Development of Local Area Groundwater Models - Gnangara Mound

LAKE BINDIAR MODEL REPORT

- Final
- December 2009
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December 2009

Prepared for
Department of Water, Western Australia

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1. Introduction

1.1. Context – The Gnangara Mound

The aquifers of the Gnangara Mound are the largest source of water for the Perth Metropolitan Area. The groundwater stored in the Gnangara system provides the people of Perth with approximately 60 percent of their 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 important environmental assets including wetlands and native vegetation.

In recent times a combination of declining rainfall and increasing demand for water resources is placing increasing stresses on the aquifers of the Gnangara Mound. 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 a key 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

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. Generally it is agreed that its relatively coarse resolution precludes its use for detailed local scale resource management objectives. The current project is aimed at formulating and calibrating local scale models that include sufficient resolution and detail for use as a local scale resource management tool.

1.2. This Project – Local Area Groundwater Models

Sinclair Knight Merz (SKM) has been engaged by The Department of Water to construct three local scale 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 in most areas) and
reliability for assessing environmental, licensing and trading issues. Three models are being developed for the following areas (Figure 1):

- Lake Nowergup
- Lake Bindiar
- Lexia Wetlands

The models are each designed as MODFLOW numerical finite-difference groundwater models. Each have been constructed within the Visual Modflow framework.

This report describes the Lake Bindiar groundwater model – its conceptualisation and model development, the calibration procedures carried out, the principal results and findings from the calibration process, and results from predictive analysis.
Figure 1 Regional locality map of the LAM's
2. 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. Allan (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 Davidsons 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.
3. **Regional Hydrogeology**

3.1. **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 Pinjara 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.

3.2. **Geology**

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

3.2.1. **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)
3.2.2. Stratigraphic Summary

The stratigraphic sequence for the Perth Basin is provided in Table 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 Formation’. 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.

Tamala Limestone

The Tamala limestone is present along the coastal strip of the Perth Region. It contains various proportions of quartz sand, shelly fragments and minor clayey lenses. At the base of the sequence, glauconite and phosphatic nodules are often present. The limestone 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.
Table 1. Stratigraphic sequence of the Perth basin (from Davidson, 1995)

<table>
<thead>
<tr>
<th>Era</th>
<th>Age</th>
<th>Stratigraphy</th>
<th>Max Thickness (m)</th>
<th>Lithology</th>
<th>Aquifer</th>
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<td>Cenozoic</td>
<td>Quaternary - Late Tertiary</td>
<td>Safety Bay Sand</td>
<td>Qs 24</td>
<td>Sand and shelly fragments</td>
<td>Superficial aquifer</td>
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<tr>
<td></td>
<td></td>
<td>Becher Sand</td>
<td>Qc 20</td>
<td>Sand, silt, clay and shell fragments</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tamala Limestone</td>
<td>Qt 110</td>
<td>Sand, limestone, minor clay</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bassendean Sand</td>
<td>Qd 80</td>
<td>Sand and subordinated silt and clay</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gngara Sand</td>
<td>Qn 30</td>
<td>Sand, gravel and subordinated silt and clay</td>
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<td></td>
<td>Guildford Clay</td>
<td>Og 35</td>
<td>Clay with subordinate sand and gravel</td>
<td>Local confining bed</td>
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<tr>
<td>2</td>
<td>Yoganup Formation</td>
<td>Ty 10</td>
<td></td>
<td>Sand, silt, clay and pebbles</td>
<td>Superficial aquifer</td>
</tr>
<tr>
<td>2</td>
<td>Rockingham</td>
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<td>Limestone, sand, shells and clay</td>
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<td>Kings Park Formation</td>
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<td>Cretaceous</td>
<td>Lancelin Formation</td>
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<td>Poison Hill Greensand</td>
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<td>Sand, silty, clayey and glauconitic</td>
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<td>Gingin Chalk</td>
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<td>88</td>
<td>Molecap Greensand</td>
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<td>98</td>
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<td>Kardinya Shale Member</td>
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<td>Pinjar Member</td>
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<td>Marginiup Member</td>
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3.3. **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 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 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.

<table>
<thead>
<tr>
<th>Age - Tertiary</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></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></td>
<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>
</tr>
</tbody>
</table>
## 3.4. 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 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. Table 3 is a summary of this work and other available publications.

Table 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>
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 .

Additional Recharge Mechanisms

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

3.5. 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.
Figure 7 Monthly averages of Pan Evaporation (Source: Bureau of Meteorology - Perth Regional Office Station No. 009034, 1946 - 2001)

Figure 8 Annual pan evaporation for Perth (Source: Bureau of Meteorology - Perth Regional Office Station No. 009034)
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.
4. Conceptual Model

4.1.1. Overview

This section describes the conceptualisation of groundwater systems in the Lake Bindiar region and documents a proposed approach for the development of the numerical model. It is noted that some of the proposed modelling features may not have been adopted in the final calibrated model.

The location of Lake Bindiar, and the local area model boundary is shown in Figure 9. The area is approximately 60km north of Perth located between the coast and Chandala Brook. It is located within the Yarragadee impact area. The lake is classified as Dampland (Remnant Wetland) and has been identified as a Conservation Category lake. There is a scarcity of detailed hydrogeological data in the area, although it is noted that there has been a recent effort to drill observation bores and to start collecting data on both the saturated and unsaturated zones in this area. Groundwater hydrographs from the Lake Bindiar region indicate that groundwater levels below the lake are dropping.

In Figure 9 there are two boundaries shown for the Lake Bindiar area. One is the LAM boundary that covers an area of approximately 10 km by 10 km centred on the Lake. The other larger area is the proposed model area. This much larger model area is proposed in an effort to include sufficient groundwater extraction to enable the model to correctly respond to extraction occurring outside the LAM area. The extended model area is considered necessary because the smaller LAM study area contains no groundwater extractions and yet groundwater hydrographs measured in bores near the Lake show strong declines (particularly in the deeper wells that intersect the Leederville and Yaragadee Formations) that are most likely partially attributable to groundwater extraction. The Lake Bindiar model area is particularly susceptible to extraction derived drawdown because there are no aquitards present in this area. The shallow Superficial Formation aquifers are in direct hydraulic connection with deeper aquifers that are being heavily pumped to the south of the LAM for municipal water supply purpose. The issue is discussed in more detail in Section 4.2.
4.1.2. Physiography

Lake Bindiar is approximately 60km north of Perth midway between the coast to the west and the Darling Scarp to the east. The area exhibits little relief, and is dominated by either plantation forestry or native vegetation. Lake Bindiar is of note through the existence of diatomaceous soils that have an extremely high field capacity. These soils affectively store large quantities of water and their influence of the hydrogeology of the area is both to reduce the amount of recharge that percolates to the water table and to increase the water content of the unsaturated zone above the water table.
4.1.3. Lake Bindiar Hydrogeology & Hydraulic Parameters

The following hydrogeological units are present in the Lake Bindiar LAM. These are described below in order from shallowest to deepest.

The Superficial Formation

Within the Lake Bindiar study area the Bassendean Sand accounts for most of the surface geology with some Tamala Limestone present in the western edge of the study area. The Tamala Limestone consists of fine to medium grained shelly fragments and quartz sand with minor clay lenses.

The superficial aquifer in the Bindiar LAM varies in thickness from approximately 40m at the western extremity to 80m in the east. The horizontal hydraulic conductivities for the Bassendean Sand range between 10 and 50 m/day, with an average of 15 m/day (Davidson & Yu, 2008).

An issue that has been identified in the area is the presence of diatomaceous soils. The spatial extent and thickness of this soil unit needs to be determined through additional consultation with DOW. It is surmised that where the diatomaceous soil exists the soil acts to retain large volumes of water within the unsaturated zone, thereby limiting the percolation of water to the saturated zone. To appropriately reflect the behaviour of the groundwater system it will be necessary to understand the nature of recharge processes where the diatomaceous soil unit is present. This may be accomplished through the use of one dimensional column modelling of the unsaturated zone to establish the relationship between surface conditions (climate/wetland levels) and recharge to the saturated zone.

Leederville Formation

Within the Lake Bindiar LAM area the superficial aquifer is underlain by the Pinjar Member in the east and the Wanneroo Member in the west. Both of these units are within the Leederville formation. Underlying these two units is Marginiuap Member, also part of the Leederville formation. The Mariginup Member exists over almost all of the LAM area, except for a localised area near the eastern boundary of the LAM where the Wanneroo Formation is in direct contact with the Yarragadee formation. The Leederville Formation consists predominantly of discontinuous, interbedded sandstones, siltstones and shales. Within the Lake Bindiar LAM the formation varies in thickness from 50 to 200m. There are no significant confining beds between the superficial aquifer and the Leederville formation within the Lake Bindiar LAM.

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 $1 \times 10^{-4}$ is believed to be appropriate for the Leederville Formation (Davidson & Yu, 2008)

**Parmelia Formation**

Underlying the Leederville Formation in a small area covering the south eastern corner of the Lake Bindiar LAM is the Parmelia Formation. The Parmelia aquifer comprises the Parmelia Sand Member. The Carnac member of the Parmelia Formation is a local confining bed which consists of dark grey silty shale similar to that of the South Perth Shale and varies in thickness within the LAM from 0 to approximately 50m.

**Yarragadee Formation**

The Yarragadee Formation underlies the entire Lake Bindiar LAM varying in thickness from approximately 1800 to 2000m. Except for the south eastern corner of the study area the Yarragadee Formation is in direct contact with the overlying Leederville Formation, which in turn is in direct contact with the overlying Superficial Formation. In the south eastern corner of the LAM the Yarragadee Formation is overlain by the Parmelia Sand formation which is confined by the Carnac Member.

