it was not possible to run daily recharge models for each cell in the GWAs. Therefore before running the daily recharge models, the grid cells of similar attributes were grouped together into units based on climate zone, soil type, land cover and depth of the watertable. This procedure was repeated and grid cells in all GWAs were divided into RRUs. Figure 2-3 shows a schematic diagram of assemblage of RRUs and the recharge calculation by VFM using WAVES and other recharge models in PRAMS.
2.3.3 Methods for VFM

Climate zones

Based on rainfall and evaporation gradients, the study area was divided into various climate zones. The area covered by PRAMS has previously been subdivided into six climate zones. Increasing the number of climate zones may result in better prediction of the recharge rates but at the cost of increasing the computation and data processing time, and requiring re-calibration of PRAMS. To avoid the need to re-calibrate the model, six climate zones covered by PRAMS were kept unchanged. The rest of the study area was divided into nine climate zones. Altogether the area covered by the 24 GWAs was divided into 15 climate zones. Averages of the last 33 years (1975 to 2007; Scenario A) of rainfall, moisture index and evaporation data were used to classify the region into these zones.

Land cover classification

The project area was divided into 14 land use classes. Since there are no pre-1988 LandSat-TM data available, the Landsat data of 1988 and every second year after that were used to classify the study area into various land use classes. Further details about the methods used for the land cover classification are provided in Chapter 3 of this report.

Soil classification

The soil data were collected from the Australian Soils Resource Information System (ASRIS) and the Department of Agriculture and Food, Western Australia. The suitability of these data for classification of the study area into various zones of similar soils and/or soil hydrological properties was assessed. Xu et al. (2008) found that recharge was most sensitive to annual rainfall, plant leaf area index, light extinction coefficient and depth of the watertable. Therefore the generalised nature of the soil hydraulic information in ASRIS seemed adequate for soil descriptions.

Soil units for use in the Vertical Flux Modelling were developed for the whole of the Perth and Collie Basins. The classification of soils was constrained by the existing soil units in the PRAMS and SWAMS models as changing the soil units in these models would have required the models to be completely re-calibrated. For the Northern Perth Basin and the PHRAMS regions of the Perth Basin the soil units were grouped into soil types of similar hydrological properties and texture based on ASRIS level 4 data. The sandy units of the coastal plain regions including the Bassendean, Spearwood, Quindalup, Scott Coastal Plain and Scott Coastal Dunes have high hydraulic conductivities and low storage capacities.
The Guildford units consisted of heavier clay sediments associated with major drainages and the base of the Darling Scarp, whilst the Lacustrine unit associated with coastal wetlands consists mainly of silt and clay deposits over sand. The lateritic unit is predominantly gravelly clays. The remainder are a mix of soil types consisting of sandy gravels (Mesozoic) and gravels associated with a crystalline basement (Mowen, Vasse, Yarragadee, Collie East and Collie West).

**Watertable depth**

The fourth parameter required to classify the study area into RRUs is depth of the watertable. For the GWAs covered by the PRAMS model, the VFM was already linked with the groundwater model and the depth to watertable information required to create RRUs was therefore automatically updated at every stress period throughout the simulation. For the GWAs covered by the SWAMS and Collie groundwater models, the VFM was dynamically linked with the models in this project following the procedure used in PRAMS. For GWAs covered by PHRAMS the potential recharge estimates were provided to the model at a nominal watertable depth and rejected recharge was estimated as part of the modelling. For the third-tier GWAs, the WAVES modelling was used to estimate deep drainage or recharge rates assuming various watertable depths in various parts of the area.

The above four parameters were used to create RRUs. For PRAMS, SWAMS and Collie model these RRUs are automatically created for each stress period. For all other GWAs, the RRUs were created for possible combinations of watertable depths, soil types and land use and recharge rates estimated for each RRU.

### 2.3.4 Recharge models in the VFM

The VFM includes the relatively complex WAVES model and simpler models for estimating net recharge. The WAVES model was used to calculate the net recharge or vertical flux to the aquifer for certain land use classes such as pasture, pine plantations and Banksia woodlands, provided the depth to watertable was more than 0.5 m from the soil surface. WAVES is a 1-dimensional biophysical model and simulates vertical water flow through soil and water uptake by vegetation. The model was developed by CSIRO (Zhang and Dawes, 1998) and is available in the public domain. WAVES is described in detail in the Stage 1 report for this project (Hatton et al., 2001).

Other simple empirical recharge models, described by Barr et al. (2003), were used if the watertable depth was less than 0.5 m from the soil surface or the land use classes were market gardens, irrigated areas, wetlands, lakes or urban areas. Two of these simple models include a ‘Linear vertical flux model’ and a ‘Piece-wise linear vertical flux model’. For the linear vertical flux model a constant multiplier for the rainfall and potential evaporation was used to calculate the recharge as expressed in the form of Equation 2.2 below:

\[
R = (C_{\text{rainfall}} \times P) - (C_{\text{evap}} \times E)
\]  

where \( R \) is the rate of recharge per unit surface area in a cell; \( C_{\text{rainfall}} \) is the multiplier for the rainfall in that cell; \( P \) is the rainfall per unit surface area per unit time; \( C_{\text{evap}} \) is the multiplier for the evaporation; and \( E \) is the potential evaporation per unit surface area per unit time.

The ‘piece-wise linear flux model’ is slightly more complex. It is based on a piece-wise linear relationship about critical watertable depths for both rainfall and evaporation. The critical watertable depths may be different for the rainfall and evaporation and a multiplier \((C_{\text{rainfall}} \text{ and } C_{\text{evap}})\) is supplied for each critical watertable depth. The depth-multiplier pairs are sorted from the lowest to the highest depth. To find a multiplier for a given watertable depth, if the watertable is at or lower than the lowest depth, the multiplier is that associated with the highest depth. If the watertable depth is at or greater than the highest specified depth, the multiplier is that associated with the highest depth. If the watertable is at one of the specified depths, then the multiplier is that associated with that depth and if the watertable is between two depths then a linear interpolation is used between the multipliers at the two adjacent depths to calculate the multiplier at the watertable. This is expressed in equation form in Equation 2.3 (Barr et al., 2003):

\[
WT \leq Depth_{\text{lowest}} : \quad MLT = \text{Multiplier}_{\text{lowest}}
\]  

where \( WT \) is the watertable depth, \( Depth_{\text{lowest}} \) is the lowest specified depth and \( MLT \) is the multiplier associated with that depth.
where $MLT$ is the multiplier for the climate quantity (it may be $C_{\text{rainfall}}$ or $C_{\text{evap}}$) at the specified watertable depth; $WT$ is the given watertable depth; $Depth_i$ is the $i$th specified depth and $Multiplier_i$ is the multiplier associated with that depth.

Figure 2-4 shows the variation in a multiplier as a function of depth to the watertable. The multipliers for the rainfall and evaporation are calculated independently, and substituted into Equation 2.3 to calculate the vertical flux for the cell.

The inputs in the form of shape files were created for the climate zones, soil classification and land cover classes and used as input in the groundwater models. For second-tier GWAs covered by the PHRAMS model, potential recharge rates were estimated for all climate zones, soil types and land cover classes assuming a nominal watertable depth and provided as input into PHRAMS. PHRAMS then used the EVT package to estimate the net recharge rates. Potential recharge rates varied according to various climate change scenarios.

For the third-tier GWAs, WAVES was run and recharge estimated in each climate zone for all soil types and land covers assuming various watertable depths in the area. This was done for all scenarios where the main variant was climate. The current land development was assumed for all scenarios conducted in the third-tier GWAs and therefore the land use remained unchanged between scenarios as was soil type.

## 2.4 Model calibrations

Four groundwater models were used in the project. The models require calibration before scenario modelling.

The PRAMS model, linked with VFM, had already been calibrated and validated to 2007. This model was used for scenario modelling without any further calibrations or modifications. The SWAMS and Collie models were first coupled with a newly developed VFM and then calibrated and validated to groundwater level and abstraction data that was collated up until 2007 or later where available. The PHRAMS model was developed during this project. This model was calibrated and validated before its use for the scenario modelling. The calibration procedure for the SWAMS and Collie models is outlined below.
Method

1. The groundwater monitoring and groundwater abstraction databases were updated for the SWAMS and Collie models.
2. Input files about the historical climate data, land cover, soil classification and other data were prepared.
3. The models were run for the calibration period and outputs were checked with calibration data.
4. The water inflows to the models were evaluated to assess how each inflow varied over the calibration period. The suitability of the modelling set up was confirmed through this analysis.
5. After calibration targets were achieved, the models were validated against independent observed data.
6. The compatibility with adjacent models was cross-checked.
7. After their validation the models were used for scenario modelling.

2.5 Modelling scenarios

Using the calibrated and validated models the behaviour of groundwater systems across SWWA was assessed under each of the following scenarios. Land use, soil type and groundwater abstractions remained unchanged under all scenarios except the future land development (Scenario D) in which groundwater abstractions were increased to full allocation levels. Therefore climate was the only variant among various scenarios except Scenario D. An exception to this rule was applied to the Gnangara Mound area where the scheduled removal of the pine plantations and expansion of the urban area was allowed to take place between 2008 and 2030. This allowed the project’s climate scenario results to be compared with those carried out in the Gnangara Sustainability Strategy.

Historical climate and current land development (Scenario A)

For the groundwater modelling, 33 years of historical climate (1975 to 2007 inclusive) was used to make 11 sequences of 23 years duration from each representative weather station in each of the climate zones. The climate data from these 11 sequences were used to estimate recharge rates using the WAVES model. These results from each climate sequence were ranked from lowest to highest recharge and the 50th percentile sequence selected. Once the 50th percentile sequence was selected, the remaining 10 years of the climate data for that sequence were added to make 33 years and this constituted the Scenario A climate. The step-wise procedure is detailed below.

The recharge rates were estimated in each climate zone for major soil types assuming bare ground and a fixed watertable depth. This was done by running the WAVES model for generic response units. The simulations were run using the climate data from 1970 to 2007. For each simulation an arbitrary initial water profile started the run, and then the final vertical profile was used as the initial condition and the simulation run again. This allowed the storage difference from start to end of each simulation to be less than 0.1 mm over 38 years in each case. Daily simulated values of the water balance components were amalgamated to 38 annual values, and the first 5 years from 1970 to 1974 were discarded. Average recharge flux across the lower boundary was determined for the 11 sequences of 23 years as shown in Table 2-5.

The 23-year sequences were ranked from lowest to highest recharge for each climate zone using the years ending the sequence as headings. Ranking of sequences in this manner makes it possible to get a consistent climate series applicable to the project area, rather than different sequences for different model domains. The 10th, 50th and 90th percentile recharge climate sequences were 1984 to 2006, 1981 to 2003 and 1979 to 2001.

A second analysis used a Z-score (a measure of how far each estimate is from the mean value assuming a normal distribution). This measure is useful for comparing populations with different means and standard deviations, such as these data. The Z-scores were summed over all climate zones for each climate sequence and results are shown in Table 2-6. The 10th, 50th and 90th percentile recharge climate sequences were 1976 to 1998, 1975 to 1997 and 1979 to 2001.
Table 2-5. Ranking of 23-year sequences using average annual recharge for climate zones across entire SWSY domain.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Chelsea</td>
<td>263</td>
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<td>246</td>
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<td>252</td>
<td>267</td>
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<td>Lancelin</td>
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<td>Wanneroo</td>
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<td>520</td>
<td>528</td>
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<tr>
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<td>515</td>
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<td></td>
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<tr>
<td>Jandakot</td>
<td>617</td>
<td>632</td>
<td>631</td>
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<td>642</td>
<td>644</td>
<td>619</td>
<td>629</td>
<td>638</td>
<td>645</td>
<td>628</td>
<td></td>
</tr>
<tr>
<td>Jarrahdale-Excess</td>
<td>703</td>
<td>706</td>
<td>722</td>
<td>735</td>
<td>715</td>
<td>724</td>
<td>738</td>
<td>737</td>
<td>728</td>
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<tr>
<td>Busselton</td>
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<td>518</td>
<td>498</td>
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<td>814</td>
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<td>239</td>
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<td>238</td>
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<tr>
<td>Average</td>
<td>491</td>
<td>496</td>
<td>503</td>
<td>504</td>
<td>505</td>
<td>508</td>
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<td>509</td>
<td>510</td>
<td>512</td>
<td>516</td>
<td></td>
</tr>
</tbody>
</table>

Note: Entries are listed by the year ending the sequence, thus a value of 2003 represents the 23-year sequence from 1981 to 2003.

Table 2-6. Ranking of 23-year sequences using Z-score of annual recharge for climate zones across entire project area.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Chelsea</td>
<td>0.26</td>
<td>-1.76</td>
<td>0.87</td>
<td>-1.61</td>
<td>0.58</td>
<td>-1.06</td>
<td>1.01</td>
<td>0.54</td>
<td>0.62</td>
<td>0.59</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Lancelin</td>
<td>-1.73</td>
<td>0.05</td>
<td>-1.41</td>
<td>-0.04</td>
<td>-0.89</td>
<td>0.93</td>
<td>-0.06</td>
<td>0.12</td>
<td>0.57</td>
<td>1.27</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>Wanneroo</td>
<td>-0.2</td>
<td>-1.9</td>
<td>0.29</td>
<td>-1.38</td>
<td>-0.06</td>
<td>-0.47</td>
<td>0.89</td>
<td>0.72</td>
<td>0.58</td>
<td>1.58</td>
<td>-0.05</td>
<td></td>
</tr>
<tr>
<td>Perth Airport</td>
<td>-1.17</td>
<td>-0.47</td>
<td>0.74</td>
<td>-0.82</td>
<td>-0.75</td>
<td>1.6</td>
<td>0.87</td>
<td>-0.2</td>
<td>-1.22</td>
<td>1.35</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Jandakot</td>
<td>-1.37</td>
<td>-1.17</td>
<td>0.04</td>
<td>-1.24</td>
<td>-0.06</td>
<td>-0.23</td>
<td>1.06</td>
<td>1.29</td>
<td>0.62</td>
<td>1.37</td>
<td>-0.31</td>
<td></td>
</tr>
<tr>
<td>Jarrahdale-Excess</td>
<td>-1.73</td>
<td>0.74</td>
<td>-1.47</td>
<td>0.94</td>
<td>-0.27</td>
<td>0.91</td>
<td>-0.79</td>
<td>-0.1</td>
<td>0.18</td>
<td>0.24</td>
<td>1.34</td>
<td></td>
</tr>
<tr>
<td>Busselton</td>
<td>-1.18</td>
<td>-1.27</td>
<td>-0.96</td>
<td>0.7</td>
<td>0.48</td>
<td>-1.3</td>
<td>0.19</td>
<td>0.26</td>
<td>0.8</td>
<td>0.73</td>
<td>1.54</td>
<td></td>
</tr>
<tr>
<td>Nannup</td>
<td>-1.77</td>
<td>0.32</td>
<td>-1.27</td>
<td>1.3</td>
<td>-0.29</td>
<td>0.51</td>
<td>-0.7</td>
<td>-0.06</td>
<td>0.44</td>
<td>-0.05</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>Donnybrook</td>
<td>-0.77</td>
<td>-1.14</td>
<td>-1.51</td>
<td>0.23</td>
<td>1.25</td>
<td>-1.02</td>
<td>0.16</td>
<td>0.87</td>
<td>0.95</td>
<td>-0.23</td>
<td>1.19</td>
<td></td>
</tr>
<tr>
<td>Cape Leeuwin</td>
<td>-1.74</td>
<td>0.98</td>
<td>-1.4</td>
<td>1.11</td>
<td>-0.71</td>
<td>0.98</td>
<td>-0.46</td>
<td>-0.15</td>
<td>0.04</td>
<td>0.33</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>Margaret River</td>
<td>-1.5</td>
<td>-0.07</td>
<td>-1.49</td>
<td>1.12</td>
<td>-0.39</td>
<td>0.33</td>
<td>-0.61</td>
<td>-0.17</td>
<td>0.44</td>
<td>0.59</td>
<td>1.74</td>
<td></td>
</tr>
<tr>
<td>Three Springs</td>
<td>1.11</td>
<td>-1.4</td>
<td>1.05</td>
<td>-1.97</td>
<td>0.93</td>
<td>-0.3</td>
<td>0.37</td>
<td>0.18</td>
<td>0.52</td>
<td>0.15</td>
<td>-0.66</td>
<td></td>
</tr>
<tr>
<td>Geraldton</td>
<td>-1.09</td>
<td>-1.29</td>
<td>-0.71</td>
<td>-1.17</td>
<td>-0.38</td>
<td>-0.07</td>
<td>0.54</td>
<td>0.61</td>
<td>1.06</td>
<td>1.56</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>-12.88</td>
<td>-8.38</td>
<td>-7.24</td>
<td>-2.81</td>
<td>-0.54</td>
<td>0.81</td>
<td>2.5</td>
<td>3.92</td>
<td>5.61</td>
<td>9.49</td>
<td>9.52</td>
<td></td>
</tr>
</tbody>
</table>

Inspecting the assembled data it is clear that the sequences 1978 to 2000 and 1979 to 2001 were consistently the wettest for individual climate zones in the groundwater project area. Similarly the most recent sequence, 1985 to 2007, was consistently the driest for all criteria. In the Z-score analysis, the 10th and 50th percentile sequences differed from those based on absolute recharge. The climate sequence rainfall variation was better reflected in the rankings based on absolute recharge; therefore it seemed reasonable to use this criterion for the selection of the 50th percentile historical climate sequence. The purpose was to use a consistent temporal sequence over the entire project area in all scenarios to avoid abrupt changes at zone boundaries. The 50th percentile climate sequence of 1981 to 2003 was selected.
because it appeared at or near the median of all absolute recharge rankings. Selection of future climate from GCM sequences was determined in the same manner.

