Development of Local Area Groundwater Models - Gnangara Mound

LAKE NOWEGERUP REPORT

- FINAL 2
- December 2009
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Final 2

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Prepared for

Department of Water, Western Australia

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1. Executive Summary

A local area groundwater model (LAM) has been developed for the Lake Nowergup region of the Gnangara Mound. The LAM is located within the PRAMS model domain and the LAM was developed in order to provide a more detailed representation of the local hydrogeological processes that influence groundwater in and around the location of the lake. While the LAM layer structure and hydrogeological properties were originally developed from the PRAMS model a number of refinements and modifications were made to the LAM during the course of the project. In particular the model grid and layer structures were modified in order to provide added detail in the Superficial Aquifer, to allow the use of the MODFLOW lake package to represent the lake and to simplify the deeper layer structure.

The model was calibrated in steady state and transient modes by matching model-predicted groundwater levels to those measured in wells located in the model domain. Satisfactory calibration was attained as illustrated by a normalised RMS error of 1.4% on the transient model. This statistic represents an excellent match between observed and predicted groundwater levels and suggests that the model can be used with confidence to predict future aquifer behaviour under a variety of future perturbations to applied groundwater stresses.

The calibrated model was run in predictive mode over a period of 23 years (2008 to 2031). A total of six predictive scenarios were considered each of which incorporated a different set of future land use assumptions. The results suggest that planned harvesting of pine plantations will have a significant beneficial effect on groundwater levels and will lead to a recovery in lake levels. Other perturbations to existing land uses will have a less significant impact on groundwater levels. Lake supplementation (pumping of groundwater into Lake Nowergup to maintain minimum water levels in the lake) is likely to be required for some time into the future, albeit at reduced rates.
2. Introduction

2.1. Context – The Gnangara Mound

The Gnangara Mound groundwater system is the largest water source for the Perth municipal water supply. The groundwater stored in the Gnangara system provides the people of Perth with approximately 60 percent of their domestic water needs. Large volumes of water from the Gnangara system are also used for agriculture, forestry and market gardens, and by local government authorities and private bore users. It is also an important water source for maintaining wetlands and native vegetation.

In recent times a combination of declining rainfall and increasing demand for water resources is placing increasing stresses on the Gnangara system. In response to these stresses a cross-government initiative known as the Gnangara Sustainability Strategy was developed. This initiative is aimed at ensuring the sustainable use of water for drinking and commercial purposes and to protect the environment.

The Department of Water is the lead agency and alliance member for the strategy and is currently in the process of developing sustainable water resource management strategies for the Perth Region. A key tool used in this process is the Perth Region Aquifer Modelling System (PRAMS). PRAMS is a regional groundwater model that has been used for:

- reviewing Section 46 environmental criteria;
- establishing allocation limits for groundwater management areas;
- assisting water licence application;
- evaluating the impact of land and water use on wetlands

However, the PRAMS model is designed as a regional groundwater model and its calibration and resolution are based on a 500 x 500 metre grid size. It cannot provide detailed information for local scale management objectives, which require smaller grid sizes, higher resolution models and more detailed targeted calibration.

2.2. This Project - Local Area Groundwater Models

Sinclair Knight Merz (SKM) has been engaged by The Department of Water to construct three local scale sub-regional models of the Gnangara Mound area. The aim of developing these Local Area Models (LAMs) is to provide quantitative tools to assess land and water use impacts on the environment and groundwater systems and to provide sufficient resolution (100 x 100 m grid) and reliability for assessing environmental, licensing and trading issues. Models have been developed for the following areas (Figure 1):
The models are aimed at assessing potential impacts of future land use changes and changes in water extraction regime. The emphasis of the investigations is on the shallow and near surface impacts with particular attention paid to the potential impacts on groundwater dependent ecosystems including vegetation and wetlands.

This report presents the Lake Nowergup Local Area Model. The report covers the hydrogeological conceptualisation on which the model is based and details the model development, calibration and use as a predictive water resource management tool.
Figure 1 Regional locality map of the LAM's
3. Previous Work

Detailed collations of previous work on the hydrogeology of the Perth Region, with specific reference to the Superficial Formations, has been completed by a number of authors. Allen (1975) provided an ‘Outline of the Hydrogeology of the Superficial Formations of the Swan Coastal Plain’. In this work he outlined the extent and nature of the large groundwater resources in the Gnangara Mound based on previous work and from the results of the drilling of 249 exploratory and production bores between 1962 and 1972.

Davidson (1995) presented a detailed summary of the state of the knowledge of ‘Hydrogeology and Groundwater Resources of the Perth Region, Western Australia’. His report presented a detailed summary and systematic investigation based on previous work and drilling in the region since 1961. The report ‘delineates the hydrogeological boundaries and quantifies the groundwater resources of the region’. In doing this Davidson estimated sustainable yields for both the unconfined (superficial) and confined aquifers of the Perth Region to be approximately 500 x 106 m³/yr (500 GL/yr). At the time rates of extraction were estimated at 300 GL/yr.

Recently, Davidson and Yu (2008), as part of the PRAMS reporting series, presented a discussion on the geology and hydrogeology of the Perth region. The report expanded and updated Davidson’s earlier work covering an increased area and presenting estimates of hydraulic properties for 23 geologic units. This study also presented a detailed account of historical groundwater use and trends along with an estimate of rainfall recharge to the superficial aquifer. The report provided the basis for the conceptual model for the PRAMS groundwater model.

Specifically relating to the nature of the shallow groundwater and interactions with lakes and wetlands was a series of investigations commissioned by the Department of Environment and Conservation. The studies were conducted in response to the acknowledgement of the serious degradation that had occurred to the wetlands of the Swan Coastal Plain since settlement and the need to develop strategies and management techniques for the protection of wetland biodiversity. As a part of this study Townley et al. (1993) presented a study into the ‘Interaction Between Lakes, Wetlands and Unconfined Aquifers’. This report had three specific objectives; the identification of groundwater capture zones, management of water levels and the development of effective parameters for groundwater models.

The following section, which presents the conceptual model for the Lake Nowergup Local Area Model is based primarily on the above stated reports.
4. Regional Hydrogeology

4.1. Physiography

The Gnangara Mound study area lies within the Swan coastal plain, a 23 to 34 km wide strip of land bounded by the Darling scarp in the east and the Indian Ocean to the west. The scarp itself rises steeply to an elevation greater than 200 m AHD. Between the Darling Scarp and the ocean there are a number of landforms each running roughly parallel to the coastline (Davidson, 1995).

In the east the foothills to the Darling and Dandaragan Plateau comprise of colluvial slopes also known as the Ridge Hill Shelf. Immediately west of the colluvial slopes lies a flat alluvial plain, known as the Pinjarra Plain. Further west again a series of undulating aeolian sand plains known as the Bassendean Dune System are present. This dune system is about 20km wide and is thought to have formed as coastal dunes during interglacial periods of high sea level. The final two systems are both aeolian dune systems which flank the Indian Ocean coastline. From east to west these are known as the Spearwood Dune System and Quindalup Dune System respectively.

4.2. Geology

The geology and hydrogeology of the Perth region was well described by Davidson (1995). The following is a summary of his work.

4.2.1. Geological Setting

The Perth Region is situated on the central portion of the eastern onshore margin of the Perth Basin and overlies the southern end of the Dandaragan Trough, a major structural subdivision within the basin. Seismic data indicates that the sedimentary succession in this part of the Perth Basin is about 12 000 m thick (Playford et al., 1976). Refer to Figure 2 for a structural geological map of Perth.

The Perth Basin was formed during periods of rifting and sagging along the continental margin of south-west Australia, as part of the breakup of Gondwana during the Early Cretaceous. The most significant structural feature resulting from the breakup is the Darling Fault, a high-angle, westerly-dipping fault line which separates the Perth Basin from the crystalline rocks of the Yilgarn Craton.

Prior to the breakup, continental sedimentation occurred through the Late Jurassic and continued into the Cretaceous. These Cretaceous sediments are mostly concealed beneath a thick succession of Late Tertiary – Quaternary sediments ranging from Tertiary marine carbonate deposits to Quaternary shoreline and coastal-dune deposits.
Figure 2 Structural geology of the Perth Region (Davidson & Yu, 2005)
4.2.2. Stratigraphic Summary

The stratigraphic sequence for the Perth Basin is provided in Table 4-1. This table summarises the stratigraphy of the entire sedimentary basin believed to be in the order of 12,000 m thick. Given this study is specifically aimed at lake and wetland interactions with the shallow groundwater systems, the following stratigraphic summary will focus on the Quaternary sequence.

A map of the superficial geology of the study area is provided in Figure 3.

- **Figure 3 Surface geology of the Gnangara Mound**

Late Tertiary – Quaternary

Rockingham Sand

The Rockingham Sand consists predominantly of a silty-sand (medium to coarse) and is of shallow marine origin. It is only known to exist on-shore in the Rockingham area (south of Perth) and therefore does not fall within this study area.
Ascot Formation

The Ascot Formation forms the base of the sedimentary sequence commonly known as the ‘Superficial Formations’. It consists of calcarenite with thinly interbedded fossiliferous sand. It has a maximum thickness of 20 to 30 m in the Perth area and is widespread at the base of the superficial formation.

Yoganup Formation

The Yoganup Formation consists of poorly sorted sand, gravels and pebbles with subordinate clay. Its extent is sporadic along the eastern margin of the Perth Basin. The formation has a maximum thickness of about 10 m and was extensively eroded prior to the deposition of the Guildford Clay.

Guildford Clay

The Guildford Clay consists predominantly of silty (and sometimes sandy) clay of fluvial origin. The unit is up to 35 m thick but commonly contains lenses of shelly sand at its base. Its extent is mainly restricted to areas in which it outcrops.

Gnangara Sand

The Gnangara Sand extends over most the central Perth region and consists of poorly sorted, fine to very-coarse quartz sand. The unit is predominantly of fluvial origin with some sediments suggesting estuarine deposition. The unit has a maximum known thickness of about 30 m.

Bassendean Sand

Like the Gnangara Sand the Bassendean Sand is present over most of the central Perth region and consists of fine to coarse quartz sand. The unit varies in thickness up to a maximum of about 80 m and can be characterised by an upward fining progression of grain size. Depositional environment is thought to be shallow-marine and aeolian dunes.

Tamala Limestone

The Tamala Limestone is present along the coastal strip of the Perth Region. It contains various proportions of quartz sand, shelly fragments, minor clayey lenses, and is constituted by unconsolidated sands in some places. At the base of the sequence, glauconite and phosphatic nodules are often present. The Tamala Limestone Formation varies in thickness along the coast with a maximum known thickness of 110m.
Becher Sand

The Becher Sand formation occurs along the coastal margin to the south-west of Perth. Therefore it is not of specific interest to this study.

Safety Bay Sand

The Safety Bay Sand occurs along the coastal margin as a surficial dune system. It is composed of calcareous quartz-sand (fine to medium grained) with shell fragments. It unconformably overlies the Tamala Limestone and Becher Sand.
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<td>Carnac Member</td>
<td>Kpc</td>
<td>Shale and siltstone</td>
<td>Local confining bed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Otorowiri Member</td>
<td>Kpo</td>
<td>Shale and siltstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yarragadee Formation</td>
<td>Jy &gt;2000</td>
<td>Sandstone, siltstone and shale</td>
<td>Yarragadee aquifer</td>
</tr>
<tr>
<td></td>
<td>Jurassic</td>
<td>Cattamarra Coal Measures</td>
<td>Jc &gt;500</td>
<td>Sandstone, siltstone and shale</td>
<td></td>
</tr>
</tbody>
</table>
4.3. Hydrogeology of the Gnangara Mound

Underlying the Perth region groundwater resources can be divided into seven distinct aquifers, including one only recently defined by Davidson & Yu (2008). The relationship of these aquifers with their associated geological formations has previously been presented in Table 4-1. This study is only concerned with the unconfined aquifers and therefore subsequent deeper aquifers will not be discussed here.

The Superficial Aquifer itself is a complex multilayered aquifer. It is bounded in the east by the Gingin Scarp and Darling Scarp and in the west by the Indian Ocean. In an east to west direction the aquifer typically grades from being predominantly clayey, near the Darling Fault, to sandy in the central plains through to sand and limestone on the coastal belt. Or to use formation nomenclature, the Guildford Clay in the east, Bassendean Sand and Gnangara Sand in the central plains and the Tamala Limestone and Safety Bay Sand on the coastal strip. Characteristics of formations are provided in Table 4-2.

Over most of the area the Superficial Aquifer unconformably overlies Cretaceous sediments and has a maximum saturated thickness of about 70 m and an average thickness of about 50 m. A summary of specific aquifer details for the Lake Nowergup Area is presented in Section 5.1.3.

