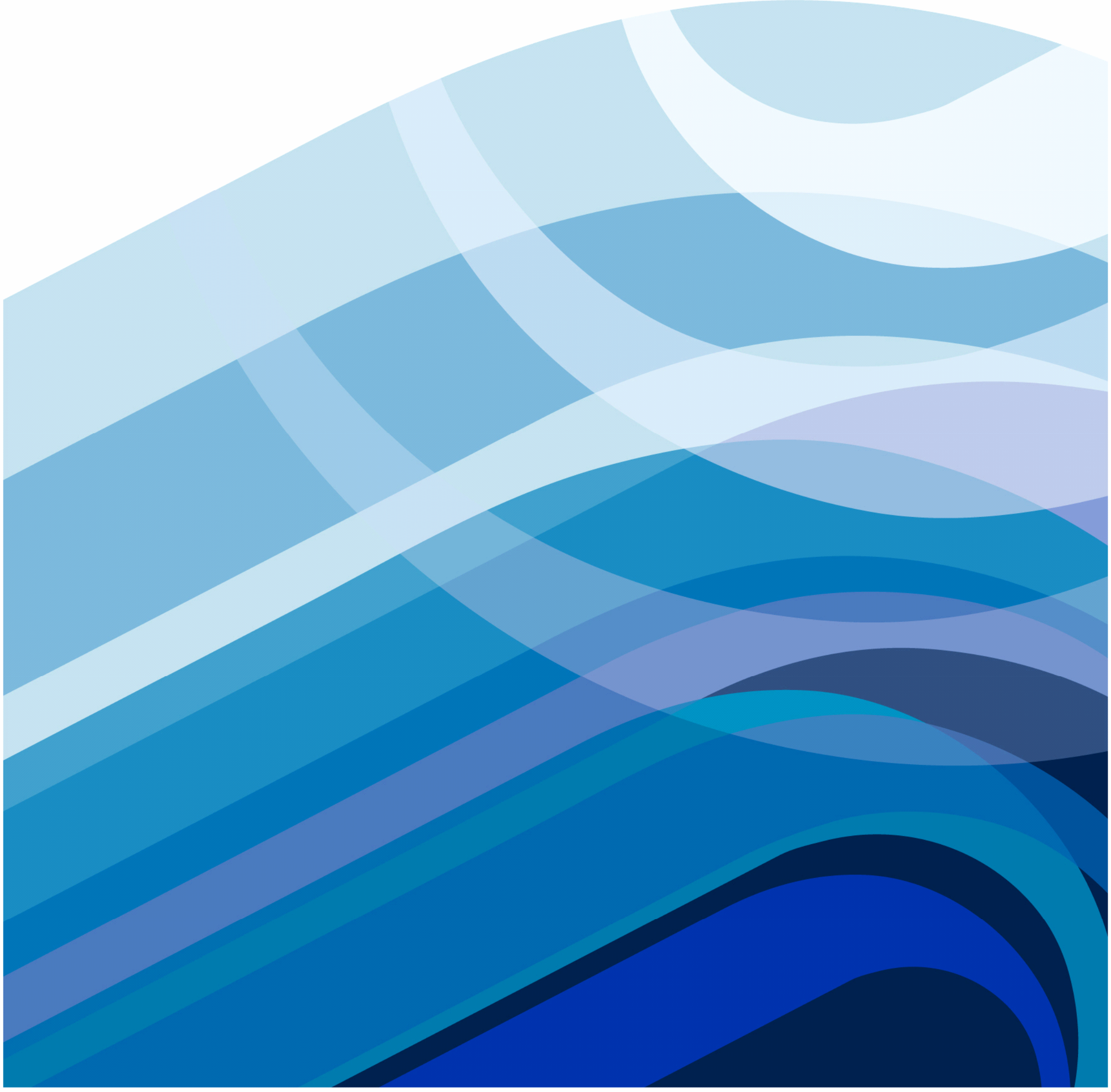
WATER
CORPORATION

# Water Balance Analysis for the Gnangara Mound under Corporation abstraction scenarios of 105, 135 and 165 GL/a



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# CONTENTS

EXECUTIVE SUMMARY ........ 5
INTRODUCTION ........ 7
SCENARIO DEVELOPMENT ........ 8
WATER BALANCE ANALYSIS ........ 9
RESULTS ........ 10
  Water Balance for the Gnangara Mound ........ 10
  Water Balance for the Yeal Area ........ 11
  Water Balance for the Pinjar Area ........ 12
  Water Balance for the Lexia Area ........ 12
  Water Balance for the Mirrabooka Area ........ 13
  Water Balance for the Yanchep Area ........ 13
  Water Balance for the Northern WGA Area ........ 14
  Water Balance for the Southern WGA Area ........ 14
  Water Balance for the Gwelup Area ........ 15
  Water Balance for the Perth Urban North Area ........ 16
  Water Balance for the Perth Metro Coastal Area ........ 16
POTENTIAL OPTIONS FOR RESTORING WATER BALANCE ........ 18
  Effects of options for burning, pine harvest and reduction in private use ........ 19
  Water Corporation's management options ........ 19
  Abstraction for the Corporation's borefields under zero storage deficit ........ 23
CONCLUSION ........ 25
RECOMMENDATION ........ 26
REFERENCES ........ 27

## Tables

Table 1 Abstraction from various aquifers for the 105 GL/a to 165 GL/a scenarios ........ 8
Table 2 Annual synthetic rainfall compared with median of historical data ........ 9
Table 3 Water balance for 105, 135 and 165 GL/a, climate of 1976-2003, Water Corporation abstraction and management options. ........ 21
Table 4 Water balance for 105, 135 and 165 GL/a, drier climate, Water Corporation abstraction and management options. ........ 22
Table 5 Potential abstraction from the Superficial and Mirrabooka aquifers for public water supply (GL/a) ........ 24

## FIGURES

Figure 1 Gnangara Mound and groundwater management areas .......... 28
Figure 2 Water balance for Gnangara Mound .......... 29
Figure 3 Estimated recharge vs rainfall for the Gnangara Mound .......... 30
Figure 4 Decline rate of water levels under the average and dry climates for the three Corporation abstraction scenarios .......... 31
Figure 5 Storage depletion vs rainfall under three Corporation abstraction scenarios .......... 32
Figure 6 Storage change on Gnangara Mound vs Corporation's abstraction .......... 33
Figure 7 Additional leakage into confined aquifer vs increased confined pumping .......... 34
Figure 8 Water balance for Gnangara Mound (as % of rainfall) .......... 35
Figure 9 Water balance for Yeal area .......... 36
Figure 10 Water balance for Pinjar area .......... 37
Figure 11 Water balance for Lexia area .......... 38
Figure 12 Water balance for Mirrabooka area .......... 39
Figure 13 Water balance for Yanchep area .......... 40
Figure 14 Water balance for Northern WGA .......... 41
Figure 15 Water balance for Southern WGA .......... 42
Figure 16 Water balance for Gwelup area .......... 43
Figure 17 Water balance for Perth Urban North area .......... 44
Figure 18 Water balance for Perth Metro Coastal area .......... 45
Figure 19 Recharge response after fire .......... 46
Figure 20 Storage depletion under various management options .......... 47
Figure 21 Storage depletion, rainfall and effects of management options for each subarea (see Fig 20 for legend) .......... 48
Figure 22 Water table decline rates after offset .......... 49
Figure 23 Storage depletion vs Corporation's abstraction on the Gnangara Mound after implementing management options .......... 50
Figure 24 Storage depletion, vs Corporation abstraction for each subarea after implementing management options .......... 51
Figure 25 Leakage into the confined aquifer in the Yeal/Pinjar areas .......... 52
Figure 26 Additional leakage into the confined aquifers in the Yeal/Pinjar area by increase in confined pumping .......... 53
Figure 27 Storage depletion vs Corporation's abstraction in the Yeal/Pinjar areas .......... 54
Figure 28 Water level decline vs Corporation abstraction from Superficial aquifer in Lexia, Mirrabooka, Gwelup and Costal scheme .......... 55
Figure 29 Water level decline vs Corporation abstraction in Yeal and Pinjar areas .......... 56

# EXECUTIVE SUMMARY

Simulations were undertaken for the Gnangara groundwater mound using the PRAMS model for three Water Corporation abstraction scenarios of 105, 135 and 165 GL/a under two climate regimes based on historical data for the periods of 1976-2003 (average) and 1997-2004 (dry). Analyses were carried out to quantify the key components of the water balance for the whole Gnangara Mound and each groundwater management sub- area delineated by the Department of Water (DoW). Major factors that affect the water balance in each subarea were identified. Potential options for restoring the water balance on the Gnangara Mound were assessed and water available for the public water supply was evaluated. Major findings of these analyses are:

- The Gnangara Mound groundwater system is predominately driven by the rainfall and affected by abstraction and landuse. Under the climate regime of 1976-2003, total recharge on Gnangara Mound is 342 GL/a or about 20% of the rainfall. Under the drier climate regime of 1997-2004, the recharge is reduced to about 252 GL/a or 18% of the rainfall. The 90 GL/a reduction represents of 26 % decrease in recharge compared with a decline in rainfall of 13%.

- Under the drier climate regime of 1997-2004, the groundwater levels on Gnangara Mound will continue to decline at a rate of 0.2 m per annum. This will extend the current observed trend until a new water balance is achieved. Even under the climate regime of 1976-2003, the PRAMS model predicts continued water decline in six out of ten groundwater management areas. A rainfall regime with annual average of 850 mm is required to maintain the current water level on the Mound if landuse and abstraction remain as current. This average rainfall has not occurred since the mid 1970s.

- Whilst an increase of abstraction from 105 to 165 GL/a slightly increases the water level decline rate, reduction in rainfall has far greater impacts on the storage depletion. The difference in storage change between the average and dry climate is about 66 GL/a compared with an 8 GL/a storage change between 105 GL/a, and 135 GL/a abstraction and 11 GL/a between 135 GL/a and 165 GL/a abstraction. Comparison of 105 GL/a and 135 GL/a abstraction scenarios indicates that there is little difference in terms of regional water table decline. There will be very little environmental benefit by reducing the abstraction for public water supply from 135 GL/a to 105 GL/a.

- Under the climate regime of 1976-2003, the storage deficit was estimated at 47 GL/a for the 135 GL/a abstraction scenario (39 GL/a for the 105 GL/a scenario). It may be possible to maintain the current water balance in most of the areas by a combination of landuse management and reduction in abstraction.

- The storage deficit for the Gnangara Mound under the drier climate regime of 1997-2004 is estimated to be 104-124 GL/a. It is unlikely that the water balance of Gnangara Mound can be restored without drastic changes in landuse to enhance the recharge and implementation of large scale managed aquifer recharge (MAR).

- Abstraction from the confined aquifers enables impacts to spread over a larger area of the superficial aquifer. Analysis indicates only one third of the confined abstraction propagates back to the Gnangara Mound area via increased leakage and less than 20% of the confined abstraction is sourced from the Year/Pinjar areas. The balance is met by confined storage depletion (short term) and increased through flows from areas outside Gnangara Mound. Increasing confined abstraction to meet demand during drought period is a sustainable strategy to minimise environmental impacts.

- To sustain a continued high abstraction rate from the confined aquifers, the water imbalance in the Yeal and Pinjar areas needs to be addressed, particularly areas with ecosystems sensitive to water table decline. Potential management options include increased burning frequency to enhance the recharge and MAR using highly treated wastewater.

- The superficial aquifer is a significant and viable source for public water supply even under a drier climate. Significant excess water is available under the climate of 1976-2003 in the Lexia groundwater subarea. This will allow increased abstraction from the superficial and Mirrabooka aquifers for public water supply from the Lexia and Wanneroo borefields. Removal of pines will further increase the amount of water available for public water supply.

This work has used a water balance approach to examine the potential water available for abstraction for public water supply based on the DoW management sub areas. Further modelling work with a focus on local impacts of abstraction is required to refine the abstraction patterns and maximise the water available for abstraction whilst minimising environmental impacts.

## *INTRODUCTION*

Groundwater from Gnangara Mound is a major source for Perth and critical to maintaining the reliability of the Integrated Water Supply System (IWSS). In recent years, low storage levels in the hills reservoirs due to prolonged drought have lead to an increased dependence upon the Gnangara Mound groundwater for public water supply. Since 1997, groundwater abstraction from the Gnangara Mound for public water supply has increased from about 100 GL per annum to 150 GL per annum to avoid the imposition of a total ban on use of sprinklers on lawns and gardens. To minimise the environmental impacts, the Corporation has reduced abstraction from the superficial aquifer and increased abstraction from the confined aquifers.

In response to the drier climate, the Corporation has accelerated source development to increase the supply capacity to restore the balance between demand and supply for the IWSS. In particular, the construction a seawater desalination plant at Kwinana as part of the ‘security through diversity’ strategy will boost IWSS capacity by 45 GL/a. Even with the new sources, the most likely abstraction from Gnangara Mound in the next ten years is estimated to be around 120 GL per annum (with a range between 105 and 165 GL/a) in order to maintain the prescribed level of supply reliability for the IWSS.

Lack of recharge due to a drier climate, maturation of the pine plantation and less frequent prescribed burning of native woodlands have caused groundwater level decline on Gnangara Mound in recent years. The situation is exacerbated by increased abstraction for public and private water supply. A study by Department of Environment (DoE) (Vogwill, 2004) using observed hydrograph data from the monitoring bores shows that water levels around the central area (~1200 km2) of the Gnangara Mound have declined since 1997 at a rate of about 0.2 m per annum with averaged annual storage depletion of about 60 GL. The continued decline of water levels on the Mound is threatening the ecological function in areas of lakes/wetlands and there are concerns about the sustainability of the Gnangara groundwater resources.

This study examines the water balance on the Gnangara Mound in the near future (~ 5 year horizon) for two climate regimes and three abstraction scenarios for public water supply using the Perth Regional Aquifer Modelling System (PRAMS 3.0) ((Barr et al. 2003, CyMod 2004, Davidson and Yu 2004, Silberstein et al. 2004, Xu et al. 2004). Key objectives of this study are

- To quantify key components of the water balance for the Gnangara Mound and each groundwater management area delineated by DoW.
- To compare recharge under two climate regimes and their impacts on storage depletion (water table decline).
- To compare the change in water balance caused by the Corporation’s abstraction scenarios.
- To examine potential options to restore the water balance in each groundwater management area based on the results of water balance analysis and data of landuse compositions.
- To examine the water availability for abstraction from the superficial aquifer in groundwater subareas with Corporation borefields under two climate regimes assuming that no further storage depletion within the subarea is allowed.

## *SCENARIO DEVELOPMENT*

The recently calibrated model PRAMS 3.0 (CyMod 2004) was used for this work. To reduce the computational time, the model set up for this study starts from January 2003 and finishes in June 2010. The model was initialised using the simulation results from a calibration run. Data used for the simulation are summarised as follows.

**Abstraction**: Abstraction from the superficial and artesian aquifers includes: 1) the Corporation abstraction (public licensed abstraction), 2) licensed abstraction by private users, and 3) unlicensed abstraction by private users (domestic garden bores).

The private licensed abstraction was based on the DoW allocation database. It is assumed that the licensed users abstract all the allocation from the designated aquifers. A 20% return flow for the abstraction from the superficial aquifer is also assumed. Abstraction by domestic garden bores was based on the results of Aquatterra (2001). It was assumed that abstraction by the private licensed users and domestic garden bores will continue at current rates in the future (i.e., no growth is considered in the model).

Public licensed abstractions were based on actual monthly production data for each bore up to June 2004. Three abstraction scenarios are considered for the future in this study: 105 GL/a, 135 GL/a and 165 GL/a, representing the likely ranges of the Corporation abstraction requirements in the near future. Pumping patterns for the scenarios were based on DoW's recommendation aimed to minimise the environmental impacts on statutory criteria bores. Abstractions from various aquifers for the three scenarios are given in Table 1. As can be seen from the table, the increased abstraction from 105 GL to 165 GL is largely from confined aquifers.

| Superficial (GL) | Mirrabooka (GL) | Leederville (GL) | Yarragadee (GL) | Total (GL) |
|---|---|---|---|---|
| 46.9 | 4.1 | 21.9 | 32.1 | 105.0 |
| 51.9 | 4.1 | 29.9 | 49.1 | 135.0 |
| 62.8 | 4.1 | 41.1 | 57.0 | 165.0 |

**Table 1 Abstraction from various aquifers for the 105 GL/a to 165 GL/a scenarios**

**Landuse**: current landuse (derived from December 2002 Landsat data) is assumed throughout the simulation period, namely density of pines will be maintained at the current level.

**Climate**: datasets from BoM (SILO PPD) were used up to June 2004. Thereafter, synthetic daily climate data were used. Two synthetic climate scenarios were generated. One was based on the climate regime from 1976 to 2003 and the other based on the drier climate regime from 1997 to 2004. One-year daily synthetic climate data were constructed for each station using the historical data at the site by an approach aimed to reproduce the median of annual rainfall over the selected period (see Canci 2004 for details of the method). This synthetic daily climate data were repeatedly used after June 2004.

The annual total of synthetic rainfall for the representative climate stations for the whole PRAMS model domain is summarised in Table 2, together with the corresponding median of historical annual total. For the Gnangara Mound, it is covered by three stations (Perth Regional Office, Perth Airport and Lancelin).

The combination of two climate regimes and three abstraction scenarios for public water supply has resulted in 6 modelling scenarios. These simulations were performed to generate the budget files for water balance analysis.

| Site | Waves climate zone | Synthetic Rainfall based on 1976-2003 (mm/yr) | Median historic rainfall (1976-2003) (mm/yr) | Synthetic rainfall based on 1997-2004 (mm/yr) | Median historic rainfall (1997-2004) (mm/yr) |
|---|---|---|---|---|---|
| Chelsea (9006) | 1 | 475 | 466 | 423 | 445 |
| Lancelin (9114) | 2 | 607 | 614 | 520 | 534 |
| Perth Airport (9021) | 3 | 701 | 714 | 664 | 669 |
| Perth Regional Office (9034) | 4 | 788 | 777 | 696 | 708 |
| Jarrahdale (9023) | 5 | 1083 | 1065 | 975 | 1005 |

**Table 2 Annual synthetic rainfall compared with median of historical data**

## *WATER BALANCE ANALYSIS*

The water balance was calculated using the cell by cell flow file as output by MODFLOW. Flow rate of the key flow components including storage change, discharge into ocean and rivers, drainage, recharge, pumping and flow interchanges among the budget zones for each stress period were first extracted and then integrated over the specified period to obtain cumulative flows. Since the algorithm used for flow integration to generate the water balance is only approximate, some small discrepancy (imbalance) of up to 1% may occur in some cases.

Water balance analyses were undertaken for the whole Gnangara Mound as well as for the ten groundwater management zones defined by DoE (Figure 1) for the period 2005-2010. To simplify the presentation of the results, averaged annual flow rates over the period are used for illustration. A schematic, (Figure 2) is drawn for the superficial aquifer (including Mirrabooka aquifer where appropriate) to illustrate the key components of the water balance including:

- Rainfall into the area. The Gnangara Mound is covered by three climate stations in the PRAMS model. However, to simplify the analysis, only Perth Regional Office data was used to calculate the rainfall input.
- Evapotranspiration (EVT) from the area. There is no detailed trace of EVT from modelling results. EVT was obtained by subtracting the net recharge from the rainfall.
- Net recharge into the area. Net recharge was calculated by the Vertical Flux Model (VFM), the recharge module of PRAMS.
- Storage change. A negative storage change indicates storage depletion, reflecting water table decline. Conversely, a positive storage change represents the situation with water table rise.
- Pumping. Abstractions from the superficial and Mirrabooka aquifers for domestic bores, private and public water supply are given.
- Leakage into the confined aquifers. Leakage into the confined aquifer is dependent upon the hydraulic connection between the superficial and confined aquifers and confined abstraction mainly by the Corporation for public water supply (see Table 1).
- Discharge. This discharge includes the drainage and groundwater flows into the ocean and rivers and throughflow into another area.

To give some indication on how the water table responds to the storage change, the schematic also shows the corresponding averaged annual change in water table. A specific yield of 0.25 was used to convert the storage volume change into average water table variations for each area.

For comparison, the results for the whole mound and each subarea are presented for the three abstraction scenarios under the two climate regimes. The values in the bracket are for the drier climate case (1997-2004).

## *RESULTS*

### Water Balance for the Gnangara Mound

Figure 2 shows the water balance for the whole Gnangara Mound area for six simulation scenarios.

**Recharge**: Recharge to the groundwater system is similar for the three abstraction scenarios and is significantly affected by the climate. Under the climate regime of 1976-2003, total recharge on Gnangara Mound is 342 GL/a (slight increase to 345 GL/a for the 165 GL/a scenario) or about 20% of the rainfall. Under the drier climate regime of 1997-2004, recharge is reduced to 252 GL/a (slightly higher - 254 GL/a for the 165 GL/a scenario) or 18% of the rainfall. This represents a reduction of 26 % in recharge compared with a decrease in rainfall of 13%. Figure 3 shows the relationship between the recharge and rainfall using a linear extrapolation.

**Storage Change:** For both climate regimes, water levels on Gnangara Mound will continue to decline. Under the climate regime of 1976-2003, area averaged decline will be about 7 cm/a compared with a declining rate of about 20 cm/a under a drier climate of 1997-2004 for the 105 GL/a abstraction scenario (Figure 4). Increased abstraction to 135 GL/a slightly increases the decline rate by about 2 cm/a. For the 165 GL/a abstraction scenario, the storage deficit will increase to 57 GL/a (a decline rate of 11 cm/a) and 124 GL/a (a decline rate of 24 cm/a) for the climate regimes of 1976-2003 and 1997-2004 respectively. This represents an increase in decline rate of 2 cm/a from the 135 GL/a abstraction scenario.

Figure 5 shows the relationship between storage depletion and rainfall for the three Corporation abstraction scenarios. The results demonstrate that whilst an increase of abstraction from 105 to 165 GL/a slightly increases the decline rate in water table, reduction in rainfall has a far greater impact on storage depletion. The difference in storage change between the average and dry climate is about 66 GL/a compared with an 8 GL/a storage change between 105 GL/a, and 135 GL/a abstraction and 11 GL/a between 135 GL/a and 165 GL/a abstraction (Figure 6). The abstraction impact is between 12% and 16% of the climate impact. A rainfall regime with annual average of 850 mm is required to maintain the current water level on the Mound if the landuse and abstraction rate remain at current conditions (Figure 5). This average rainfall has not occurred since 1975.