### 4.1.4. Lake Bindiar Groundwater Levels

Piezometric level monitoring within the vicinity of the Bindiar Lake LAM provided by the Department of Water includes ten observation bores at the locations shown in Figure 10. These bores vary in screen depth from approximately 45 to 725m.
The observation bore hydrographs are included in Figure 11 to Figure 20. It is clear from these hydrographs that there has been a decline in piezometric levels throughout the study area over the last 20 to 30 years. This decline in groundwater levels increases with measurement depth with the shallower bores (up to approximately 70 m deep) recording decreases of 5m or so since the mid 1970s. Deeper bores measuring levels in the Leederville and Yarragadee Formations show much greater decline of up 20m.
- Figure 11 Observation 6165073 - AM14 hydrograph

![AM14 Hydrograph](image1)

- Figure 12 Observation 61710031 - YY3 (I) hydrograph.

![YY3 Hydrograph](image2)
Figure 13 Observation 61710032 – YY3 (O) hydrograph

61710032 YANCHEP MONITORING YY3 (O)
Easting = 374919.00 Northing = 6516924.00 Zone = 50 TOC = 53.5m AHD WIN SITE ID = 6278

Screen Elevation: -17.88 (m AHD)

Figure 14 Observation 61710046 – YY4 (I) hydrograph

61710046 YANCHEP MONITORING YY4 (I)
Easting = 380893.00 Northing = 6516502.00 Zone = 50 TOC = 52.017m AHD WIN SITE ID = 6292

Screen Elevation: 2.89 (m AHD)
Figure 15 Observation 61710047 – YY4 (O) hydrograph

Figure 16 Observation 61710081 – YY7 (I) hydrograph
Figure 17 Observation 61710082 – YY7 (O) hydrograph

Figure 18 Observation 61715004 – AM13 hydrograph
Figure 19 Observation 61715010 – AM9 hydrograph

Figure 20 Observation 61715016 – AM10 hydrograph
4.1.5. **Groundwater Flow**

The observation hydrographs shown in Figure 11 to Figure 20 indicate that groundwater flow in the area is from east to west. With levels declining by 20m from the eastern extremity (bore AM10 shown in Figure 20) to the western extremity (bore YY3(O) shown in Figure 13).

- **Figure 21 Bindiar Model Area Regional Groundwater Levels**

(Source: Department of Water – WA)
4.1.6. Local Climate - Lake Bindiar Rainfall

In addition to the analysis for the Perth rainfall site, the Bureau of Meteorology site 9018 (Gingin) has been analysed for use in describing local conditions near Lake Bindiar. This site has been continuously monitored since 1906. The annual average rainfall is 728mm/year. An analysis of the daily cumulative rainfall residual (compared to the long term average of 1.99 mm/day) is given in Figure 22. This figure clearly shows that the period from 1915 to 1934 is relatively wet compared. This period is followed by a 40 year sequence of more or less average rainfall conditions. Since the mid 1970s the rainfall at this site has been consistently below average. This extended period of relatively dry conditions would account for at least part of the decline in groundwater levels observed within the vicinity of the Lake Bindiar area.

![Figure 22 Cumulative rainfall residual at rainfall site 9018](image)

4.1.7. Landuse & Recharge Mechanisms

The Lake Bindiar area land use maps (Appendix A) highlight the large areas devoted to plantation forestry. Additional land use information will be obtained to further characterise the land use in the Lake Bindiar area, however it appears from LANDSAT imagery that apart from plantation forestry which occurs immediately west of Lake Bindiar, the remainder of the area is predominately native vegetation.

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4.1.8. **Discharge Mechanisms**

Discharge mechanisms for all three LAM’s are discussed in a regional perspective in Section 3.5. The Lake Bindiar study area does not include the coast line and accordingly much of the discharge from the area is in subsurface flow towards the west.

4.1.9. **Bindiar Groundwater Abstractions**

There are no groundwater abstractions within the Bindiar LAM area. The public and private abstraction bores located in the extended model area will only be used in the model to assess the influence of pumping on the Bindiar LAM area.

![Figure 23 Bindiar Groundwater Abstractions](image)
4.2. Proposed Model Structure

4.2.1. Proposed Model Domain and Boundaries

The model area was initially proposed to cover a 10 x 10 km area centred on Lake Bindiar. It is however noted that there are no extraction wells located within this model domain. Should the observed declines in groundwater levels in this area be linked to groundwater extraction in the superficial formation, or deeper aquifers then model calibration will result in an erroneous outcome. Adjustments in other model inputs must be made to compensate for the lack of groundwater extraction to drive the observed declines in groundwater level.

A numerical algorithm of the THEIS (1935) analytical equation has been developed to estimate individual drawdown at the centre of the Lake Bindiar LAM that results from abstraction wells that are external to the LAM area. A spatial distribution of the contribution of each public bore on the total drawdown estimated at the Lake has been developed. Figure 24 shows the ratio in percent of drawdown contributed by each public well to the total drawdown.

In view of these results, the Bindiar model domain was extended south and west in order to incorporate the most influential groundwater extraction bores (contribution > 1 % of total drawdown). The extended model has coarse grid cells in the region outside the specified study area and no attempt has been made to calibrate the model by matching to calibration bores outside in the study region. The purpose of the extension is simply to capture sufficient levels of groundwater extraction to ensure that if the declines in groundwater level observed in the Lake Bindiar LAM are linked to remote extractions then the model can adequately represent this phenomenon. Model outputs and model calibration are focussed on the LAM model area and the model has a fine grid of 100 x 100 m cells in the LAM area and a much coarser grid of up to 5 x 5 km for the rest of the model domain.

Figure 25 shows the proposed Lake Bindiar numerical model grid.
Figure 24 Public Bores Contribution to total Drawdown at the LAM Boundary
4.2.2. Proposed Model Layering

The definition of the model layer structure is based on the PRAMS model Davidson & Yu (2008) with modifications to reflect the modelling focus of this study where the shallow groundwater processes are of particular focus. The model layers are summarised below:

- Model Layer 1 to 5: Superficial Aquifer (PRAMS layers 1 to 3)
- Model Layer 6: Leederville Formation (PRAMS layers 4 to 8)
- Model Layer 7: Carnac Formation (PRAMS layer 9)
- Model Layer 8: Parmelia Aquifer and Yarragadee Formation (PRAMS layers 9 to 13)

Model Layer 7 is the Carnac formation which is a confining layer between the Yarragadee formation and the Leederville Formation. This unit is present over part of the south east corner of the LAM.
4.2.3. Recharge

A unique feature of the Lake Bindiar region is the occurrence of diatomaceous soils that have are believed to have a strong influence on rainfall derived groundwater recharge. It is understood that these soils have a high water holding capacity and intercept a high proportion of rainfall before it is able to percolate to the water table. The recharge package in the Lake Bindiar model needs to take into account the properties of these soils. An unsaturated zone model was proposed to help model the infiltration, storage and movement of water in and through the vadose zone above the water table.

Land use will be incorporated in the unsaturated zone model with the effects of historic changes in land use being a feature of the transient calibration of the groundwater model. This approach will also allow for future land use change to be effectively incorporated in predictive scenarios.

4.2.4. Evapotranspiration

Evapotranspiration from the water table can be applied to the model through the modflow Evapotranspiration (EVT) package. Given there is little long term variability, a repeating annual cycle as represented previously in Section 3.4 is applied across the model domain.
The implementation of the EVT package will depend on successful model convergence – i.e. it may not be implemented in the final calibrated model.

4.2.5. Groundwater Abstractions

It is proposed only public abstractions are accounted for in the model (recognising that all of the abstraction is located outside the LAM in the model domain featuring coarse cells). Groundwater extraction will be included in the model in the Modflow Well Package.

The data available for the public bores is considered to be of high quality, including screened aquifer and metered pumping rates. This information can be applied directly to the model.

Private abstractions will not be included in the model because it occurs predominantly from the superficial aquifer and is not thought to influence groundwater flow in the LAM.

*Figure 27 Location of Abstraction Bores in the Bindiar Model Area*
5. Model Development and Calibration

5.1. Lake Bindiar Model Description

5.1.1. Overview

As documented in the conceptual model (Section 4), the Lake Bindiar LAM has been modelled as part of a larger regional model to capture the impacts associated with the significant levels of groundwater extraction, which occur outside the boundaries of the LAM. No extraction occurs within the LAM, yet there are significant drawdown impacts evident in observation bores. The model extent of the LAM and the extended model boundary (to capture regional pumping effects) is shown in Error! Reference source not found.. Model calibration was an iterative, two-stage process. Firstly, a steady-state model was developed and calibrated to establish the initial groundwater conditions at the start of January 1991. The second step was to calibrate a transient model for the period of January 1991 to December 2007. This step also involved recalibrating the steady-state model to develop a consistent set of aquifer parameters and boundary conditions across both models that satisfy calibration.

5.1.2. Lake Bindiar Model Domain, Layer Structure and Boundaries

The Lake Bindiar model domain was rotated approximately 20 degrees in a clockwise direction to align with the predominant groundwater flow direction (toward the coast) to speed-up solution times. The model grid comprises varying cell sizes. A fine grid of 100 x 100 m cells occurs in the LAM area, which grades to a coarser grid of up to 5 x 5 km in the outer regions of the model.