<table>
<thead>
<tr>
<th>Age</th>
<th>Aquifer</th>
<th>Stratigraphy</th>
<th>Symbol</th>
<th>Max Thickness (m)</th>
<th>Lithology</th>
<th>Horizontal Hydraulic Conductivity (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Superficial aquifer</td>
<td>Safety Bay Sand</td>
<td>Qs</td>
<td>24</td>
<td>Sand and shelly fragments</td>
<td>15</td>
</tr>
<tr>
<td>- Late Tertiary</td>
<td></td>
<td>Becher Sand</td>
<td>Qc</td>
<td>20</td>
<td>Sand, silt, clay and shell fragments</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tamala Limestone</td>
<td>Qt</td>
<td>110</td>
<td>Sand, limestone, minor clay</td>
<td>100-1000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bassendean sand</td>
<td>Qd</td>
<td>80</td>
<td>Sand and subordinate silt and clay</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gnangara Sand</td>
<td>Qn</td>
<td>30</td>
<td>Sand, gravel and subordinate silt and clay</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Local confining bed</td>
<td>Guildford Clay</td>
<td>Qg</td>
<td>35</td>
<td>Clay with subordinate sand and gravel</td>
<td>0.1-1</td>
</tr>
<tr>
<td></td>
<td>Superficial aquifer</td>
<td>Yoganup Formation</td>
<td>Ty</td>
<td>10</td>
<td>Sand, silt, clay and pebbles</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ascot Formation</td>
<td>Ta</td>
<td>25</td>
<td>Limestone, sand, shells and clay</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Rockingham aquifer</td>
<td>Rockingham Sand</td>
<td>Tr</td>
<td>110</td>
<td>Sand, silt and subordinate clay</td>
<td>20</td>
</tr>
<tr>
<td>Early Tertiary</td>
<td>Confining bed</td>
<td>Kings Park Formation</td>
<td>Tk</td>
<td>530</td>
<td>Shale, calcareous and glauconitic siltstone, minor sand</td>
<td>0.1</td>
</tr>
</tbody>
</table>
### Age Aquifer Stratigraphy Symbol Max Thickness (m) Lithology Horizontal Hydraulic Conductivity (m/day)

<table>
<thead>
<tr>
<th>Age</th>
<th>Aquifer</th>
<th>Stratigraphy</th>
<th>Symbol</th>
<th>Thickness</th>
<th>Lithology</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cretaceous</td>
<td>Local Confining Bed</td>
<td>Lancelin Formation</td>
<td>Kcl</td>
<td>120</td>
<td>Mudstone (marl)</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Mirrabooka Aquifer</td>
<td>Poison Hill Greensand</td>
<td>Kcp</td>
<td>90</td>
<td>Sand, silty, clayey, glauconitic</td>
<td>4-5</td>
</tr>
<tr>
<td></td>
<td>Local Confining Bed</td>
<td>Gingin Chalk</td>
<td>Kcg</td>
<td>40</td>
<td>Chalk, sandy</td>
<td>0.001-0.1</td>
</tr>
<tr>
<td></td>
<td>Mirrabooka Aquifer</td>
<td>Molecap Greensand</td>
<td>Kcm</td>
<td>80</td>
<td>Sand, clayey and glauconitic</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Osborne Formation</td>
<td>Kco</td>
<td>180</td>
<td>Sandstone, siltstone and shale</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mirrabooka Aquifer</td>
<td>Mirabooka Member</td>
<td>Kcom</td>
<td>160</td>
<td>Sandstone, siltstone and shale</td>
<td>4-5</td>
</tr>
<tr>
<td></td>
<td>Confining bed</td>
<td>Kardinya Shale Member</td>
<td>Kcock</td>
<td>140</td>
<td>Shale, siltstone, minor sandstone</td>
<td>$10^{-4}$ – $10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>Leederville Aquifer</td>
<td>Henley Sandstone Member</td>
<td>Kcoh</td>
<td>80</td>
<td>Sand, silty, clayey, glauconitic</td>
<td>2-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leederville Formation</td>
<td>Kwl</td>
<td>600</td>
<td>Sandstone, siltstone and shale</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pinjar Member</td>
<td>Kwlw</td>
<td>150</td>
<td>Sandstone, siltstone and shale</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wanneroo Member</td>
<td>Kwlw</td>
<td>450</td>
<td>Sandstone, siltstone and shale</td>
<td>1-10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mariginiup Member</td>
<td>Kwlw</td>
<td>250</td>
<td>Sandstone, siltstone and shale</td>
<td>0.1-1</td>
</tr>
<tr>
<td></td>
<td>Confining bed</td>
<td>South Perth Shale</td>
<td>Kws</td>
<td>300</td>
<td>Shale, siltstone, minor sandstone</td>
<td>$10^{-4}$ – $10^{-6}$</td>
</tr>
</tbody>
</table>

### 4.4. Regional Climate & Recharge Mechanisms

The climate of the Perth region is described as Mediterranean, with hot, dry summers and mild, wetter winters. Mean temperatures for each month are presented in Figure 4 depicting the average seasonal temperature variation for Perth.
Rainfall

Mean annual rainfall for Perth as recorded at the Bureau of Meteorology’s Perth Regional Office gauge is 867 mm/yr. However the region sees rainfall vary from 590 mm in the northern coastal area to 1,200 mm/yr on the Darling Plateau, south east of Perth (Davidson & Yu, 2008). Approximately 90% of rainfall falls between April and October, with the summer months characteristically hot and dry (Figure 5). A well documented trend in Perth’s climate has been the decline in rainfall observed over approximately the past three decades (Figure 6). Average annual rainfall at Perth for the decade from 1997 to 2006 inclusive was approximately 730 mm/yr, down 16% from the long term average.
Figure 5 Mean monthly rainfall for Perth (data sourced from Bureau of Meteorology, 1876-1992 – Perth Regional Office, 1993-2008 Perth Metro station no. 009225)

Figure 6 Annual rainfall for Perth from 1880 to 2006 (source: Bureau of Meteorology). Note. Data is missing for 1992 when the gauge was moved from the Perth Regional Office to the current Perth Metro site.
Rainfall Infiltration Recharge

The dominant recharge mechanism for the Superficial Aquifer is rainfall infiltration however recharge rates vary considerably depending primarily on landuse and geology.

A groundwater mound developed at Gnangara because the rate of vertical rainfall infiltration is greater than the capacity of the aquifer to transmit the water laterally to the aquifer discharge sites. Vertical infiltration rates have been enhanced over time through the clearing of bushland and urbanisation. However, due to the establishment of pine plantations and the reduction in rainfall observed over the past three decades net rainfall recharge to the aquifer has decreased significantly.

The strong seasonality of the rainfall (90% falling between April and October) also leads to a strong seasonal signature of recharge to the Superficial Aquifer. This combined with the limited number of drainage channels and discharge boundaries leads to a large seasonal variability in observed groundwater levels in bore hydrographs.

Net rainfall recharge to the Superficial Aquifer is considered to be between 10 and 40% of annual rainfall, with an average of about 20% (Davidson and Yu, 2008). However, Davidson (1995, 2006) summarised the work of others relating to rainfall recharge over specific landuses. The following Table 4-3 is a summary of this work and other available publications.

- **Table 4-3 : Recharge rates according to landuses**

<table>
<thead>
<tr>
<th>Description</th>
<th>Comment</th>
<th>% recharge applied</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banksia – high density</td>
<td>Leaf area index &gt; 1.2</td>
<td>10% - 18%</td>
<td>Silberstein &amp; al. (2004)</td>
</tr>
<tr>
<td>Banksia – low density</td>
<td>Leaf area index &lt; 0.70</td>
<td>18% - 38%</td>
<td>Silberstein &amp; al. (2004)</td>
</tr>
<tr>
<td>Pasture</td>
<td>Leaf area index = 3.0</td>
<td>45%</td>
<td>Silberstein &amp; al. (2004)</td>
</tr>
<tr>
<td>Market Garden</td>
<td>0.40 rainfall recharge</td>
<td>40%</td>
<td>Davidson &amp; Yu (2006)</td>
</tr>
<tr>
<td>Parkland</td>
<td>0.40 rainfall recharge</td>
<td>40%</td>
<td>Davidson &amp; Yu (2006)</td>
</tr>
<tr>
<td>Pine – high density</td>
<td>Leaf area index 2.5–3.5</td>
<td>12%</td>
<td>Silberstein &amp; al. (2004)</td>
</tr>
<tr>
<td>Banksia – medium density</td>
<td>Leaf area index 0.70 to 1.2</td>
<td>24%</td>
<td>Silberstein &amp; al. (2004)</td>
</tr>
<tr>
<td>Pine – low density</td>
<td>Leaf area index 0.5–1.0</td>
<td>35%</td>
<td>Silberstein &amp; al. (2004)</td>
</tr>
<tr>
<td>Urban</td>
<td>0.625 gross recharge, 0.05 EVT</td>
<td>21%</td>
<td></td>
</tr>
</tbody>
</table>
### Wetlands

<table>
<thead>
<tr>
<th>Wetlands</th>
<th>1.2 times monthly rainfall</th>
<th>120% of monthly rainfall</th>
<th>Davidson &amp; Yu (2006)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial/Industrial</td>
<td>Large sealed area with drainage directed to sumps 0.70 gross recharge, 0.05 EVT</td>
<td>70%</td>
<td>Davidson &amp; Yu (2006)</td>
</tr>
</tbody>
</table>

**Irrigation**

There is a large volume of groundwater extracted in the local area for irrigation purposes. It is estimated that approximately 20% of this volume is returned to the Superficial Aquifer as recharge across irrigated land. The areas of irrigated land are particularly prevalent in the Landsat Imagery provided in Appendix A.

**Additional Recharge Mechanisms**

Recharge and discharge from lakes will be discussed under the heading ‘Groundwater/Surface Water Interactions’.

### 4.5. Discharge Mechanisms

There are a number of groundwater discharge mechanisms however there is little information on the relative importance of each, particularly on a local scale.

**Evaporation**

Average pan evaporation from the Bureau of Meteorology Perth Regional Office is approximately 1700 mm/yr. However, there is a large variation throughout the year with monthly pan evaporation in the summer months in excess of 200 mm/month and under 100 mm/month from May to September (Figure 7). The time series of annual totals of pan evaporation (Figure 8) indicates that there is only minor long-term variation in evaporation.
Evapotranspiration from wetlands and areas of shallow groundwater is undoubtedly an important discharge mechanism. Evapotranspiration is likely to be at its highest in wetland areas where the
watertable is shallow, often exposed to the atmosphere and available for uptake by shallow rooting vegetation. Transpiration rates are also thought to be significant beneath areas of developing and mature plantations.

Coastal Discharge

Groundwater from the mound eventually discharges to the ocean above the saltwater/freshwater interface. The elevation of the watertable near the coast is dictated to a large extent by the ocean level.

River discharge

On the Eastern side of the Gnangara Mound, the groundwater will eventually discharge in the Swan River and its major tributaries, for instance Ellen Brook which constitutes the eastern limit of the Lexia wetlands model.

Groundwater Extraction

In recent years groundwater extraction has become an important groundwater discharge mechanism. The Gnangara Mound in general has been used extensively throughout the last three decades as a source of water for the Perth Metropolitan area. Groundwater extraction for municipal water supply has increased steadily as continued drought conditions are experienced and it is understood that substantial levels of drawdown in all aquifers in the area are partially attributable to groundwater extraction. In addition to the public water supply borefields there is a multitude of shallow stock and domestic wells that service the water needs of the local communities and significant groundwater extractions for irrigation purposes.
5. Conceptual Model

5.1.1. Overview

Lake Nowergup is located along the Swan coastal plain approximately halfway between Gingin Brook and the Swan River (central Gnangara Mound area) and immediately north of the Greater Perth residential precinct (refer Figure 9). The detailed hydrogeological mechanisms of the lake are not well understood as the lake has never been the subject of a detailed investigation.

Lake Nowergup is classified as a Conservation Category Wetland as it provides habitat for water birds and turtles. In recent years, in order to maintain lake water levels for habitat, the lake has been supplemented with approximately 1.4 GL of water per year, pumped from the Leederville aquifer.

The following is a summary of the current understanding of the lake and surrounds.

- Figure 9 Satellite imagery of the Lake Nowergup LAM

5.1.2. Physiography

Lake Nowergup is offset from the coastline by approximately 5 kilometres. Immediately south-west (down hydraulic gradient) of lake there is a buffer zone of remnant bushland separating the lake from the coastal dune system which has now been heavily urbanised as Perth expands north.
along the coastal strip. Immediately north and east of the lake much of the bushland has been cleared for agriculture (irrigated and dryland). Figure 9, shown on the previous page, displays satellite imagery which details the landuse surrounding the lake.

The surrounds of Lake Nowergup are topographically relatively flat. The lake itself is housed within a small karstic depression in the landscape and dune/swale systems occur between the lake and the coast. East of the lake the landscape is relatively flat until the foothills of the Darling Scarp are reached, significantly up-gradient from the lake.

5.1.3. Lake Nowergup Hydrogeology & Hydraulic Parameters

Where Section 4 provided a summary of the regional setting, this section summarises the local setting in a hydrogeological context relevant to the Lake Nowergup LAM. Contrary to standard stratigraphic descriptions, which are discussed from oldest to youngest, the following aquifers relevant to the Lake Nowergup LAM are discussed from shallowest to deepest.

The Superficial Formation

The Tamala Limestone dominates the geology of the surrounds of Lake Nowergup. This is typically a calcareous eolianite containing various proportions of fine to medium grained shelly fragments and quartz sand with minor clay lenses. Hydrogeologically, the limestone is characterised by high, but highly variable, permeability. This is a result of the numerous solution channels and cavities that occur within the limestone, and in some cases karst structures, which can produce horizontal hydraulic conductivities in the order of 100 – 1000 m/day. However, on a regional scale the permeability of the Tamala Limestone is influenced by low conductivity sandy beds and more representative conductivity of 50 m/day is thought to be appropriate (Davidson & Yu, 2008).

In the Lake Nowergup area the Tamala Limestone has a thickness of 40 to 100 m.

Along the coastal fringe the surficial geology comprises the dune systems of the Safety Bay Sand. This is typically less than 24 m thick and overlies the Tamala Limestone.

Approximately in line with Lake Pinjar is the contact between the Tamala Limestone and the Bassendean Sand. The two units are in direct hydraulic connection although both units are characterised by highly variable connectivity. However, average horizontal conductivities in the sand are approximately 15 m/day. This is typically lower than the limestone and consequently it is common to see a sharp hydraulic gradient at the contact.
Osborne Formation (Localised Confining Bed)

Immediately underlying the Tamala Limestone, over most of the Nowergup area, is the Leederville Formation, comprising the Wanneroo Member and the Marginiup Member. However there is a small exception to this near the coastal margins where the Kardinya Shale Member (Osborne Formation) occurs beneath the Superficial Formation.

The Kardinya Shale Member, where present, consists of moderately to tightly consolidated, interbedded siltstone and sandstone and is considered to be a localised confining unit. It has a typical conductivity of $10^{-4} – 10^{-6}$ m/day and a maximum thickness near the coast in excess of 100m.