Recent climate and current land development (Scenario B)

Climate data for 11 years (1997 to 2007 inclusive) were repeated three times to simulate groundwater levels until 2040 with the conditions in 2030 being reported. This climate was used as input in the VFM-coupled groundwater modelling and in the WAVES modelling in the third-tier GWAs to estimate recharge rates.

Future climate and current land development (Scenario C)

The climate sequences for the future climate were derived from historical climate data modified by GCM predictions of the annual patterns and statistics for the year 2030 under different future global warming trends. It was based on 15 Global Climate Models (GCMs) and three emission levels or degrees of warming (0.7°C, 1.0°C and 1.3°C). In total there were 45 (3 x 15) GCM series from which the future climate data were derived. For each of the low, medium and high global warming scenarios, the mean annual recharge over the region for each of the 15 climate series was determined by running the WAVES model in de-coupled mode. The resulting recharge from each of the 15 climates was ranked separately for the low, medium and high global warming scenarios. So there were 15 recharge rankings in total (one for each GCM) for low global warming scenario, 15 for medium global warming scenario and 15 for high global warming scenario. The procedure for the Cmid GCM and climate selection is detailed below. The same process was used for determining the Cdry and Cwet GCM and climate data.

The first step was to select a representative GCM for the Cmid climate. For this, the annual recharge rates were estimated for each of the 15 GCMs in each climate zone assuming +1°C global warming. An average of recharge from all climate zones was determined for each GCM (Table 2-7). The median ranked GCM was CCCMA_T47, while the GCM with recharge closest to the overall average was CNRM. Only one GCM (INMCM) resulted in a climate series with predicted recharge greater than the historical climate record. The relative ranking of GCMs remained the same as in Table 2-7 when the future +1.3°C global warming scenario was run.

Charles and Fu (2009) ranked the GCMs used in IPCC4 by their ability to reproduce climatic metrics across Australia, the Pacific and the globe using 10 criteria. Of those in Table 2-7 that were tested, MIROC (10% failure) and GDFL (17% failure) performed the best; MIROC was closest to the GCM average conditions while GDFL was drier. Of the wetter GCMs CCCMA_T63 (42% failure) and INMCM (50% failure) performed the best; CCCMA_T47 was not much wetter than MIROC but IPSL (75% failure) and NCAR_PCM (100% failure) were not considered good enough to use. Therefore the MIROC GCM was selected to represent Cmid climate since it was the best performing and closest to the average recharge.

The next step was to select a historical climate sequence from which future climate was to be derived applying scaling factors. The annual recharge rates were determined for 11 climate sequences modified by MIROC climate statistics of 2030 under +1°C global warming (Table 2-8). The 23-year sequence selected based on the full spread of values from best GCM (MIROC) was 1984 to 2006.

Following the same procedure and based on recharge rankings GFDL+1.3°C was selected for Cdry, MIROC+1°C for Cmid and INMCM+1.3°C for Cwet. Ranking 23-year sequences of average annual recharge, the modified climate from 1984 to 2006 was chosen as the representative period for simulation of the 2008 to 2030 for future climate scenarios.
Table 2-7. List of GCMs and modelled average annual recharge over various climate zones assuming 1°C global warming

<table>
<thead>
<tr>
<th>GCM</th>
<th>Average Annual Recharge (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GISS_AOM</td>
<td>453.9</td>
</tr>
<tr>
<td>MIUB</td>
<td>468.5</td>
</tr>
<tr>
<td>CSIRO</td>
<td>478.2</td>
</tr>
<tr>
<td>GFDL</td>
<td>480.3</td>
</tr>
<tr>
<td>MRI</td>
<td>488.9</td>
</tr>
<tr>
<td>NCAR_CCSM</td>
<td>498.0</td>
</tr>
<tr>
<td>MPI</td>
<td>499.3</td>
</tr>
<tr>
<td>CCCMA_T47</td>
<td>506.8</td>
</tr>
<tr>
<td>CNRM</td>
<td>507.3</td>
</tr>
<tr>
<td>MIROC</td>
<td>519.6</td>
</tr>
<tr>
<td>IAP</td>
<td>530.0</td>
</tr>
<tr>
<td>IPSL</td>
<td>530.9</td>
</tr>
<tr>
<td>CCCMA_T63</td>
<td>532.6</td>
</tr>
<tr>
<td>NCAR_PCM</td>
<td>550.6</td>
</tr>
<tr>
<td>INMCM</td>
<td>573.5</td>
</tr>
<tr>
<td>All GCM average</td>
<td>507.9</td>
</tr>
<tr>
<td>Historical 1975 – 2007</td>
<td>554.6</td>
</tr>
</tbody>
</table>

Table 2-8. Average annual recharge over 23-year sequence for climate modified by MIROC climate statistics of 2030 under 1°C global warming

<table>
<thead>
<tr>
<th>Sequence of 23-years</th>
<th>Average 23-year Recharge (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975 – 1997</td>
<td>529.0</td>
</tr>
<tr>
<td>1976 – 1998</td>
<td>530.3</td>
</tr>
<tr>
<td>1977 – 1999</td>
<td>531.8</td>
</tr>
<tr>
<td>1978 – 2000</td>
<td>541.6</td>
</tr>
<tr>
<td>1979 – 2001</td>
<td>545.3</td>
</tr>
<tr>
<td>1980 – 2002</td>
<td>539.6</td>
</tr>
<tr>
<td>1981 – 2003</td>
<td>539.7</td>
</tr>
<tr>
<td>1982 – 2004</td>
<td>539.2</td>
</tr>
<tr>
<td>1982 – 2005</td>
<td>534.0</td>
</tr>
<tr>
<td>1984 – 2006</td>
<td>534.2</td>
</tr>
<tr>
<td>1985 – 2007</td>
<td>525.7</td>
</tr>
</tbody>
</table>

Future climate and future land development

The climate data for this scenario was the same as for Scenario Cmid. This future climate was used with the future land development and defined as Scenario D. Since there were no significant new plantations or irrigation developments identified, the future land development only included increased groundwater abstractions. In the GWAs where current groundwater abstraction was below 2009 allocation limits it was increased to full allocation levels from the start of 2008.

2.5.1 Scenario details for groundwater modelling

The PRAMS, SWAMS, PHRAMS and Collie models were used for climate and development scenario modelling. The PRAMS, SWAMS and Collie models were used for the first-tier GWAs and the PHRAMS model was used for the second-tier GWAs. Recharge modelling using WAVES was done for the third-tier GWAs. Since the VFM is directly coupled with the PRAMS, SWAMS and Collie models, the RRU, watertable information and selection and running of recharge models is automatically handled internally within the VFM and groundwater models. The modelling procedure for the first, second and third-tier GWAs is described below.
2.5.2 First-tier groundwater areas

A classifying criterion of first-tier GWAs was the existence of a numerical groundwater model. The steps involved for the scenario modelling are laid out below:

1. The validated models were used to carry out simulations for Scenario A.
2. These models were also run to simulate scenarios B, C and D.
3. The accuracy of surface–groundwater exchanges were assessed in areas of significant surface–groundwater interactions.
4. The groundwater level data were extracted from various layers of the models and changes in groundwater levels between 2008 and 2030 and assessed under current and future climate and development conditions.
5. The water balance data were extracted and all components of the water balance checked and compared between scenarios. Components of the water balance were checked against data from various field and experimental studies.
6. The modelled hydrographs were compared with the statistical hydrographs for validation.
7. The storage changes were estimated in various model layers representing the unconfined and confined systems and these were then compared between scenarios. The storage change data were also used to modify the allocation limits of groundwater subareas.
8. The modelled recharge rates were also compared with the steady state recharge estimated through chloride balance method.

2.5.3 Second-tier groundwater areas

The PHRAMS model was developed for the second-tier GWAs through an external contract. This model was calibrated and validated before its use for scenario modelling. The steps involved in scenario modelling were as outlined for first-tier GWAs above. A coupled VFM was not used in PHRAMS. Potential maximum recharge rates were provided as input and the EVT package of the MODFLOW model was used to subdivide it into net recharge and ET.

2.5.4 Third-tier groundwater management units

Only four of the 24 GWAs were classified as third-tier GWAs. These GWAs have relatively low levels of groundwater development and/or a complex hydrogeology for which a groundwater model has not yet been developed. The groundwater resources in these GWAs are important for agricultural and mining industries as well as local towns. Detailed hydrogeological investigations and resource mapping of these GWAs are currently being undertaken by DoW with plans to develop a groundwater model after the completion of these investigations.

This project developed estimates of recharge rates under different climate scenarios and major land uses for these GWAs. The WAVES model was used to estimate recharge rates using inputs of soil, land cover and watertable depth under various climate change scenarios using the following stepwise method.

Method

1. A brief summary of the hydrogeological setting was prepared and reported.
2. Information about recharge estimates determined previously and estimation methods was collated.
3. The data about current and future groundwater abstraction and allocation limits was collated.
4. Groundwater monitoring data were collated and analysed to assess watertable depths in various parts of the three GWAs.
5. Input files for soil and major land covers were prepared for WAVES modelling. The climate files were prepared for all modelling scenarios.
6. WAVES was used to estimate deep drainage rates under a defined set of climate and major land use conditions.

7. The recharge estimates were then compared with those estimated from chloride balance method as detailed in Chapter 6 of this report. The recharge estimates were also compared with those estimated through previous chloride balance and experimental studies.

8. The HARTT method was used to project future groundwater levels under a range of climate conditions as detailed in Chapter 5 of this report. The recharge estimates from WAVES were converted to water level changes and then compared with those projected by the HARTT method.

9. Groundwater assessments were made based on recharge estimates determined through WAVES modelling.

10. Changes in recharge in response to varying future climate conditions were assessed.

11. The recharge assessments were reviewed and reported.

2.5.5 Summary of groundwater models

The existing groundwater models used for modelling first-tier GWAs in the project area are given in Table 2-9 showing the origin of the model, degree of modification done for its use in this project and licence agreement requirements with the agency of its origin.

A new model (PHRAMS) was developed for the second-tier GWAs as outlined in Table 2-10.

The methods/models used for the estimation of groundwater recharge in the third-tier GWAs are given in Table 2-11.

<table>
<thead>
<tr>
<th>GWA ID</th>
<th>GWA</th>
<th>Model</th>
<th>Origin</th>
<th>Degree of modification</th>
<th>Licence requirement with origin agency</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Gingin</td>
<td>PRAMS</td>
<td>DoW and Water Corp</td>
<td>None</td>
<td>DoW</td>
</tr>
<tr>
<td>5</td>
<td>Gnangara</td>
<td>PRAMS</td>
<td>DoW and Water Corp</td>
<td>None</td>
<td>DoW</td>
</tr>
<tr>
<td>6</td>
<td>Yanchep</td>
<td>PRAMS</td>
<td>DoW and Water Corp</td>
<td>None</td>
<td>DoW</td>
</tr>
<tr>
<td>7</td>
<td>Wanneroo</td>
<td>PRAMS</td>
<td>DoW and Water Corp</td>
<td>None</td>
<td>DoW</td>
</tr>
<tr>
<td>8</td>
<td>Swan</td>
<td>PRAMS</td>
<td>DoW and Water Corp</td>
<td>None</td>
<td>DoW</td>
</tr>
<tr>
<td>9</td>
<td>Mirrabooka</td>
<td>PRAMS</td>
<td>DoW and Water Corp</td>
<td>None</td>
<td>DoW</td>
</tr>
<tr>
<td>10</td>
<td>Gwelup</td>
<td>PRAMS</td>
<td>DoW and Water Corp</td>
<td>None</td>
<td>DoW</td>
</tr>
<tr>
<td>11</td>
<td>Perth</td>
<td>PRAMS</td>
<td>DoW and Water Corp</td>
<td>None</td>
<td>DoW</td>
</tr>
<tr>
<td>12</td>
<td>Jandakot</td>
<td>PRAMS</td>
<td>DoW and Water Corp</td>
<td>None</td>
<td>DoW</td>
</tr>
<tr>
<td>13</td>
<td>Cockburn</td>
<td>PRAMS</td>
<td>DoW and Water Corp</td>
<td>None</td>
<td>DoW</td>
</tr>
<tr>
<td>14</td>
<td>Serpentine</td>
<td>PRAMS</td>
<td>DoW and Water Corp</td>
<td>None</td>
<td>DoW</td>
</tr>
<tr>
<td>15</td>
<td>Rockingham</td>
<td>PRAMS</td>
<td>DoW and Water Corp</td>
<td>None</td>
<td>DoW</td>
</tr>
<tr>
<td></td>
<td>Stakehill</td>
<td>PRAMS</td>
<td>DoW and Water Corp</td>
<td>None</td>
<td>DoW</td>
</tr>
<tr>
<td>20</td>
<td>Busselton-Capel</td>
<td>SWAMS</td>
<td>DoW and Water Corp</td>
<td>VFM linking; calibration update</td>
<td>DoW</td>
</tr>
<tr>
<td>21</td>
<td>Blackwood</td>
<td>SWAMS</td>
<td>DoW and Water Corp</td>
<td>Moderate</td>
<td>DoW</td>
</tr>
<tr>
<td>23</td>
<td>Blackwood-Karri</td>
<td>SWAMS</td>
<td>DoW and Water Corp</td>
<td>VFM linking; calibration update</td>
<td>DoW</td>
</tr>
</tbody>
</table>

1. Stakehill Area was shown as part of the Rockingham Area previously
2. Blackwood-Karri is not proclaimed groundwater area. Licences are required for confined aquifers only
Table 2-10. Groundwater models to be used in second-tier groundwater areas

<table>
<thead>
<tr>
<th>GWA ID</th>
<th>GWA</th>
<th>Model</th>
<th>Modelled by</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Murray</td>
<td>New superficial aquifer model PHRAMS</td>
<td>Model developed through an external contract</td>
</tr>
<tr>
<td>17</td>
<td>South West Coastal</td>
<td>New superficial aquifer model PHRAMS</td>
<td>Model developed through an external contract</td>
</tr>
<tr>
<td>18</td>
<td>Bunbury</td>
<td>New superficial aquifer model PHRAMS</td>
<td>Model developed through an external contract</td>
</tr>
<tr>
<td>19</td>
<td>Bunbury-Karri</td>
<td>New superficial aquifer model PHRAMS</td>
<td>Model developed through an external contract</td>
</tr>
</tbody>
</table>

1. Bunbury-Karri is not a proclaimed groundwater area. Licences are required for confined aquifers only.

Table 2-11. Methods/models to be used for third-tier groundwater areas

<table>
<thead>
<tr>
<th>GWA ID</th>
<th>GWA</th>
<th>Method/Model</th>
<th>Modelled by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Casuarina</td>
<td>WAVES recharge modelling, Hydrograph Analysis</td>
<td>CSIRO</td>
</tr>
<tr>
<td>2</td>
<td>Arrowsmith</td>
<td>WAVES recharge modelling, Hydrograph Analysis</td>
<td>CSIRO</td>
</tr>
<tr>
<td>3</td>
<td>Jurien</td>
<td>WAVES recharge modelling, Hydrograph Analysis</td>
<td>CSIRO</td>
</tr>
<tr>
<td>4</td>
<td>Albany</td>
<td>WAVES recharge modelling, Hydrograph Analysis</td>
<td>CSIRO</td>
</tr>
</tbody>
</table>

2.6 Groundwater assessment

Groundwater assessment levels were defined by considering the minimum standard required for different priorities and levels of confidence in the outputs.

