CONSTRUCTION, CALIBRATION AND APPLICATION OF THE SOUTH WEST YARRAGADEE AQUIFER MODEL V2.0

September 2005

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Updated: November 2005
EXECUTIVE SUMMARY

In response to a proposal to develop the water resources of the Southwest Yarragadee Aquifer, the Water Corporation developed a groundwater model to simulate the aquifers in the Southern Perth Basin. The purpose was primarily to determine the water table impacts of abstraction from the Yarragadee aquifer. In particular, the model will be used to assess the impacts of abstraction on water levels in the superficial aquifers of the Swan and Scott Coastal Plains, and on the Blackwood Plateau. The second major aim was to estimate the fluxes in and out of the groundwater system, such as recharge to the aquifers and discharge to the ocean.

Previous modelling work by Cymod (2004) and the investigation team established the framework of the groundwater flow model of the South West Aquifer Modelling System (SWAMS 1.2.1). The current version (SWAMS 2.0) is an extensive modification of the earlier model. Major modifications include boundary conditions, faults, new model layers and parameter domains, based on newly collected data and more detailed hydrogeological interpretation.

The SWAMS 2.0 modelling system consists of an improved and comprehensive database containing abstraction, monitoring and environmental data; a MODFLOW 2000 saturated flow model; pre and post processors and a GIS database. The MODFLOW 2000 model is an industry standard model, developed by the USGS that is used extensively in groundwater modelling throughout the world.

The active model domain is approximately 190 kilometres long and 70 kilometres wide, covering an area of approximately 8500 km$^2$. A finite-difference grid involving 363 rows and 193 columns was used to represent this study area. The grid is variable, with rectangular elements (i.e. nodes) ranging in size from 250 metres x 250 metres for more environmentally significant areas, to 1000m x 1000m in less significant areas. The use of 250m x 250m elements provides sufficient resolution for the Blackwood River, lakes and wetlands, while also providing reasonable computer execution efficiency. Vertically, the model has eight layers, adequately representing the major aquifers and aquitards in the Southern Perth Basin.

Hydrogeological investigation of the Southern Perth Basin indicates that the aquifer system under study is a very complex groundwater system. Not only are there aquitards on the Blackwood Plateau, outcrop areas for the Yarragadee aquifer and perched water tables - there are also significant aquitards of basalt with irregular shapes and thickness in the middle of the groundwater system. These make the groundwater tables highly variable with sharp edges on the Blackwood Plateau. The modelling of this type of system presented a significant challenge for current model calibration as well as for the previous one.

Despite the complexities of the aquifer system, the current model setup is believed to be a reasonable representation of the hydrogeology of the study region, taking into account the current understanding of the aquifer system and the available data. Parameter zonations depict large-scale geological and hydrogeological structures in the model domain. Major hydrological processes employed in the model were conservatively selected in the previous model and were maintained in the current version.

The SWAMS 2.0 model was calibrated in steady state and under transient conditions. The transient model was calibrated from 1990 to 2003 using historical groundwater data. Figure
E.1 shows the overall calibration results of the observed and simulated head data for 328 calibration bores. This included all investigation bores on the Blackwood Plateau and all other bores with observation periods of greater than 50 months.

Table E.1 summarises the calibration error in the model by each aquifer. The average absolute error in the superficial, Leederville and Yarragadee aquifers and the Mowen aquitard on the Blackwood Plateau are 0.8, 3.6, 3.2 and 5.6 metres respectively. The relative closeness of the average root mean square error (Average RMS Error) to the average absolute error indicates that the average absolute prediction error is a valid indicator of the calibration error. The maximum and minimum errors for these aquifers indicate that some significant errors still exist in the calibration. However, these errors result mostly from the high complexity of the aquifer system and the large zonations in modelling. In other words, calibration is not able to match every bore in a single zone and under such cases, the average condition is simulated to match the majority of the observed head data in the zone. Overall, the calibration error is believed to be close to what can be achieved under existing hydrogeological interpretation and boundary conditions.

Annual water balance estimation showed that the average gross recharge to the aquifer system during 1990-2003 was 651.5 GL/year, with a net recharge of 373.6 GL/year. Average abstraction during the calibration period was modelled at 45.4 GL/year starting from 35 GL in 1990 to 62 GL in 2003.
The two versions of the SWAMS model produce similar impact areas under the same future abstraction scenarios. The differences of the two modellings are mostly in the extent of the impact areas and the magnitude of the impact. This provides confidence that the impact areas, as predicted, are likely to be a good reflection of the natural system. This is mainly due to two reasons. One is that the two versions of the SWAMS model are significantly different in terms of parameter zonations, evapotranspiration simulation and the amount of net recharge simulated. The second is that the two versions of the SWAMS model are calibrated independently.

Table E.1 Summary of model calibration error by aquifer

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>Average Absolute Error (m)</th>
<th>Average RMS Error (m)</th>
<th>Maximum Positive Error (m)</th>
<th>Maximum Negative Error (m)</th>
<th>Number of bores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial</td>
<td>0.8</td>
<td>2.9</td>
<td>8.4</td>
<td>-7.4</td>
<td>56</td>
</tr>
<tr>
<td>Leederville</td>
<td>3.6</td>
<td>7.0</td>
<td>21</td>
<td>-24</td>
<td>100</td>
</tr>
<tr>
<td>Yarragadee</td>
<td>3.1</td>
<td>4.0</td>
<td>13</td>
<td>-9</td>
<td>141</td>
</tr>
<tr>
<td>Mowen</td>
<td>5.6</td>
<td>7.6</td>
<td>17</td>
<td>-21</td>
<td>31</td>
</tr>
</tbody>
</table>

Further confidence in the modelling results stems from the modelled ages of flow paths and patterns, which matched independently observed carbon-14 data. The pumping test at Rosa Brook on the Blackwood Plateau and associated analysis and modelling provide further evidence that the parameters used in the regional model are realistic. Based on the available evidence, the current model is considered to be a reasonable and valid representation of the Southern Perth Basin aquifer system.

The calibrated model was used to assess drawdowns under various scenarios of future abstractions for the next 30 years. Major drawdown areas for the 45 GL/year Water Corp abstraction (eastern split scenario) in 30 years are: the Yarragadee outcrop areas in the middle of the Blackwood Valley between Laymen Brook and Milyeannup Brook area at up to 3 m; eastern Scott Coastal Plain and the immediate north area of up to 2 m; Yarragadee subcrop area close to Bunbury at approximately 0.5-1 m; south of Busselton in the Swan Coastal Plain of up to 2 m; St John’s Brook and further north area of up to 3 m; and areas along the Blackwood River of up to 2 m.

Drawdowns in the centre of the eastern bore field in layer 7 (-600~900 AHD) reached 8 m at the top end of the St John’s Brook, which gradually reduced outward in a ring shape. The maximum impact by the Water Corporation abstraction at the coast line is between Busselton and Bunbury with drawdowns of up to 1.5 m in layer 7. Drawdowns in the centre of the Water Corporation borefield in layer 5 (-150~350 AHD) reached 20 m at the top end of the St John’s Brook. Although the drawdown in layer 5 is high it is mainly confined in the St John’s Brook and the surrounding area, which does not extend to the coastal plains area. As a result, the Water Corp eastern split scenario does not pose a major threat to other
abstractions in the coastal plains.

The total impact at the water table by the combined abstraction of Water Corporation and Regional Growth at an average abstraction rate of 156.8 GL/year for the next 30 years are: drawdowns of 2-5 m occurring in the Yarragadee outcrop area in the middle of the Blackwood River; on the coastal plains the drawdowns are generally below 2 m with some isolated areas reaching 3 m.

The prediction of water table drawdown is believed to be a reasonable analogue of the possible outcome from the current and future abstractions, under current modelling conditions. However, since MODFLOW is a simplified representation of the real world which focuses on groundwater flow processes, it has limitations in simulating the surface hydrological processes. This is especially the case with regard to the flooding effects in the coastal plains. The observed annual flow in both the Swan and Scott coastal plains is generally an order higher than the potential annual drawdowns in the coast. This surface runoff is likely to play an important role in regulating the water table in the superficial aquifer, but this effect can not be simulated directly by MODFLOW. As a result, the predicted drawdown on the water table due to abstraction is likely to be exaggerated by the model compared to what actually occurs, or may occur, in the coastal plains. Observed and predicted water table drawdowns for the dry period of 2001-2003 suggest that for many bores, particularly the superficial bores, the predicted drawdowns are significantly exaggerated. This demonstrates that modelling results tend to be conservative under high stress conditions.

A second limitation of the MODFLOW 2000 is that it can only model saturated continuous flow. In areas where there is a perched watertable, or where the water table is deep, the model is less representative. Therefore, in these areas, the modelling result is indicative and may need to be interpreted using alternative information or a source of data that is not sufficiently represented in the regional model.

Other than the model limitations, other uncertainties of the current model may come from the complexity of the hydrogeology, the boundary conditions and the large spatial scale for a regional model. The hydrogeology represents the current understanding of the system based on available data, while the boundary conditions represent inherent uncertainty for modelling the submerged aquifers stretching out into the ocean. For the boundary condition, it is primarily related to the offshore extent of the model. That is, whether the active area should be extended to the continental shelf as is modelled, or should it be closer to the shoreline. Current investigation suggests the latter may be needed to improve calibration. The large spatial scale of the model means that modelling results may not be adequate for fine scale investigations.

Despite the uncertainties in boundary condition and the high complexity of the hydrogeology of the study area, existing evidence suggests that other than the flooding effects that can not be handled effectively by MODFLOW, which potentially makes the drawdown predictions on the water table in the coastal plains conservative, the current model as a whole is a valid representation of the real aquifer system.
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1 INTRODUCTION

Approximately 60% of the water supplied to Perth comes from groundwater supplies. Consequently, the Water Corporation has been using groundwater flow models as the primary tool for groundwater planning and management.

In response to a proposal to develop the water resources of the South West Yarragadee aquifer, the Corporation initiated an investigation team to develop a groundwater model to simulate the aquifers in the Southern Perth Basin.

Previous modelling work by Cymod (2004) and the joint investigation team (JIT) between the Water Corporation and the then Water and Rivers Commission have established the frame work of the groundwater flow model of the South West Aquifer Modelling System (SWAMS 1.2.1). The current version of the model (SWAMS 2.0) is an extensive expansion and modification of the earlier model. Major modifications include boundary conditions, parameter domains and faults that are based on more comprehensive data collection and interpretation.

Earlier hydrogeological investigations were carried out by the JIT, and reported in Baddock, et al (2003). Previous modelling work (SWAMS 1.2.1) in Cymod (2004) incorporated a limited amount of the hydrogeological investigation results and worked as the first pass of the model development for the study area. The earlier model conservatively simulated the aquifer system, given the lack of details in hydrogeological interpretation. A second version of the model (SWAMS 2.0) incorporating a more detailed hydrogeological investigation result, was announced in early 2004. The interpretation of the hydrogeological structure and mapping of parameter zonations essentially finished at the end of 2004. The calibration of the model was completed in June 2005.

1.1 Objectives

The objectives of the project are to simulate the groundwater system of the study area using a 3-D numerical model. This requires that 1): the model domain and boundary conditions are a reasonable representation of the physical entity; 2): the parameter and zonations are a reasonable representation of the hydrogeology of the area; and 3): a good calibration between the observed and calibrated heads of the groundwater flow system. Specifically, the model is designed to:

- Simulate groundwater flow within and between all hydrogeological units in the Southern Perth Basin that are within the active part of the groundwater flow system.
- Establish a water budget for the Yarragadee aquifer and other aquifers.

The model produces the following results:

- Under a range of scenarios, including the proposed Water Corporation abstraction of 45 GL/year from one or more possible bore field locations, it predicts the scale of change in groundwater potentiometric heads/water levels within the hydrogeological units.
• Evaluates likely changes in groundwater discharge to rivers (including the Blackwood River), streams and wetlands, and ocean environments.

• Predicts the general drawdown in water levels near other groundwater users, wetlands, rivers and streams in the project area under various abstractions, and provides seasonal variations in such reductions.

• Estimates the likely range and uncertainty of water level changes in areas affected by large-scale pumping to enable the assessment of the risk of water levels changes that may impact on identified groundwater dependent ecosystems (GDEs).

The model is a regional scale model. Its application to small scale drawdown analysis may require additional information and interpretation based on local conceptual knowledge and investigation results.

1.2 Modelling System

The South West Aquifer Modelling System (SWAMS) was constructed using similar technology as that developed for the Perth Regional Aquifer Model (PRAMS) groundwater modelling system. SWAMS consists of a database containing abstraction, monitoring and environmental data, a MODFLOW 2000 saturated flow model, pre and post processors and a GIS database.

The construction and validation of the SWAMS database required considerable time and resources. The monitoring data and the allocation data was updated to June 2004 with some data extending to early 2005.

The early development of the SWAMS model designated SWAMS 1.2.1 was used to predict groundwater flow and water head drawdown under various abstraction scenarios. This was peer reviewed in December 2004 (DOE, 2004). The peer review report identified a number of areas in the SWAMS 1.2.1 where improvement could be made.

The current model, designated as SWAMS 2.0, used the same model grid structure as the previous model but improved in many areas. The objective was to address the issues raised in the peer review. Major changes made during the development of the current model were:

• Modified geology and layering so that each layer has a minimum thickness to allow smoother layering systems;
• Modified faults in the Yarragadee aquifer;
• Modified boundary conditions, particularly in the offshore areas of the study region;
• Use of environmental heads in the offshore areas;
• Addition of drainages in the Swan Coastal Plain and more refined drainages on Blackwood and the Scott Coastal Plain;
• Further update of the allocation data base and the monitoring data from recently drilled bores;
• Newly developed zonations and parameter representation in the model;
• Newly developed zonations for recharge;
• New representation of the evapotranspiration in the Swan and Scott coastal plains;
• New representation of the time series scaling factor for recharge;
• New representation of the time series scaling factor for the allocation data; and
• Introduced horizontal anisotropy in modelling.
SWAMS 2.0 was first calibrated in steady state, and then calibrated as a transient state model. The result from the transient state calibration was used to simulate various abstraction scenarios, including the three basic scenarios of Current_Use, Regional_Growth and Water Corporation abstraction.

- The current use scenario, which assumes steady state abstraction at the rate of 2004 (64 GL/year) for 30 years to the end of 2033.
- The regional growth scenario, which increases abstraction from 64 GL/year in 2004 to 159 GL/year in 2033.
- The Water Corporation scenario, which assumes a constant abstraction rate at 45 GL/year. The regional growth scenario was added to generate total abstractions from 109 GL/year in 2004 to 204 GL/year in 2033.

The estimated heads at the end of the simulation period from various scenarios are subtracted from each other to obtain particular drawdowns under certain abstraction conditions. For example, the subtraction of estimated head between Regional growth and Water Corporation scenario at the end of the simulation period gives the drawdowns from the 45 GL/year of Water Corporation abstraction over 30 years. In this way the impacts of various abstractions can be mapped and the impacts at specific locations can then be analysed in more detail.
2 MODEL CONSTRUCTION

The design and construction of the numerical groundwater model, SWAMS is described below in terms of the MODFLOW and GIS datasets used, the parameter zonations and the physical processes developed for modelling.