Where the Kardinya Shale is present, it induces a degree of local confinement in the underlying Leederville. This is supported by hydrographs of nested bores west of Lake Nowergup as shown in Section 5.1.4.

Leederville Formation

The Leederville Formation, which is extensive under the Nowergup area, consists predominantly of discontinuous, interbedded sandstones, siltstones and shales and is mapped to be approximately 200m thick. The Leederville is typically considered to be a major confined aquifer, however lithological logs in the Nowergup area suggest there is no extensive confining unit above the Leederville across most of Nowergup model area.

Hydraulic conductivities in the Leederville can vary significantly depending on the nature of the interbedding and the continuity of lenses. The average hydraulic conductivity north of Swan River is typically between 1 – 10 m/day with an average of 2 m/day (Davidson & Yu, 2008). An average storage co-efficient of $1x10^{-4}$ is believed to be appropriate for the Leederville Formation (Davidson & Yu, 2008)

South Perth Shale (Aquitard)

The South Perth Shale is extensive underlying the Leederville Formation in the Nowergup area and forms a thick (30-50m) confining bed. It consists mainly of thinly interbedded, grey to black siltstone and shale with minor sandy and calcareous beds. Leakage across the South Perth Shale between underlying aquifers and the Leederville (upward or downward) is considered to be negligible. This is supported by a nested site near Lake Nowergup monitoring both the Superficial Formation and the confined Yarragadee Aquifer (refer Figure 10). This site highlights the hydraulic separation of the two aquifers by the South Perth Shale.
Given the confining nature of the South Perth Shale subsequent deeper aquifers are not discussed here.

- **Figure 10** A nested bore site near Lake Nowergup highlighting the hydraulic separation of the Superficial Formation and the Yarragadee Aquifer

5.1.4. **Lake Nowergup Groundwater Levels**

Figure 11 is a map of all available monitoring sites within the Lake Nowergup LAM area and provides a reference for the discussion on water levels below.
Superficial Aquifer

The Superficial Aquifer is well monitored in the greater area surrounding Lake Nowergup. Up-gradient of the lake the general trend is typical of the Gnangara Mound with consistently declining levels since the 1980’s (refer Figure 12).

Down-gradient of the lake, on the coastal dunes, similar trends are observed (refer Figure 13). The hydrographs shown in Figure 13 are those with extended records. In addition to these there are numerous bores that have been monitoring this coastal dunes area since approximately 1989-90. Their recent trends are consistent with those displayed in Figure 13.
Figure 12 Superficial Aquifer hydrographs in the area up-gradient of Lake Nowergup

Figure 13 Superficial Aquifer hydrographs along the coastal dunes
Leederville Aquifer

Only three bores have been identified as having continuous monitoring in the Leederville Aquifer in the vicinity of Lake Nowergup (refer Figure 13 and Figure 14). Generally these sites display very similar trends to the Superficial Aquifer bores suggesting there is a strong hydraulic connection between the two aquifers. However the two nested sites shown in Figure 15 suggest the degree of connection is variable across the area.

Bores 5581 (LN18-89) and 5555 (LN19-89), are both located immediately up-gradient of Lake Nowergup and display almost identical water levels. Down-gradient of the lake bores 5588 (LN37-89) and 5570 (LN3-89) show a 2 to 3 m hydraulic separation. Although that has decreased recently suggesting depressurisation of the Leederville is occurring.

Importantly, this hydraulic separation down-gradient of the lake, supports the presence of the confining Kardinya Shale Member along the coastal margins.
- Figure 14 Bore hydrograph from the Leederville Formation Aquifer near Lake Nowergup

- Figure 15 Bore hydrographs from two nested sites near Lake Nowergup
5.1.5. **Surface Water Levels in Lake Nowergup**

Lake water levels have been continuously monitored since 1973 as displayed in Figure 16. This figure also displays the periods during which groundwater has been pumped into the lake for the purpose of maintaining water levels and preserving biodiversity and habitat (note that intermittent pumping has occurred between January 2004 and 2008.

The artificial maintenance of the lake water levels has had an obvious affect on surrounding groundwater levels as shown in Figure 17. Here it can be seen that since the regular pumping began in 2004, groundwater levels near the lake also appear to have been maintained at a similar level. Prior to 2004, there were steady, continuous declines in groundwater levels in the Superficial Aquifer.
Figure 16. Lake Nowergup water levels from gauge 14588 (Lake Nowergup 8756)

Figure 17. Comparison of Lake Nowergup water levels and nearby groundwater levels
5.1.6. Groundwater Flow

Regional groundwater flow in the area is from east to west from the central Gnangara Mound toward the coast. Historically, two through-flow lakes, including Lake Nowergup, intersected the watertable on the coastal side of the mound. Townley et al. (1993) in an investigation of capture and release zones for these lakes found that water from Lake Pinjar (approximately 5 km east of Lake Nowergup) would recharge the Superficial Aquifer and travel down-gradient and discharge into Lake Nowergup (Figure 18). However, in recent times, Lake Pinjar has been dry and the current conceptual model is that an unsaturated zone exists beneath Lake Pinjar.

Figure 19 presents a recent watertable contour map for the Lake Nowergup LAM. A distinguishable feature of the potentiometry is in the area immediately to the west of Lake Nowergup where the water table drops 5-8 m AHD in the first ~500 m from the lake, creating a very steep hydraulic gradient before flattening off again toward the coastline. This is typical of the contact between the Bassendean Sand and the Tamala Limestone that roughly coincides with the north–south trending linear chain of lakes (including Lake Nowergup). The steep hydraulic gradients along this contact are due to the high hydraulic conductivities of the Tamala Limestone to the west, which facilitates groundwater flow in this direction, resulting in a draining effect of the groundwater from the east (Davidson & Yu, 2008).

- Figure 18 Cross-section through Lake Neerabup and Lake Pinjar (source: Townley et al. 1993). A similar conceptual model has been applied to Lake Nowergup.
Figure 19 Watertable contours for the Lake Nowergup LAM (based on recent monitoring data from Aug 2008).

5.1.7. Local Climate – Lake Nowergup Rainfall

Given its close proximity to Perth, the local climate of Lake Nowergup area is very similar to that previously presented in the regional perspective in Section 4.4. The closest rain gauge to Lake Nowergup with a continuous record is the Wanneroo Gauge #9105 located approximately 6km southeast of Lake Nowergup. This gauge has been monitored since 1905 however there is a large gap in the record between 1930 and 1963. An annual time series chart of the rainfall is presented in Figure 20.
5.1.8. Landuse & Recharge Mechanisms

The dominant recharge mechanism is rainfall infiltration as discussed in a regional perspective in Section 4.4.

A series of landuse maps are provided in Appendix A. In the Nowergup area these highlight the large areas devoted to urban expansion and plantation forestry. These both have a large impact on rainfall infiltration rates as presented in Section 4.4.

5.1.9. Discharge Mechanisms

Groundwater exits the Lake Nowergup study area through lateral flow across the western study boundary towards the coast. Other groundwater discharge mechanisms present in the study area include evapotranspiration in areas of shallow water table, evaporation off the lake surface leading to time varying groundwater discharge into the lake and groundwater extraction from wells.

5.1.10. Groundwater-Surface Water Interactions

It has already been noted that up-gradient (east) of Lake Nowergup, there is another throughflow lake (Lake Pinjar) from which water flows to Lake Nowergup via the Superficial Aquifer. However, at the time of writing it is understood that the water resources of Lake Pinjar have been severely depleted as a result of the declining groundwater levels of the Gnangara Mound.
Consequently the current conceptual model suggests that there is likely to be an unsaturated zone beneath Lake Pinjar and hence it is not directly connected to Lake Nowergup.

Lake Nowergup is also considered a throughflow lake, i.e. receives groundwater on the up-gradient side and leaks water to the groundwater system on down-gradient side. It is also one of the deeper lakes along the coastal plain. Consequently the degree of connection between the lake and the groundwater system is believed to be very good.

5.1.11. Lake Nowergup Groundwater Abstractions

For the purposes of groundwater modelling, abstractions are divided into those for public (municipal water supply) and private (irrigation and stock and domestic bores) use. Generally the public abstraction bores are high volume bores used for urban and commercial water supply. The private bores are generally related to private households and irrigators.

Public Abstractions

In the Lake Nowergup LAM public extractions have increased significantly since beginning in the late 1970’s. Figure 21 and Figure 22 present the volume and location respectively of public abstractions in the area. It is clear from this data that the majority of abstractions are from the Superficial and Leederville Aquifers with minor volumes extracted from the Yarragadee Aquifer. The conceptual model for this area is that a confining unit exists at the base of the Leederville and therefore abstractions from the Yarragadee Aquifer will not impact on surface water features such as Lake Nowergup.

Private Allocations

The volume of abstractions for private use has increased significantly over the past 20-25 years. Figure 21 and Figure 23 show the total allocated volume and location of private bores respectively. For the lack of better information it is assumed that all private abstractions occur from the unconfined sedimentary aquifers of the Superficial and Leederville Formations and therefore may be impacting on surface water features.

The Lake Supplementation Bore is also licensed as a private abstraction bore. This bore is located immediately west of Lake Nowergup and pumps water from the Leederville aquifer. Prior to 2004 there were no consistent records of volumes pumped into Lake Nowergup for supplementation purposes. However, the Water Authority of Western Australia, 1992 reports that in the early 1990’s artificial maintenance was triggered when the lake level fell to about 16.3 mAH (the EPA minimum level criteria) and then pumping continued until the lake level exceeded 16.5 mAH (the EPA preferred minimum level). Further details of lake supplementation pumping can be found in Section 6.1.3.
Figure 21 Lake Nowergup LAM Public Allocation Volumes

Figure 22 Locality map of public abstraction wells
Figure 23 Lake Nowergup LAM Private Allocation Volumes

Figure 24 Lake Nowergup LAM Private Abstraction Sites
6. Groundwater Model Structure

The Lake Nowergup Local Area Model (LAM) has been developed on a Visual Modflow platform.

6.1.1. Model Domain and Boundaries

The model area was initially specified to be constructed covering a 10 x 10 km area centred on Lake Nowergup. This was expanded somewhat to incorporate a number of important features including:

- The western boundary has been extended to the coastline to enable the use of a Constant Head Boundary (CHB) to represent the influence of the ocean on groundwater levels.
- The eastern boundary has been extended east beyond Lake Pinjar to incorporate both the lake and a line of urban supply abstraction wells (production wells P10 to P90 amongst others owned and operated by the Water Corporation). Exclusion of these wells would have rendered the model incapable of adapting to future changes in the pumping regime. The eastern boundary has also been aligned approximately parallel to the 51m AHD watertable potentiometric contour to simplify the use of a General Head Boundary (GHB) on this upgradient boundary (refer Figure 25). The conductance of the GHB was set at 1000 m$^2$/day.
- The northern and southern boundaries are both aligned approximately perpendicular to the watertable potentiometric contours allowing these boundaries to be defined as No Flow Boundaries.
- The southern boundary has also been placed south of a cluster of shallow abstraction wells in the urban coastal area.

The model grid cell size is set at 100 x 100 m with refinement to 50 x 50 m in the immediate vicinity of Lake Nowergup. A map of the model grid and boundaries is provided in Figure 26.
Figure 25. Watertable contours across the Nowergup model domain
Figure 26 Lake Nowergup calibrated model grid and boundaries (the green dots are calibration bores)
6.1.2. Lake Nowergup Hydrogeology & Hydraulic Parameters

The model layers for the Lake Nowergup LAM are based on the hydrogeological conceptualisation presented in Section 5. The layer structure is described below. Seven layers are used in total, five for the superficial, one for the underlying aquitard and one for the Leederville. This structure provides for added refinement and detail in the superficial aquifer which is the focus for the current study. At the same time the model structure provides an opportunity for drawdown generated from pumping in the deeper Leederville aquifer to be expressed in that shallow aquifer. Hydraulic parameters for each layer are based on those presented in the hydrogeological conceptualisation with refinements made during the calibration process to achieve a match with observed groundwater behaviour.

A summary of the layering structure is provided in Table 6-1 and a graphical representation is provided in Figure 27. Layer thickness ranges are provided in Table 6-2.

The final hydraulic conductivity arrangements are presented in Figure 29 to Figure 31 and all hydraulic properties including storage are provided in Table 6-3.

Base of Model – Leederville Formation

In the Lake Nowergup LAM, the base of the model is represented by the bottom of the Leederville Formation. Below this is the extensive South Perth Shale, which is conceptualised as a thick confining unit through which vertical leakage is expected to be negligible. A review of geological well logs did not find any confining unit above the South Perth Shale that that is sufficiently extensive to cover the model area, i.e. it is conceptualised that the Superficial Aquifer and Leederville Aquifer are in direct hydraulic connection across much of the model area.

The Leederville Formation is not the focus of the LAM study and therefore is represented by a single model layer. The top and bottom surface of the Leederville have been obtained directly from the PRAMS model layering (Davidson & Yu, 2008). Note that the PRAMS model has the Leederville represented as three separate layers. These layers have been merged in the Nowergup model to avoid unnecessary complexity.

Kardinya Shale Member

Overlying the Leederville Formation, along the coastal margins is the Kardinya Shale Member. Where present this layer provides a degree of confinement to the Leederville Formation. Where the Kardinya Shale is absent, this layer has been given a nominal thickness (1 m) and hydraulic parameters between those of the underlying Leederville Formation and overlying Superficial Formation. The top and bottom surface of the Kardinya Shale Member have been obtained directly from the PRAMS model layering (Davidson & Yu, 2008).
Superficial Formations

The Superficial Formations are modelled as five individual layers. The existing PRAMS model (Davidson & Yu, 2008) has the Superficial Formations represented by three layers, the bases of which have been used in the Nowergup model. Additional refinement in the Lake Nowergup LAM has been achieved by splitting the PRAMS Layer 1 into three layers as follows.