The following criteria were used for the assessment ranking:

- complexity of any numerical modelling used and whether it modelled the key processes which are operating
- nature of, and confidence in, any extraction data used
- distribution of observed data both in space and time
- availability of independent data to support parameterisation
- peer review

Based on the above criteria the following assessment standards were used for various priority GWAs.

**Very thorough** – When prioritised on the basis of a normalised index the GWAs covered by the PRAMS and SWAMS models qualified for the highest standard of analysis because these models are complex numerical groundwater models that have been calibrated using spatially well distributed long-term historical data. Some areas were not as well known or represented by the models as others and therefore assessed at a lower level. The calibration period for these models is long enough to capture the major changes in hydraulic conditions within the model domains. Extraction data from confined aquifer systems of the GWAs covered by PRAMS and SWAMS have been metered over a long period of time while unconfined extraction has been metered only recently. The hydrogeological parameters used have been derived from sufficient field measurements The PRAMS model has been extensively used and the model and its outputs have been reviewed independently.

**Thorough** – This second level of assessment was applied to the GWAs covered by the PHRAMS and Collie models. PHRAMS was developed for the GWAs covered by the Peel-Harvey Area (Table 2-10). It is a less complex numerical model. The hydrogeology of most parts is well known and adequately represented in the numerical model. The model was based on less rigorous data and a simpler conceptual model when compared with PRAMS and SWAMS. The extraction data are less reliable than the data from GWAs covered by PRAMS and SWAMS. PHRAMS requires an independent evaluation and review. The model calibration was generally good except near boundaries and in areas of poor calibration data. The Collie Basin model is also complex. This model has been developed and calibrated previously.
This project linked the VFM with the groundwater model and updated its calibration. Due to complex hydrogeology the model is not as reliable as PRAMS and SWAMS. The groundwater extraction data are also less reliable. The information and data about surface-groundwater interactions was poor. The model calibration was generally not as good as for the other three models due to the complex hydrogeology, mine dewatering, water inflow to mine voids after mining ceases and poor representation of surface–groundwater interactions.

**Moderate** – This level of assessment was applied to the four third-tier GWAs. These GWAs do not have a groundwater model because of the lack of hydrogeological and other data necessary for developing a groundwater model. The groundwater resources have not been evaluated in any detail and the extraction data, where available, are less reliable. The moderate level of assessment was based on recharge modelling, hydrograph analysis and chloride balance method.

The evaluation of the level of confidence in the groundwater modelling and assessment was also carried out by considering the following factors:

- Groundwater model availability
- Maturity and external review of a groundwater model
- Independent water balance data (groundwater abstraction, drain flows, hydrological data availability, accuracy, length of record, reliability)
- Level of understanding of the area’s hydrogeology
- Representation of the hydrogeology in the model
- Number of bores used for model calibration, their location and formation used for monitoring
- Measured and calculated water level difference and trends and Root Mean Square errors
- Comparison of modelled recharge with other independent studies
- Independent checks of model results

A confidence map was prepared cumulating the input of all of the above factors. This map is presented and discussed in Chapter 5 of the Groundwater Main Report (CSIRO, 2009).

### 2.6.1 Surface–groundwater interactions

Significant surface–groundwater interactions existed in three areas; Gingin Brook, Capel River and Collie River, and were evaluated in this project. They also existed in other areas; however, the flux exchanges between surface water bodies and groundwater were considered not sufficiently important to warrant their calculation in this project. After identifying the location of significant surface–groundwater interactions, the next steps were to characterise the type or range of connectivity using the following methodology:

**Method**

1. A list of the relevant parameters was compiled for each river reach, particularly for modelled GWAs.
2. Assessments were made of their representation in the groundwater models (losing, gaining or both).
3. The observed stream gauging data were collated for river reaches identified to have surface–groundwater interactions. River flow and salinity measurements were taken between January and March at selected sites within the gaining reaches of rivers to get an indication of groundwater discharge as baseflow.
4. A Chapman and Maxwell analysis (or an equivalent) was conducted to obtain baseflow estimates in the river from streamflow data taking into account any water extracted from the river.
5. Data on the shallowest bores within 5 km of river reaches were collated. The data about the hydraulic properties of the material which lies laterally and vertically between the river and the main aquifer were also collated.
6. The above data were used to classify and map the connection between surface water and groundwater for particular river reaches (between major nodes) according to the saturation condition under the river. The following classes were used: (i) gaining; (ii) losing; (iii) varying between gaining and losing.
7. A conductance was assigned to various reaches based on the layer-thickness weighting (must be across the full thickness of any semi-confining layer) for hydraulic properties. If there was no semi-confining layer then the vertical hydraulic conductivity of the aquifer was used.

8. The information about groundwater extraction for each reach was collated.

9. The above information and data was reviewed.

10. Average head gradients were determined using groundwater observation bores and stage height data.

After characterising the type of connectivity between surface water and groundwater systems, the second task was to quantify the fluxes between aquifers and the stream using Darcy’s Law for the current set of conditions. Since both Gingin Brook and Capel River are known groundwater discharge areas, at least under the current conditions, the estimates of flux estimated using average hydraulic head gradients and conductance were the groundwater discharge fluxes. These fluxes were then compared with the groundwater model estimates as described below.

Only localised small-scale studies of the Collie River were available, mainly focussed on GDEs. There are further complications with this model because extracted groundwater is used to maintain river stage and river pool levels. Therefore the groundwater model was calibrated using previous catchment-scale estimates of stream–groundwater interaction, and then the new modelled values of gain and loss were compared with these.

### 2.6.2 Determination of flux exchange rates through modelling

The PRAMS model (covering Gingin Brook) and SWAMS model (covering Capel River) represent these rivers as gaining streams. Their representation this way is true under current conditions but may change in future with a decline in groundwater levels due to drying climate or increased abstraction. To enable the determination of fluxes under both losing and gaining streams, their representation requires a change in the groundwater models. This change was not made in this project due to time constraints and the ensuing need to recalibrate the models.

**Method**

1. The transient river stage heights were obtained from surface water models for input into the MODFLOW River Package as initial heads in the Collie Basin groundwater model. The Collie groundwater model was run to obtain volumes of seepage from and to the river and input these into the surface water model. This process was repeated a few times until the heads converged. The flux exchange rates were then determined from the Collie groundwater model under the current climate and land use conditions.

2. Groundwater discharge rates into the Capel River and Gingin Brook were determined by running the PRAMS and SWAMS models under current land use and climate conditions.

3. The flux rates predicted by the groundwater models were compared with average flux rates determined using Darcy’s law.

4. The fluxes estimated above were converted to monthly volumes for gaining streams (Capel River and Gingin Brook) and gaining/losing streams (Collie River) under the current land use and climate conditions.

5. The baseflow determined using the observed stream gauging data were also compared with those determined through groundwater modelling and Darcy’s Law.

6. After validation of fluxes predicted by the groundwater models, the flux rates were determined under all current and future climate and land use scenarios and their impacts on future water availability from streams were assessed. For the Collie groundwater model the river stage input to MODFLOW was reduced in accordance with changes in average stream flow under future climate scenarios.

### 2.7 Hydrograph analysis

Rainfall data correlate well with groundwater level changes in unconfined aquifers (Ferdowsian et al., 2001, Yesertener, 2008). A statistical technique to predict groundwater levels from rainfall trends based on estimation of the
cumulative deviation from mean rainfall (CDFM) has been developed by Ferdowsian and McCarron (2001), which is the basis of the Hydrograph Analysis and Rainfall Time Trends (HARTT) program. In this project the HARTT program was applied to the selected groundwater monitoring bores and the projected groundwater levels estimated under the current land use and future climate conditions. The projected groundwater level trends were compared with the modelled hydrographs where they were available. The following process was used:

- A large number of groundwater monitoring bores have been drilled into the Superficial Aquifer throughout the groundwater project area. A number of bores were selected for the hydrograph analysis using the following criteria:
  - the bore needed to be away from any surface-groundwater interaction area
  - the bore needed to be away from abstraction bores
  - very shallow and deep bores were excluded
  - the bore needed to be representative of the area, hydrogeology, flow system, land cover or climate zone
  - bores that were very close to boundaries were excluded e.g. climate zones

- Groundwater level data were extracted from the DoW Water Information (WIN) database.
- Climate data from the same weather stations were used for both hydrograph analysis and for groundwater modelling. This ensured that both methods used the same climate drivers but resulted in poorer correlations between rainfall and hydrograph response.
- Monthly rainfall data from Bureau of Meteorology weather stations used for identifying the climate zones were extracted from the SILO database of meteorological data (<http://www.longpaddock.qld.gov.au/silo/>). The Patched Point Dataset (PPD) extracted for these weather stations covered the 1900 to 2008 period.
- The observed rainfall data were extended with estimated future rainfalls from January 2008 to December 2030 according to scenarios A, B, Cwet, Cmid and Cdry to produce five climate datasets for each station.
- The water levels and rainfall data were analysed using the HARTT program.
- The HARTT projected groundwater hydrographs were compared with modelled hydrographs using various statistical tools.
- Comparison between HARTT projected and model predicted hydrographs helped validate model predictions.

Further details of the hydrograph analysis are given in Chapter 5 of this report.

2.8 Isotope and hydrogeochemical groundwater recharge assessments

2.8.1 Background and proposed work program

Carbon-14 has been used extensively and successfully in the past as a tool in groundwater investigations in the Northern and Southern Perth basins (Thorpe, 1994). More recently carbon-14 data has been used to validate groundwater flow model estimates (particle tracking, groundwater travel times) in the south-west Yarragadee, thereby constraining model parameters and recharge rates. Preliminary integration of groundwater travel time estimation via particle tracking against travel times estimated from carbon-14 data in the south-west Leederville aquifer indicates a good agreement between methods (Turner and Dighton, 2008). The use of isotope data to independently validate groundwater model results adds confidence to estimates of groundwater yields.

Carbon-14 data on deep groundwater is available from nine east–west transects across the coastal plain, four transects in the Northern Perth Basin and six in the Southern Perth Basin. The most northerly transect in the Northern Perth Basin is 70 km north of Perth while the most southerly is 50 km south of Perth. The most northerly transect on the Southern
Perth Basin is near Bunbury and the most southerly is at Karridale, giving a total north to south range for both basins of 300 km. In addition, carbon-14 data are available from the south-west Leederville, south-west Yarragadee Aquifers and the Collie Basin (Table 2-12).

Table 2-12. Sources of carbon-14 data for model validation

<table>
<thead>
<tr>
<th>Data description - Carbon-14</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Perth Basin, including Seabird, Moora, Three Springs, Allannooka, Gillingarra Line, Boresite GL1 and Dathagnoorara.</td>
<td>DoW hydrogeology reports</td>
</tr>
<tr>
<td>North Perth Basin – AM series E-W coastal Plain (Four Transects)</td>
<td>DoW hydrogeology reports</td>
</tr>
<tr>
<td>Northern Perth Basin – Parmelia</td>
<td>Bekele et al., 2006.</td>
</tr>
<tr>
<td>South Perth Basin AM Series E-W coastal Plain (Five Transects)</td>
<td>DoW hydrogeology reports</td>
</tr>
<tr>
<td>Collie Basin</td>
<td>DoW/CSIRO L&amp;W Hydrogeology reports</td>
</tr>
<tr>
<td>Cowaramup-Busselton Leederville Aquifer</td>
<td>DoW/CSIRO L&amp;W Hydrogeology reports</td>
</tr>
<tr>
<td>SW Yarragadee</td>
<td>DoW &amp;Water Corporation Reports</td>
</tr>
</tbody>
</table>

In the context of this project, the objective was to capitalise on these data sources to validate modelling efforts in PRAMS, SWAMS and PHRAMS and thus to provide more scientifically defensible recharge estimates.

Groundwater travel times based on model results and those estimated by carbon-14 can be assessed using particle tracking. The model estimates not only the path-lines of groundwater but also gives time markers along the path-lines. The comparison of model-generated path-lines and time markers with carbon-14 determined groundwater travel times permits the independent validation of model parameter settings (e.g. recharge rate, hydraulic conductivity fields, boundary conditions) used in modelling the steady state groundwater condition, conventionally calibrated to observed groundwater heads. This will allow better constraints for model parameter settings. This is expected to be the case for PHRAMS and SWAMS. The PRAMS model is complex and, if found necessary from the validation check, recalibration scenarios may be required in future.

The question of isotope and hydrogeochemical methods ‘tending to underestimate recharge rates’ is recognised and actually emphasises the benefit of integrating model and carbon-14 approaches. Deeper aquifer groundwater carbon-14 travel times will reflect the rate of groundwater flow through the aquifer, while shallower carbon-14 reflects the unconfined recharge and circulation rates. A correctly calibrated steady-state groundwater model should reflect this, as should carbon-14. These considerations should lead to improved parameter setting in ‘over-specified’ models.

The work program advanced the integration of carbon-14 data with groundwater modelling results over the Northern and Southern Perth basins and south-west in terms of both the methodologies of integration and the geographical extent of application of the methods. The model aquifer for the integration was the south-west Leederville Aquifer where integration methods were refined and developed using existing isotope data and model results. The refined approaches were applied to other groundwater sub-basins where carbon-14 data are available according to priority areas outlined in the project. The detailed methodology for the isotope-based groundwater assessments is outlined below. First-tier GWAs where particle tracking model analysis is possible were identified and undertaken in the program.

Chloride and hydrogeochemical data from the Superficial and deep aquifers were examined and used as a guide to estimate net recharge rates from knowledge of rainfall chloride concentrations. These estimates were compared with Vertical Flux Model estimates of net recharge.

Methods

1. Review all existing carbon-14 data on groundwater from the Northern and Southern Perth basins and south-west aquifers in the context of the model south-west Leederville Aquifer approach.
2. Prepare and collate a summary of carbon-14 isotope and related data from the Northern and Southern Perth basins mapped across available first-tier GWAs where models are available.
3. Use existing hydrogeochemical data to develop spatial maps of groundwater quality with depth and hydrostratigraphic unit for estimating recharge.
4. Develop a systematic approach to integrating carbon-14 estimation of groundwater travel times with particle-tracked travel time estimates from first-tier GWA models. Practically, this entailed ensuring the implemented models have the capability to produce particle tracking output once the calibration to heads was attained.

5. Use the approach to validate and optimise model parameter settings and hence recharge estimates and sustainable groundwater yield for first-tier GWA models where sufficient satisfactory data were available.

6. Where important data gaps were identified, undertake limited additional sampling and carbon-14 isotope and associated isotope and water quality measurements that improve the strategic assessment.

7. Review and report on the assessments outlining the methodology for integrating groundwater carbon-14 isotope and related hydrogeochemical data with groundwater model results applicable over the south-west region.

2.9 References


Charles S and Fu G (2009) Statistical downscaling of coupled climate model historical runs. SEACI Project Report SEACI, 24 pp. Available at <http://www.seaci.org/docs/reports/1.5.2_1.5.3_final.doc>


Yesertener C (2008) Assessment of the declining groundwater levels in the Gnangara groundwater mound. Hydrogeological Record Series HG14 Western Australia, Department of Water.

3 Land cover mapping

3.1 Introduction

To estimate recharge a Vertical Flux Model (VFM) coupled with the groundwater models called PRAMS, SWAMS and Collie was used. The VFM estimates rainfall recharge utilising WAVES and other empirical equations. For the Groundwater Management Areas (GWAs) covered by the PRAMS, SWAMS and Collie groundwater models, a directly coupled VFM estimated net recharge according to the procedure described in Barr et al. (2003). For the areas covered by the PHRAMS groundwater model, the rainfall-recharge modelling was completed using a semi-linked VFM. The WAVES model was used by itself to estimate recharge rates in the Northern Perth Basin and Albany area where no groundwater models were currently available. The VFM estimates recharge rates or deep drainage based on soil type, climate, land cover and watertable depth.

