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PRAMS scenario modelling for water management of the Gnangara Groundwater Mound

Looking after all our water needs

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Department of Water

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Contents

Appendices

Figures

Tables

Summary

Change in Gnangara Groundwater Mound groundwater levels is an attenuated response to variations in climate, on which land-use and abstraction impacts are superimposed. Climate variability in the southwest of Western Australia has caused a significant decrease in rainfall, leading to decreasing groundwater recharge, and this is predicted to continue. Coincident with rainfall decline is an increase in groundwater abstraction. To better understand the implications of regional climate variability, different abstraction regimes and land-use change it is desirable to model the range of recorded and likely future water level changes, based on the extent of known and possible future conditions. This will enable us to better understand and manage groundwater abstraction and land-use from an overall systems perspective.

Currently, the Perth Regional Aquifer Modelling System (PRAMS) model is well calibrated for assessing the relative benefit of permutations of individual model components (land-use, abstraction and climate) and absolute predictions for non-wetland parts of Gnangara Groundwater Mound. The model has accurate, reliable water balances and is a powerful tool for looking at the area of influence of an individual component. Watertable difference maps, hydrographs and volumes are generated from model output.

The results presented here are based on scenario modelling undertaken in 2004 using data up to 2003 for the State of the Gnangara Mound (DOE, 2005) report. The report presents results for a limited set of scenarios designed to assist in the development of management tools that aim to mitigate further water level decline. Since 2003, there has been a significant change in abstraction and climate. This study highlights the need for more comprehensive, detailed modelling that includes sensitivity analysis. Such work is currently being addressed by the Gnangara Sustainability Strategy.

The relative impact of abstraction reduction has been modelled and shows the nature and magnitude of expected recoveries from a reduction in private and Water Corporation abstraction. Impacts from Water Corporation abstraction appear to be larger in aerial extent but smaller in magnitude (based on a 135 to 105 GL/yr reduction) than private abstraction impacts. However, the superficial aquifer component of the 30 GL/yr Water Corporation abstraction reduction scenario is 5 GL/yr. A greater reduction in superficial aquifer abstraction may result in a greater impact on water levels.

The Water Corporation has abstracted more than 135 GL/yr since 2001 and future modelling scenarios should incorporate these increases. Based on the limited set of scenarios presented here, climate and land-use appear to have a greater impact on the level of the watertable of Gnangara Groundwater Mound than abstraction, when considering the mound as a whole, but this is reversed in areas where large quantities of groundwater are abstracted.

Land-use changes can increase groundwater recharge (e.g. urbanisation) or decrease recharge (e.g. percentage area of native vegetation burning). Pine plantations can significantly reduce groundwater recharge and hence reduce groundwater levels. The reduction in burning area and burning frequency, of native vegetation over the last 25 years has likely reduced recharge, leading to minor additional watertable declines.

PRAMS 3.0 has determined a threshold for net recharge between 375 and 400 GL/yr for the Gnangara Groundwater Mound which is required to balance the decline in rainfall and the increase in abstraction. If net recharge is below this number then storage declines, and if above this number storage increases. The water balance analysis suggests that net recharge is the dominant factor controlling storage change. Climate, land-use, and to a lesser extent depth to watertable control net recharge. The recharge threshold can be used with PRAMS, to investigate future mitigation options for managing current declines in groundwater storage under various vegetation densities and climatic regimes.

1 Introduction

1.1 Background

The Gnangara Groundwater Mound is the most significant source of groundwater for the Perth region. It supports a variety of horticultural, agricultural, industrial, domestic and recreational needs totalling 487 G/L per year. The mound also sustains numerous groundwater dependent features (many with international recognition) that support a range of social, cultural and environmental values (Clark and Horwitz, 2005; Froend *et al.*, 2004).

Water level criteria were set by the Environmental Protection Agency (EPA) (EPA Bulletin 817, *Ministerial Statement No. 438* – Assessment 697; EPA Bulletin 904, *Ministerial Statement No. 496* – Assessment 932), and then revised under Section 46 of the *Environmental Protection Act 1986* (EP Act) to protect the environmental values of the Gnangara Groundwater Mound, an area of intense groundwater abstraction (Figure 1). Many of these criteria have been breached and change in water level has impacted on groundwater dependent ecosystems (GDEs) (Figure 2) (Water and Rivers Commission, 2004).

Water level criteria were set by the EPA to protect GDEs on the Swan Coastal Plain (Arrowsmith and Carew-Hopkins, 1994). However, climate change is now known to have a greater impact on regional water levels than was previously understood (Figure 3) (Yesertener, 2002, 2003, 2007; Vogwill, 2004). Furthermore, the suitability of some water level criteria is also complicated by the lack of environmental degradation in areas where criteria have been breached (WRC, 2004). The criteria breaches have led the EPA to call for a Section 46 (S46) review of the criteria and criteria system to better incorporate the effect of climate variability on the watertable. This study uses the Perth Regional Aquifer Modelling System (PRAMS) (Davidson and Yu, 2006) to assess the impact of changes, on the watertable, that are possible into the future (20-25 years) under a limited set of different management scenarios.

1.2 Aims and objectives

The overall aim of this modelling study is to determine the relative impacts of land-use, water use and climate variability, on the watertable and storage capacity of the Gnangara Groundwater Mound. Specific objectives are:

- Model the impact of different climate regimes on groundwater recharge;
- Evaluate the effect of different land-use on the watertable;
- Assess the effect of minor reductions in groundwater abstraction on the watertable;
- Compare the relative effects of each of the model components (land-use, climate, and abstraction).

1.3 PRAMS model

PRAMS stands for the **P**erth **R**egional **A**quifer **M**odelling **S**ystem. It has been developed by the Department of Water, and the Water Corporation. Cymod Systems, CSIRO, University of Western Australia, and Townley and Associates were involved in carrying out specific and contractual work in the model development and calibration. The model has been reviewed and approved by University of Technology, Sydney, based on the Murray Darling Basin Commission (2000). Documents about PRAMS development and review are listed below:

- Davidson and Yu (2007) – Hydrogeology and saturated model
- Silberstein *et al*. (2004) – Development of vertical flux model
- Xu *et al*. (2005) – Development and application of vertical flux model
- CyMod Systems (2004) – Construction and model calibration
- Merrick (2006a, 2006b) – Review of the PRAMS model

PRAMS comprises a vertical flux model and a 12-layered saturated groundwater model. A database has been developed that stores maps and data related to geology, topography, hydrogeology, land-use, water uses, monitoring, recharge, evapotranspiration, and boundaries. The maps and attributes were used to generate input datasets for the numerical model.

PRAMS was developed using GMS (Groundwater Modelling System developed by the U.S. Department of Defence, 1997) and PMWIN (Chiang and Kinzelbach, 2000). PRAMSView (Cymod Systems, 2004) has been developed as a pre-processor to provide a link between the database and model.

Figure 1. Lakes and wetlands on the Gnangara Groundwater Mound and Gnangara Mound Zone boundaries.

1.3.1 PRAMS conceptual model

The PRAMS conceptual model is illustrated in Figure 4. The model has twelve layers – seven for aquifers and five confining beds:

Aquifer / confining bed	Model layer
Superficial aquifer	1 - 2
Mirrabooka aquifer /Rockingham Sand	3
Kardinya Shale	4
Leederville aquifer	5 – 7
South Perth Shale	8
Parmelia aquifer	9
Otorowiri Siltstone	10
Yarragadee aquifer	11 – 12

1.3.2 Simulated hydrological processes

PRAMS simulates major hydrological processes and calculates the water balance of the aquifer system. The hydrological processes represented in the model include groundwater recharge from rainfall, evapotranspiration, wetland and drainage interaction with groundwater, and groundwater abstraction. These hydraulic processes are represented by respective modules in MODFLOW after generalisation and simplification of the actual physical processes. Detailed description is given by Davidson and Yu (2004), and CyMod Systems (2004). Below is a summary of the groundwater recharge calculation using VFM.

1.3.2.1 Groundwater recharge – VFM

Groundwater recharge to the superficial aquifer was calculated with a specifically developed Vertical Flux Model (VFM). The VFM provides an interface between the MODFLOW model and a selection of recharge models. The VFM calculates vertical net flux (recharge) to the saturated aquifer, and MODFLOW calculates the regional groundwater flow and other groundwater flow sources and sinks. The VFM model solves vertical flow only for subregions of the MODFLOW model. These subregions consist of Representative Recharge Units (RRUs) covering from one to several thousand MODFLOW cells, that are grouped based on depth to water level, rainfall, land-use, soil and vegetation characteristics (Silberstein *et al*., 2004).

Two MODFLOW packages, RCH (recharge) and EVT (evaporation), have been replaced by the WAVES model for physically based water balance calculation, and empirical equations that correlate land-use with recharge rate. Table 1 lists land-use codes where different recharge models were used.

Table 1 Land-use codes used in PRAMS (modified from Xu *et al*., 2005)

Land-use Code	Description	Comments	VFM Module
1,2,22	Banksia	Leaf area index 0.7-1.2	WAVES
3	Pasture	Leaf area index = 3.0	WAVES
6,7,17,18	Pine – low, medium and high density	Leaf area index 0.5 – 3.5	WAVES
4	Market Garden	0.40 rainfall recharge	Linear
5	Parkland	0.40 rainfall recharge	Linear
9	Urban	0.675 gross recharge, 0.05 EVT	Linear
10	Wetlands	1.2 times monthly rainfall	Piecewise Linear
11	Commercial/industrial	Large sealed area with drainage directed to sumps, 0.70 gross recharge, 0.10 EVT	Linear

1.3.2.2 VFM - WAVES

WAVES is used to calculate recharge for RRUs under pasture, pine plantations, and native bush land. WAVES (Zhang and Dawes, 1998) is a one-dimensional, biophysical process based model that simulates moisture movement in the unsaturated zone between vegetation and the watertable on a daily time-step. It takes into account climate, plants (including vegetation type), extent of plant development, root zone depth, and soil moisture characteristics.

1.3.2.3 VFM - No WAVES

VFM also provides linear algorithms to calculate net recharge to the aquifer for RRUs under market gardens, golf courses, large parks and reserves, and highly urbanised areas where rainfall is infiltrated into the ground through stormwater drains by runoff from impervious surfaces such as houses, roads and parking lots.

The non-WAVES models have a general form as:

$$R = \alpha \times P - \beta \times E$$

where R = net recharge, P = precipitation, E = Pan evaporation, coefficients α and β can be constant (Linear model) or varying with watertable (Piecewise linear model) and are based on a daily time-step [see Barr *et al*., (2003) for details].

The parameters (coefficients for rainfall and pan evaporation) for the non-WAVES recharge model were estimated based on available data but were subjected to fine tuning as part of the calibration of the coupled model (Table 2).

Table 2 Parameters for the non-WAVES recharge model

Land-use Code	Description	VFM module	Rainfall Coef. α	EVT Coef. β	EVT extinction depth (m)
5	Market Garden/Parkland	Linear	0.4	0	n/a
9	Urban Residential	Linear	0.62	0.05	n/a
10	Lakes/Wetlands	Piecewise linear	1.1	0.75	3.0
11	Urban Commercial & Industrial	Linear	0.75	0.05	n/a

The new model with its improved biophysical representation allows a more robust assessment of our understanding of processes controlling recharge. The processes, fluxes and stated variables are more clearly related to measurable quantities in the field and hence may be more easily tested against data. It also gives a more robust tool for assessment of future management scenarios of the groundwater resource. A vertical flux model is integrated into the saturated model for calculating water balance and recharge in the unsaturated zone developed based on WAVES (Zhang and Dawes, 1998). This model simulates the energy and water balances in the unsaturated zone and links with GIS-based recharge units across the area.

1.3.3 Model calibration

The model was set up as a transient model and was calibrated using 10-year data between 1985 and1995. The calibrated model was run for a further 5-year period for validation, using available data from 1996 to 2000. The simulation has 120 stress periods and 6 time-steps within each stress period. Manual and automated calibration methods were used to calibrate the model. The measured hydrographs were compared with model calculated time-series water levels, measured groundwater contour maps were compared with simulated flow patterns, calculated water budgets were checked with measurements and estimates, and the numerical model was confirmed with the conceptual model.

The acceptable rate of calibration, based on the error and trend, is over 90 % for the watertable layer (Layer 1) in the central Perth area (from Gingin Brook to Swan River). The simulated watertable contour matches the measured one satisfactorily. Calibration results for the confined aquifers are also acceptable for the current application.

Sensitivity analysis indicated that recharge and abstraction are sensitive parameters to the model, especially to the superficial aquifers, while vertical hydraulic conductivity is very important to the calibration of the confined aquifers.

The calibration results in potentiometric levels within 3 % of measured levels and are currently being refined.

The calibrated model was run for a further 5-year period (1996 to 2000) for validation by comparing the predicted results with measured data. The validation results indicate that model prediction within the validation period usually follows correct trends, suggesting that the model can be confidently used to run scenarios, although continuing refinement is required. It must be noted however that this is a regional model and most suitable for regional assessment and the results for a particular site must not be over analysed.

1.3.4 Modelling results

The modelling results show that groundwater in the superficial aquifer flows down gradient from recharge areas, away from the crests of Gnangara and Jandakot Mounds and the foothills of the Dandaragan and Darling Plateau. Groundwater flows towards discharge boundaries and areas formed by the major drainages, the ocean, and locally some of the wetlands.

The results indicate that the varying hydraulic conductivities as well as recharge determine the watertable fluctuation, shown in measured and simulated hydrographs. The watertable fluctuates seasonally by about 3 m in areas of clay adjacent to the Darling Fault and Gingin Scarp, by about 1.5 m in the central sandy area, to less than 0.5 m in limestone along the coast. It is typically highest during September/October and lowest during April/May.

In the Leederville aquifer, groundwater flow in the northern area is mainly southwesterly from beneath the Dandaragan Plateau. In the south it flows westerly from the eastern margin of the Swan Coastal Plain. In the central Perth area, the shape of the potentiometric surface has been affected by groundwater abstraction, as shown by the near closures of the 5 m and 10 m potentiometric contours.

Over most of the area, annual fluctuation of water level in the Leederville aquifer is less than 5 m, but in areas of high groundwater abstraction, the variations are commonly more than 10 m.

In the Yarragadee aquifer, groundwater flow is southwesterly. Over wide areas, particularly in the southern area, the gradient on the potentiometric surface is relatively flat, indicating that the rate of groundwater movement is very slow. The potentiometric surface varies by less than 1 m, seasonally. However, in areas of groundwater abstraction from the Yarragadee aquifer, the seasonal variations in potentiometric levels may be up to 7 m. The configuration of the potentiometric surface near Perth is uncertain because of lack of data where the Kings Park Formation occupies a deep channel eroded into the Yarragadee Formation.

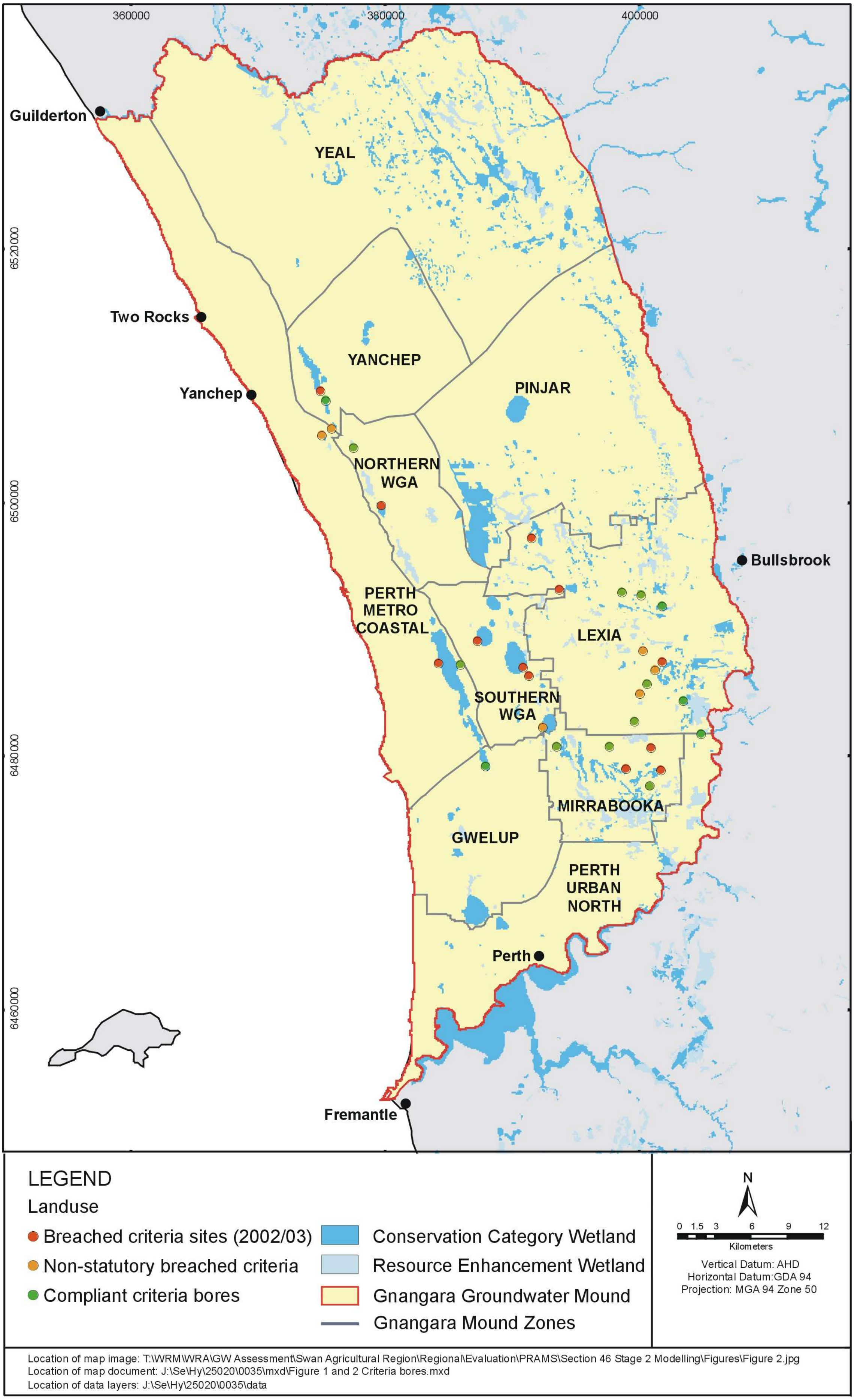

Figure 2. Ministerial criteria breaches on the Gnangara Groundwater Mound in 2003.

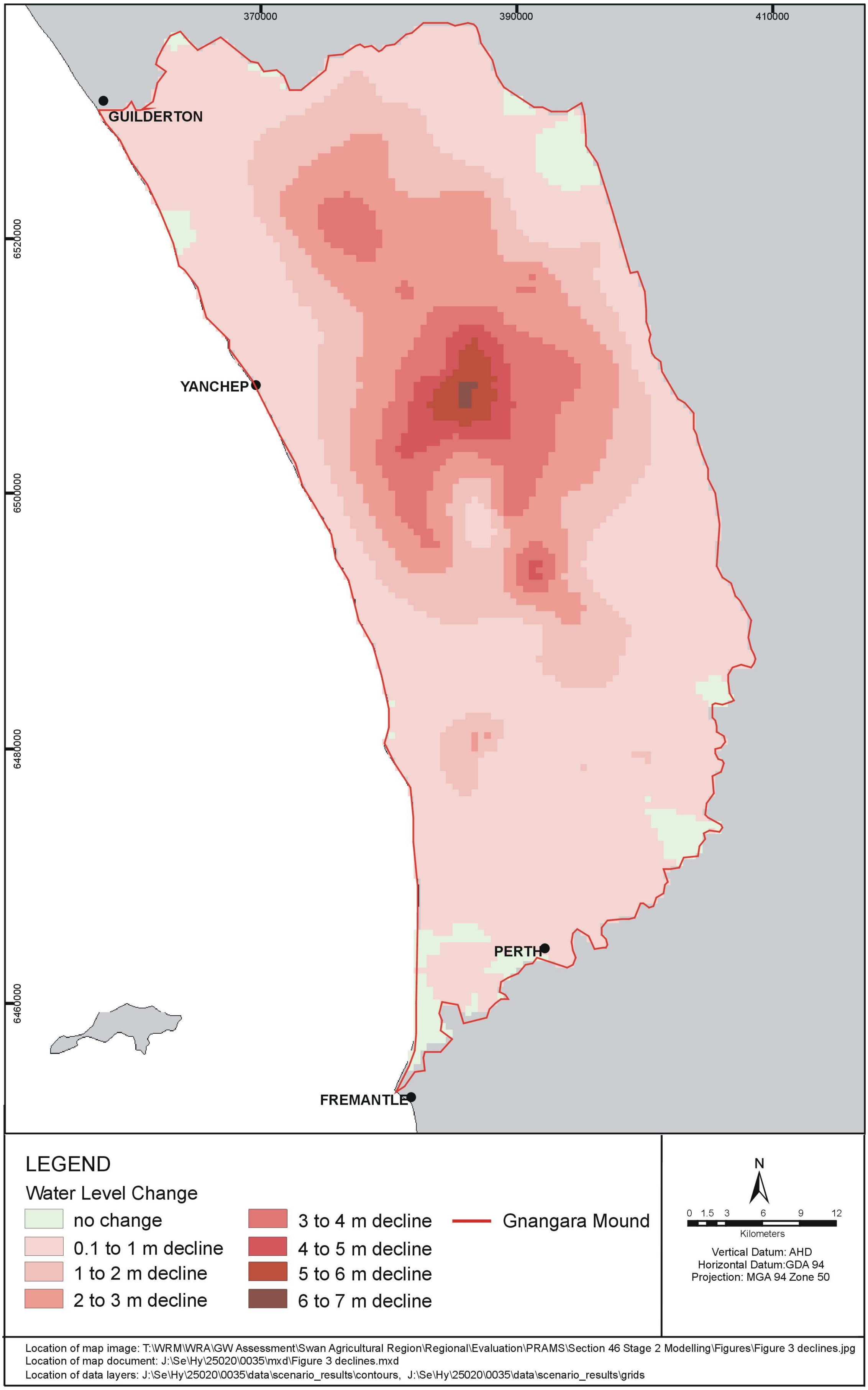

Figure 3. Change between the summer minimum water table in 1979 and the summer minimum water table in 2004.

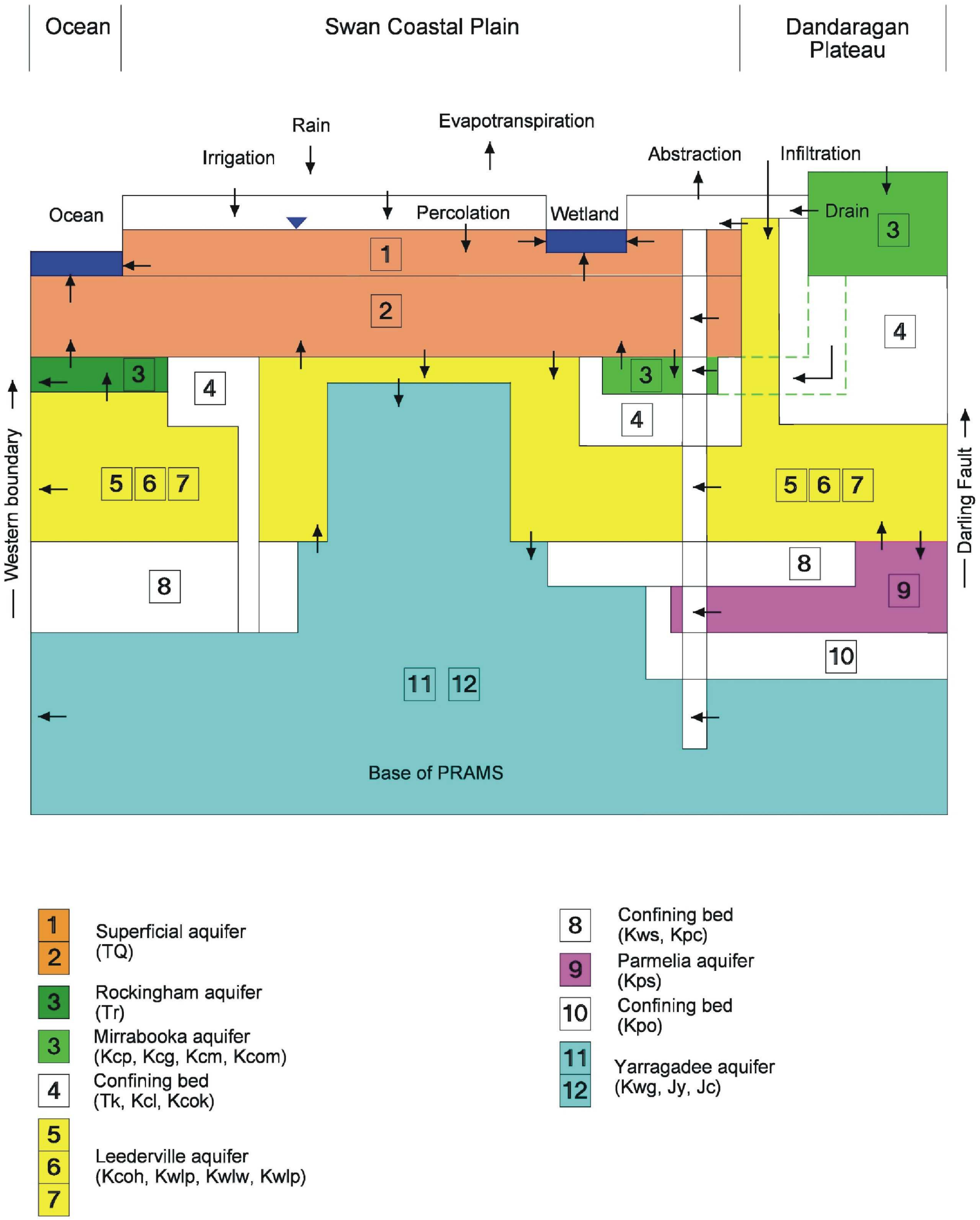

Figure 4. PRAMS conceptual model and design showing hydrological processes in the aquifer system (from Davidson and Yu, 2004).