**Abstraction in the Superficial aquifer:** Total abstraction from the superficial and Mirrabooka aquifers are 165 GL/a, 170 GL/a and 180 GL/a for the scenarios 105 GL/a, 135 GL/a and 165 GL/a respectively. For the 105 GL/a scenario, about 19% of the abstraction is drawn by domestic bores, 53% by private licensed bores and 28% by public water supply. The percentage for public water supply increases to 30% in the 135 GL/a abstraction scenario and to 33% in the 165 GL/a abstraction scenario. This result shows that abstraction by the Corporation is less than one third of the total draw from the unconfined and Mirrabooka aquifers on Gnangara Mound under these three abstraction scenarios.

**Leakage (confined pumping):** Leakage into the confined aquifers is largely due to the confined abstraction by the Corporation for public water supply (53 GL/a, 79 GL/a and 98 GL/a for 105, 135 and 165 GL/a scenarios respectively). Leakage is estimated to be 34 GL/a, 40 GL/a and 47 GL/a for the 105 GL/a, 135 GL/a and 165 GL/a abstraction scenarios respectively. Note that this leakage rate is not just induced by the current confined pumping but is also affected by the previous confined abstraction. Simulation results indicate that a significant part of the confined abstractions are not derived from leakage in the Gnangara Mound area. Water balance analysis shows that confined pumping will initially draw from storage, which in turn induces higher throughflow and this propagates the impacts outside the Gnangara Mound area. The relationship between increased abstraction in the confined aquifer and the additional induced leakage (Figure 7) indicates that increased confined abstraction by 3 GL/a will induce one GL/a additional leakage into the confined aquifers from the superficial aquifer. The balance of the abstraction is met by storage depletion and increase in throughflow.

**Discharge:** Total discharge including drainage is estimated to be 176-180 GL/a (~20 GL/a drainage) for the climate of 1976-2003 and 152-155 GL/a (~14 GL/a drainage) for the drier climate of 1997-2004. Modelling results suggest that drainage largely occurs in the Perth Urban North area. There is very little drainage in the rest of the Gnangara Mound.

Figure 8 recasts the water balance components as percentage of rainfall. Clearly evapotranspiration is the largest component, accounting for about 80% of rainfall (82% under dry climate) with about 20% of rainfall being net recharge to the groundwater system. Under the average climate, about half of the recharge is taken out of system by abstractions for gardens, horticulture and public water supply and another half of recharge becomes throughflow which maintains the groundwater mound. Leakage into the confined aquifers accounts for only 2-3% of the rainfall and the balance comes from aquifer storage (~3% of rainfall).

Under the dry climate, about 70% of recharge is abstracted by pumping and 60% of the recharge would be required for throughflow to maintain the mound with leakage of about 15% of recharge. The imbalance of 45% in recharge is sourced from aquifer storage and amounts to about 8% of rainfall. The result shown in Figure 8 also indicates that the relationship between recharge and rainfall is not linear. Under the drier climate regime, the percentage of rainfall becoming net recharge is smaller, resulting in even greater reduction in recharge in absolute terms. This may be an overestimate as the model does not account for reduced vegetation density under a drier climate.

## Water Balance for the Yeal Area

Figure 9 shows the water balance for the Yeal area for six simulation scenarios. Results show:

**Recharge**: Under the climate regime of 1976-2003, total recharge into the Yeal area is 47 GL/a or about 11% of rainfall whereas under the drier climate regime of 1997-2004, recharge is reduced to only 26 GL/a or 7% of rainfall. This represents a reduction of 45% in recharge compared with a decrease in rainfall of 13%. Low recharge in the area is due to the existence of high density of pine plantation and native woodlands.

**Storage Change:** For both climate regimes, water levels in the Yeal area will continue to decline. Under the climate regime of 1976-2003, area averaged decline rate will be about 11 cm/a compared with a decline rate of about 23 cm/a under a drier climate of 1997-2004 for the 105 GL/a abstraction scenario (Figure 4). Increased abstraction to 135 GL/a and 165 GL/a will slightly increase the decline rate by about 1 cm/a and 2 cm/a respectively.

**Abstraction in Superficial aquifer:** There is no abstraction from the superficial aquifer for public supply in the area. Abstraction by private licensed bores is estimated to be about 10 GL/a distributed along Gingin Brook.

**Leakage (confined pumping):** Leakage into the confined aquifers is largely due to the abstraction from the Yarragadee aquifer by the Corporation for public water supply. Leakage is estimated to be 13 GL/a for 105 GL/a scenario, 14 GL/a for 135 GL/a scenario and 16 GL/a for the 165 GL/a scenario. The difference in leakage due to confined abstraction between the 105 GL/a and 165 GL/a scenarios is 45 GL/a over the whole Mound. This means that only about 6.5% (1:15) of confined abstraction is propagated to the superficial aquifer in the Yeal area. An additional leakage of 1 GL/a from the Yeal area will cause an average decline of about 1 cm/a.

**Discharge:** Discharge including drainage from Yeal area is estimated to be 38 GL/a (4 GL/a drainage) for the climate of 1976-2003 and 34 GL/a (3 GL/a drainage) for the drier climate of 1997-

2004. Drainage largely occurs along the Gingin Brook. This drainage could be a potential resource yet to be exploited. Further investigation should be carried out to examine the potential to harvest the drainage for recharging the superficial aquifer in the Yeal area.

## Water Balance for the Pinjar Area

Figure 10 shows the water balance for the Pinjar area for six simulation scenarios. Results show:

**Recharge**: Under the climate regime of 1976-2003, total recharge into Pinjar area is 36 GL/a or about 14% of the rainfall whereas under the drier climate regime of 1997-2004, the recharge is reduced to only 23 GL/a or 11% of the rainfall. This represents a reduction of 35% in recharge compared with a decrease in rainfall of 13%. Low recharge in the area is due to the presence of high density of pine plantation and native woodlands

**Storage Change:** For both climate regimes, water levels in the Pinjar area will continue to decline. Under the climate regime of 1976-2003, area averaged decline rate will be about 12 cm/a compared with a decline rate of about 26 cm/a under a drier climate of 1997-2004 for the 105 GL/a abstraction scenario (Figure 4). Increased abstraction to 135 GL/a and 165 GL/a will slightly increase the decline rate by about 4 cm/a and 6 cm/a respectively.

**Abstraction in Superficial aquifer:** The Pinjar borefield is located in this area. There is no abstraction from the superficial aquifer for public supply in the area for 105 GL/a scenario and only 2 GL/a for the 135 and 165 GL/a scenarios. Abstraction by private licensed bores is about 3 GL/a.

**Leakage (confined pumping):** Leakage into the confined aquifers is largely due to the abstraction from the Leederville and Yarragadee aquifers by the Corporation for public water supply. Leakage is estimated to be 17 GL/a for 105 GL/a scenario, increasing by 2 GL/a to 19 GL/a and 5 GL/a to 21 GL/a for 135 GL/a and 165 GL/a abstraction scenarios respectively. The results indicate that an increase of 45 GL/a abstraction in the confined aquifer will induce an additional leakage of 5 GL/a from the Pinjar area. This means that only 11% (1:9) of confined abstraction is propagated to the superficial aquifer in the Pinjar area. An additional leakage of 1 GL/a from the Pinjar area will cause an average decline of about 1 cm/a.

**Discharge:** Throughflow from Pinjar area is similar for two climate regimes estimated to be 24 GL/a. There is very little drainage in the area.

## Water Balance for the Lexia Area

Figure 11 shows the water balance for the Lexia area for six simulation scenarios. Results show:

**Recharge**: Under the climate regime of 1976-2003, total recharge into the Lexia area is 34 GL/a or about 16% of rainfall whereas under the drier climate regime of 1997-2004, recharge is reduced to only 23 GL/a or 13% of the rainfall, representing a reduction of 32% in recharge compared with a decrease in rainfall of only 13%. Low recharge in the area is due to the presence of high density pine plantation and native woodlands and shallow depths to water table in some areas.

**Storage Change:** Under the climate regime of 1976-2003, the PRAMS model predicts that the water table in the area will stabilise for the 135 GL/a scenario and will slightly increase at 3 cm/a for the 105 GL/a scenario and slightly decline at 5 cm/a for the 165 GL/a scenario (Figure 4). However, under a drier climate of 1997-2004, water table will continue to decline for all abstraction scenarios with declining rates of 13 cm/a, 15 cm/a and 20 cm/a for the 105, 135 and 165 GL/a abstraction scenarios respectively.

**Abstraction in Superficial aquifer:** Lexia and Wanneroo borefields are located in the area. Abstraction from the superficial and Mirrabooka aquifers is 6 GL/a for the 105 GL/a scenario, 8 GL/a for the 135 GL/a scenario and 12 GL/a for the 165 GL/a scenario. Abstraction by private licensed bores is about 7 GL/a.

**Leakage (confined pumping):** Leakage into the confined aquifers is largely due to abstraction from the Leederville aquifer by the Corporation for public water supply. Leakage is estimated to be 2 GL/a for 105 GL/a scenario and increase by 1 GL/a to about 3 GL/a for 135 GL/a and 165 GL/a abstraction scenarios. This means that only about 2% (1:45) of confined abstraction is propagated up to the superficial aquifer in the northern part of the Lexia area where the Kardinya Shale is absent.

**Discharge:** Throughflow from the Lexia area is similar for two climate regimes estimated to be 14-16 GL/a. There is about 1 GL/a drainage as baseflows in the area.

## Water Balance for the Mirrabooka Area

Figure 12 shows the water balance for the Mirrabooka area for six simulation scenarios. Results show:

**Recharge**: Under the climate regime of 1976-2003, total recharge into the Mirrabooka area is 18 GL/a or about 27% of rainfall whereas under the drier climate regime of 1997-2004, recharge is slightly reduced to 14 GL/a or 25% of the rainfall, representing a reduction of 21% in recharge compared with a decrease in rainfall by 13%. Recharge is higher than for Lexia, Pinjar and Yeal because part of the area has been urbanised.

**Storage Change:** Under the climate regime of 1976-2003, the PRAMS model predicts that water table in the area will stabilise for 105 and 135 GL/a abstraction scenarios but slightly decline at a rate of 8 cm/a for the 165 GL/a scenario (Figure 4). However, under a drier climate of 1997-2004, the water table will continue to decline for all three abstraction scenarios with declining rates of 16 cm/a, 18 cm/a and 25 cm/a for 105, 235 and 165 GL/a abstraction scenarios respectively.

**Abstraction in Superficial aquifer:** Mirrabooka borefield (excluding Mirrabooka West) is located in the area. Abstraction from the superficial and Mirrabooka aquifers is 5 GL/a, 6 GL/a and 10 GL/a for the 105, 135 and 165 GL/a abstraction scenarios respectively. There are abstractions of about 5 GL/a by private licensed bores and another 4 GL/a by the domestic garden bores.

**Leakage (confined pumping):** There is very little leakage into the confined aquifers in the area due to the existence of the Kardinya Shale which acts as the confining bed that separates the shallow aquifers from the deep confined aquifers.

**Discharge:** Throughflow from the Mirrabooka area is similar for two climate regimes estimated to be 1-4 GL/a. There is about 1 GL/a drainage as baseflows in the area.

### Water Balance for the Yanchep Area

Figure 13 shows the water balance for the Yanchep area for six simulation scenarios. Results show:

**Recharge**: Under the climate regime of 1976-2003, total recharge into the Yanchep area is 8 GL/a or about 7% of the rainfall whereas under the drier climate regime of 1997-2004, the recharge is reduced to only 6 GL/a or 6% of the rainfall. This represents a reduction of 28% in recharge compared with a decrease in rainfall of 13%. Low recharge in the area is due to the existence of high density of pine plantation and native woodlands in the Yanchep National Park.

**Storage Change:** For both climate regimes, water levels in the Yanchep area will continue to decline. Under the climate regime of 1976-2003, area averaged decline will be about 16 cm/a compared with a decline rate of about 23 cm/a under a drier climate of 1997-2004 for the 105 GL/a abstraction scenario (Figure 4). Increased abstraction to 135 GL/a and 165 GL/a only marginally increases the decline by about 1 cm/a and 2 cm/a respectively.

**Abstraction in Superficial aquifer:** There is no abstraction from the superficial aquifer in the area.

**Leakage (confined pumping):** There is a small upward leakage (0.4 GL/a) into the superficial aquifer from the underlying confined aquifer for the 105 GL/a abstraction scenario. Increase of abstraction from 105 GL/a to 165 GL/a will reduce the upward leakage by 0.5 GL/a.

**Discharge:** Throughflow from Yanchep area is similar for two climate regimes estimated to be 14 GL/a. There is very little drainage in the area.

### Water Balance for the Northern WGA Area

Figure 14 shows the water balance for Northern Wanneroo Groundwater Area (WGA) for six simulation scenarios. Results show:

**Recharge**: Under the climate regime of 1976-2003, total recharge into Northern WGA area is 16 GL/a or about 23% of the rainfall whereas under the drier climate regime of 1997-2004, the recharge is reduced to only 13 GL/a or 22% of the rainfall. This represents a reduction of 21% in recharge compared with a decrease in rainfall of 13%.

**Storage Change:** For both climate regimes, water levels in the Northern WGA area will continue to decline. Under the climate regime of 1976-2003, area averaged decline will be about 11 cm/a compared with a decline rate of about 22 cm/a under a drier climate of 1997-2004 for the 105 GL/a abstraction scenario (Figure 4). Increase of abstraction to 135 GL/a and 165 GL/a will slightly increase the decline rate by about 1 cm/a and 3 cm/a respectively.

**Abstraction in Superficial aquifer:** There is no abstraction from the superficial aquifer for public supply in the area. Abstraction by private licensed bores is about 11 GL/a mainly for horticulture use.

**Leakage (confined pumping):** Leakage into the confined aquifers is largely due to the abstraction from the Leederville aquifer by the Corporation for public water supply. For the 105 GL/a scenario, leakage into confined aquifers in the area is estimated to be around 0.5 GL/a. Increased abstraction from 105 GL/a to 165 GL/a induces an additional leakage of 0.4 GL/a in the area.

**Discharge:** Throughflow from Northern WGA area is similar for two climate regimes and the three abstraction scenarios estimated to be 6-8 GL/a. There is very little drainage in the area.

## Water Balance for the Southern WGA Area

Figure 15 shows the water balance for the Southern WGA area for six simulation scenarios. Results show:

**Recharge**: Under the climate regime of 1976-2003, total recharge into the Southern WGA area is 22 GL/a or about 36% of the rainfall whereas under the drier climate regime of 1997-2004, the recharge is reduced to 18 GL/a or 36% of the reduced rainfall. This represents a reduction of 18% in recharge compared with a decrease in rainfall of 13%. Recharge in the area is reasonably high because a large portion of the area is cleared.

**Storage Change:** For both climate regimes, water levels in Southern WGA area will continue to decline. Under the climate regime of 1976-2003, area averaged decline rate will be about 15 cm/a compared with a decline rate of about 35 cm/a under a drier climate of 1997-2004 for the 105 GL/a abstraction scenario (Figure 4). Increased abstraction to 135 GL/a and 165 GL/a will slightly increase the decline rate by about 2 cm/a and 5 cm/a respectively due to increased leakage into the confined aquifers. Decline in water levels in this area may also be affected by the Corporation's abstraction from the Wanneroo borefield, which is outside the subarea but close to the boundary of the area.

**Abstraction in Superficial aquifer:** There is no direct abstraction from the superficial aquifer for public supply in the area. However, water levels may be affected by the abstraction from Wanneroo borefield. There are private licensed abstractions of about 15 GL/a mainly for horticulture use.

**Leakage (confined pumping):** Leakage into the confined aquifers is largely due to the abstraction from the Leederville aquifer by the Corporation for public water supply. Leakage is however relatively small less than 0.5 GL/a. Increase in abstraction from the confined aquifers will have minimal impacts on the superficial aquifer in the area.

**Discharge:** Throughflow from the Southern WGA area is similar for two climate regimes and two abstraction scenarios estimated to be 10 GL/a. There is very little drainage occurred in the area.

## Water Balance for the Gwelup Area

Gwelup area is in an urban setting. Figure 16 shows the water balance for the Gwelup area for six simulation scenarios. Results show:

**Recharge**: Under the climate regime of 1976-2003, total recharge into the Gwelup area is 47 GL/a or about 46% of rainfall whereas under the drier climate regime of 1997-2004, recharge is slightly reduced to 39 GL/a or 45% of the rainfall, representing a reduction of 17% in recharge compared with a decrease in rainfall of 13%. Recharge is quite high in this area. This is because most of the Gwelup area is urban.

**Storage Change:** For both climate regimes, water levels in the Gwelup area will continue to decline. Under the climate regime of 1976-2003, area averaged decline rate will be about 14 cm/a compared with a decline rate of about 31 cm/a under a drier climate of 1997-2004 for the 105 GL/a abstraction scenario (Figure 4). Increased abstraction to 135 GL/a and 165 GL/a will slightly increase the decline rate by about 2 cm/a and 5 cm/a respectively. The PRAMS model overestimated the decline rate of the water table in the area during the model verification period. It is suggested that a significant discrepancy may exist between the private allocation database and what is actually abstracted. In particular, the private licensed allocation for horticulture use may remain in the database even though the area has been urbanised. Based on the model performance in the verification period, it is likely the private licensed abstraction from the area may be significantly less than 15 GL/a as used in the model.

**Abstraction in Superficial aquifer:** Gwelup and Mirrabooka West borefields are located in the area. Abstractions from the superficial and Mirrabooka aquifers are 15 GL/a, 16 GL/a and 16 GL/a for the 105, 135 and 165 GL/a scenarios respectively. There are modelled abstractions of about 15 GL/a by private licensed bores and another 8 GL/a by the domestic garden bores.

**Leakage (confined pumping):** There is small leakage into the confined aquifers in the area estimated to be about 1.1 GL/a for the 105 GL/a abstraction scenario and increase to 1.6 GL/a for the 165 GL/a abstraction scenario.

**Discharge:** Throughflow from the Gwelup area is estimated to be 12 GL/a for the climate 1976-2003 and 9 GL/a for the climate 1997-2004. There is about 2 GL/a drainage in the area.

## Water Balance for the Perth Urban North Area

Perth Urban North area is in an urban setting. Figure 17 shows the water balance for the Perth Urban North area for six simulation scenarios. Results show:

**Recharge**: Under the climate regime of 1976-2003, total recharge into the Perth Urban North area is 52 GL/a or about 37% of the rainfall whereas under the drier climate regime of 1997-2004, the recharge is slightly reduced to 43GL/a or 36% of the rainfall, representing a reduction of 18% in recharge compared with a decrease in rainfall by 13%. Recharge is reasonably high in this area because most of the area is urban.

**Storage Change:** Under the climate regime of 1976-2003, the PRAMS model predicts the water table in the area will stabilise for all abstraction scenarios (Figure 4). However, under a drier climate of 1997-2004, water table will continue to decline at rates of 13 cm/a, 13 cm/a and 14 cm/a for 105, 135 and 165 GL/a abstraction scenarios respectively.

**Abstraction in Superficial aquifer:** There is no abstraction from the superficial and Mirrabooka aquifers for public supply in the area. There are abstractions of about 14 GL/a by private licensed bores for irrigating parks and 13 GL/a by domestic garden bores.

**Leakage (confined pumping):** There is small leakage into the confined aquifers in the area estimated to be about 1 GL/a for the 105 GL/a scenario and increase to 2 GL/a for the165 GL/a scenario. The impact of confined pumping is propagated through sandy parts of the King's Park Formation.

**Discharge:** Throughflow from the area is estimated to be 24 GL/a for the climate 1976-2003 and 20 GL/a for the climate 1997-2004. Estimated drainage as baseflows in the area is 13 GL under the climate 1976-2003 and 9 GL/a under drier climate of 1997-2004.

### Water Balance for the Perth Metro Coastal Area

Figure 18 shows the water balance for the Perth Metro Coastal area for six simulation scenarios. Results show:

**Recharge**: Under the climate regime of 1976-2003, total recharge into Perth Metro Coastal area is 63 GL/a or about 30% of the rainfall whereas under the drier climate regime of 1997-2004, the recharge is slightly reduced to 48 GL/a or 27% of the rainfall, representing a reduction of 23% in recharge compared with a decrease in rainfall of 13%.

**Storage Change:** Under the climate regime of 1976-2003, the PRAMS model predicts the water table in the area will stabilise (Figure 4). However, under a drier climate of 1997-2004, water table will continue to decline at rates of 6 cm/a and 7 cm/a for 105 and 165 GL/a abstraction scenarios.

**Abstraction in Superficial aquifer:** The area includes the Corporation's coastal scheme (Neerabup), which abstracts 19 GL/a from the superficial aquifer in both the 105 and 135 GL/a abstraction scenarios (increase to 20 GL/a for 165 GL/a scenario). There are abstractions of about 9 GL/a by private licensed bores and 4 GL/a by domestic garden bores.

**Leakage (confined pumping):** There is a slight upward leakage (1 GL/a) into the superficial aquifer from the underlying confined aquifer for the 105 GL/a abstraction scenario. Increased abstraction from 105 GL/a to 165 GL/a will reverse the upward leakage and induce an additional leakage of 2 GL/a into the confined aquifers.

**Discharge:** Throughflow from the area is similar for the three Corporation's abstraction scenarios estimated to be 28-32 GL/a for the climate 1976-2003 and 18-21 GL/a for the drier climate 1997-2004. There is very little drainage in the area.

## *POTENTIAL OPTIONS FOR RESTORING WATER BALANCE*

Results of the water balance analysis indicate that under the drier climate regime of 1997-2004, the groundwater levels will continue to decline at a rate of 0.2 m per annum, extending the current observed trend. Even under the climate regime of 1976-2003, PRAMS model predicts continued water decline in six out of ten groundwater management areas. Information presented in the water balance diagrams can be used in combination with landuse data and abstraction information to develop options for restoring the regional and local water balance or reducing the storage deficit hence lowering the rate of water table decline.

Assuming that the outflow will not change, to arrest the water table decline requires more water into the system or reduced abstraction from the system to offset the storage deficit. Enhancing recharge can be achieved via various options such as pine removal, urbanisation, increased frequency of burning native woodlands, harvesting drainage water where appropriate and managed aquifer recharge (MAR).

Whilst the effects of reduction in abstraction on the superficial aquifer, MAR and harvest of drainage can be considered to have a one to one benefit for storage deficit offset, the impacts of changing fire regimes, pine removal, urbanisation and confined abstraction can only be assessed approximately based on some assumptions.