This chapter describes the development of an ArcGIS-based model for mapping the historical and current land cover for the project area. The methodology is based on previous work by Furby et al. (2008), Hodgson et al. (2005), Silberstein et al. (2004), Canci (2004), Xu et al. (2004) and Allen, 2003. The model processed historical Landsat 5 Thematic Mapper (TM) data and produced land cover maps at two-yearly intervals from 1988 to 2002 and yearly maps from 2003 to 2008. Each map classified areas of Native Vegetation, Pine Plantation, Dryland Agriculture, Summer Wet areas, Urban and Bare Soil areas, Commercial and Industrial areas, and Open Water and Wetland classes of land cover. In addition a number of subclasses within Native Vegetation and Pine Plantation classes were mapped to reflect vegetation densities that affect recharge rates.

3.2 Data sources

The source data required for land cover modelling includes satellite imagery, aerial photographs, geographic datasets and ground truth information. A series of six-band Landsat images, Water Mask, Density Index and Vegetation Mask raster sequences used in the project were collected from the database of the Land Monitor project. The Land Monitor satellite data were compiled from multi-scene imagery acquired over summer from the Landsat TM sensor over the 1988 to 2008 period (Furby et al., 2008). The original data were ortho-rectified using the Land Monitor Digital Elevation Model and calibrated to the Land Monitor Landsat TM Summer 1994 base prior to processing (Furby, 2008). Density Index (DI) rasters were calculated using the original Landsat imagery for each selected year:

\[ DI = \frac{\text{red} + \text{midIR}}{2} \]  

where ‘red’ and ‘midIR’ parameters are electromagnetic regions corresponding to spectral bands 3 and 5 of the Landsat TM sensor. The algorithm for producing the Vegetation Mask raster is based on using the Conditional Probability Networks approach described in Furby et al. (2008). The final mask is a binary image of ‘bush areas’ coded by number of 1 and ‘no bush areas’ coded by number of 2. A single-band raster was also created using the original Landsat TM data from various dates to mask open water sources. As all the Land Monitor products are split into four different regions (Furby, 2008) the collected data were pre-processed to construct a series of mosaic images to fit the project area. The data pre-processing procedure is described in Section 3.3.

In addition, a cadastral map of pine plantations compiled by the Forest Products Commission (FPC) of Western Australia was used to distinguish pines from other vegetation types.

The generation of Urban/Bare Soil and Commercial/Industrial land cover layers was carried out using the urban and industrial area masks from the Perth Regional Aquifer Modelling System (PRAMS) project database (Canci, 2004) and the national map of large population centres downloaded from the Geoscience Australia website.

To identify Summer Wet areas, ground truth data on irrigated areas in the Harvey, Waroona and Collie irrigation districts was used (Ali et al., 2009).
The rasters used in the study were projected into UTM zone MGA50 area in datum GDA94 with a resolution of 25 m per pixel.

3.3 Model description

A GIS-based model was built to create a hierarchy of raster layers of land cover classes (Figure 3-1) which was combined into a final land cover map for a selected year. The process of building a land cover map consists of six stages. It starts from building a ‘Native Vegetation’ raster, then a ‘Pine Plantation’ raster is generated and the two rasters are combined into land cover Layer 1 (Figure 3-2). Next, a ‘Dryland Agriculture’ raster is added to produce land cover Layer 2. Land cover Layer 3 is then created by overlaying Layer 2 by ‘Urban/bare soil’ and ‘Commercial/Industrial’ rasters built beforehand. A ‘Summer Wet/irrigated/seeps’ raster is further created and land cover Layer 4 is formed. Finally Layer 4 is overlaid by the Water Mask (Section 3.2) to produce a land cover map. The model was implemented for producing 14 land cover maps for 1988, 1990, 1992, 1994, 1996, 2000, 2002, 2003, 2004, 2005, 2006, 2007 and 2008. The following sections describe how the land cover maps were created for the project area. Sections 3.3.1 and 3.3.2 describe the algorithm of producing a land cover map and the process of identifying individual land cover classes. Section 3.3.3 describes how the model was implemented in the ArcGIS environment.

3.3.1 Land cover classification algorithm

First the ‘Native Vegetation’ raster was created as shown in the land cover classification flowchart in Figure 3-2. It involved calculating a Leaf Area Index (LAI) established for native vegetation types such as Banksia woodlands (Allen, 2003) and Jarrah forest (Boniecka, 2004), compiling the LAI rasters into one and masking the perennial bush/forestry areas using the Vegetation Mask provided by the Land Monitor project. The LAI values were then grouped into four subclasses of native vegetation according to different degrees of vegetation density: low, medium, medium to high and high. The final raster was created by assigning pixel values of 1, 2, 3 or 4 corresponding to the density subclasses within the native vegetation area and a zero value otherwise (Table 3-1).

The ‘Pine Plantation’ raster was generated by calculating pine LAIs as described by Canci (2004) who implemented the pine index formula developed by Allen (2003) for the production of land use maps for PRAMS. Similar to the Native Vegetation raster, the pine LAI values were grouped into five density subclasses: low, low to medium, medium, medium to high and high. A raster with values of 5, 6, 7, 8 or 9 was generated and masked by the pine plantations’ base grid created using the pine plantations’ cadastral map. The two rasters were further combined so that pixel values of the Native Vegetation raster were replaced with the pixel values of the Pine Plantations’ raster if they were located within a designated pine plantation. This combined raster was denoted as land cover Layer 1.

![Figure 3-1. Hierarchy of land cover layers](image)
3 Land cover mapping

Figure 3-2. Flowchart of the land cover mapping algorithm
The ‘Dryland Agriculture’ cover was initially built as a raster with a value of 10 (Table 3-1) for all pixels outside bush areas indicated by the Vegetation Mask. This raster was then combined with land cover Layer 1 to produce land cover Layer 2 (Figure 3-2). In the final land cover map the Dryland Agriculture class was comprised of the initially defined pixels excluding all ‘Urban/Bare soil’, ‘Commercial/Industrial’, ‘Summer Wet’ and ‘Water’ areas identified later.

As mentioned in Section 3.2 the ‘Urban residential/bare soil’ and ‘Urban commercial’ rasters were generated using ‘Urban Residential’ and ‘Urban Commercial/Industrial’ layers from the PRAMS land use maps (Canci, 2004). The ‘Urban Residential’ layer was extended by 10 km buffer zones around Busselton, Bunbury, Mandurah and Collie. The bare soil areas (described later) within these buffer zones were composed with the PRAMS ‘Urban Residential’ layer to produce the ‘Urban residential/bare soil’ raster. The pixel values of this raster were coded with a value of 12. The ‘Urban commercial’ raster was a copy of the PRAMS ‘Urban Commercial/industrial’ layer. The pixel values of this raster were coded with a value of 13. Land cover Layer 2 with these two layers on the top formed land cover Layer 3 (Figure 3-2).

The ‘Summer wet/irrigated/seeps’ raster was created by cutting off all the values of Normalised Difference Vegetation Index (NDVI) below 0.3 for the areas outside the perennial Vegetation Mask from the Land Monitor project (Furby et al., 2008). Pixels located within the identified summer wet areas were assigned a value of 11. The land cover Layer 3 combined with the Summer wet raster becomes land cover Layer 4.

Finally, the ‘Water’ raster created from the water mask by the Land Monitor project was added to land cover Layer 4 to produce Final Layer of the land cover map. The water pixels in the final raster were coded with a value of 14 (Table 3-1).

### Table 3-1. Land cover classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Native vegetation</td>
<td>1 to 4</td>
</tr>
<tr>
<td>Pine plantations</td>
<td>5 to 9</td>
</tr>
<tr>
<td>Dryland agriculture</td>
<td>10</td>
</tr>
<tr>
<td>Summer wet/irrigated/seeps</td>
<td>11</td>
</tr>
<tr>
<td>Urban/bare soil</td>
<td>12</td>
</tr>
<tr>
<td>Commercial/industrial</td>
<td>13</td>
</tr>
<tr>
<td>Water/estuaries</td>
<td>14</td>
</tr>
</tbody>
</table>

## 3.3.2 Identification of land cover classes

### Native vegetation

Identification of Native Vegetation areas within the project area was based on use of LAI rasters derived from Landsat TM imagery. Studies by Hodgson et al. (2005), Silberstein et al. (2004), Allen, (2003), Fassnacht (1997), and Boniecka (2004) suggest a variety of formulas for calculating LAI depending on the type of vegetation and regions. In this project the following formulas were used for estimating LAI for Banksia (Allen, 2003) and Jarrah (Boniecka, 2004).

\[
Banksia = -0.011 \times DI + 1.51
\]  

\[
Jarrah = 4.122 \times NDVAdjusted - 0.6257
\]

where

\[
NDVAdjusted = \frac{1.081 \times nearIR - red - 5.6}{1.081 \times nearIR + red - 37.6}
\]

and Density Index (DI) was defined in equation (3-1).

The ‘red’ and ‘nearIR’ parameters are electromagnetic regions corresponding to spectral bands 3 and 4 of the Landsat TM sensor.
As shown in Figure 3-3 the project area stretches from north to south covering an extensive part of the coastal region of Western Australia where the native vegetation cover in the northern parts is presented mainly by Banksia woodland and by Jarrah forests in the southern parts. Therefore, two LAI rasters were produced for these types of native vegetation for the whole project area. Further, the northern part of the Banksia LAI raster and the southern part of the Jarrah LAI raster (Figure 3-3) were extracted from the original rasters and combined in the final LAI raster.

The LAI values were then further grouped into four density subclasses as low, medium, medium to high and high. The density ranges established for Banksia and Jarrah LAI and the corresponding subclasses are presented in Table 3-2.

An example of the ‘Native Vegetation’ layer is shown in Figure 3-4.

<table>
<thead>
<tr>
<th>Subclass</th>
<th>Code</th>
<th>Banksia</th>
<th>Jarrah</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>1</td>
<td>&lt;0.75</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Medium</td>
<td>2</td>
<td>0.75 – 0.85</td>
<td>–</td>
</tr>
<tr>
<td>Medium to high</td>
<td>3</td>
<td>&gt;0.85</td>
<td>1.0 – 2.0</td>
</tr>
<tr>
<td>High</td>
<td>4</td>
<td>–</td>
<td>&gt;2.0</td>
</tr>
</tbody>
</table>

Pine plantations

The ‘Pine Plantations’ raster layer was created by calculating LAI for Pines as detailed by Canci (2004) and Hodgson (2003):

\[
Pines = 6.08 \times NDV_{\text{adjusted}} - 0.5666
\]
and masking pixels outside pine plantations using the shapefile of commercial ‘softwood’ and ‘hardwood’ forestry in WA (Figure 3-5) supplied by the Forestry Products Commission (FPC).

The Pine raster pixels within the ‘softwood’ polygons were then grouped into five subclasses according to the LAI density ranges presented in Table 3-3.

Figure 3-6 shows a Pine Plantations’ layer overlaying the previously created ‘Native Vegetation’ layer. The combination of the two layers of native vegetation and pine plantations is named as land cover Layer 1.

It should be noted that equations 3-2 and 3-5 used for calculating LAI for Banksia and Pines in this project, were modified by Hodgson (2005) and Silberstein (2004) to increase accuracy of LAI estimations. However, the older versions of the LAI formulas were applied to match PRAMS land cover maps produced by Canci (2004) so that this model did not need to be recalibrated and so results were compatible with the Gnangara Sustainability Strategy modelling.

![Figure 3-4. Native Vegetation layer in the Perth area](image)

<table>
<thead>
<tr>
<th>Subclass</th>
<th>Code</th>
<th>Pines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>5</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Low to medium</td>
<td>6</td>
<td>1.0 to 1.5</td>
</tr>
<tr>
<td>Medium</td>
<td>7</td>
<td>1.5 to 2.0</td>
</tr>
<tr>
<td>Medium to high</td>
<td>9</td>
<td>2.0 to 2.5</td>
</tr>
<tr>
<td>High</td>
<td>10</td>
<td>&gt; 2.5</td>
</tr>
</tbody>
</table>
Figure 3-5. Commercial forestry polygons provided by the Forest Products Commission
Dryland agriculture

Dryland Agriculture areas were subtracted from the study area using the Vegetation Mask provided by the Land Monitor Project. The ‘no bush’ pixels were coded a value of 10 and the rest of the study areas had no values within the resultant ‘Dryland Agriculture’ raster. Land cover Layer 1 with the ‘Dryland Agriculture’ cover on the top formed land cover Layer 2 shown in Figure 3-7.
Urban residential/bare soil and Urban commercial areas

The urban areas within the Central Perth Basin were identical to the corresponding areas in PRAMS land use maps produced by Canci (2004). Outside the Central Perth Basin the ‘Urban residential/bare soil’ raster was presented by the pixels extracted from the Density Index raster (Section 3.2) with values varying between 92 and 105 within the 10 km buffer zones around Mandurah, Bunbury, Busselton and Collie population centres (Figure 3-8).

It was assumed that urban commercial and industrial areas are insignificant outside the Central Perth Basin. Therefore, the ‘Urban commercial’ raster was a copy of the ‘Urban Commercial/Industrial’ layer from the PRAMS land use maps. Figure 3-9 shows land cover Layer 3 created by combining land cover Layer 2 with the ‘Urban residential/bare soil’ and ‘Urban commercial’ layers on the top.
Summer wet/irrigated/seeps areas

Summer wet, irrigated and seep areas are typically characterised by their greenness over the summer months in comparison with annual crop and pastures which are dead at this time of the year. Since the late 1980s a variety of vegetation indices have been proposed and used to determine green regions from remote sensing data. In particular, it was shown by Pax-Lenney et al. (1996); Abuzar et al. (2001), Martinez-Beltran and Calera-Belmonte (2001) that the Normalised Difference Vegetation Index (NDVI) in equation (3-6)

\[
\text{NDVI} = \frac{\text{nearIR} - \text{red}}{\text{nearIR} + \text{red}}
\]

is a reliable indicator of green areas on the surface where ‘nearIR’ is the reflectance in the near-infrared band (Landsat Band 4), and ‘red’ is the reflectance in the red visible band (Landsat Band 3).

In this project, NDVI rasters were created from the Landsat imagery from the Land Monitor project database (Section 3.2). The raster pixels with NDVI values exceeding threshold \(T = 0.3\) were identified as irrigated, summer wet and seep areas if located within the ‘no bush areas’ in the Vegetation Mask (Section 3.2). Figure 3-10 (right image) shows an extract of the NDVI raster (in green) covered by Vegetation Mask (dark green) created for year 2005 within the project area. The resulting ‘Summer wet/irrigated/seeps’ raster in Figure 3-10 (left image) was defined as the NDVI area (in pink) not covered by perennial bushes or forestry. Land cover Layer 4 (Figure 3-11) was then composed from land cover Layer 3 with the ‘Summer wet/irrigated/seeps’ layer on the top.

The NDVI threshold of 0.3 was determined using the ground truth information about location of irrigated areas in the Harvey region in 2001 (Ali et al., 2009). The area of polygons shown in Figure 3-12 (in pink) was compared with the area of polygons identified as irrigated areas according to the described algorithm (in blue) and with the areas identified using NDVI threshold values such as \(T = 0.2\) and \(T = 0.4\) (Allen, 2003). It was found that \(T = 0.3\) provided more accurate results.
Figure 3-10. Determination of summer wet/irrigated/seeps areas (left) from NDVI and perennial vegetation mask rasters (right).

Figure 3-11. Land cover Layer 4 for an area in the western suburbs of Perth.
Water/estuaries mask

The Water Mask from the Land Monitor Project was used as a ‘Water/estuaries’ raster for combining with land cover Layer 4 to produce the final land cover map (Figure 3-13).
3.3.3 Creating ArcGIS toolboxes for mapping land cover

Three new ArcGIS toolboxes, which underpin the land cover classification model, were developed for pre-processing input data, land cover classification and producing maps in ArcGIS 9.3 - a software suite developed by ESRI (Environmental Science Research Institute website <http://www.esri.com>). The flowchart of the land cover classification model is shown in Figure 3-14.