As detailed in the conceptual model report (SKM, 2009), the model layer structure was based on the structure of the PRAMS model (Davidson & Yu, 2008) with modifications to reflect the modelling focus of this study (i.e. shallow groundwater processes are of particular focus). The layer structure is summarised below:

- Model Layer 1 to 5: Superficial Aquifer (PRAMS layers 1 to 3)
- Model Layer 6: Leederville Formation (PRAMS layers 4 to 8)
- Model Layer 7: Carnac Formation (PRAMS layer 9)
- Model Layer 8: Parmelia Aquifer and Yarragadee Formation (PRAMS layers 9 to 13)

The major model boundaries are depicted in Figure 28. A constant head boundary of 0 mAHD is aligned with the coast to simulate coastal discharge, and is present in the superficial aquifer (Layer 4). No coastal boundary is specified for the deeper layers (i.e. the Leederville and Yarragadee formations). In these layers coastal discharge will occur toward the constant head boundary in the Superficial Aquifer, with the flux regulated by the vertical hydraulic conductivity.
A general head boundary with a north-south gradient is specified for the eastern model boundary where it coincides with the Chandala Brook. There is assumed to be no flow across the northern model boundary.

The Swan-River, in the south of the model, is represented by a drain cells in Layer 1. Drain cells occur elsewhere in the model (in Layer 1) where surface watercourses are present. Drain cells only receive groundwater discharge when groundwater levels are greater than adjacent drain cells, and have no leakage function to recharge the groundwater. They are thus representative of gaining streams. No surface water features are modelled within the LAM and there are no specific recharge or discharge functions for Lake Bindiar or Yeal Swamp – although recharge will be moderated at these locations by the presence of diatomaceous soils, which were factored into the recharge model.
Figure 28 Bindiar model grid and boundary conditions

- Constant Head Boundary, Layer 4 (Superficial Aquifer) – 0 m AHD
- General Head Boundary, Layer 6 (Leederville Aquifer)
- No Flow Boundary
- Drains in Layer 1 (Superficial Aquifer) to align with surface water features
5.1.3. Recharge Mechanisms

Diffuse rainfall recharge for the Lake Bindiar LAM was conceptualised as being spatially and temporally complex due to frequent changes in land use and the occurrence of diatomaceous soils in parts of the landscape. An unsaturated zone model (supported by GIS analysis) was developed to capture this complexity and to quantify recharge for the groundwater flow model during the calibration period and for the period beforehand (1985 – 2007). Appendix A outlines the methodology, assumptions and outcomes of the GIS analysis and unsaturated zone modelling undertaken.

Recharge zones in the LAM were based on GIS analysis (Appendix A) that identified regions with the same soil type, land use, and land use history. A description of each recharge zone is shown in Appendix A. These zones were represented by a single ArcGIS shapefile that was directly imported to Visual Modflow using the data import function. The resulting recharge zonation for the LAM is shown in Figure 29. The zonation appears to be somewhat scattered because the generalisation process in ArcGIS involved the integration of multiple layers and datasets of land use history, and there was no attempt to manually smooth the results. It is, however, likely that the outcome provides a more accurate representation of the spatial complexity in recharge.

In the outer regions of the model, land use was assumed to be either Banksia woodland or Pine Forestry, according to the spatial coverage of Pine Plantation required.

Rainfall scaling factors were output from the unsaturated zone model for each the key land uses (Table 4). Unlike the Lexia and Nowergup models, these scaling factors were not manipulated as part of the calibration process because a physically robust process had been used to calculate the scaling factors externally.
To calculate recharge rates, these factors were multiplied by rainfall data from a synthetic rainfall dataset (a SILO\(^1\) patched point-dataset based on the centroid of the LAM). For the steady-state model, average annual rainfall during the 4 year lead-up period to January 1991 was used (1986-1990). In recharge zones where a land use change occurred during this timeframe – e.g. for the area of Banksia that was initially cleared but experienced regrowth during 1986-1990 (Cleared / Banksia) – an average scaling factor was used that was weighted according to the time of the land use change. For the transient model, monthly rainfall totals were multiplied by the scaling factors as required.

Table 4 Rainfall recharge scaling factors as output from the unsaturated zone model

<table>
<thead>
<tr>
<th>Rainfall recharge scaling factors (% Rainfall)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleared / Grassland</td>
</tr>
<tr>
<td>50%</td>
</tr>
</tbody>
</table>

5.1.4. Discharge mechanisms

Evapotranspiration

Direct evapotranspiration from the water table was not modelled because the MODFLOW evapotranspiration package caused model instability due to dry cells in the upper layers of the model in the superficial aquifer. However, because the depth to the water table is generally greater than 10 m across the LAM (i.e. deeper than the root zone), it is not expected there would be direct evapotranspiration from the water table. Evapotranspiration from the unsaturated zone was considered as part of the recharge model so this component of the water balance is accounted for.

Groundwater abstractions

Public abstraction data was accessed for the Gnangara mound and imported to visual modflow. This data is summarised in Figure 30, which shows that abstractions doubled during the calibration period. Private abstraction was not included in the model as this occurs predominantly from the superficial aquifer and was not thought to influence groundwater flow in the LAM.
Lateral discharge

The other major groundwater discharge mechanism in the model is lateral discharge to the ocean (constant head cells), across the eastern boundary (general head boundary) and to gaining streams (drain cells).

Observation Bores

Ten observation bores occur within or in the immediate vicinity of the Lake Bindiar LAM, which were all included in the model as calibration targets (Table 5). The network includes three nested sites: 1) YY4_I and YY4_O; 2) YY7_I, YY7_O and AM9; 3) YY3_I, YY3_O and AM13.

Table 5 Observation bores implemented in the Bindiar LAM

<table>
<thead>
<tr>
<th>Obs Bore ID</th>
<th>Easting</th>
<th>Northing</th>
<th>Top of Screen (mAHD)</th>
<th>Bottom of Screen (mAHD)</th>
<th>Mid-screen point (mAHD)</th>
<th>Model Layer</th>
<th>Aquifer</th>
</tr>
</thead>
<tbody>
<tr>
<td>YY4_I</td>
<td>380893</td>
<td>6516502</td>
<td>11.9</td>
<td>-6.1</td>
<td>2.9</td>
<td>4</td>
<td>Superficial</td>
</tr>
<tr>
<td>YY4_O</td>
<td>380908</td>
<td>6516531</td>
<td>40.6</td>
<td>-39.3</td>
<td>0.6</td>
<td>4</td>
<td>Superficial</td>
</tr>
<tr>
<td>YY7_I</td>
<td>380966</td>
<td>6522451</td>
<td>22.0</td>
<td>-39.3</td>
<td>13.2</td>
<td>4</td>
<td>Superficial</td>
</tr>
<tr>
<td>YY7_O</td>
<td>380987</td>
<td>6522476</td>
<td>51.1</td>
<td>-18.9</td>
<td>16.1</td>
<td>4</td>
<td>Superficial</td>
</tr>
<tr>
<td>YY3_I</td>
<td>374947</td>
<td>6516911</td>
<td>1.2</td>
<td>-13.9</td>
<td>-6.4</td>
<td>5</td>
<td>Superficial</td>
</tr>
<tr>
<td>YY3_O</td>
<td>374919</td>
<td>6516924</td>
<td>-9.4</td>
<td>-27.4</td>
<td>-18.4</td>
<td>5</td>
<td>Superficial</td>
</tr>
<tr>
<td>AM14</td>
<td>386757</td>
<td>6516654</td>
<td>-15.8</td>
<td>-22.6</td>
<td>-19.2</td>
<td>6</td>
<td>Leederville</td>
</tr>
<tr>
<td>AM13</td>
<td>374938</td>
<td>6516946</td>
<td>-337.4</td>
<td>-342.4</td>
<td>-339.9</td>
<td>6</td>
<td>Leederville</td>
</tr>
<tr>
<td>AM9</td>
<td>380987</td>
<td>6522462</td>
<td>-147.1</td>
<td>-152.1</td>
<td>-149.6</td>
<td>6</td>
<td>Leederville</td>
</tr>
<tr>
<td>AM10</td>
<td>392252</td>
<td>6521849</td>
<td>-33.1</td>
<td>-38.1</td>
<td>-35.6</td>
<td>6</td>
<td>Leederville</td>
</tr>
</tbody>
</table>

5.1.5. Aquifer parameters

Aquifer parameters and zones were imported from the PRAMs model. To achieve calibration for this particular model set-up, many of the parameters were altered from PRAMs. The following new hydraulic conductivity zones were also implemented: Zones 17 and 19 in the Superficial Aquifer, and Zone 18 in the Leederville Aquifer.

Hydraulic conductivities

The final calibrated aquifer hydraulic conductivities are listed in the Table 6 and the zonation shown in Figure 31. Whilst broadly similar to the PRAMs model, there are some differences in the hydraulic conductivities that were used. The most notable differences occur in the Leederville aquifer where the horizontal hydraulic conductivities (K_x and K_y) are generally an order of
magnitude higher than they appear in the original version of PRAMs – although these values have been increased in the latest version of PRAMs (Binh Anson, Dept. of Water, pers. comm., 2009). The vertical conductivities are significantly lower than the horizontal hydraulic conductivities. This was necessary to model the vertical gradients observed at two nested observation sites, and was particularly necessary for Leederville and Yarragadee Aquifers which were modelled as single, thick layers.