For example, if the 210 km$^2$ pine plantations are removed and replaced by native woodlands, recharge in these areas will return to a natural rate of about 25% of rainfall, which will result in about 40 GL/a additional recharge on Gnangara Mound. However, it is unlikely that the pine plantation can be harvested in the next few years. If the pines are removed in the next twenty five years as scheduled for the LVL plant, the recharge benefits will increase gradually with time to the maximum of 40 GL/a by the year 2030. By using a linear function for pine removal and recharge increase, the maximum benefit for the next five years is estimated to be in order of 25 GL with an average of 5 GL per annum.

Burning is normally used to reduce the build up of dead biomass on the land surface. It can increase recharge to the groundwater by reducing the interception loss and transpiration by the living vegetation. Recharge response after fires may be estimated and used for evaluating potential recharge benefits. An example of a simple recharge response model is given in Figure 19, and was developed based on an estimate of vegetation regrowth after a fire using remote sensing data (Canci, 2005) and WAVES simulation results.

A recent study revealed that the frequency of burning has reduced significantly from 2-3 times per decade before about 1880 to more than 10 year intervals over the last two decades, with some locations being unburnt for over thirty years (Ward et al. 2004). Doubling the current burning frequency for the ~1000 km$^2$ native woodlands will increase recharge by about 20 GL/a using the relationship shown in Figure 19.

Abstraction by private licensed users on the Gnangara Mound is about 90 GL/a. Improving water use efficiency by 20% will lead to a saving of about 18 GL.

Increased recharge by urbanisation will depend on the previous landuse and the use of domestic bores in the new urban area. If the area was originally land cleared for horticulture use, the recharge benefits may not be significant since the recharge for the shallow rooted horticulture crops is already quite high. The major benefits will be the reduction in abstraction if the domestic garden bores use is less than the original abstraction for horticulture. For this analysis, the effect of urbanisation is not considered.

The effects of confined pumping are reflected in an increase in the leakage component of the water balance. Comparison of leakage for the 105, 135 and 165 GL/a abstraction scenarios indicate that increasing confined pumping by 45 GL/a induces an additional leakage of 13 GL/a, namely less than 30% of the confined abstraction is derived from direct leakage from the Gnangara Mound (Figure 7). In some areas, the change in leakage will be negligible.

## Effects of options for burning, pine harvest and reduction in private use

Potential management options of increased burning frequency, pine harvest and reduction in private use for each subarea are identified and their effects on the water balance are examined. Results are presented in Figure 20-21 and Table 3 and 4.

Results for the climate regime of 1976-2003 is summarised in Table 3. The storage deficit for all of the Gnangara Mound under the climate regime of 1976-2003 is estimated in the range of 39-57 GL/a for the three Corporation abstraction scenarios. Analysis indicates that by increasing the burning frequency, pine harvesting in the Lexia area and 20% reduction in private licensed abstraction will result in an offset total of 41 GL/a (2 GL from pine removal, 21 GL from improved burning regimes and 18 GL for water efficiency improvement in irrigation) in the next 5 years, the timeframe of this water balance analysis.

Locally, the water balance is positive or close to zero for the Perth Metro Coast, South Wanneroo groundwater area, Mirrabooka, Lexia and Perth Urban North sub-areas. There is a slightly negative imbalance in the Gwelup sub area partly reflecting adjustment to a new equilibrium following start up of the West Mirrabooka borefield. In the Gwelup area the PRAMS model over predicts the pumping impacts and implies that actual abstraction from the private licensed bores may be much less than those in the allocation database due to urbanisation.

The greatest negative imbalance occurs in the Yanchep, Yeal and Pinjar sub areas. Of these, the Yanchep sub area is not impacted by public (superficial and confined) and private abstraction, and the imbalance is largely a result of reduced rainfall and continued growth of the northern pine plantation.
Figure 21 shows the rainfall regimes required to allow the water balance for each subarea to be restored under different Corporation abstraction scenarios with and without the implementation of these management options.

Under the drier climate regime of 1997-2004, the storage deficit is significantly greater in a range of 105-127 GL/a (Table 4 and Figure 20). Even if the full range of additional management options as described above were exercised, regional storage depletion is still substantial in the range of 64-83 GL/a. Under these conditions, there are unlikely to be any viable management options that can maintain Gnangara Mound at current levels. Figure 22 shows the water table declines in each subarea after the offsets. Seven out of the ten sub areas have decline rates greater than 10 cm/a. The areas with high decline rates include Gwelup, Southern WGA and Pinjar.

## Water Corporation's management options

The water balance for each sub area after implementing management options of burning, pine removal and reduction in private abstraction together with Corporation's abstraction from the superficial (including the Mirrabooka) aquifer and impacts of confined abstraction are summarised in Table 3 and Figure 20 for the climate regime of 1976-2003. For the 105 GL/a abstraction scenario, the groundwater on the Gnangara Mound is regionally balanced but with some minor imbalance in each subarea. The regional deficit increases to 7 GL/a and 17 GL/a for the abstraction scenarios of 135 and 165 GL/a with the greatest negative imbalance in the Yeal and Pinjar sub areas (Figure 23-24).

In the subareas that the Corporation abstracts from the superficial and Mirrabooka aquifers, reduction in the abstraction may be possible to restore the balance. As mentioned earlier, reduction in abstraction will have a one to one benefit in restabilising the water balance.

Water Corporation abstraction from the confined aquifers largely manifests within the Yeal and Pinjar sub areas, which also contain some groundwater dependent ecosystems (GDE), particularly within Yeal Nature Reserve. Reduction in confined abstraction or increased recharge to the confined aquifer may appear a solution. However detailed analysis indicates that the ratio between confined abstraction and leakage from the superficial aquifer for these areas is between 10:1 and 15:1. That is, for every 10 GL/a change in abstraction from the confined aquifer there will be a 1 GL/a change in storage in the superficial aquifer. This indicates that reducing abstraction from the confined aquifers is unlikely to be a significant option to manage storage depletion in the superficial aquifer.

Other possible Water Corporation options to manage the storage imbalance caused by abstraction for public water supply include Managed Aquifer Recharge (MAR) and Managed Pumping (MP) from existing borefields. A major research project is currently being developed to evaluate reuse of reverse-osmosis treated wastewater for recharge to aquifers. Because of the large groundwater depth over much of the area, this option offers benefit for storage and reuse and managing storage deficit within the flanking groundwater dependent ecosystems. However, implementation of a full scale MAR on Gnangara Mound is unlikely to occur in the next five years.

Research projects have been approved to evaluate changing our abstraction pattern to match the winter recharge pattern rather than the summer demand pattern when environmental demand is also high or by using a longer- duration, lower- rate pumping strategy. The issue of managing system demand is to be addressed in a research project to evaluate MAR to the Leederville aquifer on Gnangara using groundwater from the superficial aquifer.

| Sub area | Storage change | Burning | Pine removal | Private 20% | Balance | WC superficial | Confined offset | WC Option |
|---|---|---|---|---|---|---|---|---|
| **Yeal** | (-15, -17,-18) | 10 | 0 | 2 | (-3,-5,-6) | (0,0,0) | 15:1 | MAR |
| **Perth Metro Coast** | (0,-1,-1) | | 0 | 2 | (2,1,1) | (19, 19,20) | 15:1 | |
| **Yanchep** | (-6,-6, -6) | 2 | | 0 | (-4,-4,-4) | (0,0,0) | n/a | |
| **Pinjar** | (-9,-12,-14) | 6 | | 1 | (-2,-5,-7) | (0,2,2) | 10:1 | MAR |
| **North WGA** | (-3,-3,-3) | 0 | 0 | 2 | (-1,-1,-1) | (0,0,0) | n/a | |
| **South WGA** | (-3,-3,-3) | | | 3 | (0,0,0) | 0 | n/a | |
| **Mirrabooka** | (0,0,-2) | 0 | | 1 | (1,1,-1) | (5,6,10) | n/a | MP |
| **Lexia** | (2,0,-3) | 3 | 2 | 1 | (8,6,3) | (6,8,12) | 45:1 | MP |
| **Gwelup** | (-4, -5,-6) | 0 | 0 | 3 | (-1,-2,-3) | (15,16,16) | n/a | MP |
| **Perth Urban North** | (0,0,0) | 0 | 0 | 3 | (3,3,3) | (0,0,0) | n/a | |
| **Gnangara Total** | (-39,-47, -57) | 21 | 2 | 18 | (2, -7, -17) | (45,51,60) | 3:1 | MAR, MP |

All values are GL/a, + increase storage, - reduce storage. Blank cells indicate non viable in 5 year timeframe. n/a not applicable. MAR: managed aquifer recharge. MP managed pumping. WGA: Wanneroo Groundwater Area.

Value in bracket for 105, 135 and 165 GL/a abstraction scenarios

**Table 3 Water balance for 105, 135 and 165 GL/a, climate of 1976-2003, Water Corporation abstraction and management options.**

| Sub area | Storage change | Burning | Pine removal | Private 20% | Balance | WC superficial | Confined offset | WC Option |
|---|---|---|---|---|---|---|---|---|
| **Yeal** | (-32, -34,-35) | 10 | 0 | 2 | (-20,-22,-23) | (0,0,0) | 15:1 | MAR |
| **Perth Metro Coast** | (-4,-4,-5) |  | 0 | 2 | (-2,-2,-3) | (19, 19,20) | 15:1 |  |
| **Yanchep** | (-8,-9, -9) | 2 |  | 0 | (-6,-7,-7) | (0,0,0) | n/a |  |
| **Pinjar** | (-22,-24,-26) | 6 |  | 1 | (-15,-18,-20) | (0,2,2) | 10:1 | MAR |
| **North WGA** | (-5,-5,-5) | 0 | 0 | 2 | (-3,-3,-3) | (0,0,0) | n/a |  |
| **South WGA** | (-7,-7,-8) |  |  | 3 | (-4,-4,-5) | 0 | n/a |  |
| **Mirrabooka** | (-3,-4,-5) | 0 |  | 1 | (-2,-3,-4) | (5,6,10) | n/a | MP |
| **Lexia** | (-8,-10,-13) | 3 | 2 | 1 | (-2,-4,-7) | (6,8,12) | 45:1 | MP |
| **Gwelup** | (-10, -10,-11) | 0 | 0 | 3 | (-7,-7,-8) | (15,16,16) | n/a | MP |
| **Perth Urban North** | (-6,-6,-6) | 0 | 0 | 2 | (-4,-4,-4) | (0,0,0) | n/a |  |
| **Gnangara Total** | (-105,-113, -124) | 21 | 2 | 18 | (-64, -73, -83) | (45,51,60) | 3:1 | MAR, MP |

All values are GL/a, + increase storage, - reduce storage. Blank cells indicate non viable in 5 year timeframe. n/a not applicable. MAR: managed aquifer recharge. MP managed pumping. WGA: Wanneroo Groundwater Area.
Value in bracket for 105, 135 and 165 GL/a abstraction scenarios

**Table 4 Water balance for 105, 135 and 165 GL/a, drier climate, Water Corporation abstraction and management options.**

### Abstraction for the Corporation's borefields under zero storage deficit

As showed in Figure 20, the storage change on the Gnangara Mound is strongly affected by rainfall. Under the drier climate conditions of 1997-2003, analysis indicates that even if the Corporation stops all abstraction, water levels on Gnangara Mound will continue to decline. Under these conditions, there are unlikely to be any viable management options that can restore the water balance of the Gnangara Mound and a new equilibrium with lower groundwater levels will eventuate.

The following analysis to determine the water available for abstraction from the Corporation's borefields using the water balance approach assumes that the future climate is similar to the climate regimes of 1976-2003 and 1997-2004 respectively. It should also be noted that it may not be appropriate to use this water balance approach to determine sustainable abstraction in each sub-area, particularly for the new borefield such as Mirrabooka West and Lexia, where the groundwater levels are in a transient process to reach a new hydraulic equilibrium in response to the recent pumping. Similarly, in the areas with depth to water table greater than 10 m, ecological systems are detached from the subsurface groundwater level. Storage depletions in these areas will have minimal impacts on the environment. Therefore, storage depletion should not constrain the groundwater abstraction in those areas provided that the long term average abstraction rate does not exceed the long term recharge.

### Abstraction from the confined aquifers

Water balance analysis shows that confined pumping will initially draw from storage, which in turn induces greater throughflow and propagates the impacts outside the Gnangara Mound area. Modelling results indicate that an increase in confined abstraction by 3 GL/a will approximately induce 1 GL/a additional leakage into the confined aquifers from the superficial aquifer on the Gnangara Mound. The balance of abstraction is met by the confined storage depletion (in short term) and increase in throughflow. The major areas impacted by the confined abstraction are the Yeal and Pinjar sub areas. Figure 25 shows the leakage into the confined aquifers from the superficial aquifer in the Yeal and Pinjar areas under different abstraction scenarios. It is estimated that about 20% of the confined abstraction propagates back to these areas (Figure 26).

The water balance analysis indicates that the strategy of increasing pumping from the confined aquifers during drought is the best operational strategy to minimise the risk of environmental impacts. Continued high abstraction from the confined aquifers would need to address the environmental impact around the Yeal and Pinjar sub areas. Figure 27 shows the relationship between storage depletion and the Corporation abstraction under the two climate regimes. This indicates that even if the confined abstraction is reduced to zero, the water balance in the Yeal/Pinjar area can not be restored. Increased burning frequency to enhance recharge and MAR will help to restore the water balance and mitigate environmental impacts. However, implementation of large scale MAR is unlikely to happen within a 10 year timeframe. Increased burning frequency (within the tolerance of biodiversity) to improve the recharge is perhaps the best strategy to slow the water level decline in these two areas.

### Abstraction from the Superficial and Mirrabooka aquifers

**Coastal Scheme:** The coastal schemes (including Whitfords, Quinns and Yanchep) are in a groundwater discharge area and the impacts of pumping are minimal due to the very high transmissive Tamala limestone. Water balance analysis indicates that under the average climate regime, the current abstraction rate of 19 GL/a from the superficial aquifer is sustainable. Under a drier climate regime, sustainable draw may slightly reduce to about 17 GL/a.

**Pinjar Borefield:** Modelling results indicate that without significant change to landuse use (pine removal) and land management (increase in burning) and MAR to increase the recharge, any abstraction by the Pinjar borefield from the superficial aquifer will increase the decline of water levels in the area. However, depth to water table at the north end of borefield (P120-P140) is greater than 10 m, and therefore abstraction from these bores is unlikely to have an adverse environmental impact.

**Wanneroo and Lexia:** Both borefields are within the Lexia subarea. Water balance analysis indicates that there will be significant excess water available in this area if management options to enhance the recharge are exercised. Under these conditions, there are opportunities for the Corporation to increase the abstraction from the superficial and Mirrabooka aquifers to 15 GL/a. Under the drier climate of 1997-2004, analysis indicates that only about 4 GL/a is available.

**Mirrabooka:** Under the climate of 1976-2003, about 7 GL/a is available for abstraction. Under the drier climate of 1997-2004, only about 4 GL/a is available for abstraction. Mirrabooka borefield is located in area with relatively shallow depth to water table. It may be possible to increase the abstraction by changing the abstraction patterns (eg, winter pumping). Research is being undertaken to assess the viability of this option.

**Gwelup and Mirrabooka West:** Both borefields are located in the Gwelup management sub area and in an urban setting. As mentioned earlier, the PRAMS model performs unsatisfactorily in this area due to the uncertainty in the private abstraction data. Nevertheless, it is estimated that under the climate of 1976-2003, abstraction of 15 GL/a should be sustainable. Under the drier climate of 1997-2004, a sustainable draw is about 10 GL/a.

A Summary of potential abstraction from the superficial and Mirrabooka aquifers is given in Table 5.

| Borefield | Water available for abstraction under zero storage depletion | | Scenarios | | | Most likely abstraction 120 |
|---|---|---|---|---|---|---|
| | Climate 1976-2003 | Climate 1997-2004 | 105 | 135 | 165 | |
| Coastal Scheme | 19 | 17 | 19 | 19 | 20 | 19 |
| Pinjar | 0 | 0 | 0 | 2 | 2 | 1 |
| Wanneroo and Lexia | 15 | 4 | 6 | 8 | 12 | 7 |
| Mirrabooka | 7 | 4 | 5 | 6 | 10 | 6 |
| Gwelup and Mirrabooka West | 15 | 10 | 15 | 16 | 16 | 16 |
| **Superficial/Mirrabooka total** | **56** | **35** | **45** | **51** | **60** | **48** |

**Table 5 Potential abstraction from the Superficial and Mirrabooka aquifers for public water supply (GL/a)**

**Conjunctive operation:** Current operating rules for conjunctive use of groundwater and surface sources for the IWSS allow the Corporation to abstract groundwater in the range of 105 – 165 GL/a depending on the storage level in the hills reservoirs. Assuming that high storage levels occur under a climate regime of 1976-2003, groundwater abstraction will be at the minimum end and about 105 GL/a. Given that availability from the superficial will be about 60 GL (listed in Table 5 plus 4 GL from Jandakot), this will require abstraction from confined aquifers of about 45 GL/a.

Under the drier climate of 1997-2004, the statistical water balance model (SWBM) developed by Stokes (Pers. Comm.) to examine the balance between the demand and supply for the IWSS estimates that the most likely groundwater abstraction for the IWSS is, on average, about 120 GL/a in the next few years. Modelling results show that the probabilities for the Corporation to abstract 105 GL/a and 165 GL/a are 53.8% and 7.4% respectively with a probability of 38.8% that groundwater draw will be between these two values. Using the 135 GL/a abstraction pattern as representative for the abstractions between 105 and 165 GL/a, the future expected abstraction from the superficial aquifers from each subarea under the drier climate regime can be approximately estimated as given in Table 5. Total abstraction from the superficial/Mirrabooka aquifers is around 48 GL/a with the remainder (72 GL/a) drawn from the confined aquifers. The abstraction rate of 48 GL/a from the superficial aquifer, however, exceeds the water available for abstraction of 35 GL/a under the drier climate regime (Table 5). To minimise the risk of environmental impacts, the shortfall (13 GL/a) between the required 48 GL/a and the available 35 GL/a may be met by:

- Increasing abstraction from the confined aquifers,
- Increasing abstraction from the superficial aquifer in the less environmentally sensitive areas, e.g., Gwelup and Coastal schemes.
- Increasing abstraction from areas with shallow water table by modifying abstraction patterns to be sympathetic to rather than in competition with environmental demand, that is, operating the Corporation borefields during winter and at lower rates for longer duration. A research project is currently underway to assess whether this approach is a viable option.

An increase in confined abstraction of 13 GL/a will induce an additional leakage of about 4 GL/a from the superficial aquifer into the confined aquifers in the Gnangara Mound area. This is unlikely to cause significant environmental impacts given that the drawdown impacts of confined pumping will spread over a large area, mostly in areas with high depth to water table. Further work is required to refine the groundwater abstraction patterns to minimise environmental impacts under the drier climate condition.

The above analysis for sustainable abstraction for public water supply assumes that no storage depletion is allowed, namely trying to maintain the current groundwater levels. A recent study (Froend et al 2004) however shows some groundwater dependent ecosystems (GDEs) on Gnangara Mound, in particular the terrestrial phreatophytic vegetation, are capable of adapting to the dynamic change in water table provided the drawdown rate does not exceed a certain threshold. A decline rate of 10 cm/a in water table is considered to pose low risk to the GDEs. If a maximum decline rate of 10 cm/a is used as the criterion, as opposed to zero storage depletion, to determine the sustainable abstraction, there will be significant increase in water available for abstraction in the Lexia (12 GL/a) and Coastal areas (>20 GL/a) under the drier climate condition (Figure 28). Under this condition, the required 48 GL/a draw from the superficial aquifers as described above can be met by increasing abstraction from the superficial bores at Wanneroo, Lexia and Coastal schemes. However, the rate of water level decline at the top of the Mound (Yeal and Pinjar sub areas) is still greater than 10 cm/a ( Figure 29). Even if the Corporation ceases confined abstraction, the groundwater level decline rate in Pinjar still exceeds 10 cm/a due to reduction in recharge.

The work described above takes a simplified approach to examine the potential water available for abstraction for public water supply based on an area average water balance analysis. Typically, the Corporation borefields that draw water from the superficial aquifer are located away from environmentally sensitive areas. Use of an area average decline or storage deficit as a measure to assess the water availability for abstraction may overestimate impacts of abstraction on GDEs thereby reducing the water availability. Further modelling work with more focus on local impacts is required to refine the abstraction patterns to minimise the environmental impacts.

## ***CONCLUSION***

Water balance analysis has demonstrated that:

1. Recharge to the Gnangara Mound groundwater system is significantly affected by the rainfall. Under the climate regime of 1976-2003, total recharge on Gnangara Mound is 342 GL/a or about 20% of the rainfall whereas under the drier climate regime of 1997-2004, the recharge is

reduced to only 252 GL/a or 18% of the rainfall, representing a reduction of 26 % in recharge compared with a decrease in rainfall of 13%.

2. Under the drier climate regime of 1997-2004, the groundwater levels on Gnangara Mound will continue to decline at a rate of 0.2 m per annum, extending the current observed trend. Even under the climate regime of 1976-2003, the PRAMS model predicts continued water decline in six out of ten groundwater management areas.
3. Comparison of 105 GL/a and 135 GL/a abstraction scenarios indicates that there is very little difference in terms of regional water table decline between scenarios. There will be very little environmental benefits in reducing abstraction for public water supply from 135 GL/a to 105 GL/a.
4. Under the climate regime of 1976-2003, the storage deficit was estimated at 47 GL/a for the 135 GL/a abstraction scenario (39 GL/a for the 105 GL/a scenario). It may be possible to restore the water balance by a combination of landuse management and reduction in abstraction.
5. Storage deficit for the Gnangara Mound under the drier climate regime of 1997-2004 was estimated to be 104-124 GL/a. It is unlikely that the water balance of Gnangara Mound can be restored without drastic changes in landuse to enhance the recharge and implementation of large scale MAR.
6. Abstraction from confined aquifers enables the impacts to be spread over a larger area of the superficial aquifer. Analysis indicates only one third of the confined abstraction propagates back to the Gnangara Mound area via increased leakage. The balance is met by confined storage depletion and increased throughflow. Increased confined abstraction to meet demand during drought periods is the best strategy to minimise the risk of environmental impacts.
7. To sustain continued high abstraction from the confined aquifers, the water imbalance in the Yeal and Pinjar areas, particularly areas with ecosystems sensitive to water table decline, needs to be addressed. Potential management options include increased burning frequency to enhance recharge and MAR.
8. The Superficial aquifer is a significant and viable source for public water supply even under drier climate conditions. Significant excess water is available under a climate of 1976-2003 in the Lexia groundwater subarea which will allow increased abstraction from the superficial and Mirrabooka aquifers for public water supply from Lexia and Wanneroo borefields. Removal of pines will further increase the amount of water available for public abstraction.