Data pre-processing

The first ArcToolbox included three geoprocessing tools (Figure 3-15) for pre-processing data: ‘Mosaicing’, ‘NDVI’ and LAI’. The ‘Mosaicing’ tool was built for joining original images from the Land Monitor project and clipping the resultant image to fit the project area. The ‘NDVI’ tool was created for calculating NDVI and NDVI-adjusted vegetation indices as defined by equations 3-6 and 3-4 to produce NDVI rasters. The ‘LAI’ tool was used for calculating LAIs for Banksia, Jarrah and Pines by equations 3-2, 3-3 and 3-5 respectively and producing LAI rasters. Pre-processing starts by running the ‘Mosaicing’ tool (Figure 3-15) which uses the ArcGIS model ‘Mosaic To New Raster’ from the ‘Data Management Tools’ ArcToolbox. Figure 3-16 shows the ‘Mosaicing’ tool generated using the ArcGIS graphical environment ‘ModelBuilder’. The input information included the Land Monitor rasters for bands 3, 4 and 5 used for calculation of LAI and NDVI, the Density Index, Vegetation Mask and Water Mask rasters. The outputs of the tool were used by the second tool ‘NDVI’ (Figure 3-17) which produced NDVI and NDVI adjusted rasters. The third tool ‘LAI’ (Figure 3-18) built three LAI rasters.

![Figure 3-14. Flowchart of ArcGIS-based land cover classification model](image)

![Figure 3-15. Data pre-processing Toolbox](image)
Figure 3-16. Geoprocessing tool for mosaicing Land Monitor rasters
Figure 3-17. Geoprocessing tool for calculating NDVI and NDVI adjusted rasters

Figure 3-18. Geoprocessing tool for calculating LAI
Land cover classification

The second ArcToolbox was created for generating raster layers of land cover (Figure 3-19). It included five tools for identifying land classes indicated in Figure 3-1 except the Water/estuaries layer. The land cover rasters were generated according to the land cover classification algorithm described in Sections 3.3.1 and 3.3.2.

![Figure 3-19. Land cover classification Toolbox](image)

The ArcGIS tool created for producing a ‘Native Vegetation’ raster for a selected year is shown in Figure 3-20. The LAI rasters for Banksia and Jarrah created previously were classified according to the density classes in Table 3-2 and combined into one raster as described in Section 3.3.2.

![Figure 3-20. Geoprocessing tool for producing 'Native Vegetation' rasters](image)

The tool for building the ‘Pine Plantation’ rasters is shown in Figure 3-21. It consisted of two operations ‘Plus’ and ‘Reclassify’. The first operation used the pine plantations shapefile to mask the LAI raster for Pines generated earlier by the ‘LAI’ tool. Then the masked Pines LAI raster values were classified into five density classes presented in Table 3-3. The output of the tool was a raster with pixel values between 5 and 9. The Pine plantations and Study area shapefiles were the model variables for masking the raster.
The ‘Dryland Agriculture’ raster, which overlays the two previous layers, was produced by the tool shown in Figure 3-22. The tool simply reclassifies the input Vegetation Mask raster values for no bush area to be notified as the Dryland Agriculture land cover class with pixel values equal to 10.

The urban areas both residential and commercial identified by Canci (2004) for the PRAMS project were combined with the areas determined to be ‘urban’ or ‘bare soil’ around the four selected towns (Sections 3.3.1 and 3.3.2). The ArcGIS based tool for producing a raster for urban areas is shown in Figure 3-23.
The PRAMS urban areas were extracted from the land use map (Canci, 2004) and coded to produce the PRAMS Urban 1 layer. The PRAMS urban residential areas in this layer were coded by the number 12 and the commercial or industrial urban areas by the number 13. The ‘Reclassify’ procedure extends the PRAMS urban areas to the size and shape of the project area with no-urban areas coded as 0.

The ‘urban’ or ‘bare soil’ areas outside the PRAMS region were identified by the two-step procedure using the ArcGIS Map Algebra tool. First, the Density Index Map pixels with values between 92 and 105 were extracted and labelled as 12 to form the Urban 1 layer. Then the Urban 1 layer was masked by the Urban Mask raster preliminary created from a shapefile of 10 km buffer zones around Busselton, Bunbury, Mandurah and Collie to create the Urban 2 layer. This layer was a raster with pixel values equal to 12 within the 10 km buffer zones about the selected towns and 0 otherwise. The PRAMS Urban 2 and Urban 2 layers were then combined by the ‘Plus’ operation and reclassified to have only two types of urban areas such as Urban residential/bare soil and Urban commercial coded as shown in Table 3-1.

The ‘Summer wet/irrigated/seeps raster was created by the tool shown in Figure 3-24.

![Figure 3-24. Geoprocessing tool for producing 'Summer wet/irrigated/seeps' rasters](image)

The tool masked the NDVI raster to exclude perennial bush and forestry areas from the Vegetation Mask. Then only those pixels with NDVI values exceeding 0.3 were extracted. The resulting raster was then generated by assigning the value of 11 to the extracted NDVI pixels and 0 to the rest of pixels within the project area.

The geoprocessing tools presented in Figure 3-16 to Figure 3-24 were built for generating relevant rasters for a selected year.

Land cover mapping

The structure of the Land cover mapping ArcGIS Toolbox is shown in Figure 3-25. Land cover mapping Toolbox Each model of the Toolbox produced one land cover map for each of the selected years.

![Figure 3-25. Land cover mapping Toolbox](image)

Figure 3-26 presents the ArcGIS tool for building a land cover map. The tool created four intermediate land cover layers which were consequently combined to produce a final land cover map. It started from building land cover Layer 1 by combining the ‘Native Vegetation’ and ‘Pine Plantations’ raster layers. Land cover Layer 2 was generated by overlaying
land cover Layer 1 by the ‘Dryland Agriculture’ raster. Land cover Layer 3 was produced by adding the final urban layer built from the ‘Urban residential/bare soil’ and ‘Urban commercial’ rasters over land cover Layer 2. Then land cover Layer 3 was covered by the ‘Summer wet/irrigated/seeps’ raster to build land cover layer 4. The final land cover map was created by composing land cover Layer 4 with the Water Mask on the top.

3.4 Land cover classification

3.4.1 Model application

Fourteen land cover maps were produced using the GIS-based land cover classification model described in the previous sections to provide the VFM with the information about temporal and spatial changes in land cover within the project area over the period between 1988 and 2008.

Figure 3-27 shows two land cover maps produced for years 1988 and 2008 with the corresponding areas for each land cover class presented in Table 3-4.
Figure 3-27. Land cover maps of the project area for 1988 and 2008

Visually the presented maps do not differ significantly. In the north-east the density of native vegetation appears to have thinned and in the south-east the spatial pattern of the high density native vegetation subclass has changed, with some of this likely to be due to the expansion of eucalypt plantations. Variations in allocation and density of pine plantations north of Perth are also evident as pines have matured and been logged. It is difficult to find any visible changes in the spatial distribution of Dryland Agriculture.

Table 3-4 shows total areas covered by various land cover classes in 1988 and 2008 and changes over the last 21 years. The total area of Native Vegetation was reduced by about 2300 km$^2$ while the area of Dryland Agriculture increased by about 1600 km$^2$. This may reflect active clearing of bush or the gradual thinning of native bush until it has a reflectance more similar to Dryland Agriculture. At the same time, the area of the high density native vegetation grew by 1880 km$^2$ with eucalypt plantations contributing to this rise. The total area of pine plantations slightly increased, mostly due to the growth in the high density pine area. The areas of the Summer wet/Irrigated/Seeps and Urban residential/bare soil increased, which may reflect further urbanisation (urban / bares soil increased by about 77%) and the irrigation of private and public open space in the last 20 years.
Table 3-4. Areas (km$^2$) of land cover classes in the project area

<table>
<thead>
<tr>
<th>Code</th>
<th>Class</th>
<th>1988</th>
<th>2008</th>
<th>Change</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low density native vegetation</td>
<td>13,724</td>
<td>12,795</td>
<td>-929</td>
<td>-7</td>
</tr>
<tr>
<td>2</td>
<td>Medium density native vegetation</td>
<td>3,495</td>
<td>2,852</td>
<td>-643</td>
<td>-18</td>
</tr>
<tr>
<td>3</td>
<td>Medium to high density native vegetation</td>
<td>14,492</td>
<td>11,885</td>
<td>-2,607</td>
<td>-18</td>
</tr>
<tr>
<td>4</td>
<td>High density native vegetation</td>
<td>4,314</td>
<td>6,195</td>
<td>1,881</td>
<td>44</td>
</tr>
<tr>
<td>5</td>
<td>Low density pines</td>
<td>78</td>
<td>94</td>
<td>16</td>
<td>21</td>
</tr>
<tr>
<td>6</td>
<td>Low to medium density pines</td>
<td>59</td>
<td>73</td>
<td>13</td>
<td>23</td>
</tr>
<tr>
<td>7</td>
<td>Medium density pines</td>
<td>80</td>
<td>79</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>8</td>
<td>Medium to high density pines</td>
<td>77</td>
<td>65</td>
<td>-12</td>
<td>-16</td>
</tr>
<tr>
<td>9</td>
<td>High density pines</td>
<td>203</td>
<td>223</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>Dryland agriculture</td>
<td>24,220</td>
<td>25,816</td>
<td>1,596</td>
<td>7</td>
</tr>
<tr>
<td>11</td>
<td>Summer wet/irrigated/seeps</td>
<td>224</td>
<td>476</td>
<td>252</td>
<td>112</td>
</tr>
<tr>
<td>12</td>
<td>Urban/bare soil</td>
<td>594</td>
<td>1,049</td>
<td>455</td>
<td>77</td>
</tr>
<tr>
<td>13</td>
<td>Commercial/industrial</td>
<td>127</td>
<td>85</td>
<td>-43</td>
<td>-34</td>
</tr>
<tr>
<td>14</td>
<td>Water/estuaries</td>
<td>809</td>
<td>809</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 3-28 to Figure 3-41 present the land cover maps produced for years from 1988 to 2008.

### 3.4.2 Accuracy assessment

The accuracy of land cover classification was assessed for the extracts from the built maps covering the Central Perth Basin. These CPB maps were compared with the PRAMS land use maps produced by Canci (2004). The kappa coefficient (Cohen, 1960) was estimated to express the level of agreement between the two series of maps. Kappa is always less than or equal to one (Landis and Koch, 1977). A value of one implies a perfect agreement and a value of zero indicates a random classification of the map pixels. Kappa values between 0.6 and 0.8 are usually interpreted as substantial agreement; values from 0.4 to 0.6 show moderate agreement; values from 0.2 to 0.4 and from 0 to 0.2 are interpreted as fair and slight agreement respectively. Table 3-5 shows values of the kappa statistic which varies between 0.6 and 0.75. This indicates substantial strength of agreement between this project and Canci (2004).

Table 3-5. Kappa values showing a degree of agreement between this project and Canci (2004) for the CPB area

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>kappa</td>
<td>0.68</td>
<td>0.70</td>
<td>0.69</td>
<td>0.60</td>
<td>0.68</td>
<td>0.71</td>
<td>0.61</td>
<td>0.68</td>
<td>0.75</td>
<td>0.74</td>
<td>0.74</td>
<td>0.72</td>
<td>0.74</td>
</tr>
</tbody>
</table>
Figure 3-28. Land cover map for 1988
Figure 3-29. Land cover map for 1990
Figure 3-30. Land cover map for 1992

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Figure 3-31. Land cover map for 1994

1994
- Low density native veg
- Medium density native veg
- Medium to high density native veg
- High density native veg
- Low density pines
- Low to medium density pines
- Medium density pines
- Medium to high density pines
- High density pines
- Dryland agriculture
- Summer wet/irrigated/seeps
- Urban residential/bare soil
- Urban commercial
- Water/estuaries

Kilometres
Figure 3-32. Land cover map for 1996
Figure 3-33. Land cover map for 1998
Figure 3-34. Land cover map for 2000
Figure 3-35. Land cover map for 2002
Figure 3-36. Land cover map for 2003
Figure 3-37. Land cover map for 2004
Figure 3-38. Land cover map for 2005
Figure 3-39. Land cover map for 2006

- Low density native veg
- Medium density native veg
- Medium to high density native veg
- High density native veg
- Low density pines
- Low to medium density pines
- Medium density pines
- Medium to high density pines
- High density pines
- Dryland agriculture
- Summer wet/irrigated/seeps
- Urban residential/bare soil
- Urban commercial
- Water/estuaries
Figure 3-40. Land cover map for 2007

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Figure 3-41. Land cover map for 2008
## 3.5 References


CSIRO (2008b) Description of Project Methods, South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia, 70 pp.


3 Land cover mapping


Yesertener C (2008) Assessment of the declining groundwater levels in the Gnangara groundwater mound. Hydrogeological Record Series HG14 Western Australia, Department of Water.

Groundwater area prioritisation

Three approaches were used to prioritise groundwater areas (GWAs) considered for groundwater modelling and assessment in the South-West Western Australia Sustainable Yields project. The results from the Murray-Darling basin prioritisation approach are described, followed by the results from the National Land and Water Resources Audit/Department of Water prioritisation method. The last section provides results from the tier-based prioritisation approach.

4.1 Murray-Darling Basin prioritisation approach

Prioritisation index

This index is listed for each GWA of the project area in Table 4-1. The levels of priorities were assigned according to their priority ranking.

A prioritisation index between 0 and 1 and priority ranking of ‘very high’ indicates a high importance for all GWAs requiring ‘thorough to very thorough’ assessments.

By being similarly classified throughout, this prioritisation index does not distinguish between groundwater resources that have different development pressures as experienced in this project area. It may however be suited to areas where groundwater resources are less utilised.

Table 4-1. Groundwater areas, their MDB normalised index, priority rank, minimum assessment and actual assessment

<table>
<thead>
<tr>
<th>Peel-Harvey Area</th>
<th>Southern Perth Basin</th>
<th>Collie Basin</th>
<th>Albany Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>N16 Murray</td>
<td>Busselton-Capel</td>
<td>Collie</td>
<td>Albany</td>
</tr>
<tr>
<td>N17 South West Coastal</td>
<td>Blackwood</td>
<td></td>
<td>N24 Albany</td>
</tr>
<tr>
<td>N18 Bunbury Karri</td>
<td>Blackwood Karri</td>
<td></td>
<td>N9 Mirrabooka</td>
</tr>
<tr>
<td>N19 Bunbury</td>
<td></td>
<td></td>
<td>N10 Gwelup</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N11 Perth</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N12 Jandakot</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N13 Cockburn</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N14 Serpentine</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N15 Rockingham</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Normalised index</th>
<th>Priority rank</th>
<th>Minimum assessment</th>
<th>Actual assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>N11</td>
<td>Perth</td>
<td>0.13</td>
<td>Very high</td>
<td>Very thorough</td>
<td>Very thorough</td>
</tr>
<tr>
<td>N12</td>
<td>Jandakot</td>
<td>0.01</td>
<td>Very high</td>
<td>Very thorough</td>
<td>Very thorough</td>
</tr>
<tr>
<td>N13</td>
<td>Cockburn</td>
<td>0.01</td>
<td>Very high</td>
<td>Very thorough</td>
<td>Very thorough</td>
</tr>
<tr>
<td>N14</td>
<td>Serpentine</td>
<td>0.02</td>
<td>Very high</td>
<td>Very thorough</td>
<td>Very thorough</td>
</tr>
<tr>
<td>N15</td>
<td>Rockingham</td>
<td>0.03</td>
<td>Very high</td>
<td>Very thorough</td>
<td>Very thorough</td>
</tr>
</tbody>
</table>

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Groundwater methods used in the SWWA Sustainable Yields Project
4.2 National Land and Water Resources Audit/Department of Water prioritisation approach

The level of licensed allocation as a proportion of the allocation limit was used to assign the level of use category (C1 to C4) for all GWAs in the project area (Table 4-2). The level of licensed use as a proportion of the Allocation Limit defines the management response (R1 to R4) that the GWA should receive. The response level was estimated mainly from a consideration of whether areas had a calibrated groundwater model (it being assumed to be 3 if this was the case) and therefore these may not be very accurate. For the purposes of this project, the use categories were the main consideration.