2.1 Spatial Discretization

2.1.1 Horizontal Discretization

The southern Perth Basin area is shown in Figure 2.1, and the SWAMS model grid for the area is shown in Figure 2.2. The active model domain is approximately 190 km long and 70 km wide, covering an active area of about 8500 km$^2$, of which 6013 km$^2$ is onshore.

SWAMS was developed to determine the impact of abstraction from the Yarragadee aquifer in various aquifers and at the water table close to the land surface, under varying abstraction scenarios. There are areas of particular interests, such as the discharge areas from the Blackwood River and Scott Coastal Plain, and the recharge areas such as on Blackwood Plateau and Lake Jasper. To better define those interest areas a variable grid is used, with rectangular elements (i.e. nodes) ranging in size from 250m x 250m to 1000m x 1000m. This ensures that the high interest areas have finer spatial resolution. Horizontally, the finite-difference grid consists of 363 rows and 193 columns. The use of 250m x 250m elements provides relatively high resolution for a regional model, while maintaining numerical efficiency.

2.1.2 Vertical Discretization

The model comprises 8 layers that typically represent the major hydrogeological aquifers and aquitards within the Southern Perth Basin. Representative hydrogeological units associated with each of the model layers are described in Table 2.1, and the conceptual relationship is shown schematically by Figure 2.3. The numerical model layering and grid is shown in Figure 2.4 for an interpreted north-south hydrogeological cross-section. Characteristics for each of these hydrogeological units are described in the associated hydrogeological report for the South West Yarragadee investigations (Baddock, 2005).

The model layers are defined by digital terrain models (DTMs) of the top and bottom aquifer surfaces prepared in a Geographical Information System (ArcGIS). The DTMs of each layer were constructed based on available geological logs and drilling information. Appendix A shows the surfaces of each model layer as used in constructing the model.

None of the geological formations fully extends over an entire model layer. Consequently, while the model layering is based on aquifers, in areas where a formation is absent, the hydrogeological properties of the layer are changed to reflect the formation occupying the layer. This modified layering of aquifers based on formations is required because the MODFLOW does not allow the pinching out or the absence of a model layer. Where hydrogeological units representing particular layers pinch-out, or become thin, a minimum thickness is applied to the layer. A minimum thickness of 10 m is applied to layers 1 to 3,
20 m for layer 4, 30 m for layers 5 and 6, 100 m for layer 7, and 1 m for layer 8. However, where the layer surface falls below the base of active groundwater flow, then the layer thickness is truncated to 1 m.

The interpolation from DTMs onto the model grid was performed using ArcGIS, to generate formation elevation and thicknesses in raster format. These elevations were then transformed into text files where each MODFLOW cell is assigned with an elevation value, for each model row and column in a model layer. These file were then loaded to the MODFLOW layer elevation files so that the top and bottom elevations of the model layers were obtained. In cases where no formation exists in a layer, a minimum thickness is assigned, normally greater than 10 m, and the properties of the underlying formation are assigned to that layer.

Table 2.1 Representative hydrogeological units of model layers.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Representative hydrogeological unit</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coastal Plain superficial sediments; Blackwood Plateau surface sediments.</td>
<td>Coastal Plain: minor aquifer associated with Bassendean Sand, Tamala Limestone and Safety Bay Sand, with aquitard units within the Guildford Formation. Blackwood Plateau: sediments to 30 m depth below surface, decreasing to 10 m in main streams and rivers, and comprising aquifer and aquitard units of Leederville Formation members, and the Yarragadee Formation in outcrop areas.</td>
</tr>
<tr>
<td>2</td>
<td>Mowen aquitard</td>
<td>Aquitard with minor aquifer units within the Quindalup and Mowen Members of the Leederville Formation.</td>
</tr>
<tr>
<td>3</td>
<td>Leederville aquifer</td>
<td>Minor to major aquifer with some aquitard units in the Vasse Member of the Leederville Formation.</td>
</tr>
<tr>
<td>4</td>
<td>Parmelia aquitard</td>
<td>Aquitards of the Bunbury Basalt and Parmelia Formation shale member.</td>
</tr>
<tr>
<td>5</td>
<td>Yarragadee unit 1 aquifer</td>
<td>Minor to major aquifer with aquitard units within the Yarragadee Formation unit 1.</td>
</tr>
<tr>
<td>6</td>
<td>Yarragadee unit 2 aquifer</td>
<td>Major aquifer within the Yarragadee Formation unit 2</td>
</tr>
<tr>
<td>7</td>
<td>Yarragadee unit 3 aquifer</td>
<td>Major aquifer within the Yarragadee Formation unit 3 – regionally dominant aquifer.</td>
</tr>
<tr>
<td>8</td>
<td>Cockleshell Gully / Lesueur Sandstone aquifer.</td>
<td>Major aquifer within the Cockleshell Gully Formation and Lesueur Sandstone containing fresh groundwater; CGF has some aquitard units.</td>
</tr>
</tbody>
</table>

The ground surface of the model was developed using existing Department of Land Administration (DOLA) information to construct a high-resolution topographic surface with a spatial resolution of 20 metres, and an elevation resolution of approximately ±2 m for the entire SWAMS area. Consequently, the absolute accuracy of any surface in the model is limited to ±2 m. Survey data was used, where available, to quality check and amend the surface representation. The data was also used to calculate the depth to the water table, which acts as the reference surface for evapotranspiration (EVT) estimation of the model (used to calculate EVT extinction depth), and to define the drain invert levels for drainage in the model.
Figure 2.1 Model domain showing major hydrogeological units and the river systems; rivers
in model domain are modelled as drains in MODFLOW

Figure 2.2 Model grid for the study region with finer grids for more important areas and coarser grids for less important areas
Figure 2.3 Conceptualization of the aquifer system into model layers
Figure 2.4  North-South model grid and cross-section of the aquifers it represented
Figure 2.5 East-west cross section showing the aquifers, observed bore log data and hydrogeological interpretation


2.2 Boundary Conditions

The conceptual hydrogeology of the Southern Perth Basin proposes that all groundwater resources originate from rainfall recharge. This rainfall recharge infiltrates the superficial aquifer, the Leederville aquifer, and outcrops of the Yarragadee aquifer in different areas over the model domain. The groundwater flows predominantly north and south, where it discharges to the ocean or into rivers and streams. This groundwater may also be used by vegetation on the coastal plains. The Southern Perth Basin is bounded on the east and west by major faults. These faults do not permit groundwater flow into or out of the model area from the east or west. Consequently, based on this conceptual model, there are potentially 18 boundary conditions that may be defined; 16 associated with the north and south boundaries of each layer, the top of the model and the bottom of the model.

The vertical extent of the model is defined as the depth at which groundwater TDS exceeds 1000 mg/L. This represents the limit of significant groundwater flow, but does not necessarily reflect a surface across which no flow occurs. However, for the purposes of this model, the lower boundary is assigned as no-flow, thereby implying that no water leaves or enters the model across this surface.

2.2.1 Constant Head

In the superficial aquifer, (defined only on the Swan Coastal Plain and the Scott Coastal Plain), the northern and southern boundaries are the ocean. The ocean boundary is modelled as a constant head coincident with the shoreline in layer 1, with a head of 0.0 m AHD. Aquifers below the superficial aquifer are presumed to extend offshore and discharge upwards into the ocean. The boundary conditions off-shore for the north and south consist of constant heads covering the submerged areas of layer 2, and the aquifer limits off-shore for layers 3 to 8. This allows upward groundwater flow and discharge as defined in the hydrogeology investigations (Baddock, 2005).

Environmental heads (heads >0.0 m AHD) were used in all the offshore parts of the model domain using the Ghyben-Herzberg principle. That is, a 2.5 m constant head value is defined for every 100 m depth of sea water. Environmental heads in the north and south of the model domain are generally within 0.8 and 1.8 m respectively. Constant head mapped for the model are shown in Appendix B.

2.2.2 Drainage

All major drainages within the model domain were modelled. These drainages were constructed to represent discharge from the river system of the model, and are consequently modelled as drains within MODFLOW. The drainage system, modelled as drains within MODFLOW, does not allow river water to recharge the aquifers. This is, therefore a continuation of the conservative approach adopted in the previous version of the model which was retained in the current version.

Drains, as implemented in MODFLOW, are elements where water discharges once the water table rises above the specified drain invert level. Groundwater discharged into a drain permanently leaves the model via that drain node, at that location. There are two parameters used to define drains - drain conductance and drain bed level. The first
parameter, drain conductance, is the bed resistance to flow into the drain. It is used to scale the drain area relative to the area of the element used to model the drain, and to account for converging flow losses. Drain conductance was generally set on a layer basis which means that the drain conductance for all drain cells are the same within a layer, but occasionally on a river basis (drain conductance the same for a river) to better simulate individual rivers. The second parameter, bed level, specifies the level at which water will begin to discharge into the drain.

The bed level for the Blackwood River was surveyed at a number of points in the Yarragadee discharge area, and combined with the topographic DTM to generate a surface for the Blackwood River with a spatial resolution of 20 m. Model calibration required drain cells within layers 1, 2 and 3 for the Blackwood River and the Donnelly River. Drains upon the Swan and Scott coastal plains were applied only to layer 1. The conductance of drains was varied according to calibration. Drains mapped for the model are shown in Appendix C.

2.3 Model Parameters

Parameter zonation for each model layer has been defined based upon the distribution of hydrogeological units and topography. Appendices G to J contain figures of main parameter values for each model layer showing the model parameter zonation and the hydrogeological unit present at the surface of that layer.

The available data for the formations making up the aquifer system of the SWAMS model were reviewed with estimated ranges for selected aquifer parameters. Table 2.2 summarises the range of horizontal and vertical hydraulic conductivity for selected formations. The ranges and spatial distributions of the aquifer parameters represented best estimates of the upper and lower bounds for aquifer properties that may be assigned during calibration. In some cases the spatial distribution of these aquifer parameters was modified as part of the calibration of the model. The basis for these ranges/distributions is given by Baddock (2005).

<table>
<thead>
<tr>
<th>Formation</th>
<th>Horizontal permeability (m/day)</th>
<th>Vertical permeability (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quindalup/Moven Members</td>
<td>0.1 to 0.5</td>
<td>10^{-5} to 10^{-3}</td>
</tr>
<tr>
<td>Vasse Member</td>
<td>0.1 to 10</td>
<td>10^{-3} to 10^{-2}</td>
</tr>
<tr>
<td>Parmelia Fm (3B)</td>
<td>0.005 to 0.05</td>
<td>10^{-6} to 10^{-4}</td>
</tr>
<tr>
<td>Bunbury Basalt</td>
<td>10^{-7} to 10^{-6}</td>
<td>10^{-7} to 10^{-6}</td>
</tr>
<tr>
<td>Yarragadee 1</td>
<td>5 to 25</td>
<td>10^{-5} to 10^{-2}</td>
</tr>
<tr>
<td>Yarragadee 2</td>
<td>3 to 20</td>
<td>10^{-4} to 10^{-2}</td>
</tr>
<tr>
<td>Yarragadee 3</td>
<td>3 to 25</td>
<td>10^{-4} to 0.5</td>
</tr>
<tr>
<td>Yarragadee 4</td>
<td>2 to 5</td>
<td>10^{-4} to 10^{-2}</td>
</tr>
<tr>
<td>Cockleshell Gully Fm</td>
<td>1 to 8</td>
<td>5x10^{-5} to 10^{-2}</td>
</tr>
<tr>
<td>Lesueur Sandstone</td>
<td>0.2 to 5</td>
<td>10^{-9} to 10^{-7}</td>
</tr>
</tbody>
</table>
2.4 Recharge

The initial recharge mapping was primarily developed from the hydrogeology and chloride data in shallow groundwater water aquifers. The calibration of the model requires the adjustments of the recharge to fit with observed head data. Errors can occur in this process, particularly when perched head is involved. However, if there are several observed bores in an aquifer within the same area, then the risk or error can be significantly reduced as most of the heads respond to local recharge. Recharge is the primary input in a groundwater model and is related to other parameters, such as the hydraulic conductivity, drains and evapotranspiration. Modelled annual gross areal recharge distribution is shown in Appendix D.

Annual recharge needs to be scaled temporally to obtain monthly recharge for modelling. Traditionally, recharge is scaled temporally by the rainfall time series. This is generally accepted with regard to the annual recharge cycle where the wet and dry seasons are distinct. That is, recharge is concentrated in the winter months and only a limited amount is distributed in the summer months. However, common sense suggests that the summer months should not generate any recharge under normal conditions, and winter rainfall does not generate recharge at the same rate as the rainfall amount indicates. For example, early winter rainfall may be used to saturate the soil profile, while the same amount of rainfall later in the season may generate a lot more recharge as the soil profile increasingly gets saturated. In other words, rainfall itself is not an ideal tool in representing recharge in the landscape.

Hydrological studies show that there are generally two types of runoff generation mechanisms. These are saturation runoff generation and infiltration excess runoff generation. The former generally occurs in wet and temperate climates, and the latter in arid and semiarid climates. Saturation runoff assumes that when the top soil profile is saturated, runoff would be generated. This runoff generation mechanism is applicable to most temperate areas including the study area, particularly given that most soils of the south west of WA is of a sandy nature so that the infiltration capacity is considered to be too high to allow infiltration excess runoff to occur.

Recharge studies in Australia generally assume that recharge is generated when the soil profiles saturates. This is also the condition for surface and subsurface runoff to be generated. There is sufficient data and evidence to indicate that soil profile saturation is the condition for recharge and runoff generation to occur, under most circumstances. Based on the runoff and recharge generation mechanism, it can be concluded that the relationship between runoff and recharge is much closer than the relationship between rainfall and recharge. If there is sufficient runoff data, it would be a better indicator for recharge than using rainfall as the indicator. In addition, annual rainfall variation of 50% is often regarded as a major variation, but for recharge numerous studies showed that there are easily orders of difference between recharge in wet years and dry years. If rainfall is used as an indicator for recharge, the general change of annual recharge would be mostly in the 10-50% range. However, if annual runoff is used as an indicator for recharge, the general change of annual recharge may be in the range of 100-500%, which is likely to be closer to the real variability range of recharge.

A review of previous modelling results (SWAMS1.2.1) in the study area indicates that seasonal recharge variation is generally under represented when using rainfall as the temporal scaler for recharge distribution in the landscape. SWAMS 2.0 improves the recharge time series in modelling.
The Scott River has one of the longest observed runoff data (1970-2003) for a major river in the study area. The runoff data was used to develop the scaling factor for recharge using monthly runoff to scale monthly recharge (one stress period in modelling). Annual runoff from the Scott River was plotted against that from the Blackwood River at Hutt Pool, which shows that they are closely related ($R^2=0.77$). Similarly, runoff from the Scott River was plotted against runoff from the Vasse River in the Swan Coastal Plain and obtained an $R^2$ of 0.61. The analysis suggests that the three regions of the study area are hydrologically closely related and that a single scaling factor developed from the Scott River runoff is applicable to all parts of the study area. Figure 2.4 shows the similar patterns of annual runoff from the Scott River and Vasse River.

To further illustrate that recharge is related to runoff volume in the study area, a model called Watbal (Sun, 2004) was used to predict recharge in the Scott River. The estimated recharge was then plotted with the runoff from the Scott River catchment. The results shows a highly linear relationship ($R^2=0.68$) between the two, which once again confirms that runoff is a good indicator for recharge in the study area.