2 Scenario design

The modelling methodology used to assess various management options for the mitigation of watertable decline is based on running sets of scenarios using PRAMS 3.0 as devised for the State of the Gnangara Mound (DoE, 2005). Each scenario is composed of a range of components and each component is run as an “end” member or solo variation. This facilitates comparison between scenarios and components, and enables determination of the relative impact of altering individual components of the groundwater system. The component scenarios can be recombined to form additional combined scenarios and utilised in future groundwater allocation and planning processes. The components have been varied to look at the absolute watertable changes under the most likely and realistic water and land management scenarios and likely climatic regimes (as determined in 2003). As such, the components have not been varied equally, for example, the reduction in the rainfall component represents a larger decrease in recharge when compared to the reduction in Water Corporation abstraction.

Comparison between scenarios is achieved by showing scenario results relative to a base case. A base case is a groundwater modelling scenario that represents a particular set of conditions. The base case developed for this modelling study is based on the following components:

- Water Corporation abstraction at 135 GL/yr (Water Corporation Abstraction Strategy 2001/2002 approved by the Department of Water which accounts for the back-off strategy to reduce abstraction from 165 to 105 GL);
- Private allocation at 100% of 2002 levels (from the DoW Water Resources Licensing database);
- Climate/rainfall at the medium term (1976 - 2004). A synthetic daily rainfall sequence was constructed from months from different years, where the sum of the monthly totals was close to the 1976 – 2004 median annual rainfall (Water Corporation, 2004).
- Pines removed as per the Forest Products Commission (FPC) Laminated Veneer Lumber (LVL) agreement (*Wood Processing (Wesbeam) Agreement Act 2002*),
- Native vegetation burning at 2.5% of the area of the native vegetation on the Gnangara Groundwater Mound (DEC, 2005). This percentage is similar to current levels of native vegetation burning,
- No additional urbanisation.

From 2001 to 2006, there has been a further decline in average annual rainfall to 693 mm/yr which has necessitated an increase in Water Corporation abstraction to about 165 GL/yr. To account for these changes, an additional scenario that models the impact of Water Corporation abstraction at 165GL/yr has been added to the original scenario matrix (see Table 3).

Table 3 is a summary of the scenarios devised for this modelling study. The results of the modelling are presented in a variety of ways:

- Watertable contour maps, or watertable difference maps, show the difference between the manipulated modelling component (e.g. short-term climate) and the base case. Each map shows change as either a watertable increase (in blue) or a decrease (in red).
- Hydrographs show the predicted changes to the watertable under each scenario at a particular location (i.e. a groundwater monitoring bore).
- Volumetric analysis calculates the change in groundwater storage over a period of time for various zones of the Gnangara Groundwater Mound for different scenarios. This analysis allows the relative impacts of each scenario to be assessed for different areas of the mound.
- Water balance tracks the movement of water through a system and enables a better appreciation of how the groundwater system functions.

It should be noted that the results from combined scenarios would be different to the sum of the component scenarios. New combined scenarios must be re-run with the component input data recombined. It is not sufficient just to add the increases or decreases in the watertable from the component scenarios to give a net watertable change. Further details of the input for the component scenarios follow.

2.1 Climate components

The two main climate inputs that are relevant to the PRAMS modelling are rainfall and evapotranspiration (EVT). Climate is modelled in PRAMS using data from five stations considered representative for the modelled area: the Perth Regional Office (located in Mount Lawley), Perth Airport, Lancelin, Chelsea and Jarrahdale. Three climatic zones are relevant to the Gnangara Mound and are shown in Figure 5.

Annual rainfall at the Perth Regional Office for the last 100 years is given in Figure 6. The long-term average is about 860 mm/yr. However, there is significant variation in rainfall amount and patterns. The ten-year moving average of the rainfall indicates that there is a significant decline in annual rainfall since 1968. Two climate components have been used to evaluate impact of climate on water levels and water balance.

Rainfall sequences were generated by extracting daily rainfall data from a series of months, from different years, where the sum of the monthly totals matches as closely as possible the median annual rainfall for the chosen period. The synthetic rainfall sequence is then repeated for the duration of the model run. Details for setting up the scenarios are given by the Water Corporation (2004).

2.1.1 Medium-term, dry climate (1976-2004)

This climate scenario represents an average and medium-term climate condition for the Perth region. The annual average rainfall at the Perth Regional Office is 788 mm/yr.

2.1.2 Short-term, very dry climate (1996-2004)

This climate scenario represents the dry climate condition in recent years. The annual average rainfall at the Perth Regional Office is 696 mm/yr.

Table 3 Modelling components and scenario summary

		Modelling Components									
		Climate		Abstraction				Land-use			
Scenario Number	**Scenario Name**	Medium-term, dry climate (1976-2004)	Short-term, very dry climate (1996-2004)	Water Corporation abstraction at 135 GL/yr	Water Corporation abstraction at 105 GL/yr	Private abstraction at 100% of 2002 allocation	Private abstraction at 80% of 2002 allocation	Pine plantation removal as per LVL agreement	Pine plantation removal as immediate clear-fell	Current % area of native vegetation burning – 2.5%	Increased % area of native vegetation burning – 7.5%
1	Base case	X		X		X		X		X	
2	Short-term, very dry climate		X	X		X		X		X	
3	Water Corporation abstraction reduction	X			X	X		X		X	
4	Private abstraction reduction	X		X			X	X		X	
5	Pine removal	X		X		X			X	X	
6	Increase % area of native vegetation burning	X		X		X		X			X

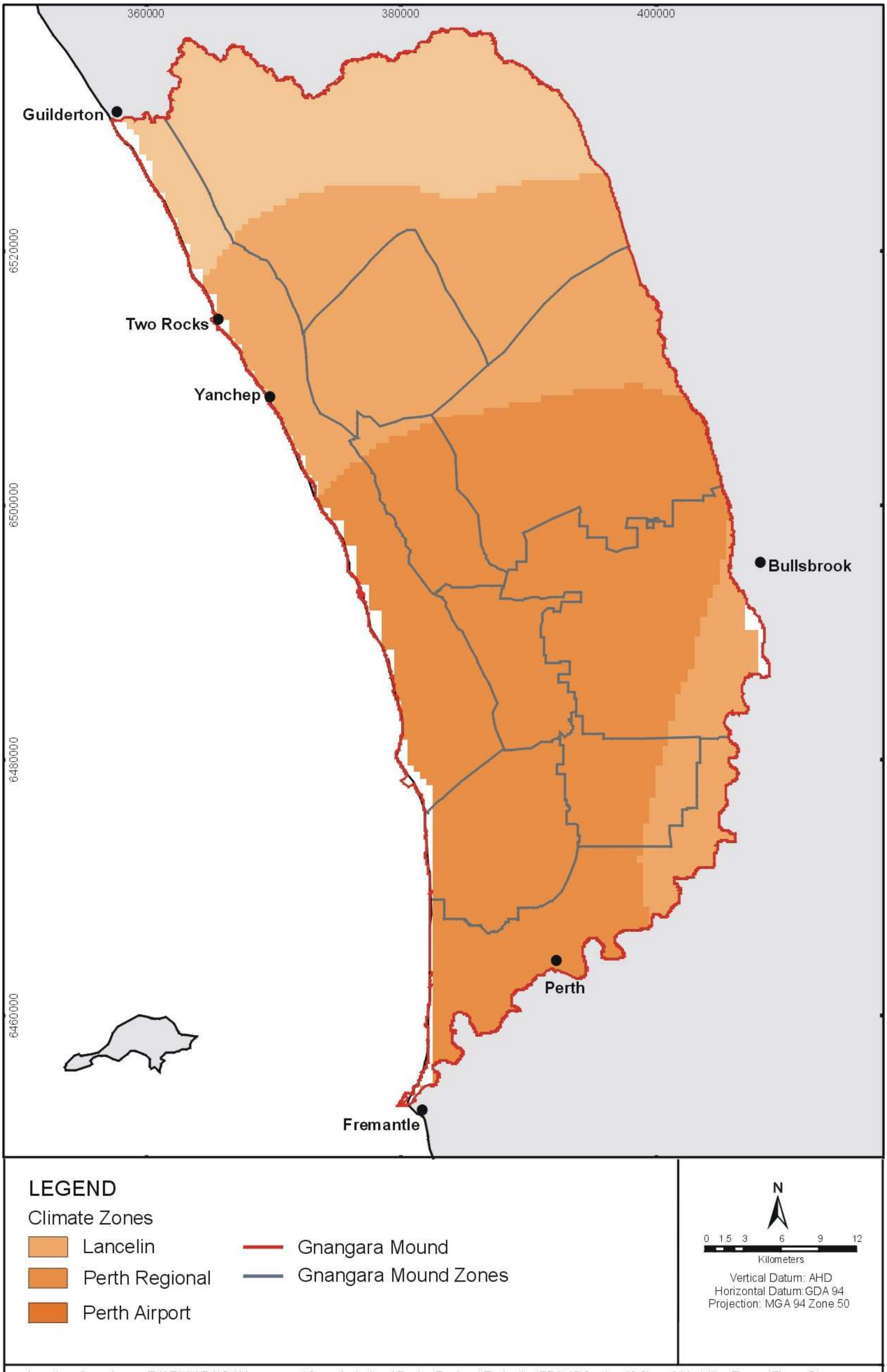

Figure 5. Climate zones used in PRAMS for the Gnangara Groundwater Mound.

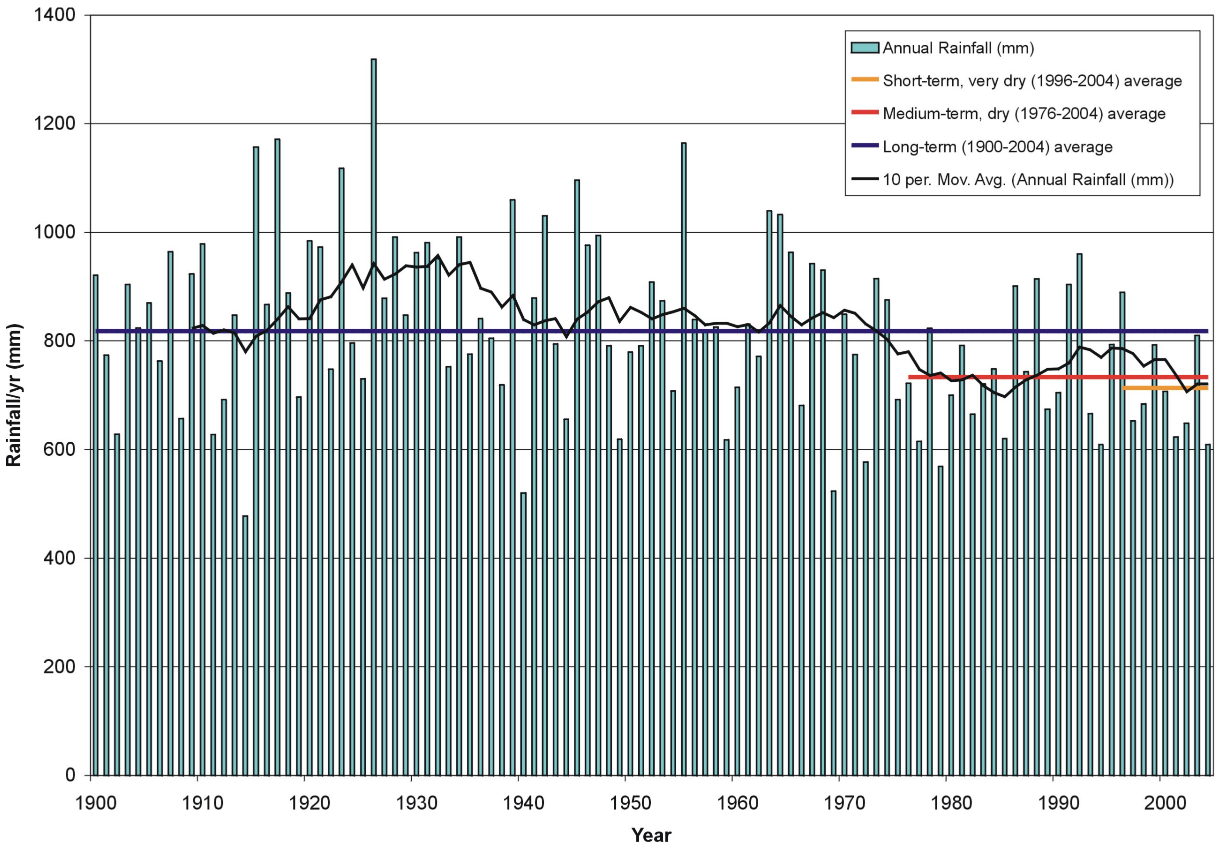

Figure 6. Annual rainfall for the Perth Regional Office , 1900 to 2004

PRAMS uses daily data from five climate stations (Table 4) and requires the following meteorological parameters (Xu *et al.,* 2005). Complete statistical details of the climate zones are in Xu *et al.,* 2005.

1. Total Daily Solar Radiation
2. Maximum Daily Temperature
3. Minimum Daily Temperature
4. Mean Daily Vapour Pressure Deficit (VPD)
5. Total Daily Precipitation

Table 4 Climate Stations used in PRAMS

Station Name	BoM Station Number	Easting	Northing	Average 1978-2002
Chelsea	9006	382913	6611110	477.7
Lancelin	9114	340595	6566985	623.8
Perth Airport	9021	403580	6466870	739.0
Perth Regional Office	9034	392892	6464545	793.1
Jarrahdale	9023	410956	6422503	1067.1

2.2 Abstraction components

Abstraction is a significant component of the water balance in PRAMS. There are three types of groundwater abstraction: Water Corporation abstraction for the public water supply, private licensed abstraction, and unlicensed abstraction for home gardens. In 2002, these three components accounted for 150 GL/yr, 224 GL/yr and approximately 105 GL/yr of abstraction respectively, from the Perth Metropolitan area (Mandurah to Gingin Brook). Water Corporation abstraction and private licensed supply dominate groundwater abstraction, particularly in the areas of greatest watertable decline and hence are the focus of the abstraction modelling.

2.2.1 Water Corporation abstraction (135 GL/yr)

The base case models public abstraction by the Water Corporation at 135 GL/yr, which is the mean of the current allocation range. Table 5 shows the distribution of this abstraction by aquifer and borefield, and Figure 7 shows the location of the borefields on Gnangara Groundwater Mound. Metered data is used and represented in the Well Package in PRAMS.

2.2.2 Water Corporation abstraction (105 GL/yr)

To assess the sensitivity of the watertable to a reduction in groundwater abstraction by the Water Corporation, the public abstraction component is reduced from the 135 GL/yr (base case) to 105 GL/yr. Abstraction is reduced from the superficial aquifer by 2GL/yr in the Wanneroo and Pinjar borefields and by 1 GL/yr in the Mirrabooka. Leederville aquifer abstraction is reduced by 3.6 GL/yr in the Mirrabooka borefield, 4 GL/yr in the Wanneroo and 0.4 GL/yr in the Pinjar borefield. Yarragadee abstraction is reduced by 10 GL/yr in the Wanneroo, 5.9 GL/yr in the Independent Artesian and 1.1 GL/yr in the Pinjar borefields (Table 6, Figure 8).

2.2.3 Private abstraction (licensed self supply)

In 2002, it is estimated that a total of 224 GL/yr of groundwater was extracted from the superficial and three confined aquifers (Davidson and Yu, 2004). Two components have been designed to look at the impact of private abstraction on groundwater levels.

- Private abstraction at 100% of 2002 allocation.
- Private abstraction at 80% of 2002 allocation.

Licensed private abstraction is based on the licensed entitlement as stored in the DoW WRL database. Each abstraction bore is represented in the PRAMS Well Package. The monthly abstraction figure is derived using a scaling coefficient to reflect water use seasonality (Davidson and Yu, 2004).

2.2.4 Unlicensed abstraction

There are an estimated 135 000 unlicensed garden bores across the Perth Metropolitan area, that use around 100 GL/yr. This abstraction is represented in each model scenario as a density distribution and is held constant for this modelling study.

Table 5 Abstraction by borefield and aquifer (GL/yr) (Water Corporation abstraction at 135 GL/yr) (from Water Corporation Abstraction Strategy 2001/2002)

Borefield	Superficial	Mirrabooka	Leederville	Yarragadee	Total
Gwelup	7.45	3.75	7.80	0.00	19.00
Independent Artesian	0.00	0.00	0.00	36.00	36.00
Jandakot	3.90	0.00	2.10	0.00	6.00
Lexia	3.90	0.10	0.00	0.00	4.00
Mirrabooka	9.62	0.28	7.10	0.00	17.00
Neerabup	19.50	0.00	8.50	2.00	30.00
Pinjar	2.00	0.00	0.40	1.10	3.50
Ravenswood	1.00	0.00	0.00	0.00	1.00
Two Rocks	0.50	0.00	0.00	0.00	0.50
Wanneroo	4.50	0.00	4.00	10.00	18.50
Yanchep	0.50	0.00	0.00	0.00	0.50
Total	52.87	4.13	29.90	49.10	136.00

Table 6 Abstraction by borefield and aquifer (GL/yr) (Water Corporation abstraction at 105 GL/yr) (from Water Corporation Abstraction Strategy 2001/2002)

Borefield	Superficial	Mirrabooka	Leederville	Yarragadee	Total
Gwelup	7.45	3.75	7.80	0.00	19.00
Independent Artesian	0.00	0.00	0.00	30.10	30.10
Jandakot	3.90	0.00	2.10	0.00	6.00
Lexia	3.90	0.10	0.00	0.00	4.00
Mirrabooka	8.62	0.28	3.50	0.00	12.40
Neerabup	19.50	0.00	8.50	2.00	30.00
Pinjar	0.00	0.00	0.00	0.00	0.00
Ravenswood	1.00	0.00	0.00	0.00	1.00
Two Rocks	0.50	0.00	0.00	0.00	0.50
Wanneroo	2.50	0.00	0.00	0.00	2.50
Yanchep	0.50	0.00	0.00	0.00	0.50
Total	47.87	4.13	21.90	32.10	106.00

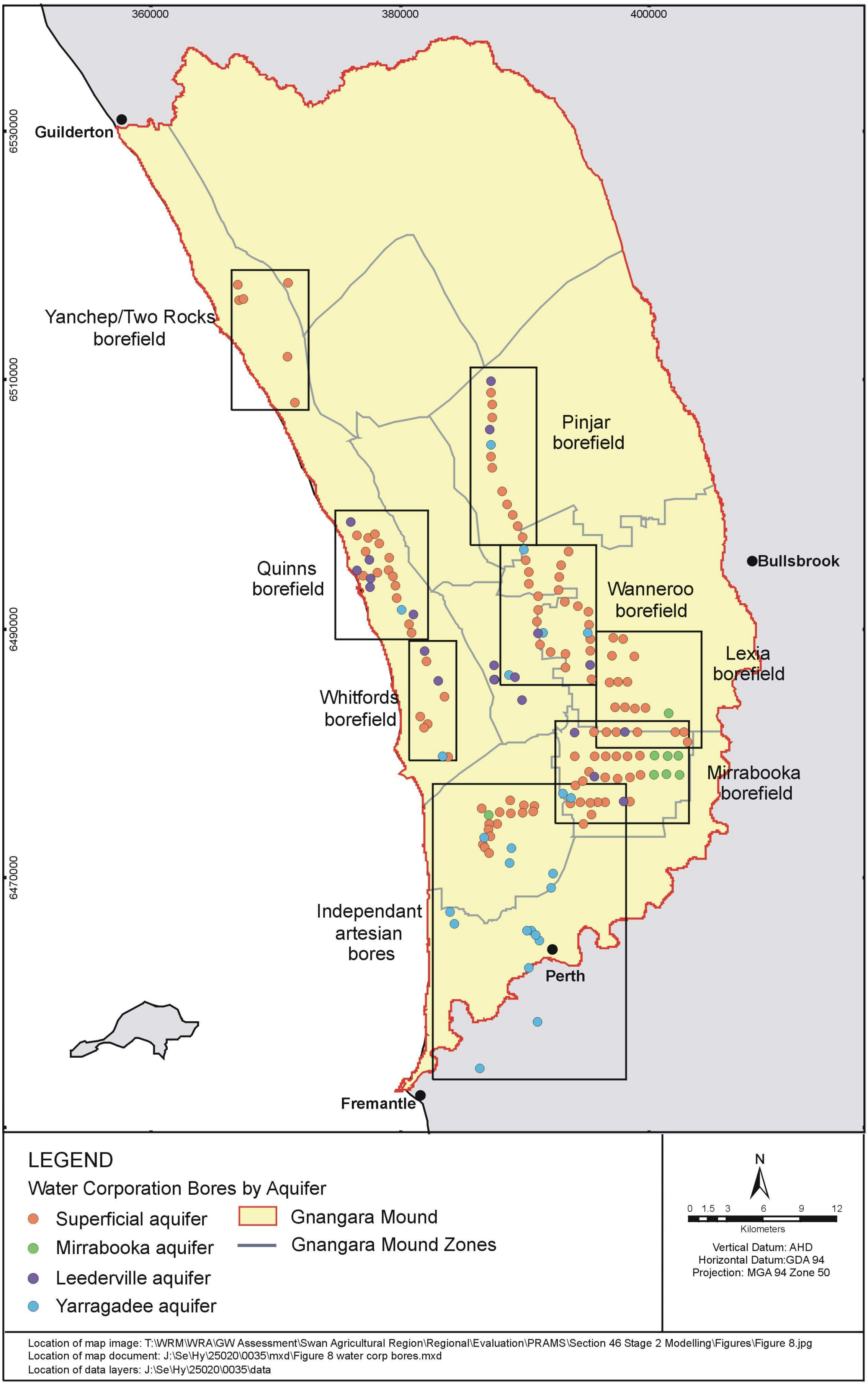

Figure 7. Distribution of Water Corporation borefields on the Gnangara Groundwater Mound, shown by aquifer.

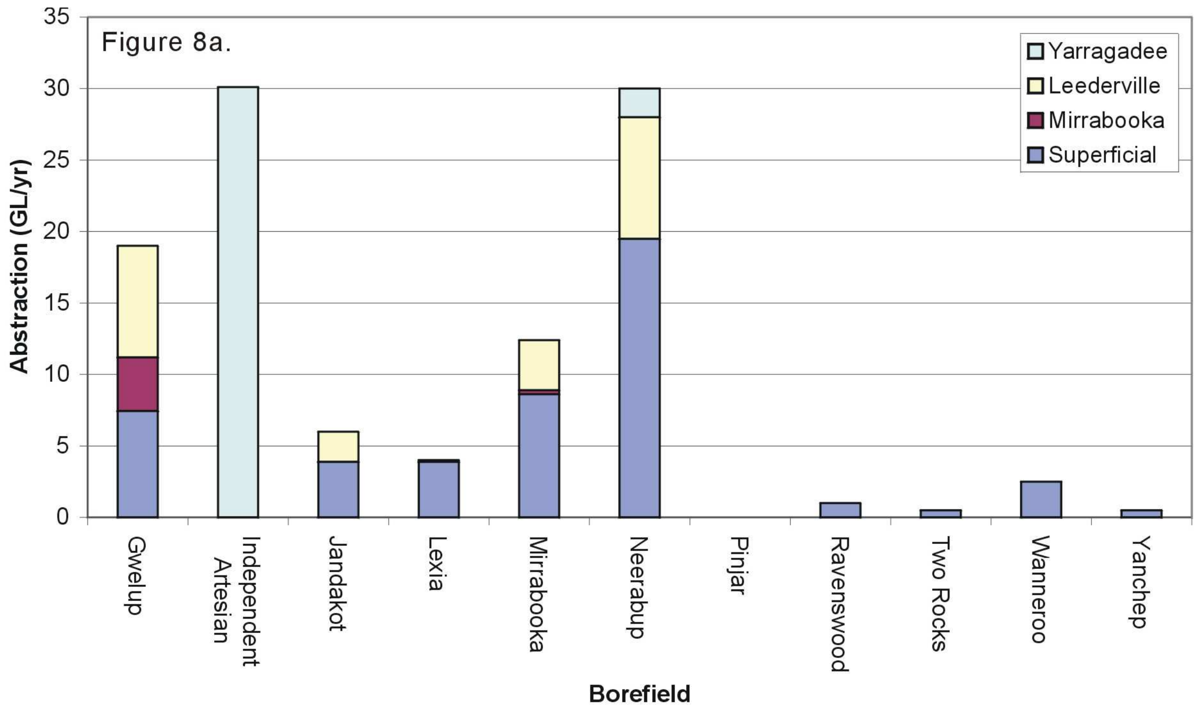

Figure 8a. Water Corporation abstraction modelling component showing abstraction by borefield and aquifer for 135 GL/yr component used in the base case.