Except for Albany the management response for all GWAs is either equal to or higher than the required management level. For most of the GWAs the response is either R3 or R4 meaning that the required level of modelling resources has been applied to ensure proper management of these GWAs. For most of the GWAs, except Arrowsmith, Casuarina and Jurien, detailed knowledge of aquifers and understanding of hydrogeology exists along with continuous monitoring, determination of Groundwater Dependent Ecosystems (GDEs) and an understanding of the water balance. Relatively complex models have been developed and refined over time for 16 of the 24 GWAs. A new regional groundwater flow model (PHRAMS) was developed for the area covering Murray, South West Coastal, Bunbury-Karri and the Bunbury GWAs which raised the level of management response in these GWAs from 1 to either 2 or 3.

### Table 4-2. Level of use and management response categories for all groundwater areas in the project area as at 7 July 2009

<table>
<thead>
<tr>
<th>Groundwater area</th>
<th>Allocation Limit (kL/y)</th>
<th>Licensed Allocation (kL/y)</th>
<th>Licensed allocation as % of allocation limit</th>
<th>Level of use category</th>
<th>Required management input category</th>
<th>Actual management response category</th>
<th>Gap between use and management response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Perth Basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casuarina sub-area</td>
<td>15,700,000</td>
<td>1,859,000</td>
<td>12</td>
<td>C1</td>
<td>R1</td>
<td>R1</td>
<td>0</td>
</tr>
<tr>
<td>Arrowsmith</td>
<td>184,860,000</td>
<td>56,891,736</td>
<td>31</td>
<td>C1</td>
<td>R1</td>
<td>R1</td>
<td>0</td>
</tr>
<tr>
<td>Jurien</td>
<td>91,570,000</td>
<td>20,206,732</td>
<td>22</td>
<td>C1</td>
<td>R1</td>
<td>R1</td>
<td>0</td>
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<tr>
<td>Central Perth Basin</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gingin</td>
<td>325,922,000</td>
<td>156,000,174</td>
<td>48</td>
<td>C2</td>
<td>R2</td>
<td>R4</td>
<td>+2</td>
</tr>
<tr>
<td>Gnangara</td>
<td>41,250,000</td>
<td>41,921,960</td>
<td>102</td>
<td>C4</td>
<td>R4</td>
<td>R4</td>
<td>0</td>
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<tr>
<td>Yanchep</td>
<td>11,620,000</td>
<td>2,999,383</td>
<td>26</td>
<td>C1</td>
<td>R1</td>
<td>R4</td>
<td>+3</td>
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<tr>
<td>Wanneroo</td>
<td>33,700,000</td>
<td>39,548,392</td>
<td>117</td>
<td>C4</td>
<td>R4</td>
<td>R4</td>
<td>0</td>
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<tr>
<td>Swan</td>
<td>21,500,000</td>
<td>24,526,175</td>
<td>114</td>
<td>C4</td>
<td>R4</td>
<td>R4</td>
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<tr>
<td>Mirrabooka</td>
<td>26,640,000</td>
<td>21,674,326</td>
<td>81</td>
<td>C3</td>
<td>R3</td>
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<tr>
<td>Gwelup</td>
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<td>14,600,000</td>
<td>114</td>
<td>C4</td>
<td>R4</td>
<td>R4</td>
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<td>Perth</td>
<td>173,030,000</td>
<td>130,278,220</td>
<td>75</td>
<td>C3</td>
<td>R3</td>
<td>R4</td>
<td>+1</td>
</tr>
<tr>
<td>Jandakot</td>
<td>25,280,000</td>
<td>17,260,817</td>
<td>68</td>
<td>C3</td>
<td>R3</td>
<td>R4</td>
<td>+1</td>
</tr>
<tr>
<td>Cockburn</td>
<td>44,680,000</td>
<td>36,707,180</td>
<td>82</td>
<td>C3</td>
<td>R3</td>
<td>R3</td>
<td>0</td>
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<tr>
<td>Serpentine</td>
<td>48,970,000</td>
<td>16,469,809</td>
<td>34</td>
<td>C2</td>
<td>R2</td>
<td>R4</td>
<td>+2</td>
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<tr>
<td>Rockingham</td>
<td>10,075,000</td>
<td>3,944,618</td>
<td>39</td>
<td>C2</td>
<td>R4</td>
<td>R3</td>
<td>+2</td>
</tr>
<tr>
<td>Peel-Harvey Area</td>
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<td></td>
</tr>
<tr>
<td>Murray</td>
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<td>16,748,495</td>
<td>24</td>
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<td>R1</td>
<td>R3</td>
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<td>28,675,935</td>
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<td>C2</td>
<td>R2</td>
<td>R3</td>
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<td>5,346,875</td>
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<td>R4</td>
<td>R2</td>
<td>-2</td>
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</table>
4.3 Tier-based prioritisation approach

Using this approach 16 out of 24 GWAs were classified as first tier GWAs and assigned very high priority because:

- These GWAs were important and critical for drinking water supplies and/or supporting agriculture.
- They have been heavily allocated or used already.
- They have already been modelled by state agencies.
- They have an existing well-calibrated model that, for most of the GWAs, will be able to be applied directly to scenario modelling.

All GWAs categorised as first tier have complex multi-layered and multi-aquifer regional groundwater flow models in the form of the PRAMS, SWAMS and Collie models (Table 4-3).

Four GWAs were classified as second tier (Table 4-3) and the Peel Harvey Regional Aquifer Modelling System (PHRAMS) model was developed as part of this project to meet this need. Second tier GWAs were assigned a high priority.

One GWA in the south (Albany) and three GWAs in the Northern Perth Basin were classed as third tier and lower priority because there were either no recent groundwater models, groundwater use was relatively low or the hydrogeology was poorly known. A local area model, covering the public wellfield part of the GWA exists and is being upgraded. To expand this model to the full area covered by this GWA requires hydrogeological information which is not currently available. Detailed groundwater models for the three Northern Perth Basin geologically-complex GWAs will be developed by the Department of Water Western Australia (DoW) by 2011 after further hydrogeological investigations of the area.

The only difference between the first tier and second tier GWAs was that there was no existing groundwater model for second tier GWAs. Five GWAs were classified as second tier GWAs (Table 4-3). There are some major irrigation areas within their boundaries. For these GWAs this project developed, through an external contract, a new superficial aquifer model.

Only four of the 24 GWAs were classified as third tier (Table 4-3). Three of the four GWAs are within the Northern Perth Basin (Casuarina, Arrowsmith and Jurien) and the fourth is in the south-west (Albany). These GWAs do not have an existing groundwater model. This project carried out VFM in these GWAs which will be an input for the regional computer modelling to be undertaken by the West Australian Department of Water.

<table>
<thead>
<tr>
<th>GWA number and name</th>
<th>Tier classification</th>
<th>Region (Model)</th>
<th>Model status</th>
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<td></td>
<td></td>
<td></td>
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<td>6. Yanchep</td>
<td>7. Wanneroo</td>
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<td>8. Swan</td>
<td>9. Mirrabooka</td>
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<td>14. Serpentine</td>
<td>15. Rockingham</td>
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<td>23. Blackwood-Karri</td>
<td></td>
<td>Collie Basin (Collie model)</td>
<td>An existing multi-layered, multi-aquifer regional groundwater flow model</td>
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<tr>
<td>Second</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Murray</td>
<td>17. Southwest Coastal</td>
<td>Peel-Harvey Area (PHRAMS)</td>
<td>A new multi-layered regional groundwater flow model</td>
</tr>
<tr>
<td>Third</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Casuarina</td>
<td>2. Arrowsmith</td>
<td>Northern Perth Basin (WAVES)</td>
<td>Limited model for Albany bore field only</td>
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</tbody>
</table>
5  Statistical hydrograph analysis

5.1  Introduction

This chapter compares estimates of future groundwater levels made by the Hydrograph Analysis and Rainfall Time Trends (HARTT) program and by numerical groundwater models. The HARTT method is an automated derivation of a statistical technique called Cumulative Deviation from the Mean (CDFM) for the prediction of groundwater levels from rainfall data. It was used to check groundwater model projections of groundwater levels at a monitoring point by an independent method.

The CDFM method is based on the assumption that rainfall, or cumulative departure from mean rainfall, at a groundwater monitoring site explains changes in groundwater levels of unconfined aquifers. In this method the actual rainfall over a defined period is subtracted from the long-term mean rainfall of the same period. This simple statistical technique may be modified to account for other possible impact factors such as changes in land and water use (Ferdowsian and McCarron, 2001; Yesertener, 2007).

The approach has been successfully applied by hydrologists for studying groundwater fluctuations caused by rainfall events over selected periods of time (e.g. Wenzel, 1936; Sophocleous, 1991; Wu et al., 1996). The CDFM approach has also been used to separate the effect of atypical rainfall from the time trend (Ferdowsian et al., 2001), understand factors affecting groundwater levels (Yesertener, 2007) and estimate recharge (Xu and Van Tonder, 2001). Although the technique is simple and easy to apply, some researchers have warned about possible misapplications of the method when a wrong period of rainfall is chosen (e.g. Weber and Stewart, 2004).

The CDFM method is applicable to bores drilled in aquifers that receive direct rainfall recharge. It is not usually used for bores located within or in close proximity to significant surface-groundwater interaction areas or where watertables are very shallow or very deep. This method is also not applicable in areas where the land use and groundwater abstraction change significantly over time, unless the analysis is aimed at separating these effects from rainfall once a relationship has been established between rainfall and groundwater levels.

5.2  Observed hydrographs, typical rainfall and future climate

Eighty two monitoring bores located across the project area were chosen for this analysis (Figures 5.1 to 5-3). Out of 82 bores, 36 were in the Central Perth Basin, 27 in the Southern Perth Basin and 19 in the Northern Perth Basin. Most of the selected bores satisfied the above-mentioned applicability criteria. All bores monitored unconfined aquifers and their locations were distant from discharge zones (the ocean, rivers, lakes and abstraction areas) except a few which were deep or close to pumping bores. These records were used because no alternative bores were available for HARTT analysis. No suitable bores were available in the Three Springs climate zone (Figure 5-3) which is a deficiency as this zone has the lowest rainfall. The observed groundwater level data were extracted from the Department of Water Western Australia (DoW) Water Information (WIN) database for each of the selected bores. The monitoring period of the selected bores varied from 10 to 30 years between 1975 and 2007.

Monthly rainfall datasets from the Bureau of Meteorology (BoM) weather stations were used for identifying climate zones. Data were extracted from the SILO database of meteorological data (http://www.longpaddock.qld.gov.au/silo/) for the period between 1900 and 2007 in Patched Point Dataset (PPD) format. Accumulative residual rainfall was calculated by HARTT for the observed data and analysed to establish the start and end points of typical rainfall events in the project area.

Figure 5-4 presents cumulative departures of rainfall from the mean for four BoM weather stations: Geraldton Airport, Lancelin, Perth Airport and Donnybrook. The curves show similar patterns by having pre-1914 and post-1968 dry periods but with a wetter mid 20th Century period in the southern stations (Donnybrook, Perth Airport) compared with the northern stations (Geraldton Airport, Lancelin). The falling and rising parts of the curves indicate drier and wetter periods, respectively. The curves show similar patterns of declining accumulative residual rainfall for the pre-1914 and post-1968
dry periods across the project area. For the statistical hydrograph analysis the dry period between 1968 and 2007 was chosen as the period for comparison with groundwater model estimates. This period was chosen because:

- the surface water and groundwater models have used similar periods for calibration
- other HARTT studies have used similar historical periods
- the last 45 years of historical data are more relevant for the analysis than the previous 50 years
- the comparison between HARTT-projected and groundwater model projected levels will be meaningful

The observed rainfall data were then extended to 2030 with the future projected rainfall estimated for the Historical, Recent, Median, Wet Extreme and Dry Extreme future climate scenarios (see Section 2.5). Since the HARTT method cannot be used for future periods, it was assumed that the current year was 2030 and therefore five climate datasets, compiled for each BoM station for the period between 1965 and 2030, are assumed as being historical data.
Figure 5-1. Bore sites and Bureau of Meteorology weather stations selected for the statistical hydrograph analysis in the Central Perth Basin.
Figure 5-2. Bore sites and Bureau of Meteorology weather stations selected for the statistical hydrograph analysis in the Southern Perth Basin.

Figure 5-3. Bore sites and Bureau of Meteorology weather stations selected for the statistical hydrograph analysis in the Northern Perth Basin.
5.3 HARTT algorithm description

Ferdowsian and McCarron (2001) developed a CDFM-based algorithm for separating the effect of atypical rainfall events from the underlying time trend which has been implemented in the HARTT software package. In this software two forms of accumulative residual rainfall are used: Accumulative Monthly Residual Rainfall (AMRR) and Accumulative Annual Residual Rainfall (AARR).

The accumulative monthly residual rainfall (AMRR) in mm is estimated by:

\[ \text{AMRR}_t = \sum_{i=1}^{t} (M_{ij} - \bar{M}_j) \]  \hspace{1cm} (5.1)

and accumulative annual residual rainfall (AARR) in mm is estimated by:

\[ \text{AARR}_t = \sum_{i=1}^{t} (M_{ij} - \bar{A} / 12) \]  \hspace{1cm} (5.2)

where \( M_{ij} \) is rainfall in month \( i \) (a sequential index of time since start of the data set), which corresponds to the \( j \)-th month of the year, \( \bar{M}_j \) is mean monthly rainfall for the \( j \)-th month of the year, and \( t \) is months since start of the dataset; \( \bar{A} \) is mean annual rainfall.

The AMRR\(_t\) variable tends to have relatively low inter-annual fluctuations while AARR\(_t\) has higher inter-annual fluctuations due to the constant value of \( \bar{A} \). To predict depth \( D_t \) of groundwater level below the ground surface given accumulative residual rainfall \( A_t \) and time trend \( t \) HARTT uses the following regression model:

\[ D_t = k_0 + k_1 A_t - L + k_2 t \]  \hspace{1cm} (5.3)
where $k_0$, $k_1$, and $k_2$ are unknown parameters to be determined, $L$ is time delay in months between rainfall and its impact on groundwater level, $A_t$ is either AMRR$_t$ or AARR$_t$ depending on which of the two parameters provide the highest R-squared between the observed and modelled groundwater levels.

## 5.4 Results and Discussion

The HARTT program was run five times for each selected bore to produce regression models (Equation 5.3) for predicting groundwater levels under the Historical, Recent, Wet Extreme, Median and Dry Extreme future climate scenarios.

### 5.4.1 Analysis of historical and future CDFMs

Cumulative deviations from mean values of rain from 1965 to 2030 were estimated by HARTT using Equations 5.1 and 5.2. Variations in the 2008 to 2030 rainfall introduced differences in the estimates of the accumulative annual (AARR) and monthly (AMRR) residual rain variables calculated for the 1965 to 2030 period. Therefore, for each BoM weather station selected for the analysis, five CDFM distributions were produced for five climate scenarios. Figure 5-5 presents CDFM distributions of eight BoM weather stations selected for the analysis. The prediction period starts at 2008 and is marked by a vertical grey coloured line. For the purpose of this analysis it is assumed that the current year is 2030 and therefore the period between 1965 and 2030 is treated as historical by HARTT. The grey coloured vertical line on Figure 5-5 indicates the start of 2008. Although HARTT treats the whole period between 1965 and 2030 as historical, the report refers to the hydrographs between 1965 and 2007 as historical and between 2008 and 2030 as future. The CDFM curves have similar shapes under all scenarios with some exceptions. Generally, the CDFM curve for the Dry Extreme future climate scenario overlies CDFM curves of all other scenarios. The Median future climate CDFM curve lies below the CDFM for the Dry Extreme future climate but above the other CDFM curves. It can coincide with the Dry Extreme climate CDFM as for the Jandakot station or be close to the Recent climate CDFM as for the rest of climate zones except Donnybrook. The Median future climate CDFM for this BoM weather station is not grouped with the other graphs.