![Figure 2.4](image.png) Annual runoff from Scott River of Scott Costal Plain and Vasse River of the Swan Coastal Plain

### 2.5 Evapotranspiration

Not all recharge applied to a model domain is net recharge for groundwater generation. Part of it is applied as gross recharge to allow evapotranspiration loss to the atmosphere. For the coastal plains, it is likely that some groundwater, including currently rejected groundwater is discharging via evapotranspiration (EVT). Consequently, on the Swan and part of the Scott coastal plains recharge is specified as gross recharge, and the EVT package of MODFLOW is used to account for water loss due to evapotranspiration. For the Blackwood Plateau and part of the Scott Coastal Plain, EVT is not modelled. This represents a conservative approach adopted in the previous version of the model that was retained in the current version. For the Blackwood Plateau and part of the Scott Coastal Plain, net recharge is used which effectively removes recharge that can be potentially induced due to future abstraction. While it appears convenient to use EVT for all areas, there are potential issues
associated with EVT set up on the Blackwood Plateau, such as the stability of the model due to dry cells and the high variability in topography of the Blackwood Plateau. Although EVT was tested on the Blackwood Plateau, it was decided not to apply it and keep the original simple, but conservative, approach.

There are three parameters specified in the evapotranspiration module:

1. reference surface;
2. extinction depth; and
3. maximum evapotranspiration rate.

The reference surface is surface topography (ground surface) as interpolated onto the model grid. The extinction depth ($E_x$) specifies at what depth below the reference surface evapotranspiration ceases. Since the reference surface is specified as an absolute elevation, the extinction depth also specifies an absolute elevation at which evapotranspiration ceases. The extinction depths of 2 and 5 metres were used for agriculture land and a mix of agriculture and forest respectively.

The maximum evapotranspiration rate, $E_m$, is specified as a fraction of the measured monthly pan evaporation as measured at Bunbury. $E_m$ varies spatially but remains constant during the model run. The seasonal variation in EVT is accounted for in the model by scaling $E_m$ with the measured average daily pan EVT, for each month (i.e. stress period), as measured at Bunbury. The spatial distribution of the parameters is shown in appendix E.

The areas using EVT and those that do not use it, as well as the EVT parameters used are shown in Appendix E. Lake Jasper forms its own EVT zone as well as its own recharge zone. Gross recharge for Lake Jasper is based on water balance estimation for the Lake (Varma, 2003) with EVT calibrated in modelling.

The maximum rate of evapotranspiration, the extinction depth and the gross recharge were subject to change during calibration.

2.6 Faults

Based on a review of piezometric heads, geology and carbon-14 data, a number of major faults were identified as being hydrogeologically significant and included in the model. These faults include Darling Fault, Dunsborough Fault, Darradup Fault and Busselton Fault. Appendix F shows the location of the faults modelled.

The Darling Fault forms the eastern boundary of the model domain, and is impermeable. The Dunsborough Fault forms part of the western boundary of the model and is also impermeable.

The Darradup, Busselton and other faults, which lie within the model domain, are modelled as horizontal flow barriers for the lowest four layers of the model using the HFB package in MODFLOW. The modelling of a fault using the HFB requires two parameters. These are a directional parameter related to the rectangular geometry of the grid, and a conductance (with units of 1/m) across the fault. For most faults, the present conceptual hydrogeological model implies that they are relatively impermeable flow barriers. Consequently, flow across these faults is impeded, which means they would have impacts on the abstraction of water and drawdown. The conductances of the faults are subject to change in calibration.
2.7 Abstraction

Abstraction for the SWAMS model area occurs from both the superficial and confined aquifers (i.e. Leederville and Yarragadee). There are two major types of abstraction from these aquifers:

1. measured abstraction, which includes Water Corporation abstraction (public licensed abstraction) and other large users such as mining companies; and
2. licensed abstraction by private users, which is not generally metered or measured.

These abstractions were quantified both spatially and temporally, on a monthly basis over the model calibration period. The data is defined in terms of unique drawpoints, where each drawpoint is a single well, which is licensed and in some cases metered. A license groundwater allocation is granted by the previous Water Rivers Commission (WRC). Water use is represented by one or more drawpoints. The WRC assigns the total allocation amongst drawpoints based on the intended use for each bore (domestic, irrigation etc) and, in some instances, on site audit information. Where no information is available for a licence having multiple drawpoints, each drawpoint is assigned an equal portion of the annual allocation.

The Water Corporation, private utilities and mining companies typically measure and report abstraction on a monthly basis, as volumes, for their operating bores. This monthly volume data is used as an estimate of the flow rate for wells in MODFLOW. The licensed abstraction by private users is based on an annual allocation assigned to a water user, after a successful application by the landowner for a licence from the WRC. The allocation granted by the WRC specifies the volume of water that may be extracted via specified wells during a 12-month period. This annual abstraction for private allocations must be converted into monthly usage in MODFLOW.

Unlicensed abstraction, which is permitted from bores that abstract groundwater at less than 1500 kilolitres per year, is mainly from the superficial aquifer and considered to be negligible in the model area, and is ignored.

There are 184 large operating bores accounting for approximately two-thirds of the total abstraction, while the rest 2982 bores contribute one third of the total abstraction. Total abstraction increased from 36 GL/year in 1990 to 62 GL/year in 2003, with approximately 60% from Yarragadee and 30% from Leederville. Figures 2.5 to 2.7 show current abstraction distribution from the Superficial, Leederville and Yarragadee aquifer respectively.

2.7.1 Measured Abstraction

In general, the WRC requires licence holders with allocations in excess of 0.5 GL/year to provide monthly abstraction data to the WRC. Actual monthly abstraction volumes from 127 drawpoints, with a combined allocation of 50 GL/year, were obtained either directly from the user or from annual compliance reports for the simulation period. The focus in data collection was large-scale users of the Yarragadee and Leederville aquifer systems. Most large-scale users abstract significantly less than their licensed allocation.

Measured abstraction consists of meter readings for each drawpoint, starting in 1990, The Water Corporation and others provided raw data of abstraction volumes for their borefields
for various periods, most beginning in 1990 until June 2004. This data was processed for input into SWAMS by:

- extracting metered volumes for each bore in the model domain;
- integrating the volumes into a cumulative production curve for the simulation period;
- calculating the average bore production rate for each model stress period by taking the difference between cumulative production at the beginning and end of the stress period and dividing by the length of the stress period; and
- saving the estimated average bore abstraction rate for each stress period for each bore in a MODFLOW compliant format.

The above procedure results in some smoothing of production data but guarantees that the simulated abstraction from an aquifer, as modelled by SWAMS will be equal to the abstraction as measured by the owners of the bores.

Table 2.3 summarizes the annual metered abstraction used in the SWAMS model from 1990 to 2003.

Table 2.3 Metered Abstraction by aquifer 1990-2003

<table>
<thead>
<tr>
<th>Year</th>
<th>Superficial (GL)</th>
<th>Leederville (GL)</th>
<th>Yarragadee (GL)</th>
<th>Total (GL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>0.0</td>
<td>6.7</td>
<td>19.9</td>
<td>26.6</td>
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<td>7.7</td>
<td>19.3</td>
<td>27.0</td>
</tr>
<tr>
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<td>0.0</td>
<td>7.0</td>
<td>19.1</td>
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</tr>
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<td>19.5</td>
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</tr>
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<td>0.0</td>
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<td>30.4</td>
</tr>
<tr>
<td>1996</td>
<td>0.0</td>
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<td>22.8</td>
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</tr>
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<td>34.6</td>
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<td>2001</td>
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<td>2003</td>
<td>0.0</td>
<td>7.8</td>
<td>32.3</td>
<td>40.1</td>
</tr>
</tbody>
</table>

2.7.2 Licensed Private Bores

The WRC’s database contains all existing licensed allocations for private users. This database records current and expired licenses as of the end of 2004. The database records annual allocation, the start and end of each licence, the location of the property or bore that has been assigned the allocation, the aquifer to which abstraction is licensed, and the use to which the groundwater is applied. Table 2.4 summarises the estimated licensed abstraction for the designated aquifer, excluding metered allocations, for the entire model domain.

Historical site audit information collected by WRC officers was useful in estimating actual use. The WRC reviewed client files for licensees with allocations between 0.2 GL/year and 0.5 GL/year. For licences <0.2 GL/year, it was assumed that 80% of the annual licensed
allocation is actually abstracted.

The classification of abstraction by aquifer by the WRC does not necessarily conform to the terminology or aquifer designations as set out in the conceptual hydrogeology of the model area (Baddock et al, 2005). Consequently, the model characterisation of allocation by aquifer may not be the same as reported by the WRC. The allocation by aquifer as reported in Table 2.4 is based on the formation the drawpoint is completed within the model. The completion formation is determined from the layer and formation the screened interval (in m AHD), as recorded for a drawpoint, falls in with respect to the model grid.

The change in licensed allocation over the calibration period is modelled by turning drawpoints on and off, based on the issue date and expiry date of WRC licenses. In extracting the licensed allocations from the SWAMS database and converting them into MODFLOW wells, the following algorithm is used.

a) Current licensed allocations are extracted from the database according to their model layers based on the screen interval of bores.

b) The licensed allocations, starting when issued and active until expiry, are converted to monthly abstractions by dividing by 12 to give average monthly abstraction and scaling by a monthly use factor.

c) The monthly abstractions over the life of the license are integrated into a cumulative production curve for the simulation period.

d) The average drawpoint abstraction rate for each model stress period is calculated by taking the difference between cumulative production at the beginning and end of the stress period and dividing by the length of the stress period; and

e) Abstractions that fall within the same element are aggregated into one well, negated to be consistent with MODFLOW sign convention (i.e. negative abstraction is out of the model).

The licensed allocation database does not provide any information as to the monthly pattern of abstraction for individual licensed bores. However, groundwater monitoring suggests that licensed and unlicensed abstraction from private bores has a strong seasonal component. A review of water usage for licensed bores by the WRC, suggests that the majority is used for irrigation and potable water. Irrigation abstraction has a strong seasonal pattern with maximum volumes occurring in January and February, with typically no abstraction in May, June and July. Potable water has a similar pattern, but a weaker seasonal component, because water use is more strongly related to population than temperature. Based on the investigation of water use pattern in the study area by the DoE, six main seasonal water use pattern were developed. One for Swan Coast, one for Scott Coast, and one each for mining, golf course, parks and town water supply which are shown in Figure 2.8. Using these seasonal factors, the annual abstraction for licensed bores was scaled on a monthly basis to account for seasonal water trends for different areas and industries.

<table>
<thead>
<tr>
<th>Year</th>
<th>Superficial (GL)</th>
<th>Leederville (GL)</th>
<th>Yarragadee (GL)</th>
<th>Total (GL)</th>
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Figure 2.5 Abstraction from the Superficial aquifer for the year 2003
Figure 2.6 Abstraction from the Leederville aquifer for the year 2003
Figure 2.7 Abstraction from the Yarragadee aquifer for the year 2003
**SEASONALITY FACTORS USED IN MODELLING**

![Seasonal Scaling Factors used for Private Abstraction](image)

**Figure 2.8** Seasonal Scaling Factors used for Private Abstraction
No return of groundwater to the superficial aquifer from irrigation has been accounted for. Similarly, the importation of water from the Leederville and Yarragadee aquifers into the superficial aquifer, via irrigation is also ignored. This is a conservative approach in modelling and would impact on areas where irrigation is significant. The reasons for not simulating irrigation return water are that the irrigation area is relative small and the effort to simulate the distribution of deeper aquifer water to shallow aquifer water is substantial.
3 MODEL CALIBRATION

The calibration of a groundwater model involves the iterative adjustment of selected aquifer parameters to minimize the error between measured and simulated heads in all aquifers. Two types of calibration can be undertaken - steady state (or quasi steady-state) where input variables and boundary conditions are constant with time (or periodic); and transient where predicted hydrographs are compared to measured hydrographs over a selected period, and input variables vary with time. In the case of the SWAMS model, there is sufficient data to consider that most of the model area was close to steady state prior to 1990. After 1990 there is sufficient data to undertake a transient calibration in most areas of the model, although in some areas the only change in transient conditions is rainfall. Given the available data, the SWAMS model was calibrated in steady state and under transient conditions.

The calibration of a model is specific to the conditions used to construct the model. In the case of SWAMS, variations in the geology, recharge, EVT, drainage, faults and parameter zonation have resulted in a number of model versions. This report details the calibration of the final version SWAMS 2.0 model. Other versions of SWAMS should not be considered alternative conceptualisations, but rather as incorporating different model processes to bring about improvements in model fidelity to the same conceptual hydrogeology.

3.1 Run Parameters

3.1.1 Steady State

Initially, the model was set up for a classical steady calibration, in which storage is set to zero and a solution for the heads is undertaken based on a constant water balance. It was found that due to the complexity of the model, the high variability of the topography on the Blackwood Plateau and the large dynamic range of horizontal and vertical hydraulic conductivity, that the resulting steady state solution tended to be either unstable due to the dry cells in the top three layers on the Blackwood Plateau, or unrealistic due to low $K_v$ in controlling layer, restricting water leakage downward. To remove the dry cells, the controlling aquifer property for the dry cells on the Plateau (which is normally the vertical hydraulic conductivity $K_v$ in layer 2), needed to be sufficiently low compared to recharge. However, low $K_v$ restricted infiltration of water to the lower layers causing head build up in the upper layer and head dropping to below that observed in the lower layers.

In addition to the numerical problem of drying elements, problems with rainfall recharge and perching of elements were also encountered in the steady state model. In the case of rainfall recharge, the MODLOW option allowing recharge to the highest active cell in the model was used. The advantage of using this option is that the model determines where recharge occurs, and eliminates the need for prior assumptions inherent in fixing the recharge into certain layers. However, as elements go dry, recharge is shifted to the next lower layer. Due to the occurrence of low hydraulic conductivity basalt and Leederville Formation underlying some areas, recharge to these formations resulted in unrealistic high heads. This problem was eliminated by removing recharge, on an element-by-element basis, for those areas that had heads greater than 200 m AHD at the end of the steady state simulation. This results in a small loss of recharge in the cells, as the area affected is small (the loss is recovered in transit calibration).
The simulation of perched aquifers in MODFLOW is not well supported by the program, which assumes that elements below the water table are saturated. The occurrence of a perched water table reflects observed conditions, and from that perspective provides a measure of validation of MODFLOW with respect to modelling features of the aquifer system. The perched elements can be removed by forcing all saturated elements overlying dry elements to be inactive prior to starting the simulation. This normally results in a more stable model requiring significantly reduced computational effort. However, by forcing perched elements to be inactive two artefacts are introduced to the model:

- recharge is forced into a lower saturated layer, requiring the recalibration of recharge based on net recharge to the lower layer; and
- shallow calibration bores may be eliminated from the model, as some measure perched water levels.

The allowance of perching results in recharge only to the highest saturated layer could mean that no recharge is possible through the unsaturated zone. While this is not necessarily the case, the lack of recharge via the unsaturated zone, due to perching, is only over a very limited area in the model, and in most cases alternative flow paths are available for recharge to flow to underlying layers. As a result, the perching of water was retained in steady state and transient calibrations.

