East Wanneroo integrated groundwater-lake flow modelling

Predictive scenario modelling to support the Gnangara Sustainability Strategy

Looking after all our water needs

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Department of Water  
168 St Georges Terrace  
Perth Western Australia 6000  
Telephone +61 8 6364 7600  
Facsimile +61 8 6364 7601  
www.water.wa.gov.au  
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For more information about this report, contact Chris O'Boy, Water Resource  
Assessment Branch (chris.oboy@water.wa.gov.au)  

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Summary

We have used a local-scale numerical model of the east Wanneroo area to investigate the potential influence of land-use change and water management practices on water levels in Lake Mariginiup, Lake Jandabup and the superficial aquifer.

A suite of seven predictive modelling scenarios have been run from 2001 to 2031 to assess the affect of artificial lake supplementation, pine clearing, urbanisation and directed urban drainage. These scenarios assume that the climate remains as per 1997-2006 (730 mm of rainfall per year).

This scenario modelling will inform the Gnangara Sustainability Strategy, a cross-government initiative to develop an action plan for the sustainable use of water resources of the Gnangara Mound.

The modelling suggests that the current regime of augmentation at Lake Jandabup increases the maximum water levels in the lake by 0.7 m. Urbanisation as per the W.A. Planning Commission’s east Wanneroo land use concept (WAPC 2007) could increase seasonal maximum water levels in Lake Mariginiup by 0.4 m and Lake Jandabup by 0.7 m. Pine clearing has the potential to increase seasonal maximum water levels in Lake Mariginiup by 0.2 m and Lake Jandabup by 0.7 m. Re-establishment of banksia woodlands in areas where pines have been cleared reduces these gains by 0.1 m in Lake Mariginiup and 0.3 m in Lake Jandabup. Re-direction and injection of urban stormwater from roads into an infiltration swale up-gradient of Lake Mariginiup could increase spring peak water levels by 0.1 m above the increases under conventional diffuse-recharge development.

Increases in summer water levels in Lake Mariginiup are predicted under urbanisation with pine clearing are minimal (0.2 m). However, this may be sufficient to reduce oxidation of acid sulfate soils if the lake bed sediments remain saturated. Minimal increases are predicted under the directed recharge scenario. Summer minimum water levels in Lake Jandabup are increased through land-use change to the extent that artificial supplementation may be offset and no longer required.

Water levels in the superficial aquifer are predicted to increase up to 4.0 m by 2031 if the full range of land-use changes including urbanisation and pine clearing is implemented. Water table increases are up to 3.3 m with only pine clearing and 2.7 m with only urbanisation. These water level increases are not evenly distributed across the model domain, with the largest increases to the south and south-east of Lake Jandabup.

We have demonstrated that local-scale modelling explicitly incorporating groundwater-lake interactions can be a useful tool for assessing land and water management options. Further scenario modelling should be undertaken using this local-scale model to assess the impacts of private abstraction and climate on water levels in Lakes Mariginiup and Jandabup.
1 Introduction

Groundwater management decisions in the Perth region are often informed by outputs from the Perth Regional Aquifer Modelling System (PRAMS) (Davidson and Yu 2008). Regional scale modelling of the Gnangara Groundwater Mound using PRAMS suggests that land use change, including pine clearing and urbanisation, can alter water levels in the superficial aquifer (Vogwill et al. 2008).

However, the PRAMS model cannot accommodate groundwater-lake interaction and is not able to simulate lake water levels. To overcome these limitations a local-scale numerical model was built of the superficial aquifer in the east Wanneroo area that is able to predict lake stage and groundwater levels (Figure 1).

Current land use in the model domain is predominantly horticulture and state forest with some urban and industrial zones (Figure 2).

We have run 7 predictive modelling scenarios to assess the effects of land and water management regimes on water levels in Lakes Mariginup and Jandabup, and groundwater levels in the superficial aquifer. Four management issues were considered:

- Artificial lake supplementation
- Pine clearing
- Urbanisation
- Directed urban drainage

This scenario modelling will inform the Gnangara Sustainability Strategy (GSS). The GSS is a multi-agency project working towards sustainable integrated land and water management on the Gnangara Groundwater Mound (GGM). The Department of Water is the lead agency for the GSS.

The GGM is a significant source of water for the City of Perth and supplies around 60 per cent of the Water Corporations’ integrated water supply system. The model domain includes Public Drinking Water Source protection areas and Water Corporation production wells (Figure 3).

Groundwater levels on the GGM have been declining, in part due to declining rainfall, since the 1970’s (Yesertener 2005). Global climate models predict that this drying trend will continue across south-western W.A. (IPCC 2007).

The GGM supports numerous lakes and wetlands that provide habitat for wading birds, aquatic fauna and fringing vegetation (Davidson 1995, Froend et al. 2004). Water levels in these lakes are declining, threatening the ecosystems they support.