## ***RECOMMENDATION***

This work takes a broad approach of examining the potential water available for abstraction for public water supply based on subarea water balance. Further modelling work with a focus on local impacts of abstraction is required to refine abstraction patterns to minimise the risk to the environment and maximise potential water available for abstraction.

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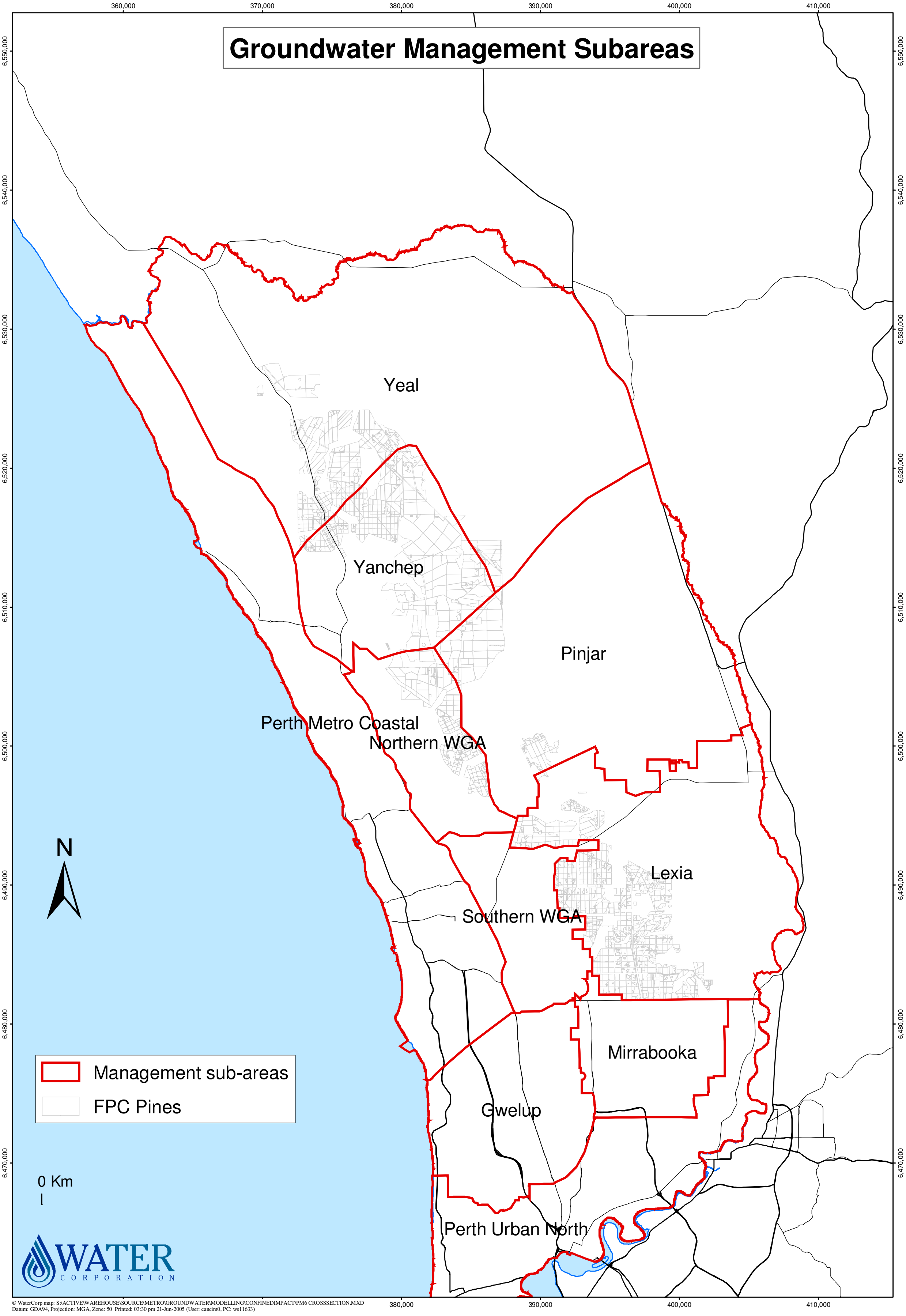


**Figure 1 Gnangara Mound and groundwater management areas**

# Water Balance for Gnangara Mound

(in GL/a, value in the bracket is for dried climate 97-04)

Area: 2115 km$^2$, 1028 km$^2$ native, 210 km$^2$ pine
Rainfall at Perth Region Office: 788 mm/a for 1976-03, 696 mm/a for 1997-04

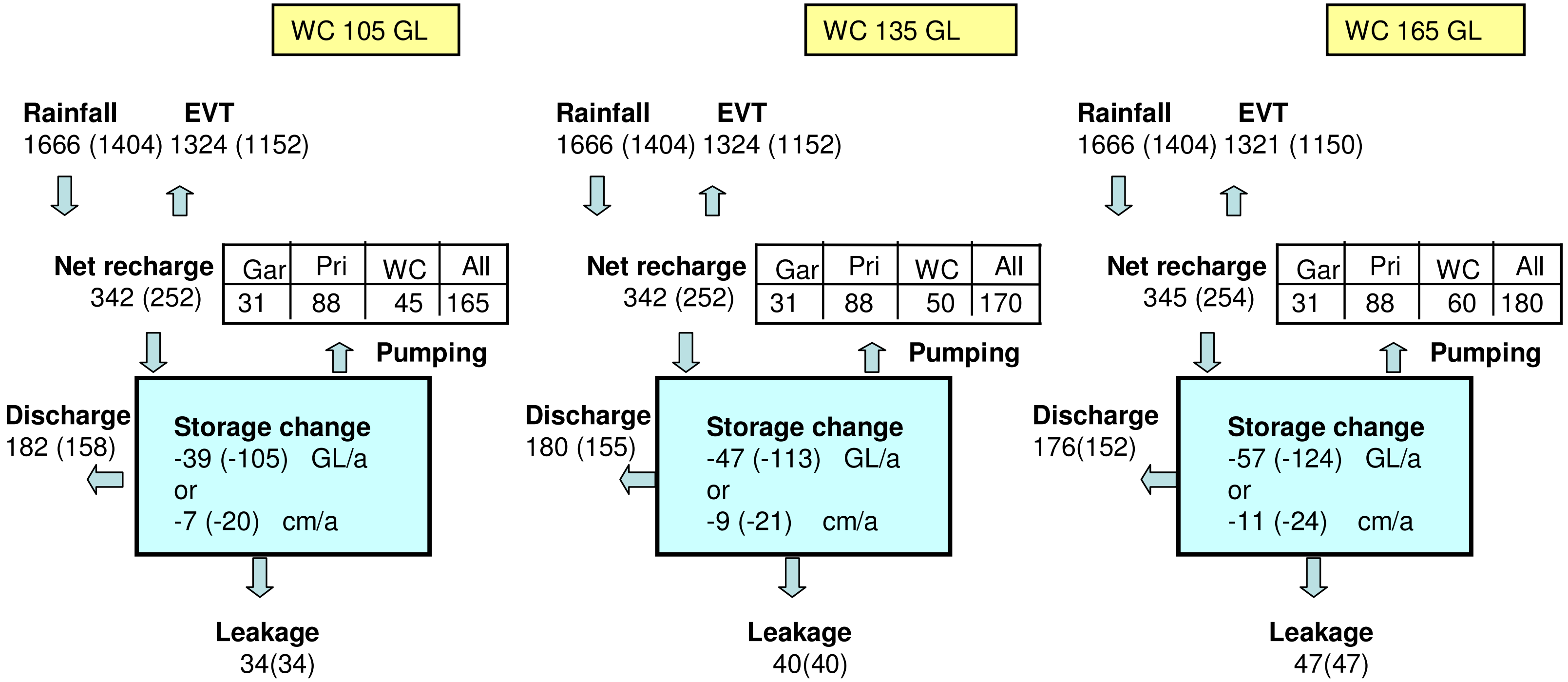


**Figure 2 Water balance for Gnangara Mound**

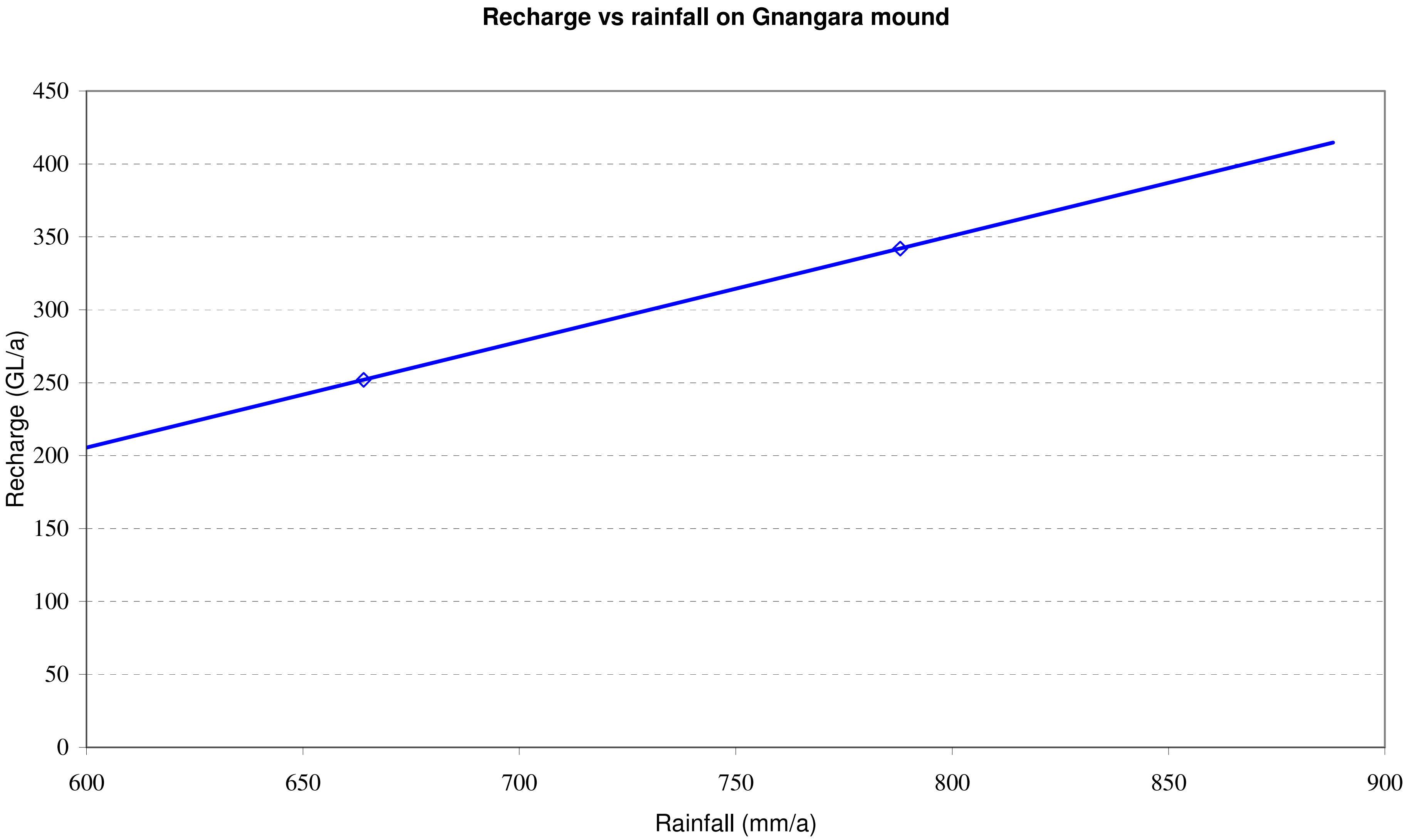


**Figure 3 Estimated recharge vs rainfall for the Gnangara Mound**

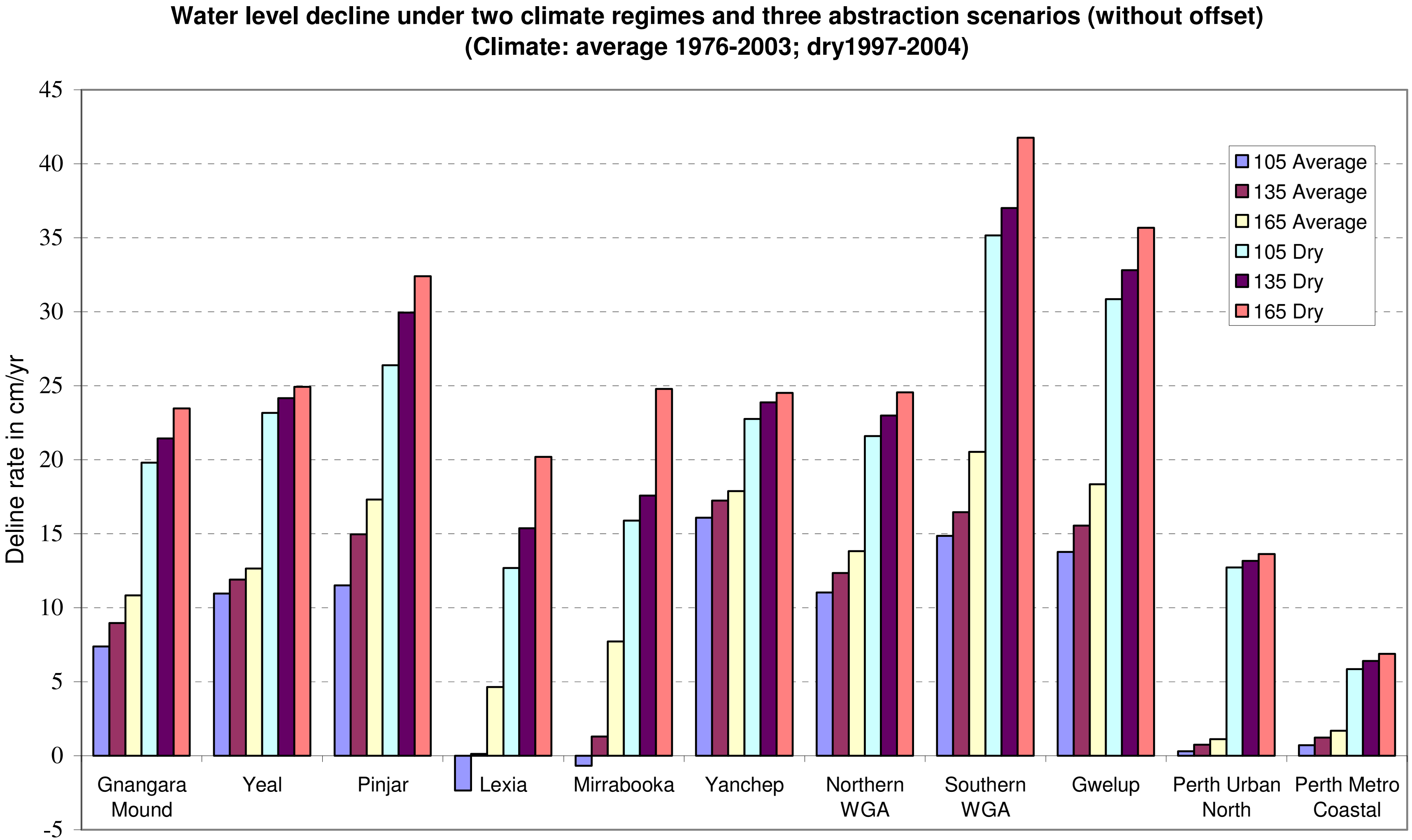


**Figure 4 Decline rate of water levels under the average and dry climates for the three Corporation abstraction scenarios**