Horizontal anisotropy was introduced in steady state calibration for layers 3-8. This is because the observed head data mapped from the available data showed very sharp head drop from the eastern part to the middle of the Blackwood Plateau, particularly for layer 3. The model can not match the head drop gradient without introducing the anisotropy factor. This factor allows the horizontal hydraulic conductivity to be different along the north-south direction as compared to the east-west direction, with the Kh in east-west direction acts as the basis of calculation. For example, anisotropy factor of 2 means that Kh in north-south direction is twice as large as in the east-west direction. The derived anisotropy factor is 2 for layer 4 and 1.5 for layer 3 and layers 5-8 through steady state calibration. This means that the north-south direction Kh in layers 3-8 are larger than the east-west direction Kh, which is supported by the pumping test and local area modelling on the Plateau and the general hydrogeology of the area.

Although a steady state calibration was obtained, there are several issues that need to be further addressed in the transient model. The main one is that to obtain the steady state solution, certain areas on the Blackwood Plateau require very low Kv. A more refined calibration is undertaken in transient state.

### 3.1.2 Transient

The steady state simulation is more stringent on the components of water balance and model convergence. Due to the high complexity of the aquifer system, some significant changes have to be made to parameters to produce the transit calibration. The transit state involves the simulation of heads in individual bores and is often a more complicated process.

The transient model was calibrated from 1990 to 2003. Stress periods were defined as calendar months, with model units defined in metres and days. Each stress period has 6 time steps. The model was simulated using MODFLOW 2000, with the Block-Centred Flow (BCF6) package, and the PCG2 solver. Head and residual convergence criteria were 0.1 m
and 200 m$^3$/day.

A review of calibration runs shows that the total water balance (m$^3$) error started from 0.11% in stress period 1 and gradually reduced to 0.01% at the end of calibration, while the error in rates (m$^3$/day) during each time step is generally less than 0.08% for the entire model run.

### 3.2 Calibration Bores

337 bores were initially selected to calibrate the model. A number of bores were found to have false or non representative values (CL3W, BP11B&C). A number of shallow bores went dry during calibration (BP49A, BP50A, BP59B, BUS23S&D, BUS35S). As a result, the total number of valid bores for calibration is 328. These bores include all of those most recently drilled (mostly BP series bores) on the Blackwood Plateau, and all other bores with observation records of greater than 50 months. Of these, 56 were in the superficial aquifer; 100 in the Leederville; 31 in the Mowen aquitard and 141 in the Yarragadee aquifers. The calibration bores are reasonably well distributed by area and by aquifer using the best available bore data.

The calibration bore data was extracted from the SWAMS database. The database has over 2000 monitor locations, and 37000 data points. Data begins in 1902 and finishes in February 2005. Initial model head distributions and transient calibration hydrographs were all sourced from this database.

The monitor bores were sorted by aquifer with the monitoring interval (screened interval) of each bore compared to the elevation of all the modelled formations in the aquifer system, referenced to topography. The completion formation was identified as those in which the screened interval of the bore is in, based on elevation. This procedure may result in monitor bores being classified differently in the model, as compared to other databases. The model classification was used in calibrating the model, because this represents the position of the bores with respect to the updated geological structure of the model.

A few of the calibration bores were drilled later than the calibration period and have no data during calibration. In such cases, the average head data during monitoring period is used to calibrate heads in calibration period. All calibration and observation data are included in error estimation.

The number of calibration bores, although smaller than the earlier version, is still large for manual or automated calibration which means considerable time and efforts are required for calibration. There are still a number of bores that do not seem to represent regional water levels. Nevertheless, they are retained in calibration. Further investigation may be needed to identify whether the abnormal heads are caused by localised hydrogeology features in large zonations, or complex hydrogeology that are yet to be fully understood.

### 3.3 Transient Model Calibration

#### 3.3.1 Calibration to Observed Bore Data

The transient model was calibrated from 1990 to 2003 using a manual iterative technique. The calibration consisted primarily of minimising error in water levels. However, the model was also calibrated to estimate river discharge in the Blackwood and Donnelly rivers and
others in the Swan and Scott coast. Figures 3.1 to 3.4 show the overall calibration results for all calibration bores in the Superficial, Leederville and Yarragadee aquifers, and the Mowen aquitard. Figure 3.5 shows the error distribution of calibrated heads in Layer 3 of mostly the Leederville aquifer, with positive numbers showing over-estimation and negative numbers under-estimation. Other error distribution maps are found in Appendix K.

It can be seen that simulated heads have been fitted reasonably well with the observed. The distribution of error for the aquifers generally shows a well-distributed error, around the unity slope line, suggesting no significant systematic calibration error in calibration. The calibrated heads in the Yarragadee aquifers showed a slight bias on the positive side. This is likely due to the boundaries conditions that are not conducive for discharge into the sea. Heads in the coastal areas tend to build up under these conditions which may cause head build-up further upslope.

Table 3.1 summarises the calibration head error by aquifer. The average absolute error measures the average simulation away from the average observation, which are 0.8, 3.6 and 3.1 metres for the superficial, the Leederville and Yarragadee aquifers respectively. Calibrated average absolute head error for the Mowen aquitard is also listed in Table 3.1 (5.6 m). The average root mean square error (Average RMS Error) measures the scattering of data; the closer they are to the average absolute error the better they are. Calibration result shows that approximately 75% of bores are simulated within 5 m of the observed head and 90% of bores are simulated within 8.4 m of the observed.

The calibration head error is close to the best that can be achieved under current modelling conditions, and significant improvements without major changes to the model are unlikely to be achieved. Given the complexity of the hydrogeology and large zonations for the regional model, the calibration result is regarded as a good fit to the observed, and the model is a reasonable analogue of the aquifer heads in the model domain. Calibration hydrographs for individual bores are shown in Appendices M to P.

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>Average Absolute Error (m)</th>
<th>Average RMS Error (m)</th>
<th>Maximum Positive Error (m)</th>
<th>Maximum Negative Error (m)</th>
<th>Number of bores in aquifer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial</td>
<td>0.8</td>
<td>2.9</td>
<td>8.4</td>
<td>-7.4</td>
<td>56</td>
</tr>
<tr>
<td>Mowen</td>
<td>5.6</td>
<td>7.6</td>
<td>17</td>
<td>-21</td>
<td>31</td>
</tr>
<tr>
<td>Leederville</td>
<td>3.6</td>
<td>7.0</td>
<td>21</td>
<td>-24</td>
<td>100</td>
</tr>
<tr>
<td>Yarragadee</td>
<td>3.1</td>
<td>4.0</td>
<td>13</td>
<td>-9</td>
<td>141</td>
</tr>
</tbody>
</table>

### 3.3.2 Calibration to Observed Drain Data

The calibration of major drain flows as compared to the measured is shown in Table 3.2. While this comparison gives a general guide as to the simulation results of drain discharge, there are several problems that can potentially distort the comparison. Firstly, the observed dry summer flow is assumed to be constant throughout a year to derive the annual groundwater discharge, which underestimates the total, observed groundwater discharge.
Secondly, where the EVT is simulated, such as at the Coastal plains, the EVT can cause significant variation on the modelled drain discharge. On the Blackwood Plateau, where the EVT function is not used, local discharge from the aquifers can only take place through the model drains, while in reality the discharge might be through evapotranspiration. For example, the observed average annual discharge from the Donnelly River system is approximately 6 GL/year, yet the modelled discharge is at 22.2 GL/year. Even though the drain conductance and recharge at the area were reduced to unrealistically low levels, the discharge is still much higher than the observed. Analysis of groundwater head in the area suggests that heads not far from the drains are generally 10 m above the inverse of the drains. This means that either the conductance of the drain is so low that little water can discharge into the Donnelly River (which is unlikely and is not supported by the local bore and soil data), or that discharge is mostly via EVT. The latter is a realistic possibility and may need to be investigated further. Literature research suggests that significant amount of groundwater can discharge via the EVT in various landscapes (Meinzer and Stearns, 1927; Rasmusen and Andreasen 1959; Tschinkel 1963; Arnold et al., 1993; Sun and Cornish, 2004). These discharges often occur at the lower parts of the landscape such as riparian zones or lower downslopes, where groundwater discharges are accessed by evapotranspiration processes.

Total average annual discharge between Nannup and Hutt Pool from the Blackwood River is modelled at 59.5 GL/year. A salt balance model applied to the Blackwood River estimated total discharge of 41 GL/year between Nannup and Hutt Pool (Mauger, 2003). This compares to the observed discharge of 24 GL/year when the summer groundwater baseflow is extended to the whole year. The salt balance model includes some evaporation from the water surface and riparian zones and is a closer match to that modelled. This partly confirms that EVT plays a significant role in groundwater discharge to the Blackwood River.

Modelled discharge from the Yarragadee outcrop in the middle of the Blackwood River is 9.7 GL/year, which compares well with the observed average discharge of 10 GL/year from the same area. The heads are matched particularly well in this area as well. These suggest that the Yarragadee outcrop area is modelled realistically which adds confidence in the modelling results.

The observed dry summer flow in the Scott River is very low which is matched well by the modelling result. The real drainage from the Swan coast is difficult to derive because some drainages are not monitored, and where they are monitored, irrigation return flow complicates the discharge estimation. Therefore, modelling result for the Swan coast is a reasonable depiction of the reality.

The large variation between the observed and modelled drainages in the Blackwood and Donnelly rivers are due mostly to the errors in modelling the surface processes and upper aquifers, rather than the modelling errors of the Yarragadee aquifer. These errors are likely to be dealt with in future modelling so that water balance in all aquifers can be improved. The calibration focused on matching the drain water balance in the Yarragadee aquifer as this is the most important aquifer for future abstraction. Modelling result suggests that this primary goal was achieved.

Table 3.2  Comparison of modelled and observed annual drainages for major rivers and areas with observed data (GL/year)

<table>
<thead>
<tr>
<th>Drain discharge</th>
<th>Blackwood: between Nannup and</th>
<th>Blackwood: from Yarragadee</th>
<th>Donnelly River</th>
<th>Scott River</th>
<th>Swan Coastal Plain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hutt pool</td>
<td>outcrop area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>-----------</td>
<td>--------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modelled</td>
<td>59.5</td>
<td>9.7</td>
<td>22.2</td>
<td>1.5</td>
<td>26.8</td>
</tr>
<tr>
<td>Observed</td>
<td>24.0</td>
<td>10.0</td>
<td>6.0</td>
<td>0.03</td>
<td>44.5*</td>
</tr>
</tbody>
</table>

* Data less reliable

Figure 3.1 Comparison of calibrated and head observed head in the Superficial Aquifer
Figure 3.2 Comparison of calibrated and observed head in the Vasse of Leederville Aquifer
Figure 3.3 Comparison of calibrated and observed head in the Yarragadee Aquifer

Figure 3.4 Comparison of calibrated and observed head in the Mowen Aquitard
Figure 3.5 Calibration head error distribution for bores in layer 3 (mostly Leederville aquifer), with positive numbers representing overestimation and negative numbers underestimation, maps for other layers are found in Appendix K.
3.4 Calibrated Model Parameters

The following parameters were adjusted as part of the model calibrations: horizontal hydraulic conductivity \( K_h \), vertical hydraulic conductivity \( K_v \), recharge and drain conductance. No adjustment of boundary conditions, specific yield, and specific storage were made during calibration.

<table>
<thead>
<tr>
<th>Table 3.3 Calibrated Aquifer Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Superficial Aquifer (Layer 1)</strong></td>
</tr>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Horizontal Hydraulic Conductivity</td>
</tr>
<tr>
<td>(m/day)</td>
</tr>
<tr>
<td>Specific Yield (-)</td>
</tr>
<tr>
<td>Drain Conductance</td>
</tr>
<tr>
<td>Specific Storage (1/m)</td>
</tr>
<tr>
<td>Vertical Hydraulic Conductivity (m/day)</td>
</tr>
<tr>
<td><strong>Leederville Aquifer (Layer 2-4)</strong></td>
</tr>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Horizontal Hydraulic Conductivity</td>
</tr>
<tr>
<td>(m/day)</td>
</tr>
<tr>
<td>Specific Yield (-)</td>
</tr>
<tr>
<td>Drain Conductance</td>
</tr>
<tr>
<td>Specific storage (1/m)</td>
</tr>
<tr>
<td>Vertical Hydraulic Conductivity (m/day)</td>
</tr>
<tr>
<td><strong>Yarragadee Aquifer (Layer 5-8)</strong></td>
</tr>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Horizontal Hydraulic Conductivity</td>
</tr>
<tr>
<td>(m/day)</td>
</tr>
<tr>
<td>Specific Yield (-)</td>
</tr>
<tr>
<td>Specific storage (1/m)</td>
</tr>
<tr>
<td>Vertical Hydraulic Conductivity (m/day)</td>
</tr>
</tbody>
</table>

A summary of the calibrated aquifer parameters is given in Table 3.3. The ranges of the calibrated aquifer parameters are consistent with those recommended in the conceptual
hydrogeological model (Table 2.1). The spatial distributions of Kh, Kv, specific yield and specific storage for all layers are shown in Appendices G to J.
3.5 Water Balance

Using the calibrated transient model, average annual water balance from 1990 to 2003 for the study area was estimated. The water balance was calculated from the cell-by-cell flow file as output by MODFLOW 2000, in compact format. The method of constructing the water balance from model cell-by-cell flow rate data is approximate, as it is based on the integration of rates rather than cumulative totals. Comparison of these integrated flow components over the entire model run with MODFLOW cumulative totals show that the error in an integrated water balance is generally less than 2%, this is considered to be sufficiently accurate for the annual water balance estimations.

A water balance was determined by zones in aquifers. Each zone was given a unique identifying code, which was assigned to each layer as required. Average annual water balance was performed for the major geological units of the Blackwood Plateau, and the Swan and Scott coastal plains. The offshore areas have their own water balance zones allowing the estimation of discharge to the sea. Table 3.4 summarises the water balance during the modelling period of 1990 to 2003.

Table 3.4 Water balance from the model calibration during 1990-2003 (GL/year)

<table>
<thead>
<tr>
<th>Region</th>
<th>Gross recharge</th>
<th>Evapotranspiration</th>
<th>Net recharge</th>
<th>Flow to the ocean</th>
<th>Abstraction</th>
<th>Storage depletion</th>
<th>Drainage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blackwood</td>
<td>234.4</td>
<td>0</td>
<td>234.4*</td>
<td>0</td>
<td>72.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swan coastal</td>
<td>208.7</td>
<td>166.4</td>
<td>42.3</td>
<td>89.4</td>
<td>26.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scott coastal</td>
<td>208.4</td>
<td>111.5</td>
<td>96.9</td>
<td>147.7</td>
<td>33.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>651.5</td>
<td>277.9</td>
<td>373.6</td>
<td>237.1</td>
<td>45.4</td>
<td>41.1</td>
<td>132.2</td>
</tr>
</tbody>
</table>

*Direct recharge from the Yarragadee outcrop in the middle and south of the Blackwood Plateau is 58 GL/a, of which 44 leaks to lower layers and 14 discharges as drainage.

Gross recharge distribution over the land surface of the model domain is shown in Appendix D. Net recharge is based on the average annual gross recharge during the modelling period for each aquifer zone receiving recharge, minus any EVT. EVT is only active on the coastal plains. Therefore, for all other areas of the model, recharge is net to the aquifer or zone. Annual gross recharge varies from 24-170% of the average recharge during the calibration period, with the maximum and minimum recharge occurring in 1996 and 2001 respectively. Net average annual recharge from 1990 to 2003 is 373.6 GL/year. Average flow to the ocean is 237.1 GL/year. Modelled average drainage for the model domain is 132.2 GL/year.