The Department of Water has an obligation to ensure Ministerial Criteria water levels (based on ecological water requirements) are met to maintain the ecological values of these systems. These water levels are measured at staff gauges in lakes Mariginup and Jandabup also at bores adjacent to the lakes (Figure 4).
Ministerial Criteria are mostly based on static water levels and do not account for long term climatic change. The department is currently working towards updating this management framework to one based on eco-hydrological states which will more accurately reflect climate-driven changes in these systems.

The lowering of water levels can also expose organic sediments that acidify when they dry out (McHugh and Bourke 2007). These materials are known as acid sulfate soils (ASS). Oxidation of acid sulfate soils has already caused the acidification of Lake Gnangara (pH<4 since 1978), which is unlikely to recover (WAWA 1995). Lakes Jandabup and Mariginiup are at risk of acidification (Froend et al. 2004). To mitigate this risk of acidification at Lake Jandabup the Water Corporation supplements the lake with water from the Leederville aquifer during the dry summer months. This is not an ideal solution as it is costly and depletes the water resources of the source aquifer.

Perth’s population is projected to more than double by 2056 (ABS 2008) and development will continue to occur along Perth’s north-west corridor. The Western Australian Planning Commission published a report in 2007 outlining their concept for future land use in the east Wanneroo area (WAPC 2007). This concept includes a shift away from groundwater intensive horticulture towards increased urbanisation. This could increase water levels in the superficial aquifer through decreased abstraction and increased recharge. The benefits could be enhanced by directing the water captured on impermeable surfaces in the urban area towards lakes, either via pipes directly into the lake or infiltrated into the superficial aquifer diffusely across the lake capture zone. Treating this intercepted water as a resource can have dual benefits; allowing the developer to fulfil their obligations for on-site water retention while also maintaining water levels in the lake, reducing the risk of acidification.

Much of the state forest in the model domain is pine plantation managed by the Forest Products Commission (FPC). Research has demonstrated that pines may not just reduce recharge to the superficial aquifer through evapotranspiration but could actually result in a net flux of water away from the watertable to the atmosphere (Silberstein 2007). As such, pine clearing has the potential to significantly increase recharge to the superficial aquifer.

This modelling study will assess the potential impacts of land-use change in the east Wanneroo area on water levels in the superficial aquifer and lakes Mariginiup and Jandabup. This local-scale modelling will supplement previous regional-scale studies to inform the management of water and land resources in a context of competing demand from communities and the environment.
Figure 1 Locality map
Figure 2 Land use map
Figure 3 Public drinking water supply areas and Water Corporation production wells in the superficial aquifer
Figure 4 Ministerial criteria sites at Lakes Mariginup and Jandabup. Site MT3S (Bore 5086) is used to report modelling results.
2 Model Construction

2.1 Hydrogeological conceptualisation

The regional groundwater flow regime in the study area is dominated by the Gnangara Groundwater Mound (GGM). Flow through the model domain is from the north east to the south west, with a hydraulic gradient of approximately 20 m along a NE-SW transect (Figure 5).

The superficial formations in the area are predominantly sands and silty sand of the Spearwood and Bassendean sand units and are up to 60 m thick. The superficial formations form the unconfined superficial aquifer, which is underlain by the Leederville and Mirrabooka aquifers. Leakage is downward from the superficial aquifer to the Leederville aquifer in the north of the model domain, and to the Mirrabooka aquifer in the east, with upward leakage from the Mirrabooka to the superficial aquifer in the south-western region of the model domain.

Mariginiup and Jandabup lakes are through-flow lakes that sit on the superficial formations of the Swan Coastal Plain (Hall 1983, Allen 1979). Water levels in the lakes vary seasonally in response to groundwater levels. Other lakes in the model area (e.g. Lakes Gnangara, Pinjar and Adams) are also expressions of the watertable but do not hold significant surface water bodies and were not explicitly included in the model as lakes.

2.2 The calibrated model (2001-2006)

The numerical model was built by RPS Environmental using GMS as a pre- and post-processor for MODFLOW 2000. A brief summary of the model construction is provided here. For full details of the model construction, sensitivity and uncertainty analysis please refer to RPS (2009a).

Model design

Boundaries are specified head at 60 m in the north-east, specified head at 36 m in the west with no-flow boundaries in the north and south-east (Figure 6). A finite difference grid was constructed within these boundaries using the conceptual model approach in GMS. Grid cell size ranges from 50 m adjacent to the lakes up to 250 m at the boundaries.

The superficial aquifer was discretised into 7 horizontal layers (Figure 7). Leakage between the superficial aquifer and the underlying formations occurs through the bottom of layer 7. The layers in the model do not represent lithological units.