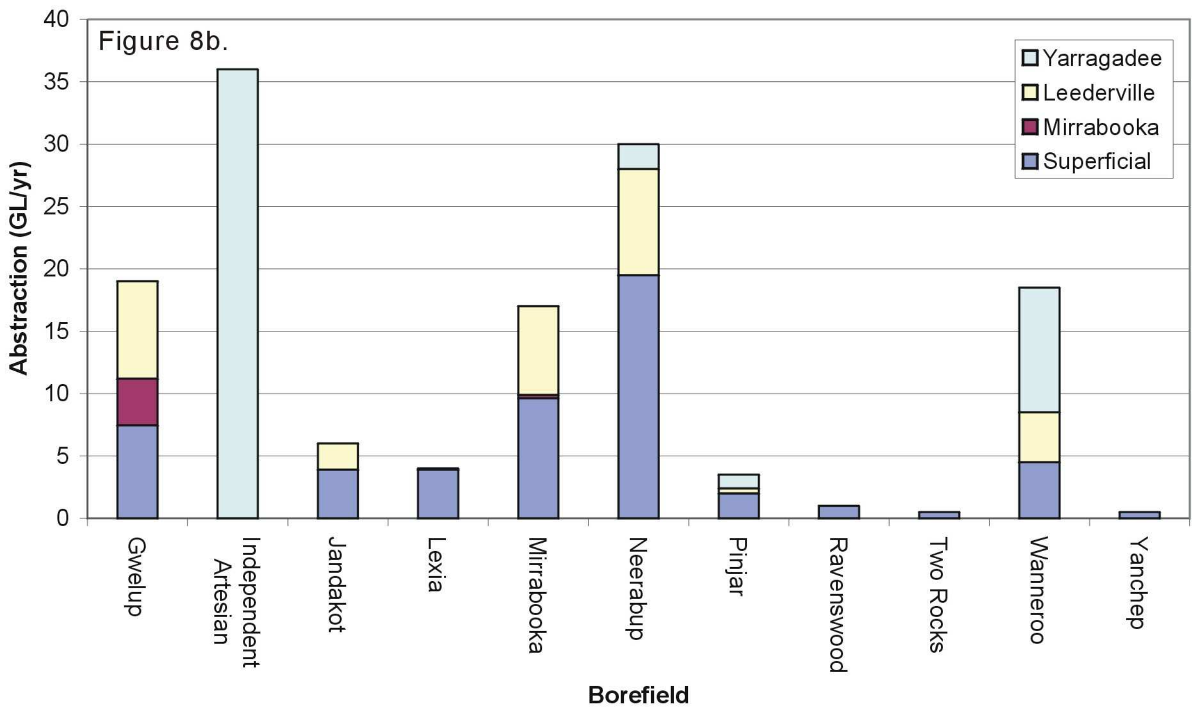

Figure 8b. Water Corporation abstraction modelling component showing abstraction by borefield and aquifer for 105 GL/yr used in Scenario 3.

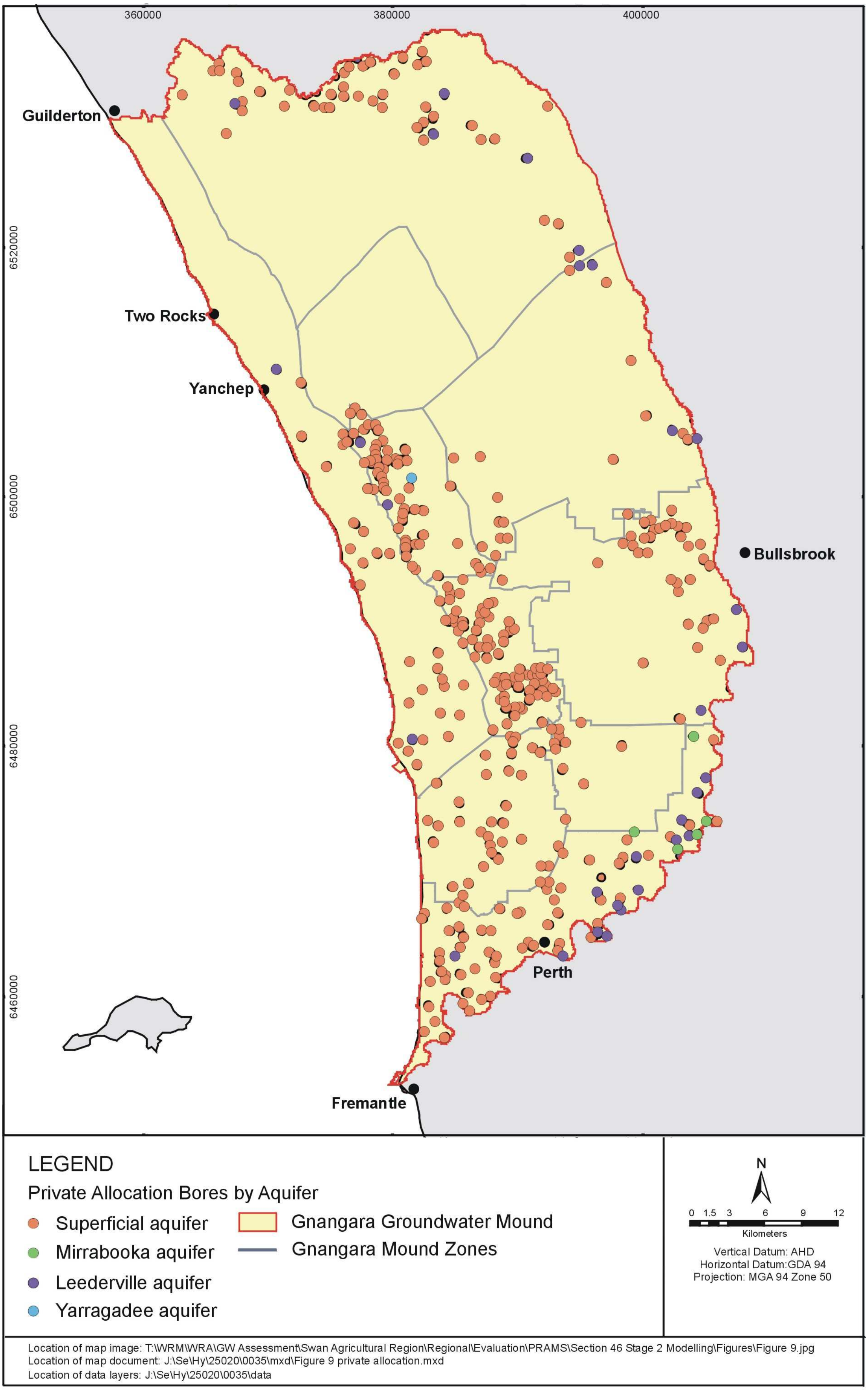

Figure 9. Private allocation (licensed self supply) bores greater than 50 000 kL/yr.

2.3 Land-use components

There are 14 land-use types used in PRAMS 3.0 (Table 7 and Figure 10). Groundwater recharge under different land-use types is modelled by the VFM (Vertical Flux Model, see Section 1.3.2.1) and each is assigned a recharge conversion factor. The recharge conversion factors are the multiplication figures applied to the rainfall and pan evaporation rates and are derived from WAVES (Zhang and Dawes, 1998; Barr *et al.*, 2002). Where it is not appropriate to use WAVES to estimate recharge conversion factors (e.g. land-use types that are not well represented by the biophysical assumptions in WAVES) constant coefficients are used (Xu *et al.,* 2005).

Table 7 PRAMS 3.0 land-use types

		Recharge conversion factors	
VFM ID #	**Land-use Type**	**Rainfall**	**EVT/Pan Evaporation**
1	Banksia - high density	WAVES	WAVES
2	Banksia - medium density	WAVES	WAVES
2	Banksia - low density	WAVES	WAVES
3	Pasture	WAVES	WAVES
4	Market Gardens	0.4	0
5	Parkland	0.4	0
6	Pines - high density	WAVES	WAVES
17	Pines - high/medium density	WAVES	WAVES
7	Pines - medium density	WAVES	WAVES
18	Pines - low/medium density	WAVES	WAVES
8	Pines - low density	WAVES	WAVES
9	Urban	0.625	0.05
10	Lakes	1.1	0.75
11	Commercial/Industrial	0.70	0.05

2.3.1 Pine plantation removal

The Water Corporation, FPC and CSIRO have studied the relationship between groundwater recharge and pine tree density and distribution, as part of the VFM development. The relationship between LAI (leaf area index) and basal area of pine plantations and the relationship between percentage of groundwater recharge and depth to watertable is defined in Yu (2002).

Two pines components are used in this PRAMS 3.0 modelling assessment:

- Pine plantation thinned as per LVL agreement: the pine plantations will be thinned as per the current preliminary LVL agreement as defined in *Wood Processing (Wesbeam) Agreement Act 2002*. This component is used in the base case.
- Total immediate clear-felling of pine plantation: all pines are instantaneously removed and replaced with low-density native vegetation.

It is also assumed that clear-felled areas are maintained as low-density native vegetation throughout the duration of the simulations.

2.3.2 Increased % area of native vegetation burning (*Banksia* woodland)

There are two native vegetation components used in the modelling design based on the frequency of burning and expressed as a percentage of the area of native vegetation:

- Current percentage area of native vegetation burning (2.5%). The base case scenario models average annual percentage of burning 2.5% of the native vegetation area. This is similar to the present levels of native vegetation burning.
- Increased percentage area of native vegetation burning (7.5%). This scenario represents an increase in the frequency of burning and is at upper end of the range experienced in the last 25 years.

The current frequency of burning on Gnangara Groundwater Mound is believed to be a distinct decrease from the pre-1980 frequency, when there were more frequent, higher temperature, wildfire-style burns, and a significant decrease from the pre-European frequency of a burn every 2-4 years by the Indigenous population (Ward *et al*., 2004). This apparent decrease in native vegetation burning frequency is a possible, partial cause of existing watertable declines particularly in the Yeal, Yanchep and Pinjar zones (see Figure 3). The temporal distribution of both DEC controlled burns and wildfires is given in Appendix 1 and is summarised as percentage of the Gnangara Groundwater Mound in Table 8 and Figure 11.

The algorithm used to quantify and model changes in burning regimes is summarised below and the resulting land-use grids are given in Appendix 1:

- "Burning" of cells converts native vegetation cells from high to low density, or medium to low density.
- After 5 years a cell "grows" a *Banksia* category, i.e. every 5 years cells will increase in density, hence a low density cell will take 10 years to become a high density cell.
- High density cells are "burnt" first, followed by medium density cells, in an attempt to mimic DEC burning regimes.

The ArcInfo script created for this manipulation is given in Appendix 1.

The result of this modelling approach is a dynamic native vegetation density that can be varied to allow for changes in the burning regime. This approach is a simplification of natural processes, however without a detailed research program this is considered an acceptable simplification to assess the sensitivity of the model to variations in vegetation density and the percentage area of native vegetation that is burnt.

Table 8. Annual variations in the percentage of pine and native vegetation areas burned by wildfires and prescribed burns, and the total area of Gnangara Groundwater Mound that is burned.

	Wildfire Burns		**Prescribed Burns**		**Total % of the Gnangara Mound Burned**
Year	% of Pines Burned	% of *Banksia* Burned	% of Pines Burned	% of *Banksia* Burned	
1979-80	0.2	2.9	4.6	10.7	9.1
1980-81	1.4	0.2	6.0	3.3	3.2
1981-82	0.4	3.5	5.5	2.3	4.1
1982-83	0.0	0.1	6.6	3.3	3.1
1983-84	0.1	0.0	4.0	1.8	1.6
1984-85	0.0	0.1	5.7	3.2	2.7
1985-86	1.6	11.3	10.3	2.6	9.5
1986-87	0.4	0.0	17.4	0.7	2.7
1987-88	0.1	0.0	4.6	1.5	1.6
1988-89	0.1	0.7	9.1	0.7	2.2
1989-90	No Data	No Data	No Data	No Data	No Data
1990-91	11.0	8.5	0.4	0.0	6.8
1991-92	0.3	0.8	11.3	1.9	3.0
1992-93	26.8	4.1	No Data	No Data	6.2
1993-94	11.7	1.8	No Data	No Data	2.6
1994-95	14.9	12.7	0.2	No Data	9.8
1995-96	26.7	0.0	26.7	4.7	6.3
1996-97	0.0	0.0	24.3	2.9	4.8
1997-98	0.8	0.1	17.4	2.2	3.8
1998-99	0.2	0.0	21.0	1.9	4.0
1999-00	0.3	0.1	20.4	1.7	3.9
2000-01	0.3	1.2	28.8	1.3	5.6
2001-02	0.0	0.5	31.7	2.7	6.1
2002-03	22.1	5.7	22.1	0.8	7.0
Av	5.2	2.4	13.2	2.5	4.8
Min	0.0	0.0	0.2	0.0	1.6
Max	26.8	12.7	31.7	10.7	9.8

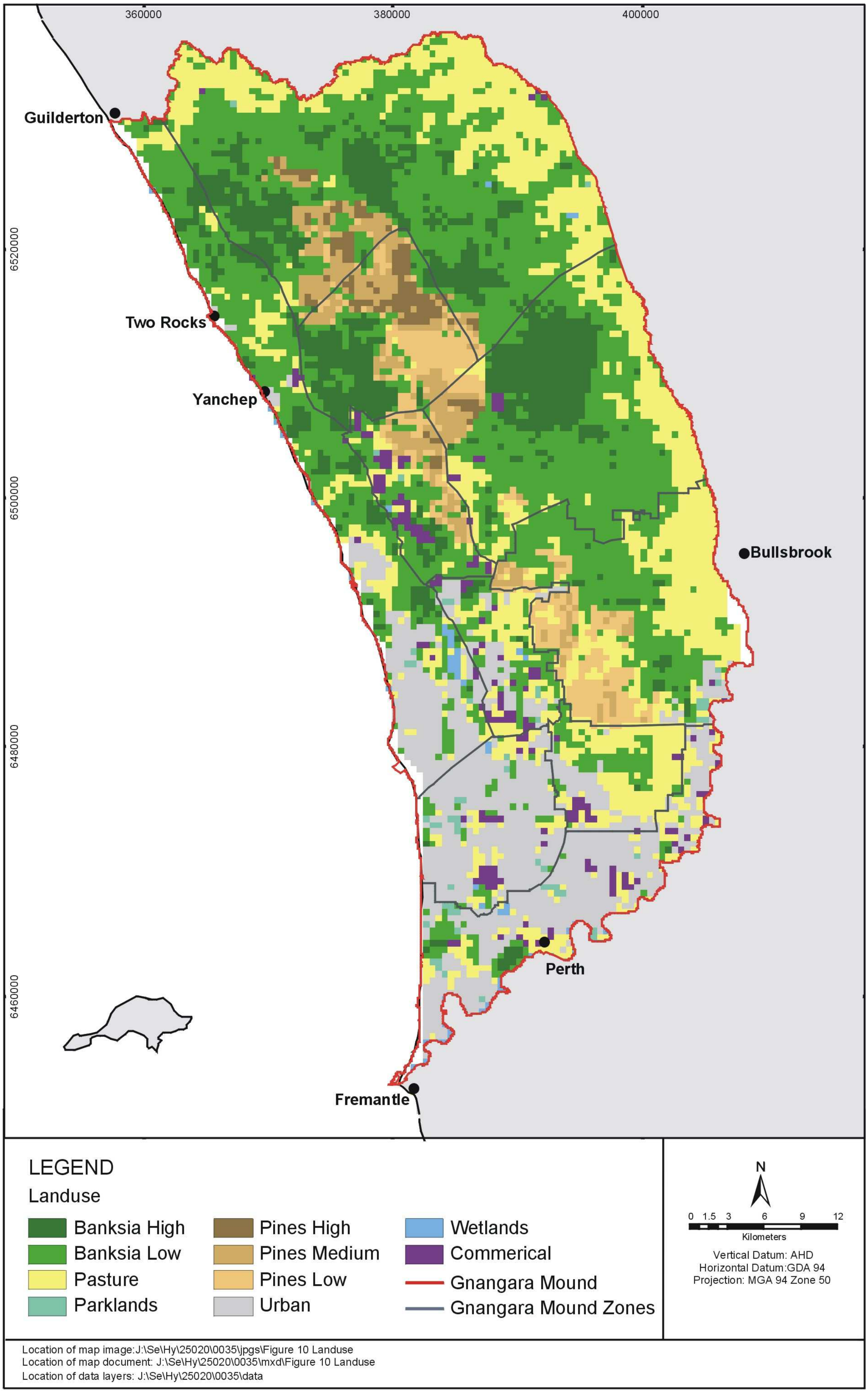

Figure 10. Land-use distribution in PRAMS.

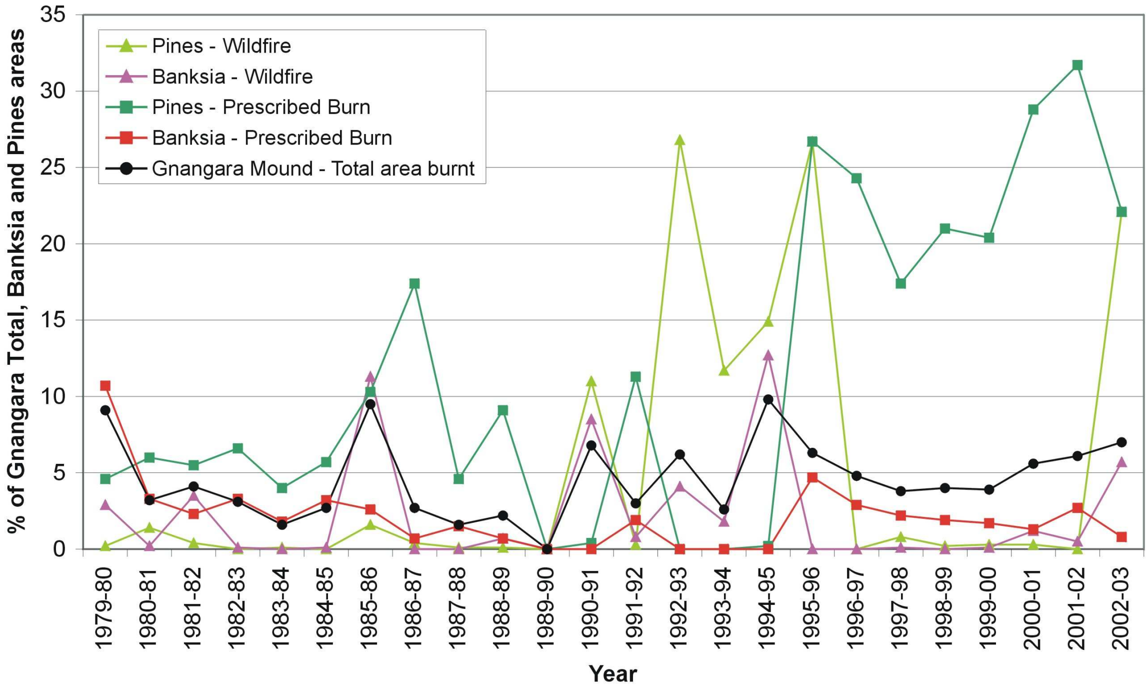

Figure 11. Percentage areas burned (prescribed and wildfires) for pines, *Banksia* and the Gnangara Groundwater Mound.

3 Scenario Results

Scenario results generated from PRAMS are presented and analysed by four different methods: contour analysis, hydrograph analysis, volumetric analysis and a water balance.

3.1 Contour analysis

Contour analysis produces “plan view” plots of the Gnangara Groundwater Mound watertable that show a prediction of groundwater levels after 10 years. To assess the sensitivity of the watertable to changes in each of the model components (climate, abstraction and land-use) the watertable contour maps presented here are shown as differences between the base case and each scenario. The results are colour coded with rising groundwater levels in blue and falling water levels in red.

3.1.1 Base case scenario

3.1.1.1 Base case: Scenario 1

The absolute prediction of change to the watertable of Gnangara Groundwater Mound is shown for the base case (Scenario 1: medium-term, dry climate) in Figure 12. The contour map shows that the base case watertable is predicted to decline between 2 and 3 m over most of the mound and up to 5 m in the Yeal area from 2004 to 2014. There is a small area of net watertable rise under the southern part of the pine plantations due to increased recharge from thinning/clear-felling of pines.

3.1.2 Climate scenario

3.1.1.2 Short-term, very dry climate: Scenario 2

Scenario 2 models the sensitivity of the watertable to short-term, very dry climate. The difference between the base case and the short-term, very dry climate scenario is shown in Figure 13. The results show substantial, additional decline of the watertable under a low rainfall, very dry climate regime from 2004 to 2014. This suggests that rainfall reduction is the main driver of watertable trends across the mound and land-use and abstraction impacts are more local. These results are consistent with the hydrograph analysis undertaken by Yesertener (2002, 2003, 2007).

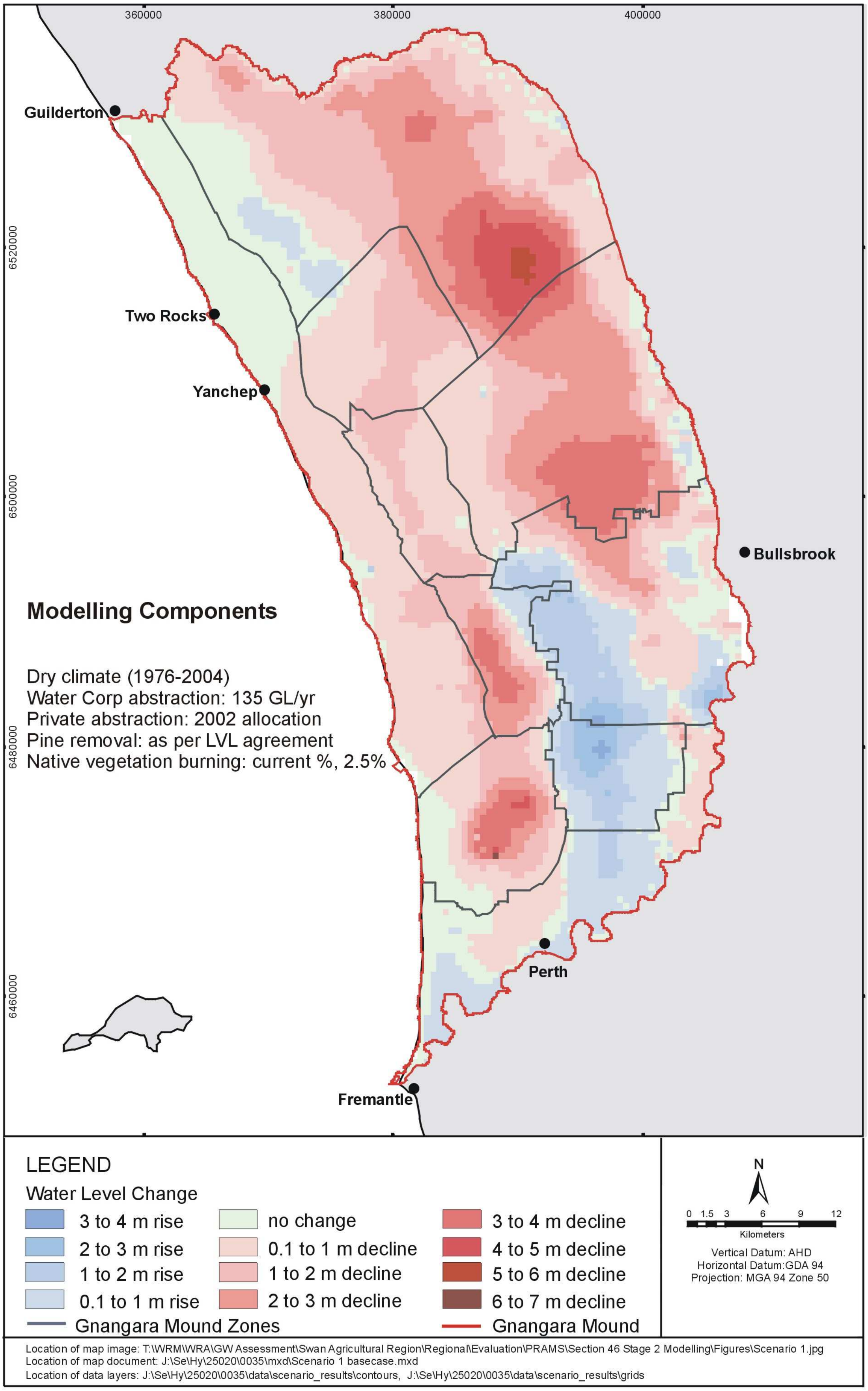

Figure 12. Scenario 1: Base case, showing predicted watertable change from 2004 – 2014.