Table 6 Aquifer hydraulic conductivities for the calibrated Lake Bindiar model

<table>
<thead>
<tr>
<th>Zone</th>
<th>$K_x$ (m/d)</th>
<th>$K_y$ (m/d)</th>
<th>$K_z$ (m/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Superficial Aquifer: Layers 1-5</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 1</td>
<td>10</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>Zone 2</td>
<td>10</td>
<td>10</td>
<td>0.01</td>
</tr>
<tr>
<td>Zone 6</td>
<td>25</td>
<td>25</td>
<td>0.75</td>
</tr>
<tr>
<td>Zone 7</td>
<td>100</td>
<td>100</td>
<td>0.01</td>
</tr>
<tr>
<td>Zone 8</td>
<td>10</td>
<td>10</td>
<td>0.001</td>
</tr>
<tr>
<td>Zone 9</td>
<td>12</td>
<td>12</td>
<td>0.5</td>
</tr>
<tr>
<td>Zone 17</td>
<td>30</td>
<td>30</td>
<td>0.001</td>
</tr>
<tr>
<td>Zone 19</td>
<td>5</td>
<td>5</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Leederville Aquifer: Layer 6</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 3</td>
<td>10</td>
<td>10</td>
<td>0.0001</td>
</tr>
<tr>
<td>Zone 10</td>
<td>20</td>
<td>20</td>
<td>0.001</td>
</tr>
<tr>
<td>Zone 18</td>
<td>25</td>
<td>25</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Carnac Formation: Layer 7</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 11</td>
<td>4</td>
<td>4</td>
<td>0.04</td>
</tr>
<tr>
<td>Zone 12</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Zone 13</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Zone 14</td>
<td>0.01</td>
<td>0.01</td>
<td>0.005</td>
</tr>
<tr>
<td><strong>Parmelia Aquifer and Yarragadee Formation: Layer 8</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 5</td>
<td>0.1</td>
<td>0.1</td>
<td>0.001</td>
</tr>
<tr>
<td>Zone 15</td>
<td>0.1</td>
<td>0.1</td>
<td>0.001</td>
</tr>
<tr>
<td>Zone 16</td>
<td>0.1</td>
<td>0.1</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Figure 31a Hydraulic conductivities in the Bindiar model: South-North cross sections
Figure 6b
Hydraulic conductivities in the Bindiar model: layers 1-4
Figure 6c
Hydraulic conductivities in the Bindiar model: layers 5-8
Aquifer storage parameters

The final calibrated aquifer storage parameters are listed in the Table 7 and the zonation shown in Figure 32. The specific storage ($S_s$) was set to compressibility of water and is most relevant in the deeper layers (6-8) that behave like a confined aquifer in the model. The specific yield is most relevant to the superficial aquifer (Layers 1-5), which will behave as an unconfined aquifer in the model. The $S_y$ was varied as a calibration parameter during the transient calibration process.

Table 7 Aquifer storage parameters for the Bindiar model

<table>
<thead>
<tr>
<th>Zone</th>
<th>$S_s$ ($m^{-1}$)</th>
<th>$S_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial Aquifer: Layers 1-5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 1</td>
<td>$5 \times 10^{-6}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Zone 2</td>
<td>$5 \times 10^{-6}$</td>
<td>0.02</td>
</tr>
<tr>
<td>Zone 3</td>
<td>$5 \times 10^{-6}$</td>
<td>0.0002</td>
</tr>
<tr>
<td>Zone 4</td>
<td>$5 \times 10^{-6}$</td>
<td>0.02</td>
</tr>
<tr>
<td>Zone 5</td>
<td>$5 \times 10^{-6}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Zone 9</td>
<td>$5 \times 10^{-6}$</td>
<td>0.25</td>
</tr>
<tr>
<td>Zone 10</td>
<td>$5 \times 10^{-6}$</td>
<td>0.25</td>
</tr>
<tr>
<td>Zone 11</td>
<td>$5 \times 10^{-6}$</td>
<td>0.4</td>
</tr>
<tr>
<td>Leederville Aquifer: Layer 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 6</td>
<td>$5 \times 10^{-6}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Carnac Formation: Layer 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 7</td>
<td>$5 \times 10^{-6}$</td>
<td>0.3</td>
</tr>
<tr>
<td>Parmelia Aquifer and Yarragadee Formation: Layer 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 8</td>
<td>$5 \times 10^{-6}$</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Figure 32a Specific yield in the Bindiar model: North-south cross sections
Figure 7b
Specific Yield in the Bindiar model: layers 1-8
5.2. Lake Bindiar Calibration results

Calibration Process

The calibration process was undertaken by varying aquifer parameters and boundary conditions to achieve a match to measured and estimated data. Model calibration performance is demonstrated in quantitative (head value matches) and qualitative (pattern-matching) terms, by:

- scatter plots of modelled versus measured head, and the associated statistical measure of the normalised root mean square value (RMS);
- contour plans of modelled head, with posted spot heights of measured head;

The main quantitative model performance indicator is the normalised RMS value (the RMS error term divided by the range of heads across the LAM). Given the uncertainties associated with a lack of detailed hydrogeological data at the Lake Bindiar site, it is proposed that a 10% normalised RMS value on aquifer water levels would be an appropriate upper range target. An ideal target for long term model refinement is suggested at 5% or lower. This approach is consistent with the Australian best practice groundwater modelling guideline (MDBC, 2001).

Steady-state calibration

The scatter plot of measured versus modelled heads and calibration statistics for the steady-state model is shown in Figure 33. A normalised RMS of 7.3 is achieved, which is within the target of 10%. The calibration performance is best in the Superficial Aquifer (layers 1-5) where there is a greater range in heads. The calibration performance is not as strong in the Leederville Aquifer (layer 6), where there is a small range of heads.

A difficulty encountered in calibrating the model was associated with the different potentiometric surfaces evident in the Superficial and Leederville Aquifers. Observed groundwater level data suggested an east-west gradient (i.e. sloping toward the coast) occurred in the Superficial aquifer and a relatively flat potentiometric gradient occurred in the Leederville aquifer over the same region. Observed groundwater level data is plotted against model contours in Figure 34 (Superficial Aquifer) and Figure 35 (Leederville Aquifer) for the steady state model. The results suggest that the calibrated steady-state model has been able to replicate the different potentiometric surfaces in these two aquifers.
- Figure 33 Normalised RMS plot for the Lake Bindiar steady-state model
Figure 34 Modelled potentiometric surface for the Superficial Aquifer, steady-state model
Figure 35 Modelled potentiometric surface for the Leederville Aquifer, steady-state model

Transient calibration

Model hydrographs and observed groundwater level data for the calibration period are shown in Figure 36. There is a good trend match between modelled and observed data for bores in the Superficial Aquifer (shaded blue in Figure 36), particularly in the latter stages of the calibration period. The calibration is less robust in the Leederville Aquifer (shaded tan in Figure 36), with the modelled decline in water levels not quite matching the magnitude of the observed decline. The poorest match between observed and modelled data was at Bore # AM10, to the east of LAM. The difficulties encountered to lower the model heads in this region, suggests there may be some underlying limitations associated with the model conceptualisation in this part of the model. However, given the lack of detailed hydrogeological data in the region and because the Superficial Aquifer is the focus of this modelling exercise the model calibration is considered to be fit for purpose.
Figure 36
Transient model hydrographs for the Bindiar LAM
Water Balance Results

The whole-of-model water balance (LAM and outer regions) for the calibrated steady state and transient models is presented in Table 8. The steady-state water balance is representative of average groundwater fluxes in the period leading up to January 1991 (1986-1990) assuming no change in water levels (no change in storage). The transient model water balance is representative of average groundwater fluxes during the calibration period of 1991 – 2007. Compared to the steady-state model, the transient model water balance shows declining recharge, increased groundwater abstraction, more water being extracted from storage (defining water levels) and less groundwater recharge to boundaries and streams (drains). These findings are consistent with the lower rainfall and increased abstraction that occurs over the calibration period.

Table 8 Whole of model water balances for the Transient and Steady-State model

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>GL/yr</td>
<td>GL/yr</td>
</tr>
<tr>
<td>IN:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>na</td>
<td>159</td>
<td></td>
</tr>
<tr>
<td>Recharge</td>
<td>294</td>
<td>259</td>
<td></td>
</tr>
<tr>
<td>Total IN</td>
<td>294</td>
<td>419</td>
<td></td>
</tr>
<tr>
<td>OUT:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>na</td>
<td>103</td>
<td></td>
</tr>
<tr>
<td>Constant Head</td>
<td>151</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>Wells</td>
<td>67</td>
<td>113</td>
<td></td>
</tr>
<tr>
<td>Drains</td>
<td>47</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>General-Head</td>
<td>30</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Total OUT</td>
<td>294</td>
<td>419</td>
<td></td>
</tr>
<tr>
<td>IN - OUT</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

A water balance is also presented for the LAM (Table 9). Within the LAM there is no direct abstraction, no drain cells and no specified head boundaries. Therefore the groundwater balance is quite simple: inputs from recharge, lateral inflow and storage; outputs to lateral outflow and to storage. As evident in Table 9, the water balance of the transient model (1991-2007) shows a significant reduction in recharge (compared to the steady-state model) that results in declining water levels (from storage) and reduced lateral outflows.
5.3. Lake Bindiar 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 exceeds 10% 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 10% is still calibrated and that a model with a normalised RMS error that is greater than 10% 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 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 10% 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.

SKM

Table 9 Bindiar LAM water balances for the Transient and Steady-State model

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GL/y</td>
<td>GL/y</td>
</tr>
<tr>
<td>In:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge</td>
<td>34</td>
<td>19</td>
</tr>
<tr>
<td>Lateral inflow</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>From storage</td>
<td>na</td>
<td>14</td>
</tr>
<tr>
<td>Total In</td>
<td>43</td>
<td>44</td>
</tr>
<tr>
<td>Out:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral outflow</td>
<td>43</td>
<td>39</td>
</tr>
<tr>
<td>To storage</td>
<td>na</td>
<td>5</td>
</tr>
<tr>
<td>Total Out</td>
<td>43</td>
<td>44</td>
</tr>
<tr>
<td>In - Out</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
In this case the sensitivity analysis has been undertaken on the horizontal and vertical conductivities (Kh and Kv), and the specific yield (Sy).