A water balance was also undertaken for the Yarragadee aquifer (downward flux to layer 4 and below) as shown in Table 3.5. Average annual net influx to the Yarragadee aquifer for the calibration period is 151.1 GL/Year, of which 44 GL/year comes from the outcrop area and 120.4 GL/year comes from the other areas. Although the influx from the Yarragadee outcrop area is less than that from the rest of the model domain onshore, it needs to be remembered that the Yarragadee outcrop area as modelled is only 291 km², compared to the rest of the recharge area of 5722 km². If we use the area of recharge as the base of calculation, the flow concentration from the Yarragadee outcrop area can be calculated as approximately 8 times the rest of the areas. The high flow concentration from the Yarragadee outcrop area means that it will dominate the Yarragadee aquifer system at the outcrop area and beyond, particularly for the Unit 3 of the Yarragadee. As a result, chemical
properties and carbon-14 age data at the outcrop area and surroundings would generally reflect the properties of water from the Yarragadee outcrop area.

The 120.4 GL/year leakages to layer 4 and below from areas other than the Yarragadee outcrop area includes leakage from the western part of the model domain, which are not parts of the Yarragadee aquifer, such as the Lesueur Sandstone. On the eastern part of the model domain there are two other Yarragadee units (unit 1 and 2) on top of the Unit 3 with their own recharge areas and discharge routes into the sea. The ages of Yarragadee Unit 1 water are generally older than that of units 2 and 3, suggesting downward leakage from Leederville is slower than that of the Yarragadee outcrop area. Recharge from the Yarragadee outcrop area is particularly concentrated in unit 3 which explains why the lower Yarragadee has fresher and younger aged water (Rockwater, 2004). It is therefore important to regard the aquifers under study as a whole aquifer system with multiple flow regimes and multiple recharge regions and discharge routes, and this is where the strength of a regional model really lies.

Table 3.5 Water balance for the Yarragadee aquifer during 1990-2003 (GL/year)

<table>
<thead>
<tr>
<th>Total influx to Yarragadee</th>
<th>Influx through outcrop Yarragadee</th>
<th>Influx other than the outcrop Yarragadee</th>
<th>Upward flux from Yarragadee</th>
<th>Net influx to Yarragadee</th>
</tr>
</thead>
<tbody>
<tr>
<td>164.4</td>
<td>44</td>
<td>120.4</td>
<td>13.3</td>
<td>151.1</td>
</tr>
</tbody>
</table>

3.6 Calibration - Discussion

The model calibration was undertaken based on parameter zonations that are developed in Baddock (2005). In general, the zonations reflect large-scale geological and hydrogeological structures that are a generalisation of the hydrogeology of the model domain. As such, it is not appropriate for the zonations to account for small-scale structures and localised variation in aquifer properties or recharge. The parameters for each zonation need to be regarded as effective parameters for the zone, which account for matrix flow as well as preferential or bypass flow. The calibration process is a process to find these parameters that best match the observed data, which is often the observed head data in the zone as other data is generally not available or less reliable.

The calibration hydrographs for each bore within each aquifer are shown in Appendices M to P. It is believed that these are generally sound simulations of the aquifer bores in terms of head, seasonal variation and trend matching. Therefore, there is a reasonable representation of the flow system. The high complexity of the aquifer system presents a major constraint on the calibration of the hydrographs.

Despite the significant effort put into the calibration of the model, there are still areas and bores where improvement in calibration can be made. However, major improvements are unlikely to be made under current hydrogeological mapping. The parameters in the major zonations were searched comprehensively a number of times for refinement and it is believed there is very limited room for significant improvement in terms of better head fitting to the observed. Minor improvement, particularly with regard to the trend of the hydrographs over the calibration period and seasonal variation of the hydrographs, can be achieved.

Major improvements of the model may need to focus on more fundamental changes, such
as the boundary conditions or new data and new interpretation of data for various zonations. The former will change the external condition of a model or the horizontal gradient of the aquifers. An example is a change of model domain in the offshore area. This will be important for the whole model, in particular the areas closer to the shoreline as the hydraulic gradients in these areas would be changed most. The second major change may occur on parameter zonations, for example for refined zonations on hydraulic properties and recharge based on improved data or improved interpretation of the existing data.

The dry cells have been a major hindrance to steady state calibration. They distort the flow system and this causes instability within the system. Efforts to eliminate the dry cells are limited to lowering Kv in the controlling layer which may limit water infiltration to the lower layers. Further study may use a more smoothed surface on the Blackwood Plateau to reduce the dry cells, caused by sharp variation in topography. Thicker top layer(s) to bypass some part of the Mowen may also be considered. The second hindrance on the steady state calibration is that recharge on basalt in several layers causes high head in the model, which needs to be removed via reducing recharge to zero in these areas to stabilize the system. These two factors mean that the steady state solution can not be directly used as the initial condition for transient calibration. This complicates the modelling system and adds significant complexity and efforts required for the calibration.

Horizontal anisotropy was introduced into the modelling and was found to be a necessary component of the model. North-south flow appears to be easier than the west-east flow which may be associated with the faulting of aquifers not currently mapped. There is not enough information with regard to the faults, and observed head data often show sharp changes which can not be adequately simulated by the model. More efforts are needed to understand how these sharp changes occurred or whether they are hydraulically significant or just perched water tables.

The new scaling time series for recharge based on runoff generation proved to be a significant improvement for fitting the seasonal variability of hydrographs. The recharge time series is much more variable than using the rainfall, and generally matched the majority of bores. However, for a number of bores, the dry climate since 2001 appears to be exaggerated in the model which showed higher drop in head than that of the observed. It is suspected that the observed bore data since 2001 was impacted by the flooding effect, particularly on the coastal plains. The result was that the observed hydrographs did not show as large drawdowns as the predicted in the dry period since 2001.

The new seasonal factor for unmetered abstraction from different geography and industries helped to refine the time sequence of the abstraction data, so that seasonal variation can be better simulated.

Theoretically, EVT needs to be implemented on the Blackwood Plateau and the Eastern Scott Coast. This could remove some of the EVT potentially contained in the modelled drainages. There are two considerations that prevent the setting up of EVT on the Plateau. The first is the conservative approach adopted in the previous version of modelling; the second is the extra complexity and potential adverse consequence it might bring about (such as stability of the model). However, it is worth trying in future model development so that water balance components can be better aligned to the observed.

The estimated drainage on the Plateau is higher than the observed baseflow, primarily as a result of no EVT set up in the area. On the coastal plains, the drainages generally matched the observed despite the fact that some observed data is less reliable. The flooding effect
however, can not be modelled adequately by the model, and this can lead to exaggerations on the simulated impact by abstraction. This is a limitation of MODFLOW and further improvement is required in this area. The Rivers package of MODFLOW may be used to allow river water to be recharged back into the aquifers. This would have limited effect on the Blackwood Plateau because upward head or high head relative to drain elevation are found in most areas; but it may work for the coastal plains area.

Significant efforts were put into compiling and improving the abstraction and observation data for the calibration period and beyond. The data quality is considered to be sufficiently accurate for the modelling purposes.

3.6.1 Estimated Net Recharge

The model estimated net recharge of 373.6 GL/year. 63% goes to the sea while the rest discharges as drainages. There are several methods, such as water balance modelling and chloride balance analysis, that can be used to determine recharge to the aquifers. A review of the results from these studies suggests that the major difference in estimated recharge is how recharge in shallow groundwater areas is assessed. In agricultural studies any excess water beyond the root zone capacity is regarded as recharge, but for groundwater studies some of this recharge is rejected recharge due to low permeability of the aquifers or upward head in these areas. If the rejected recharge is not counted as recharge (as it should not be for defensible groundwater studies), then net recharge for the modelled area can be estimated relatively consistently using a number of models. Table 3.6 shows the results from several water balance models and the current groundwater modelling result.

Table 3.6 Comparison of annual net recharge estimation between water balance modelling and groundwater modelling (GL/year)

<table>
<thead>
<tr>
<th>Models</th>
<th>WEC-C</th>
<th>WAVES</th>
<th>WATBAL</th>
<th>SWAMS2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net recharge</td>
<td>330</td>
<td>360</td>
<td>341</td>
<td>374</td>
</tr>
</tbody>
</table>

The water balance models listed in Table 3.6 are quite different. WEC-C (Mauger, 2003) and WAVES (Xu, 2003) are fully distributed deterministic models describing detailed physical processes in atmosphere and aquifers. WATBAL (Sun, 2004) is a lumped conceptual model that uses vegetation as the controlling factor for water balance estimation in a landscape. Despite the differences of the models, all three models estimate very close net recharges for the study area which are slightly less than the groundwater model predicted.

In addition to modelling, water balance based on chloride concentration mapping in the Vasse member of the Leederville aquifer (including Yarragadee outcrop area) can also be made. It is done by estimating chloride concentration in rainfall as a function of distance to the sea, and chloride concentration in aquifers to derive the ratio of recharge to rainfall for the study area. The estimated net recharge for the combined Leederville and outcrop Yarragadee aquifer, based on chloride data compiled (Rockwater, 2004) is 282 GL/year. Recharge to the superficial aquifer alone can be estimated approximately based on Darcy flow estimation and discharge to the sea in current groundwater modelling, which is between 20-60 GL/year depending on whether the discharge from the sand dune in the Scott coast is counted in or not. Therefore, total net recharge to the aquifer system, based primarily on chloride balance would be between 302-342 GL/year. This is consistent with the modelling results and provides an independent source of confirmation to the modelling results.
The above suggests that several water balance modelling efforts and chloride balance analysis all support the result of the current groundwater modelling in terms of net recharge into the aquifer system.

### 3.6.2 The Superficial Aquifer and Shallow Aquifers on Blackwood Plateau

Major processes involved in the calibration of water levels in the superficial aquifer are the drainage and evapotranspiration functions in the MODFLOW. Both functions help to control the water table in the coastal areas and are reasonable representations of the real situation. However, there are several processes that can not be modelled adequately by the MODFLOW. Observed data in the coastal plains show very high annual run-off from the coastal areas (greater than 200 mm/year for the Swan and Scott coasts). The amount of run-off can effectively fill a 1 m column of moist soil every year, and can significantly alleviate modelled drawdowns in the coastal plains. The flooding feature, however, can not be modelled directly in the MODFLOW which will likely lead to the exaggeration of the impact estimated by the model in the costal areas. This can be seen from the fitted hydrographs for many bores during the dry period 2001-2003, where calibrated head decline is far more severe than the observed. Other processes, such as irrigation return water, is not modelled which may be significant with increasing irrigation in the area. It is, however, a minor factor when compared to the flooding effect on the superficial aquifer.

The average absolute error, as measured at 56 bores, is 0.8 m. This is a very good match between the predicted and measured water levels. The maximum positive error in the superficial aquifer is 8.4 m at monitor bore SC4B, while the maximum negative error is −7.4 m at CL8C. Most of the simulated heads at monitor bores in the superficial aquifer have a response consistent with measured data. The monitor bores maintain correct trends and the magnitude of the error is typically constant, indicating that most of the error stems from initial conditions.

SC4B is sitting on a drain element at the lower reaches of the Blackwood River. By increasing the drain conductance at the local area, the head can be calibrated to the observed level. However, since the Blackwood River has the same conductance for every drain element in a layer (to maintain consistency in modelling, but not necessary right), it is not possible to match the head at the SC4B site. The second reason is that some elements in Layer 1 went dry, which impacts SC4B in Layer 2. CL8C is at a high head level (~133 m) and the relative error is small (less than 6 percent) for the bore. The high head bores often have high head gradient, where the head observed may not match where the head is calibrated by the model. This may be suitable for low head gradient areas, such as in most of the Yarragadee aquifer, but can cause serious discrepancies in the high head gradient areas.

The model error in the superficial aquifer is the smallest of all aquifers. The seasonal variability of the calibration has vastly improved from previous modelling. Due to the winter flooding effect not being specifically modelled, head decline is likely to be exaggerated when the aquifer is under high stress.

### 3.6.3 The Leederville Aquifer

Figure 3.3 shows a comparison of predicted and measured water levels for the calibration bores completed in the Leederville aquifer. The upper part or the high head area shows a
larger scatter of errors in the simulated water levels in the Leederville aquifer. This is normal as the Leederville includes high head areas which are difficult to fit all the bores in. The lower part of the graph shows some systematic error, or a positive bias of the predicted. This is likely to have been caused by the boundary conditions in the coast that restrict flow towards the ocean thereby causing simulated head to build up in the coastal areas.

The average absolute error, as measured at 100 bores, is 3.6 m. This is considered to be a reasonably good match between the predicted and measured water levels, given the high variability and high heads on the Blackwood Plateau. The maximum positive error in the Leederville aquifer in predicted head is 21 m at BP17B, while the maximum negative error is -24 m at BP42A. The error range suggests that there are significant local errors in the modelling results that need to be addressed in future modelling. The errors are probably associated with the mapping of Parmelia and basalt in the middle of the model (layer 4). For example, the two largest errors mentioned above are clearly associated with the mapping of the basalt zones - BP17B is sitting on the basalt while BP42A is not on basalt; and both are at the edges of the basalt. While the head at BP42A is observed at ~84 m, the area where BP42A is located would generally not support head that is above 70 m under current modelling conditions. Large errors are found to be mostly associated with high head which may also be caused by some local hydrogeological features that can not be mapped in large zonations. It appears that the hydrogeology for the upper Leederville on Blackwood Plateau is a lot more complex than that mapped currently.

BP13B appears to be a perched head or a local head. BP67 bores are higher than nearby bore BP62 and may represent local heads. BUS24D needs a higher Kh to match the head, but it is within the same area of bore CL1W which requires very low Kh to maintain the head. BUS35D, at 34 m head is well above nearby BUS20D at 19 m and may represent local head. CL5B is at the transitional zone from the high head at the east to lower head at the west. CL8B is also at the transitional zone from the high head at the north to lower head in the south.

Quite a number of bores such as BUS30D and BUS24D may be impacted by the boundary condition at the coast. The constant head zone may be a little too far off the coast which requires an increase of Kh to lower head in the aquifer, but the consequence in increasing Kh is borne by the bores close to the shoreline. The heads in these bores tend to be simulated higher than the observed. This is the reason the lower head bores generally have a positive bias as compared to the observed.

A review of the calibration hydrographs shows that the monitor bores maintain correct trends and the magnitude of the error.

Sources of errors may be removed by refining the zonations based on improved interpretation of the hydrogeology. As a first step, a thorough review and analysis of monitor bore data so that only those representing regional groundwater heads are selected for future modelling endeavours. This, however, may need to be done in combination with the improved interpretation of the hydrogeology. Other sources of calibration error in the Leederville are due to differences in measured versus simulated monitor elevation, in the presence of high vertical gradients, and the perching of the water table, which is not well simulated using the MODFLOW.

3.6.4 The Yarragadee Aquifer

Figure 3.4 shows a comparison of predicted and measured water levels for the calibration
bores completed in the Yarragadee aquifer.

From Figure 3.4, the model predicted water levels show some systematic error to measured data. The piezometric levels in the Yarragadee are not randomly distributed, but tend to be higher at some bores with water levels below 40 m. However, this pattern of error is not widely scattered but relative close to the middle line. As discussed earlier, this is likely to be caused by boundary conditions that are not conducive to discharge to the sea, which tend to elevate heads in the coastal zones. In turn, this impact bores further up in the aquifers.