Different periods of distinctive wetter and drier climates are evident on the ascending and descending segments of the CDFM curves. Some of these periods include the monitoring end point; for others 2008 is a point of climate change as would be expected by imposing a new climate regime from this date. For example, 2008 is a turning point for Lancelin from a drier to a wetter climate for all scenarios except under the Median and Dry Extreme future climate scenarios. For Perth Airport, Donnybrook and Geraldton Airport weather stations the curve starts descending at 2008 under the Median and Dry Extreme climate scenarios while for other scenarios the CDFMs do not show significant variations. Therefore, in such cases HARTT may overestimate future falls or rises in groundwater levels if the observed groundwater levels and the changed climate show similar trends.
Figure 5-5. Accumulative annual residual rainfall of the selected BoM weather stations for 1965 to 2030.
5.4.2 Projected historical and future hydrographs

Figures 5-6 to 5-8 show the observed and HARTT-projected historical and future hydrographs for several monitoring bores located in the Central, Southern and Northern Perth Basins. The observed and HARTT-projected historical hydrographs are shown for the period between 1990 and 2007. The future HARTT-projected hydrographs cover 2008 to 2030 period. The observed and statistical hydrographs for all remaining bores are shown in Appendix A.

The observed hydrograph for bore CS27D located in the Central Perth Basin shows rising groundwater levels between 1990 and 2000 followed by stable levels until 2007. Under a continuation of the Historical climate the levels are projected to rise by 2030, whereas under the Recent and Median future climate scenarios, any rise will be modest. Under the Dry Extreme future climate scenario the water levels are projected to fall at this location. The hydrographs for bore 3A located in the Central Perth Basin project about a 1 m rise under the relatively wetter Historical and Wet Extreme scenarios and a decline of between 2 and 6 m under the Recent, Median and Dry Extreme future climate scenarios by 2030.

The groundwater levels at bore NR7A decline under all scenarios. Under the Dry Extreme climate scenario a decline of up to 7 m is expected while under all other scenarios (Historical, Recent and Median and Wet Extreme) modest declines of 2 to 4 m are expected.

The statistical hydrographs fit reasonably well with the observed hydrographs for the bores in the Southern Perth Basin. Most future hydrographs show a declining trend. However, the magnitude of the decline varies between bores.

Figure 5-6. The observed and HARTT-projected hydrographs for the historical period and HARTT-projected future hydrographs for monitoring bores CS27D, 3A, and NR7A in the Central Perth Basin
Water levels in bore BN34S, located in the Southern Perth Basin, are projected to decline between 15 and 22 m under the Median and Dry Extreme future climate scenarios respectively (Figure 5-7). Under wetter scenarios (Recent and Wet Extreme) a decline of up to 4 m is expected. If the Historical climate continues until 2030, little change in water levels is expected by 2030. For bore KL7B a decline in water levels of more than 15 m is estimated using HARTT under the Dry Extreme future climate scenario. Under the Median future climate scenario a decline of about 10 m is expected, while a moderate decline of 1 to 3 m is estimated under other scenarios. The future hydrographs for bore SC4B show a 3 m decline under the Dry Extreme future climate scenario, up to 2 m decline under the Recent and Median future climate scenarios and almost no change under the wetter Historical and Wet Extreme scenarios.

The observed hydrographs for bores GS7, GS14 and OB1-75 in the Northern Perth Basin match well with HARTT-projected hydrographs of the historical period (Figure 5-8). HARTT-projected future hydrographs for these bores show rising trends under the Historical and Wet Extreme future climate scenarios. The estimated rise in levels between 2008 and 2030 varies between these bores. Under the Historical climate scenario the expected rise at bores GS7 and GS14 is insignificant while a 5 m rise is expected at bore OB1-75.

Under the Wet Extreme future climate scenario a rise of less than 4 m is expected at bores GS7 and GS14 and up to 7 m in the deep bore OB1-75. This bore has the strongest rising trends over the historical (1975 to 2007) and future periods under all climate scenarios. These trends may be due to its dryland agricultural land use which is known to have high recharge rates. A slight decline of up to 1.5 m in bore GS14 and a relatively larger decline of up to 4 m is expected under the drier scenarios.
5.4.3 Analysis of HARTT statistics

Tables 5-1 to 5-3 list estimates of the time delay and R² correlation coefficients between rainfall and groundwater level response, model parameters and P-values of model variables for the best regression under the Historical climate scenario for all 82 bores.

The P-values show the statistical significance of the model parameters for predicting groundwater levels. In most cases the P-values estimated for the rain parameter are less than 0.05 indicating dependence between the observed groundwater levels and the cumulative residual rainfall. Only one bore, CL8C located in the Southern Perth Basin area has a P-value of more than 0.05 for the rain variable. For this bore the null hypothesis cannot be rejected as there is no relation between the cumulative residuals of rain and the observed hydrographs. Figure 5-9 shows a poor fit between the observed and modelled hydrographs for this bore. This is possible if factors other than rainfall affected the observed groundwater levels. For example, changes in land use or groundwater abstraction near bore CL8C between 1990 and 1998 could have affected the model projections. Differences between rainfall at the station and the bore may also affect the relationship.

There are 16 bores with time parameter P-values above 0.05. One bore is located in the Central Perth Basin, 13 in the Southern Perth Basin and two bores in the Northern Perth Basin. Higher P-values for these bores are due to stable groundwater levels during the monitoring period (). No trends in observed water levels in these mostly shallow bores are apparent from these hydrographs. Due to high time variable P-values in the regression models the groundwater level fluctuations for these bores are statistically insignificant. Therefore, HARTT models are entirely derived from the cumulative residual rain variable with very low P-values (Ferdowsian et al., 2001). About 80% of the HARTT models provide 0.5 or higher R² coefficients. The bores with low R² values have almost no trends in groundwater levels. In most of these bores only the rain parameter contributes to the models.

Figure 5-8. The observed and HARTT-projected hydrographs for the historical period and HARTT-projected future hydrographs for monitoring bores GS7, GS14 and OB1-75 in the Northern Perth Basin

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Table 5-1. HARTT analyses results for the monitoring bores located in the Central Perth Basin

<table>
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<th>Name</th>
<th>Time delay</th>
<th>$k_0$</th>
<th>$k_1$</th>
<th>$k_2$</th>
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* P-values > 0.05 are shown in bold
Table 5-2. HARTT analyses results for the monitoring bores located in the Southern Perth Basin

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<th>Name</th>
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<th>(k_0)</th>
<th>(k_1)</th>
<th>(k_2)</th>
<th>(P_{\text{rain}})</th>
<th>(P_{\text{time}})</th>
<th>(R^2)</th>
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* P-values > 0.05 are shown in bold
Table 5-3. HARTT analyses results for the monitoring bores located in the Northern Perth Basin

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<td>0.95</td>
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<td>-0.0038</td>
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<td>0.001</td>
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* P-values > 0.05 are shown in bold

Figure 5-9. The statistical hydrograph for the monitoring bore with high rain variable P-values
Figure 5-10. Statistical hydrographs for the monitoring bores with high time variable P-values
Figure 5-11. Statistical hydrographs for the shallow monitoring bores with high time variable P-values
Figure 5-12. Statistical hydrographs for the shallow monitoring bores with high time variable P-values
5.4.4 Comparison of results from HARTT, PRAMS and SWAMS models

To provide an independent check on PRAMS and SWAMS projected future groundwater levels, the HARTT model was also used to predict hydrographs. As mentioned in Section 5.1, the CDFM-based HARTT program builds a simple regression model from typical rainfall data to predict groundwater levels at a selected bore site with a number of limitations. PRAMS and SWAMS are complex numerical models developed for the assessment of groundwater levels using information about hydrogeology, topography, climate, soil, land use and groundwater abstraction. The model outputs are reported for a spatial grid consisting of 500 x 500 m cells. Therefore, any comparison of the spatial assessments from PRAMS and SWAMS with the local HARTT prediction at a particular location within a grid cell is necessarily approximate.

The comparison of projected water level changes in groundwater level between 2008 and 2030 between the models was based on a comparison of box-plots, QQ-plots and scatter-plots. In addition, the HARTT model results were grouped into seven classes and presented spatially at the locations of the selected bores to indicate projections of significant rise or decline (> 6 m), moderate rise or decline (3 to 6 m), slight rise or decline (0.5 to 3 m) or no change in groundwater levels.

The statistical characteristics of HARTT-, PRAMS- and SWAMS-based groundwater level change projections for all climate scenarios within the Central Perth Basin, Southern Perth Basin and Northern Perth Basin are presented in . These tables contain the maximum and minimum values (excluding outliers), median, mean and 1st and 3rd quartiles and outliers. The box-plots in provide visual summaries of the projections within each area. The QQ-plots and scatter diagrams in compare results from HARTT with the PRAMS and SWAMS projections respectively.

Central Perth Basin

The box-plots in Figure 5-13 show the distribution of groundwater level changes projected by HARTT and PRAMS. All distributions show varying skewness, contain positive and negative values and have outliers. The boxes for PRAMS are shifted up the vertical axis in comparison with HARTT-based box-plots. However, the box-plots for both models show similar patterns across the climate scenarios. This indicates that both models respond similarly to future projected climate inputs. The PRAMS-based box-plots are mostly above zero except for those under the Dry Extreme climate. This shows that PRAMS predicts higher groundwater levels compared to HARTT for which the data are mainly negative.

The box-plots of HARTT projections are almost symmetrical meaning that the data are evenly distributed around the median values except for the Historical climate scenario which is skewed to the right. The inter-quartile range varies little under all scenarios. The median values are negative and larger for wetter scenarios (Table 5-4). The number of positive values including outliers is very low. Generally, HARTT projects declining groundwater levels in the area. Only a few projections are positive, including the outlier.

Figure 5-14 shows the spatial distribution of HARTT projections grouped into various classes of decline and rise in groundwater levels by 2030. A slight rise in levels is expected in the northern part of the Lancelin climate zone under the Historical climate scenario. CS16D is the only bore where a significant rise has been projected under the Historical and Wet Extreme future climate scenarios. Some bores located in the Perth Airport climate zone are expected to have slightly higher water levels by 2030 under the Wet Extreme future climate scenario. The rest of the bores show no change or a decline under these scenarios. No groundwater rise is expected under the Dry Extreme future climate scenario in all climate zones. The Perth Airport and Wanneroo climate zones are expected to be drier than the Lancelin climate zone.

The PRAMS projection ranges are wider compared to HARTT results under all scenarios except under the Recent climate which have a similar spread of values (Figure 5-13). The distributions are left-skewed under the wetter scenarios. Under the Dry Extreme future climate scenario the practically symmetrical box shows that most of the projected values are negative and evenly distributed within the range. The median values are positive under the Historical, Median and Wet Extreme future climate scenarios. The box-plots for the Median and Wet Extreme future climate scenarios are similar with comparable statistics. Overall, PRAMS projections are larger compared to HARTT-projected values. Under the Historical, Recent and Dry Extreme future climate scenarios an abnormal watertable rise is projected in bores CS27D and NR7A.
To determine whether the data from the two models came from the same population distribution, non-parametric quantile-quantile (QQ) plots were analysed. Based on the assumption that projections for bores located within a climate zone come from the same distribution, the datasets were split into three groups according to their climate zones; Lancelin, Perth Airport and Wanneroo. Data from the Jandakot climate zone were not considered as only one bore is located in this zone. Figure 5-15 presents QQ-plots for HARTT and PRAMS projections under the Historical climate scenario.

Data from each climate zone lie along the straight lines almost parallel to, and above, the 1:1 line. This indicates that HARTT and PRAMS data came from the same distribution, although the PRAMS projections are high compared to HARTT projections. Due to the equal size of datasets within the groups, the quantiles on the plot are presented by single pairs of points. This allows the identification of bores associated with abnormal projections. The six highest points appear to deviate from the 1:1 line for the Perth Airport climate zone. Generally the highest 30 percent of PRAMS projections within the Perth Airport climate zone are substantially higher than HARTT estimates. Similarly, the two highest points in the Wanneroo climate zone QQ-plot are also outliers. Hence, the highest 40 percent of data from the Wanneroo climate zone are high as estimated by PRAMS relative to HARTT. The data points on the Lancelin climate zone QQ-plot are evenly scattered around the fitted line except the third highest point which may be considered as an outlier. When the pairs of bores associated with the outliers were analysed it was found that the eight highest projections by PRAMS were made for two bores (NR7A and WM5) from the Wanneroo climate zone and six bores (GA13, GA14, GA17, GA18, P290...
and Y320) from the Perth Airport zone (Figure 5-1). Interestingly, all eight bores for which PRAMS predicts a rise of up to 4 m are located in pine plantations which will be removed by 2028. Information on future pine removal (which increases recharge) was taken into account by PRAMS but not by the HARTT model. This explains the future rise in groundwater levels projected by PRAMS. The HARTT model is based only on cumulative rain observed in the area and predicts declines in groundwater levels at these bores. This explains the main discrepancy between the two models.

Figure 5-14. HARTT-projected groundwater level changes in the Central Perth Basin

Figure 5-15 shows scatter-plots of groundwater level changes estimated using the PRAMS and HARTT models under all climate scenarios. The points on each plot are superimposed by regression lines with the multiplicative parameters nearly equal to 1 (except for the Wet Extreme climate scenario) and positive constants which are estimates of the additive difference between the datasets.

In the case of the Wet Extreme future climate scenario the multiplicative parameter is biased due to an over-prediction of groundwater level change by HARTT at bore CS16D located in the Lancelin climate zone (Figure 5-1). Under the
Historical climate HARTT estimated groundwater level change at bore CS16D is an over prediction relative to the projection made by the PRAMS model, although the difference is small and the fitted regression line is not biased. In both cases HARTT projections are biased due to the behaviour of the CDFM curves as explained in Section 5.4.1.

The $R^2$ coefficients vary between 0.4 and 0.6 indicating positive correlations between HARTT and PRAMS datasets under all climate scenarios.

Figure 5-15. QQ-plots and scatter-plots of groundwater level changes projected by HARTT and PRAMS models

Southern Perth Basin

The box-plots shown in Figure 5-16 are the distribution of groundwater level changes projected by the HARTT and SWAMS models. The box-plots for wetter scenarios show ranges of relatively larger values indicating the projections by both models are sensitive to climate change similar to the box-plots shown in the previous section.

Almost symmetrical box-plots of HARTT projections mean an even distribution of data around the median values except for the Wet Extreme future climate scenario for which the distribution is skewed to the right. The inter-quartile range widens for relatively drier climate scenarios.
Table 5-5. Statistics of groundwater level changes projected by HARTT and SWAMS in the Southern Perth Basin

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<th>Recent</th>
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<td>BN34S</td>
<td>CL6W</td>
<td>CL6W</td>
<td>CL6W</td>
<td>CL6W</td>
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</tr>
<tr>
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<td>KL7B</td>
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<td>SC4B</td>
<td></td>
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</table>

Under the Median and Dry Extreme future climate scenarios HARTT box-plots indicate substantial declines which affect the medians and ranges. This appears to be abnormal compared to the box-plots for the rest of the scenarios. Figure 5-17 shows the spatial distribution of HARTT projections grouped into various classes of decline or rise in the groundwater levels by 2030. A slight rise in groundwater levels is expected in the Margaret River climate zone at most bores under the Historical climate. Slightly declining or stable water levels are projected by HARTT at bore locations in the Busselton climate zone. The Donnybrook climate zone is also expected to become drier by 2030 in general. At some of the bores no change in groundwater levels is projected. Under the Wet Extreme future climate scenario a moderate rise is expected in the Margaret River climate zone. In the Busselton climate zone a slight rise at bore BY23B (Figure 5-2) and almost no changes at the other bores are expected. However, the Donnybrook climate zone appears to experience the largest decline under the Dry Extreme future climate scenario relative to the Historical climate scenario. HARTT projects no groundwater level rise under the drier scenarios. Under the Median climate scenario a moderate
decline is expected in the Busselton and Margaret River climate zones while at most bore locations in the Donnybrook climate zone HARTT predicts a moderate or substantial decline in groundwater levels. Under the Dry Extreme future climate scenario HARTT projects a significant decline at most bore locations.

The range of SWAMS projections is narrower compared with HARTT under all scenarios (Figure 5-16). The distributions are almost symmetrical around the medians under the Historical, Recent and Dry Extreme climate scenarios and right-skewed under the Wet Extreme and Median climate scenarios. The median values are positive only under the wetter scenarios (Table 5-5). Similar to HARTT projections, SWAMS projects declines in groundwater levels across the Southern Perth Basin under drier scenarios. Bores CL6W and CL7W (Figure 5-2) are outliers under all scenarios due to projected declines.