- The top-most layer was used to facilitate the implementation of the MODFLOW LAKE package. Subsequently it was set at a nominal thickness except where the lake is present. Layer 1 becomes dry (and therefore inactive) across almost the entire model domain.

- The remaining portion of PRAMS Layer 1 was initially divided approximately in half. However through the calibration process it was found that this caused significant areas of the newly formed layer 2 to become dry which caused model instability. Subsequently the base of layer 2 was lowered to improve model stability.

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>PRAMS Layers</th>
<th>Nowergup LAM layers</th>
<th>Indicative Hydraulic Conductivity (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety Bay Sand</td>
<td>1,3</td>
<td>1-5**</td>
<td>15</td>
</tr>
<tr>
<td>Becher Sand</td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Tamala Limestone</td>
<td></td>
<td></td>
<td>50 – 1000</td>
</tr>
<tr>
<td>Bassendean Sand</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Gnangara Sand</td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Guildford Clay</td>
<td></td>
<td></td>
<td>0.1 – 1</td>
</tr>
<tr>
<td>Yoganup Formation</td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Ascot Formation</td>
<td></td>
<td></td>
<td>8</td>
</tr>
</tbody>
</table>

**Note that layer 1 is set at a nominal thickness except where Lake Nowergup is present. This was done to facilitate the use of the Modflow LAKE package.
Figure 27 3D image of the geological structure of the Nowergup LAM

Table 6-2. Summary of Lake Nowergup LAM layer thickness

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1m – Nominal thickness except under Lake Nowergup where thickness is increased to</td>
</tr>
<tr>
<td></td>
<td>accommodate the lake package</td>
</tr>
<tr>
<td>2</td>
<td>1 - 40</td>
</tr>
<tr>
<td>3</td>
<td>1 - 10</td>
</tr>
<tr>
<td>4</td>
<td>7 - 17</td>
</tr>
<tr>
<td>5</td>
<td>3 - 35</td>
</tr>
<tr>
<td>6</td>
<td>5 - 130 (&lt;10 where Kardinya Shale is absent)</td>
</tr>
<tr>
<td>7</td>
<td>70 - 250</td>
</tr>
</tbody>
</table>
Figure 28. Cross-section through Nowergup Lake – colouring represents hydraulic conductivity zones which are presented in Table 6-3, Figure 29, Figure 30 and Figure 31.
Figure 29. Hydraulic conductivity distribution for the Superficial Aquifer (Layers 1 through 5)

Note: In all zones $K_y = K_x$ and $K_z$ is one tenth of $K_x$ (except for Zone 14 where $K_x = 0.0015$ and $K_z = 0.015$)
Figure 30. Hydraulic conductivity distribution for the Kardinya Shale Member (Layer 6)

Zone 7
- $K_x = 2 \text{ m/day}$
- $K_z = 0.0015 \text{ m/day}$

Zone 8
- $K_x = 8 \text{ m/day}$
- $K_z = 0.8 \text{ m/day}$
(Kardinya Shale Absent)
Figure 31. Hydraulic conductivity distribution for the Leederville Aquifer (Layer 7)
Table 6-3 Hydraulic property zones for the calibrated Lake Nowergup model

<table>
<thead>
<tr>
<th>Property Zone</th>
<th>Aquifer Represented</th>
<th>Kx</th>
<th>Ky</th>
<th>Kz</th>
<th>Specific Storage Ss (m⁻¹)</th>
<th>Specific Yield Sy</th>
<th>Effective Porosity</th>
<th>Total Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial Aquifers – Layers 1 through 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 2 Tamala Limestone</td>
<td></td>
<td>200</td>
<td>200</td>
<td>20</td>
<td>0.0005</td>
<td>0.25</td>
<td>0.2</td>
<td>0.35</td>
</tr>
<tr>
<td>Zone 3 Bassendean Sand/Gnangara Sand</td>
<td></td>
<td>30</td>
<td>30</td>
<td>3</td>
<td>0.0005</td>
<td>0.25</td>
<td>0.2</td>
<td>0.35</td>
</tr>
<tr>
<td>Zone 4 Bassendean Sand/Gnangara Sand</td>
<td></td>
<td>30</td>
<td>30</td>
<td>3</td>
<td>5x10⁻⁵</td>
<td>0.2</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>Zone 5 Bassendean Sand/Gnangara Sand</td>
<td></td>
<td>10</td>
<td>10</td>
<td>1</td>
<td>5x10⁻⁵</td>
<td>0.2</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>Zone 10 Bassendean Sand/Gnangara Sand</td>
<td></td>
<td>30</td>
<td>30</td>
<td>3</td>
<td>5x10⁻⁵</td>
<td>0.2</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>Zone 11 Tamala Limestone</td>
<td></td>
<td>400</td>
<td>400</td>
<td>40</td>
<td>5x10⁻⁵</td>
<td>0.25</td>
<td>0.2</td>
<td>0.35</td>
</tr>
<tr>
<td>Zone 12 Bassendean Sand/Gnangara Sand</td>
<td></td>
<td>1</td>
<td>1</td>
<td>0.1</td>
<td>5x10⁻⁵</td>
<td>0.2</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>Zone 13 Tamala Limestone</td>
<td></td>
<td>750</td>
<td>750</td>
<td>75</td>
<td>5x10⁻⁵</td>
<td>0.25</td>
<td>0.2</td>
<td>0.35</td>
</tr>
<tr>
<td>Zone 14 Bassendean Sand/Gnangara Sand</td>
<td></td>
<td>0.015</td>
<td>0.015</td>
<td>0.015</td>
<td>5x10⁻⁵</td>
<td>0.2</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>Osborne Formation – Layer 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 6 Kardinya Shale</td>
<td></td>
<td>0.005</td>
<td>0.005</td>
<td>0.0015</td>
<td>1x10⁻⁶</td>
<td>0.2</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>Zone 7 Kardinya Shale</td>
<td></td>
<td>2</td>
<td>2</td>
<td>0.0015</td>
<td>1x10⁻⁶</td>
<td>0.2</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>Zone 8 Nominal thickness where Kardinya Shale is absent</td>
<td></td>
<td>8</td>
<td>8</td>
<td>0.8</td>
<td>1x10⁻⁶</td>
<td>0.2</td>
<td>0.1</td>
<td>0.25</td>
</tr>
<tr>
<td>Leederville Aquifer – Layer 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 9 Leederville Aquifer</td>
<td></td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1x10⁻⁶</td>
<td>0.2</td>
<td>0.1</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Note there is no zone 1 in the model (purely a chance artefact of the calibration process

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6.1.3. Representation of Lake Nowergup

Lake water levels have been continuously monitored since 1973. Figure 32 displays the historical record of lake water levels for the calibration period. This figure also displays the periods during which groundwater from the Leederville Aquifer has been pumped into the lake for the purpose of maintaining water levels and preserving biodiversity and habitat.

The Modflow “Lake Package” (Merritt and Konikow, 2000) was used to simulate Lake Nowergup. This package allows the simulation of the interaction between lake and aquifer. The lake package includes the following features; resistance to flow through the lake bed, direct rainfall and evaporation, overland runoff and direct pumping to/from the lake. Final inputs to the calibrated model (run on Visual Modflow 4.1) are as follows:

- Lake bed conductance – 0.01 (based on calibration results)
- Rainfall – based on recorded rainfall (refer to section 6.1.4)
- Evaporation – based on the time series given in section 6.1.5
- Overland Runoff – Set at 5, found to be an insensitive parameter
- Direct pumping – As per time series given in Figure 32 (refer also to discussion below)

![Figure 32 Water Levels in Lake Nowergup and modelled volumes of water pumped into the lake](image-url)
Artificial Maintenance Pumping

Prior to 2004 there were no consistent records of volumes pumped into Lake Nowergup for supplementation purposes. However, the Water Authority of Western Australia, 1992 reports that in the early 1990’s artificial maintenance was triggered when the lake level fell to about 16.3 mAHD (the EPA minimum level criteria) and then pumping continued until the lake level exceeded 16.5 mAHD (the EPA preferred minimum level).

Based on this information it was assumed that when the historical lake level fell below 16.4 mAHD the artificial maintenance was triggered and this continued until the lake level rose above 16.5 mAHD. The rate of pumping was assumed to be 2750 kL/day. This was the rate required to maintain the lake level during dry periods (from the 1992 case study by the Water Authority). These rules and the recorded data where combined to create the time series of pumping applied to the model as shown in Figure 32.

6.1.4. Landuse & Recharge Mechanisms

The dominant recharge mechanism is rainfall infiltration as discussed in the conceptual model report.

Rainfall Infiltration Recharge

Rainfall recharge is based on rainfall measurements from the Bureau of Meteorology (BoM) as follows:

- Wanneroo Rainfall Gauge #9105 which has a good record since 1963. Where there are gaps in the monthly record these have been infilled via linear regression with Perth Metro Station (009225) which prior to 1993 was measured at the BoM’s Perth Regional Office Station (009034).

Historical monthly rainfall was scaled via a scaling factor (Table 6-4 and Table 6-5) to a monthly recharge value dependent on landuse. This is simply calculated by multiplying the monthly rainfall by the scaling factor. The scaling factors are based on landuse categories defined in existing literature and have subsequently been refined during the calibration process. These references and the final scaling factors used in the calibrated model are presented in Table 6-4 and Table 6-5.

This methodology differs from that used in PRAMS which utilises a 2-D unsaturated zone model to estimate recharge across the Gnangara Mound.

Irrigation
20% of the total volume of private groundwater abstractions was assumed to be returned to the shallow groundwater system via recharge across irrigated land. However, to maintain consistency with the PRAMS model this was simply applied by reducing the abstracted volume by 20% instead of applying it as irrigation recharge. Refer to section 6.1.6 for details of private abstraction volumes.

**Change in land use over time**

Changes in land use over the period of calibration were obtained from a detailed assessment of satellite imagery, mapping of forest cover (Australian Greenhouse Office) and land use overlays. Examples of these were provided in the conceptual model report. The final recharge zones as defined in the calibrated model are shown in Figure 33.

- **Figure 33 Landuse zones as applied to the Lake Nowergup LAM**

<table>
<thead>
<tr>
<th>Description</th>
<th>Comment</th>
<th>Recharge Estimate from Literature</th>
<th>Calibrated model</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dryland</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
<td>-</td>
</tr>
<tr>
<td>2 Lake</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3 Pine Plantation - Mature</td>
<td>Leaf area index 2.5–3.5</td>
<td>0.12</td>
<td>0.05</td>
<td>Silberstein &amp; al. (2004)</td>
</tr>
<tr>
<td>4 Pine Plantation - Young</td>
<td>Leaf area index 0.5–1.0</td>
<td>0.35</td>
<td>0.2</td>
<td>Silberstein &amp; al. (2004)</td>
</tr>
<tr>
<td>5 Banksia Forest - High Density</td>
<td>Leaf area index &gt; 1.2</td>
<td>0.1 - 0.18</td>
<td>0.15</td>
<td>Silberstein &amp; al. (2004)</td>
</tr>
<tr>
<td></td>
<td>Category</td>
<td>Leaf Area Index</td>
<td>Value 1</td>
<td>Value 2</td>
</tr>
<tr>
<td>---</td>
<td>-------------------------------------------------------</td>
<td>-----------------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>6</td>
<td>Banksia Forest - Med Density</td>
<td></td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>7</td>
<td>Banksia Forest - Low Density</td>
<td>Leaf area index &lt; 0.70</td>
<td>0.18 - 0.38</td>
<td>0.3</td>
</tr>
<tr>
<td>8</td>
<td>Urban</td>
<td></td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>9</td>
<td>Irrigation – High Intensity</td>
<td>Leaf area index = 3.0</td>
<td>0.4 - 0.45</td>
<td>0.4</td>
</tr>
<tr>
<td>10</td>
<td>Irrigation – Low Intensity or Dryland Farming</td>
<td>Leaf area index = 3.0</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>11</td>
<td>Banksia Low &gt; Urban (1992)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Pine Young &gt; Pine Mature (1992)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Banksia Low &gt; Urban (1995)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Banksia High &gt; Urban (1995)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Banksia Low &gt; Urban (1998)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Banksia High &gt; Urban (1998)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Banksia High &gt; Dryland (1998)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Banksia Low &gt; Urban (2002)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Banksia High &gt; Urban (2002)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6-5 Recharge and EVT factors by landuse

<table>
<thead>
<tr>
<th>Zone</th>
<th>Land use Description</th>
<th>Rainfall Infiltration Factor</th>
<th>Average Recharge (mm/yr)</th>
<th>EVT Scaling Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dryland</td>
<td>0.4</td>
<td>303</td>
<td>0.04</td>
</tr>
<tr>
<td>2</td>
<td>Lake</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Pine Plantation - Mature</td>
<td>0.05</td>
<td>38</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>Pine Plantation - Young</td>
<td>0.2</td>
<td>151</td>
<td>0.15</td>
</tr>
<tr>
<td>5</td>
<td>Banksia Forest - High Density</td>
<td>0.15</td>
<td>114</td>
<td>0.12</td>
</tr>
<tr>
<td>6</td>
<td>Banksia Forest - Med Density</td>
<td>0.24</td>
<td>182</td>
<td>0.08</td>
</tr>
<tr>
<td>7</td>
<td>Banksia Forest - Low Density</td>
<td>0.3</td>
<td>227</td>
<td>0.05</td>
</tr>
<tr>
<td>8</td>
<td>Urban</td>
<td>0.21</td>
<td>159</td>
<td>0.02</td>
</tr>
<tr>
<td>9</td>
<td>Irrigation – High Intensity</td>
<td>0.4</td>
<td>303</td>
<td>0.12</td>
</tr>
<tr>
<td>10</td>
<td>Irrigation – Low Intensity or Dryland Farming</td>
<td>0.4</td>
<td>303</td>
<td>0.08</td>
</tr>
</tbody>
</table>

6.1.5. Discharge Mechanisms

Evapotranspiration

Evapotranspiration is applied to the model via the modflow Evapotranspiration (EVT) package. Given there is little long term variability, a repeating annual cycle based on the average Pan Evaporation values shown in Figure 21 was applied across the model domain. An EVT extinction depth of 2m was used. The Pan Evaporation values were scaled according to landuse as per the same zones used for recharge (Figure 33). The calibrated scaling factors are provided in Table 6-5 above.
6.1.6. Groundwater Abstractions

Abstractions are divided into public and private. Generally the public abstraction bores are high volume bores used for urban and commercial water supply. The private bores are generally related to private households and irrigators.