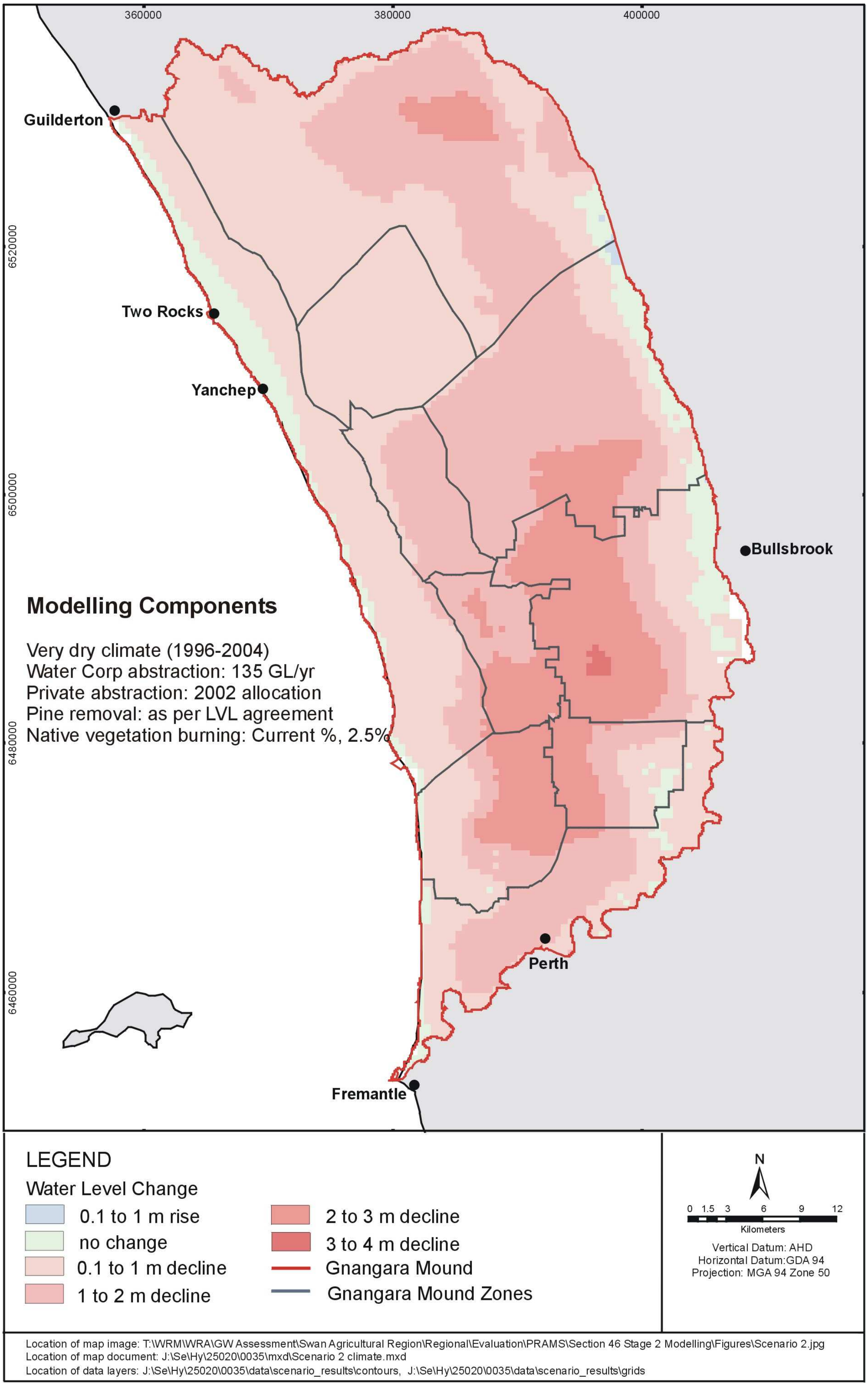

Figure 13. Scenario 2: Short-term, very dry climate, showing predicted watertable change from 2004 – 2014, relative to the base case.

3.1.3 Abstraction scenarios

3.1.3.1 Water Corporation abstraction reduction: Scenario 3

The difference between the base case (Water Corporation abstraction at 135 GL/yr) and the Water Corporation abstraction reduction scenario (Scenario 3, abstraction at 105GL/yr) from 2004 to 2014, manifests as a cone of recovery in the superficial aquifer to the east of the Wanneroo Groundwater Area near the Wanneroo and Pinjar borefields (Figure 14). The model predicts up to 3 m difference in water levels over a very small area and a small recovery of between 0.1 and 1 m over a large area. This suggests that the impact of reducing public water supply from 135 GL/yr to 105 GL/yr is only substantial near the Water Corporation borefields, where abstraction has been reduced.

The predicted areas of water level recovery shown in Figure 14 are directly related to the distribution of abstraction reduction by borefield and by aquifer (Figure 7, Tables 5 and 6). The greatest reduction in superficial abstraction is from the Wanneroo (reduced by 2 GL/yr) and Pinjar (reduced by 2 GL/yr) borefields and this correlates to the greatest recovery in groundwater levels (Figure 14).

The distribution of abstraction reduction from the Leederville aquifer is mostly from Wanneroo and Mirrabooka borefields. There is a 3.6 GL/yr reduction from the Mirrabooka, 0.4 GL/yr from the Pinjar and 4 GL/yr from the Wanneroo borefields. It is likely that these reductions will affect groundwater levels in the superficial aquifer in the areas of superficial-Leederville aquifer connectivity on the crest of the mound.

In the Yarragadee aquifer there is a 5.9 GL/yr reduction from the Independent Artesian bores, 1.1 GL/yr from the Pinjar borefield and 10 GL/yr from the Wanneroo borefields. As expected, there is some impact in the confined aquifer recharge areas, although it is not substantial. The 0.1 m difference contour extends into the northern part of the mound and corresponds to where the Leederville Formation and Yarragadee Formation subcrop beneath the Superficial Formations.

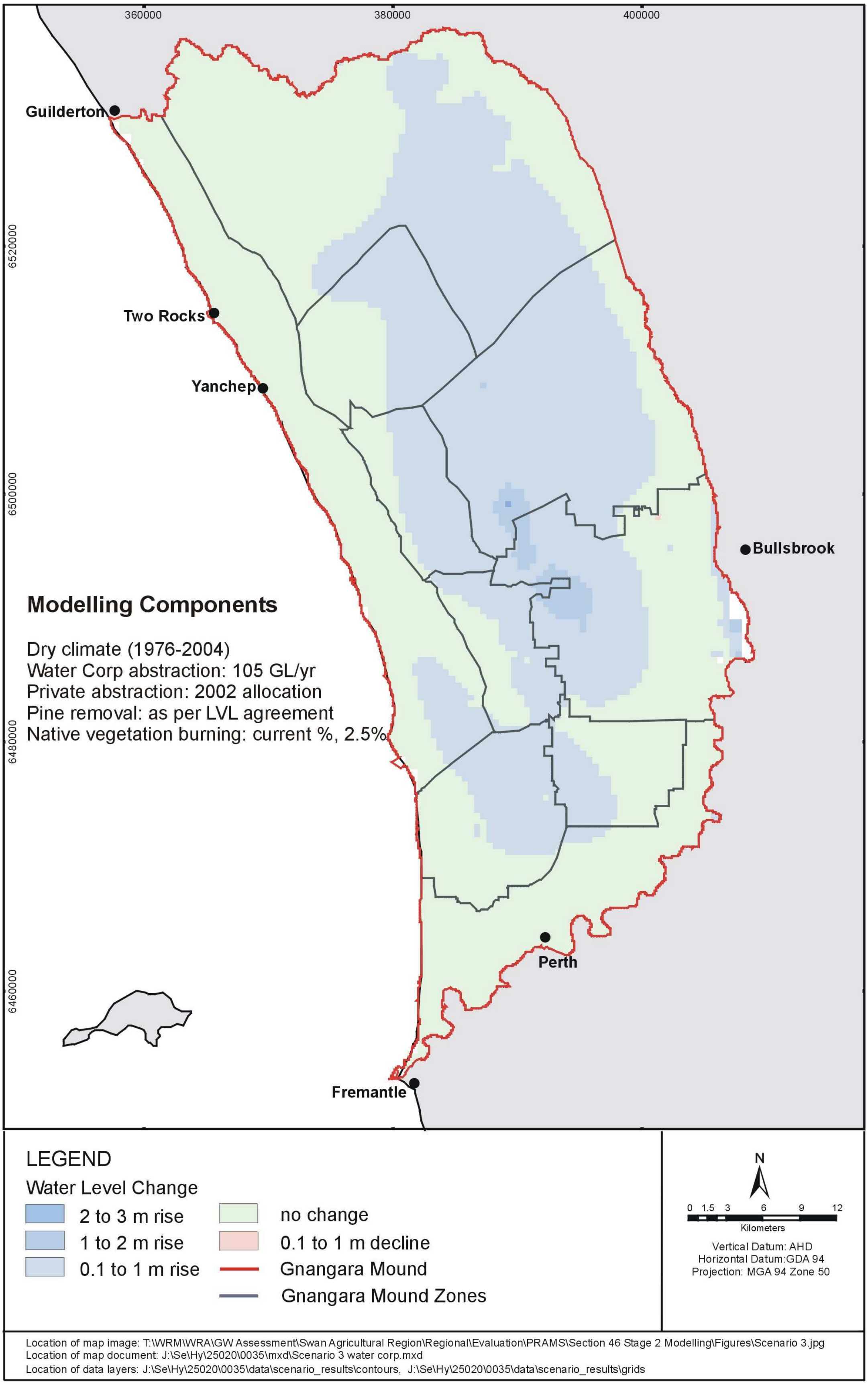

Figure 14. Scenario 3: Water Corporation abstraction reduction (to 105 GL/yr) showing predicted watertable change from 2004 – 2014, relative to the base case.

3.1.3.2 Private abstraction reduction: Scenario 4

The difference between Scenario 4 (private abstraction at 80% of 2002 levels) and the base case (100% of 2002 allocation) shows up to a 1.5 m difference in the highest private abstraction areas (the southern Wanneroo Groundwater area) (Figure 15). This shows that a 20% reduction in private abstraction gives a 1.5 m difference in groundwater levels, after 10 years from 2004 to 2014. Nearly two thirds of the mound shows a watertable increase between 0.1 m and 1 m.

3.1.4 Land-use scenarios

The distribution of land-use, together with climate, controls the amount of groundwater recharge, which in turn dominates the distribution and flow of groundwater in the superficial aquifer on the Gnangara Groundwater Mound. Urbanisation typically increases recharge while increased vegetation density will reduce recharge to the point where it can be negligible (or even negative) under the densest of pine plantations, if they have access to the capillary fringe (Xu *et al.,* 2005).

3.1.4.1 Pines removal: Scenario 5

The two pines components used to assess the impact of pine thinning and clear-felling are described in Section 2.3.1. The base case involves thinning and clear-felling as per the current Forest Products Commission model for the LVL plant. Scenario 5 models a total, instantaneous large-scale, clear-fell of pines and a conversion to low density native vegetation. The difference in groundwater levels, after 10 years (2014), is in the order of 1-2 m in the southern part of the plantation and 5 to 6 m underneath the northern Yanchep part of the plantation (Figure 16). The difference in impact between the northern and southern areas is due to the southern part of the plantation being removed first (2005-2015) and the northern part of the plantation, which is denser, being harvested later (2020-2025). See Appendix 1 for more detail of the location and timing of pine removal.

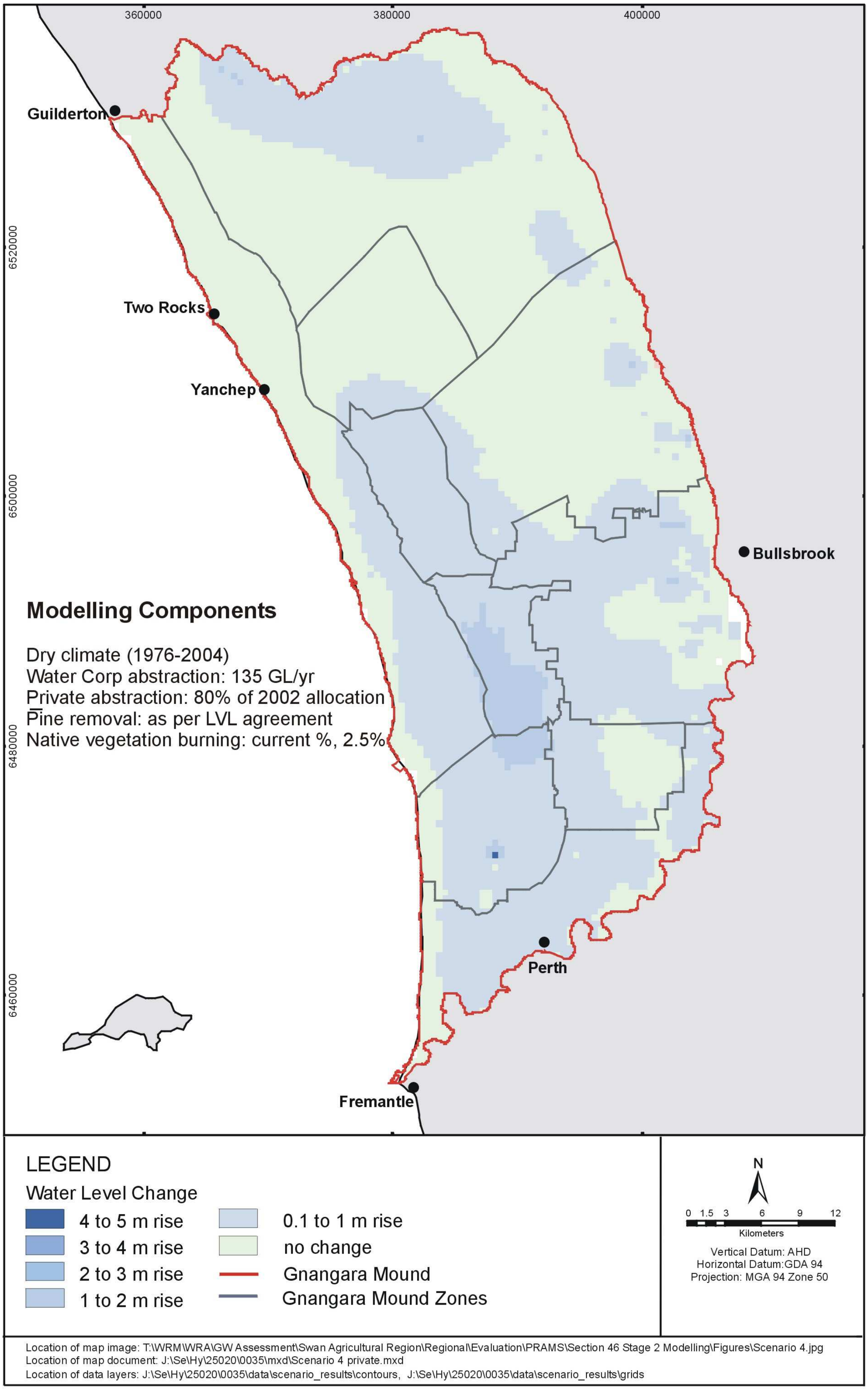

Figure 15. Scenario 4: Private abstraction reduction, showing predicted watertable change from 2004 – 2014, relative to the base case.

3.1.4.2 Increased % area of native vegetation burning: Scenario 6

PRAMS indicates that high-density native vegetation, particularly *Banksia* woodland areas, are heavy water users, similar in magnitude to pine trees at a medium to high density. More field observations are required to confirm these relationships, but this similarity is significant given the very broad distribution of native vegetation (*Banksia* woodland) and the relatively small distribution of pine trees. The results of Scenario 6 (increased % area of native vegetation burning) show how sensitive the model is, over much of Gnangara Groundwater Mound, to native vegetation (*Banksia* woodland) density.

The base case models a burning area of 2.5% per year from 2004 to 2014 which is indicative of current levels of burning. Scenario 6 models an increase in the area of burning to 7.5% per year from 2004 to 2014. In both scenarios, an attempt has been made to model burning and re-growth (see Section 2.3.2).

The difference between native vegetation being burnt over 2.5% of the area of Gnangara Groundwater Mound and 7.5% is shown in Figure 17. The greatest impact is centred on the northeast corner of the Gnangara Groundwater Mound in the Yeal and Pinjar areas, the area of densest existing native vegetation. By 2014, there is an additional 1 to 1.5 m of water in storage from this increased burning. This increase is significant as native vegetation burning and climate are the only components that have a significant impact in this part of the model domain, which contains some important GDEs.

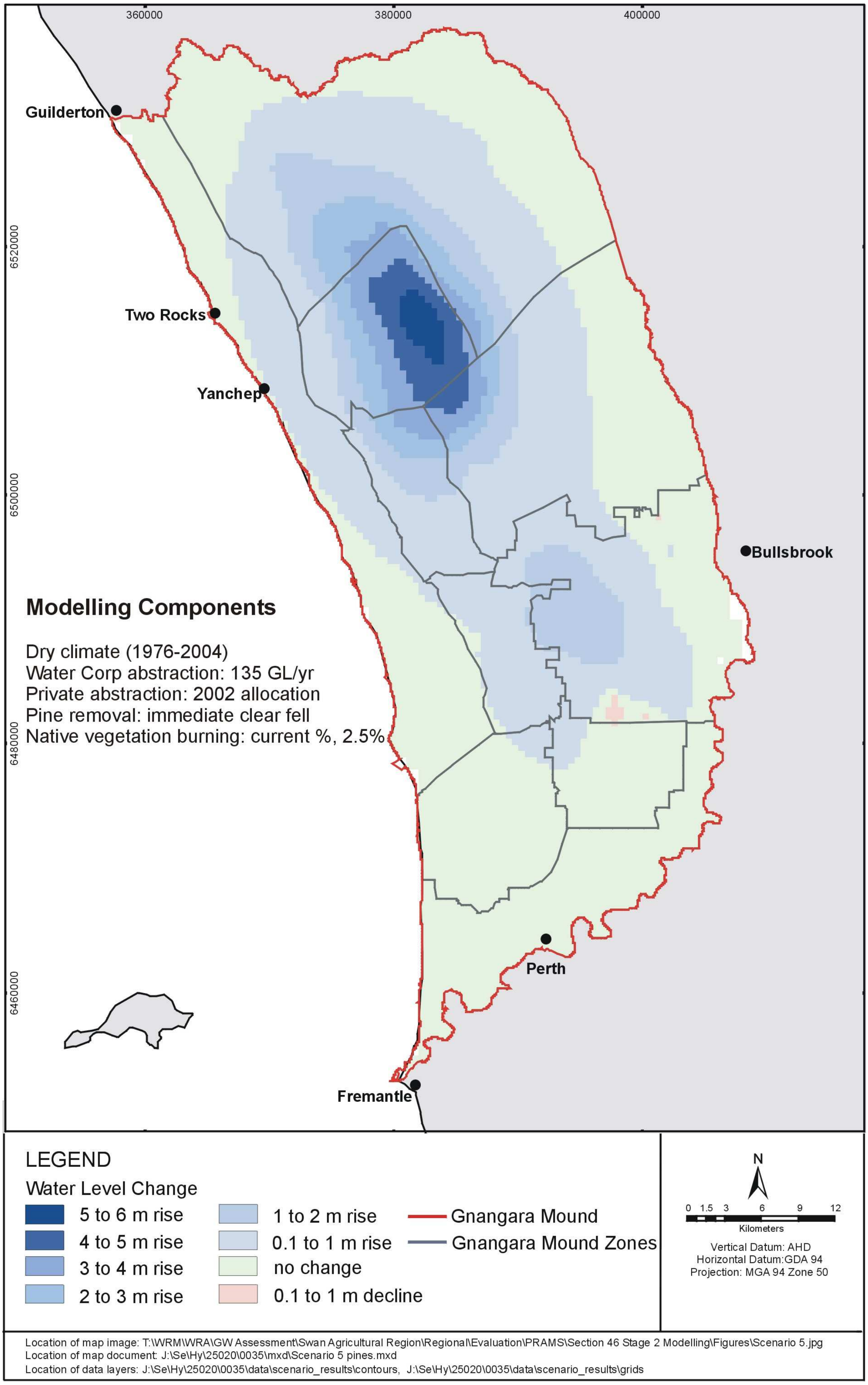

Figure 16. Scenario 5: Pine removal, showing predicted watertable change from 2004 – 2014, relative to the base case.

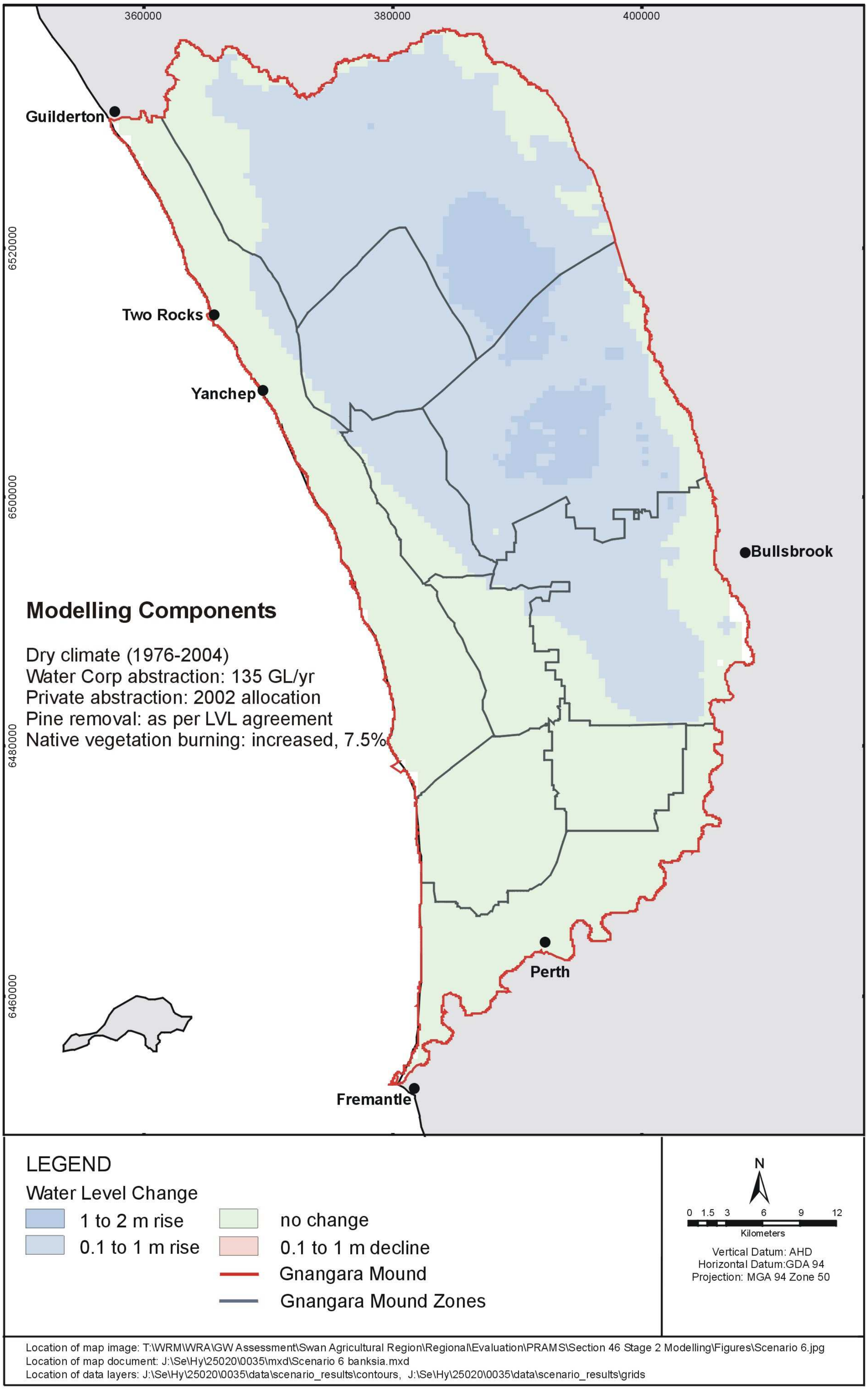

Figure 17. Scenario 6: Native vegetation burning increase, showing predicted watertable change from 2004–2014, relative to the base case.

3.2 Hydrograph analysis

The purpose of hydrograph analysis is to give an indication of the likely rate of change in water levels at chosen sites, under various scenarios. Sites for hydrograph analysis have been selected from well-calibrated bores from PRAMS (Figure 18). The use of wetland criteria bores was considered but rejected due to fact that they are often not well calibrated. This is due to their proximity to surface water bodies (e.g. wetlands). Wetlands are not accurately modelled in PRAMS because it is a regional scale model with a coarse model grid. If criteria bore hydrographs were used in the analysis it could give some very misleading results. Furthermore, the doubt over the suitability of many of the current criteria bores still exists (Rockwater, 2003).

In the following hydrograph analysis the observed data (1979 -2004) is shown in black and the PRAMS simulated hydrograph for the same period is shown in blue. The other predictive scenarios shown on each hydrograph plot are the results from Scenarios 2 to 6 and represent variations from the base case (Scenario 1). The individual scenarios show how the base case would change if a particular action were taken. For example, by how much the immediate clearing of pines would change the predicted base case hydrograph. This enables a comparison to be made between the impact of different management actions on the base case and the impact of climate variability and change.