Following the assumption about similar distributions of HARTT and PRAMS projection data within a climate zone, the pair-points from HARTT and SWAMS were split into groups according to their climate zones; Busselton, Donnybrook and Margaret River. However the QQ-plots built for these groups exhibited deviations from a linear pattern (Figure 5-18).
Such non-linearity indicates differences in data distributions. Therefore, it was decided to consider other possible factors which may affect the pair-point distributions of model projections. Differences in the geological structure of aquifers could contribute to distortions on the QQ-plot for the Donnybrook climate zone data. In addition, model projections at shallow bores with no trends in their observed hydrographs could also introduce a skew into data distributions.

Figure 5-19 shows surface geology and bore locations. Four bores, KL5W, KL5A2, SC18A and SC8B from the Donnybrook climate zone (Figure 5-2), are located in the Yarragadee Aquifer. These bores were therefore separated in a different group of data.

A group of bores was also separated that had time variable P-values of more than 0.05 in HARTT regression models (Table 5-2). These bores are: BN21S, BN22S and BN8S in the Busselton climate zone; BN30S, BN34S and BN36S in the Donnybrook climate zone; and KL2B and SC4B in the Margaret River climate zone. Three bores from the Busselton climate zone monitor the Superficial Aquifer. The three bores from the Donnybrook climate zone and two from the Margaret River climate zone monitor the Leederville Aquifer. As discussed earlier (Section 5.4.1) the observed hydrographs at these bores showed no changes in groundwater levels over the monitoring period. The remaining data for the Busselton and Donnybrook climate zones were then combined into one group. The last group contained the remaining data from the Margaret River climate zone.

Figure 5-20 presents QQ-plots for four groups of HARTT-SWAMS pair-points under the Historical climate scenario. The QQ-plot for the group of data from the Donnybrook and Busselton climate zones (in pink) shows the two lowest points on the plot as outliers. This is due to suspicious projections by SWAMS at bores CL6W and CL7W. As mentioned above, these bores were also identified as outliers in the box-plots (Table 5-5) of the SWAMS datasets. It should be noted that the area where these bores are located is poorly calibrated by the SWAMS model due to an insufficient number of suitable bores for model calibration. To avoid possible biases in data distributions caused by these data, bores CL6W and CL7W were excluded from further analysis. The rest of the ordered pairs lie parallel to the 1:1 line indicating a similar distribution and an insignificant additive difference in model projections within the Donnybrook and Busselton climate zones. The pair-points relating to the Yarragadee Aquifer are concentrated far above the previous dataset but can be fitted by a regression line parallel to the 1:1 line. This shows similar projection trends of the Yarragadee bores from both HARTT and SWAMS although with a substantial additive difference. The QQ-plot for the group of data with high time variable parameter P-values show a similar range of magnitudes from both models although the SWAMS projections are slightly larger. The ordered pair-points for three bores in the Margaret River climate zone also lie almost parallel to the 1:1 line.
Scatter-plots (Figure 5-20) illustrate the relationships between the paired data for each group under all climate scenarios. The fitted regression lines overlay the datasets. The regression equations along with R² coefficients are shown for the main group of the combined data from the Donnybrook and Busselton climate zones (at the top) and for a small group of bores monitoring the Yarragadee Aquifer (lower right side). The identified outliers are marked by hollow circles.

Under the Historical climate the Donnybrook-Busselton group shows a considerable positive correlation between HARTT and SWAM projections. The points lie along the fitted regression line above and almost parallel to the 1:1 line. The additive difference between the datasets is about 1.6 m. The points related to the Yarragadee Aquifer also show a positive correlation with an additive relationship of up to 3.3 m. These bores are located close to an area where extensive flooding occurs during winter and spring. SWAMS accounts for this condition and predicts a rise in groundwater levels. The HARTT model cannot take into account such seasonal conditions and therefore underestimates future groundwater levels in this area. The points from the shallow bores group with the high P-value are concentrated around zero within the 1 m range. Two points for the Margaret River climate zone lie close to the 1:1 line, while bore SC1C is an outlier. The same bore was also identified as an outlier by the HARTT box-plot under the Historical climate scenario. This bore may be an outlier because of an erroneous over-estimation by the HARTT model as discussed in Section 5.4.1. The CDFM curves for the Margaret River climate zone under the Historical and Wet Extreme climate scenarios show rising trends about two years after the start of the prediction period (Figure 5-5). The observed hydrograph at this bore (see Appendix) also shows a slightly rising trend. This may result in the HARTT model overestimating future rises in groundwater levels at this bore location relative to groundwater levels projected by SWAMS.

Under the Recent climate scenario the correlation between datasets from the Donnybrook-Busselton group of bores is higher and the additive difference is about 1.6 m. Bore SC13B lies far from the fitted regression line and is considered an outlier. The observed hydrograph for this bore (see Appendix) show a slight decline over the monitoring period. Therefore, the further declines of up to 5 m projected by HARTT under the Recent and Wet Extreme climate scenarios are reasonable. Moreover, HARTT output statistics for this bore (Table 5-2) indicate a high degree of dependence.
between the observed groundwater levels and climate and time trend: the P-values for both parameters of HARTT regression equations are low and the $R^2$ coefficient is significant. However, under the drier climate scenarios, HARTT overestimates future decline at this bore because of changes in the CDFM trends at the start of the prediction period for the Donnybrook climate zone under the Median and Dry Extreme scenarios as discussed in Section 5.4.1. The Yarragadee Aquifer group of bores shows a positive relationship; however, it becomes multiplicative due to the greater declines projected by HARTT relative to the SWAMS projections. The points from the Margaret River climate zone are mixed with the “no change” data from the shallow bores group. Both datasets are distributed around zero, although the range of magnitudes is wider (up to 2 m) than under the Historical climate.

Under the Wet Extreme climate scenario the correlation between the main group data is significant if the outlier is ignored. Bore SC13B is an outlier under both the Wet Extreme and Recent climate scenarios. The additive difference under the Wet Extreme scenario is less than 1 m. The correlation between the points from the Yarragadee Aquifer group is low compared to the Recent climate scenario but remains positive. The Margaret River group has one outlier due to an overestimation of groundwater levels by HARTT for bore SC1C as explained above. The points from the group of bores with high P-values are concentrated around the 1:1 line. The range in HARTT projections at these bores varies within 1 m while the range in SWAMS projections is slightly wider. Bores BN30S, BN34S and BN36S were identified as outliers due to abnormal declines projected by HARTT. All these bores are located in the Donnybrook climate zone and exhibit strong seasonal fluctuations in groundwater levels. The CDFM curves for the Wet Extreme, Median and Dry Extreme scenarios for this climate zone change their trends at 2008 which is the start of the prediction period (Figure 5-5). The slightly declining trends in the observed hydrographs at these bores (see Appendix) coincide with the future climate trends under these scenarios. As mentioned in Section 5.4.1, in such situations the HARTT model overestimates changes in future groundwater levels. Although the CDFM curve started declining a few years before 2008 under the Wet Extreme climate scenario, the future projections were slightly overestimated.

Under the drier climate scenarios (Median and Dry Extreme) the relationship between the points from the Donnybrook-Busselton group became multiplicative due to an overestimation of water level declines in bore SC13B by HARTT relative to SWAMS projections. The dataset of the shallow bores with no temporal trends also have three outliers as was the case under the Wet Extreme scenario. The declines projected by the HARTT model are even larger than those

Figure 5-20. QQ-plots and scatter-plots of groundwater level changes projected by HARTT and SWAMS
projected by SWAMS due to steeper slopes of the CDFM for the drier scenarios (Figure 5-5). For the same reason, points from the Yarragadee Aquifer group show almost no relation with the CDFM. Both models project insignificant declines in groundwater levels under the Median climate for the Margaret River climate zone bores. In the case of the Dry Extreme climate scenario, the declines projected by the HARTT model are slightly overestimated.

**Northern Perth Basin**

Box-plots for HARTT projections in the Northern Perth Basin are shown in Figure 5-21. The size of the boxes is similar and comparable among scenarios except box-plots for the Wet Extreme scenario. The range of HARTT projections under the Wet Extreme scenario is about 7 m. This is about three times larger than that of the projections under the rest of the scenarios. Therefore, some overestimation of groundwater levels may be expected under the Wet Extreme future climate scenario.

The data distributions under relatively wetter Historical, Recent and Wet Extreme climate scenarios are skewed to the left indicating that the highest 50 percent of data vary within a wider range than the lower 50 percent. The box-plots for the Median and Dry Extreme climate scenarios are almost symmetrical. The median values are positive under the Historical and Wet Extreme scenarios and negative under rest of the scenarios. The deep bores DL3W and OB1-75 and a shallow bore GS1B (Figure 5-3) are identified as outliers under all climate scenarios. HARTT projections at these bore locations highly correlate with the observed hydrographs (Table 5-3). In general, the box-plots show a similar pattern across the climate scenarios as was the case for the Central Perth and Southern Perth Basins: the box-plots for the wetter climate scenarios are located above the boxes for the drier climate scenarios. The Median future climate scenario appears to be wetter than the Recent climate scenario as was the case in the Central Perth Basin (Central Perth Basin).

Figure 5-22 shows spatial distribution of future changes in groundwater levels in the Northern Perth Basin projected by HARTT. A slight rise in groundwater levels is projected at most bore locations under the Historical climate scenario. At two bores, DL3W and OB1-75, a moderate rise is projected. No changes are expected at bores GS1B and LS1B in the northern part of the Geraldton Airport climate zone and in the southern part of the Lancelin climate zone respectively. Under the Wet Extreme scenario a moderate rise is expected at most bore locations. However, in the Lancelin climate zone no changes are expected at the selected bore locations except at bore CS29S located on the boundary with the Central Perth Basin in the south. Under the Recent climate scenario a moderate rise in groundwater levels is expected.
only at locations where the bores are relatively deeper, while at the rest of the bore locations slight to moderate declines are expected except at a few bore locations where no temporal trends in the modelled hydrographs are expected. Almost no changes in groundwater levels are expected across the southern part of the Northern Perth Basin under the Median climate scenario. In the northern part only a slight decline is expected at two bores (GS7 and LS31C) and a moderate decline at one bore (GS19B) in the north of the Geraldton Airport zone. Under the Dry Extreme climate scenario a slight decline is expected at most bore locations. A relatively larger decline is projected at GS7 and GS19B. The deep bores, DL3W and OB1-75, seem least sensitive to climate change and a moderate rise is expected even under the driest climate scenario. Currently no suitable numerical models are available in the Northern Perth Basin to compare its projections with HARTT. However, from the positive correlation between HARTT and the numerical model (PRAMS and SWAMS) projections discussed earlier it can be assumed that HARTT projections estimated in the Northern Perth Basin are reasonable.

Table 5-6. Statistics for groundwater level changes projected by HARTT in the Northern Perth Basin

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Analysis of HARTT projections in the Northern Perth Basin

Comparison of projections from the HARTT, PRAMS and SWAMS models help to cross-verify any future projections. As discussed above, HARTT can overestimate groundwater levels in bores with seasonal fluctuations in groundwater levels. If a CDFM curve changes its trend near the start of a prediction period and the observed hydrograph show a slight trend in the same direction, HARTT may overestimate the projected decline or rise at such bores.

The CDFM curves (Figure 5-5) for the Geraldton Airport climate station show changes in trends at 2008 under two scenarios: the Dry Extreme scenario where the CDFM exhibits a steep negative trend and under the Recent climate scenario where it shows a short rising trend which changes its direction at 2011. From the analysis of outliers when comparing results from HARTT, PRAMS and SWAMS some overestimations by HARTT are expected at bores showing close to zero trends in the observed hydrographs. The CDFM curves for the Lancelin climate station show positive trends starting from 2008 under three scenarios: Historical, Recent and Wet Extreme. Under the Recent climate scenario the rising trend is very short which may not result in model overestimations.

Among 16 bores with close to zero trends only six bores were identified as possible outliers. Three of these bores, CS19S, LS10A and LS5B, are located in the Lancelin climate zone. The other three bores, GS19B, GS1B, and LS20B, are located in the Geraldton Airport climate zone. However, the observed hydrographs of these six bores show no significant variation. Therefore, it is unlikely that HARTT produced erroneous projections for any of these bores, even for bore GS1B with a high time variable P-value. The other bore (LS1B) with a high P-value also cannot be considered as a possible outlier due to its negative trend. Consequently, it appears that HARTT-projected future groundwater level trends in the Northern Perth Basin are reasonable.
5.5 Conclusions

The CDFM-based HARTT program was applied to project future groundwater levels under future climate scenarios in three regions within the project area: Central Perth Basin, Southern Perth Basin and Northern Perth Basin. The changes in groundwater levels between 2008 and 2030 were then computed and compared with the projections from the complex numerical groundwater models, PRAMS and SWAMS.

It was found that all models show similar sensitivity to climate change. Generally the groundwater model projections were consistent with HARTT projections except at sites affected by land use and water abstraction changes. The pair-point comparison showed positive correlations between projections from HARTT and those from the PRAMS and SWAMS. However, at most bore locations the PRAMS and SWAMS over-predict changes in groundwater levels.

Due to a lack of suitable bores in some areas, the HARTT model was applied for predicting future groundwater levels for relatively deeper bores in the Arrowsmith region of the Northern Perth Basin and at bore locations close to bores with a high level of abstraction in the Southern Perth Basin. HARTT-projected hydrographs at deep bore locations (3-93 and OB1-75) showed stable growth in future groundwater levels under all future climate scenarios exhibiting no or low dependence on the drying climate conditions. This is consistent with the projections from PRAMS and SWAMS that also showed insignificant changes in groundwater levels in the Yarragadee Aquifer. It appears that proximity of a monitoring bore to an abstraction bore may not affect HARTT projections if it is not in combination with the other influencing factors such as changes in cumulative rain deviations from mean. Comparisons with the relevant SWAMS projections showed that HARTT produced similar results at bore locations that were close to abstraction bores within the Busselton climate zone even for bores with high time variable P-values in the regression equations. However, in the Donnybrook climate zone the declines projected by HARTT at bores with high time variable P-values were overestimated under the Median and Dry Extreme scenarios. The CDFM curves for the Donnybrook climate zone change their trends at the start of the prediction period. The CDFM curves for the Busselton climate zone show almost no changes under the drier climate scenarios. Amongst the bores close to abstraction zones, three bores - BN30S, BN34S and BN36S, located in the Donnybrook climate zone - were affected by both factors.

Changes in the CDFMs caused overestimation of groundwater levels at shallow, medium and deep bores far from allocation bores. All of these bores had no trends during the monitoring period in spite of seasonal changes in groundwater levels. Therefore, it was concluded that projections at bore locations with close to zero trends in the observed hydrographs and strong seasonal fluctuations in groundwater levels may be overestimated by HARTT if relevant CDFMs change their trends at or near the start of prediction period. The effect may be stronger if the observed and the changed CDFM trends are both negative and positive. However, shallow or medium bores may provide reasonable projections of close to zero trends if relevant CDFMs do not change trends at the start of prediction period despite high time variable P-values in HARTT regression models.

5.6 References


Appendix A  Statistical hydrographs

The hydrograph analysis techniques were used to project groundwater levels in various regions of the project area. This Appendix (A) displays these hydrographs for three regions: Central Perth Basin; Southern Perth Basin and Northern Perth Basin. Their methodology is detailed in Chapter 5 of this report. The location (bore name) of each hydrograph is also shown in each figure.
Appendix A: Statistical hydrographs

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Appendix A: Statistical hydrographs

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Appendix A: Statistical hydrographs

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Groundwater methods used in the SWWA Sustainable Yields Project 111
Northern Perth Basin

**LS1B**
- Groundwater level (m)
- 1995 to 2030
- Observed level
- Range between wet and dry extreme, future climate
- Fitted 1975-2007
- Historical climate
- Recent climate
- Median future climate

**LS20B**
- Groundwater level (m)
- 1995 to 2030
- Observed level
- Range between wet and dry extreme, future climate
- Fitted 1975-2007
- Historical climate
- Recent climate
- Median future climate

**LS23B**
- Groundwater level (m)
- 1995 to 2030
- Observed level
- Range between wet and dry extreme, future climate
- Fitted 1975-2007
- Historical climate
- Recent climate
- Median future climate

**LS27B**
- Groundwater level (m)
- 1995 to 2030
- Observed level
- Range between wet and dry extreme, future climate
- Fitted 1975-2007
- Historical climate
- Recent climate
- Median future climate