Both private and public abstractions are accounted for in the Nowergup LAM. These are applied using the modflow Well Package.

Public Abstractions

The data available for the public bores is considered to be of high quality, including screened aquifer and metered pumping rates. Therefore these were applied as recorded to the model.

Figure 21 and Figure 22 present the volume and location respectively of public abstractions in the area. Note the conceptual model for this area is that a confining unit exists at the base of the Leederville and therefore abstractions from the Yarragadee Aquifer will not impact on surface water features such as Lake Nowergup.
- Figure 35 Lake Nowergup LAM Public Abstraction Volumes

![Graph showing total annual abstraction (ML/yr) from 1975 to 2007, with separate lines for Leaderville, Superficial, and Yarragadee aquifers.]

- Figure 36 Locality map of public abstraction wells

![Locality map showing public pumping bores, Superficial Aquifer, Leaderville Aquifer, and Yarragadee Aquifer locations.]

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Private Allocations

The data for private abstractions is less definitive as metering has been progressively implemented since 2005. Due to this the following assumptions about private abstractions have been applied to the calibration model:

- All private abstractions are applied to the Superficial Formation unless there was specific information to the contrary,
- The annual volume extracted in the model is set at 50% of the annual allocated volume. This was based on recent metered data from 2005 onwards which suggested that private abstraction licence holders are only using between 40-60% of their allocated volume (refer to discussion below on “Private Usage vs. Allocation”),
- The annual volumes are disaggregated into estimated monthly usage via the factors obtained from the PRAMS model (presented below in Figure 37).
- The monthly volume is then reduced by a further 20% to allow for assumption that 20% of abstractions are returned to the aquifer through irrigation recharge.

Figure 23 and Figure 24 show the total allocated volume and location of private bores respectively. In the absence of better information it is assumed that all private abstractions occur from the unconfined sediments of the Superficial and Leederville Formation and therefore may be interacting on surface water features. The Lake Supplementation Bore is also licensed as a private abstraction bore. This bore is located immediately west of Lake Nowergup and pumps water from the Leederville aquifer. Details of lake supplementation pumping can be found in Section 6.1.3.

- **Figure 37 Factors to disaggregating private allocation volumes into monthly usage**
Private Usage vs. Allocation

Due to the unavailability of metering data it was initially intended (as specified in the conceptual model report) to set private abstractions at 100% of the allocated volume. Throughout the
calibration process this proved to cause excessive drawdown compared to recorded observations. Since 2005 the Department of Water have started metering private abstraction bores. The metered data for 2005, 2006, 2007 and 2008 was made available for analysis for this study. Two methods of analysis were trialled and the method and results are summarised below:

Method 1
Average per metered bore, i.e. the annual volume extracted from each bore was calculated and this volume was compared to the allocated volume. This leads to a “percent use” for each individual metered bore. The averages for all available metered bores were as follows:

- 2006 – 60% of allocation
- 2007 – 55% of allocation
- 2008 – 47% of allocation

Method 2
Total volume metered as a percentage of total volume allocated to metered bores, i.e. the total volume extracted from all metered bores was calculated and the total allocation for all metered bores was calculated. The calculated percent use values per year were as follows:

- 2006 – 51% of allocation
- 2007 – 52% of allocation
- 2008 – 40% of allocation

Method 2 focuses on the total abstraction volumes and aims to avoid any bias toward small or large licence holders. Note also that 2005 was not analysed because there were only a very small number of bores that had a full year of meter readings.

There are a number of limitations and assumptions that need to be made in order to derive the above results, however the results (of both methodologies) do appear to consistently show that the actual volume extracted from private wells collectively is probably somewhere between 40 and 60% of the total allocation. Consequently, in the calibrated model an abstraction volume of 50% of the total allocation has been set. This is obviously a gross simplification but for the purposes of developing a consistent rule for the Nowergup model this methodology is considered reasonable within the level of accuracy of numerical groundwater modelling.
6.2. Calibration Methodology

Calibration was conducted using a manual iterative process. Parameter estimation (PEST) was found not to be cohesive with the model, possibly due to the implementation of the LAKE package.

The calibration period for the transient model was from 1991 to 2006. A steady state model was calibrated as the first model stress period, i.e. January 1991. The hydraulic heads from the steady state calibration were used as initial heads for the transient model runs.

6.2.1. Lake Nowergup Calibration Sites

Monitoring wells used as calibration sites for the Lake Nowergup LAM are shown in Figure 40 and are listed in Table 6-6. There is good detail in the area immediately surrounding the lake including two nested sites monitoring both the Superficial and Leederville aquifers. Away from the lake monitoring sites were chosen to provide good spatial representation across the model.

In addition to the groundwater monitoring wells, the measured water levels in Lake Nowergup were used as a model calibration target. These are based on the staff gauge “Lake Nowergup 8756”, or reference number 6162567.
Figure 40 Proposed calibration bores for the Lake Nowergup LAM
## Table 6-6. Calibration sites for the Nowergup LAM

<table>
<thead>
<tr>
<th>WIN Site Id</th>
<th>AWRC Reference</th>
<th>AWRC Context Name</th>
<th>AWRC Name</th>
<th>Easting</th>
<th>Northing</th>
<th>Aquifer Monitored</th>
<th>Bore Depth</th>
<th>Screened From</th>
<th>Screened To</th>
</tr>
</thead>
<tbody>
<tr>
<td>4924</td>
<td>61610583</td>
<td>JOONDALUP MONITORING</td>
<td>JP12</td>
<td>376713</td>
<td>649728</td>
<td>Perth - Superficial Swan</td>
<td>64.5</td>
<td>42.5</td>
<td>60.5</td>
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<tr>
<td>4925</td>
<td>61610584</td>
<td>JOONDALUP MONITORING</td>
<td>JP15</td>
<td>377572</td>
<td>6500470</td>
<td>Perth - Superficial Swan</td>
<td>63</td>
<td>38</td>
<td>56</td>
</tr>
<tr>
<td>4926</td>
<td>61610585</td>
<td>JOONDALUP MONITORING</td>
<td>JP19</td>
<td>378159</td>
<td>6502989</td>
<td>Perth - Superficial Swan</td>
<td>61</td>
<td>46</td>
<td>58</td>
</tr>
<tr>
<td>4945</td>
<td>61610604</td>
<td>YANCHEP MONITORING</td>
<td>YY1 (I)</td>
<td>381159</td>
<td>6503449</td>
<td>Perth - Superficial Swan</td>
<td>92</td>
<td>77.6</td>
<td>80.6</td>
</tr>
<tr>
<td>4975</td>
<td>61610634</td>
<td>JOONDALUP MONITORING</td>
<td>JP13 (I)</td>
<td>384852</td>
<td>6496529</td>
<td>Perth - Superficial Swan</td>
<td>91</td>
<td>49.5</td>
<td>79.5</td>
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<td>4979</td>
<td>61610638</td>
<td>JOONDALUP MONITORING</td>
<td>JP16</td>
<td>383390</td>
<td>6499264</td>
<td>Perth - Superficial Swan</td>
<td>71</td>
<td>34</td>
<td>70</td>
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<tr>
<td>5037</td>
<td>61610696</td>
<td>GNANGARA OLD</td>
<td>GN19</td>
<td>386993</td>
<td>6495193</td>
<td>Perth - Superficial Swan</td>
<td>67.06</td>
<td>47.854</td>
<td>48.463</td>
</tr>
<tr>
<td>5094</td>
<td>61610753</td>
<td>GNANGARA OLD</td>
<td>GN23</td>
<td>389030</td>
<td>6499466</td>
<td>Perth - Superficial Swan</td>
<td>76.81</td>
<td>37.49</td>
<td>38.1</td>
</tr>
<tr>
<td>5737</td>
<td>61611664</td>
<td>PERTH COASTAL SCHEME</td>
<td>QV 26-89</td>
<td>379102</td>
<td>6495576</td>
<td>Perth - Superficial Swan</td>
<td>43.5</td>
<td>35.5</td>
<td>41.5</td>
</tr>
<tr>
<td>5740</td>
<td>61611667</td>
<td>PERTH COASTAL SCHEME</td>
<td>EG 2-89</td>
<td>375328</td>
<td>6501408</td>
<td>Perth - Superficial Swan</td>
<td>65.5</td>
<td>50.4</td>
<td>62.4</td>
</tr>
<tr>
<td>5555</td>
<td>61611220</td>
<td>LAKE NOWERGUP</td>
<td>LN19-89</td>
<td>379947</td>
<td>6499724</td>
<td>Perth - Superficial Swan</td>
<td>5.3</td>
<td>2.3</td>
<td>5.3</td>
</tr>
<tr>
<td>5569</td>
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<td>LAKE NOWERGUP</td>
<td>LN5-89</td>
<td>379672</td>
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<td>Perth - Superficial Swan</td>
<td>13.4</td>
<td>11.4</td>
<td>13.4</td>
</tr>
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<td>LAKE NOWERGUP</td>
<td>LN3-89</td>
<td>379157</td>
<td>6499430</td>
<td>Perth - Superficial Swan</td>
<td>29.8</td>
<td>27.8</td>
<td>29.8</td>
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<td>61611236</td>
<td>LAKE NOWERGUP</td>
<td>LN24-89</td>
<td>379005</td>
<td>6499384</td>
<td>Perth - Superficial Swan</td>
<td>29.4</td>
<td>27.4</td>
<td>29.4</td>
</tr>
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<td>5579</td>
<td>61611244</td>
<td>LAKE NOWERGUP</td>
<td>LN17-89</td>
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<td>6499801</td>
<td>Perth - Superficial Swan</td>
<td>31.4</td>
<td>26.4</td>
<td>31.4</td>
</tr>
<tr>
<td>5582</td>
<td>61611247</td>
<td>LAKE NOWERGUP</td>
<td>LN2-89</td>
<td>379431</td>
<td>6499522</td>
<td>Perth - Superficial Swan</td>
<td>26</td>
<td>23</td>
<td>26</td>
</tr>
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<td>5583</td>
<td>61611248</td>
<td>LAKE NOWERGUP</td>
<td>LN32-89</td>
<td>380104</td>
<td>6499295</td>
<td>Perth - Superficial Swan</td>
<td>46.3</td>
<td>44.3</td>
<td>46.3</td>
</tr>
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<td>LN18-89</td>
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<td>Perth - Leederville</td>
<td>40.9</td>
<td>38.9</td>
<td>40.9</td>
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<td>LAKE NOWERGUP</td>
<td>LN37-89</td>
<td>379158</td>
<td>6499431</td>
<td>Perth - Leederville</td>
<td>8.2</td>
<td>5.2</td>
<td>8.2</td>
</tr>
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<td>14588</td>
<td>6162567</td>
<td>LAKES AND WETLANDS</td>
<td>LAKE NOWERGUP 8756</td>
<td>379746</td>
<td>6499839</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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</tbody>
</table>
6.3.  Lake Nowergup Calibration Results

6.3.1. Steady State Potentiometric Surface

The potentiometric surface produced from the steady state model is shown below in Figure 41. This surface simulates groundwater levels as at January 1991 and was used as the initial heads for the transient model calibration runs.

- Figure 41 Steady-state potentiometric surface for the Superficial Aquifer (Jan 1991). Red contours are the model results, black contours are observed.

6.3.2. Calibrated Model Hydrographs

The final calibrated model hydrographs are shown below on Pages 69 and 70. Generally a fair to good match between observed and modelled groundwater levels was achieved. Long term trends, in particular groundwater decline rates, were achieved both on a regional and local scale around Lake Nowergup. The key anomalies and points of note are discussed below:

- Groundwater levels in the Tamala Limestone, west of the lake, were generally matched with high accuracy except for post 2004 in Bore QV26-89. It is possibly that the observed increase in levels was a response to a localised landuse change or cessation of pumping that was not recorded.
- The model underestimates levels in Bore JP13 (I) particularly through the late 1990’s, however long-term trend appears to be accurate.
- The model does not achieve the amplitude of observed annual variation in Bore GN23. This is due to its close proximity to the up-gradient GHB boundary which dampens its ability to mimic the response to pumping.

- There appears to be a bore failure in JP16 after 1998 that causes a discrepancy between modelled and observed water levels. Prior to the suspected failure there is a good match and the observed trend is replicated through the calibration period.

- Bores LN2-89 and LN5-89 are both constructed on the down-gradient bank of Lake Nowergup with very shallow screens that are likely to sit within the lake bed sediments. Consequently the observed hydrographs effectively mimic water levels in the lake. Due to the adopted methodology of representing lake bed sediments through the LAKE package it was not possible to model these observation wells in the lake bed sediments. Instead the model results for these wells can be considered as being in the aquifer below the lake bed sediments. Consequently the modelled response in these wells is more representative of the regional groundwater trends as opposed to the near lake-aquifer interactions.

- Despite the above discussion, the model does effectively model lake-aquifer interactions as indicated by the staff gauge LAKE NOWERGUP 8756. The modelled versus observed heads at the staff gauge represent a very good match and for the most part lake levels are replicated to within +/- 50cm. This includes good representation of seasonal fluctuations in the early 1990’s when the lake and groundwater system were highly connected. Furthermore there is very good representation of lake levels from 2004 onwards when the lake was largely artificially maintained and pumping volumes have been consistently recorded.
6.3.3. **Calibrated Model Statistics**

The calibration statistics for the Lake Nowergup Calibration model are well within the minimum guidelines recommended for numerical modelling (refer Figure 42).