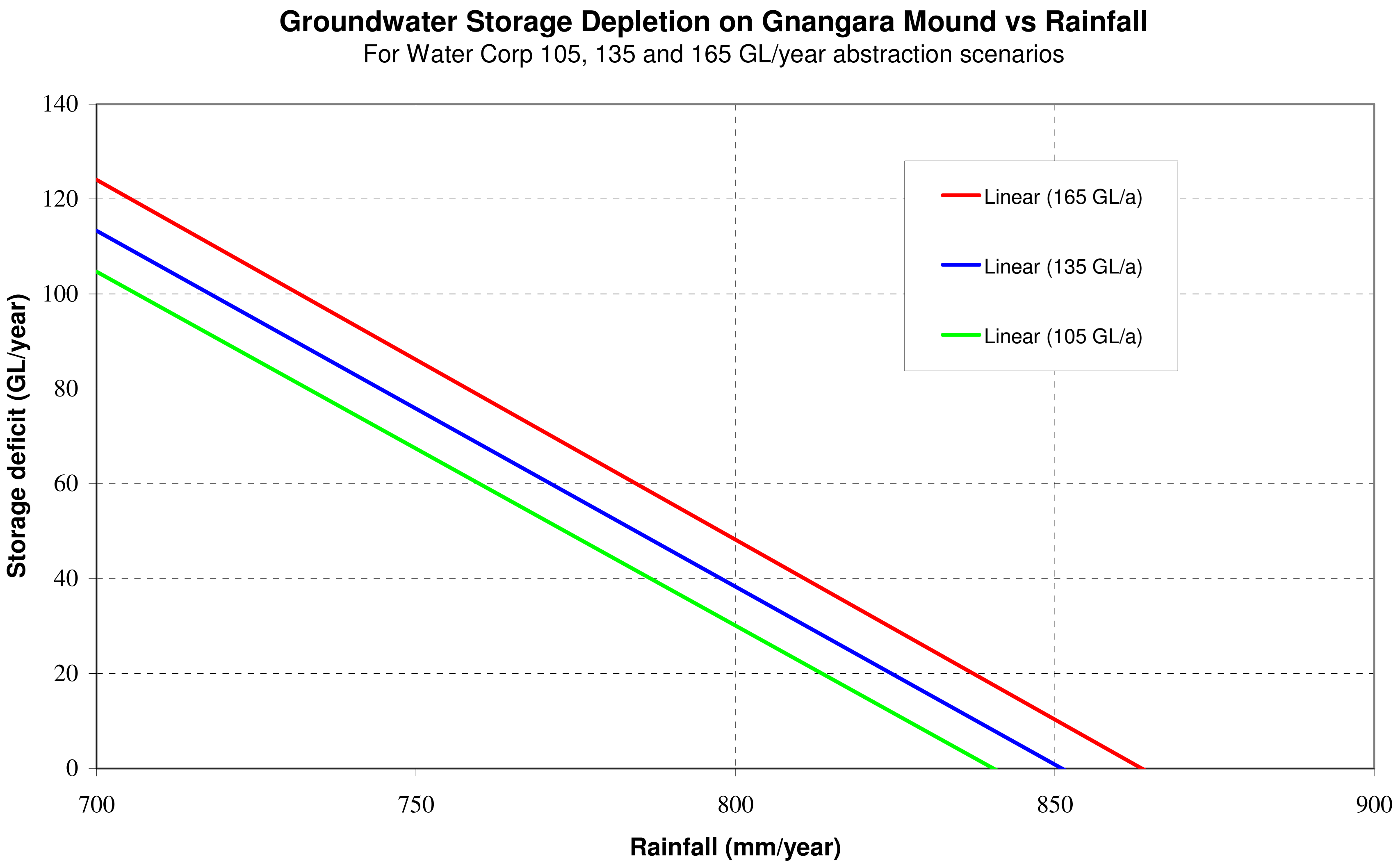


**Figure 5 Storage depletion vs rainfall under three Corporation abstraction scenarios**

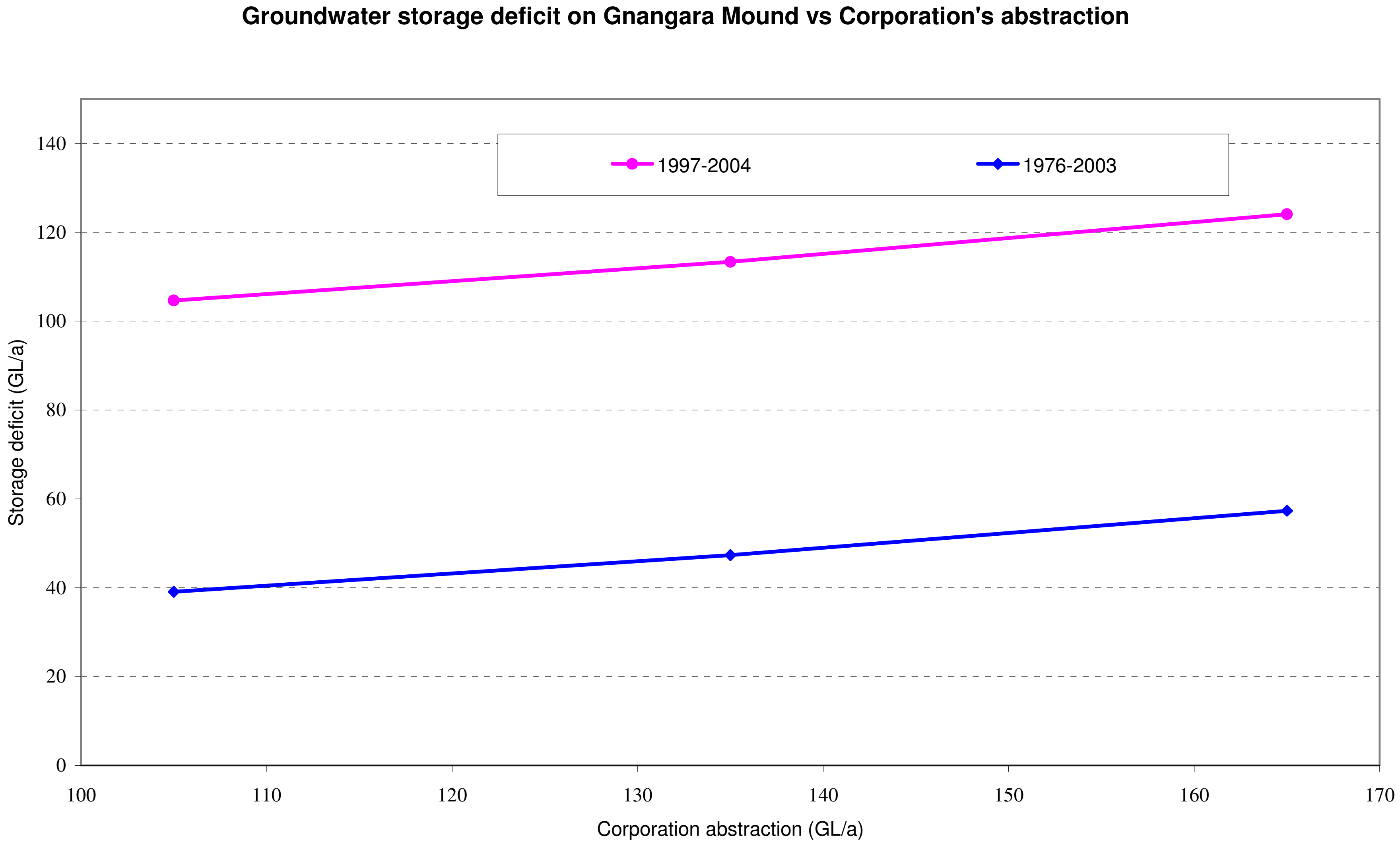


**Figure 6 Storage change on Gnangara Mound vs Corporation's abstraction**

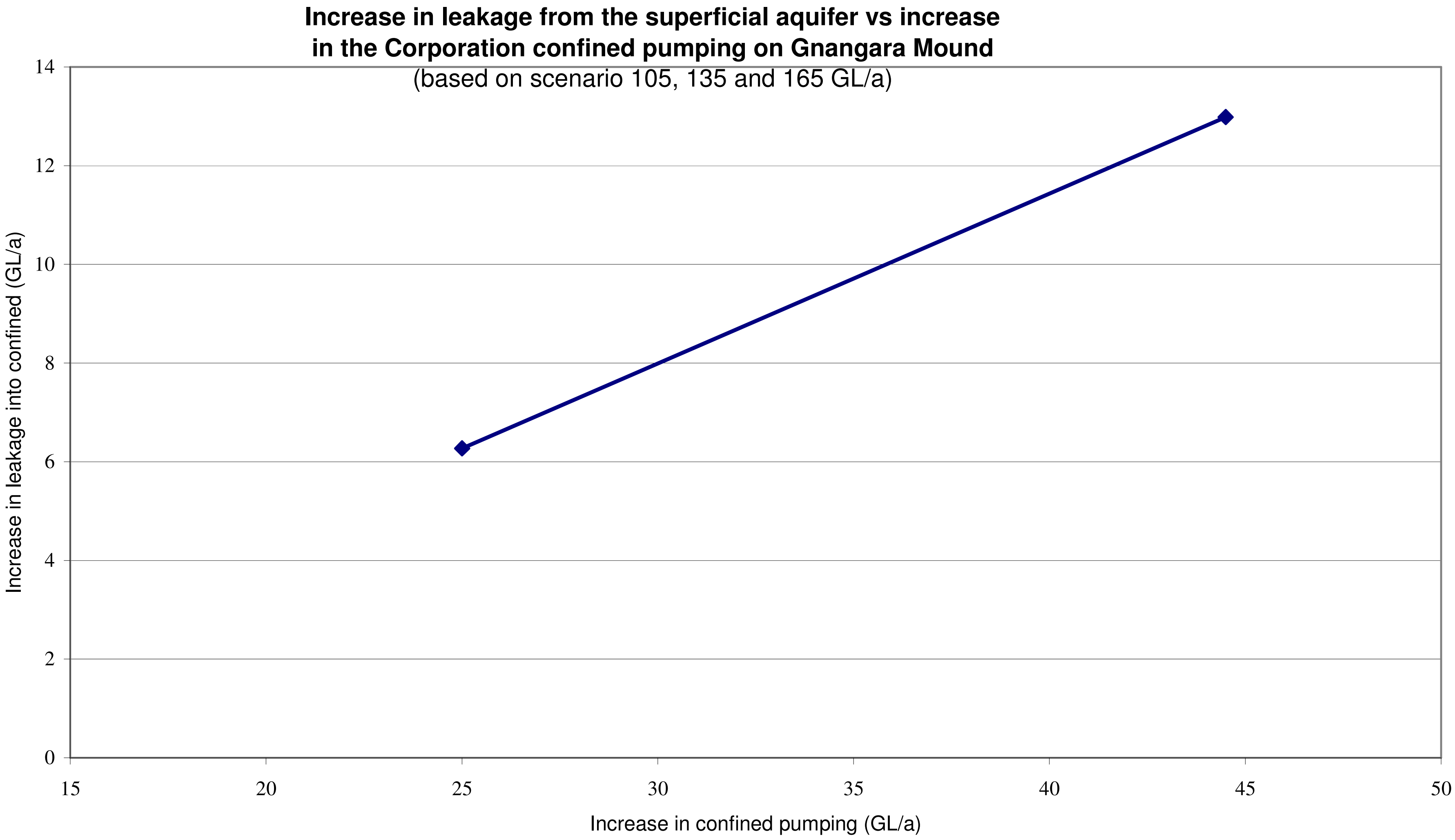
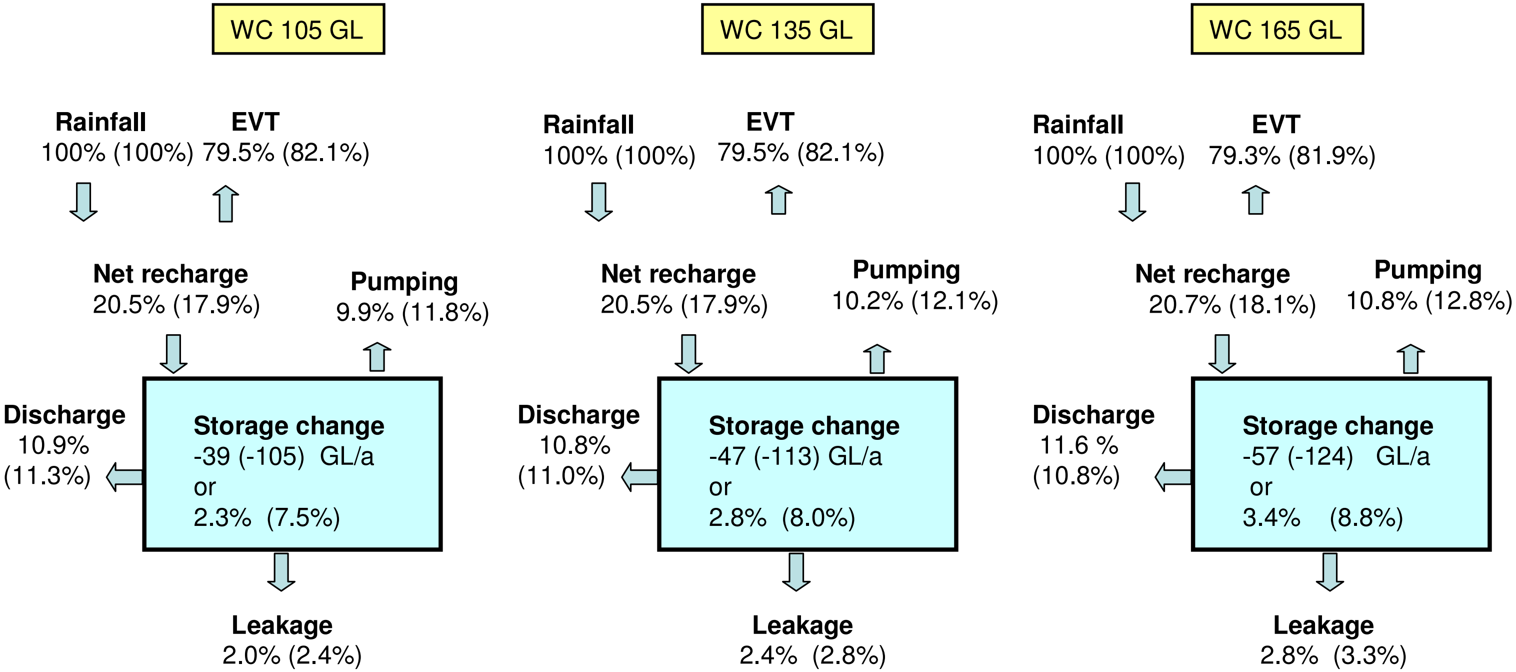


**Figure 7 Additional leakage into confined aquifer vs increased confined pumping**

# Water Balance for Gnangara Mound

(as % of rainfall, value in the bracket is for dried climate 97-04)

Area: 2115 km$^2$, 1028 km$^2$ native, 210 km$^2$ pine
Rainfall at Perth Region Office: 788 mm/a for 1976-03, 696 mm/a for 1997-04



WC 105 GL

**Rainfall** 100% (100%)
**EVT** 79.5% (82.1%)
**Net recharge** 20.5% (17.9%)
**Pumping** 9.9% (11.8%)
**Discharge** 10.9% (11.3%)
**Storage change** -39 (-105) GL/a or 2.3% (7.5%)
**Leakage** 2.0% (2.4%)

WC 135 GL

**Rainfall** 100% (100%)
**EVT** 79.5% (82.1%)
**Net recharge** 20.5% (17.9%)
**Pumping** 10.2% (12.1%)
**Discharge** 10.8% (11.0%)
**Storage change** -47 (-113) GL/a or 2.8% (8.0%)
**Leakage** 2.4% (2.8%)

WC 165 GL

**Rainfall** 100% (100%)
**EVT** 79.3% (81.9%)
**Net recharge** 20.7% (18.1%)
**Pumping** 10.8% (12.8%)
**Discharge** 11.6 % (10.8%)
**Storage change** -57 (-124) GL/a or 3.4% (8.8%)
**Leakage** 2.8% (3.3%)

**Figure 8 Water balance for Gnangara Mound (as % of rainfall)**

# Water Balance for Yeal Area

(in GL/a, value in the bracket is for dried climate 97-04)

Area: 558 km^2, 365 km^2 native, 44 km^2 pine
Rainfall at Perth Region Office: 788 mm/a for 76-03, 696 mm/a for 97-04

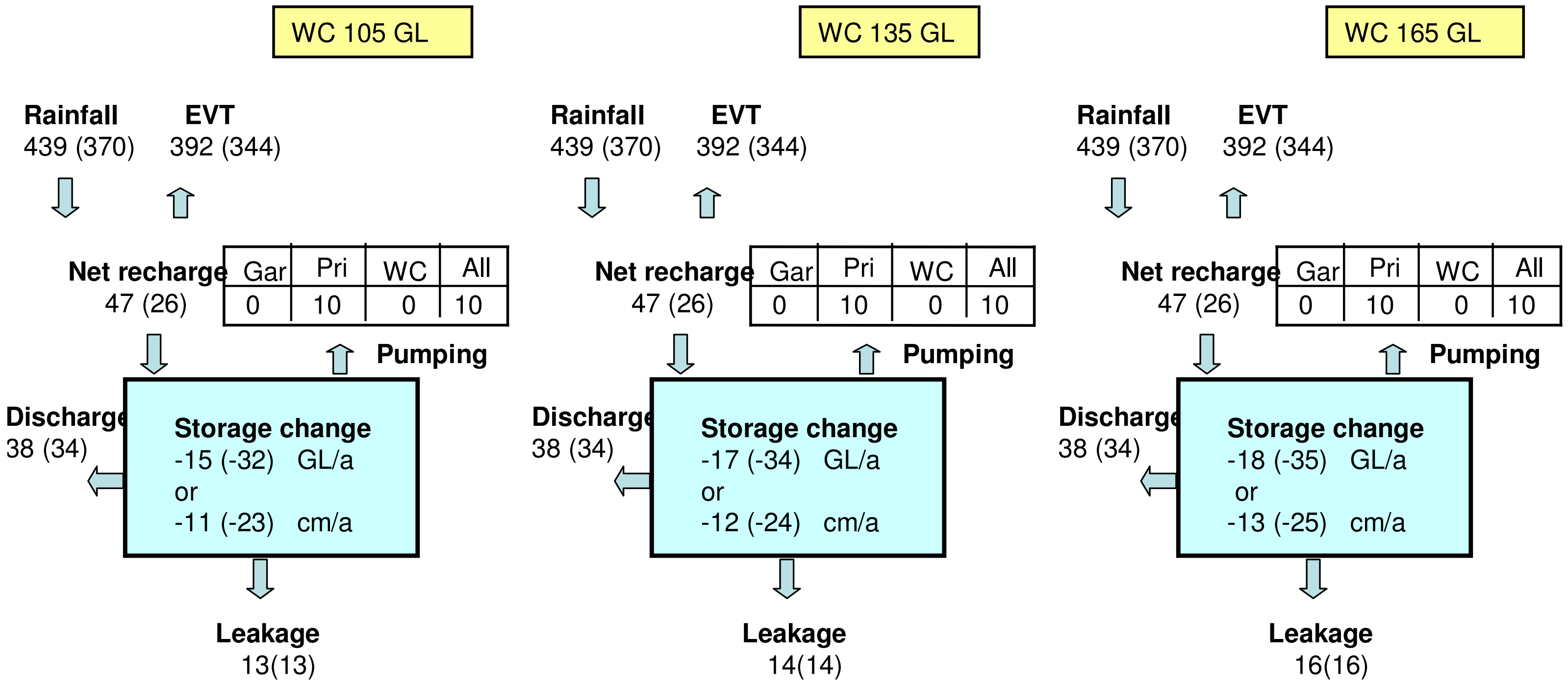


**Figure 9 Water balance for Yeal area**

## Water Balance for Pinjar Area

(in GL/a, value in the bracket is for dried climate 97-04)

Area: 326 km^2,  236 km^2 native, 20 km^2 pine
Rainfall at Perth Region Office: 788 mm/a for 76-03, 696 mm/a for 97-04

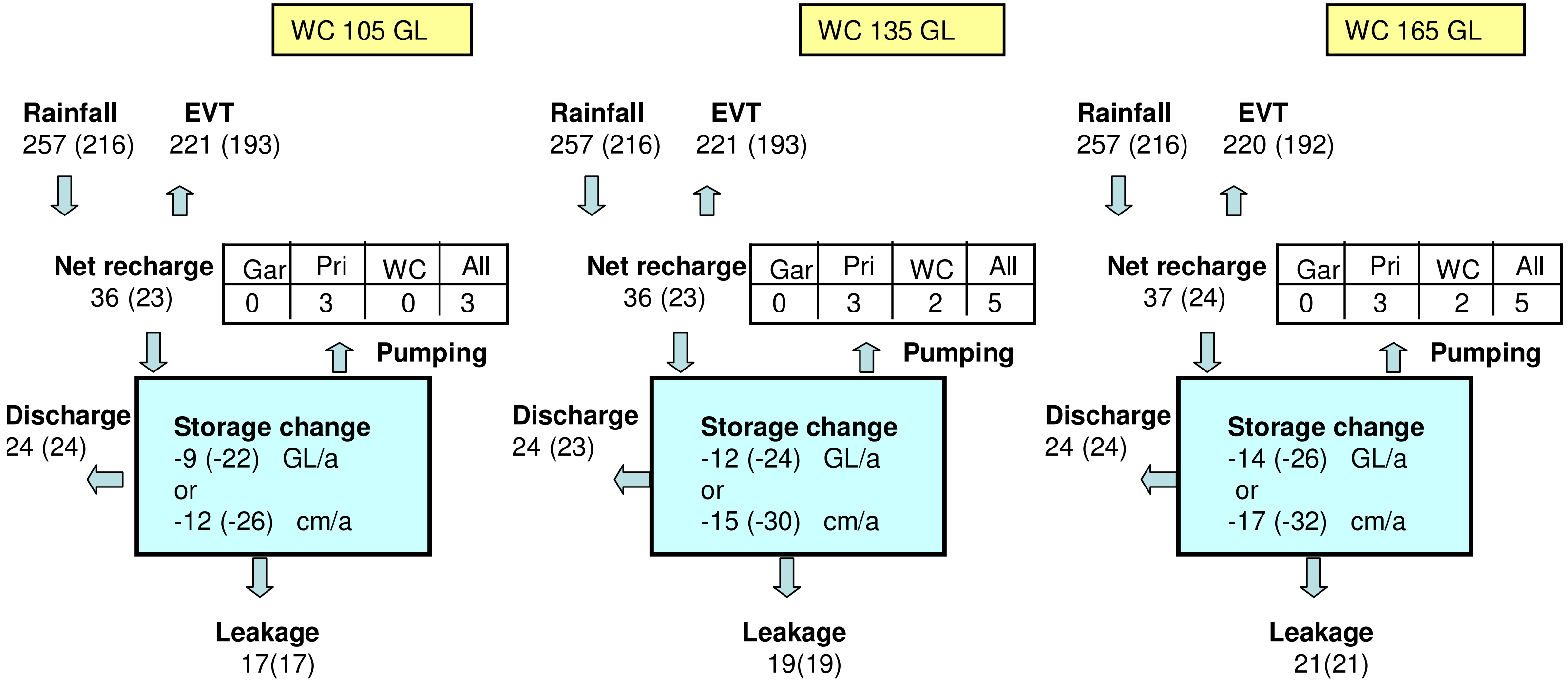
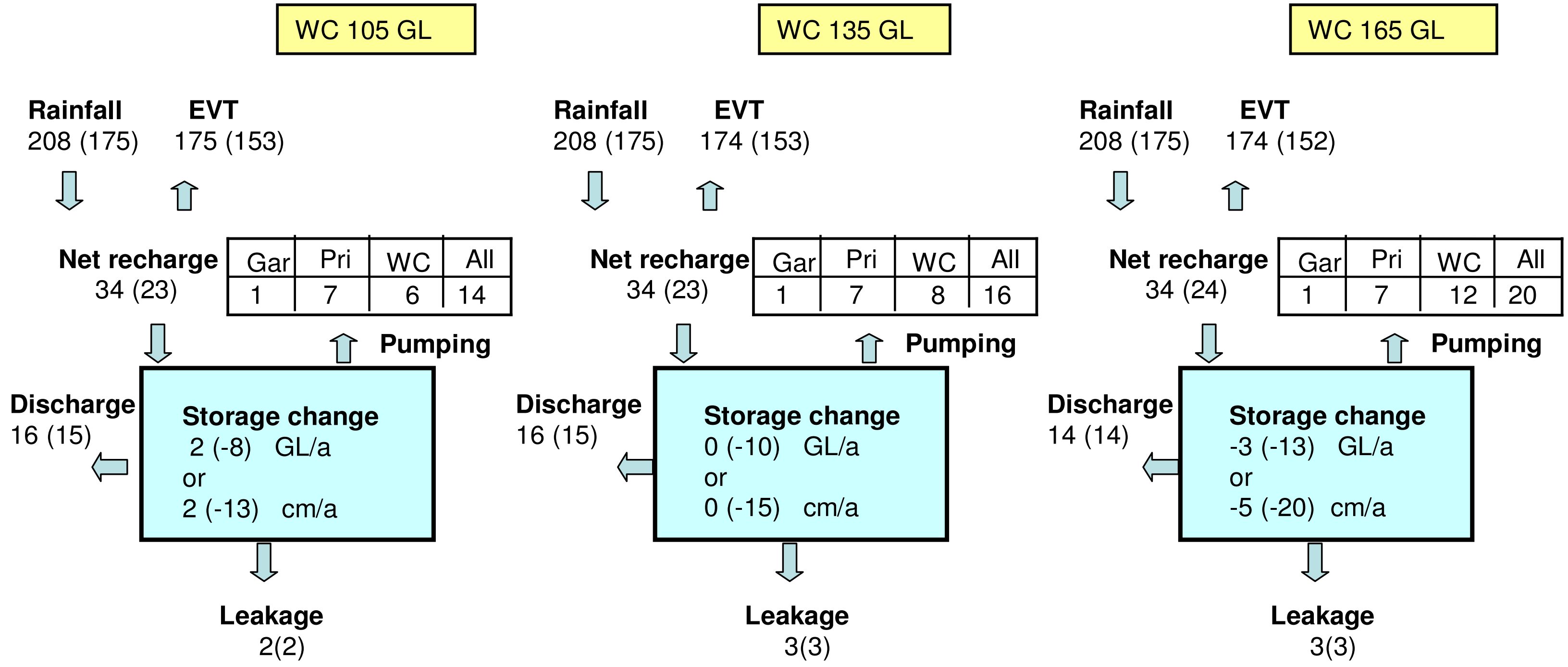


**Figure 10 Water balance for Pinjar area**

# Water Balance for Lexia Area

(in GL/a, value in the bracket is for dried climate 97-04)

Area: 264 km^2, 100 km^2 native, 81 km^2 pine
Rainfall at Perth Region Office: 788 mm/a for 76-03, 696 mm/a for 97-04



| Gar | Pri | WC | All |
|---|---|---|---|
| 1 | 7 | 6 | 14 |

| Gar | Pri | WC | All |
|---|---|---|---|
| 1 | 7 | 8 | 16 |

| Gar | Pri | WC | All |
|---|---|---|---|
| 1 | 7 | 12 | 20 |

**Figure 11 Water balance for Lexia area**

# Water Balance for Mirrabooka Area

(in GL/a, value in the bracket is for dried climate 97-04)

Area: 83 km^2,  20 km^2 native, no pine
Rainfall at Perth Region Office: 788 mm/a for 76-03, 696 mm/a for 97-04