Leakage between the superficial aquifer and the underlying units is included as described above, based on Davidson (1995), the most up-to-date reference at the time of model construction. These flux estimates have since been updated, suggesting that leakage within the model domain is only downward, with no upward flow from the Mirrabooka aquifer (Davidson and Yu, 2008). However, upward
leakage is only 4 per cent of the total leakage in the model and is unlikely to significantly affect water balances in the model.

**Groundwater-surface water interaction**

Groundwater-surface water interactions are simulated using the MODFLOW Lakes Package (Meritt & Konikow 2000). The Lakes Package calculates flow between a lake and the adjacent aquifer based on water levels and lake-bed conductance. ‘Lake’ cells are defined in the model grid that are able to dry and re-wet over time. When the lake is dry (the lake stage is below the lake-bed) these cells become inactive. As water levels rise above the bottom of the lake-bed, these cells are re-activated. While the lake cells are active the water balance is calculated from precipitation, evaporation and runoff.

**Calibration**

- The model was calibrated over the period 1 October 2001 to 1 October 2006.
- Hydraulic conductivities in the model range from 10 to 13 m/day for Spearwood Sand and from 15 to 18 m/day for Bassendean Sand.
- Observation bore data was from the Department of Water’s WIN database.
- Private abstraction rates were based on 80 per cent of licensed allocation to private users as recorded in the Department of Water WRL database in October 2007. Annual allocations were distributed to monthly volumes concentrated over the dry summer months.
- Groundwater abstraction by the Water Corporation for public water supply was measured monthly volumes from the Department of Water database.
- All abstraction and observation wells are located in layer 7, irrespective of the actual screened interval. As all of the layers in the model are hydraulically connected, the vertical location of the well screens is unlikely to be significant.
- Lake Jandabup augmentation was based on measured values for each summer (~1GL each summer), distributed across the summer months.
- Rainfall data was from Bureau of Meteorology Wanneroo station (9105).
- Evapotranspiration data was from the Bureau of Meteorology’s Perth Airport station (9021) with values in the model set at 75 per cent of pan evaporation, with an extinction depth of 3 m. The ET coverage in the model applies these rates to the areas of lakes Mariginiup, Jandabup, Pinjar and Gnangara.
- Recharge from rainfall was distributed by land use according to Figure 8.
- Specific yield of 0.28, vertical anisotropy of 3, lake-leakance of 1 and 0.1.

This model yielded a root mean square residual head difference of 0.9 m or 4 per cent of the measured change in hydraulic head across the domain (RPS 2009a).
Figure 5 Groundwater contours, historical minimum (m AHD)
Figure 6 Map of model grid and boundaries
Figure 7 Cross section of model domain showing layers and the lakes coverage.
Figure 8 Map of calibrated recharge coverage showing land use and per cent of rainfall recharged to the aquifer
3 Predictive scenarios

3.1 Scenario development

A suite of seven scenarios were conceived to capture the range of land-use options being considered by the Gnangara Sustainability Strategy.

- Scenario 1 is the basecase, simulating the extension of current management practices into the future. This provides a reference point for understanding the effects of land and water management regimes simulated in the other six scenarios.
- Scenario 2 simulates water levels if artificial supplementation of Lake Jandabup ceases.
- Scenario 3 simulates water levels when pine plantations are cleared and replaced with pasture/grassland.
- Scenario 4 simulates water levels when pine plantations are cleared and banksia woodland is established.
- Scenario 5 simulates urbanisation in line with current plans and policies.
- Scenario 6 simulates the full range of land-use change by combining the urbanisation of scenario 5 with pine clearing of scenario 3.
- Scenario 7 provides a variation on Scenario 6 by simulating the recharge of water captured from roads in the urbanised area directly into the lakes, given full land-use change.

A simulated rainfall sequence generated by the Water Corporation to approximate the Perth climate from 1997 to 2006 (730 mm per year) was used in all future scenario runs. This represents a drier climate than the long-term average for Wanneroo (820 mm per year). This synthetic rainfall sequence was used instead of measured rainfall data to be consistent with modelling scenarios run using PRAMS. Impacts of different possible climate regimes have not been not explicitly modelled. Possible effects of groundwater abstraction by the Water Corporation were outside the scope of this project and have also not been explicitly considered.

Land-use change was simulated through the recharge coefficient that was applied to the rainfall sequence. Annual recharge rates were applied to the monthly rainfall data to produce a step-wise function of monthly recharge in each polygon. The recharge coverage used in the calibrated model was refined to accommodate land-use changes on smaller spatial scales than the calibrated model, as required for the scenario runs. Three sources were used to determine the future land use (and therefore rainfall recharge) for each polygon. These were the Wanneroo future land use concept outlined in WAPC (2007), Cedar Wood’s development schedule for the Mariginiup precinct and the Forrest Products Commission pine harvesting schedule.