- **Figure 42. Calibration statistics for the Lake Nowergup model**

```
| All Time Points: 38480 |
| Max. Residual: -3.651 (m) at 5655/2555 |
| Min. Residual: 0 (m) at 5575/5575 |
| Residual Mean: -0.283 (m) |
| Abs. Residual Mean: 0.519 (m) |
```

6.3.4. **Calibrated Model Water Balance**

The calibrated model water balance is displayed in Figure 43. As expected recharge, through rainfall infiltration and irrigation, is the dominant source of water for this area of the Gnangara Mound. Figure 43 appears to indicate a very small volume of groundwater interacting with Lake Nowergup. However, this is purely a function of the area of the lake compared to the area of the entire model. Had the model been constructed for a smaller area, lake interactions as a proportion of the water balance would have been more significant.
Figure 44 and Figure 45 represent the water balance for Lake Nowergup as an average monthly and monthly time series respectively. Both figures highlight the reliance on artificial supplementation to maintain water levels in the lake.

Possibly the most important result is identified in Figure 45 with the timeseries of groundwater discharging to Lake Nowergup. This shows that through the 1990’s, groundwater discharges to the lake continually decreased and since approximately 2000 there has been only negligible groundwater discharges to the lake. This is a direct result of groundwater levels in the area falling and remaining below the lake bed.

- **Figure 43. Cumulative water balance for the Lake Nowergup calibration model**

- **Figure 44. Average monthly water balance for Lake Nowergup**
Figure 45: Time series of inputs and outputs to Lake Nowergup (ML/mth)

- Rainfall
- Evaporation
- GW Discharge
- GW Recharge
- Artificial Maintenance Pumping
6.4. Lake Nowergup Sensitivity Analysis

A sensitivity analysis has been carried out on some of the key model input parameters. The calibration model was used for this analysis. The methodology applied in this case involved running the model consecutively with one of the input parameters varied by different amounts. In each case the normalised RMS error for the particular model is noted. Model runs are repeated until the normalised RMS error reaches approximately 3% or the parameter value is varied outside a reasonable range for that particular parameter. The rationale behind this methodology is to demonstrate the parameter range that can result in a model that is calibrated. In this case it is assumed that a model with an RMS error of 3% is still calibrated and that a model with a normalised RMS error that is greater than 3% is not calibrated. This definition is somewhat arbitrary, however the approach is aimed at only considering sensitivity within reasonable bounds as defined by calibration criteria. In other words varying a particular parameter to the point that the model is not calibrated does not provide a useful understanding of sensitivity. In this manner, model sensitivity only considers the impacts of uncertainty within the bounds set by reasonable calibration criteria.

If necessary the analysis can be expanded to include the predictive scenario model once these have been defined. The baseline model can be run in predictive mode with the sensitive parameter set at its upper and lower limits (as defined by the 3% normalised RMS error limit) and then key model outcomes reported. In this manner it is possible to illustrate the range in model outcomes given perturbation (within reasonable bounds) of the key uncertain input parameters.

In this case the sensitivity analysis has been undertaken on the following parameters:

- Hydraulic Conductivity,
- Specific Yield,
- Recharge,

Results of the sensitivity analysis are presented in Table 6-7. It is was found that increasing the hydraulic conductivity, even by small amounts, caused significant model instability problems. Therefore an upper bound to the hydraulic conductivity could not be estimated. It is believed that the main cause of the instability is the steep hydraulic gradients (and contrasting conductivities) at the contact between the Bassendean sands and the Tamala Limestone. This is most prevalent immediately down-gradient from Lake Nowergup.

The results of the sensitivity analysis suggest that:

- Calibration is considered to be relatively sensitive to changes in hydraulic conductivity. Although this is probably more observable in hydrograph trends than in the RMS error.
Whilst an upper bound was not found it was estimated that the conductivities could be halved before the calibration criteria was breeched.

- Model calibration is relatively insensitive to increasing specific yield. This occurs because increasing the specific yield tends to ‘flatten’ out hydrographs, which detracts from qualitative matches to the hydrographs but can actually improve the normalised RMS error. In this case an upper bound was placed on specific yield (0.3) to reflect the maximum likely value of this parameter. At the same time the calibration is also relatively insensitive to decreasing specific yield with the calibration criteria breeched at a value of 0.17 times the calibrated model specific yield.

- Recharge is obviously a key input parameter, and both increasing and decreasing the recharge invoked reasonable changes to the model calibration statistics. Increasing and decreasing recharge by approximately 55% and 32.5% respectively was found to be required to breech the calibration criteria.

### Table 6-7. Results of the Lake Nowergup sensitivity analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Upper/Lower Bound</th>
<th>Change to calibrated model</th>
<th>Normalised RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic Conductivity</td>
<td>Upper</td>
<td>Model proved to be unstable under these conditions</td>
<td>na</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>0.5 * K</td>
<td>3.2</td>
</tr>
<tr>
<td>Specific Yield</td>
<td>Upper</td>
<td>Sy = 0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Sy * 0.17</td>
<td></td>
</tr>
<tr>
<td>Recharge</td>
<td>Upper</td>
<td>R * 1.55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>R * 0.675</td>
<td></td>
</tr>
<tr>
<td>Calibrated Model</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
7. Predictive Scenario Models

7.1. Scenario Definitions

The following scenarios are simulated with the Lake Nowergup Local Area Groundwater Model. Each scenario model is run over the period Jan 2008 to Dec 2031 (inclusive). Initial conditions for the model runs are set as the final heads of the calibration model.

Table 5-8. Lake Nowergup model scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Climate</th>
<th>Public Abstractions</th>
<th>Private Abstractions</th>
<th>Lake Artificial Supplementati on</th>
<th>Landuse Change (Pine harvest)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>Median climate of 1997 to 2006</td>
<td>As per WaterCorp 135 GL dataset</td>
<td>100% of current usage</td>
<td>Equivalent to current annual licensed volume</td>
<td>Pines harvested as per LVL, replaced with grass</td>
</tr>
<tr>
<td>1</td>
<td>11% drier</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>80% of current usage*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Immediate (2008) pine removal, replace with grass</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>No supplementation</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>24/7 ongoing pumping</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>Off-peak pumping</td>
<td></td>
</tr>
</tbody>
</table>

Note – a blank cell indicates the parameter is not changed from the base case

* In Scenario 2 the reduction in private abstractions does not apply to the Lake Supplementation bore. The Lake Supplementation bore remains at 100% of current usage.
7.2. **Lake Nowergup Scenario Model Inputs**

Note: Only those inputs discussed below in this section have changed from the calibration model. Therefore, as an example, the specified head boundary conditions in the model are as described for the calibration model.

### 7.2.1. Landuse (Pine Harvesting)

The initial (2008) landuse pattern is assumed the same as the landuse at the conclusion of the model calibration runs (i.e. Dec 2006). Following this the only changes to landuse occur over pine plantation areas. The pine plantation areas are shown in Figure 46 along with the predicted year in which they will be harvested. It is assumed that all pines are replaced with grass once harvested. The recharge rate for grass was set at 30% of rainfall.

- **Figure 46 Pine plantation areas and predicted harvesting years**

### 7.2.2. Rainfall & Evapotranspiration

Rainfall for the Nowergup model is based on rainfall data from the Wanneroo climate station. The model climate input data sets (recharge and evapotranspiration) assume a repeated annual cycle as used in PRAMS modelling scenarios. The annual cycles of both rainfall and ET for both the base and dry scenarios are presented in Figure 47.
7.2.3. Groundwater Abstractions

Public Groundwater Extractions

Public groundwater extractions are predefined in accordance with the Water Corporation 135GL/yr predictions. Within the Nowergup model domain this results in annual abstractions of approximately 21 GL/yr. The monthly distribution of abstractions is shown in Figure 48.
Private Groundwater Extractions

Current usage was assumed to continue into the future for the base case scenario. This was set as a repeating annual cycle based on the last year of the calibration model (i.e. 2006). Total usage in 2006 was estimated at approximately 8 GL/yr within the model domain, this was calculated as 40% of the allocated volume of 20 GL/yr. The monthly distribution is shown below in Figure 49.
7.2.4. Lake Nowergup Artificial Maintenance

For the base case scenario the artificial maintenance pumping is set at an annual volume of 1.2 GL/yr (i.e. equivalent to the allocated abstraction volume). Water is extracted from the Leederville Aquifer. A seasonal cycle was developed based on the metered pumping data for the period 2004-2006 inclusive (refer Figure 50 and Figure 51). Prior to 2004 there are no records of pumping rates. The annual cycle of artificial maintenance pumping for the various scenarios is displayed in Figure 51.

- Figure 50. Metered artificial maintenance pumping volumes for 2004 to 2006.

- Figure 51. Monthly volumes of artificial maintenance in the scenario models.
7.3. Lake Nowergup Predictive Scenario Results

Hydrographs and lake water balance results for all scenarios can be found in Figure 53 and Figure 54.

7.3.1. Base Case Results and Discussion

A map of the recovery of groundwater levels across the model is provided in Figure 52. Hydrographs from the base case scenario run are presented in Figure 53 and Figure 54. These figures highlight that immediately after pine plantations are harvested groundwater levels begin to recover rapidly. This is most apparent in the north and centre of the model domain where between 2008 and 2031 median groundwater levels are predicted to rise by approximately 4 m. The rising trend is predicted across the model domain to varying degrees. Rapid and relatively substantial recovery in groundwater level are predicted to occur in those areas where pine plantations are removed and replaced with grass. Along the coastal limestone formations rises in groundwater levels are predicted to be significantly more subdued and gradual than elsewhere in the model domain.

A secondary phenomenon predicted after pine clearing is a dramatic increase in the seasonal fluctuation in groundwater levels. This occurs due to the increasing influence of the seasonal rainfall pattern as more rainfall infiltrates into the groundwater system.

In the immediate vicinity of Lake Nowergup (Figure 54), median groundwater levels are predicted to increase by approximately 2 m between 2008 and 2031. Most of this increase is observed before 2020 as the system appears to approach a new equilibrium state thereafter. The increasing groundwater level is almost matched by the gauged level in the lake which is predicted to increase by approximately 1.8 m by 2031.

The implications of this predicted rising groundwater and lake levels are shown in Figure 55 with the time series fluxes into and out of Lake Nowergup. In Figure 55 the following can be observed:

- There is a significant increase in groundwater discharging to the lake. Where in 2008 there was effectively no modelled groundwater discharges, in 2031 there is a predicted 446 ML of natural groundwater discharging into the Lake.
- There is an increase in both rainfall and evaporation from the lake through the scenario model period. This is due to the increasing level and hence increasing surface area of the lake.
- As the lake level rises there is also an increase in seepage losses (groundwater recharge). This is most prominent in winter. A possible explanation for this is that during winter artificial pumping is at its lowest, groundwater levels are at their highest, hence the lake is behaving in its most natural state, i.e. as a through-flow lake with both groundwater discharge and recharge occurring.
Figure 52. Recovery of groundwater levels (in meters) during the base case scenario from 2008 to 2031
Figure 53. Base case scenario hydrographs for the Nowergup LAM
Figure 54. Base case scenario hydrographs for bores in the immediate vicinity of lake Nowergup
Figure 55. Times series water balance results for the base case scenario

- Rainfall
- Evaporation
- GW Discharge to the Lake
- GW Recharge from the Lake
- Artificial Maintenance Pumping
7.3.2. Lake Nowergup Water Levels – Comparison between Scenarios

Figure 56 displays time series graphs of the predicted gauged water level in Lake Nowergup for all scenarios. With the exception of Scenario 4 (no lake supplementation) the water level trends in the lake can be considered analogous for groundwater levels across the greater area. A few key observations from the results are as follows:

- Under all scenarios the predicted water levels fail to reach the EPA criteria level of 16.3 mAHD, however, there are significant increases in water level in all scenarios due to rising groundwater levels as a result of pine harvesting;
- Even under drier conditions (scenario 1) there is a general increase in water levels although the increase is less pronounced and more gradual than in other scenarios;
- Immediately harvesting all pine plantations (scenario 3) has the most rapid impact on lake water levels, however the levels appear to plateau and by 2031 the base case water levels match that of scenario 3;
- Reducing private abstractions (scenario 2) appears to have long term benefits with water levels continuing to rise slowly from 2008 to 2031;
- After removing the artificial maintenance pumping (scenario 4) the model predicts the lake to dry up rapidly due to very low current groundwater levels. As groundwater levels increase so too does the lake water level and by 2031 it was predicted that the lake level, without pumping, would only be approximately 1 m lower than with pumping of 1.2 GL/yr.
- Continuous artificial lake level maintenance pumping was predicted to significantly increase lake water levels, particularly in the first decade when surrounding groundwater levels are still low. In the long-term it was predicted to increase lake water levels by approximately 1 meter compared to the base case.
- The off-peak scenario, compared to the base case, had the biggest impact during winter when the lake levels were already naturally high. This year round consistent pumping regime, as opposed the seasonal cycle in the base case, means that the natural seasonal variation in lake levels is better retained.
- The year-round continuous pumping of both Scenarios 5 and 6 is predicted to be particularly effective in the first few years where it prevents the lake water levels from dropping dramatically.
Figure 56 Comparison between predicted water levels in Lake Nowergup

- Base Case
- Scn 1 - 11% Drier
- Scn 2 - Private Abstraction 80%
- Scn 3 - Immediate Pine Removal
- Scn 4 - No Lake Supplementation
- Scn 5 - 24/7 Lake Supplementation
- Scn 6 - Off-Peak Lake Supplementation
7.3.3. Lake Nowergup Water Balance – Comparison between Scenarios

The long-term average annual water balance is not considered as informative as the time series plots however they allow for simple comparisons between scenarios. This is shown in Figure 57 where the following can be observed:

- The lake remains heavily reliant on artificial pumping to maintain high water levels
- Most of the pumped water is lost through seepage (groundwater recharge). This is observed through the high correlation between pumping and groundwater recharge.
- The variation within rainfall and evaporation shown here are due to changes in the lake level and hence lake surface area
- Groundwater discharges are lowest in the dry scenario due to this scenario having the lowest groundwater levels
- Groundwater discharge is highest in the ‘no supplementation’ scenario. This is due to the lower levels in the lake increasing the hydraulic gradient from the groundwater to the lake.