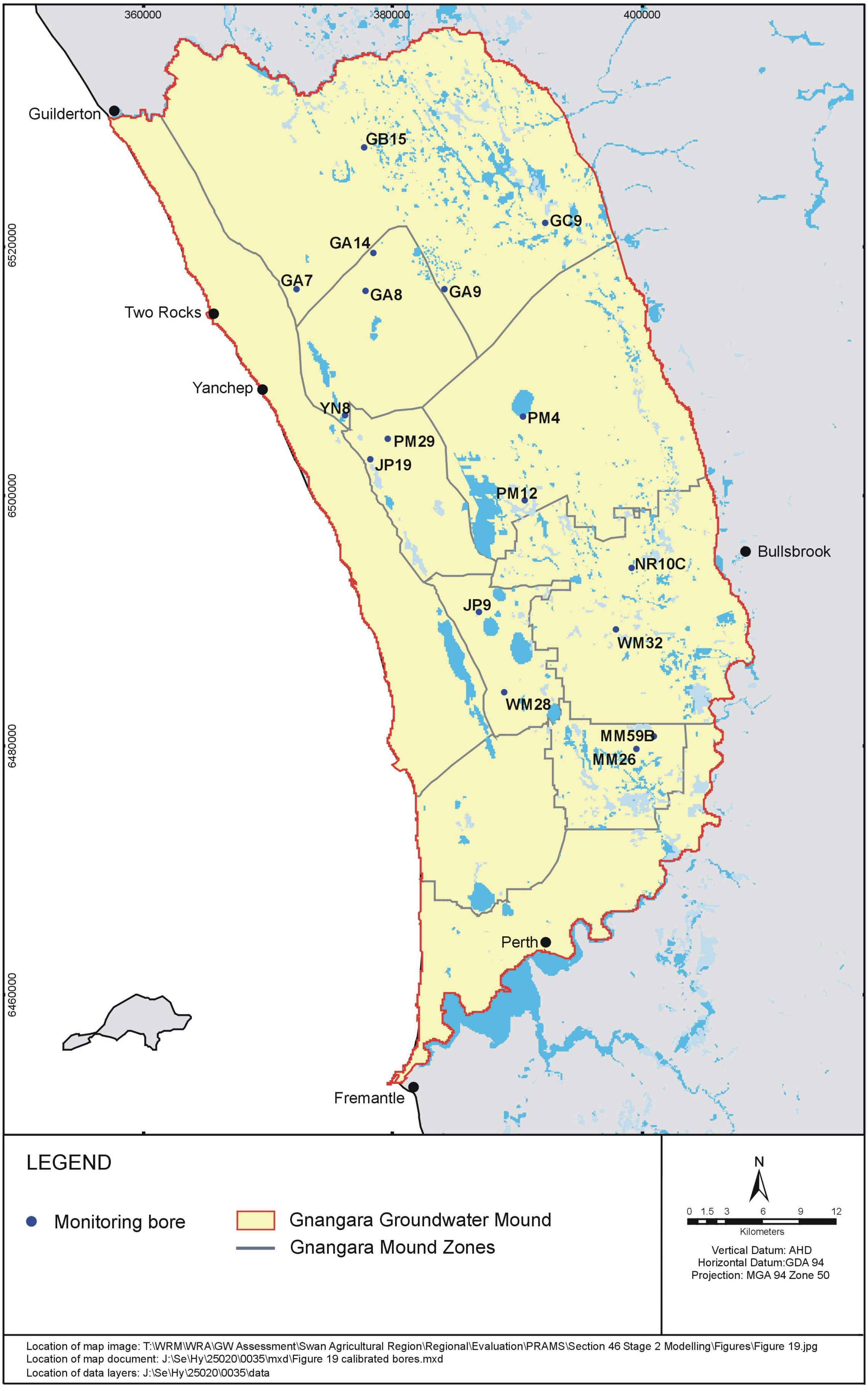

Figure 18. Location of calibrated bores on the Gnangara Groundwater Mound used for hydrograph analysis.

3.2.1 Hydrograph – GB15

GB15 is located in the northern part of the mound in an area of native vegetation near potential GDEs. The observed hydrograph (Figure 19) shows a distinctly declining trend, which appears to accelerate from 2000 to 2003. The hydrograph suggests a decrease in recharge, as indicated by the distinct decrease in seasonal water level fluctuation, caused by increased vegetation density and reduced rainfall quantities. The predictive results also support this with the model showing greatest sensitivity to the climate scenarios, i.e. the relative water level difference between the base case (Scenario 1, modelled with the medium-term, dry climate component, 1976 to 2004) and Scenario 2 (modelled with the short-term, very dry climate component,1996 to 2004) is the greatest. The results of the pine removal component (Scenario 5) and native vegetation burning component (Scenario 6) have the least difference to groundwater levels in the vicinity of GB15 when compared to the base case scenario. This is only a semi-quantitative analysis as the parameters are being manipulated at different magnitudes but the dominance of climate over the other two parameters is distinct. This implies that at GB15 the impacts on future groundwater levels, in order of greatest to least are: climate, percentage area of native vegetation burning and pines equally and the Water Corporation confined aquifer pumping and private abstraction near equal.

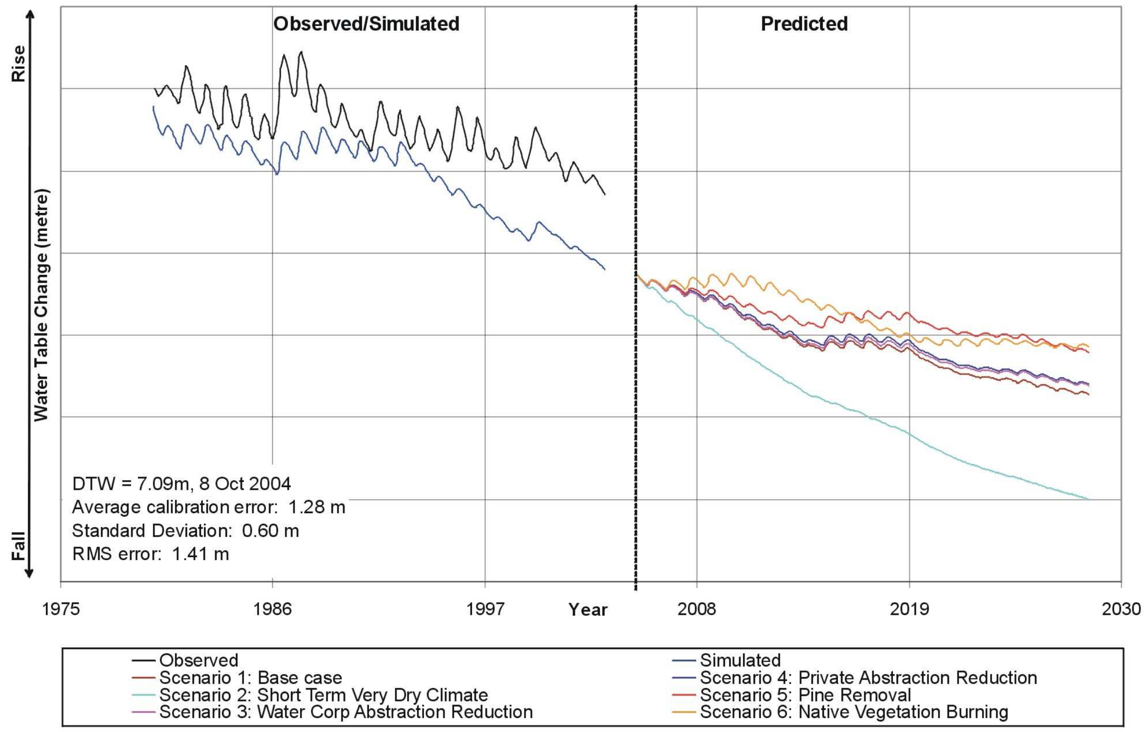

Figure 19. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore GB15.

3.2.2 Hydrograph – GC9

GC9 is located in the northeast part of the mound covered by native vegetation. This site is close to the discharge areas of the mound and as such there are abundant GDEs. The observed CG9 hydrograph (Figure 20) over 28 years (1976 to 2004) initially shows a stable trend, then a decline over six to eight years from (1998 to 2004). The decrease in seasonal fluctuation is not as pronounced as at GB15 due to the proximity of this bore to the discharge flanks of the mound. The predicted decline at this site appears somewhat unrealistic, possibly due to the land-use changes in the base case, so the predicted hydrographs should not be used to assess the potential impact on vegetation or other GDEs. In the predictive scenarios the negative impact of the short-term dry climate (1996 to 2004) component versus the medium-term, dry climate (1976 to 2004) component in the base case (Scenario 1) is about the same as the positive impact of increasing the burning area (7.5%) of native vegetation (Scenario 6). The modelled impact of the total pine removal component (Scenario 5) versus the removal as per the LVL agreement in the base case (Scenario 1) is about the same as the relative increase caused by increased burning native vegetation scenario.

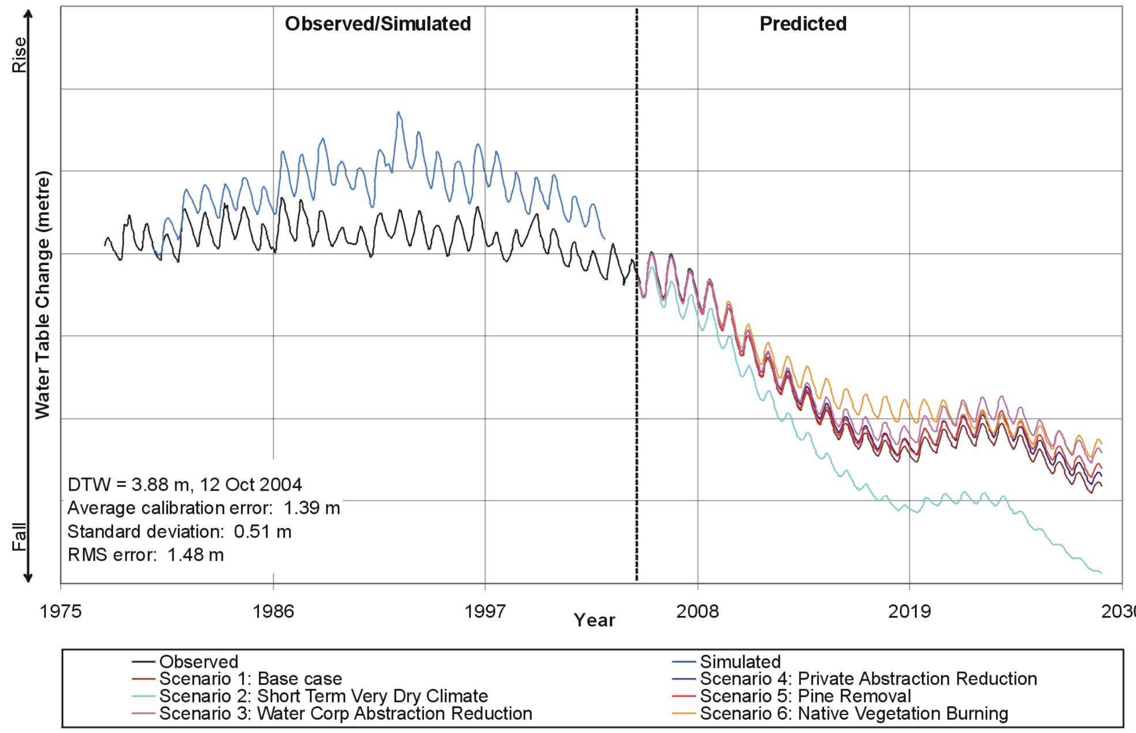

Figure 20. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore GC9.

A reduction in Water Corporation abstraction (Scenario 3) shows some positive impact at GC9 (~ 0.5 m) due to the proximity of this site to the window of hydraulic connection between the unconfined and confined aquifers. This implies that at GC9 the dominant impacts on future groundwater levels, in order of greatest to least are: climate, percentage area of native vegetation burning and pine removal equally, then Water Corporation confined aquifer pumping and private abstraction.

3.2.3 Hydrographs – GA14 and GA8

GA14 and GA8 are located in the middle of the Yanchep pine plantation. The observed hydrographs (Figures 21 and 22) show a declining trend which accelerates in the last 8 years (1996 to 2004). A 0.5 m rise in the mid to late 1980s is associated with the clearing of vegetation prior to pine planting. The lack of seasonal fluctuations shown by the hydrographs is due to the dense vegetation (previously from native vegetation and now pine litter) and the high depth to groundwater (35 m at GA14 and 25m at GA8). This may indicate an attenuation of the seasonal recharge signal resulting in a more constant downward flux. The base case (Scenario 1) predictive hydrograph shows continued declines, until the pine plantation is removed, which coincides with a significant rise in groundwater levels. This rise is due to the large increase in groundwater recharge following pine plantation removal in 2020. The pine removal component (Scenario 5, modelled with a total instantaneous pine removal and replacement with low density native vegetation), suggests that the rise will be about 2 m but will not cause groundwater levels to recover to those observed in the late 1970s. The impact of the short-term, very dry climate component (Scenario 2) compared to the medium-term, dry climate component (Scenario 1) is an additional 1.5 m of decline which would almost negate the likely rise if the pine plantation was removed. The impact of the private abstraction reduction (Scenario 4) appears negligible but the 30 GL/yr reductions in Water Corporation abstraction component (Scenario 3) result in a 0.3 to 0.4 m relative recovery, due to the proximity of GA8 and GA14 to the area of hydraulic connection between the three major aquifers. This implies that at GA14 and GA8 the dominant impacts on future groundwater levels, in order of greatest to least, are: climate and pines equally, percentage area of native vegetation burning, Water Corporation confined aquifer pumping and private abstraction.

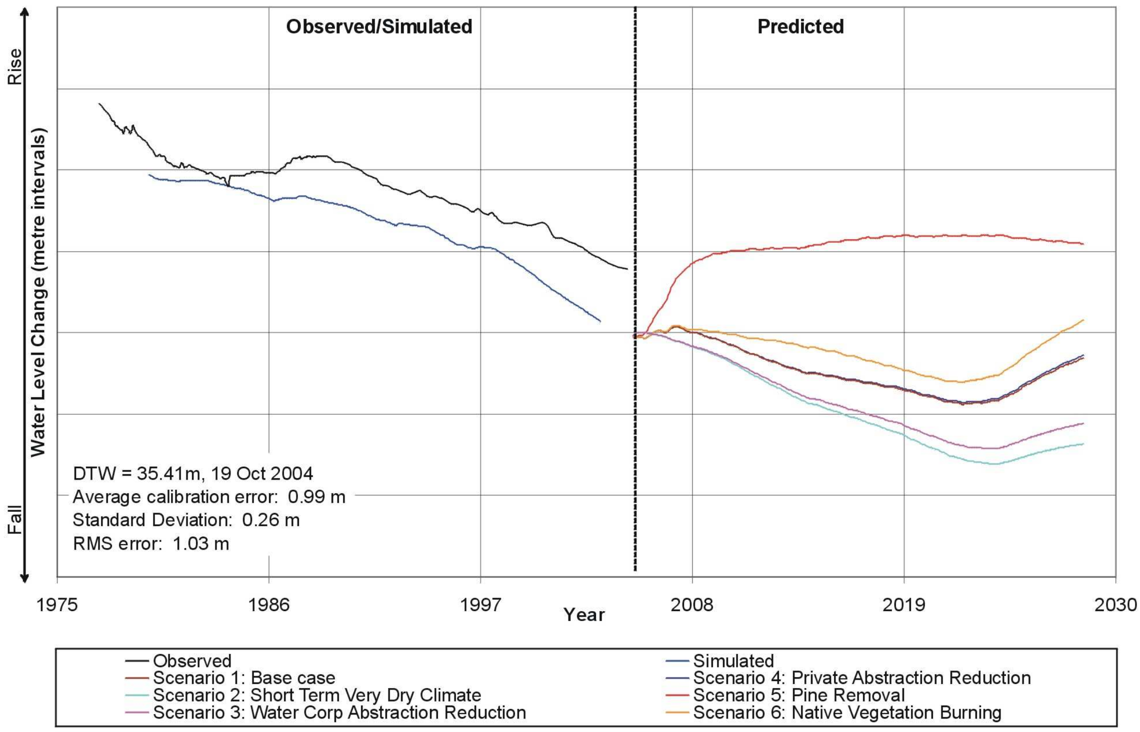

Figure 21. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore GA14.

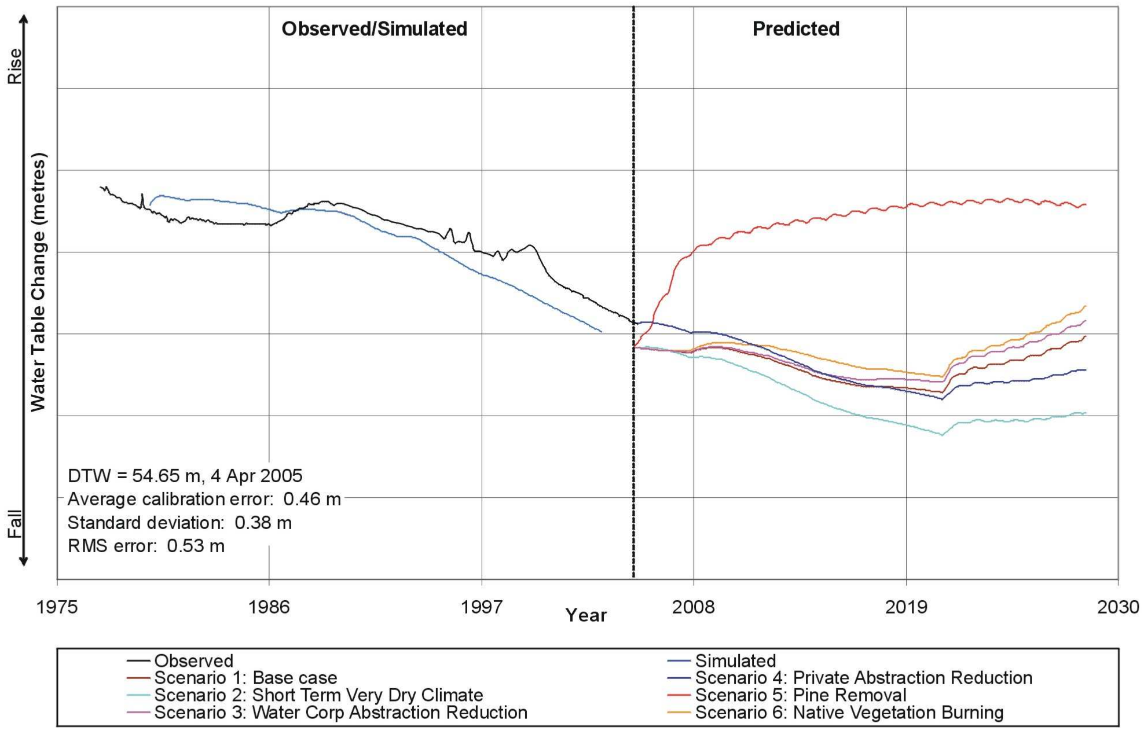

Figure 22. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore GA8.

3.2.4 Hydrograph – GA7

GA7 is located to the west of the Yanchep pine plantation very close to the aquifer system discharge area and in the coastal limestone (Tamala Limestone). Due to the proximity of this site to the discharge area of the mound, the decline in groundwater level at GA7 is modest compared to other hydrographs (Figure 23). However, even a modest decline is significant since a change in water levels near the discharge margins is indicative of a system in distinct decline. The hydrograph shows an accelerating decline from 2000 with almost no seasonal fluctuation. The pines removal component (Scenario 5, modelled with a total instantaneous pine removal and replacement with low density native vegetation), suggests that the rise will be in the order of 0.5 m but will not cause groundwater levels to recover to those observed in the late 1970s. The impact of the short-term, very dry climate component (Scenario 2) as compared to the medium-term, dry climate component in the base case (Scenario 1) is an additional 0.5 m of decline, which would almost negate the likely rise if the pine plantation was removed. The impact of a reduction in both private abstraction (Scenario 4) and Water Corporation abstraction (Scenario 3) appears negligible. This implies that at GA7 the dominant impacts on future groundwater levels are, in order of greatest to least: climate and pines equally, percentage area of native vegetation burning followed by Water Corporation and private abstraction. The predictive hydrographs illustrate the difficulty in changing groundwater levels near the discharge areas of the mound as none of the scenarios result in a change of more than 0.5 m from the base case.

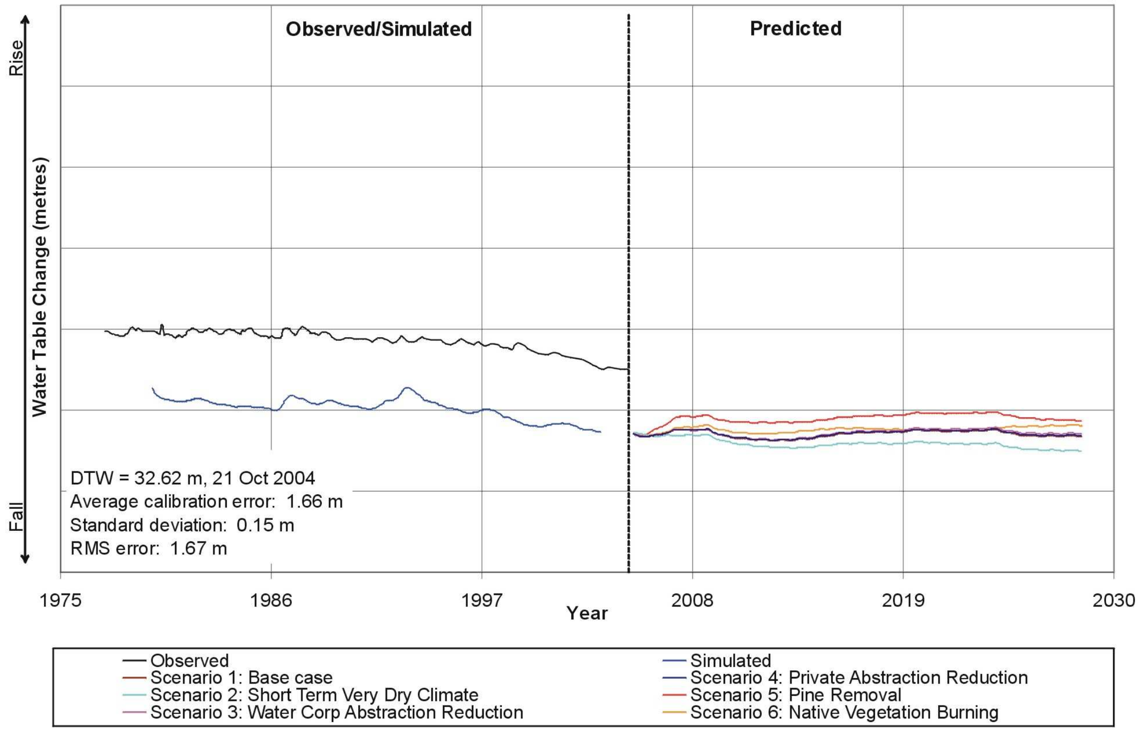

Figure 23. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore GA7.

3.2.5 Hydrograph – GA9

GA9 is located in the northern central part of the mound and is on the eastern (up gradient) edge of the pine plantation. The observed hydrograph (Figure 24) shows an initial rise, associated with the native vegetation clearing for the pine plantation, followed by a steep decline as the pine plantation matures. Again there is a lack of seasonal fluctuations towards the end of the observed data suggesting no recharge to the watertable due to low rainfall and high vegetation density.

The hydrograph for Scenario 1, the base case, suggests that a continuation of the observed decline is likely under present rainfall levels until the pines are removed, when a 1-2 m rise is predicted. This is followed by stabilisation and a possible decline toward the end of the model simulation (2029). The predicted rise is however 2 m less under the last short-term, very dry climate (Scenario 2) than the medium-term, dry climate component in the base case scenario. A reduction in native vegetation density via increased burning area (Scenario 6) provides a 0.5 m relative recovery, which is about the same as the 30 GL/yr reductions in Water Corporation abstraction (Scenario 3). The impact of private abstraction reduction (Scenario 4) at this site is negligible. This implies that at GA9 the dominant impacts on future groundwater levels are, in order of greatest to least impact: climate and pines equally, and percentage area of native vegetation burning and Water Corporation confined aquifer pumping equally followed by private abstraction.