Results of the sensitivity analysis are presented in Table 10, which suggest that calibration is considered to be relatively sensitive to changes in hydraulic conductivity and specific yield. The model was particularly sensitive to increasing these parameters, less sensitive to lowering the parameters.

Table 10 Results of the Lake Bindiar 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>Kh</td>
<td>Upper</td>
<td>1.10 * Kh</td>
<td>10.2%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>0.70 * Kh</td>
<td>9.3%</td>
</tr>
<tr>
<td>Kv</td>
<td>Upper</td>
<td>1.05 * Kv</td>
<td>10.2%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>0.50 * Kv</td>
<td>9.6%</td>
</tr>
<tr>
<td>Sy</td>
<td>Upper</td>
<td>1.05 * Sy</td>
<td>9.9%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>0.70 * Sy</td>
<td>10%</td>
</tr>
</tbody>
</table>
6. Scenario Analysis

6.1. Scenario definitions

The scenarios simulated for the Lake Bindiar LAM are listed in Table 11. Each scenario model is run over the period of Jan 2008 to Dec 2031 (inclusive). Initial conditions for the model runs are set as the final heads of the calibration model.

- Table 11 Lake Bindiar LAM scenario descriptions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Climate</th>
<th>Groundwater Abstractions</th>
<th>Pine Plantation Strategy</th>
<th>Native Woodland (Banksia) strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>Median climate 1997 - 2006</td>
<td>Water Corporation 135 GL/y strategy</td>
<td>Pines harvested as per LVL, replaced with grass</td>
<td>10 yr burning cycle for Banksia Woodland</td>
</tr>
<tr>
<td>Sc 1</td>
<td>11% drier than median climate of 1976 - 2006</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sc 2</td>
<td></td>
<td></td>
<td>Immediate 100 % pine removal, replaced with 100 % grassland</td>
<td></td>
</tr>
<tr>
<td>Sc 3</td>
<td></td>
<td></td>
<td></td>
<td>6 yr Burning cycle for Banksia woodland</td>
</tr>
<tr>
<td>Sc 4</td>
<td></td>
<td></td>
<td>Immediate 100 % pine removal, replaced with 100 % Banksia woodland</td>
<td></td>
</tr>
<tr>
<td>Sc 5</td>
<td></td>
<td>Base case pumping doubled in the Leederville Aquifer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sc 6</td>
<td></td>
<td>Base case pumping doubled in the Yarragadee Aquifer</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: a blank cell indicates no change from the Base Case

6.2. Scenario model inputs

Climate

Climate datasets were obtained that are used by the PRAMS model for scenario modelling (based on data from the Perth Airport weather station). The base case climate is the median climate for the 1997-2006 period. The data consists of a single median year, which repeats itself during the predictions. The ‘drought scenario’ (Scenario 1) is 11% drier than the median climate of 1976-
2006. As with the base case, this data repeats itself during the predictions. The key output from the climate data was monthly rainfall as this drives recharge in the groundwater model.

**Land use and recharge**

There are four main land uses in the Bindiar LAM: pine forestry, native (banksia) woodland, grassland/cleared vegetation, and the extent of diatomaceous earth associated with the wetlands. These land uses are implemented in the model as recharge by applying a rainfall scaling factors (Table 4) to the monthly rainfall totals from the climate datasets.

The scenario analysis was designed to examine various land use options that affect recharge. Land use options within pine plantation areas, and land use options within areas of native woodland (Banksia woodland) were all varied under the different scenarios. The land use inputs are summarised in Figure 37.

![Figure 37 Landuse shapefiles created for scenario inputs](image)

In the base case scenario, the areas in the model covered by pine plantations were subjected to a clearing strategy, whereby individual blocks were cleared according to an assigned harvest date.
according to the LVL (see Figure 37). From this time onward these model cells were assigned as grassland. This strategy is varied for Scenarios 2 and 4, under which the area of pine plantations are immediately replaced at the start of the predictive run by either grassland (Scenario 2), or Banksia Woodland (Scenario 4). The following assumptions were made when implementing the LVL:

- Some blocks were listed as pine plantations in the calibration model but not listed in the LVL – in the predictive scenarios they were assumed to have been cleared prior to the model run;
- It was assumed that blocks with no clear-felling date listed were cleared in 2016;
- Thinning prior to clear-felling was not simulated as recharge was not calibrated to thinning strategies.

The scenarios also examine the role of burning strategies within Banksia woodland. The base case scenario implements a strategy whereby 1/10th of the Banksia woodland is burnt every year, such that after 10 years the total area of Banksia woodland has been burnt. This is implemented in the recharge model by assigning a recharge scaling factor of grassland when the area of Banksia is burnt, which is assumed to occur in June. The recharge scaling factor is then gradually decreased according to linear function such that after 5 years the recharge is equivalent to a mature Banksia woodland. In this way the recovery of the native vegetation (post-burn) is simulated. The zonation of the 10 blocks was assigned randomly. The same methodology was applied to Scenario 3, but in this strategy 1/6th of the Banksia woodland is burnt every year.

**Groundwater abstractions**

In the base case scenario, groundwater abstraction was set according to the pumping schedule defined by the Water Corporation 135 GL dataset. As the name implies, this pumping schedule abstracts a total of 135 GL per annum from public bores in the Gnangara Mound. This strategy is implemented in the greater model extent of the Bindiar model. Note that not all bores in this dataset are located within the Bindiar model domain so the model does not quite match the 135 GL/y output. The rate of pumping is varied for Scenarios 5 and 6, under which the pumping rates are doubled in either the Leederville Aquifer (Scenario 5) or the Yarragadee Aquifer (Scenario 6).

### 6.3. Scenario results and discussion

**Hydrographs**

Model hydrographs are presented (Figure 38 - Figure 44) to show the predicted groundwater levels under each of the scenarios for observation bores present in the LAM. Note that hydrographs from some of the observation wells are not shown (YY3-I, YY4-I and YY7-I) because they closely resemble data from adjacent nested bores (i.e. YY3-O, YY4-O and YY7-O), which are also installed in the superficial aquifer.
Figure 38 Model hydrograph for observation bore YY4-O showing predicted groundwater levels for each scenario as compared to observed and calibrated data.

Figure 39 Model hydrograph for observation bore YY7-O showing predicted groundwater levels for each scenario as compared to observed and calibrated data.
Figure 40 Model hydrograph for observation bore YY3-O showing predicted groundwater levels for each scenario as compared to observed and calibrated data.

Figure 41 Model hydrograph for observation bore AM9 showing predicted groundwater levels for each scenario as compared to observed and calibrated data.
Figure 42 Model hydrograph for observation bore AM10 showing predicted groundwater levels for each scenario as compared to observed and calibrated data.

Figure 43 Model hydrograph for observation bore AM13 showing predicted groundwater levels for each scenario as compared to observed and calibrated data.
The hydrographs shown in Figure 38 - Figure 40 report on groundwater levels in the superficial aquifer. They show a recovery in groundwater levels for all scenarios. The increased recharge, associated with pine removal and burning of the banksia woodland, results in an immediate recovery in groundwater levels. The recovery is most pronounced in Scenario 2 (immediate replacement of all pine forestry with grassland), and least pronounced in Scenario 4 (immediate replacement of all pine forestry with Banksia woodland). All other scenarios are broadly similar to the base case which results in an intermediate level of recovery compared to the two extremes. The recovery associated with the drought scenario (Scenario 1) does not appear to be appreciably less than recovery associated with the base case.

Some minor differences are noted between the hydrographs for YY7-O (Figure 39) and the hydrographs for YY4-O (Figure 38) and YY3-O (Figure 40) that are associated with the location of the observation bores – YY7-O is located amongst Banksia woodland, whereas the other bores are surrounded by pine forestry. Pumping does not appear to influencing water levels in the superficial aquifer, with Scenarios 5 and 6 exhibiting a virtual identical response.

The hydrographs shown in Figure 41 - Figure 44 report on groundwater levels in the Leederville aquifer. In general, groundwater levels stabilise under the base case scenario. It is probable that the stabilisation of water levels is primarily due to reduced pumping – the 135 GL/y
scenario is significantly less than the pumping that was implemented toward the end of the calibration period, which was in the order of 160 GL/y (see Figure 30). Some differences are noted between the base case and scenarios 1-4, which suggests that differences in recharge rates (due to land use change) will have some impact on water levels in the Leederville aquifer.

A pumping response is also seen in the lower groundwater levels for Scenarios 5 and 6, under which higher pumping rates were applied. Drawdown is more immediate when abstractions are doubled from the Leederville Aquifer (Scenario 5). But when a new dynamic equilibrium is reached at approximately 2027, there is no difference between Scenarios 5 and 6.

It is probable that the muted response in the Leederville aquifer (as compared to the Superficial aquifer) is related to the calibration, which was not as robust in the deeper layers of the model.

**Water level recovery maps**

The following maps (Figure 45 - Figure 51) show the recovery in groundwater levels (i.e. the head difference between Dec 2031 and Jan 2008) in the Superficial Aquifer across the LAM for each of the Scenarios run.
Figure 45 Recovery of groundwater levels (m) in the Superficial Aquifer for base case

Figure 46 Recovery of groundwater levels (m) in the Superficial Aquifer for scenario 1
Figure 47 Recovery of groundwater levels (m) in the Superficial Aquifer for scenario 2

Figure 48 Recovery of groundwater levels (m) in the Superficial Aquifer for scenario 3
Figure 49 Recovery of groundwater levels (m) in the Superficial Aquifer for scenario 4

Figure 50 Recovery of groundwater levels (m) in the Superficial Aquifer for scenario 5
As evident in the base case scenario (Figure 45), the biggest recovery in groundwater levels occurs under pine plantations and is associated with their removal. The pattern of water level recovery across the LAM is broadly similar to the base case for Scenarios 1, 3, 5 and 6. The exceptions are Scenario 2 (Figure 47) and Scenario 4 (Figure 49). The immediate replacement of pine with grassland (Scenario 2) results in the greatest recovery of water levels, whilst the immediate replacement of pine plantations with Banksia woodland (Scenario 4) results in a more muted recovery.