The average absolute error, as measured at 141 bores, is 3.1 m, and is considered to be a reasonably good match between the predicted and measured water levels. The maximum positive error in the Yarragadee aquifer, in predicted head, is 12.9 m at BUS5D, while the maximum negative error is –8.8 m at CL6A1. BUS5D observation is impacted by abstraction in the first half of the calibration which dropped head by as much as 20 m. In the later half of the calibration period the abstraction stopped and the head recovered to a high level. The modelled did not pick up as much as the drawdown during the abstraction period, but reasonable modelled the recovery part. This suggests that the modelled Kh, as required by the zonation, is higher than the actual for the bore BUS5D. For CL6A1, the calibration could not calibrate the three bores CL6A1, CL7A1, and CL8A1 at the same time with the first two bores in the same zone. In the end CL7A1, where major leakage occurs, is chosen for the best fit.

Most of the simulated heads at monitor bores in the Yarragadee aquifer have a response consistent with measured data. Generally, monitor bores maintain correct trends and the magnitude of the error is constant, indicating that the error stems from initial conditions.

Review of the calibration hydrographs shows that the monitor bores maintain correct trends and the magnitude of the error is constant.

Generally the calibration of the Yarragadee aquifer is reasonably accurate which is similar to the earlier version of the calibration. Boundary condition seems to have a major impact on the calibration, and needs to be addressed in future modelling endeavours.

### 3.6.5 The Mowen Aquitard

Figure 3.5 shows a comparison of predicted and measured water levels for the calibration bores completed in the Mowen aquitard. The Mowen represents some high head areas on the Blackwood Plateau. In some areas, such as the Donnybrook area, it is similar to the Leederville and may supply pumping for irrigation.

The bores BP11B and BP11C have very high downward head gradient in the Mowen, with very tight horizontal and vertical conductivity, as well as low recharge. This makes head matching quite difficult. In addition, BP11C needs to be in layer 1 rather than in layer 2 as it currently stands. Since no correction was made for the two bores with regard to their position to model layers and hydraulic gradient which leads to errors of up to 55 m, the two bores are removed from calibration. Further calibration may include these bores after relevant corrections, although these bores are among the least important calibration bores for the aquifer system. BP24C head was adjusted by head gradient of the bore in the Mowen so that observed head is as the same elevation as the modelled elevation, this reduced head for BP24C from 126.3 to 95.4 m. All other bores are not adjusted by the difference in elevations of the observation and modelling. As a result, the fitting of the calibrated to the observed is not exactly accurate and the result should be used as a
general guide for head in the aquitard.

Despite the data inadequacy for the calibration in the Mowen, the scattering of data as shown in Figure 3.5 is better than expected suggesting that the error range is generally within the acceptable levels for the aquitard.

Most of the bores in Mowen are BP bores which do not have long records to provide trend data, but the few hydrographs does show that the calibrated hydrographs display the right trend as the observed.
# 4 Sensitivity Analysis

The objective of Sensitivity Analysis is to quantify the sensitivity of calibration parameters and inputs to observed data. By varying aquifer parameters and input data and rerun the model, the effect on simulated heads in the observation bores can be estimated, and the relative importance or uncertainty in model parameters can be evaluated.

SWAMS uses the MODFLOW 2000 and the BCF package to solve the flow equations for the saturated aquifers. To take advantage of the statistical capabilities of the MODFLOW 2000 with respect to sensitivity analysis, SWAMS was reformulated using the Layer-Property-Flow (LPF) package in the MODFLOW 2000 (USGS, 2000). However, the use of the LPF package results in a slightly different solution than the MODFLOW BCF package, and is less stable in some cases. To allow the MODFLOW 2000 to generate dimensionless scaled sensitivities, which estimate the impact of calibration parameters on observed heads, the following changes to the SWAMS model were made:

- The model run length was reduced to simulate a five-year period starting in 1998.
- The model layers were made to be non-converting (constant transmissivity);
- The predicted water levels in December 2002 were used to remove dry elements from the model.
- The LPF package was modified to be consistent with the BCF package in the MODFLOW 2000.

The above changes were required to obtain a solution for the Sensitivity Analysis, both in terms of head and sensitivity convergence. While these changes reduce the fidelity of the sensitivity model to the hydrogeological model, a review of the head solution compared to the calibration model, showed that the simulated heads were consistent.

The composite scaled sensitivities for the parameters were calculated using the modified calibrated model. The composite scaled sensitivities rank the relative importance of different aquifer parameters in calibrating the model to observations. The model sensitivities were obtained using the following procedure:

- The MODFLOW calibrated model was reconfigured to simulate the period from 1998 to 2002, using the MODFLOW 2000 and the LPF package. The truncated version of the model was used to reduce model running time.
- A set of layer sensitivity parameters were defined for aquifer horizontal hydraulic conductivity, vertical hydraulic conductivity for the 8 model layers and specific yield for Layer 1 in the model. Specific storage was identified to be not sensitive in the previous version of the sensitivity test, and was removed from current sensitivity test.
- The model was run on a cluster of 16 processors, using the parallel version of the MODFLOW 2000, to generate the composite sensitivities for 17 parameters, using the calibration bores for each aquifer. The calculation of sensitivities required 30 hours of cluster execution time (each node runs a 1.7 GHz - AMD processors).
- The model was run three times, using the calibration bores for the superficial, Leederville and Yarragadee aquifers, so as to determine the sensitivity of the calibration in each aquifer to the changes in the sensitivity parameters.
• The composite sensitivities were extracted and analysed for each set of calibration bores, to determine the relative sensitivity of simulated measured heads in each aquifer to variations in the defined parameters.

In addition to the sensitivity test of the parameters, the sensitivity of recharge was also tested as recommended by the previous peer review team (DoE, 2004). This was done separately by using two recharge inputs, with one slightly less than the other and run the model to obtain the differences in head response for all bores caused by the difference in recharge. The method and equations used for the recharge sensitivity test is the same as for the parameter sensitivity test. Table 4.1 summarises the sensitivity parameters used in the sensitivity analysis with the results of the sensitivity analysis presented in Table 4.2.

Table 4.1 Layer sensitivity parameters and input data tested

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal hydraulic conductivity, Kh</td>
<td>1-8</td>
</tr>
<tr>
<td>Vertical hydraulic conductivity, Kv</td>
<td>1-8</td>
</tr>
<tr>
<td>Specific yield</td>
<td>1</td>
</tr>
<tr>
<td>Recharge</td>
<td>Aquifer based test</td>
</tr>
</tbody>
</table>

The composite sensitivities (i.e. the sum of the response at all the calibration bores) are based on varying all aquifer parameters in each layer. Hence, the composite sensitivities provide information on layer sensitivity, not on specific zonations within a layer. The zonation-based sensitivity test which can test the sensitivity of major zonations was planned initially but was found to be too time consuming to run and, in the end, had to be dropped.

## 4.1 Sensitivity Analysis Results

The results of the sensitivity analysis are presented in Table 4.2 which summarises the scaled composites sensitivities of Kh, Kv, specific yield and recharge, in the superficial, Leederville and Yarragadee aquifers.

The most important parameters for each aquifer are highlighted in red, yellow and green in descending order. In general, the sensitivity test results are consistent with the conceptual understanding of the modelling system. Recharge is found to be by far the most sensitive variable compared to the parameters tested.

In the superficial aquifer, the sensitivity analysis indicates that the horizontal hydraulic conductivity in Layer 1 and the vertical hydraulic conductivity in Layer 2 are the most important for horizontal and vertical conductivity respectively. The horizontal hydraulic conductivity in Layers 3 and 7 are also important, suggesting the Leederville and Yarragadee flows both have a significant effect on superficial aquifer heads. The results indicate the connections between horizontal flow processes in the aquifers are important, while vertically the top few layers are the most important for the superficial aquifer.

In the Leederville aquifer, heads are most strongly influenced by the properties of the Leederville aquifer or Layer 3, and the vertical hydraulic conductivity of the top two layers.
This indicates that vertical flow processes are important for the Leederville aquifer. The spatial mapping of vertical leakage in Layers 2 and 3 of the model has been proved to be one of the most difficult in calibration. This is mostly caused by the high complexity in hydrogeology of the aquifer which may require more refined data and interpretation of the aquifer to improve future calibration. Calibrated heads are also sensitive to the horizontal hydraulic conductivity of Layer 2 and Layer 7 of the Yarragadee aquifer.

Heads in the Yarragadee aquifer are most sensitive to horizontal hydraulic conductivity in Layer 7. They are also strongly influenced by the vertical hydraulic conductivity of the Leederville aquifer, reinforcing the importance of vertical leakage through the Leederville for simulating heads in the Yarragadee aquifer. The Yarragadee aquifer is also sensitive to horizontal hydraulic conductivity in Layers 5 and 8; and to vertical hydraulic conductivity in Layer 1, reflecting the significance of recharge in the Yarragadee outcrop area.

<table>
<thead>
<tr>
<th>Parameter/layer</th>
<th>Superficial Aquifer</th>
<th>Leederville Aquifer</th>
<th>Yarragadee Aquifer</th>
</tr>
</thead>
<tbody>
<tr>
<td>HK_1</td>
<td>0.79</td>
<td>0.73</td>
<td>0.48</td>
</tr>
<tr>
<td>HK_2</td>
<td>0.17</td>
<td>1.22</td>
<td>0.22</td>
</tr>
<tr>
<td>HK_3</td>
<td>0.71</td>
<td>2.50</td>
<td>0.60</td>
</tr>
<tr>
<td>HK_4</td>
<td>0.24</td>
<td>0.28</td>
<td>0.34</td>
</tr>
<tr>
<td>HK_5</td>
<td>0.19</td>
<td>0.88</td>
<td>1.14</td>
</tr>
<tr>
<td>HK_6</td>
<td>0.14</td>
<td>0.23</td>
<td>0.80</td>
</tr>
<tr>
<td>HK_7</td>
<td>0.49</td>
<td>1.09</td>
<td>3.23</td>
</tr>
<tr>
<td>HK_8</td>
<td>0.10</td>
<td>0.28</td>
<td>1.18</td>
</tr>
</tbody>
</table>

| VK_1            | 0.43                | 2.26                | 1.03               |
| VK_2            | 0.49                | 2.29                | 0.86               |
| VK_3            | 0.45                | 2.72                | 1.37               |
| VK_4            | 0.12                | 1.08                | 0.87               |
| VK_5            | 0.10                | 0.78                | 0.75               |
| VK_6            | 0.15                | 0.33                | 0.70               |
| VK_7            | 0.08                | 0.18                | 0.42               |
| VK_8            | 0.06                | 0.07                | 0.71               |

| Specific Yield_1| 0.67                | 0.85                | 0.31               |

| Recharge        | 5.96                | 6.00                | 7.35               |

Table 4.3 Most Sensitive Bores by Aquifer

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Superficial</th>
<th>Leederville</th>
<th>Yarragadee</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SC8B</td>
<td>BP39A</td>
<td>KL5W</td>
</tr>
<tr>
<td>2</td>
<td>SC18B</td>
<td>CL8B</td>
<td>KL5A1</td>
</tr>
<tr>
<td>3</td>
<td>BUS22S</td>
<td>BP34B</td>
<td>BP31A</td>
</tr>
<tr>
<td>4</td>
<td>BUS34S</td>
<td>BP24C</td>
<td>BP14C</td>
</tr>
<tr>
<td>5</td>
<td>SC22B</td>
<td>BP24B</td>
<td>Q9D</td>
</tr>
<tr>
<td>6</td>
<td>BUS29S</td>
<td>BP42B</td>
<td>BP30A</td>
</tr>
<tr>
<td>7</td>
<td>SC17B</td>
<td>BP09B</td>
<td>BP14A</td>
</tr>
</tbody>
</table>
Table 4.3 shows the top 10 monitoring bores, with the highest dimensionless scaled sensitivities to changes in the above sensitivity parameters. Conversely, the measured heads at these bores listed in Table 4.3 have the largest impact on the calibrated values of the sensitivity parameters.
5 Validation of the Calibration Model

Validation of the calibration model normally requires an independent set of bore data in addition to the calibration data set. This is often not possible because the data sequence is frequently not long enough for a validation period. In addition, large scale use of groundwater resources is often of a very recent event for a regional groundwater area. Even though the data sequence can be extended to much earlier data, there is often not sufficient abstraction to make a significant impact over a large region. As a result, despite much effort put into the collection and compilation of the bore data, relative reliable abstraction data can only be sequenced from 1990 to the present. The abstraction rate of 35.5 GL/year in 1990 may be sufficient to cause significant local water table drawdowns, but it is not considered to be high enough to cause noticeable regional water table drawdowns. In other words, abstraction data prior to 1990 would be of limited use to validate the calibration of the model.

However, there has been a reasonable amount of data on carbon-14 collected from the region (Rockwater, 2004), which can be used to assess the relative age and the pathway indicated in the calibration model. This can be done by using the PMPATH module of the PMWIN. Comparison of the carbon-14 estimates, the simulated travel times and flow patterns can provide an independent and therefore very valuable verification of the simulated groundwater flow.

5.1 Model Validation Using Carbon-14 Data

The path lines as simulated in PMPATH are actually flow lines that track the paths of the flow solution in the model. Using the back-tracking, it can track from the shoreline to where the flow initiated, or major sources and sinks in the flow system. Since we know that the Yarragadee outcrop area in the middle south of the Blackwood Plateau is a major recharge area, back-tracking of the flow line should end in this area if the model is right.

The carbon-14 dating was made under the assumption of minimal or no retardation of carbon due to interaction with the aquifer (Rockwater, 2004). The estimations should therefore be regarded as the upper limits of the ages of water. The carbon dating is also impacted by the climate and sea level change over the last 30,000 years and the ages need to be regarded as an approximation.

Figure 5.1 shows the simulated path lines using back-tracking from the shoreline for Yarragadee 3 unit, with each arrow or dot representing 1,000 years. The top left part shows the plain view, the top right part shows the north–south cross section, and the lower left part shows the east-west cross section. It can be seen that major flow systems originate from the Yarragadee outcrop area. The flow lines to the south indicate that water is generally a few thousand years old with only one line indicating ages of more than 10,000 years. Flow to the north varies generally from 7,000 to 23,000 years old. This suggests that ages are younger than the carbon-14 data indicate, but generally fit with the trend and pattern in carbon-14 dating for the Yarragadee 3 unit (Rockwater, 2004). The difference between the modelled and the estimated carbon-14 age is generally less than half the carbon-14 age. This level of discrepancy is consistent with the uncertainties in age determination described above, and does not reflect on the accuracy of the model. Figure 5.2 shows the simulated flow lines for the Leederville aquifer which also matched well with the carbon-14 dating in both ages and
pattern of flow (Rockwater, 2004).

Figure 5.1 Simulated flow lines for the Yarragadee 3 unit with each arrow or dot representing 1,000 years. The indicated ages and pattern fit well with observed Carbon-14 data for the aquifer.

The simulated flow lines and carbon-14 age data for both the Leederville and Yarragadee aquifers produce similar spatial patterns of flow and relative groundwater ages to the observed data, which provide support for the model's representation of the flows in the relevant aquifers. This is significant because validation is an important part of modelling, which is often needed after calibration; to demonstrate that what is modelled is right or reasonable. Carbon-14 data provides an independent set of data which can be regarded as good as a second set of bore data and therefore provides invaluable information to assess.
the validity of the simulation and calibration model.