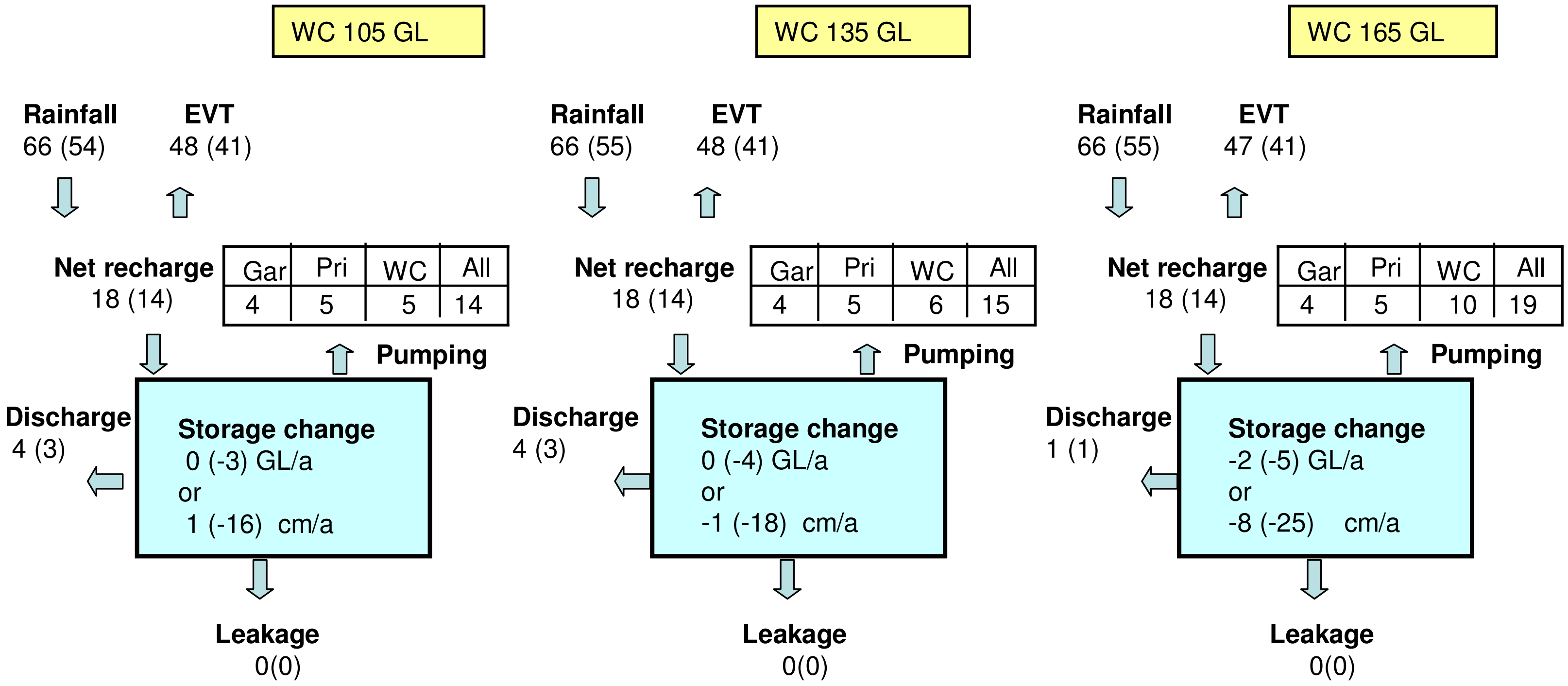
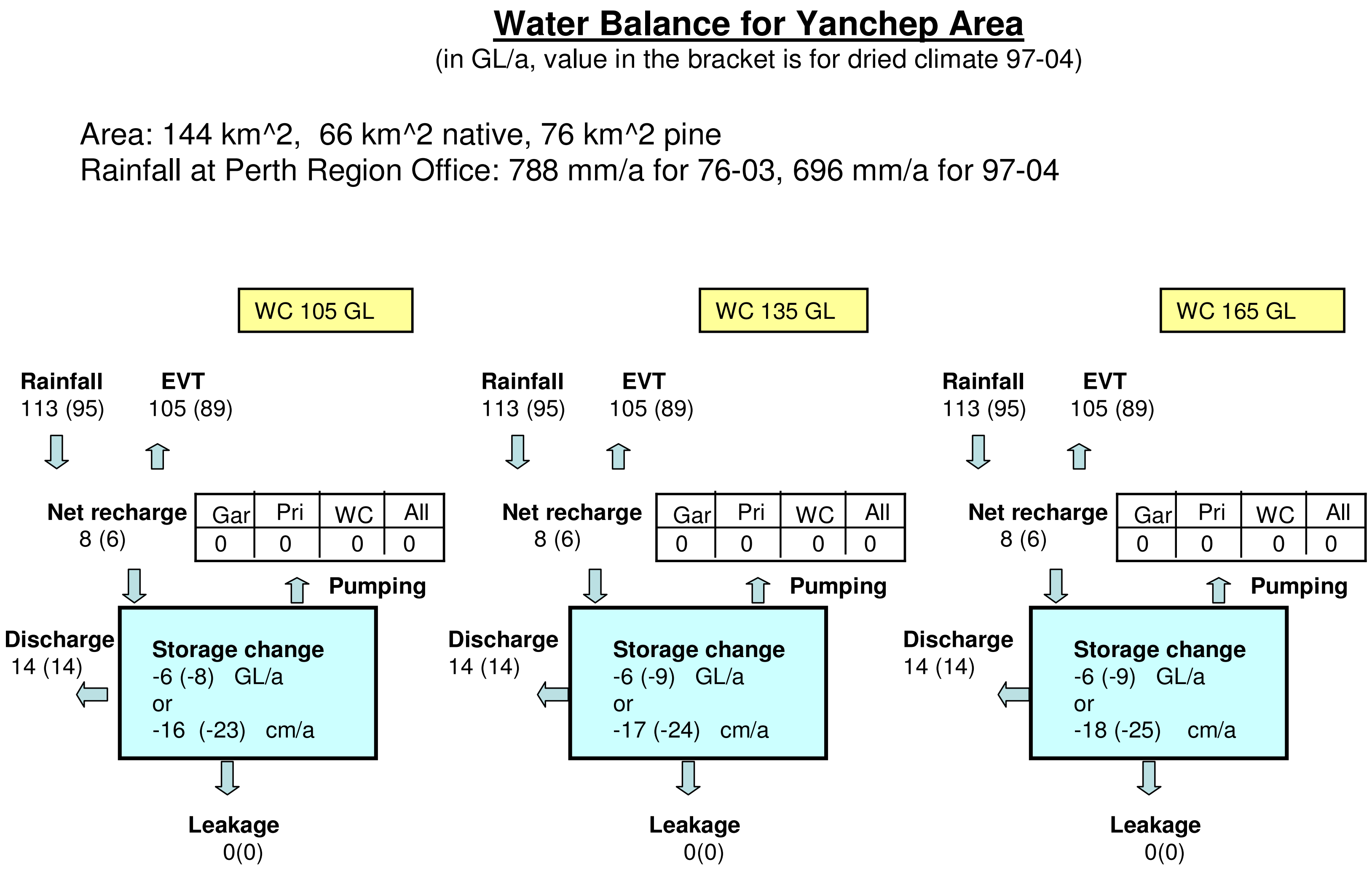


**Figure 12 Water balance for Mirrabooka area**



## Water Balance for Yanchep Area

(in GL/a, value in the bracket is for dried climate 97-04)

Area: 144 km^2, 66 km^2 native, 76 km^2 pine
Rainfall at Perth Region Office: 788 mm/a for 76-03, 696 mm/a for 97-04

**WC 105 GL**

**Rainfall** 113 (95)

**EVT** 105 (89)

**Net recharge** 8 (6)

| Gar | Pri | WC | All |
|---|---|---|---|
| 0 | 0 | 0 | 0 |

**Pumping**

**Discharge** 14 (14)

**Storage change**
-6 (-8) GL/a
or
-16 (-23) cm/a

**Leakage** 0(0)

**WC 135 GL**

**Rainfall** 113 (95)

**EVT** 105 (89)

**Net recharge** 8 (6)

| Gar | Pri | WC | All |
|---|---|---|---|
| 0 | 0 | 0 | 0 |

**Pumping**

**Discharge** 14 (14)

**Storage change**
-6 (-9) GL/a
or
-17 (-24) cm/a

**Leakage** 0(0)

**WC 165 GL**

**Rainfall** 113 (95)

**EVT** 105 (89)

**Net recharge** 8 (6)

| Gar | Pri | WC | All |
|---|---|---|---|
| 0 | 0 | 0 | 0 |

**Pumping**

**Discharge** 14 (14)

**Storage change**
-6 (-9) GL/a
or
-18 (-25) cm/a

**Leakage** 0(0)

**Figure 13 Water balance for Yanchep area**

# Water Balance for Northern Wanneroo Groundwater Area (WGA)

(in GL/a, value in the bracket is for dried climate 97-04)

Area: 88 km^2,  38 km^2 native, 34 km^2 pine
Rainfall at Perth Region Office: 788 mm/a for 76-03, 696 mm/a for 97-04

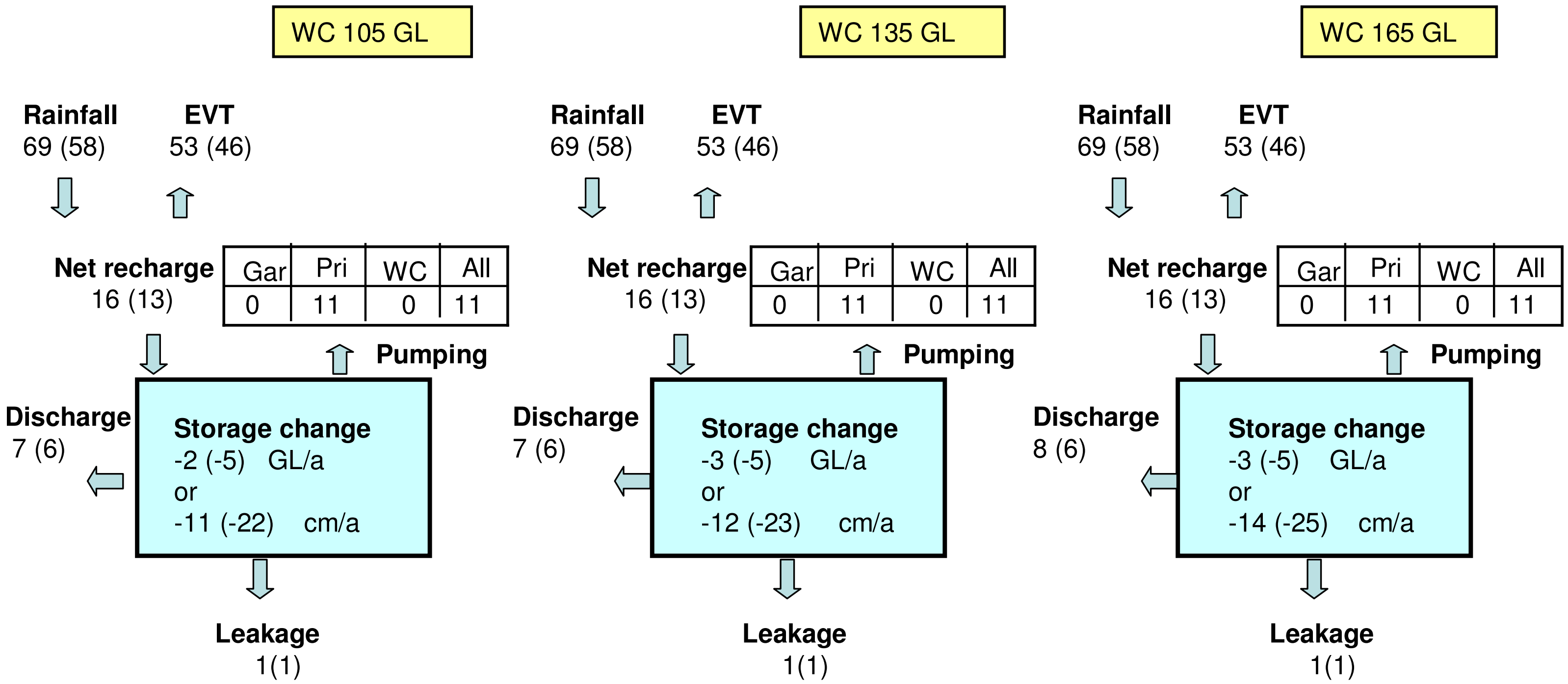


**Figure 14 Water balance for Northern WGA**

# Water Balance for Southern Wanneroo Groundwater Area (WGA)

(in GL/a, value in the bracket is for dried climate 97-04)

Area: 78 km^2, 22 km^2 native, no pine
Rainfall at Perth Region Office: 788 mm/a for 76-03, 696 mm/a for 97-04

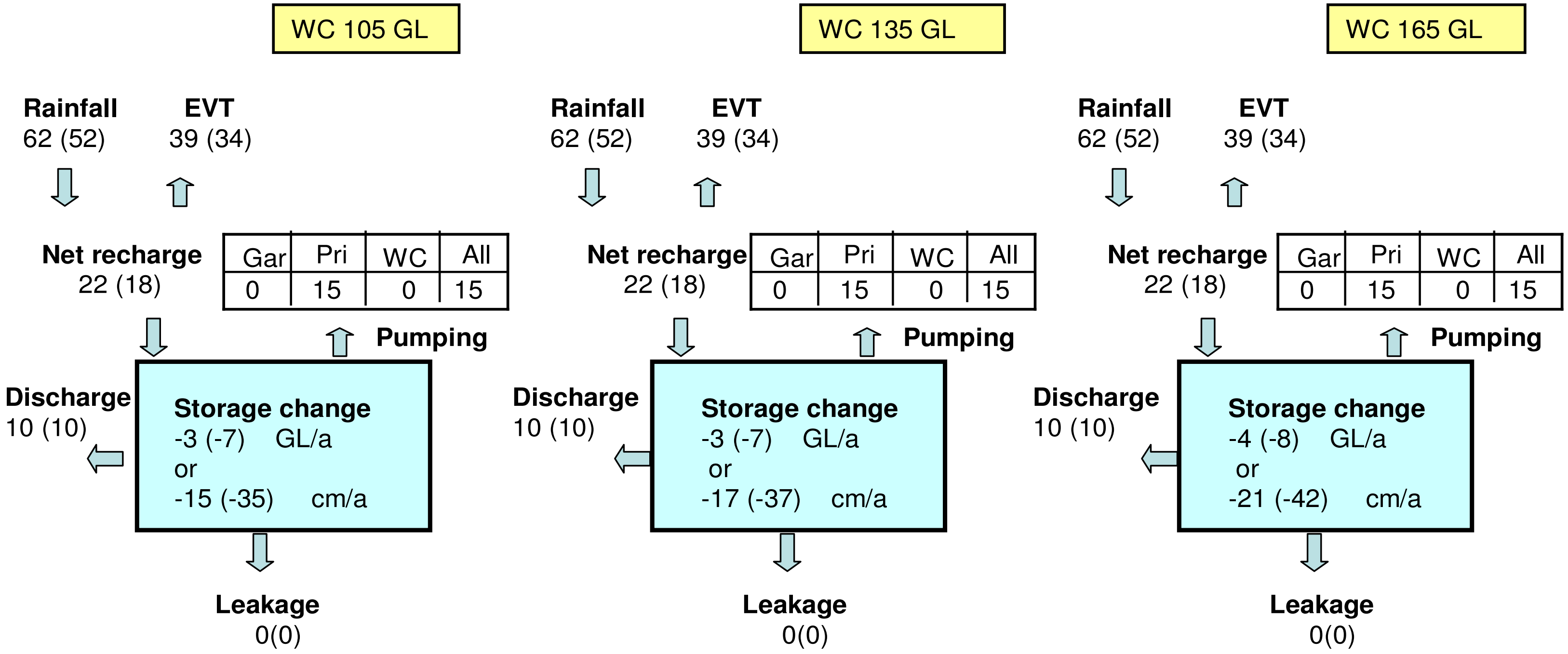


**Figure 15 Water balance for Southern WGA**

## Water Balance for Gwelup Area

(in GL/a, value in the bracket is for dried climate 97-04)

Area: 128 km^2, urban
Rainfall at Perth Region Office: 788 mm/a for 76-03, 696 mm/a for 97-04

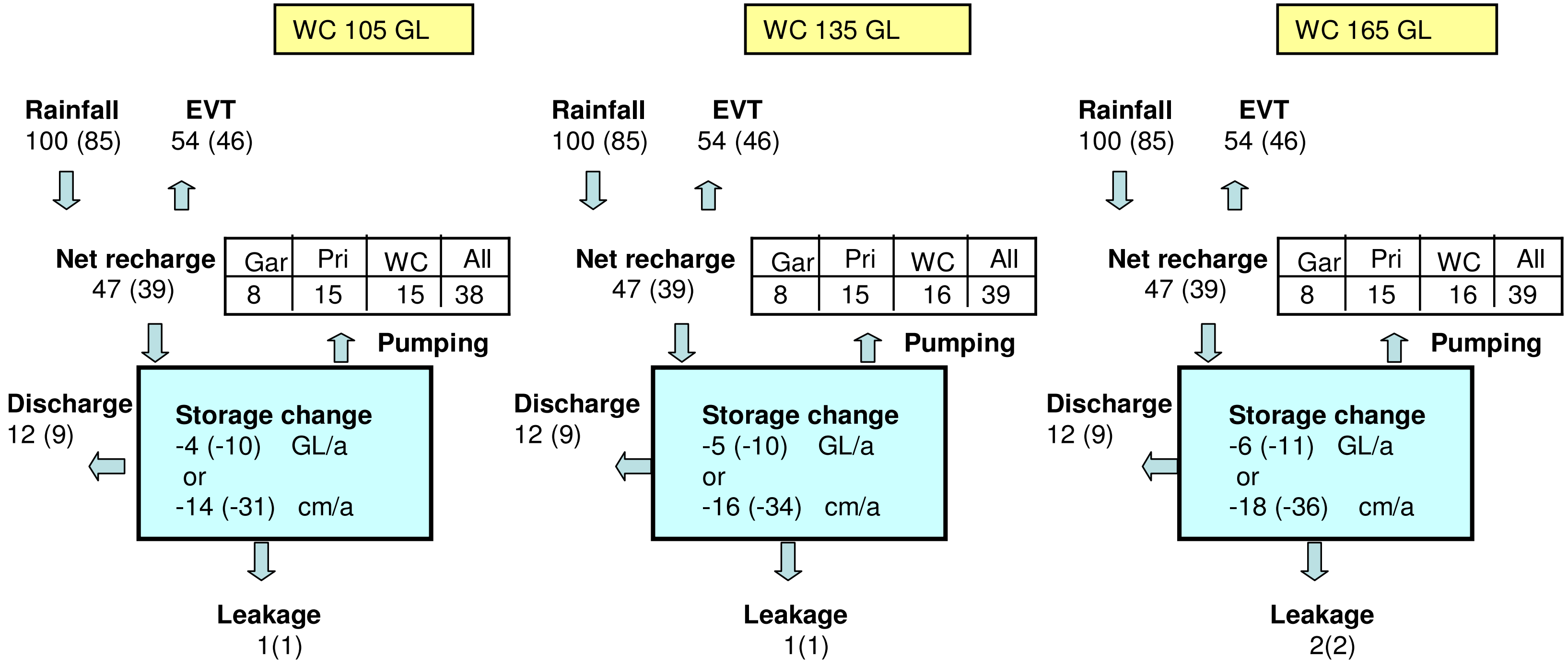


**Figure 16 Water balance for Gwelup area**

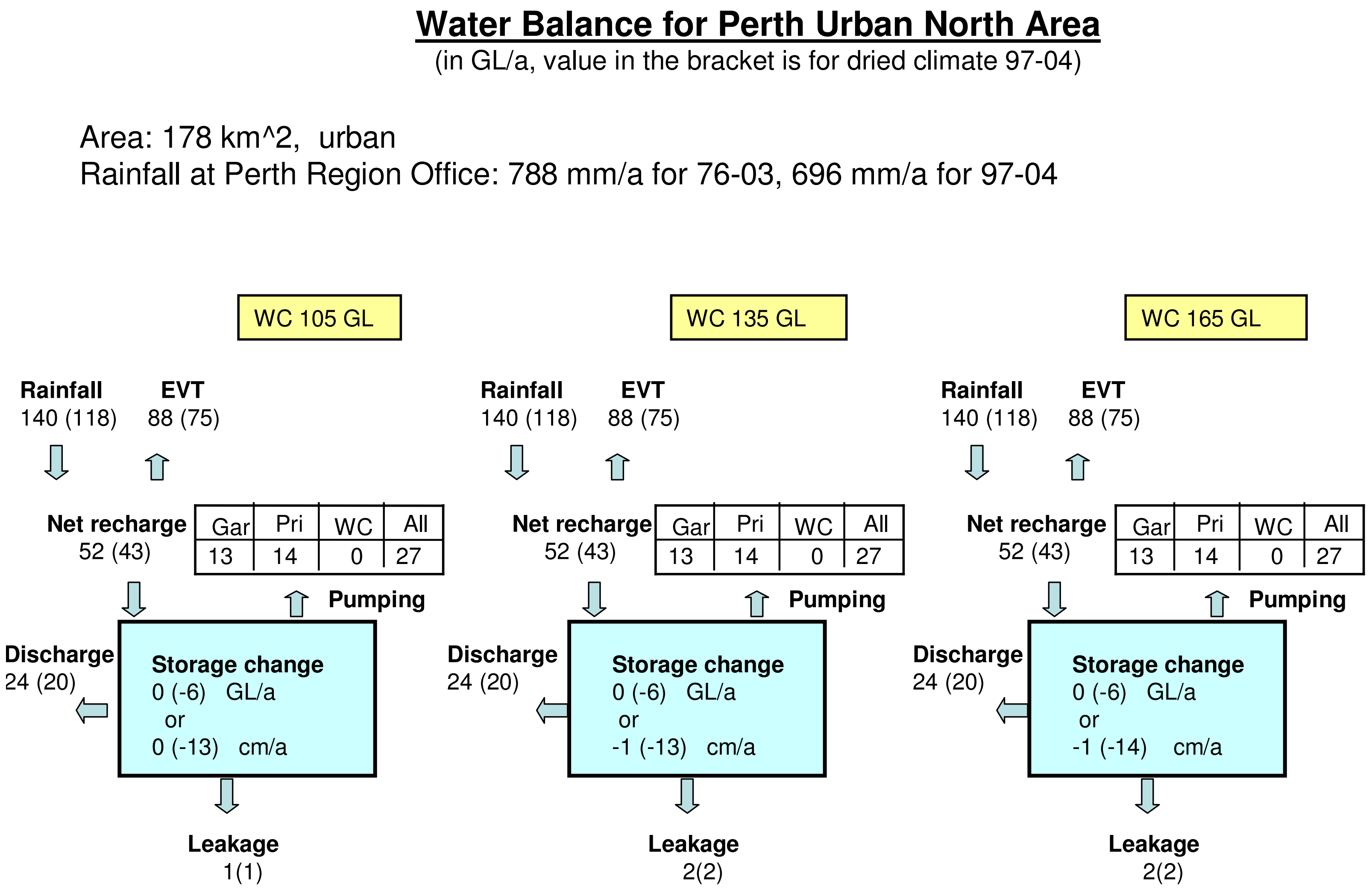


**Figure 17 Water balance for Perth Urban North area**

## Water Balance for Perth Metro Coastal Area

(in GL/a, value in the bracket is for dried climate 97-04)

Area: 269 km^2, 157 km^2 native
Rainfall at Perth Region Office: 788 mm/a for 76-03, 696 mm/a for 97-04