**Water Balance**

Average annual water balances (based solely on the LAM, not the outer model domain) are shown in Table 4. The results are consistent with the hydrographs and the head difference plots in the sense that Scenarios 2 and 4 are the two outliers. Scenario 2 has the highest recharge, whilst scenario 3 has the lowest recharge. The drought scenario (Scenario 1) is not significantly less than than the base case. Increased pumping (Scenarios 5 and 6) appears to have no impact on the water balance.
Table 12 Average annual water balances for the Bindiar LAM under each scenario

<table>
<thead>
<tr>
<th>Flux</th>
<th>Base Case</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
<th>Scenario 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GL/y</td>
<td>GL/y</td>
<td>GL/y</td>
<td>GL/y</td>
<td>GL/y</td>
<td>GL/y</td>
<td>GL/y</td>
</tr>
<tr>
<td>In:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Recharge</td>
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<td>40</td>
<td>48</td>
<td>43</td>
<td>36</td>
<td>42</td>
<td>42</td>
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<tr>
<td>Lateral inflow</td>
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<td>10</td>
<td>10</td>
<td>11</td>
<td>12</td>
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<td>From storage</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>15</td>
<td>13</td>
<td>15</td>
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<tr>
<td>Total In</td>
<td>67</td>
<td>66</td>
<td>74</td>
<td>69</td>
<td>60</td>
<td>69</td>
<td>69</td>
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<tr>
<td>Out:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Lateral outflow</td>
<td>47</td>
<td>46</td>
<td>51</td>
<td>48</td>
<td>44</td>
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<tr>
<td>To storage</td>
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<td>19</td>
<td>22</td>
<td>20</td>
<td>16</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Total Out</td>
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<td>74</td>
<td>69</td>
<td>60</td>
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</table>

6.4. Conclusions

The following broad conclusions are drawn from the analysis of the predictive scenarios in relation to the superficial aquifer:

- There was an immediate recovery in groundwater levels under all scenarios;
- Immediate pine replacement with grassland resulted in the biggest recovery in groundwater levels, whereas pine replacement with Banksia woodland resulted in the smallest recovery;
- Water levels in the superficial aquifer do not appear to be impacted by increased pumping.

The following broad conclusions are drawn from the analysis of the predictive scenarios in relation to the Leederville aquifer:

- The recovery in groundwater levels was not as pronounced as the superficial aquifer, but this may be related to the less robust calibration in the Leederville;
- Increased pumping scenarios (5 and 6) resulted in a water level decline until new a new dynamic equilibrium was established in 2027;
- There were some difference noted between the base case and scenarios 1-4 suggesting that differences in recharge affect water levels in the Leederville aquifer;
- Pine replacement with grassland and frequent burning of the Banksia woodland results in the greatest water level recovery.
7. Model limitations and recommendations

The aim of developing the Lake Bindiar LAM was to provide a quantitative tool to assess land and water use impacts on the environment and groundwater systems and to provide sufficient resolution (100 x 100 m grid in most areas) and reliability for assessing environmental, licensing and trading issues. The developed model is capable of being used for these purposes but it is important to recognise a number of limitations when using the model as a predictive tool.

Whilst the model calibration is acceptable in the superficial aquifer (< 10 % normalised RMS), which was the focus of the modelling exercise, the calibration is not ideal in the Leederville aquifer. This was particularly evident in the east of the model domain where the poorest head match occurred at observation bore AM-10. In general the modelled heads in the Leederville do not decline to the same extent as observed heads, which indicates some model insensitivity with respect to changing recharge and pumping rates. Predictive results from the Leederville aquifer should therefore be considered qualitatively rather than quantitatively.

It is possible that such insensitivity was related to the conceptualisation of the Leederville aquifer as a singular, thick, transmissive layer, which results in significant storage. However, reverting to a multi-layer aquifer (like PRAMs) would lead to significantly greater model run times.

A limitation to further model calibration refinement is the paucity of observed groundwater level data in the Lake Bindiar region. Observed data is limited to only 10 observation bores at 6 sites (there are 4 nested sites). The installation of new observation bores in places of interest (such as Lake Bindiar), and data from pumping tests would facilitate better calibration. An ideal long-term target is suggested as 5% or lower normalised RMS.

Recharge for the Bindiar LAM was defined using an unsaturated zone model (Appendix A). Whilst the approach provided a physically robust process to estimate recharge, there is some uncertainty regarding the relative differences in recharge rates between land uses because the unsaturated model was not calibrated. Some further investigation of recharge rates in the area, via calibrating the unsaturated zone model using soil moisture data or by providing alternative estimates through other methods (e.g. chloride mass balance or recharge dating tracers such as CFCs), could be used to improve calibration to reduce such uncertainty.

The developed model does not simulate direct evapotranspiration (ET) losses from the watertable (activating the modflow evt package caused model convergence problems related to dry cells in the upper layers of the model). This was considered to be appropriate under the calibration period (1991-2007), because the observed watertable depth is generally greater than 10 m across the LAM (i.e. deeper than the root zone in pine plantations or Banksia woodland) so it is expected that ET
losses from the groundwater are minimal. However recovery of groundwater levels may lead to shallow watertable areas in the LAM such that higher ET losses would be expected.
8. References


Townley, L. R., Turner, J., Barr, A., Trefry, M., Wright, K., Gailitis, V., Harris, C., & Johnston, C. (1993) *Wetlands of the Swan Coastal Plain, Volume 3; Interaction between lakes, wetlands and unconfined aquifers*. Water Authority of Western Australia
Appendix A  Land Use 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

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Appendix B  Bore logs.

Lake Bindiar LAM - Example Stratigraphic Logs
Appendix C  Unsaturated Zone Model Report

Development of Local Area Groundwater Models - Gnangara Mound

LAKE BINDIAR UNSATURATED ZONE MODELLING REPORT

- Draft V1
- 4 September 2009
Development of Local Area Groundwater Models - Gnangara Mound

LAKE BINDIAR UNSATURATED ZONE MODELLING REPORT

- Draft V1
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Author: Dougal Currie  
Project manager: Brian Barnett  
Name of organisation: Government of Western Australia - Department of Water  
Name of project: Development of Local Area Groundwater Models - Gnangara Mound  
Name of document: Lake Bindiar unsaturated zone modelling report  
Document version: Draft V1  
Project number: VW05025
1. Introduction

Sinclair Knight Merz (SKM) was engaged by the Western Australia Department of Water (DoW) to develop three local area groundwater flow models for the Gnangara Mound. For the Lake Bindiar Local Area Model (LAM), groundwater recharge was conceptualised as being spatially and temporally complex due to frequent changes in land use and the occurrence of diatomaceous soils in parts of the landscape. An unsaturated zone model was developed to capture this complexity and quantify recharge for the groundwater flow model during the calibration period and for the period beforehand (1986 – 2007). This report outlines the methodology, assumptions and outcomes of the unsaturated zone modelling undertaken.
2. Methods

The following process was used to quantify recharge for the Bindiar LAM:

1) The major factors affecting recharge were identified (land use and soil types);
2) These factors were analysed over space and time (using GIS) to quantify their variability and interaction over the study area, and to establish individual recharge zones;
3) A 1-D unsaturated zone model was built and the different combinations of land use and soil type were passed through the numerical model to quantify recharge rates (in mm/y) for the individual recharge zones during the calibration period of the LAM;
4) The recharge rates were converted to rainfall scaling factors for input into the groundwater flow (Modflow) model

2.1. Factors affecting recharge at Lake Bindiar

In general, the key factors affecting diffuse rainfall recharge to groundwater are rainfall, land use, soil hydraulic properties and the depth of the watertable. Land use and soil hydraulic properties were considered to be of most importance to the Bindiar LAM because rainfall is unlikely to vary significantly over a small study area, and the observed depth to watertable was greater than 10 m over the majority of the area. A deep watertable is not subject to direct evapotranspiration such that net recharge is affected.

The major land uses in the Lake Bindiar region are native vegetation (Banksia woodland) and pine plantation forestry. There are also small patches of grassland. These land uses have significant differences in water consumption to affect recharge.

Soil types are predominantly Bassendean sands, with areas of diatomaceous soils. Due to the exceptionally high water holding capacity of diatomaceous soils, they are likely to significantly influence recharge where they occur.

2.2. Identification of recharge zones

Both land use and soil types were plotted over the extent of the LAM using ArcGIS.

To classify major soil types across the LAM, the Digital Atlas of Australian Soils was used in conjunction with McKenzie et al. (2000). Three different soil types were identified, but each had similar hydraulic properties (identical saturated hydraulic conductivities and very similar field capacities and wilting points). Given the similarity in soil hydraulic properties, it was reasonable to represent soils as being uniform across the LAM for the purpose of unsaturated zone modelling. The occurrence of diatomaceous soils was the exception, the extent of which was defined by

SINCLAIR KNIGHT MERZ
digitising the hyperspectral mapping results of Lau et al. (2006). The coverage of diatomaceous soils was not extensive, and limited to Lake Bindiar itself and other swamp features in the LAM.