Values of recharge coefficients are outlined in Table 1. These values were chosen so as to be consistent with published literature (e.g. Appleyard 1995, Davidson 1995,
Silberstein et al. 2004 and 2007), regional scale modelling (PRAMS) and the calibrated local area model (2001-2005). When significant variation in recharge coefficients was encountered in these three sources preference was given to values that were consistent with the calibrated model period. This was to ensure consistency in recharge coefficients for each land-use category between the calibrated model and the predictive scenarios. The change in recharge coefficient was applied in full immediately at Jan 1 in the year of the scheduled land-use change.

Table 1 Annual rainfall recharge coefficients

<table>
<thead>
<tr>
<th>Land use</th>
<th>Literature</th>
<th>Calibrated model</th>
<th>Predictive scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>37-60%</td>
<td>40-45%</td>
<td>40%</td>
</tr>
<tr>
<td>Industrial</td>
<td>60-70%</td>
<td>40-45%</td>
<td>40%</td>
</tr>
<tr>
<td>Banksia woodland</td>
<td>10-38%</td>
<td>10 to 18%</td>
<td>18%</td>
</tr>
<tr>
<td>Market garden</td>
<td>36 to 40%</td>
<td>25 to 35%</td>
<td>25 to 35%</td>
</tr>
<tr>
<td>Pasture</td>
<td>&lt;36 to 60%</td>
<td>25 to 35%</td>
<td>35%</td>
</tr>
<tr>
<td>Pine plantation</td>
<td>-13 to 15%</td>
<td>-13 to -9%</td>
<td>-13 to -9%</td>
</tr>
</tbody>
</table>

Groundwater abstraction is also changed in areas that are urbanised, with the allocation from the calibrated model replaced with abstraction rates based on previous studies of domestic water consumption in W.A. (Water Corporation 2003, ABS 2003).

Grid and aquifer properties remained the same as the calibrated model for all scenarios. Full details of each scenario are provided in section 3.2 and summarised in Table 2.
Table 2 Scenario matrix

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Climate</th>
<th>Abstraction</th>
<th>Land Use</th>
<th>Drainage/Supplementation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water Corp.</td>
<td>Private</td>
<td>Pine clearing</td>
<td>Jandabup augmentation</td>
</tr>
<tr>
<td></td>
<td>(730 mm/yr)</td>
<td>volumes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
3.2 Predictive scenario description

Scenario 1: Basecase

This scenario simulates the continuation of current water and land management regimes, to provide a baseline for interpretation of the other six scenarios.

Recharge coefficients remain the same as the calibrated period 2001–2006 (see Figure 8).

Rainfall and evaporation data have been updated to include measured data up to and including December 2008. A synthetic 12 month sequence for each parameter provided by the Water Corporation to represent the actual climate of 1997-2006 (730mm/yr) is used, looped, between Jan 09 and Dec 2030.

Groundwater abstraction for both public and private use is the 5 year 2001–2006 data-set repeated until 2030.

Augmentation of water levels in Lake Jandabup was included in the basecase in line with current management practices (~1 GL/yr delivered to the lake between November and May). Total volumes for each summer were interpolated between the start and end dates for pumping as recorded by the Department of Water.

Scenario 2: No Jandabup augmentation

This scenario simulates water levels in the absence of artificial water level maintenance of Lake Jandabup. The augmentation component was removed from the lakes package after the supplementation over the 2008-2009 summer was complete and the scenario then run to 2030.

Scenario 3: Pine clearing

This scenario models the effects of clearing the pine plantations. Projected dates for pine clearing of areas within the model domain were provided by the Forest Products Commission in line with their pine harvesting schedule (current as at August 2008). Where there were multiple dates within a model polygon a median value was used as the date of pine clearing for the scenario run (Figure 9). Pine clearing was implemented instantaneously on 1 January of the relevant year. A 35 per cent recharge coefficient was applied to the rainfall sequence after pine clearing to simulate grassland/pasture. Urbanisation remained as per current land use.

Scenario 4: Post-pine banksia

This scenario simulates pine clearing followed by the re-establishment of banksia woodland. All model components as per the previous pine clearing scenario, except with an 18 per cent recharge coefficient applied to the rainfall sequence after pine clearing. This percentage of rainfall recharge has been used previously for medium density banksia in regional groundwater modelling using PRAMS (Silberstein, 2004). There is no accommodation made for growth or burning of the banksia, the recharge
rate is changed to 18 per cent immediately on the date of pine clearing and remains constant until the end of the model run.

**Scenario 5: Urbanisation**

This scenario models water level changes associated with urban development under conventional water management practices. Two data sources were incorporated into the recharge coverage; the land use concept prepared by the Western Australia Planning Commission (WAPC 2007) and Cedar Wood’s local scale development plan for the area around Lake Mariginiup (Zagwocki pers comm.).