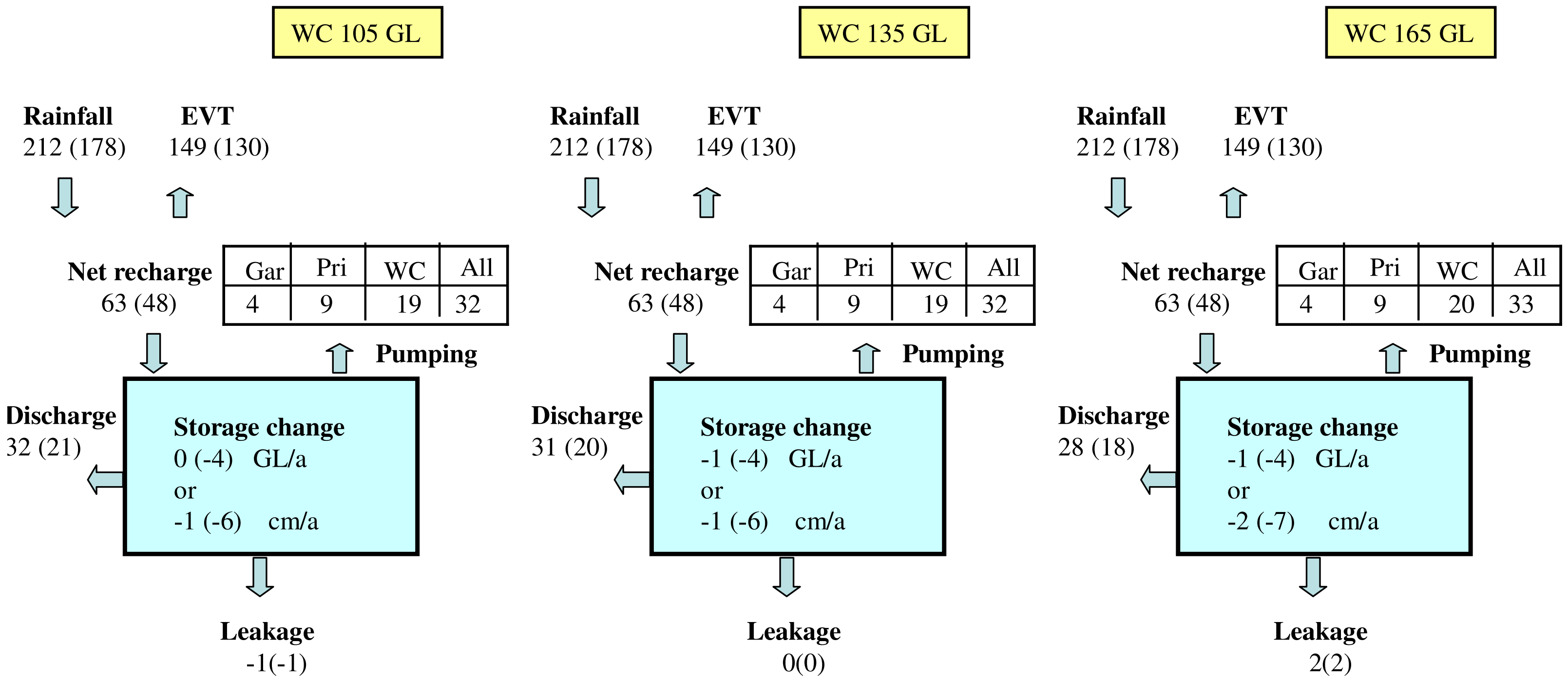


**Figure 18 Water balance for Perth Metro Coastal area**

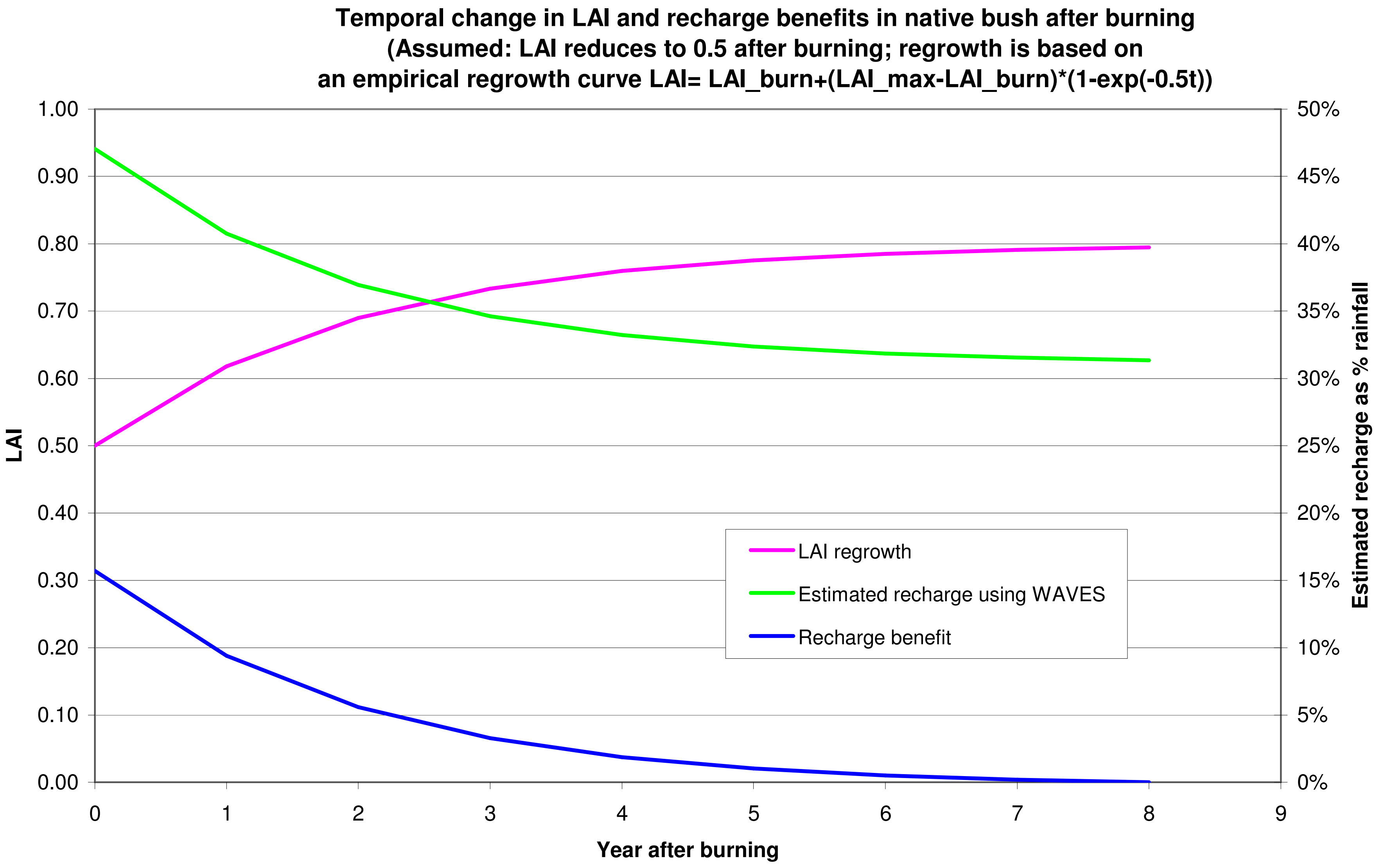


**Figure 19 Recharge response after fire**

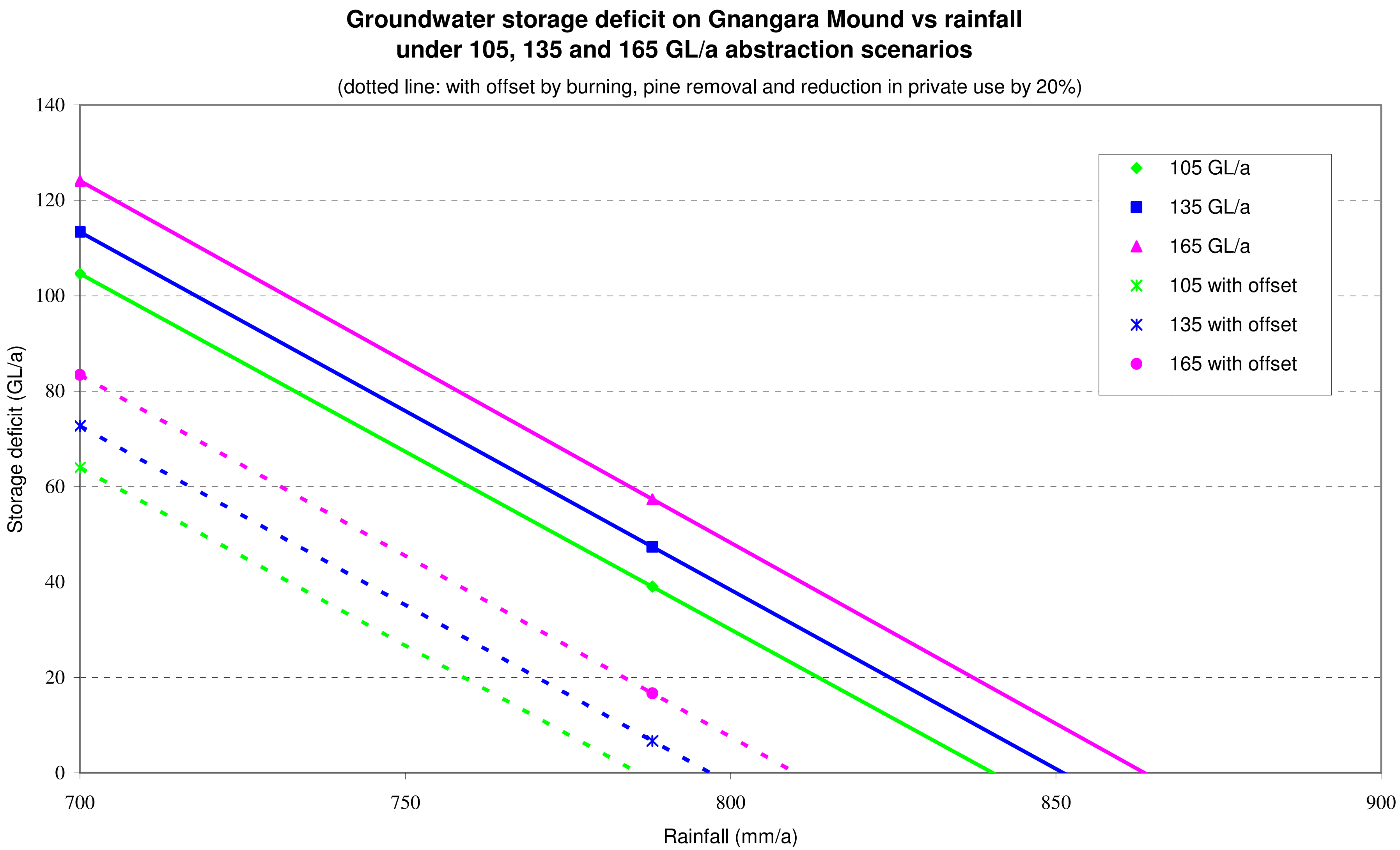


**Figure 20 Storage depletion under various management options**

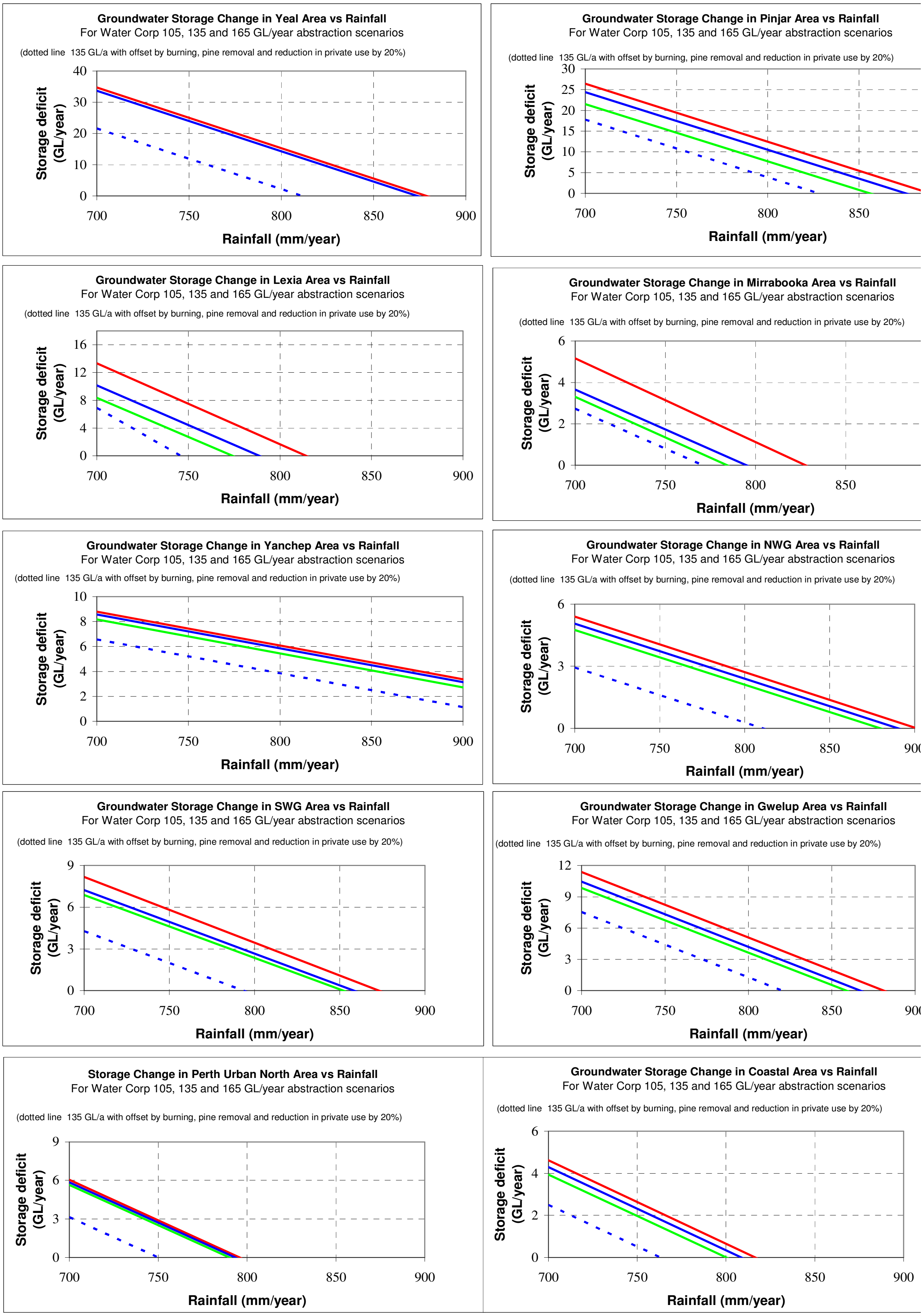


**Figure 21 Storage depletion, rainfall and effects of management options for each subarea (see Fig 20 for legend)**

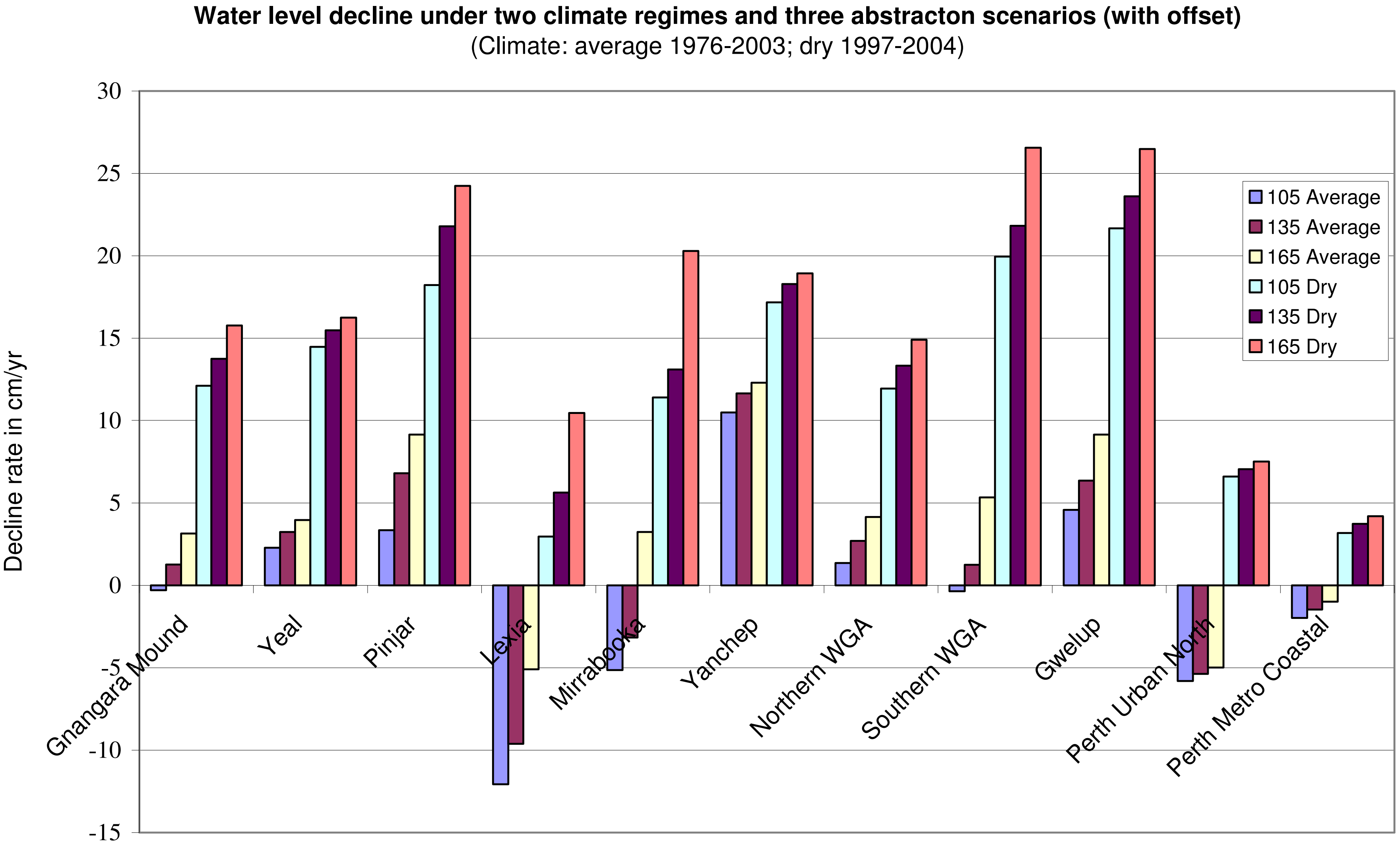


**Figure 22 Water table decline rates after offset**

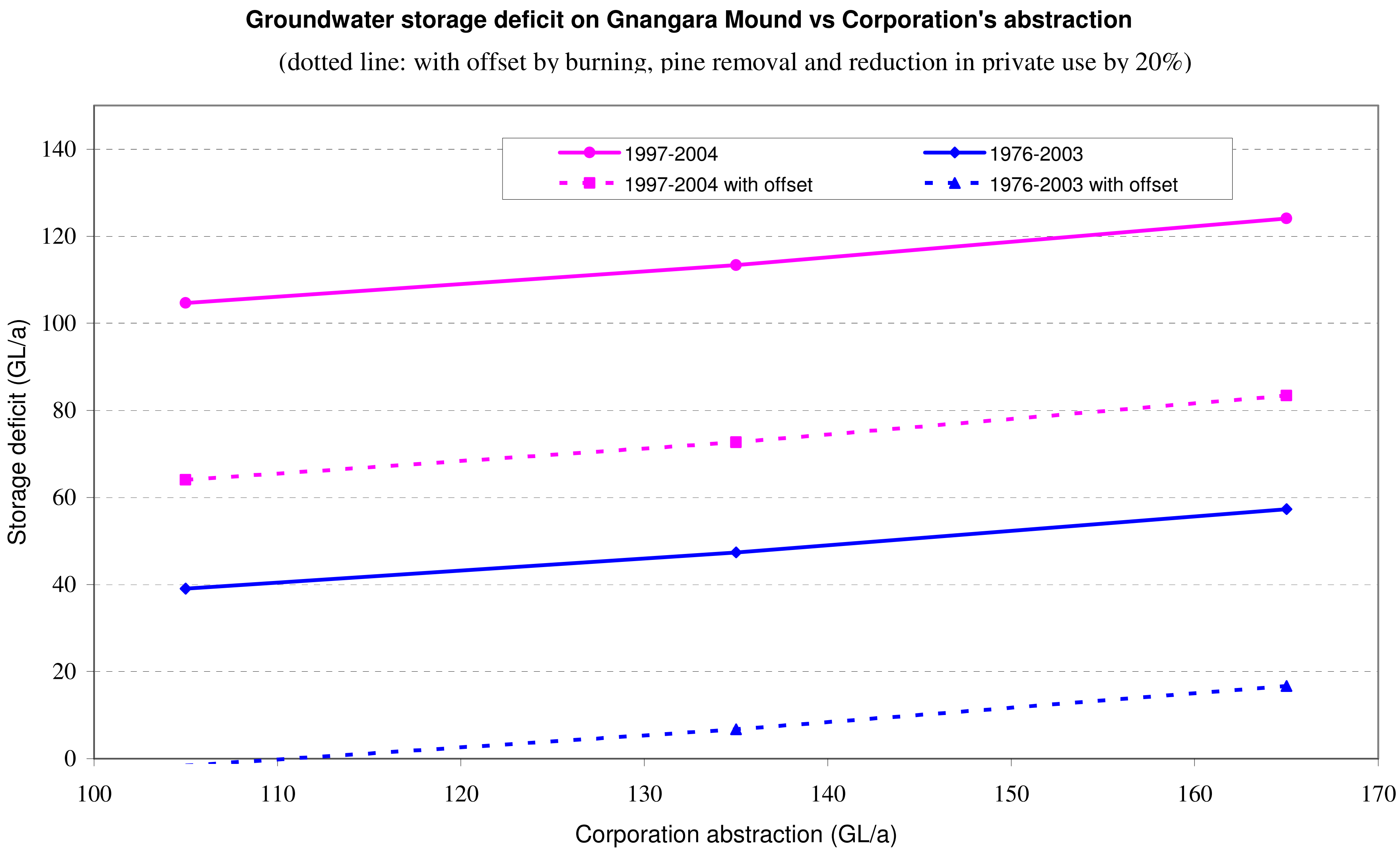


**Figure 23 Storage depletion vs Corporation's abstraction on the Gnangara Mound after implementing management options**

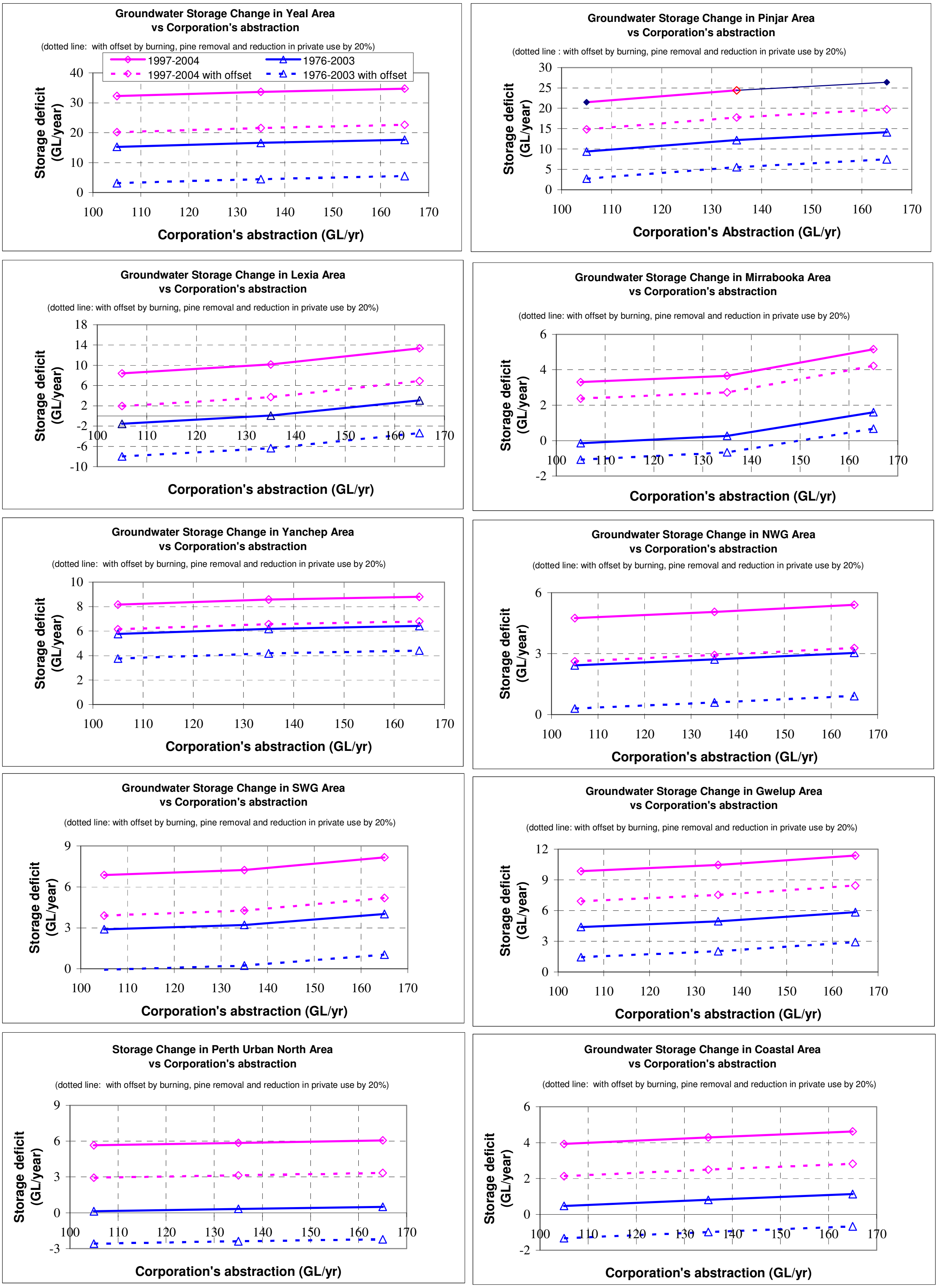