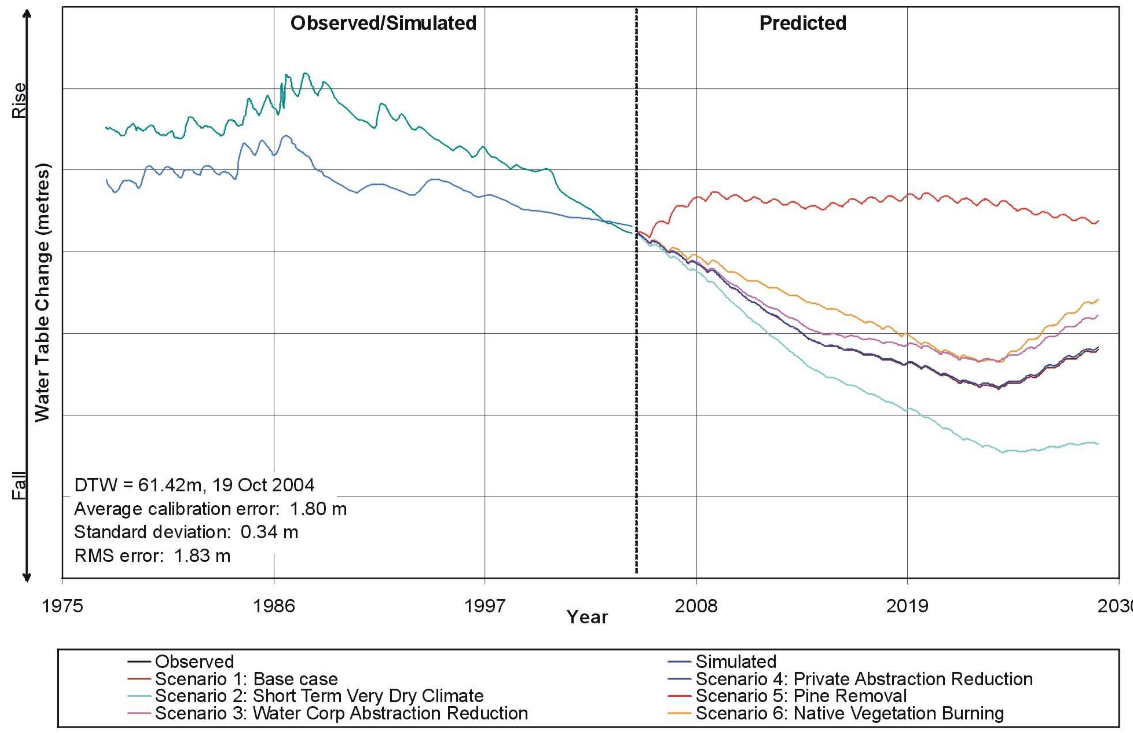

Figure 24. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore GA9.

3.2.6 Hydrograph – YN8

YN8 is located on the western margin of the Northern Wanneroo Groundwater Area at the boundary between the Bassendean Sand and the Tamala Limestone. This site is close to the discharge areas of the mound, but not as close as GA7. The observed hydrograph (Figure 25) shows a steadily declining trend since the bore was constructed in the early 1990s.

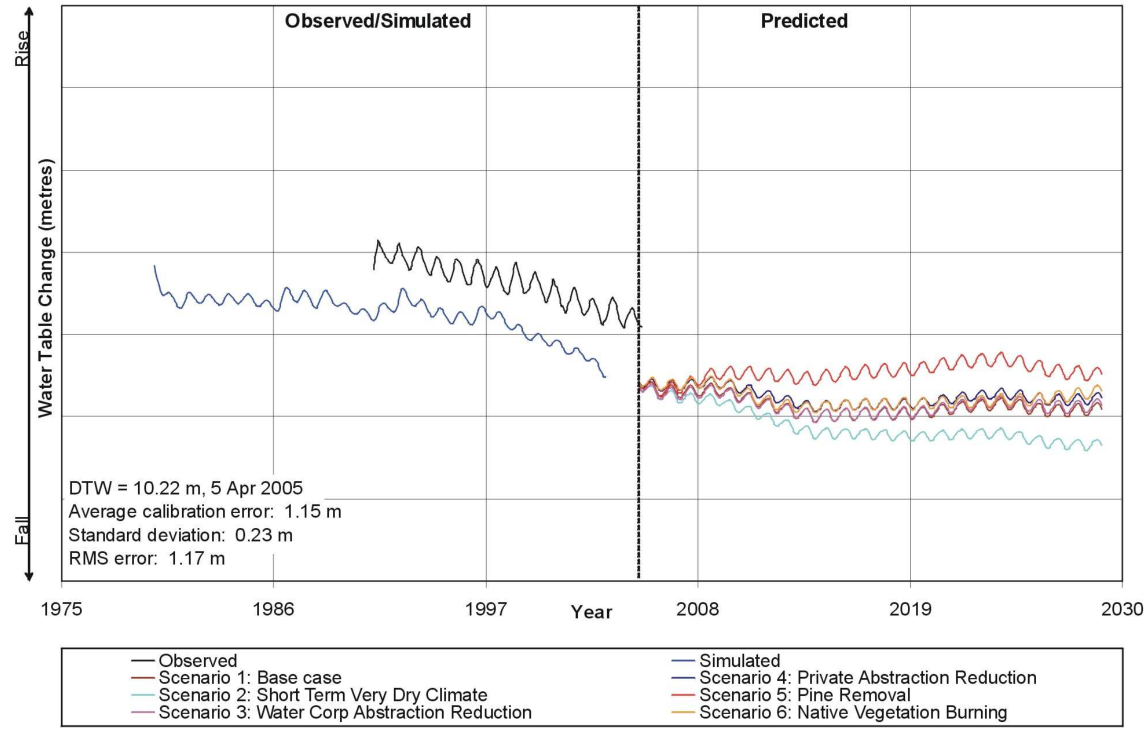

Figure 25. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore YN8.

The predictive hydrographs show a continued declining trend followed by some degree of hydraulic equilibrium. However, the equilibrium under the short-term, very dry climate (Scenario 2) is about 1 m lower than the medium-term, dry climate component in the base case (Scenario 1). Near YN8, the model shows limited sensitivity to manipulations in other components. Only the pine removal component (Scenario 5) and the short-term, very dry climate component (Scenario 2) appear to have a strong influence on the groundwater levels. Private abstraction reduction (Scenario 4) and an increased burning area of native vegetation (Scenario 6) have a minor impact (0.2 to 0.3 m). The removal of the pine plantations (and replacement with low density native vegetation) (Scenario 5) causes about 1 m of relative recovery modelled with the medium-term, dry climate component. Although not modelled, a water level recovery would be less using the short-term, very dry climate component. This rise would be insufficient, in terms of returning natural flowing water to the Yanchep Caves, as the groundwater level prior to supplementation is 1.5 m below the floor of the Crystal Cave. This implies that the dominant impacts on future groundwater levels at YN8 are, in order of greatest to least impact: climate and pines equally, then percentage area of native vegetation burning and private abstraction equally, followed by the Water Corporation pumping.

3.2.7 Hydrograph – PM4

PM4 is located near the crest of the Gnangara Groundwater Mound. This site is located up gradient of the pine plantation in an area of native vegetation where steep declines in groundwater level, particularly over the last 8 years (1996 to 2004), have been recorded (Figure 26). The lack of a distinct seasonal fluctuation in the hydrograph suggests that under current recharge quantities little or no water infiltrates from the unsaturated zone to the watertable.

The predictive hydrographs show that under the current rainfall and vegetation density the observed declines are likely to continue. The base case hydrograph (Scenario 1) shows an additional decline of 3 m. Scenario 2, modelled with the short-term, very dry climate component, shows a further 3 m decline relative to the base case and a 6 m decline from the observed hydrograph. Pine removal (Scenario 5) and an increased % area of native vegetation burning (Scenario 6) show about 1 m of relative recovery as does a reduction in Water Corporation abstraction of 30 GL/yr (Scenario 3). The impact of reductions in Water Corporation abstraction are relatively large in this locality due to the proximity of the Pinjar borefield, which has zero abstraction under the 105 GL/yr scenario and 2 GL/yr in the 135 GL/yr scenario. The impact of reducing private allocation by 20% (Scenario 4) is negligible in this area. This implies that the dominant impacts on future groundwater levels at PM4 are, in order of greatest to least impact: climate, pines and percentage area of native vegetation burning equally, closely followed by Water Corporation confined aquifer pumping, and finally private abstraction.

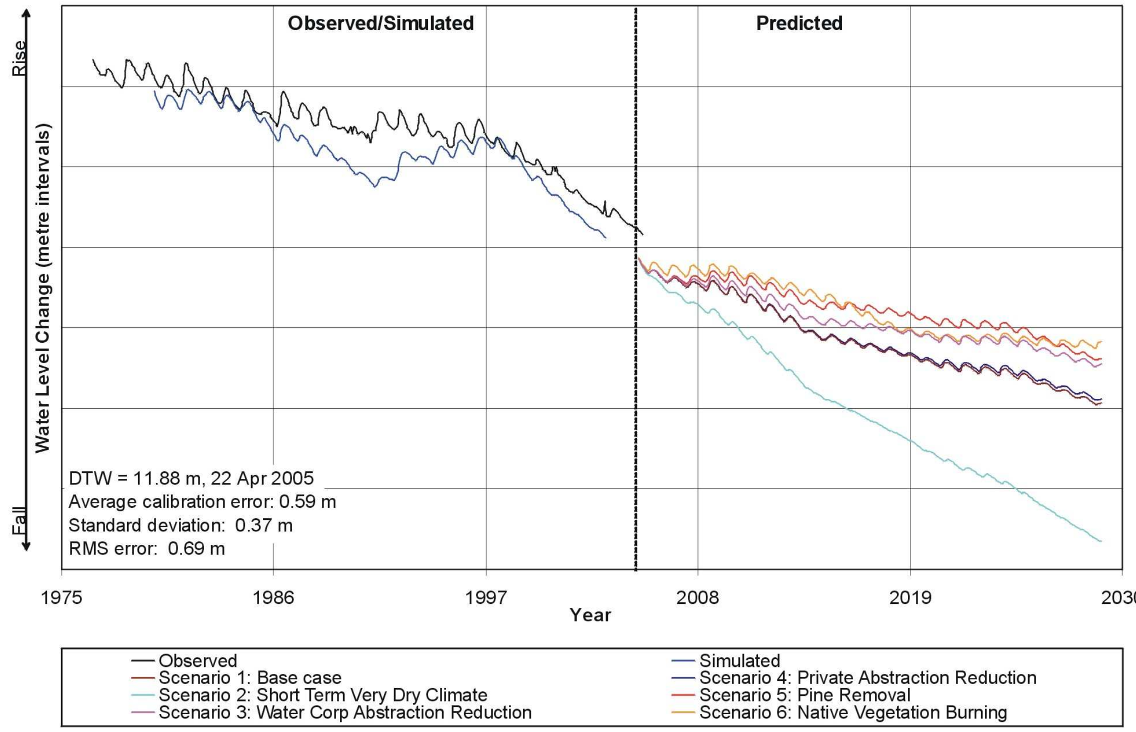

Figure 26. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore PM4.

3.2.8 Hydrograph – PM29

PM29 is located near the eastern edge of the Northern Wanneroo Groundwater Area on the margin of the pine plantation. The observed hydrograph (Figure 27) shows an accelerated declining trend, with a 0.5 m rise in the early 1980s associated with increased recharge due to clearing for pine planting.

This decline is predicted to continue, until pine plantation removal, under both the medium-term, dry climate component in the base case (Scenario 1) and short-term, very dry climate component (Scenario 2). Stabilisation under the short-term, very dry climate component (Scenario 2) and a subtle rise in level under the medium-term, dry climate (Scenario 1) is predicted after 2020-2025 when the pines are removed under the existing LVL agreement. Scenario 5 (total pine removal) predicts an initial 1 to 1.5 m rise in the watertable, which then stabilises after about 2007. The hydrograph also shows a possible decline towards the end of the predictive model run (2029). The impacts of increasing the % area of native vegetation burning (Scenario 6) and a reduction in Water Corporation abstraction (Scenario 3) are similar and low in magnitude (about a 0.2 to 0.3 m rise). The predicted impact of the private abstraction reduction component (Scenario 4) is about 0.5 m of recovery, compared to the base case, due to relatively large private groundwater allocations in Northern Wanneroo Groundwater Area.

The model results imply that at PM29 the dominant impacts on future groundwater levels are, in order of greatest to least impact: climate and pines equally, followed by private abstraction, then percentage area of native vegetation burning and Water Corporation pumping equally.

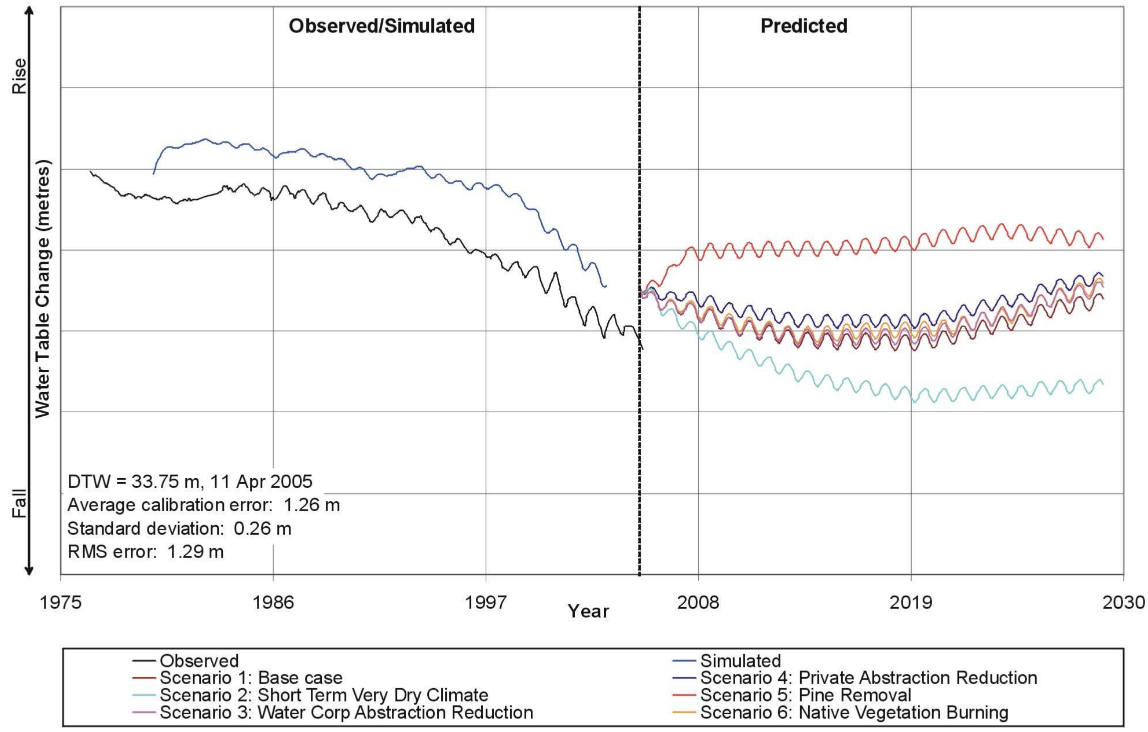

Figure 27. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore PM29.

3.2.9 Hydrograph – JP19

JP19 is located in the western, down gradient area of the Northern Wanneroo Groundwater Area, on the boundary between the Bassendean Sand and the Tamala Limestone. The observed hydrograph (Figure 28) shows an accelerated declining trend from 1999 to 2004. The predictive model simulations suggest that this decline is likely to continue but some degree of stabilisation is likely, due to the proximity of this area to the discharge flanks of the Gnangara Groundwater Mound system. This equilibrium is reached at a 1 m lower level using the short-term, very dry climate component (Scenario 2). The model shows limited sensitivity to other components at JP19, although the pine removal component (Scenario 5) shows relative recovery of approximately 1 m. The increased burning area component (Scenario 6) and the Water Corporation reduction component (Scenario 3) have no impact while the private abstraction reduction component (Scenario 4) shows a 0.2 m rise.

The model results indicate that the dominant impacts at JP19 on future groundwater levels are in order of greatest to least impact; climate, pines, private abstraction, then percentage area of native vegetation burning and Water Corporation pumping equally.

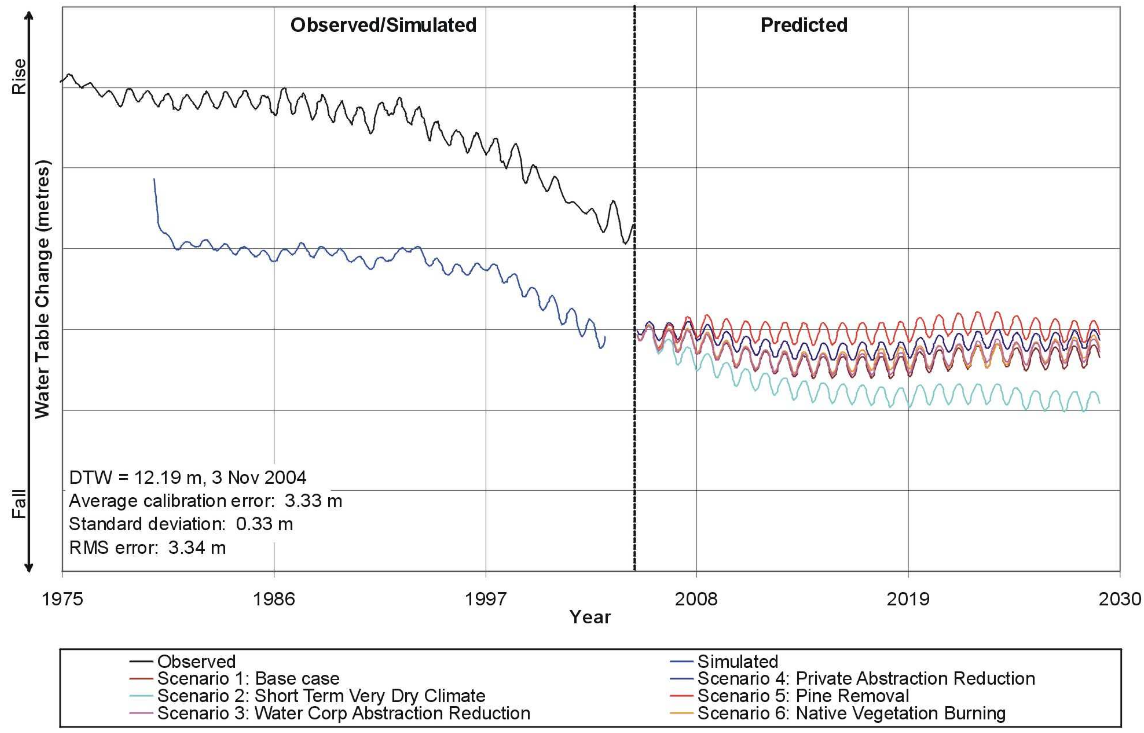

Figure 28. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore JP19.

3.2.10 Hydrograph – PM12

PM12 is located in the central part of the Gnangara Groundwater Mound, near a small plantation of pines to the southeast of the main Pinjar pine plantation. The observed hydrograph (Figure 27) initially shows a steady downward trend and a slightly more rapid decline over the last 8 years (1996 to 2004) with a distinct decrease in the magnitude of seasonal fluctuation suggesting decreased recharge.

The predictive hydrographs (Figure 29) suggest the declining groundwater levels are likely to continue. The modelled watertable shows a greater sensitivity to climate at PM12 than at other sites. The hydrograph for Scenario 2 (short-term, very dry climate component) shows an additional 3 to 4 m of decline, with greatly reduced seasonal fluctuation, compared with the base case (Scenario 1). Pine removal (Scenario 5) produces a relative recovery of slightly less than a metre and the Scenario 6 hydrograph (increased % area of native vegetation burning) shows a 1 m recovery, which initially exceeds the impact of pine removal. The reduction in Water Corporation abstraction (Scenario 3) generates 1 m of relative recovery. The impact of reductions in Water Corporation abstraction is relatively large in this locality due to the nearby Pinjar borefield, which has no abstraction under the 105 GL/yr component and 2 GL/yr in the 135 GL/yr component. A private abstraction reduction of 20% produces almost no impact at this site (Scenario 4). This implies at PM12 the dominant impacts on future groundwater levels are, in order of greatest to least impact: climate, Water Corporation pumping, pines, percentage area of native vegetation burning and finally private abstraction.

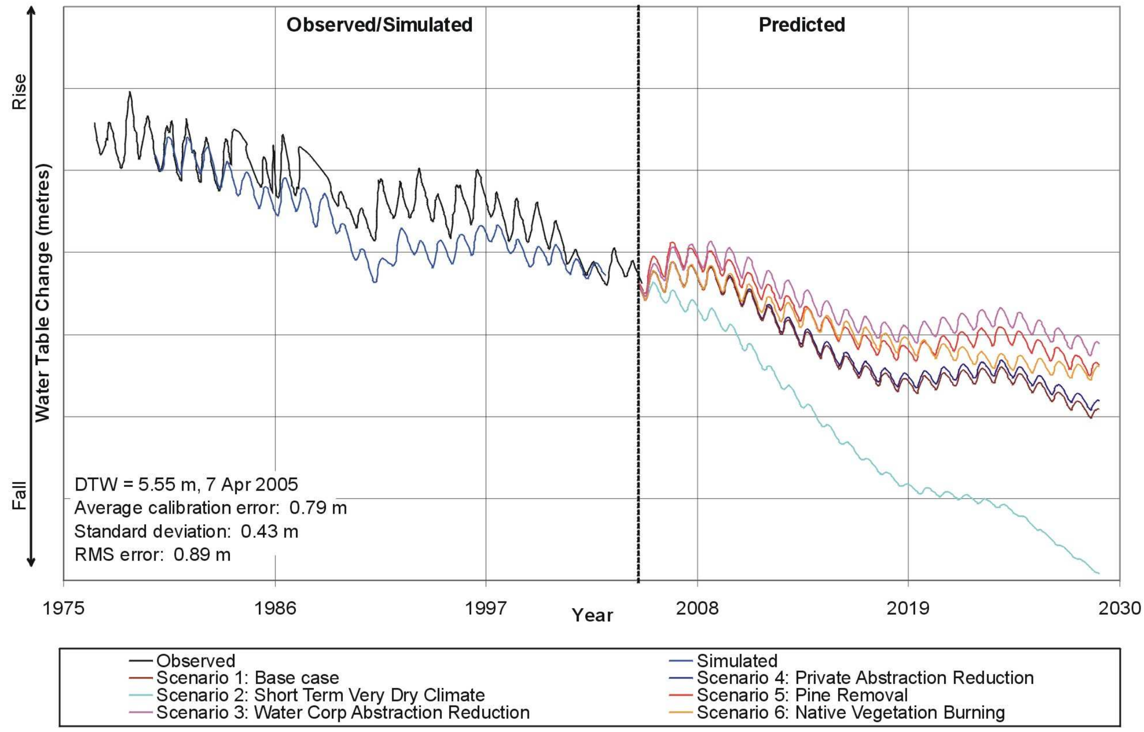

Figure 29. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore PM12.

3.2.11 Hydrograph – NR10c

NR10c is located in the Lexia area to the east of the pine plantation in an area of native vegetation. Lexia contains abundant wetlands, many of which have dried over recent years. The observed hydrograph (Figure 30) has a relatively stable trend initially but shows a decline from 1996 to 2004.

The predictive hydrographs (Figure 30) indicate that this decline is likely to continue, and may accelerate under the short-term, very dry climate component (Scenario 2) which results in a 3 to 4 m lower watertable when compared with the medium-term, dry climate component in the base case (Scenario 1). The impact of total instantaneous pine removal (Scenario 5) and private abstraction reduction (Scenario 4) appears negligible. The impact of reducing Water Corporation abstraction (Scenario 3) also appears negligible because there is no difference in the quantity of groundwater abstracted from the scheme in both the 105 GL/yr and 135 GL/yr components. There is a 0.2 m to 0.8 m rise from an increased percentage area of native vegetation burning component (Scenario 6). This implies that at NR10c the dominant impacts on future groundwater levels are, in order of greatest to least impact: climate, percentage area of burning, Water Corporation pumping (reductions in the 4GL/yr abstracted from the Lexia borefield in both scenarios will have a distinct positive impact) and finally private abstraction.

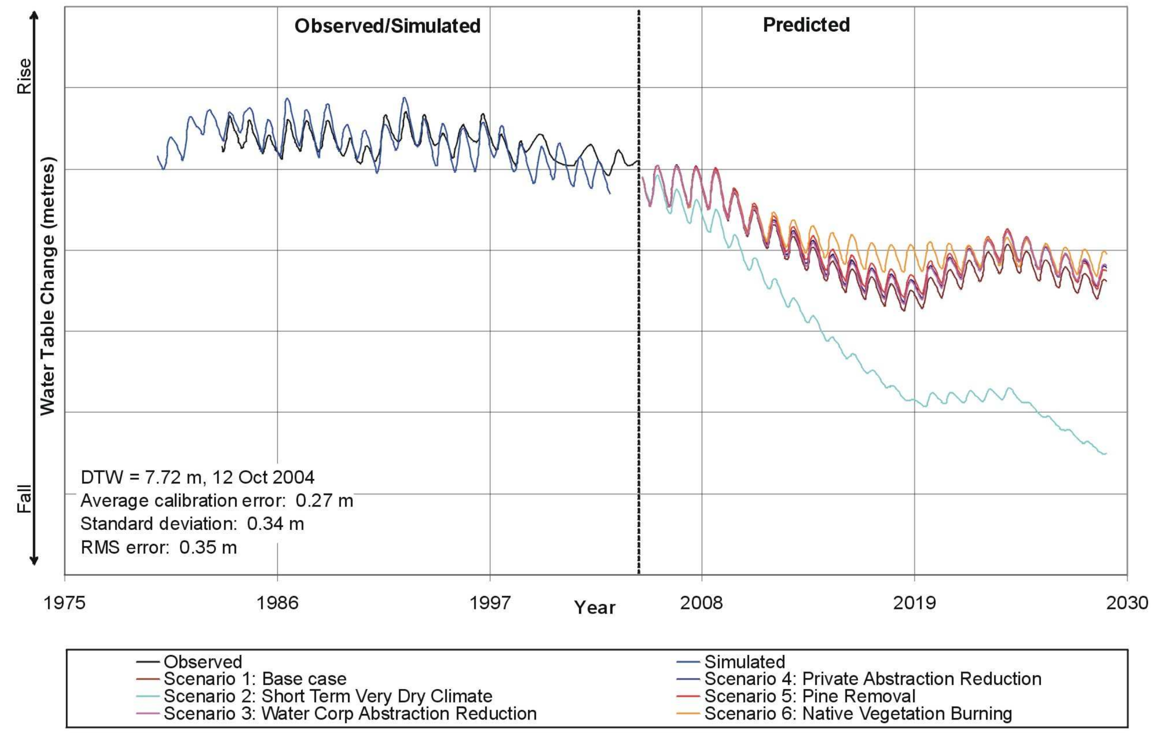

Figure 30. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore NR10c.