Areas that changed to urban land use were set to 35 per cent rainfall recharge on 1 January of the year they were scheduled to be developed (Figure 9). Development dates were available for the Cedar Woods development, with initiation of new allotments each 5 years. For areas of the model planned to be urbanised outside of the Cedar Woods development area (as indicated in WAPC 2007), it was assumed that a similar staged approach would be utilised at 5 yearly intervals, beginning with the lots closest to the Cedar Woods development area.

In areas that shifted from horticulture to urban land use the private abstraction as included in the basecase was removed and a new coverage was applied to simulate groundwater use in these areas. Abstraction rates in these newly urbanised areas were based on estimations from the Water Corporation (2003) and the Australian Bureau of Statistics (2003).

**Scenario 6: Urbanisation plus pine clearing**

This scenario incorporates land-use changes in both the urbanisation and the pine clearing scenarios. Recharge rates in areas where pines are cleared are converted to pasture at 35 per cent rainfall recharge as per Scenario 3. The WAPC and Cedar Woods land-use plans are incorporated as per Scenario 5.

**Scenario 7: Directed recharge**

The directed recharge scenario simulates the collection of water from roads in the urbanised area and direction of this water into an infiltration swale directly up-gradient (50 m east) of Lake Mariginiup. It is assumed that 30 per cent of the urban development will be roads and 80 per cent of rainfall from these roads is directed to the infiltration swale. All other facets of the model are the same as Scenario 6.

The interception and re-direction of run-off from the urban area would presumably reduce the amount of recharge. However, it is difficult to estimate the amount by which the recharge should be reduced so rainfall recharge in urbanised areas is still 35 per cent. This may elevate the predicted groundwater levels in the urban area, but is unlikely to significantly affect the predicted water levels in Lake Mariginiup.
Figure 9 Recharge rates and date of change for predictive scenario recharge coverages
4 Predictive scenario results

Scenario results are presented as:

- time series of lake stage data
- time series of observation well data
- a map of groundwater levels simulated by the basecase
- maps of groundwater level change between each scenario and the basecase.

Time series of groundwater levels in bore 5086 (WIN ID) (see site MT3S on Figure 4) are presented for all scenarios. This bore was selected because it is located centrally within the model domain (and therefore not subject to boundary effects), between lakes Marigindiup and Jandabup and was well calibrated over the 2001–2006 period. Further time series of observation bore data are presented where they are particularly relevant for an individual scenario.

Contour plots for the basecase are simulated groundwater levels in m AHD. For all other scenarios the contours maps show the change in hydraulic head (the difference between the basecase and that scenario). In these maps, positive values represent an increase in groundwater levels above the basecase, and negative values a decrease relative to the basecase. A map of the hydraulic head difference between Scenario 7 (directed recharge) and Scenario 6 (conventional urbanisation) is also presented.

All of the groundwater level contour maps are based on the hydraulic head as predicted in Layer 3 on 1 April, 2030. This layer represents the top-most layer of the model that does not contain “lake” cells and reflects the predicted height of the water table. Layers 1 and 2 were not considered suitable for mapping as the cells assigned to the lakes package can be inactivated, resulting in “holes” in the data set. Further, as all of the layers are hydraulically connected the predicted heads at each time step do not vary significantly between layers.

4.1 Scenario 1 - Basecase

Water level predictions under the basecase scenario do not represent expected actual water levels, but provide a reference point for comparison with other scenario predictions. This follows from the recommendations of RPS (2009) based on model calibration, sensitivity and uncertainty analysis.

Lake Marigindiup water level trends show steady seasonal variation from 2009 under the basecase scenario. Water levels peak at 41.5 m AHD in October of each year, which is consistent with the water level maxima observed in 2008. The lake is predicted to be dry (≤41.1 m AHD) for approximately 4 months between January and May each year. The discrepancy between the observed and simulated minimum water levels is because bottom of the staff gauge is at 41.3 m AHD, 0.2 m above the absolute minimum of the lake bed (Figure 10).
Lake Jandabup experiences a slight declining trend over the simulation period. Water level maxima are 45.0 m AHD, with minima of 44.5 m AHD at the end of the simulation. The inter-annual variation is a result of artificial supplementation, with different volumes applied each year as per the 2001–2006 supplementation regime (Figure 11).

The groundwater gradient remains east to west across the model domain, with the fixed head boundaries constraining the flow field. The influence of Water Corporation production wells is evident with some of the groundwater contours indicating drawdown caused by well abstraction (Figures 12 and 13).

Figure 10 Basecase scenario: Predicted water levels in Lake Mariginiup
Figure 11 Basecase scenario: Predicted water levels in Lake Jandabup

Figure 12 Basecase scenario: Predicted water levels in bore 5086
Figure 13 Basecase scenario: Predicted hydraulic head contours in layer 3, April 2030 (m AHD, 1m intervals)
4.2 Scenario 2 - No Jandabup augmentation

In this scenario artificial supplementation of Lake Jandabup has been removed from the lakes package as of 2010. Mariginiup water levels remain unchanged from the basecase (Figure 14). Jandabup water levels decrease after augmentation ceases, with water level maxima declining by 0.7 m and minima by 0.5 m (Figure 15). Groundwater levels decline by up to 1.0 m directly beneath the lake and 0.5 m south and west of the lake basin when Jandabup following cessation of augmentation (Figure 17). This is a localised decline with groundwater levels in bore 5086 showing minimal change in seasonal maxima, and a decrease of 0.1 m in seasonal minima (Figure 16).