Land use over the calibration period was defined according to Landsat Imagery, which showed the presence or absence of woody vegetation in 1989, 1991, 1992, 1995, 1998, 2000, 2002, 2004, 2005, 2006. Any woody vegetation that occurred within the bounds of the plantation forestry zonation was assumed to be Pine Forestry. All woody vegetation outside of this extent was assumed to be Banksia Woodland. Land with no woody vegetation was assumed to be cleared/grassland.

The series of Landsat images and the diatomaceous soils coverage were analysed over the calibration period and generalised to form 8 distinct land use/soil combinations over the LAM, as depicted in Figure 1. These land use/soil combinations form the basis of the individual runs for the unsaturated zone model, and in turn represent recharge zones for the groundwater flow model.
A description of each land use /soil combination is provided in Table 1, with each category based on the soil type, land use and land use history.

Table 1 Description of Soil / Land Use combinations for the Bindiar LAM

<table>
<thead>
<tr>
<th>Soil / Land Use Combination</th>
<th>Soil</th>
<th>Land Use / Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banksia</td>
<td>Bassendean sand</td>
<td>Banksia woodland for all years</td>
</tr>
<tr>
<td>Banksia/Cleared</td>
<td>Bassendean sand</td>
<td>Banksia woodland until 2004, cleared 2005-07</td>
</tr>
<tr>
<td>Pine</td>
<td>Bassendean sand</td>
<td>Pine forest for all years</td>
</tr>
<tr>
<td>Pine/Cleared</td>
<td>Bassendean sand</td>
<td>Pine forest to 2002, Cleared 2003-2007</td>
</tr>
<tr>
<td>Cleared</td>
<td>Bassendean sand</td>
<td>Cleared land for all years</td>
</tr>
<tr>
<td>Diatomaceous</td>
<td>Diatomaceous earth</td>
<td>Cleared land for all years</td>
</tr>
</tbody>
</table>

2.3. Modelling platform

The SWAP model (Soil Water Atmosphere Plant) was selected as the platform for the unsaturated zone model. SWAP is a 1D unsaturated zone modelling platform based on the Richards equation. It was selected for this study due to its ‘crop rotation’ functions, whereby the user can specify distinct changes in land use over time (e.g. a pine forest being cleared). The model is well documented (Kroes et al., 2008), has been validated numerically and has been refined over a number of years. It can be freely downloaded from [http://www.swap.alterra.nl/](http://www.swap.alterra.nl/).

In the vertical direction, the model domain reaches from a plane just above the vegetation canopy to a plane in the shallow groundwater. It is capable of simulating rainfall, interception, evaporation, transpiration, infiltration, runoff, soil water flow, solute transport, groundwater recharge and drainage. For the purpose of this study, the model can be conceptualised as a single soil column with the upper boundary represented by the atmosphere and vegetation, and the lower boundary represented by a fixed groundwater level. Soil water flow within the column is governed by the Richards equation and soil hydraulic parameters.
2.4. Model inputs and assumptions

Upper boundary conditions

In SWAP, the upper boundary condition is based on daily meteorological data inputs and regulated by soil and vegetation parameters. Synthetic meteorological data was sourced from SILO\(^2\) as a patched-point dataset for the centroid of the LAM. The key daily variables required for this particular model set-up were rainfall and a FAO56 reference evapotranspiration rate (ET\(_{\text{ref}}\)).

Runoff, interception and surface ponding were not modelled, so it was assumed that all rainfall immediately infiltrates the rootzone.

Atmospheric evaporative demand is driven by ET\(_{\text{ref}}\). This is converted to a potential ET of a uniform surface (ET\(_p\)) by applying a ‘crop factor’ (\(k_c\)) as specified by the user according to the vegetation type, such that:

\[
ET_p = k_c ET_{\text{ref}}
\]

Note that the ‘crop factor’ applied by SWAP is higher than traditional crop factors because further reductions are applied to ET\(_p\) in SWAP in order to calculate an actual ET (ET\(_a\)). By contrast, a traditional crop factor is used to directly calculate ET\(_a\).

ET\(_p\) is partitioned into potential soil evaporation \(E_p\) and potential plant transpiration \(T_p\) according to the leaf area index (LAI) and light extinction coefficient (Kgr), whereby:

\[
E_p = ET_p e^{-KgrLAI}
\]

Further reductions are applied to \(E_p\) and \(T_p\) to calculate actual ET\(_p\). Soil evaporation is limited by Darcy flux in the soil, which will supply water to the evaporating soil surface at a diminishing rate as the soil dries. Transpiration is dependent on soil water availability and is weighted such that root water uptake reduces to zero as the soil moisture approaches wilting point.

As apparent in the above equations, evapotranspiration (and hence recharge) is very sensitive to the \(K_c\), LAI and Kgr. Another important vegetation parameter is the rooting depth, as it defines the volume of soil water accessible to the plant. The root distribution is also important, but it was not varied between vegetation types in this model (a triangular root distribution was assumed). Table 2 summarises the parameters used in the SWAP modelling for the three main land use / vegetation types.


**SKM**

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Table 2 Model vegetation parameters

<table>
<thead>
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<th>$K_c$</th>
<th>$K_{gr}$</th>
<th>LAI</th>
<th>Rooting depth</th>
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<tbody>
<tr>
<td>Pine forestry</td>
<td>0.95</td>
<td>0.45</td>
<td>1.5</td>
<td>10 m*</td>
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<tr>
<td></td>
<td>(assumed)</td>
<td>(assumed)</td>
<td></td>
<td>(Xu et al. 2003; Silberstein et al., 2007)</td>
</tr>
<tr>
<td>Banksia woodland</td>
<td>0.95</td>
<td>0.45</td>
<td>0.8</td>
<td>10 m</td>
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<td></td>
<td>(assumed)</td>
<td>(Xu et al., 2003)</td>
<td></td>
<td>(Xu et al. 2003; Silberstein et al. 2007)</td>
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<tr>
<td>Cleared / grassland</td>
<td>0.95</td>
<td>0.45</td>
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<td>1 m</td>
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<tr>
<td></td>
<td>(assumed)</td>
<td>(assumed)</td>
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<td>(assumed)</td>
</tr>
</tbody>
</table>

*note that the assumed rooting depth is well above the assumed groundwater level (15 m). Therefore direct plant water extraction from watertable does not occur. A triangular root distribution was assumed.

$K_c$ was unknown and was therefore assumed to be equivalent for each of the vegetation types modelled. A $K_{gr}$ of 0.45 had been assigned as 0.45 is the vertical flux component of the PRAMs model (Xu et al., 2003), but was not reported for Pine forestry or grassland. It was assumed to be equivalent across the vegetation types. In contrast to the paucity of information regarding $K_c$ and $K_{gr}$, LAI has been documented for Pine forestry and Banksia Woodland in the Gnangara Mound region (Xu et al., 2003; Silberstein et al., 2007; URS et al., 2008). The LAI is thus the key parameter which differentiates ET between the vegetation types. The LAIs selected were based on an average LAI for an entire year for a vegetation stand of mid-maturity (the model parameters do not vary with time). The rooting depth was based on literature values for Pine forestry and Banksia Woodland (Xu et al., 2003; Silberstein et al., 2007) and was assumed to be shallow for grassland.

**Soil hydraulic parameters**

Soil hydraulic parameters were based on published material. Hydraulic parameters of Bassendean sand were acquired from Salama et al (2005). The hydraulic parameters for diatomaceous soils were acquired by averaging the parameters presented for two diatomaceous soil by Githinjii et al. (2006). The soil water retention curves and saturated hydraulic conductivities ($K_{sat}$) used are shown in Figure 2, where the exceptional water holding properties of diatomaceous soils are evident.
Figure 2 Soil water retention curves for Bassendean Sand and Diatomaceous Earth

In the SWAP model the soil hydraulic functions $[\theta(h) \text{ and } k(\theta)]$ are represented by the Maulem - Van Genuchten functions (Van Genuchten, 1980). To obtain the necessary parameters for these functions, soil water retention data was input into the RETC fitting model (Van Genuchten et al., 1991). The parameters obtained are listed in Table 3, where $\theta_s$ is the saturated water content (cm$^3$cm$^{-3}$), $\theta_r$ is the residual water content (cm$^3$cm$^{-3}$), and $\alpha$ (cm$^{-1}$), $m$ (-) and $n$ (-) are empirical shape factors.

Table 3 Soil hydraulic parameters used for the SWAP model

<table>
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<th>$\theta_s$ (cm$^3$cm$^{-3}$)</th>
<th>$\theta_r$ (cm$^3$cm$^{-3}$)</th>
<th>$\alpha$ (cm$^{-1}$)</th>
<th>$n$ (-)</th>
<th>$m$ (-)</th>
<th>Ksat (cm day$^{-1}$)</th>
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<td>Bassendean sand topsoil (0-0.5 m)</td>
<td>0.45</td>
<td>0.0543</td>
<td>0.0594</td>
<td>2.4626</td>
<td>0.59</td>
<td>200</td>
</tr>
<tr>
<td>Bassendean sand sub soil (0.5-15 m)</td>
<td>0.42</td>
<td>0.02431</td>
<td>0.05941</td>
<td>2.4626</td>
<td>0.59</td>
<td>600</td>
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<tr>
<td>Diatomaceous earth</td>
<td>0.75</td>
<td>0.3282</td>
<td>0.2109</td>
<td>1.4249</td>
<td>0.30</td>
<td>1000</td>
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Lower Boundary conditions

The lower boundary condition was assumed to be a fixed groundwater level of 15 mbgl. The observed depth of the watertable does vary across the LAM, but is greater than 10 mbgl over the majority of the area and 15 mbgl represents an approximate average.
3. **Results**

3.1. **Overview of SWAP results**

Eight model runs were processed through the SWAP model – each run representing a unique soil and land use combination that occurs across the Lake Bindiar LAM (Table 1). Groundwater recharge was output from the SWAP model as the flux passing through the lower boundary of the soil profile in monthly timesteps. These outputs are presented in Figure 3, which were converted to % rainfall.