3.2.12 Hydrograph – JP9

JP9 is located in the northeastern part of the Southern Wanneroo Groundwater Area in an area of high density private abstraction. There are a large number of lakes and wetlands in the Southern Wanneroo Groundwater Area and watertable (and lake level) declines have been associated with documented environmental impacts (WRC, 2004). The observed hydrographs (Figure 31) show a fairly stable trend, with declining levels over the last 8-10 years (1996 to 2004).

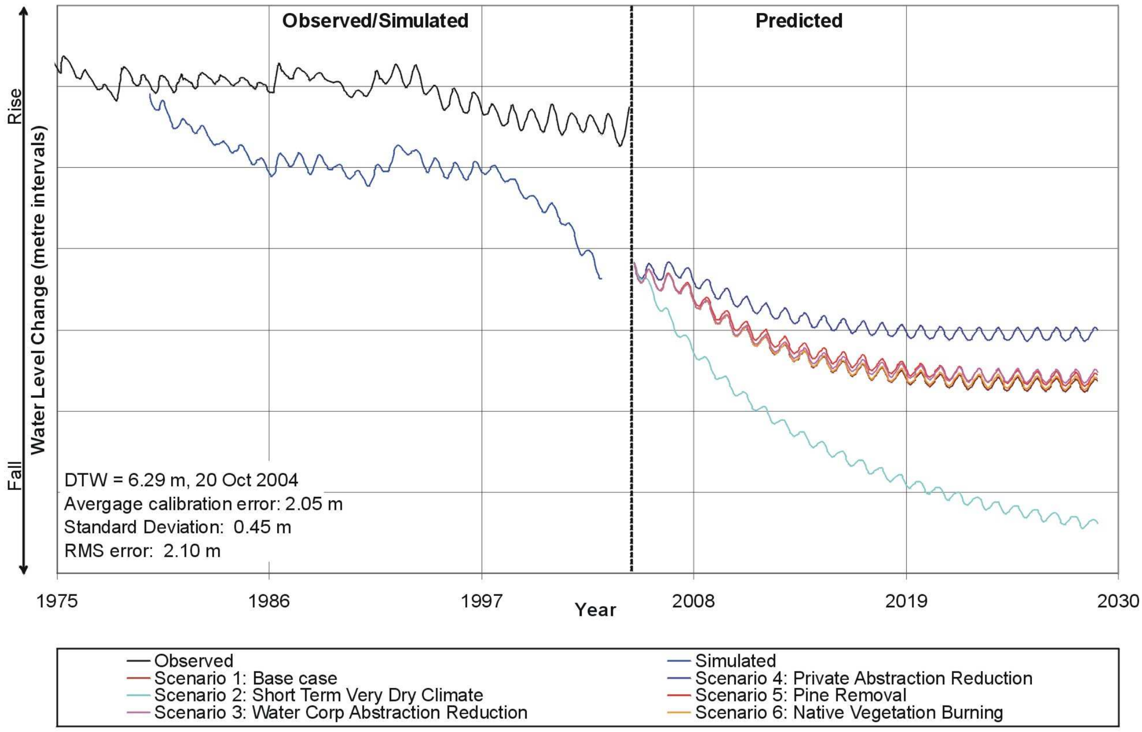

Figure 31. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore JP9.

The predictive hydrographs (Figure 31) show watertable declines are likely to continue, however given the large, unrealistic declines predicted, compared to those observed, the validity of the model in this area must be considered. The level of allocation in the Southern Wanneroo Groundwater Area is approximately 20 GL/yr and for the purposes of modelling it assumed that all of this volume is abstracted. Considering the model output, it is likely that the level of abstraction currently used in the model is too high. The unrealistic declines could also be caused by the poor representation of lake-aquifer interaction by PRAMS.

The most effective way to refine the model in the area is to increase our understanding of the location, quantity and temporal distribution of abstraction by installing flow meters on bores, then recalibrating. If the errors are still intractable they are likely be related to insufficient representation of surface water groundwater interaction. The Gnangara Groundwater Mound Metering Program in the Carabooda Subarea of the Northern Wanneroo Groundwater Area and the Southern Wanneroo Groundwater Area has been included in the Department of Water metering program and these results will be used to refine PRAMS.

Regardless of the level of uncertainty in the predictive modelling, the sensitivity of the model to the main components can be discerned. At JP9 the difference in groundwater levels between the climate at the medium-term, dry climate component in the base case (Scenario 1) and the short-term, very dry climate component (Scenario 2) is as much as 3 m. The 20% private abstraction reduction (Scenario 4) produces a relative recovery of 1.5 to 2 m after 20 years. The other modelled scenarios produced little or no impact in this area.

3.2.13 Hydrograph – WM28

WM28 is located in the southern part of the Southern Wanneroo Groundwater Area, a region of high private abstraction. The model results at WM28 are similar to the model results at JP9, except that manipulations in Water Corporation abstraction (Scenario 3), percentage area of native vegetation burning (Scenario 6) and pine removal (Scenario 5) produce about 1 m of relative recovery. This is due to the proximity of this site to the Wanneroo borefield, the area of remnant vegetation and the pine plantations.

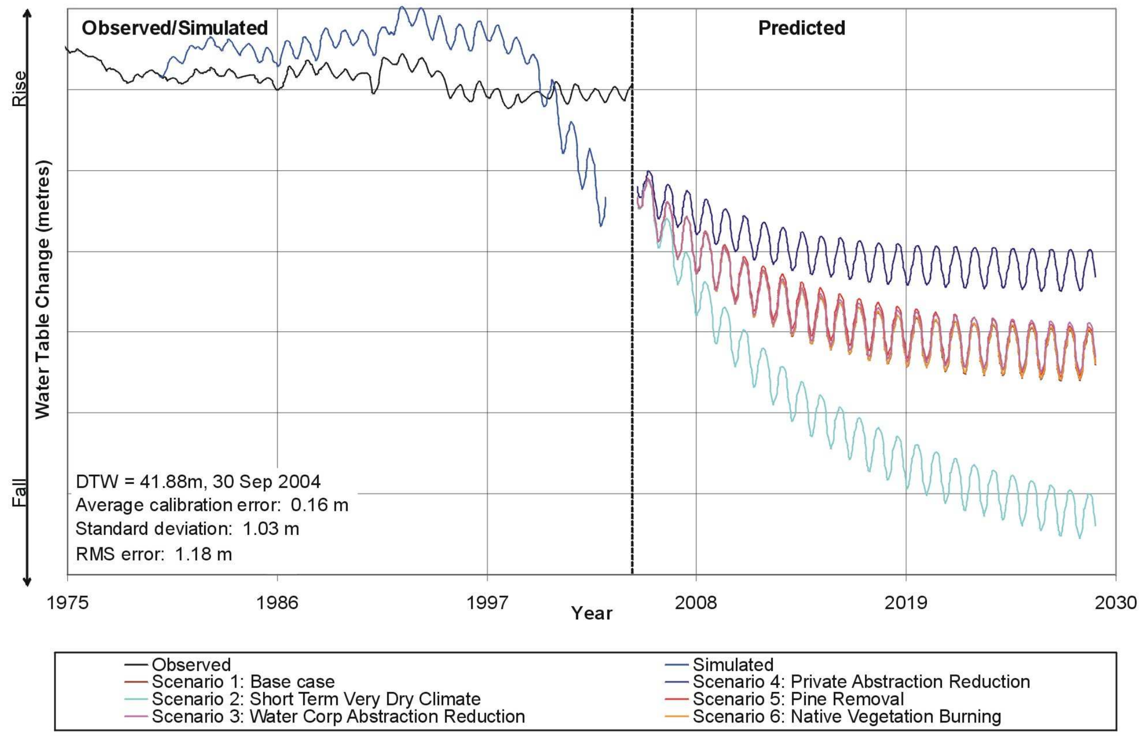

Figure 32. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore WM28.

3.2.14 Hydrograph – WM32

WM32 is located in the Lexia pine plantation, close to an area of remnant native vegetation. Lexia also contains abundant wetlands, many of which contained open water bodies. The water bodies have since dried and the wetlands have terrestrialised over recent years. The observed hydrograph (Figure 33) has a relatively stable trend but has begun to decline sharply in the last 6-8 years (1996 to 2004).

The predictive hydrographs (Figure 33) show the high sensitivity of this area to climate. There is 4 to 5 m watertable difference between the hydrographs for Scenario 1 (the base case using the medium-term, dry climate component) and Scenario 2 (using the short-term, very dry climate component). The model shows limited sensitivity to the other scenarios. Pine removal (Scenario 5) produces the greatest relative recovery initially (1 to 1.5 m) but the difference rapidly decreases until the curves rejoin. This clearly shows how the effect of a large increase in recharge (due to vegetation density reduction) is dampened by the short-term, very dry, low rainfall climate component. The other model scenarios show little impact at WM32, with the Water Corporation abstraction reduction (Scenario 3) producing 0.5 m of relative recovery, an increased percentage area of native vegetation burning (Scenario 6) and private abstraction reduction (Scenario 4) producing no increase in watertable.

The model results imply that at WM32 the dominant impacts on future groundwater levels are, in order of greatest to least impact: climate, pine plantations, Water Corporation pumping and finally private abstraction and percentage area of native vegetation burning equally. The results clearly demonstrate the distinctly differing responses of the watertable to the medium-term, dry climate in the base case scenario (watertable stabilisation/recovery) and the short-term, very dry climate scenario (substantial watertable decline).

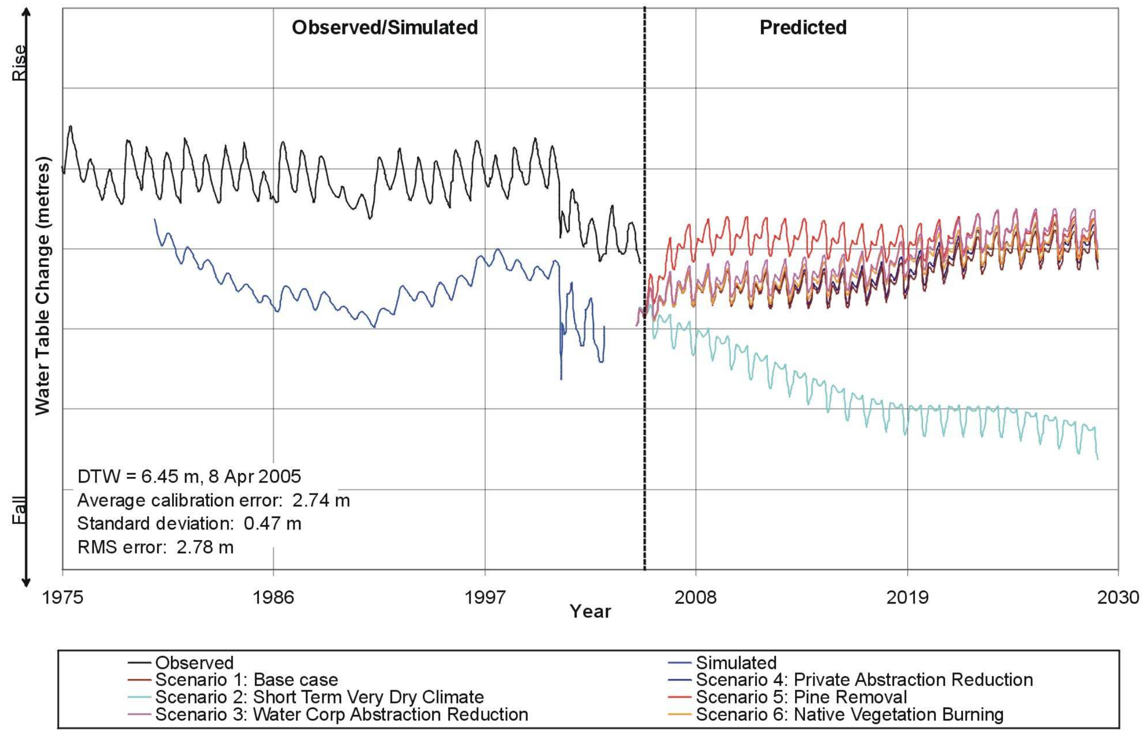

Figure 33. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore WM32.

3.2.15 Hydrographs – MM59B and MM26

MM59B and MM26 are located in the Mirrabooka Groundwater Area, south of the pine plantations in Whiteman Park. The observed hydrographs (Figures 34 and 35) show a gradual declining trend in water levels compared to hydrographs at the other sites. MM59B and MM26 are located near the discharge flanks of the mound and hence long-term watertable fluctuations are attenuated. This attenuation is due to the large quantities of water flowing through the system and discharging at the margins, and by evapotranspiration. By comparison, there is evidence that the watertable at the recharge core of the mound has fluctuated substantially throughout recent geological time (McHugh and Vogwill, 2005).

The predictive hydrographs (Figures 34 and 35) indicate the gradual decline in groundwater levels is predicted to continue. The watertable appears stable under the medium-term, dry climate (Scenario 1) and shows a gradual decline under the short-term, very dry climate component (Scenario 2). The difference between both hydrographs is approximately 1.5 m at 2029. The model shows limited sensitivity of the watertable at these two bores to manipulations in other components.

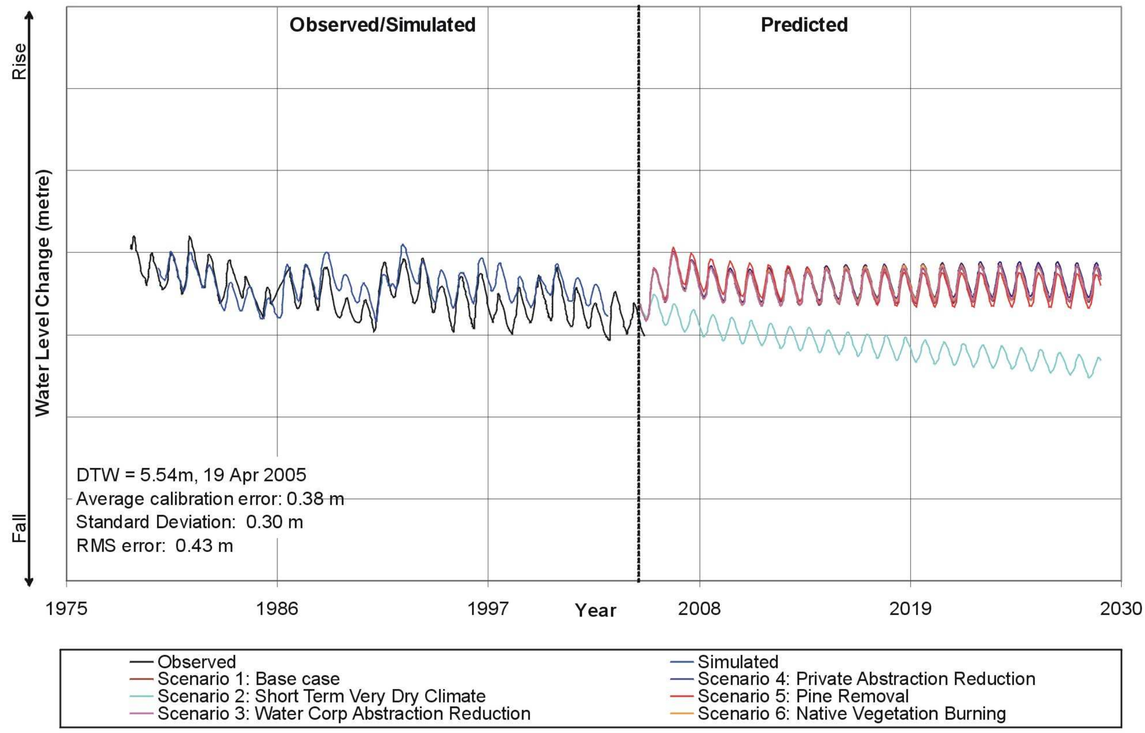

Figure 34. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore MM59B.

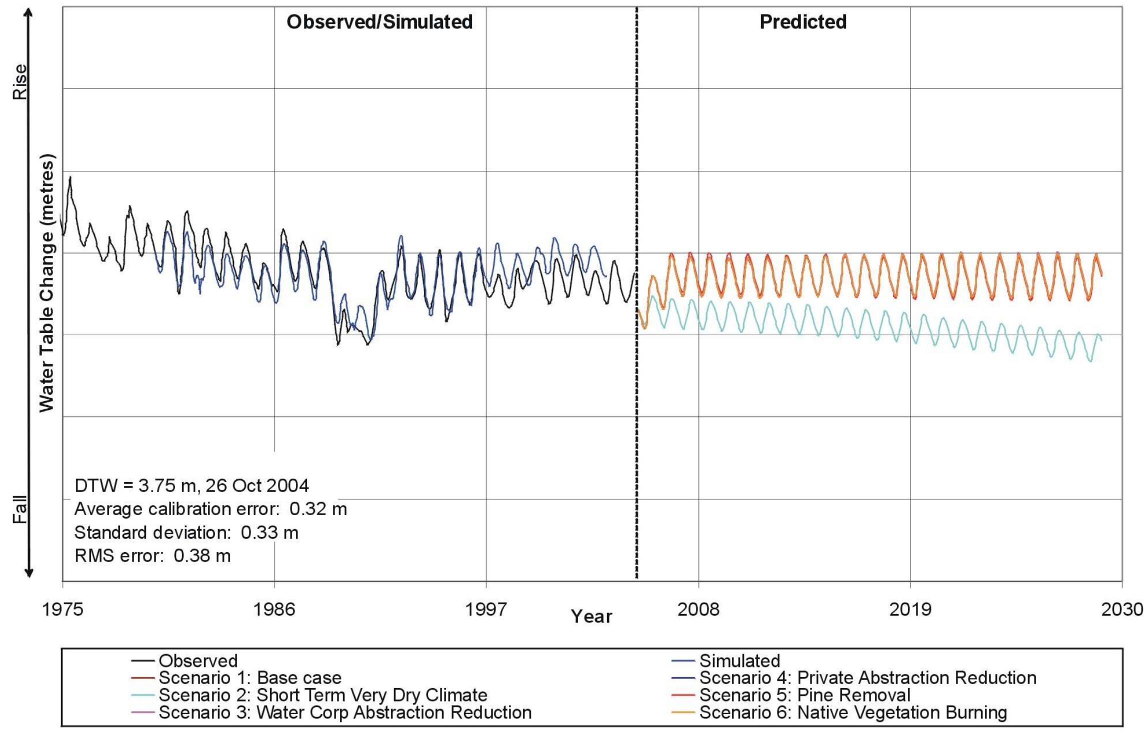

Figure 36. Observed and predicted hydrographs for the 6 modelling scenarios at monitoring bore MM26.

3.3 Volumetric analysis

Volumetric analysis uses PRAMS to calculate the change in groundwater storage in the superficial aquifer from 2004 to 2014 for the 10 Gnangara Mound zones (see Figure 1) for each of the six modelling scenarios (Table 9). Storage change is also shown graphically for each scenario in the sections below. This analysis allows changes in land and water use to be compared with the storage change. The validity of using PRAMS to model storage change is proven by comparing the storage changes calculated from hydrographs with the modelled results (Figure 36). The correlation coefficient (r) between the modelled and measured storage changes is 0.91 (r^2=0.85) and indicates that PRAMS based storage changes are acceptable. The specific yield (S_y) used in the calculations was 0.25, which is within the range of the PRAMS values for the Gnangara Groundwater Mound of between 0.2 and 0.3. Cymod Systems (2004) provides more information on the parameters used in PRAMS.

3.3.1 Base case: Scenario 1

Under the base case (Scenario 1), additional storage declines are predicted across most of the Gnangara Groundwater Mound after 10 years to 2014 (Figure 37 and Table 9). Nearly 400 GL of additional storage decline is predicted using PRAMS. Most of this decline occurs in the Pinjar and Yeal zones with slight storage increases predicted for the Mirrabooka and Perth Urban North zones due to the removal of the pine plantation and urbanisation respectively. The Lexia zone is stable and the remaining zones experience modest declines in storage. This storage decline is in addition to the 550 to 600 GL decline in storage that has already occurred.

Table 9. Gnangara Groundwater Mound storage declines (GL) based on PRAMS.

	Model Scenario					
Gnangara Mound Zone	**Base Case (GL)**	**Private Abstraction Reduction (GL)**	**Native Vegetation Burning (GL)**	**Short Term Climate (GL)**	**Pine Removal (GL)**	**Water Corporation Abstraction (GL)**
Gwelup	-32.08	13.10	0.01	-39.33	0.55	3.70
Lexia	0.33	9.49	13.43	-86.24	26.08	16.45
Mirrabooka	16.28	3.73	0.11	-24.07	0.67	1.89
Northern WGA	-15.13	6.71	2.69	-21.97	21.59	2.78
Pinjar	-122.58	4.90	45.54	-83.17	37.96	22.56
Perth Coastal	-20.54	6.52	1.83	-21.89	4.90	2.33
Peth Urban North	3.78	7.55	0.04	-32.66	0.08	1.29
Southern WGA	-23.59	14.89	0.39	-32.38	5.81	2.99
Yanchep	-27.64	1.42	11.83	-16.44	91.37	3.90
Yeal	-171.88	10.95	59.89	-106.17	66.98	15.08
Total	-393.04	79.27	135.77	-464.31	256.00	72.98

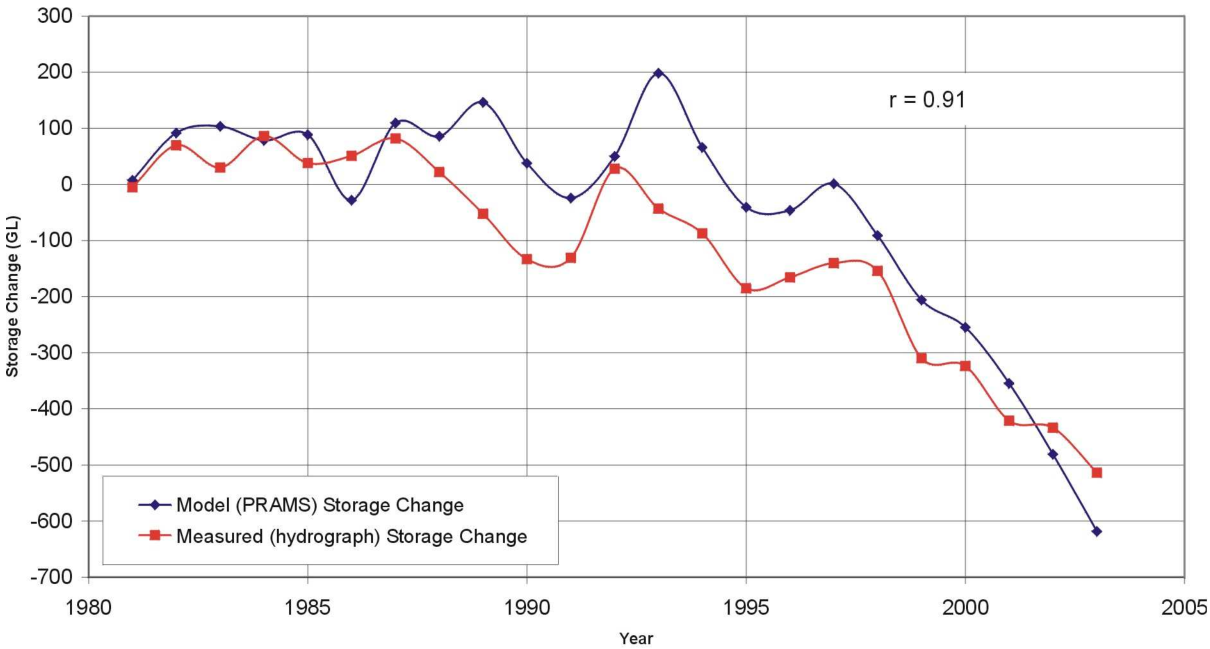

Figure 36. Correlation of measured (hydrograph) and modelled (PRAMS) storage declines 1980 – 2003.