Figure 14 Scenario 2: Predicted water levels in Lake Mariginiup
Figure 15 Scenario 2: Predicted water levels in Lake Jandabup

Figure 16 Scenario 2: Predicted water levels in bore 5086
Figure 17 Scenario 2: Change in hydraulic head relative to the basecase, layer 3, April 2030
4.3 Scenarios 3 and 4 - Pine clearing and Post-pine banksia

These scenarios simulate the possible impact of clearing the pine plantations on water levels. The pine clearing scenario assumes that there will not be any active re-vegetation and the land will remain as pasture with 35 per cent rainfall recharge. The post-pine banksia scenario simulates the re-establishment of banksia on land where pines have been cleared, with 18 per cent rainfall recharge.

Water levels in Lake Jandabup are more influenced by the pine clearing than Lake Mariginiup due to proximity and flow directions (Figures 18 and 19).

When pasture remains after pine clearing the maximum and minimum water levels at Lake Jandabup are increased approximately 0.7 and 0.6 m, respectively. Water level minima at Lake Mariginiup remain unchanged with the lake-bed dry over summer, while maximum water levels are increased by 0.2 m relative to the basecase. Oscillations in water predicted water levels after summer are possibly associated with the re-wetting process in the simulation (RPS 2009a).

With the establishment of banksia woodland seasonal maximum water levels at Lake Jandabup increased by 0.4 m and Lake Mariginiup by 0.1 m (Figures 18 and 19). Summer minima at Lake Jandabup are increased by 0.3 m.

Increases in groundwater levels of up to 3.3 m are predicted directly beneath and down-gradient of the cleared pines where pine plantation is replaced by pasture (Figure 21). The establishment of banksia woodland reduces the increase to 2.1 m (Figure 22). Water levels in bore 5086 increased by 1.0 m under pasture and 0.7 m under banksia (Figure 20) relative to the basecase at the end of the simulation.
Figure 18 Scenarios 3 and 4: Predicted water levels in Lake Mariginiup

Figure 19 Scenarios 3 and 4: Predicted water levels in Lake Jandabup
Figure 20 Scenarios 3 and 4: Predicted water levels in bore 5086
Figure 21 Scenario 4: Change in hydraulic head relative to basecase, layer 3, April 2030
Figure 22 Scenario 4: Change in hydraulic head relative to basecase, layer 3, April 2030
4.4 Scenarios 5 and 6 - Urbanisation and urbanisation plus pine clearing

The urbanisation scenario suggests seasonal maxima could be increased by up to 0.4 m in Lake Mariginiup, with seasonal minima increasing by 0.1 m relative to the basecase (Figure 23). Maximum water levels in Lake Jandabup increase by 0.7 m and minima by 0.6 m relative to the basecase (Figure 24).

When urbanisation is combined with pine clearing the model suggests that the Lake Mariginiup maintains surface water during summer from 2026. However the predicted water levels are only at the height of the bottom of the staff gauge is (41.3 m AHD). Maximum water levels in Lake Mariginiup increase by 0.6 m relative to the basecase under this scenario, while the minima remain the same. As a result, the amplitude of seasonal fluctuation in water levels almost doubles.

In both scenarios 5 and 6 the increases in maximum water levels in Lake Jandabup commence later than in Lake Mariginiup because of the dates of pine clearing and urbanisation in the area. However, the magnitude of the increase is larger, with maximum water levels up to 1.4 m higher than the basecase. Minimum water levels in Lake Jandabup are increased by 1.2 m, and so the amplitude of seasonal water level fluctuation in Lake Jandabup increases by 0.2 m.

Groundwater levels increase by up to 2.7 m under urbanisation, with the maximum increase south of Lake Jandabup (Figure 26). When pine clearing is also included the same area experiences an increase of 3.9 m relative to the basecase, with the highest increases (4.0 m) east of Lake Jandabup where pines have been cleared (Figure 27). Seasonal maximum water levels in bore 5086 increase by 1.2 m in the urbanisation scenario and 1.9 m when pine clearing is also incorporated (Figure 25).
Figure 23 Scenarios 5 and 6: Predicted water levels in Lake Mariginiup

Figure 24 Scenarios 5 and 6: Predicted water levels in Lake Jandabup
Figure 25 Scenarios 5 and 6: Predicted water levels in bore 5086
Figure 26 Scenario 5: Change in hydraulic head relative to basecase, layer 3, April 2030
Figure 27 Scenario 6: Change in hydraulic head relative to basecase, layer 3, April 2030
4.5 Scenario 7 - Directed recharge

This scenario is based on Scenario 6 (urbanisation plus pine clearing) with the addition of directed urban runoff. Water is captured from road surfaces in the urban and injected into an infiltration swale 50 m up-gradient (east) of Lake Mariginiup.