**Figure 24 Storage depletion, vs Corporation abstraction for each subarea after implementing management options**

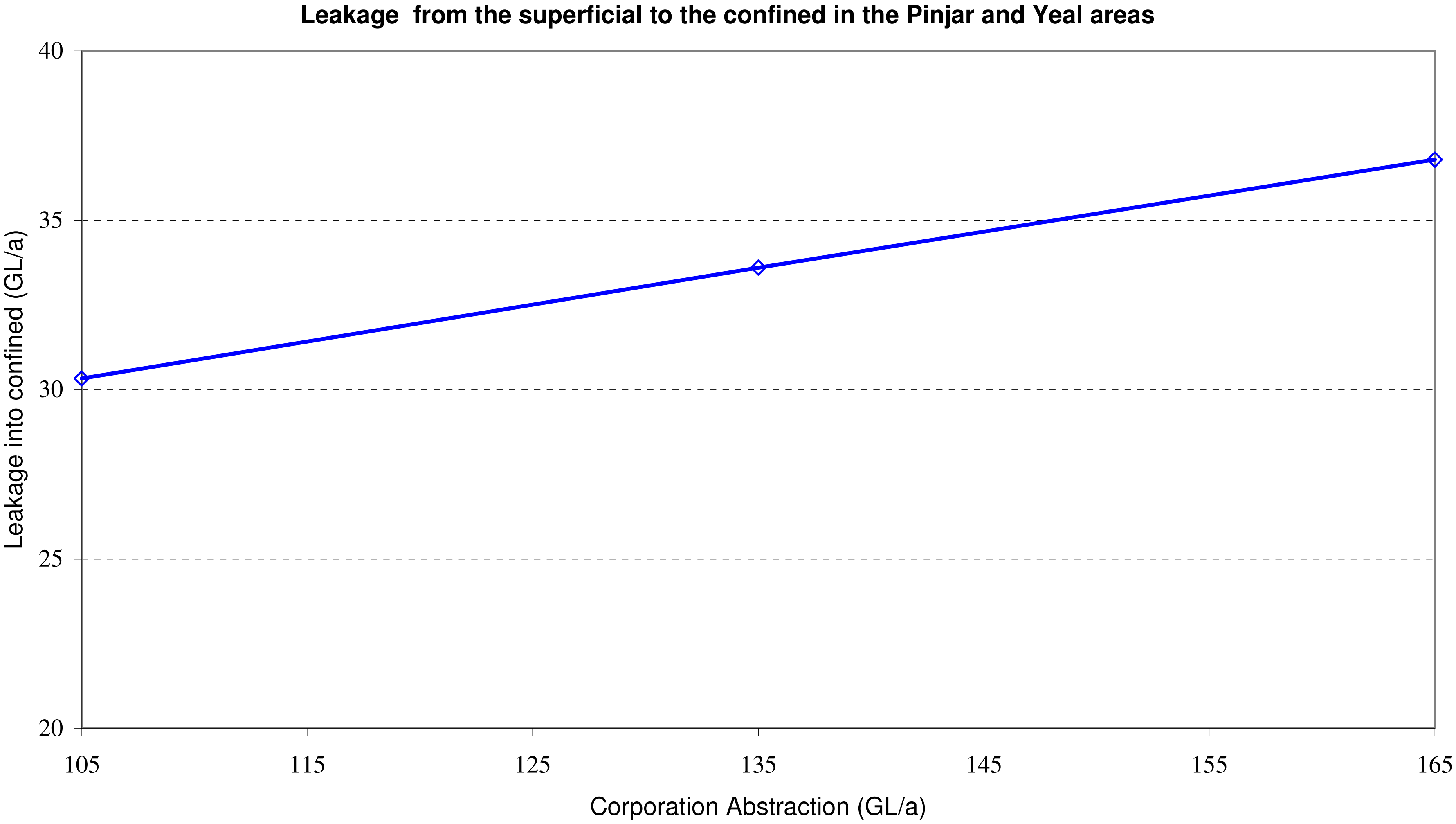


**Figure 25 Leakage into the confined aquifer in the Yeal/Pinjar areas**

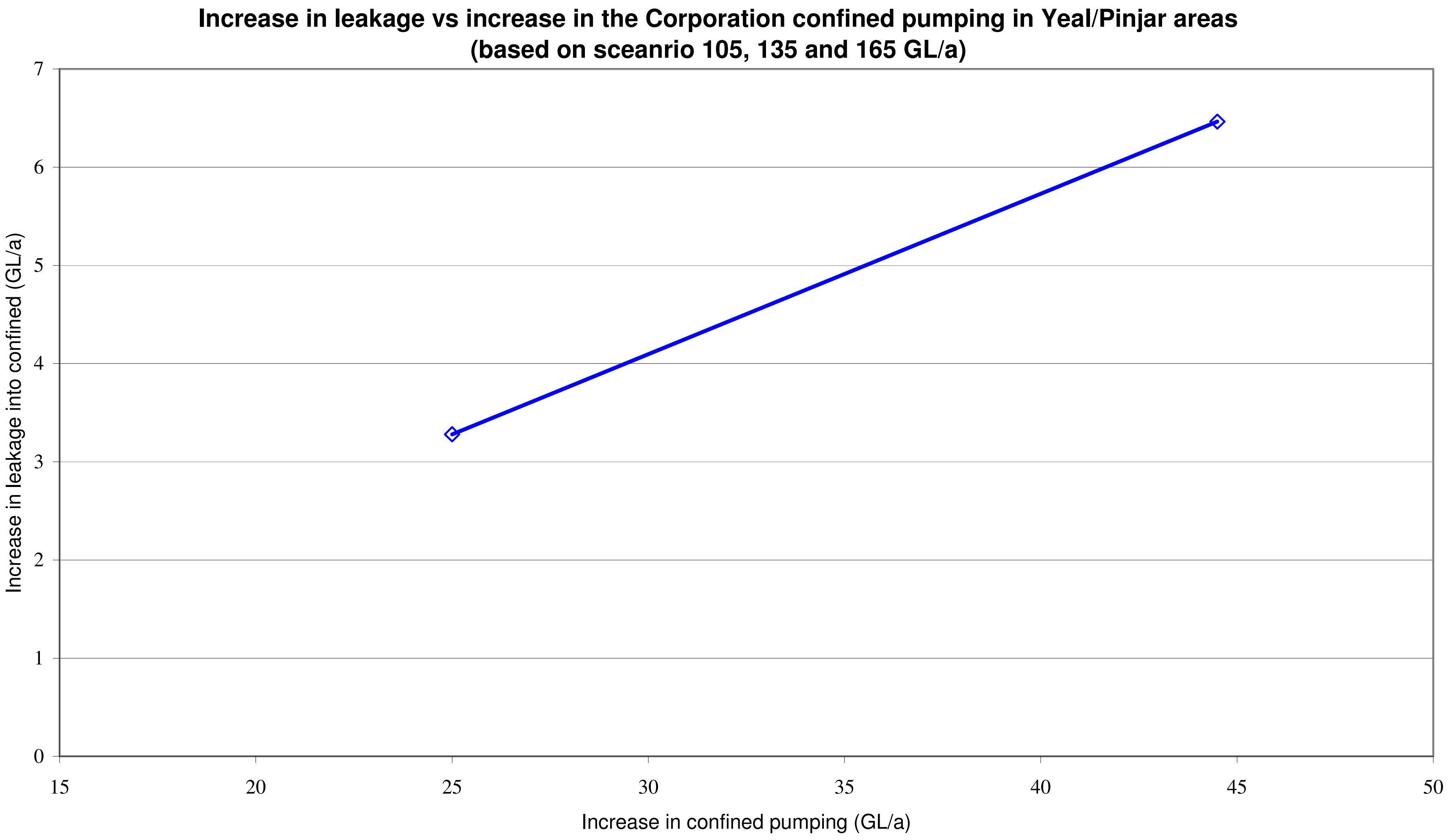


**Figure 26 Additional leakage into the confined aquifers in the Yeal/Pinjar area by increase in confined pumping**

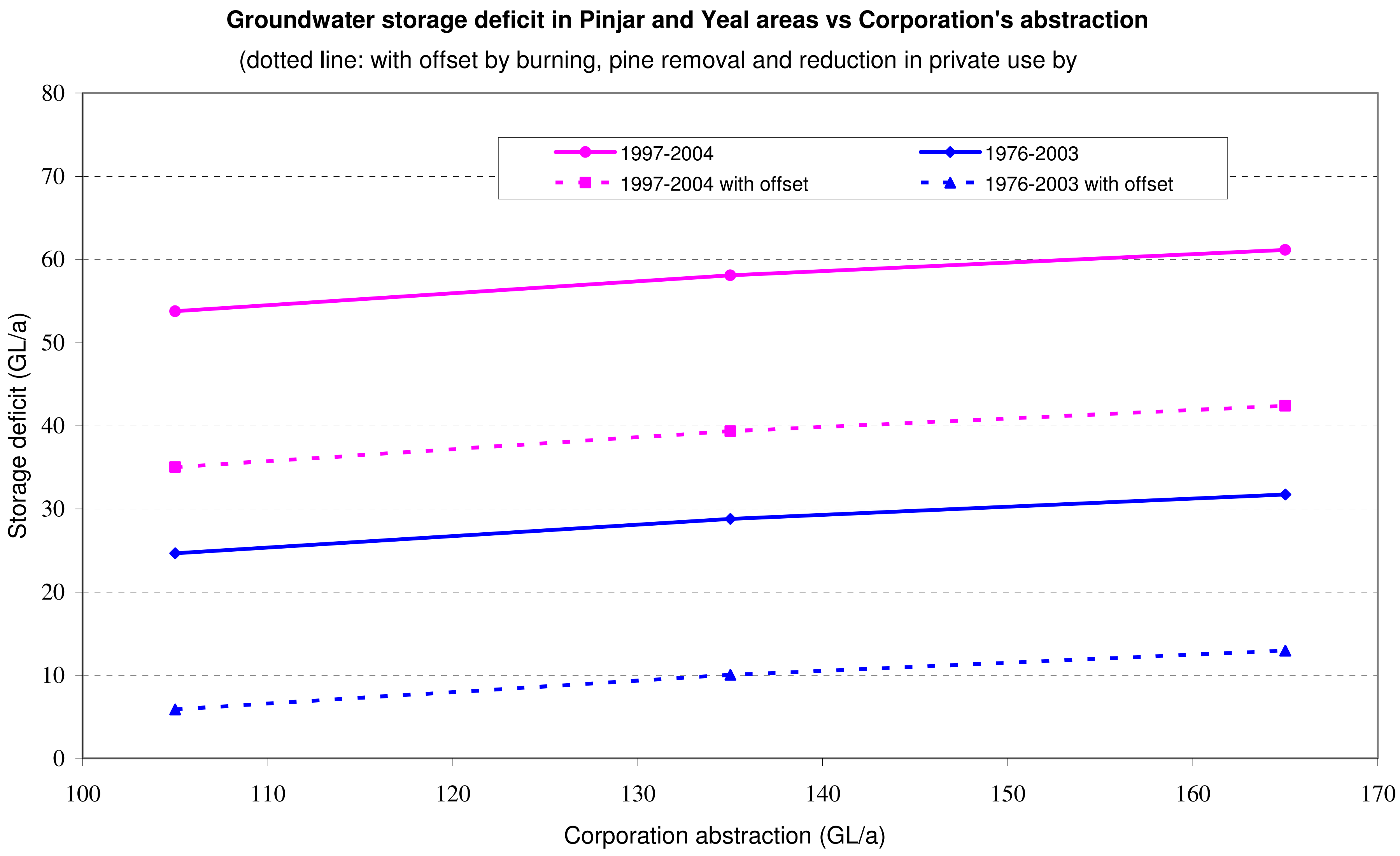


**Figure 27 Storage depletion vs Corporation's abstraction in the Yeal/Pinjar areas**

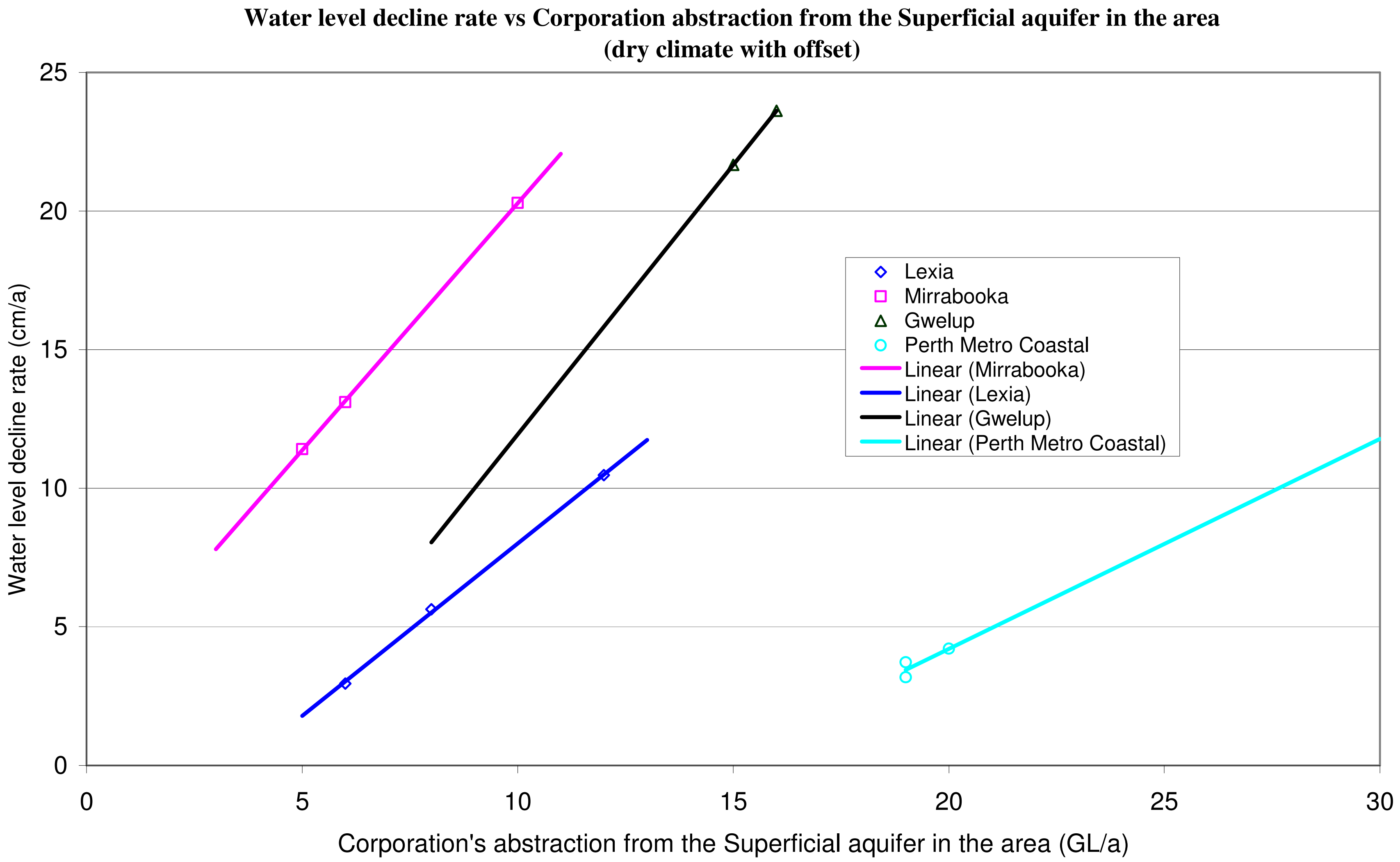


Figure 28 Water level decline vs Corporation abstraction from Superficial aquifer in Lexia, Mirrabooka, Gwelup and Costal scheme

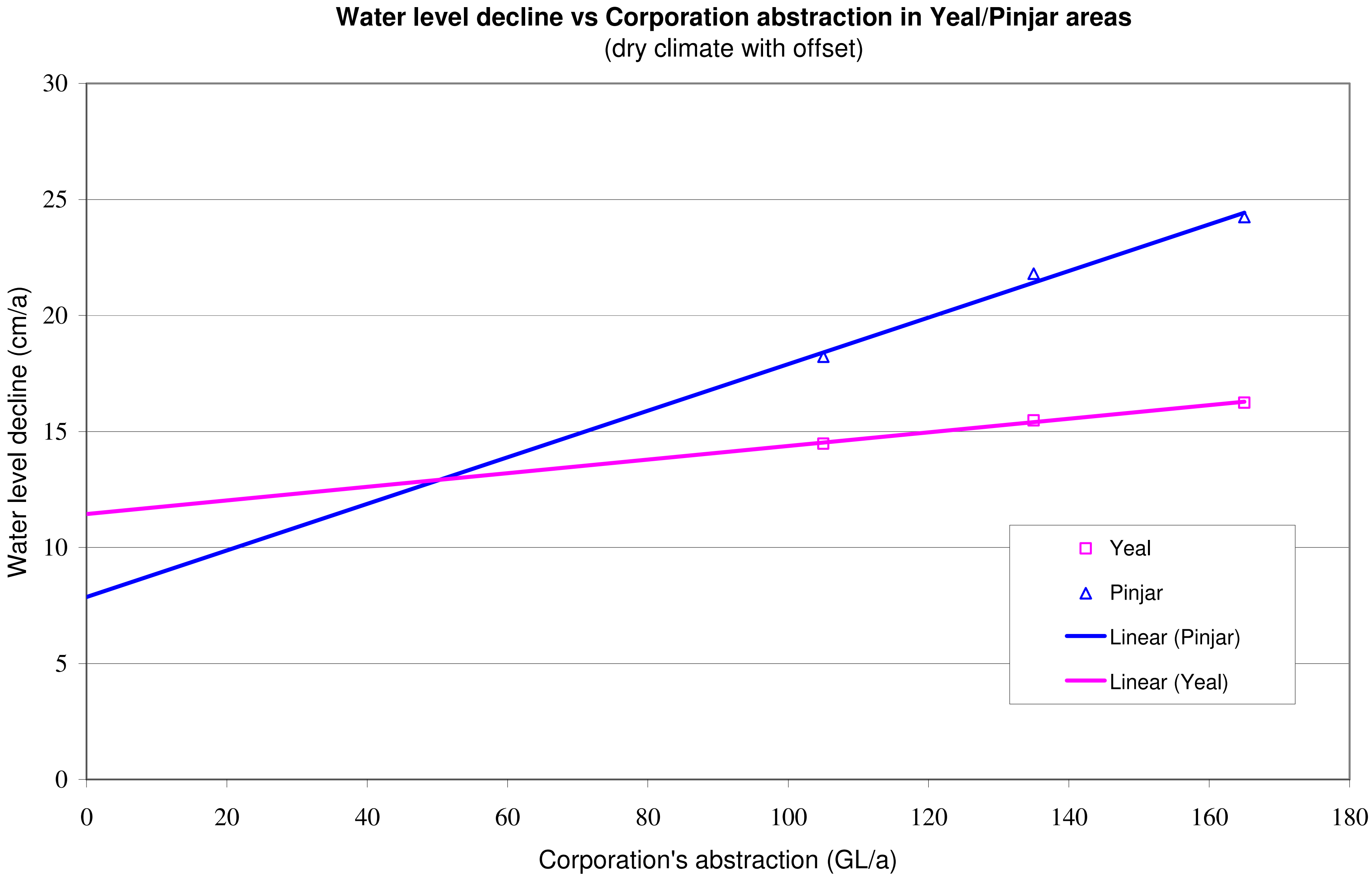


**Figure 29** Water level decline vs Corporation abstraction in Yeal and Pinjar areas