- **Figure 57. Predicted average monthly water fluxes for Lake Nowergup**
7.3.4. Groundwater Levels – Comparison between scenarios

Difference maps of groundwater levels at the end of the scenario runs compared to the base case have been plotted. Two examples are provided in Figure 58 and Figure 59 (the remaining scenarios can be found in Appendix C). These difference maps highlight the impact of the various scenarios compared to the base case.

In Figure 58 it can be seen that the drier climate in Scenario 1 is predicted to lower groundwater levels by up to 1 meter across much of the area. The exception to this is the Tamala Limestone along the coast where there is negligible predicted groundwater level changes in any of the scenarios. The results along the western boundary are constrained by the GHB. In contrast, Figure 59 highlights how reducing the level of private abstractions will lead to an increase in groundwater levels compared to the base case.

For all other scenarios, there was minimal variation in groundwater levels across the greater model domain. Scenarios 4, 5 and 6 all relate to changes with the lake supplementation bore. Therefore groundwater level changes are localised around the supplementation bore and the lake itself. These maps can also be found in Appendix C.

- Figure 58 Difference between groundwater levels at the end of Scenario 1 (11% drier) compared to the base case (red indicates lower groundwater levels in scenario 1)
Figure 59 Difference between groundwater levels at the end of Scenario 2 (reduced private abstractions) compared to the base case (blue indicates higher groundwater levels in scenario 2)
8. Model Limitations and Recommendations for Further Work

The Lake Nowergup Model is aimed at assessing potential impacts of future land use changes and changes in water extraction regime. The emphasis of the investigations is on the shallow and near surface impacts with particular attention paid to the potential impacts on groundwater dependent ecosystems including vegetation and wetlands (in particular Nowergup Lake). The developed model is deemed to be suitable for these purposes and should provide the user with good reliability and accuracy of predictions relating to these matters. Nevertheless it is important to recognise the limitations when using the model as a predictive tool.

Model results need to be considered within the context of the calibration and also the common limitations of numerical groundwater models. Whilst the calibration achieved an excellent RMS error score, the calibration hydrographs highlighted the model is not perfect. Deviations from observed readings, at some locations, of up to 3 meters were modelled, both overestimations and underestimations. However, in general the model is good at depicting trends over time. Therefore it is recommended that model results be considered not in an absolute sense, but in a relative sense (i.e. instead of reporting that the results for Scenario X suggest that water levels in the lake will rise to 17 mAH, it is more suitable to report that Scenario X is likely to result in water levels 1-2 meters higher than the base case scenario).

The accuracy of model input data is also an important consideration. Private abstraction data is one input with a low reliability. In this report a simple analysis based on a few years of metered data was completed to estimate a percentage of allocation used. As further metering data is collected it may be appropriate to re-evaluate the private abstraction rates that have been entered into the calibration model. If significant discrepancies are found it is recommended that the model be recalibrated with the new metered data.

The model was also calibrated over a long dry period. Therefore, should a “wetter” period be encountered in the future, the model may not respond accurately. Therefore, if such climate conditions return it may be appropriate to recalibrate the model over a period that includes both a dry and wet period.

Only limited calibration took place in the Leederville aquifer. Therefore it is not recommended that the model be used for assessments into the Leederville aquifer in this area. It may be possible, with further work to add more calibration sites into the Leederville aquifer and recalibrate the model. However, it would be important to ensure that this does not occur at the expense of the calibration in the Superficial Formation (particularly around Lake Nowergup).
A practical limitation of the model is the numerical instability that has been observed in some scenarios. The cause of this is believed to be the high contrast in conductivities across the sand-limestone boundaries. If the numerical instability becomes a significant problem it may be appropriate to recalibrate the model in manner that improves the numerical stability (although probably at the expense of model accuracy). This would most likely involve altering the conductivity values in the limestone and also immediately west of Lake Nowergup.

Another practical limitation of the model is the inability of the Lake Package to function in recent versions of modflow or Visual Modflow. If these problems are resolved then it would be worthwhile updating the model to be able to run in these newer versions of modflow.
9. Modelling Conclusions

The harvesting of pines within the greater area surrounding Lake Nowergup is predicted to have a significant impact on groundwater levels and water levels in the lake. Some of the key observations are as follows:

- Following the LVL pine harvest schedule groundwater levels are predicted to rise across the region.
- The most significant rises in groundwater level will occur under the plantations where up to four meters (median level) of groundwater level rise is predicted by 2031.
- In the immediate vicinity of Lake Nowergup, groundwater levels are predicted to rise by approximately two meters by 2031.
- The rising groundwater levels will directly benefit lake water levels with increases of approximately 1.8 m predicted by 2031.
- This may reduce the reliance on lake supplementation pumping, however it is noted that predicted lake levels still remain below the criteria level of 16.3 mAHD.
- A drier climate will reduce the benefits of pine harvesting, however groundwater levels and lake levels are still predicted to rise gradually in the dry climate scenario.
- Decreasing private abstractions will have long-term benefits for groundwater levels (and lake levels)
- Stopping the lake supplementation pumping immediately is predicted to dry the lake up due to current low groundwater levels. However the groundwater level recovery predicted over the next 20 years as a result of pine harvesting will result in a recovery of lake water levels over the same time frame.
10. References


Appendix A  Landuse Maps

A.1  Landsat Imagery (captured in 2007)
A.2  Current Planning Overlay
A.3 Current Plantation Forestry Area
A.4 Possible Future Planning Overlay

The image shows a map of the Lake Nowegup Local Area Groundwater Model with a focus on possible future planning overlays. The map includes various land use categories such as Central City Area, Care & Cultural, Enduring Special Rural, Biodiversity Wetlands, Industrial, Other Regional Roads, Parks & Recreation, Possible Future Urban, Possible Areas: Stormwater, Primary Regional Roads, Proposed Future-Non-Building, Proposed Parks & Recreation, Proposed Special Residential, Proposed Special Use Tourism, Public Purposes, Railways, Railways - Water Protection, State Forests, and Urban. The map highlights specific areas designated for different land use purposes, illustrating potential future planning considerations.
Appendix B  Bore logs.

Lake Nowergup LAM - Example Stratigraphic Logs
Appendix C  Lake Nowergup Model Results – All Scenarios

C.1  Scenario Model Hydrographs
C.1.1 Base Case Hydrographs
C.1.2 Scenario 1 Hydrographs – 11% Drier
C.1.3 Scenario 2 Hydrographs – 80% Private Abstractions
C.1.4 Scenario 3 Hydrographs – Immediate pine harvest
C.1.5 Scenario 4 Hydrographs – No lake Supplementation
C.1.6 Scenario 5 Hydrographs – 24/7 Lake Supplementation
C.1.7 Scenario 6 Hydrographs – Off-Peak Lake Supplementation

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C.2 Scenario Model Lake Water Balance

C.2.1 Base Case Scenario
C.2.2 Scenario 1 – 11% Drier

- Rainfall
- Evaporation
- GW Discharge to the Lake
- GW Recharge from the Lake
- Artificial Maintenance Pumping
C.2.3 Scenario 2 – 80% Private Abstractions

Rainfall

Evaporation

GW Discharge to the Lake

GW Recharge from the Lake

Artificial Maintenance Pumping
C.2.4 Scenario 3 – Immediate Pine Harvest
C.2.5 Scenario 4 – No lake supplementation

[Graphs showing Rainfall, Evaporation, GW Discharge to the Lake, GW Recharge from the Lake, and Artificial Maintenance Pumping over the years 2000 to 2030.]
C.2.6 Scenario 5 – 24/7 lake supplementation
C.2.7 Scenario 6 – Off-peak lake supplementation

C.3 Scenario Model Groundwater Level Recovery and Difference Maps
The first map under each of the scenario headings is a groundwater level recovery map. This is calculated as the difference between groundwater levels at the end of the calibration period (December 2006) and the end of the scenario run (December 2031). Darker blues indicate the greatest recoveries.

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The second map is a difference map of the groundwater levels at the end of each scenario run compared to the end of the base case. Blue (+) indicates higher groundwater levels, red (-) indicates lower groundwater levels compared to the base case.

All units are in meters.

C.3.1 Base Case Scenario

C.3.2 Scenario 1 – 11% Drier
Groundwater level recovery to 2031

Groundwater level difference compared to base case at 2031

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C.3.3 Scenario 2 – 80% Private Abstractions

Groundwater level recovery to 2031

Groundwater level difference compared to base case at 2031
C.3.4 Scenario 3 – Immediate Pine Harvest

Groundwater level recovery to 2031

Groundwater level difference compared to base case at 2031
C.3.5 Scenario 4 – No lake supplementation

Groundwater level recovery to

2031

Groundwater level difference compared to base case at 2031
C.3.6 Scenario 5 – 24/7 lake supplementation
Groundwater level recovery to 2031

Groundwater level difference compared to base case at 2031
C.3.7 Scenario 6 – Off-peak lake supplementation

Groundwater level recovery to 2031

Groundwater level difference compared to base case at 2031
Appendix D  Model User Guide

D.1  Introduction
This report provides a basic summary of how the Lake Nowergup LAM model can be manipulated in order to run the various scenarios. Note that it is assumed that the reader has a working knowledge of Visual Modflow and as such this report in no way attempts to rewrite the Visual Modflow Handbook. Furthermore, this report also assumes the reader has a good understanding of the model structure and inputs as described in the main report.

D.2  Directory Structure

Figure 60 and Figure 61 presents the major directory structures for the Lake Nowergup Local Area Model. The directory is first split into two major sub-folders, one each for the calibration models and one for the scenario models. Beneath each of these the directory structure is identical for both the calibration and scenario models. The structure is then based on three tiers:

- ‘Model Inputs’ contains all the spreadsheets and files that were used in the processing and creation of the Visual Modflow input files
- ‘Model Outputs’ contains all the spreadsheets and routines used in the processing of model output files
- ‘Models’ contains all the model files including both calibration and scenario models which can be opened and run in Visual Modflow

Each of these three directories will be discussed in more detail in the following sections. Note that not every folder or file is shown in this report, only those deemed relevant or of particular value are represented and described.
Figure 60 Flow chart of the Lake Nowergup model directory structure

D.3 Model Inputs
D.3.1 Directory structure

D.3.2 Model Boundaries
The upgradient and downgradient model boundaries are simulated by the General Head Boundary (GHB) Package and the Constant Head Boundary Package (CHB) respectively. The CHB simulates the ocean level and therefore will not change for simulation runs. The GHB on the upgradient boundary was introduced at the 51 mAHD potentiometric contour as at 1990. For simulation runs commencing at a later date it may be appropriate...
to adjust the GHB to another level. This would need to be completed within Visual Modflow. However changes to the boundary conditions between scenario runs should be avoided as this can predispose the model to a certain flow response.

There are no spreadsheets or tools required to edit model boundaries. Any edits, if necessary, are made within the model in Visual Modflow.

D.3.3 The Lake Package

The Modflow “Lake Package” (Merritt and Konikow, 2000) was used to simulate Lake Nowergup. This package allows the simulation of the interaction between surface water bodies such as lakes and the aquifer. In particular the Lake Package allows the calculation of lake level on the basis of a lake water balance that includes model-predicted inflows and seepage to groundwater. The lake package requires the following inputs;

- Lake bed conductance – 0.01 (based on calibration results)
- Rainfall (100% of measured rainfall)
- Evaporation (Areal potential evaporation)
- Overland Runoff – Set at 5, (calibration shows that the model is insensitive to this parameter)
- Direct pumping

Figure 62 Directory structure and key files for the Lake Package

The Lake Package allows the calculation of lake level on the basis of a lake water balance that includes model-predicted inflows and seepage to groundwater. The lake package requires the following inputs:

- Lake bed conductance – 0.01 (based on calibration results)
- Rainfall (100% of measured rainfall)
- Evaporation (Areal potential evaporation)
- Overland Runoff – Set at 5, (calibration shows that the model is insensitive to this parameter)
- Direct pumping
Note: The Lake Package has only been successfully implemented with Visual Modflow Version 4.1. Trials with later versions of Visual Modflow have not been successful. However, it can also be run through Modflow 2000 or Modflow 2005 through the command prompt.

Implementation of the lake package occurs as follows:

1) The Lake Package is activated in the model via the addition of the “Nowergup.LAK” file in the model directory.

2) In addition the following line needs to be added to the “Nowergup.MODFLOW.IN” file or the “Nowergup.NAM” file if running through the command prompt:

   \begin{verbatim}
   LAK 32 '...filepath../Nowergup.LAK'
   \end{verbatim}

3) The LAK file can be manipulated manually via a text editor and the key inputs are highlighted in Figure 63. Alternatively, a spreadsheet and macro has been created that will automatically create the “Nowergup.LAK” file. This spreadsheet “LAK_FILE_CREATOR.xls” contains three worksheets. The first two are input sheets which enable the user to specify rainfall, evapotranspiration and artificial maintenance pumping rates. The third is an output sheet that is read by the macro. The macro also reads from the file “Template.LAK” so please do NOT change the template file. There are two directory references within the macro code that will need to be updated prior to running on a new system.

4) When entering the “Run” menu in Visual Modflow, modflow should detect the LAK file and will ask whether or not to include it in the simulation. Select “YES”.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{Diagram showing line numbers and key inputs for Lake Nowergup implementation.}
\end{figure}
Figure 63 Structure of the Lake Package Input file “Nowegup.LAK”

- Inputs for Stress Period No. 1
  - Col 1 – Rainfall (m/day)
  - Col 2 – Evap (m/day)
  - Col 3 – Rainfall Runoff Factor
  - Col 4 – Pumping (m$^3$/day)

  (repeated for every stress period in the model run)
D.3.4 Recharge, Evapotranspiration and Landuse Change

The impacts of landuse change are modelled via changes to recharge and evapotranspiration. Both of these inputs can be modified through Visual Modflow, however, some excel spreadsheets with macros have been developed which can speed up the manipulation of this data. More specific details are as follows:

Any changes to the spatial distribution of recharge or evapotranspiration can ONLY be done through Visual Modflow. None of the spreadsheets or macros has the ability to modify the spatial distribution.