Spring peak water levels in Lake Mariginiup are 0.1 m higher than those predicted under conventional urban water management in Scenario 6 (Figure 28).

Water levels in Lake Jandabup and bore 5086 remain unchanged from Scenario 6 (Figures 29 and 30). Groundwater contours are also not significantly different to Scenario 6 (Figure 31). Hydraulic head directly under the infiltration swale is 0.1 m higher than Scenario 6, while all other areas have changed by less than 0.1 m.

![Figure 28 Scenario 7: Predicted water levels in Lake Mariginiup](image-url)
Lake Jandabup water levels
Basecase, Urbanisation plus pine clearing and Directed recharge scenario predictions

Figure 29 Scenario 7: Predicted water levels in Lake Jandabup

Water levels Bore 5086
Basecase, Urbanisation plus pine clearing and Directed recharge scenario predictions

Figure 30 Scenario 7: Predicted water levels in bore 5086
Figure 31 Scenario 7: Change in hydraulic head relative to Scenario 6, Layer 3, April 2030
5 Interpretation of scenario predictions

5.1 Uncertainty in recharge coefficients

The water level changes simulated in these scenario runs are heavily dependant on the coefficients of rainfall recharge assigned to reflect land-use change. As described in Section 3.1 there are a range of values reported in the literature. The values applied in these scenarios are on the conservative end and were chosen to be in line with values utilised in the calibrated model. The actual percentage of rainfall that is recharged to the aquifer will vary spatially and temporally, even within areas that are classified as having the same land use.

The change in model outputs when different recharge coefficients are applied is demonstrated by variation between the Pines and Banksia scenarios. The only difference between these two scenarios is the value of the recharge coefficient applied after pine clearing (35 per cent for Scenario 3, 18 per cent for Scenario 4). The difference in the predicted groundwater level change relative to the basecase between these scenarios is 1.2 m at the location of maximum groundwater increase (3.3 m with grassland, 2.1 m with banksia). That is, an 18 per cent difference in rainfall recharge resulted in a 1.2 m difference in maximum groundwater level change relative to the basecase. The difference in predicted lake levels under the Pines and Banksia scenarios was 0.3 m at Lake Jandabup and 0.1 m at Lake Mariginiup.

Literature suggests that the percentage of rainfall recharge in urbanised areas could vary by up to 20 per cent (Appleyard 1995, Silberstein et al. 2004). This constitutes a significant source of uncertainty within the model simulations in addition to those discussed by RPS (2009a). Running multiple scenarios that encompass the possible range of recharge values would allow for this uncertainty to be more accurately quantified.

The inclusion of processes at the surface and in the unsaturated zone explicitly within the model (e.g. WAVES, VFM) could reduce the influence of uncertainty in recharge rates. This explicit modelling approach would also increase computational effort and data input requirements.

5.2 Implications for management

This local-area modelling study supports the implementation of land-use change as a tool for managing water levels in the east Wanneroo area. The results suggest that pine clearing and urbanisation can both lead to significant rises in the water table and lake water levels (Table 4).

Artificial supplementation of Lake Jandabup maintains water levels by up to 0.7 m. This amount is less than the gain in water level under urbanisation and pine clearing (Scenario 6). As such, this modelling suggests that if the full scope of land-use change is implemented water levels in Lake Jandabup may be sufficient without augmentation in the future. However, it must be remembered that these modelling
scenarios do not account for any decline in rainfall below 1996-2007 levels, which Perth is predicted to experience (IPCC 2007). Regional scale groundwater models have shown that climate plays a significant role in determining water levels on the Gnangara Mound, and a drier climate could lower the water table in the east Wanneroo area by up to 2 m (Vogwill et al. 2008). The impact of climate-driven watertable decline on lake water levels is not known and could be a subject of further investigation using this local area model.

Water levels in Lake Mariginiup are increased more by urbanisation than pine clearing. This is likely due to the spatial distribution of each land-use change with more urbanisation occurring within the capture zone of the lake. With combined urbanisation and pine clearing, spring peak water levels are 0.6 m higher than the basecase. Increased summer minima, while not high enough to be recorded on the staff gauge, would increase sediment saturation and could thereby reduce the oxidation of potential acid sulfate soils (Turvey, 2007).