Figure 5.2 Simulated flow lines for the Leederville unit with each arrow or dot representing 1,000 years. The indicated ages and pattern fit well with observed Carbon-14 data for the aquifer.

5.2 Parameter Validation Using Pumping Test Data

A large-scale pumping test was undertaken by the Water Corporation during Oct-Nov. 2003 near Rosa Brook to test and obtain aquifer parameters for the Yarragadee 3 unit in the local area. The test includes a 14-day constant pumping period with an average abstraction rate
of 9936 m$^3$/day, and a comprehensive monitoring network for the test period. The pumping test results were analysed both analytically and modelled to provide estimations of horizontal conductivity for Yarragadee 3 unit for the local area. The outcome to date includes an analytical estimation, two estimations from regional modelling, and two estimations from local models derived from regional modelling. The overall results are listed in Table 5.1.

Table 5.1 Horizontal conductivity of Yarragadee 3 at Rosa Brook estimated from current and previous investigations (m/day)

<table>
<thead>
<tr>
<th>Estimations</th>
<th>Analytical</th>
<th>SWAMS 1.2.1</th>
<th>SWAMS 2.0</th>
<th>SWAMS 1.2.1 Local model</th>
<th>SWAMS 2.0 Local model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Conductivity</td>
<td>6</td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>9</td>
</tr>
</tbody>
</table>

The result in Table 5.1 shows that the horizontal conductivities derived from various methods are consistent with each other. The local models are developed by using telescoping method in PMWIN to focus on a particular area and then subject the area to the new stresses of a pumping test. The local models can be calibrated in two ways. One way is to recalibrate the local area under new conditions using new parameters. The other is to use existing parameters and examine the drawdowns under new pumping conditions. The SWAMS 1.2.1 local model used the former method, while the SWAMS 2.0 local model used the latter method.

The simulation result from the SWAMS 2.0 local model is close to the pumping test result without effectively any change from the regional model (other than the new pumping stresses). This can be illustrated by the observed and predicted drawdown data at the monitoring bores. The five closest observation bores in Yarragadee 3 surrounding the pumping test site give an average observed drawdown of 2.4 m over the test period, while the modelling simulates an average drawdown of 1.9 m for the same bores during the period. One factor to keep in mind is that a local pumping test may involve significant localised preferential flows, resulting in closer monitoring bores having less drawdown than further away bores. These preferential flows can not be modelled in a regional model or a local model with regional parameter setting (where the aquifer parameters are normally the same for the bores involved). Therefore, the pumping test results needs to be averaged to make sense to regional scale modelling. A detailed local model needs much finer hydrogeological data and interpretation for the local area to be able to match monitoring data on an individual bore basis. The result is that much more data are required for such a modelling attempt.

The above analysis and associated modelling effort provide partial but significant evidence that the parameters used in regional modelling are consistent with those derived from pumping test, which provides further support on the validity of the model in representing the natural aquifer system.
6 APPLICATION OF THE MODEL

The main purpose of calibrating the model is to apply it to a series of scenarios that can describe future responses of the modelled aquifer system to various stresses that may possibly be applied to it. Such stresses normally come in the form of increased abstraction, but may also come from climate changes and other sources.

A number of scenarios have been developed, based on several proposed or predicted abstractions for the future. The three basic scenarios represent current use at 2004, regional growth and Water Corporation proposed abstraction for the next 30 years (2004-2034). The regional growth scenario was developed jointly with DoE, based on individual industry reports, groundwater applications and potential groundwater resources. The spatial distribution of the regional growth abstraction is shown in Figure 6.1. The levels of abstraction for the three scenarios are shown in Table 6.1.

Table 6.1 Current and projected abstractions for the next 30 years (GL/Year)

<table>
<thead>
<tr>
<th>Scenarios and their break down components</th>
<th>2004 abstraction</th>
<th>2033 abstraction</th>
<th>Average annual abstraction</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current use</td>
<td>63.9</td>
<td>63.9</td>
<td>63.9</td>
<td>Abstraction as in 2004</td>
</tr>
<tr>
<td>Net Regional growth</td>
<td>0</td>
<td>94.8</td>
<td>47.9</td>
<td>Net increase on top of Current use</td>
</tr>
<tr>
<td>Net Water Corp</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>Water Corporation abstraction</td>
</tr>
<tr>
<td>Regional growth</td>
<td>63.9</td>
<td>158.7</td>
<td>111.8</td>
<td>Current_use + net regional growth</td>
</tr>
<tr>
<td>Water Corporation</td>
<td>108.9</td>
<td>203.7</td>
<td>156.8</td>
<td>Current_use + net regional growth + net Water Corporation</td>
</tr>
</tbody>
</table>

The calibrated head data in December 2003 is used as the starting head for the scenario runs, starting from January 2004. The average recharge during 1971-2003, which is slightly lower than the calibration period (1990-2003) was used as the average recharge for general scenario runs. This average recharge represents a reduced recharge under current dry climate condition, compared with the longer term climate condition. For most of the scenario runs (other than those with specific changes on recharge), recharge does not change during the 30-year simulation period. This is contrary to the calibration period. Other parameters maintain the same for both calibration and scenario runs.

The scenario runs are based on cumulated abstraction data (the highlighted rows in Table 6.1 are scenarios) with each scenario inputted into the model and run individually. The Current_use scenario represents the base scenario where current abstraction as at 2004 is
used for the next 30 years. The Regional_growths growth scenario represents the projected abstraction for the next 30 years, based on the current use scenario and net increases. The Water Corporation scenario is the total abstraction scenario projected for the next 30 years. When the model runs are completed, the drawdown impact for a particular set of abstraction can be estimated by subtracting the heads data of each model layer from two scenario runs. For example, the impact of the Water Corporation abstraction (45 GL/year) is obtained by subtracting the Water Corporation scenario run result from the Regional_growth scenario run result.

In addition to the volume of abstraction, the positions of abstraction are also important factors that need consideration in modelling. In some cases the borefields need to be shifted to avoid major drawdown impact in a particular area. The Regional_growth_with Lesuer scenario (Scenario 2) has major abstractions in the Lesueur sandstone aquifer which causes water table drawdowns of up to 12 m in some sensitive areas. The borefield was later shifted to the Western Scott coast which forms the new Regional growth scenario (Scenario 3). For the Water Corporation abstraction, three borefields (Scenarios 4, 5 and 6) are developed to compare the relative impact on the water table. To simulate a drier climate than the current one, reductions in gross recharge are used to further test the scenarios under drier climate condition. A total of 8 major scenarios were developed and listed in Table 6.2.

Table 6.2 List of 10 scenario runs under various abstraction and other conditions

<table>
<thead>
<tr>
<th>Scenario number</th>
<th>Scenarios</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Current_use</td>
<td>Abstraction at the end of 2004</td>
</tr>
<tr>
<td>2</td>
<td>Regional_growth_withLesuer</td>
<td>Approx. 13 GL/year of abstraction is taking from the Lesueur sandstone</td>
</tr>
<tr>
<td>3</td>
<td>Regional_growth</td>
<td>abstraction from the Lesueur sandstone is shifted to the western Scott Coast Plain</td>
</tr>
<tr>
<td>4</td>
<td>WaterCorp_Eastern_juy1&amp;3</td>
<td>Water Corporation abstraction from eastern bore field Yarragadee 1 and 3 units</td>
</tr>
<tr>
<td>5</td>
<td>WaterCorp_Eastern_juy3_45</td>
<td>Water Corporation abstraction from eastern bore field Yarragadee 3 unit</td>
</tr>
<tr>
<td>6</td>
<td>WaterCorp_Western</td>
<td>WaterCorp abstraction from western bore field Yarragadee 3 unit</td>
</tr>
<tr>
<td>7</td>
<td>Current_useRechaReduct5%</td>
<td>Same as scenario 1 but with 5% reduction of recharge at the end of simulation</td>
</tr>
<tr>
<td>8</td>
<td>Current_useRechaReduct10%</td>
<td>Same as scenario 1 but with 10% reduction of recharge at the end of simulation</td>
</tr>
</tbody>
</table>

An assessment of the three Water Corporation scenarios (Scenarios 4, 5, 6) shows that the eastern split scenario (Scenario 4) demonstrates the least overall impact of abstraction, and this becomes the preferred option for Water Corporation abstraction. Scenario 4 abstracts half of the proposed abstraction (22.5 GL/year) from the Yarragadee 1 unit and half from the Yarragadee 3 at the top of the St John’s Brook area. Scenario 5 abstracts all 45 GL/year from Yarragadee 3 at the same location as Scenario 4, while Scenario 6 abstracts 45 GL/year from Yarragadee 3 around the Rosa brook and its immediate north area. Scenarios
7 and 8 represent a hypothetical climate that is drier than the past 30 years with gross recharge reducing linearly from the start of simulation to 5 and 10 percent of gross recharge respectively at the end of 30-year simulation period. These scenarios are presented as the worst case scenarios for the modelling.

### 6.1 Drawdown from Scenario Runs

Figure 6.2 shows the drawdown impact in water table by the Water Corporation abstraction at the eastern split borefield with half the abstraction from the Yarragadee 1 unit and half from the Yarragadee 3 (Scenario 4 in Table 6.2). Figure 6.3 shows the drawdowns of Scenario 4 in Layer 7 of the model (Yarragadee 3 unit). There are a number of dry cells in the Yarragadee outcrop area (at the middle south of the Blackwood River) which influences the presentation of drawdown at the area. To better present that area, the drawdowns in Layer 4 where there are no dry cells is brought up to represent the drawdown in the water table (Layer 1), as well as in Layers 2 and 3. This representation is conservative, but is believed to be a suitable representation of modelling results due to the high vertical permeability of the Yarragadee outcrop area.

From Figure 6.2 it can be seen that major drawdown areas due to the 45 GL/year Water Corporation abstraction are: the Yarragadee outcrop areas in the middle of the Blackwood Valley between Laymen Brook to Milyeannup Brook area (up to 3 m); Eastern Scott Coastal Plain and the immediate north area (up to 2 m); the Yarragadee subcrop area close to Bunbury (approximately 0.5-1 m), south of Busselton in the Swan costal plains (up to 2 m), and areas north of and along the St John’s Brook (up to 2 m).

Drawdowns in the centre of the Water Corporation borefield in Layer 7 (-600~-900 AHD) reached 8 m at the top end of the St John’s Brook, which gradually reduced outward in a ring fashion. The maximum impact at the coastline is between Busselton and Bunbury with drawdowns of up to 1.5 m in Layer 7. Drawdowns in the centre of the Water Corporation borefield in Layer 5 (-150~-350 AHD) reached 20 m at the top end of the St John’s Brook. Although the drawdown in Layer 5 is high, it is mainly confined in the St John’s Brook and the surrounding area, which does not extend to the coastal plains area. Consequently, the Water Corporation eastern split scenario does not pose a major threat to other abstractions in the coastal plains area, and from its relatively small drawdowns at the coast line, it does not appear to pose major threat to seawater intrusion as well.

The drawdown at the water table by Regional growth abstraction is shown in Figure 6.4. The impact is mainly on the coastal plains where major abstractions occur. This is different to the impact of the Water Corporation abstraction where major drawdowns occur on the Blackwood Plateau with less impact on the coastal plains.

The impact at water table by the combined abstraction of Water Corp and Regional Growth is shown in Figure 6.5. Major impact of 2-5 m drawdowns occur in the Yarragadee outcrop area in the middle of the Blackwood River. The impacts on the coastal plains are generally below 2 m with some area reaching 3 m.

The impact of the combined Water Corp and Regional Growth abstraction reached a maximum of 12 m in the centre of the Water Corp bore field in layer 7. The maximum impact at the coast line is between Busselton and Bunbury with drawdowns of up to 5 m in layer 7, which are mainly caused by the regional growth abstraction.

Drawdowns for all layers of the three basic scenario runs as well as other scenario runs are
shown in Appendices Q, R, S at the end of 30, 20, and 10-year periods respectively. The proposed Water Corp eastern and western borefields are shown in Appendix T.

Analysis of the drawdown impacts due to the abstraction in the calibration period, and several runs based on the current use scenario, suggest that the impacts at the water table are likely to be overestimated. This is mainly because the model is not able to account for the flooding effects on land surface. For example, a 2 m drawdown in 30 years means annual average drawdown of 13.3 mm/year using a specific yield of 0.2 for the coastal plains soils. For both the Swan and Scott coastal plains, average annual runoff is in excess of 200 mm/year, which is 15 times or more of the potential annual drawdown at the water table. While drawdowns in deeper layers of the model may not be subject to this flooding water, drawdowns on the water table are impacted by the flooding water. As a result of high surface flow, the predicted drawdown can be overwhelmed by the flooding effect on the coastal plains. To what extent the predicted drawdowns can be lessened or even diminished is not easy to determine using the current model, but the flooding has a realistic potential to diminish the predicted drawdowns on the coastal plains. As a result, the predicted drawdowns need to be interpreted as abstraction drawdowns, which excludes the potential impact of flooding on the coastal plains.

6.2 Water Balance of Scenario Runs as Compared to Calibration

Water balance for the study area was divided into three regions of Blackwood Plateau, Swan Coastal and Scott Coastal. These regions are geographical regions, rather than topographical catchment areas. Table 6.3 shows the net recharge estimation for the Calibration period (during 1990-2003), Regional growth and the Water Corporation eastern split scenario runs (Scenarios 3 and 4 in Table 6.2) during 2004-2033. Gross recharge in the calibration period is 651.5 GL/year (1990-2003), which is slightly higher than the average of 631.5 GL/year during 1971-2003. For both scenario runs, evapotranspiration on the coastal plains dropped significantly in response to further abstraction, leading to significant net recharge increases. This further confirms that having no EVT on the Blackwood Plateau is a conservative approach in modelling.

Table 6.3 Net recharge estimation for Calibration, Regional growth and Water Corp scenario (GL/year)

<table>
<thead>
<tr>
<th>Region</th>
<th>Gross recharge</th>
<th>Evapotranspiration</th>
<th>Net recharge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cali-</td>
<td>Water</td>
<td>Cali</td>
</tr>
<tr>
<td></td>
<td>bration</td>
<td>Corp eastern</td>
<td>bration</td>
</tr>
<tr>
<td></td>
<td>growth</td>
<td>split</td>
<td>growth</td>
</tr>
<tr>
<td>Blackwood Plateau</td>
<td>234.4</td>
<td>227.1</td>
<td>0</td>
</tr>
<tr>
<td>Swan Coastal</td>
<td>208.7</td>
<td>202.2</td>
<td>166.4</td>
</tr>
<tr>
<td>Scott Coastal</td>
<td>208.4</td>
<td>201.9</td>
<td>111.5</td>
</tr>
<tr>
<td>Total</td>
<td>651.5</td>
<td>631.5</td>
<td>631.5</td>
</tr>
</tbody>
</table>
Figure 6.1 Spatial distribution of regional growth abstraction for the year 2032
Figure 6.2 Model predicted drawdowns at the water table by the Water Corporation eastern split borefield abstraction. The prediction may be subject to interpretation by local information and hydrogeology in some areas.
Figure 6.3 Model predicted drawdowns for the Water Corporation eastern split borefield abstraction in layer 7 showing maximum drawdowns of the Water Corporation abstraction in the confined Yarragadee 3 aquifer.
Figure 6.4 Model predicted drawdowns at the water table by Regional growth abstraction. The prediction may be subject to interpretation by local information and hydrogeology in some areas.
Figure 6.5 Model predicted drawdowns at the water table by the combined Water Corporation eastern split and regional growth abstraction. The prediction may be subject to interpretation by local information and hydrogeology in some areas.
Table 6.4 presents the water balance components of flow to the ocean and the modelled drainages for the same model runs shown in Table 6.3. It can be seen that both scenario runs show major reductions in flow to the ocean and moderate reductions on discharge through drains. These demonstrate the impact of increased abstraction on the water balance of the aquifer system. That is, discharges out of the modelling system are reduced in response to the extra stress of increased pumping, while net recharge is increased, as shown in Table 6.3.