The temporal distribution with recharge or evapotranspiration can be modified through Visual Modflow. However a series of tools have been established which can speed up their manipulation. Three excel workbooks have been developed and are discussed below:

- **Nowergup_Rch.xls**

  This spreadsheet is used to calculate the recharge inputs for each zone within modflow (refer Figure 65). The main inputs are a monthly timeseries of rainfall and the factors used to convert rainfall to recharge. The calculated monthly recharge values from this spreadsheet can then easily be copied directly into Visual Modflow or into VMod_VMP_RCH_EVT_Editor.xls.

**Figure 64 Directory structure and key files for recharge and evapotranspiration**
The first worksheet in this file has an identical structure to the Nowergup_Rch.xls (refer Figure 66). Key inputs are monthly pan evaporation and a reduction factor to account for the fact that modflow models groundwater ET not total ET.

The calculated ET from this workbook can be copied directly into Visual Modflow.

There is also an additional worksheet titled “EVT_Macro_Input”. This worksheet simply reformats the columns to include the ET extinction depth (always set to 2m in this model) which enables easy copying into ‘VMod_VMP_RCH_EVT_Editor.xls’.

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**Figure 65. Screenshot of the Nowergup_Rch.xls**

**Nowergup_EVT.xls**

The first worksheet in this file has an identical structure to the Nowergup_Rch.xls (refer Figure 66). Key inputs are monthly pan evaporation and a reduction factor to account for the fact that modflow models groundwater ET not total ET.

The calculated ET from this workbook can be copied directly into Visual Modflow.

There is also an additional worksheet titled “EVT_Macro_Input”. This worksheet simply reformats the columns to include the ET extinction depth (always set to 2m in this model) which enables easy copying into ‘VMod_VMP_RCH_EVT_Editor.xls’.
Figure 66. Screenshot of the Nowergup_EVT.xls

VMod_VMP_RCH_EVT_Editor.xls

DISCLAIMER: This workbook contains complex macros that should only be used if you have a good understanding of Visual Modflow and preferably the functionality of the key input files for both Visual Modflow and Modflow 2000.

This workbook was created to enable rapid adjustment to recharge and/or evapotranspiration timeseries. It CANNOT change the spatial distribution of zones, only the temporal. Its structure consists of 5 worksheets backed by 11 macros (only four of the macros are relevant to users, the remainder are called upon automatically if required).

The first worksheet is titled ‘Macro Inputs’ (refer Figure 67). This can be considered as the control room for running the macros. The inputs to this worksheet are the file paths to the relevant input and output files. The yellow boxes represent possible input files, the blue are possible output files.
The most common steps for using this spreadsheet are described below:

**Step 1** – Ensure the model you are trying to edit is NOT open in Visual Modflow.

**Step 2** – Update all necessary file path references. The input files need to refer to the model you are currently trying to edit. The output files can have any name. It is strongly recommended that you do NOT use the same file name as the input file, if you do it will be overwritten and unrecoverable if you want to change back.

**Step 3** – Run the first macro by clicking the button called “Extract Current VMP Data”. This will clear and then update the contents of the four additional worksheets in this workbook (titled Ks, Ss, Rch and EVT). The worksheets ‘Ks’ and ‘Ss’ can be used to manipulate the hydraulic conductivity and storage parameters, however this should not be necessary for running the Nowergup scenario models.

**Step 4** – Update the recharge zones’ time series as required. This is simply done in the ‘Rch’ worksheet. After successful completion of steps 1 to 3, the worksheet should look like Figure 68. The first two columns are the start and end day of each stress period. Then each column thereafter stores the timeseries recharge data for each recharge zone. This data can be edited as required as long the structure of the sheet does not change. You may choose to use “Nowergup_Rch.xls” to help in this process (as described earlier).
Step 5 – Update the evapotranspiration zones’ timeseries data. After successful completion of steps 1 to 3 the ‘EVT’ worksheet should look like Figure 69. It is similar to the ‘Rch’ worksheet except that there are two columns for each EVT zone. The first has the EVT vale and the second has the EVT extinction depth (hence in the case of the Nowergup model every second column is a column of 2’s. Again these EVT and extinction depth numbers can be edited as required as long as the structure of the worksheet does not change. You may choose to use “Nowergup_EVT.xls” to help in this process (as described earlier).
Step 6 – Once all relevant edits have been made to the recharge and/or EVT data the next step is to create a new VMP file (this is the Visual Modflow input file which stores both recharge and EVT input data). This file is created by returning to the ‘Macro Inputs’ worksheet. Then you need to ensure that the output file path is correct (under VMP File Out). Then run the “Write New VMP File” macro.

For the purpose of the Nowergup model, this is the useful limit of this workbook. There are additional macros however these are not recommended for use with the Nowergup model.

Step 7 – Copy the created VMP file to the relevant model directory and open the model in Visual Modflow. It is always good to check in Visual Modflow that the edits have occurred correctly before running the model.
D.3.5 Groundwater Abstraction

Groundwater abstractions are modelled through the modflow “WELL” package. Individual bores can be adjusted within Visual Modflow however this may not be appropriate for large scale changes such as to all private bores. For large changes to the private pumps, such as increasing or decreasing all bores by a certain percentage, three tab delimited text file “.txt” are provided. These are:

- Private_Pumps_Scn_100%.txt (private abstractions at 100% of current levels)
- Private_Pumps_Scn_80%.txt (reduce current levels of private abstractions by 20%)
- Private_Pumps_Scn_100%_NO_LAKE.txt (private abstractions at 100% of current levels but with the Lake Nowergup supplementation bore switched off)

Each of these allows easy importing into Visual Modflow through the standard well menu. The structure of these files is as follows:

- Column 1 – Bore ID
- Column 2 – Easting
- Column 3 – Northing
- Column 4 – Top elevation of screen
Column 5 – Bottom elevation of screen
Column 6 – Layer Reference (indicative only)
Column 7 – Start of stress period (day)
Column 8 – End of stress period (day)
Column 9 – Pumping rate (l/sec) (negative indicates abstraction)

If, for example, the user wanted to reduce all private abstractions in the model by 50%, it is possible to open these txt files in excel, multiply column 9 by 0.5, resave as a tab delimited text file and then re-import into Visual Modflow.

The same can be done with public abstractions. Here, the relevant file is “Public_Pumps_Scn_Input.csv”. The column structure is the same as per the private abstraction bores.

Note: The Lake Nowergup supplementation bore is included in the Private Pumps input files. Therefore if you increase or decrease all private pumping, the supplementation well will also change, which may not be a desired result. The best way to remedy this is to modify the bore directly in Visual Modflow. It is important to remember that the pumping rate for the supplementation bore should be the same as the pumping rate going into the lake (i.e. you need to edit both the well input and the lake package input if you want to change the supplementation regime)

D.4 Model Outputs

Note: It is possible to load, view and export almost all model outputs within the standard Visual Modflow output screen. The only exception is the lake water levels. These are sourced from the modflow listing file “Nowergup.LST” in the model directory. The programs described in this section can extract this information automatically.

D.4.1 Directory Structure
The model outputs folder contains all post processed outputs from the calibration model and also the scenario models run to date. In addition the post processing utilities and spreadsheets used are provided in the top directory “Model Outputs” and sub-directory “Hydrograph Extractor”.

D.4.2 Hydrograph Extractor
As the title suggests, the folder Hydrograph Extractor contains a program that is used to extract hydrograph data out of the raw modflow output files. The program titled “mod2smp.exe” is freeware (available on the internet) and was developed by John Doherty. User manuals for this program (and others created by John Doherty) have been supplied in this directory.

All the necessary input files to run this program have already been created and are stored in the “Hydrograph Extractor” sub-directory. Therefore the following steps can be followed to quickly extract model hydrographs without the need to enter Visual Modflow:

**Step 1** – Run the hydrograph extractor programs. Two batch files have been created, “Extract_Hydrographs_Calib.bat” and “Extract_Hydrographs_Scenarios.bat”, which can be used to automatically call upon the mod2smp program and all its necessary inputs. Batch files are run like executables, simply double-click on the relevant batch file and the programs will commence.

**Step 2** – Open relevant hydrograph spreadsheet (either “Calibration_Bore_Hydrographs.xls” or Scenario_Bore_hydrographs.xls”). Navigate to the worksheet titled “Map View”

*Important: Before step 3 is completed for the first time it is necessary to update two file path references in the macro in this workbook. This is done through the Visual Basic editor.*

**Step 3** – Click once on the button titled “Update Hydrographs”. This will start a macro the sources the outputs from Step 1 and then inputs them into this workbook such that the hydrographs are automatically updated. Both the hydrographs in the worksheet “Map View” and “Map View Lake” are updated.

**Step 4** – By successfully completing steps 1, 2 and 3, the worksheet “Lake Outputs” will have also been automatically updated. This worksheet summarises the timeseries outputs from the Lake Package. However, the lake package outputs are NOT in standard units. They are provided as a instantaneous rates as at the last time step of each stress period. Therefore, most of this information is not of specific use. However, the stage, surface area and volume columns are useful as they give the instantaneous lake level at the end of each stress period.

D.4.3 Lake Water Balance
Following on from Step 4 described above, due to the lack of direct monthly water balance outputs from the Lake Package, the extraction of lake water balance results requires the user to follow a complex process as follows:

**Step 1** – Complete steps 1 to 4 described in section D.4.2.
Step 2 – Open “Scenario Model Outputs > Lake_Outputs_Scenario.xls”. This is the file which was developed to gather and calculate the lake water balance outputs.

Step 3 – Copy the table from step 4 in the previous section into the sheet “Lake_Outputs”

Step 4 – Update the rain and evaporation data in columns K and L. This data needs to be sourced from “LAK_FILE_CREATOR.xls” described previously in section D.3.3.

Step 5 – Update the Lake Seepage data. This step can only be done through the Visual Modflow results menu. Once in the Visual Modflow results you need to plot the timeseries water balances and the export the Lake Seepage cumulative timeseries data, both ‘Out’ and ‘In’. Copy this data into columns AD and AE in the “Lake_Outputs” worksheet.

If completed successfully the above steps will have updated the timeseries charts in the worksheet titled “Timeseries charts”.

D.4.4 Scenario Model Outputs
All of the key output files from the scenario modelling are stored in the “Scenario Model Outputs” sub-directory.

Also in this sub-directory is the file “Pot_Surf_Diff_Plots.srf”. This is the surfer file used to create all the potentiometric surface maps for the scenario models. This is a relatively quick process but requires a good understanding of the Surfer software and Visual Modflow (to output the relevant grids).

D.5 MODELS
D.5.1 Directory Structure
The “MODELS” directories are relatively self explanatory in that they store all of the model files. The following models are stored:

- The calibration model
- The steady-state calibration model
- The scenario model (currently set with inputs for the base case)
- All completed scenario models

Each of the model folders contains all the necessary input files to open, run and view the results of the models through Visual Modflow (including the Lake Package). The executables for running modflow 2000 “mf2k.exe” and modflow 2005 “mf2005.exe” are also provided and therefore the models can also be readily run through the command prompt.

Initial Heads for each of the models is provided in the sub-directories titled “Initial Heads”. The calibration model uses the steady-state model outputs as initial heads. The scenario models should be set to the final time-step of the calibration model run.
D.5.2 Running the models

The Lake Nowergup model was built on the Visual Modflow 4.1 platform which runs with Modflow 2000 Version 1.15.00. Flowing the completion of the modelling process it has been discovered that later versions of Modflow 2000 (and therefore also later versions of Visual Modflow) have actually introduced changes to the lake package which have introduced instabilities in models running with lake package. As a result, the Lake Nowergup model cannot be run within Visual Modflow 4.2, 4.3 or VM2009. However a work around solution has been developed.

The models can be opened, viewed and edited in any version of Visual Modflow (although not yet tested with VM2009).

Once a model has been setup in Visual Modflow and is ready to run the following process should be followed:

1) In Visual Modflow, enter the run menu and translate the model (but do not run the model)
2) The translation process will have created all the necessary modflow input files required to run modflow externally from Visual Modflow
3) Close Visual Modflow
4) Navigate to the relevant model directory folder
5) Run the program “mf2k.exe”. This will bring up the dos command prompt window.
6) Modflow will prompt the user to enter the name of the relevant modflow name file. In this case enter “Nowergup”. The model will commence running. Scenario model run time can be expected to be in the order of 1.5 to 2 hrs.
7) When the model is finished a successful model termination message will be shown in the command prompt window.
8) The can then be reopened in Visual Modflow and the model outputs can be viewed using the standard modflow features in the output menu. Model results can also be viewed using the utilities created for this project and described throughout this report.

D.6 Troubleshooting

The Lake Nowergup model does occasionally stop running due to non-convergence. The cause of this appears to be due to the very steep gradients observed at the contact of the sands and the limestone. This is replicated in the model by a contact between a low permeability material and a very high permeability material (a common cause of instability in modflow). During the calibration process it was necessary to create a ‘highly strung’ model in order to replicate these steep gradients.

Due to the above problem it was necessary in some of the scenario models to adjust the solver parameters to improve model stability. The Lake Nowergup model is set to run using the PCG solver package. Therefore the most common means of improving model stability is to reduce the damping factor slightly. The main impact of this is that it slows down the model run time. A secondary impact can be an increased risk of mass balance errors, however there was no evidence of this being a problem in the 7 scenarios run to date.

With regards to all programs, macros and spreadsheet calculations described in this report, all attempts have been made to ensure these are robust and transportable for easy use across the different scenarios. However, it

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is always important that the user complete a reality check for all results to ensure that the outputs (or inputs) are being reported correctly.