Table 3 Predicted changes in minimum and maximum water levels in Lakes Mariginiup and Jandabup.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Change in water level relative to the basecase (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lake Mariginiup</td>
</tr>
<tr>
<td></td>
<td>minima Datum</td>
</tr>
<tr>
<td>1. Basecase</td>
<td>Datum Datum</td>
</tr>
<tr>
<td>2. No Jandabup augmentation</td>
<td>0 0</td>
</tr>
<tr>
<td>3. Pine clearing</td>
<td>0 0.2</td>
</tr>
<tr>
<td>4. Post-pine banksia</td>
<td>0 0.1</td>
</tr>
<tr>
<td>5. Urbanisation</td>
<td>0.1 0.4</td>
</tr>
<tr>
<td>6. Pine clearing plus urbanisation</td>
<td>0.2 0.6</td>
</tr>
<tr>
<td>7. Road runoff injected into swale</td>
<td>0.2 0.7</td>
</tr>
</tbody>
</table>

Directed recharge of water captured from roads in the urban area in the immediate vicinity of Lake Mariginiup could raise seasonal maximum water levels by 0.1 m above standard water management practices (diffuse infiltration of urban runoff). It would be possible to increase the captured volume by including the roofs of houses as a source as well as roads. RPS has estimated that the seasonal maximum could increase by an additional 0.1 m under this scenario (Carl Davies, pers. comm.).

The cost-effectiveness of this type of directed stormwater management must be evaluated in the context of possible environmental benefits. The re-direction of stormwater away from the source urban area would reduce the recharge to the watertable in that development zone. Therefore, under a directed drainage scenario the increases in lake water levels occur at the expense of watertable rise in the urban area. A directed recharge scheme would also require infrastructure to be installed and maintained over the life of the scheme.
In addition to economic considerations, implementation of such a stormwater redirection scheme outside the immediate catchment of the lake would contravene the principles of the Stormwater management manual for Western Australia (DOW 2007). This manual promotes the retention of stormwater within the immediate urban catchment so as to preserve the pre-development hydrology and minimise the transport of pollutants.

The Water Corporation has concluded from steady-state modelling that pine clearing is essential to maintain water levels on the mound under a drying climate (Xu 2008). The transient scenarios we have run using this local-scale model of the east Wanneroo area supports the positive impact pine clearing can have on groundwater and lake water levels.

In addition, this local-scale modelling shows that urbanisation in the east Wanneroo area has the potential to increase water levels in the superficial aquifer by a similar order of magnitude to pine clearing (3.3 m maximum increase under pine clearing with pasture, 2.7 m maximum increase under urbanisation only). This supports the findings of Vogwill et al. (2008) that urbanisation can act as a tool for mitigating groundwater level declines on the GMM. As discussed in Section 5.1 the increases under urbanisation are likely to be conservative, assuming rainfall-recharge is toward the lower end of rates reported in the literature.

Management of private abstraction in newly urbanised areas will ultimately determine the actual gains in rainfall recharge experienced. This study assumes that groundwater usage by home owners continues in line with recent trends (Water Corporation 2003, ABS 2003). A shift in policy away from the use of garden bores could lead to increased water levels in addition to those simulated in these scenarios.

Impacts of groundwater abstraction were not assessed in this study. Regional scale modelling suggests that groundwater abstraction can play a significant role in determining water levels on the GGM (Xu 2008, Vogwill et al. 2008). Groundwater is abstracted from the superficial aquifer in the east Wanneroo area by the Water Corporation for public water supply, and also by private users. Scenario modelling using PRAMS has estimated that reducing private abstraction by 20 per cent could increase water table levels in the east Wanneroo area by up to 1.5 m (Vogwill et al. 2008). Further modelling should be undertaken with this local-scale model to assess the impacts of groundwater abstraction on lake water levels and the watertable in the east Wanneroo area.
6 Conclusions and recommendations

- Local-scale modelling that explicitly incorporates surface water-groundwater interactions is a useful tool for evaluating land and water management options.

- Land-use change in the east Wanneroo area is likely to increase water levels in the superficial aquifer and lakes Mariginiup and Jandabup.

- The maximum water level increase in the superficial aquifer under pine clearing is of comparable magnitude to maximum increases under urbanisation. However, the location of the maximum increase differs according to the distribution of the land-use change.

- Urbanisation and pine clearing combined could potentially off-set the need for artificial supplementation of water levels in Lake Jandabup.

- Summer minimum water levels in Lake Mariginiup are unlikely to increase significantly if both pine clearing and urbanisation are implemented, but the increase may be sufficient to maintain the saturation of sediment and reduce the oxidation of potential acid sulfate soils.

- The implementation of a directed recharge regime could provide small increases lake water levels but this would occur at the expense of groundwater level increases and needs to be further evaluated for cost-effectiveness and environmental significance.

- Further scenario modelling should be carried out using this model to assess the impacts of public and private abstraction on water levels in the east Wanneroo area.

- Future scenario modelling should report results as ranges of possible water level change to better communicate the level of uncertainty in the scenario results.
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