![Figure 3 Rainfall recharge (% rainfall) as output from the SWAP model](image)

There is considerable variation in recharge between the different soil / land use combinations. Regions of cleared land (grassland) that occur on Bassendean sands show the highest recharge rates (average of 50% rainfall). The diatomaceous soil class has the same vegetation parameters as the cleared / grassland yet shows a 20% reduction in recharge due to different soil hydraulic parameters. This is consistent with the hypothesis that the occurrence of diatomaceous soils around Lake Bindiar and other swamplands in the LAM causes a reduction in recharge. There is also considerable difference between recharge under Banksia woodland (average of 22% rainfall) and
Pine forestry (average of 10% rainfall) as a result of greater plant density (high LAI) in the Pine forests. In cases where Pine or Banksia has been cleared or regrows, there is a quick change in recharge after a land use change is implemented. A gradual regrowth rate was not used in the model; therefore the change in recharge from one land use to another is quite rapid (2 years).

A summary of the average % rainfall recharge rates (1986 to 2007) for the four major land uses is shown in Table 4 (the results of the model runs, which consider land use changes are not shown).

- **Table 4 Average % rainfall recharge rates as output by SWAP**

<table>
<thead>
<tr>
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<th>Cleared / Grassland</th>
<th>Pine Forestry</th>
<th>Banksia Woodland</th>
<th>Diatomaceous Soils</th>
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</thead>
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<tr>
<td>Average % rainfall recharge (1986-2007)</td>
<td>50%</td>
<td>10%</td>
<td>22%</td>
<td>32%</td>
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### 3.2. Outputs to the Modflow model

Initially, the outputs from the SWAP model were to be directly imported into the Modflow model. When this was trialled, it was noted that some of time lags associated with recharge from the SWAP model were not evident in the observed hydrographs from monitoring bores in the LAM. The time lags from SWAP for the key landuses are shown in Figure 4, where the recharge ‘peak’ does not occur for 6-12 months after the rainfall ‘peak’. This time lag varies between land uses.

Such time lags are not evident in the observed hydrographs, which fluctuate more in line with seasonal rainfall. This suggests recharge may not be purely diffuse (as modelled by SWAP) but may occur more as preferential flow or by fingering (due to hydrophobicity) in which case lag times are minimal. Hence rather than using the SWAP outputs directly, the average % rainfall recharge rates generated by SWAP (Table 4) were used as scaling factors to calculate recharge for Modflow. Whilst this removes some of the sophistication available with using SWAP directly, it allows recharge for the groundwater model to be calculated more easily (by non-specialists), and it is still reliant on the results from SWAP where a physically robust process was followed.
Figure 4 Example of recharge time lags from SWAP
4. References


Appendix D  Lake Bindiar Model User Guide

Local Area Groundwater Models - Gnangara Mound

BINDIAR MODEL USER GUIDE

- Draft 1
- 15 September 2009
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File name: I:\VWES\Projects\VW05025\Deliverables\Reports\Bindiar LAM model calibration and scenarios.doc
Author: Vic Waclawik, Dougal Currie
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1. Introduction

This report is the fourth in a series of reports documenting the development and application of three local area groundwater models within the Gnangara Mound. Previous reports in this series are listed below and a complete background to the project can be found in these reports:

- Local Area Groundwater Models – Conceptual Model Report (SKM, 2009a)
- Local Area Groundwater Models – Calibration Report (SKM, 2009b)
- Local Area Groundwater Models – Scenario Modelling Report (SKM, 2009c)

This report provides a basic summary of how the models 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 Conceptual Model Report and the Calibration Report.
2. Directory Structure

Figure 1 presents the main structure for the Bindiar Local Area Model (LAM). It is constituted of two main directories:

- ‘Calibration Models’ which contains all the files used in the calibration processing of the Bindiar model
- ‘Predictive Models’ contains all the files required for running the predictive scenarios

![Flow Chart for the Bindiar Model directory structure. Main directories](image)

Figure 2 presents the major directory structure for each of the two main directories presented in Figure 1. The structure is based on three tiers:

- ‘Model Inputs’ contains spreadsheets and files used in the processing and creation of the Visual Modflow input files
- ‘Model Outputs’ contains spreadsheets used in the processing of model output files
- ‘Models’ contains 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 2A Flow chart of the Bindiar ‘Calibration Models’ directory structure

Figure 2B Flow chart of the Bindiar ‘Predictive Models’ directory structure

For the rest of the report, flow charts represent the directory structure of the “Predictive Model” sub directory unless specifically stated.
3. Model Inputs for Predictive Scenarios

The predictive models for the scenario analysis were constructed such that only two main input variables were manipulated: recharge and groundwater abstractions. This chapter describes how each of these variables was input to the predictive models.

3.1. Land Use Change and Recharge

The impacts of land use change are modelled via changes to recharge. The following process is used to incorporate these recharge impacts into the predictive models:

   **Step 1: Construct spatial coverages of land use change in ArcGIS.**

A spatial coverage has been developed for the Pine LVL clearing strategy under the following directory:

   \(\text{Bindiar Models} \backslash \text{Predictive Models} \backslash \text{Model inputs} \backslash \text{Recharge} \backslash \text{Zonation} \backslash \text{Pine} \backslash \text{LVL shapefileHarvest_sched_dissolve_dc_ver2.shp}\)

The spatial coverages detailing the Banksia burning strategies are listed here:

   \(\text{Bindiar Models} \backslash \text{Predictive Models} \backslash \text{Model inputs} \backslash \text{Recharge} \backslash \text{Zonation} \backslash \text{Banksia}\)

Two shapefiles are listed in this directory. The 6 yr burning strategy is \(\text{Banksia 6y burn cycle.shp}\). The 10 yr burning strategy is \(\text{Banksia 10yr burn cycle.shp}\).

   **Step 2: Import GIS coverages to Visual Modflow**

To define recharge zonation in the model, the GIS coverages are imported via the standard import function. For the scenarios already developed, these were imported to overlay the existing zonation in the calibrated model.

   **Step 3: Develop recharge rates for each of zone**

Excel spreadsheets have been developed that define recharge rates for each zone for each scenario, and allow for easy importation to Visual Modflow. They are stored in the following directory:

   \(\text{Bindiar Models} \backslash \text{Predictive Models} \backslash \text{Model inputs} \backslash \text{Recharge}\)

The spreadsheet \(\text{Recharge for Scenarios.xlsx}\) outlines how recharge was calculated for a particular land use under a particular scenario. The data presented was rearranged into a second spreadsheet (\(\text{Recharge for Scenarios_mdf input.xlsx}\)), which is formatted to allow for easy importation into modflow. Note that there is a deliberate offset in this spreadsheet to allow for one of Visual Modflow’s quirks. The data is copied to the clipboard (from excel) and pasted into Visual Modflow under the recharge/edit recharge zones menu.
3.2. 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. A Modflow input file has been prepared for scenario runs. Three files were prepared for public abstraction. One was prepared for the Water Corporation 135GL scenario, one for the Leederville 200% scenario and one for the Yarragadee 200% scenario. The Leederville 200% was used for scenario 5, the Yarragadee 200% for Scenario 6 and Water Corporation 135GL was prepared for all remaining scenarios including the Base Case.

Each of these ‘.txt’ file 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 – Aquifer (indicative only)
Column 5 – Bottom elevation of screen
Column 6 – Top elevation of screen
Column 7 – End of stress period (day)
Column 8 – Pumping rate (l/sec) (negative indicates abstraction)

If, for example, the user wanted to reduce all abstractions in the model by 50%, it is possible to open these .txt files in excel, multiply column 8 by 0.5, resave as a tab delimited text file and then re-import into Visual Modflow.
4. Model Outputs

Note: It is possible to load, view and export almost all model outputs within the standard Visual Modflow output screen. The programs described in this section can extract this information automatically.

4.1. Directory Structure

- **Figure 3 Models Outputs directory structure**

The model outputs folder contains all post processed outputs from the scenario models run to date. The models outputs for “predictive models” are shown on Figure 3.

**Note:** In the “Calibration Models” folder a similar self explanatory folder tree is present with a division between Steady state and Transient calibration output file.
5. MODELS

5.1. Directory Structure

The “MODELS” directories are relatively self explanatory in that it stores all of the model files. The following models are stored:

The calibration models directory contains two folders containing ‘transient’ calibration model and ‘steady-state’ calibration model.

The ‘Predictive models’ directory contains one folder for each of the scenario runs. Each of the model folders contains all the necessary input files to open, run and view the results of the models through Visual Modflow.

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.

The scenario models are run with rewetting activated to allow for the rewetting of dry cells in the superficial aquifer as water levels recover. The rewetting parameters used are shown in Figure 4.

![Rewetting parameters used in predictive models](image)

**Figure 4 Rewetting parameters used in predictive models**
Note: In the calibration folder (cf. Figure 5) a self explanatory folder tree is present with a division between Steady state and Transient calibration output file.

Figure 5 Models Runs directory tree for the "predictive models"

Note: In the calibration folder (cf. Figure 6) a self explanatory folder tree is present with a division between Steady state and Transient calibration output file.

Figure 6. Models Runs directory tree for the calibration models.

5.2. Troubleshooting

The Bindiar model is stable and non-convergence issues have not been encountered during the scenarios runs.

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