Major reduction of flow to the ocean due to future abstraction during the next 30 years occur in the Swan coast, with a maximum reduction of 40%, of which regional growth abstraction explains two thirds while Water Corp abstraction explains one third. Reduction of flow to the ocean in the Scott coast is 9%. Maximum drain reduction from the Blackwood Plateau, Swan and Scott coasts in the next 30 years are 18, 21, and 11% respectively.

Most of drainage reduction will occur on the Blackwood Plateau with the Regional growth scenario causing 11.2% (10.2 GL/year) and the Water Corporation scenario causing 6.5% (5.9 GL/year). Maximum drain reduction in the Yarragadee outcrop area in the Blackwood Valley (Layman Brook to Milyeannup brook area) is estimated at 26% (2.5 GL/year), with the Regional growth scenario and the Water Corporation scenario contributing roughly equally during the next 30 years.

The abstraction and storage depletions are shown in Table 6.5. The abstraction data is generated by model runs and are marginally less than the database abstraction data due to dry cells (wells) arising from the calibration. The three tables (Table 6.3 to 6.5) provide the full accounting of the water balance for the three model runs.

From the three tables, it can be calculated that out of the 45 GL/year Water Corporation abstraction, 13 GL/year comes from flow to the ocean, 19 GL/year comes from storage, 6 GL/year comes from increased net recharge and 7 GL/year comes from drainage, mostly from the Blackwood River.

Table 6.4 Drainage and flow to the ocean for Calibration, Regional growth and the Water Corporation scenario (GL/year)

<table>
<thead>
<tr>
<th>Region</th>
<th>Flow to ocean</th>
<th>Drainage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calibration</td>
<td>Regional growth</td>
</tr>
<tr>
<td>Blackwood Plateau</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Swan Coastal</td>
<td>89.4</td>
<td>64.6</td>
</tr>
<tr>
<td>Scott Coastal</td>
<td>147.7</td>
<td>134.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>237.1</strong></td>
<td><strong>199.5</strong></td>
</tr>
</tbody>
</table>
Table 6.5 Abstraction and storage depletion for Calibration, Regional growth and the Water Corporation scenario (GL/year)

<table>
<thead>
<tr>
<th>Abstraction</th>
<th>Storage depletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>Regional growth</td>
</tr>
<tr>
<td>Regional growth</td>
<td>Water Corp</td>
</tr>
<tr>
<td>45.4</td>
<td>110.5</td>
</tr>
<tr>
<td>41.1</td>
<td>28.9</td>
</tr>
</tbody>
</table>

6.3 Model Limitations for Impact Assessment

A groundwater model simulates water fluxes and heads, or water table changes, for essentially saturated and continuous flow systems. It is not good when used for simulating dry or perched flow system as occur in parts of the Blackwood Plateau. Predictions in these areas serve only as indicative of the real happening.

The predictions on drawdowns at the water table need to be analysed and interpreted with other information to gain a better understanding on its interaction with the environment. This can be illustrated by two cases when the water table is either shallow or deep. Under shallow water table conditions, saturation of the soil profile is expected which leads to close interaction between the water table and surface runoff processes. The MODFLOW is not designed to deal with such circumstances, particularly when the surface runoff volume is high, as in the coastal plains. In fact, the drawdowns estimated by the MODFLOW can be regarded as abstraction drawdowns rather than the actual drawdown, as there is no process in the MODFLOW that simulates the flooding effect in shallow water table areas. When the water table is deep, its interaction with the surface processes is greatly reduced. Consequently, changes in the water table would have little or greatly reduced impact on the land surface processes.

Since the model does not model the flooding effects, the drawdowns on the coastal plains are likely to be exaggerated. Without a numerical method to assess the potential impact of flooding, it is not known to what extent the predicted drawdown can be mitigated by the flooding, which leads to conservative drawdown estimations on the coastal plains.

SWAMS 2.0 is a regional model with relatively large zonations to average the properties of the aquifer system, and modelling results need to be interpreted as such. It may not be appropriate to treat model results as exact or absolute for specific spots in the landscape, particularly for areas where no or few observation bores are available for calibration. In such cases modelling results need to be considered as indicative.

In summary, the model has certain limitations when used for impact assessment. These limitations need to be taken into account so that environmental assessments based on model outcome can be carried out within the context of model performance.
7 CONCLUSIONS AND RECOMMENDATIONS

In general, there is sufficient confidence in the modelling of the aquifer system and the modelling results. The confidence comes from two independent calibrations on the two versions of the model which are significantly different yet produce similar impact areas. The second area that adds confidence is that the modelled ages of flow paths and pattern essentially follow those of the independently observed carbon-14 data. The pumping test adds further evidence that the parameters used in the model are realistic at the test site. A series of comprehensive tests done on the model indicates that the predictions of the model is very stable and consistent (Nield, 2005). As a result, the current model is believed to be a reasonable and valid representation of the real aquifer system.

Nevertheless, the modelling result needs to be taken as one realisation on the simulation of the natural system, and there are limitations associated with the MODFLOW representation of the natural system. This mainly refers to the flooding effect of the coastal plains which the MODFLOW can not handle effectively. It means that the predicted drawdowns in the coastal plains are effectively drawdowns by the abstraction, with the flooding effects essentially not accounted for. This limitation of the MODFLOW would result in predictions on the coastal plains being conservative.

Existing errors within the model mainly come from the imperfect understanding and mapping of the aquifer system. This is unlikely to be completely resolved for a regional model, as the data requirement can be enormous and the cost prohibitive. However, further efforts in targeted areas may lead to improvement in modelling for those areas.

Further improvement of the model may need to introduce more complex processes, such as using the River Package rather than the Drain Package of the MODFLOW to simulate the drainage systems. However, it needs to be realised that most of the surface processes as developed in the MODFLOW are very simple processes (such as Drains and EVT) for good reasons) with inherent limitations on their representation of the natural systems. To better model these surface processes would require a coupled surface water model with the MODFLOW. Such coupled models exist, but the added complexity, computational requirements and the stability of modelling are potential issues that need to be tested out and addressed.

The recommendations list a number of areas for further development. Improvements within the current model, such as using more complex MODFLOW processes, are generally considered to be minor improvements, which are unlikely to cause significant changes upon the conclusions reached in this report. Major improvements such as enabling the simulation of the flooding effect on the coastal plains require a change of model and substantial time and effort to accomplish.

7.1 Conclusions

A saturated flow model of the Southern West Yarragadee Aquifer System (SWAMS 2.0) was constructed and calibrated using available water level monitoring data. The construction of the model is consistent with, and based on the conceptual hydrogeology developed from the extensive investigations of the project.
The model consists of 8 layers, and was constructed using available geological and hydrogeological information; it covers an area of approximately 8500 km² with land area totalling 6013 km².

Steady state and transient calibrated models were constructed for the study area. For the transient calibration, the average absolute calibration error by flow system during 1990-2003 is:

- Superficial - 0.8 m;
- Leederville - 3.6 m;
- Mowen - 5.6 m; and
- Yarragadee - 3.1 m.

The majority of the simulated heads at monitor bores have a response consistent with measured data. The monitor bores maintain correct trends and the magnitude of the error is relatively constant. The simulated heads in the Leederville and Mowen show larger errors in some cases, however, most bores are consistent with measured data.

Errors and uncertainties in calibration mostly arise from the imperfect understanding and mapping of the aquifer systems, rather than the calibration processes. The latter is believed to be close to what can be achieved under current modelling conditions. The imperfect mapping of the aquifer systems arises from the lack of more detailed data which is always an issue for regional modelling, even though enormous amount of investment and efforts have been put into the investigation processes. Given the sheer scale of the model domain, some risk in the modelling of the actual system due to the lack of detailed information may need to be accepted.

The present calibration of the model is adequate for the assessment of changes in water levels due to changes in abstraction from the Yarragadee and coastal superficial aquifers at a regional scale. Due to the presence of the Mowen aquitard, the water levels and, in particular, the high water tables, in some areas of the Blackwood Plateau are sensitive to topography, local drainage and recharge which are less well understood and modelled. Consequently, there is some uncertainty in these simulated water levels, and changes in them should be used as an indicative measure of relative impacts. On the coastal plains, the winter flooding effects can not be modelled effectively by the MODFLOW. This means that the estimated drawdowns on the coastal plains by various scenarios are conservative and may be highly conservative, particularly under high stress conditions. This is a limitation of the MODFLOW model.

The water balance for the calibration period indicates an average gross recharge of 651.5 GL/year with a net recharge of 373.6 GL/year. The water balance indicates just under 7% of rainfall becomes net recharge over the model domain. This is consistent with, though slightly higher than, the net recharges obtained using other analytical and mathematical methods.

Application of the calibrated model to major scenarios shows the impact of future abstraction on the water table drawdowns and on the water balance of the aquifer system. These predictions can generally be relied upon for decision-making and management of the aquifer system. The prediction results should generally be used to indicate the potential impacts for a certain area but not used to pinpoint the impact for a specific spot in the landscape.

Water balance analysis on the application of the model suggests that major reduction in flow to the ocean due to abstraction occurs in the Swan coast, with a maximum reduction of
40%. Drainage reduction due to abstraction occurs mostly on the Blackwood Plateau with an overall reduction of just under 18%. Drainage reduction at the Yarragadee outcrop area in the Blackwood Valley is estimated at 29% for the next 30 years.

Of the 45GL/year Water Corporation abstraction, 13 GL/year comes from flow to the ocean, 19 GL/year comes from storage, 6 GL/year comes from increased net recharge due to increased abstraction and 7 GL/year comes from drainage, mostly from the Blackwood River.

With respect to the stated objectives of the modelling project, SWAMS 2.0 can be used to:

a) Simulate groundwater flow within and between all hydrogeological units in the Southern Perth Basin that are within the active part of the groundwater flow system.

b) Establish a water budget for the aquifers and groundwater regions.

c) Under a range of scenarios, including the proposed Water Corporation abstraction of 45 GL/year from one or more possible borefield locations, predict the scale of changes in groundwater potentiometric heads/water levels within the hydrogeological units.

d) Evaluate likely changes in groundwater discharge to rivers (including the Blackwood River), streams and wetlands, and ocean environments.

e) Estimate the likely range and uncertainty of water level changes in areas affected by large-scale pumping to enable the assessment of the risk of water levels changes that may impact on GDEs.

f) Predict the general drawdown in water levels near other groundwater users, wetlands, rivers and streams in the project area, and provide seasonal variations in such reductions.

7.2 Recommendations

Further full scale calibration of the SWAMS model is not required unless significant changes are made to the mapping of the hydrogeological units, primarily in the Leederville aquifer on the Blackwood Plateau. Improvement on particular areas that are identified during the scenario runs can be achieved with minimal efforts. Additional calibration may be required when major boundary conditions with regard to offshore discharge are changed. This is likely to lead to improvement of the calibration.

Improvement in model calibration can be achieved with a comprehensive analysis of the observed head data in conjunction with modelling results. This may also need to be done with further interpretation of the hydrogeological data to improve the understanding of the aquifer system.

The dry cells of the model, although they do not impact on the performance of the model, do produce problems for steady state solution as well as on drawdown estimation. Further modelling may need to eliminate them by allowing thicker top layers or making them inactive, so effort can be concentrated on simulating the real aquifers.

The evapotranspiration package of the MODFLOW may be introduced on the Blackwood Plateau, but this needs to be done carefully so that it does not cause other issues. This may lead to better water balance estimation by eliminating the evapotranspiration component in the drain discharge. St John’s Brook and the Donnelly River are the two main areas which
can benefit most from introducing EVT.

There is a need to develop a better method to simulate the flooding effects, particularly on the coastal plains. This would provide a key improvement on the estimation of drawdown impact at water table due to future abstraction. The River package of MODFLOW may be used to simulate the drains, so that high river water table can recharge back to the aquifer. This may also be used to simulate some of the flooding effect on the costal plains. Ultimately, a coupled surface and groundwater water model appears to be needed to better define the flooding effect on predicted drawdowns at the water table, although it would require considerable effort to achieve a comprehensive surface and groundwater solution for a regional model.

Irrigation return water may also need to be simulated, particularly as the volume increases in the future. This will require further development of the current modelling system.

Lake Jasper may require the introduction of the Reservoir package of the MODFLOW to better simulate the lake water table which fluctuates regularly due to frequent flooding. These flooding conditions can be better modelled using the Reservoir package of the MODFLOW.

In summary, there are a number of areas where improvements can be made. However, it needs to be realised that the aquifer system under study is a very complex system. A newly introduced process does not automatically translate into improvement and it may need to be done on a trial and error basis so that it won’t cause new issues. The potential improvements, although significant in several areas, are not expected to fundamentally change the conclusions from the current modelling.
8 REFERENCES


DOE (Department of Environment, Western Australia), 2004. South-West Yarragadee aquifer: Peer review panel report on South-West Aquifer Modelling System (SWAMS V1.2.1). Environmental Resources Management Australia Ltd.


Mauger, G, 2003. A spatially and time distributed estimate of recharge to groundwater based on the WEC-C physical process water balance model. Geographic Information Analysis Pty Ltd.


9 APPENDICES (ENCLOSED IN ATTACHED CD)

Appendix A Land surface elevation (topography) and bottom elevation of the 8 model layers.

The bottom elevation of a layer also acts as the top elevation of the lower layer where applicable.

Appendix B Constant head areas for the 8 model layers (for layer 8 constant head in the north is not used as there is a major inactive area gap there)

Appendix C Drains mapped for the model

Appendix D Gross recharge for the calibrated model

Appendix E Area and parameters for the evapotranspiration simulation

Appendix F Faults mapped for layers 4-8 (shown layer 4 faults only, as the other layers are identical)

Appendix G Horizontal conductivity for the model layers

Appendix H Vertical conductivity for the model layers

Appendix I Specific yield for the model layers

Appendix J Specific storage for the model layers

Appendix K Calibration head error distribution by layer

Appendix L Monitoring bore data in spreadsheet

Appendix M Calibration hydrographs for Superficial aquifer

(Some of the hydrographs are lacking the observed data as a result of bore data later than the calibration period. These bores are actually included in calibration but not in modelled hydrographs. These hydrographs are retained for reference, the same applied for other aquifer hydrographs. See Appendix L for monitoring bore data)

Appendix N Calibration hydrographs for Leederville aquifer

Appendix O Calibration hydrographs for Yarragadee aquifer

Appendix P Calibration hydrographs for Mowen aquifer (aquitard)

Appendix Q Drawdowns for various scenarios and abstractions over 30 years
Appendix R  Drawdown for various scenarios and abstractions over 20 years
Appendix S  Drawdown for various scenarios and abstractions over 10 years
Appendix T  Proposed Water Corp eastern and western borefields