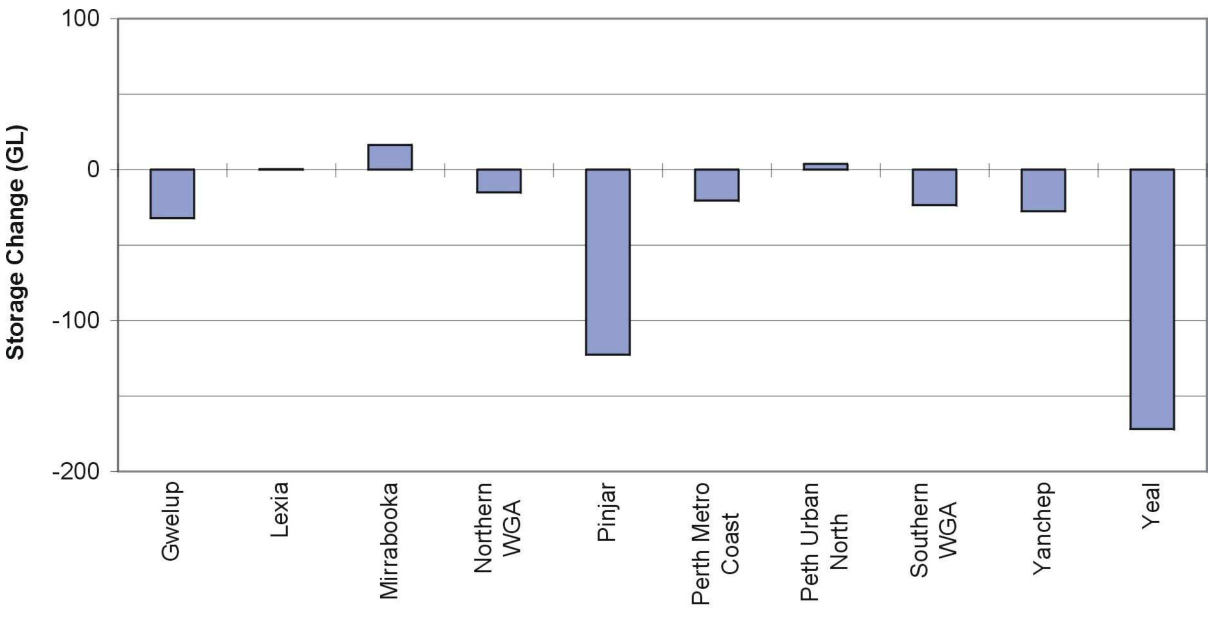

Figure 37. Storage changes for each of the Gnangara Mound Zones – Scenario 1: base case.

3.2.2 Short-term, very dry climate: Scenario 2

The results of the short-term, very dry climate scenario show that substantial additional declines (450 to 500 GL) on top of the base case declines (~400GL) equate to 850 GL of storage decrease across Gnangara Groundwater Mound (Figure 38).

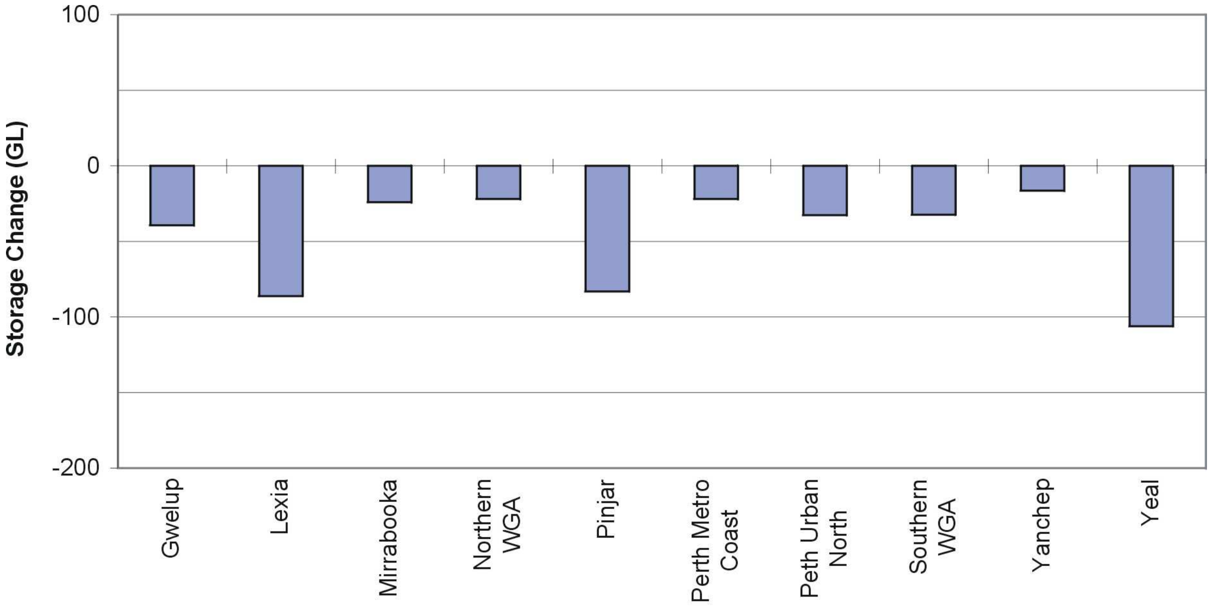

Figure 38. Storage changes for each of the Gnangara Mound Zones – Scenario 2: Short-term, very dry climate.

3.3.3 Water Corporation abstraction reduction: Scenario 3

The impact on storage of reducing Water Corporation abstraction by 30 GL/yr is given in Figure 39 (and Table 9). This modelling component reduces abstraction by 5, 8 and 17 GL/yr from the superficial, Leederville and Yarragadee aquifers respectively. The impact of reducing the Water Corporation abstraction by 30 GL/yr is only an additional 70 GL of water in storage to the superficial aquifer after 10 years. As previously discussed, the impact of the additional 25 GL of confined aquifer abstraction is a small drawdown in the superficial aquifer over a very large area (primarily in the areas of aquifer connectivity, but small increases in leakage will occur elsewhere). Superficial aquifer abstraction produces large magnitude impacts but with a small aerial extent, i.e. large drawdown close to the bore.

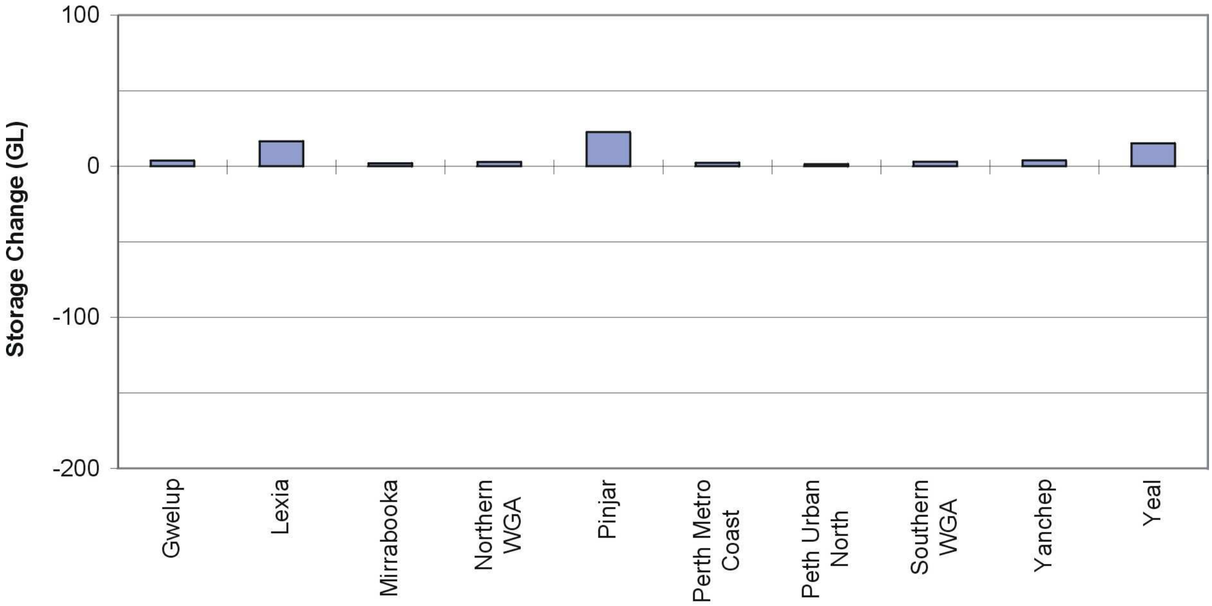

Figure 39. Storage changes for each of the Gnangara Mound Zones – Scenario 3: Water Corporation abstraction reduction.

3.3.4 Private abstraction reduction: Scenario 4

The 20% reduction in private abstraction equates to a reduction in abstraction of approximately 43.5 GL/yr; 37 GL/yr from the superficial aquifer and 6.5 GL/yr from the confined aquifers. A 20 % reduction has been used as it is the quantity currently assumed to be gained from increases in efficiency as opposed to other reductions such as crop area. The impact on storage is similar in magnitude to the reduction in Water Corporation pumping and produces a similar volumetric outcome of 80 GL of additional water in storage after 10 years to 2014 (Figure 40 and Table 9).

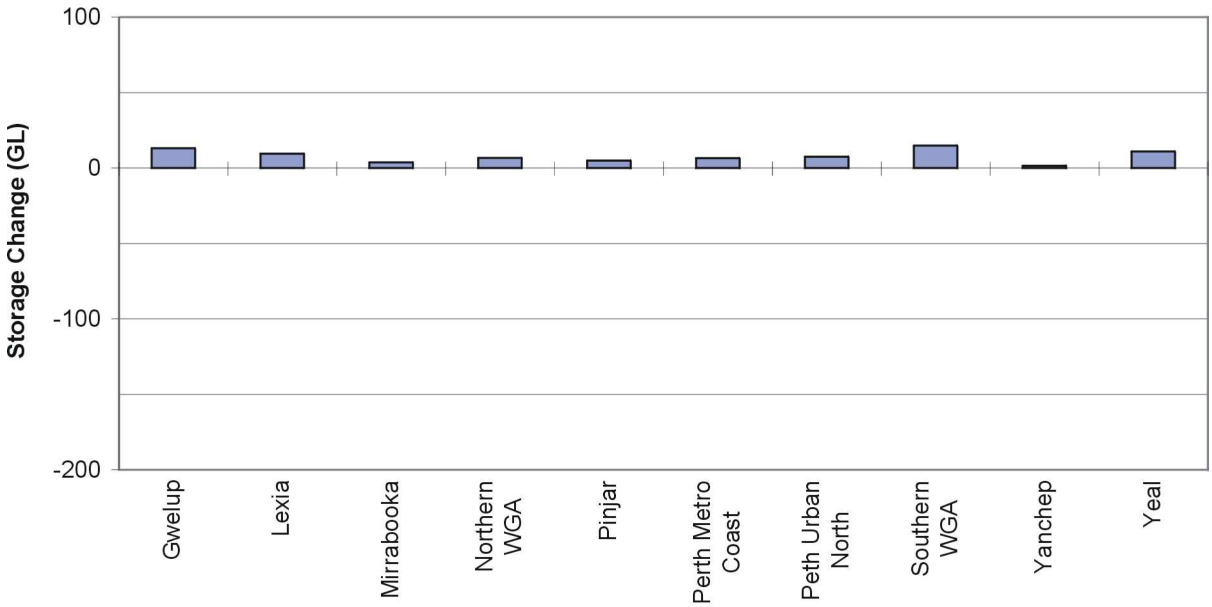

Figure 40. Storage changes for each of the Gnangara Mound Zones – Scenario 4: Private abstraction reduction.

3.3.5 Pines removal: Scenario 5

In the base case, the pine plantations on the Gnangara Groundwater Mound are being removed as per the LVL agreement over the next 20 years. The volume of additional water stored in the Superficial aquifer, if the pines were instantaneously removed and replaced with low-density native vegetation, is an additional 250 GL of water in storage after 10 years to 2014 (Figure 41 and Table 9). These results are similar in magnitude to the native vegetation burning area increase (see Section 3.3.6) except in the Yanchep zone where pines are scheduled to be removed last. The Yanchep zone has high depth to groundwater and hence little dependence on groundwater levels.

3.3.6 Increased % area of native vegetation burning: Scenario 6

Changing native vegetation density by increasing the percentage area of burning potentially shows a significant impact on water levels. Increasing the percentage area to 7.5% results in 135 GL of additional water in storage in the superficial aquifer (Figure 42 and Table 9). This relative increase in storage occurs mostly in the zones of dense native vegetation in the Pinjar and Yeal zones.

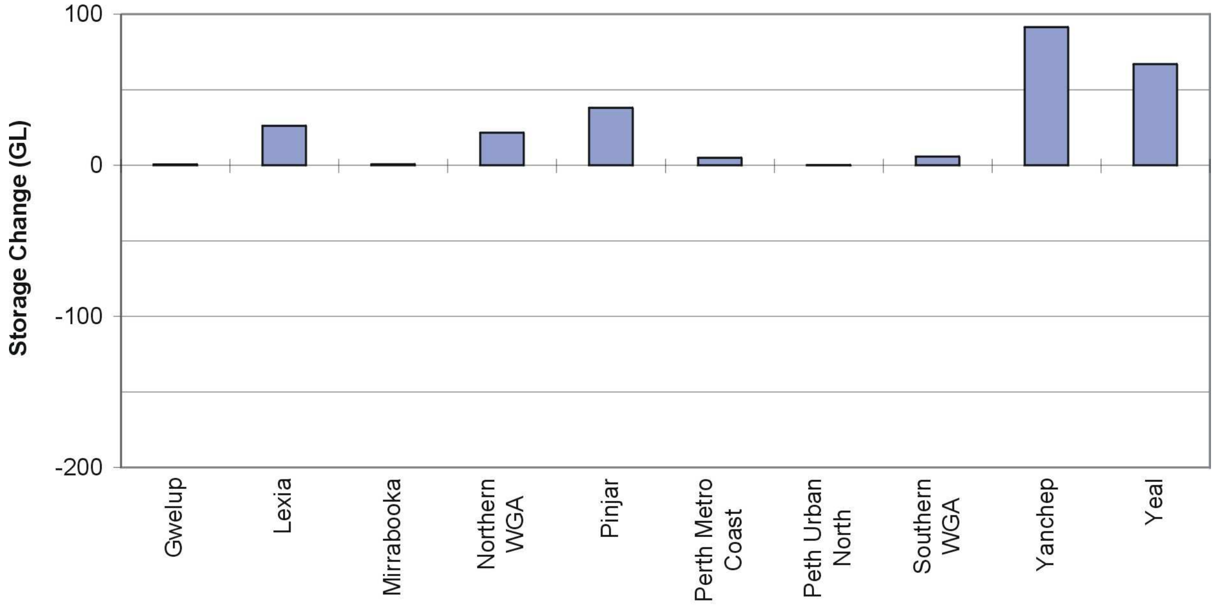

Figure 41. Storage changes for each of the Gnangara Mound Zones – Scenario 5: Pines removal.

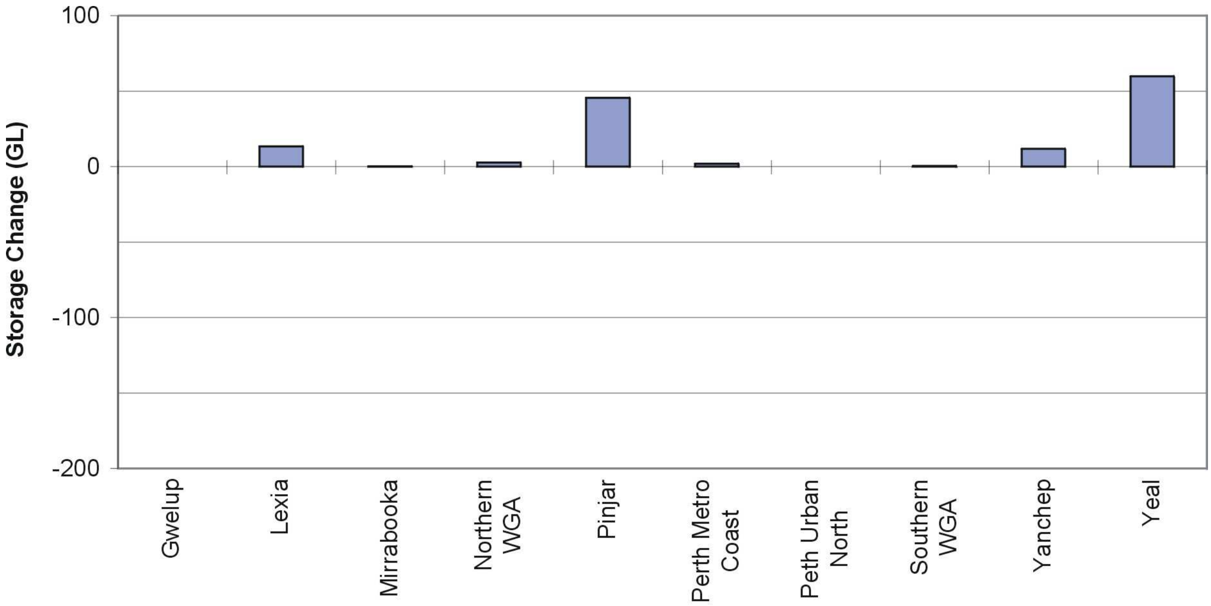

Figure 42. Storage changes for each of the Gnangara Mound Zones – Scenario 6: Increase in % area of native vegetation burning.

3.4 Water balance

The model water balance is a useful tool for tracking the “movement” of water, enabling a better appreciation of how the system functions. By computing annual water balances for the Gnangara Groundwater Mound (i.e the superficial aquifer) (Figure 43) and looking at storage changes for each year it is possible to improve the understanding of the main causes of change to the groundwater system.

Figure 43 shows a water balance for the Gnangara Groundwater Mound. Storage is represented as a water source in the water balance and hence positive numbers represent increases in storage and negative numbers represent water decreases. Net recharge ranges between about 200 GL/yr and 600 GL/yr. After 1994 net recharge is distinctly lower. It is the lack of high net recharge years such as 1987 or 1993 that explains the failure to “replenish” storage in Gnangara Groundwater Mound. This analysis may also explain the sensitivity of the model to the synthetic rainfall sequence used in the modelling, which by its method of construction may omit high (and very low) rainfall years. Future scenario modelling using rainfall time-series that includes high rainfall years will determine whether the scenario modelling presented here underestimates recharge and overestimates the sensitivity of the model to rainfall.

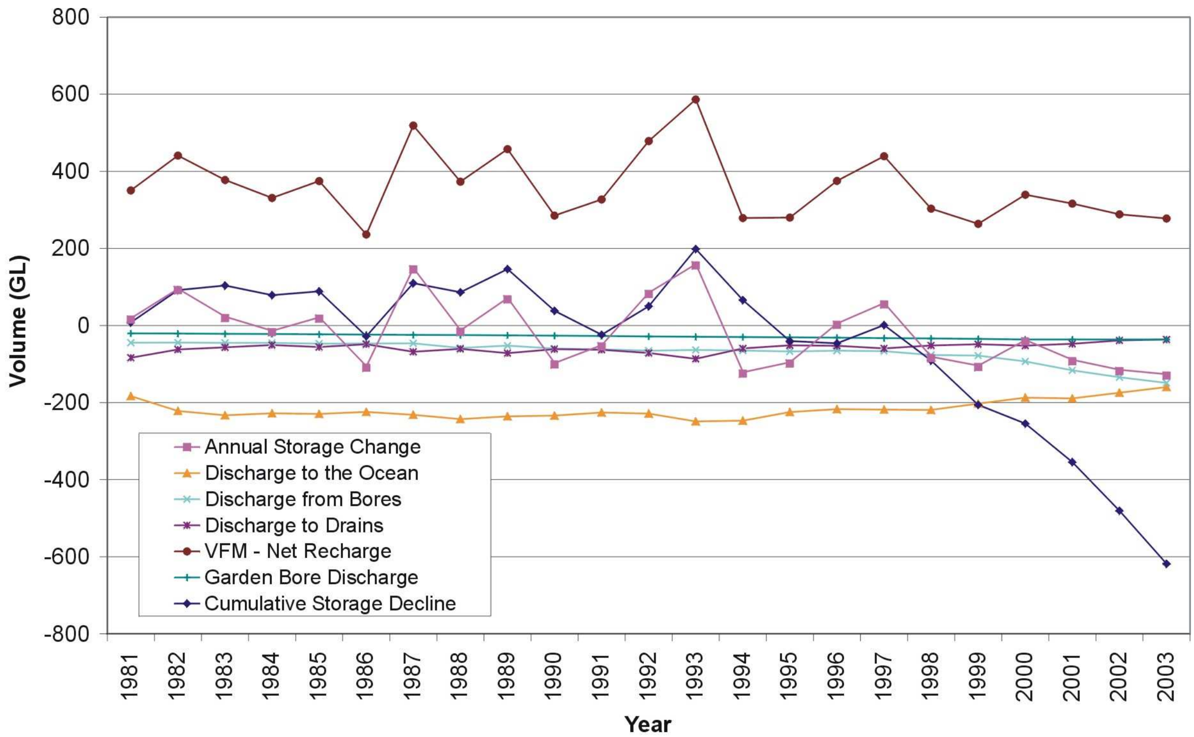

Figure 43. PRAMS annual water balances for the Gnangara Groundwater Mound.

Storage changes in the superficial aquifer of Gnangara Groundwater Mound vary by as much as 150 GL/yr. There is a distinct positive relationship between annual storage change and net recharge, clearly demonstrating the strong control net recharge has on storage change (Figure 44). Net abstraction from the superficial aquifer has increased gradually from 44 GL in 1981 to 150 GL in 2003. It is the decrease in net recharge combined with the increase in net abstraction that mainly results in a cumulative storage decline of 600 GL at the end of 2003. In order to balance the rainfall decline and abstraction increase, modelling shows that, to prevent further storage decline, given the abstraction rates used in the model, about 375 to 400 GL/yr of net recharge is required. This recharge rate represents a fulcrum or threshold in the net recharge of Gnangara Groundwater Mound. Section 3.3 discusses how closely the model output matches with the observed storage changes and validates modelling storage changes and net recharge of Gnangara Groundwater Mound.

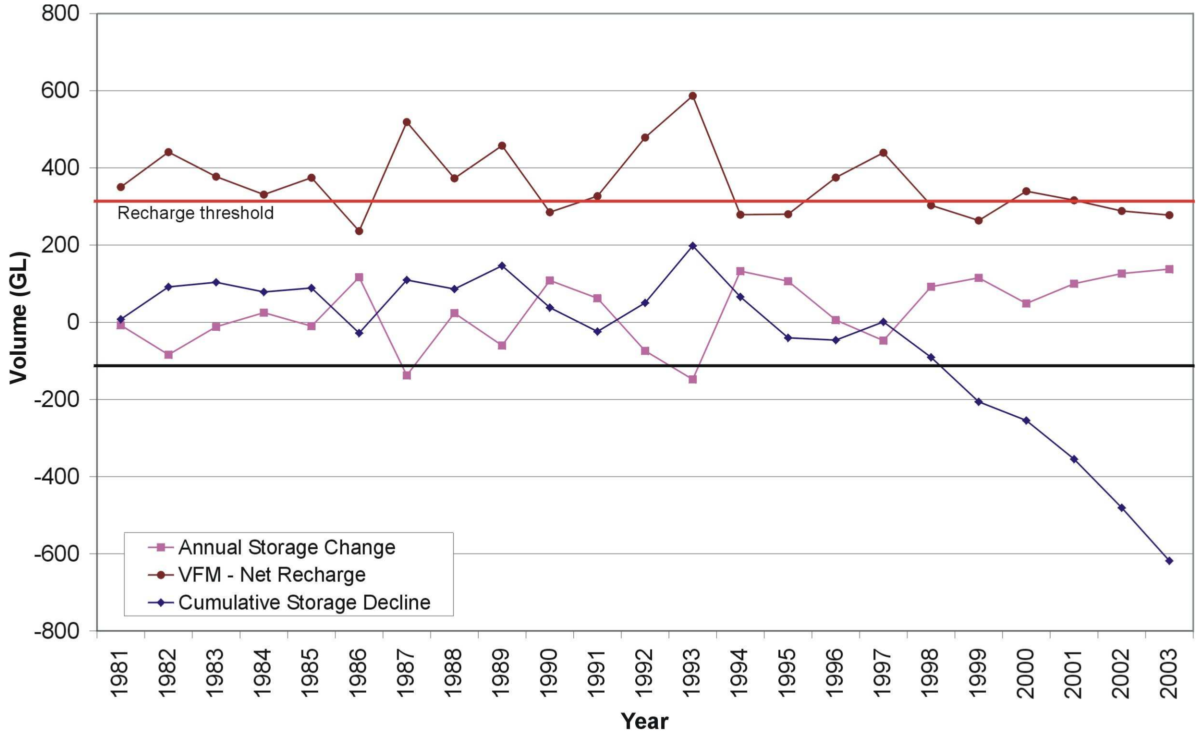

Figure 44. PRAMS storage changes (annual and cumulative) and net recharge for the Gnangara Groundwater Mound.

4 Discussion of results

4.1 Climate

PRAMS modelling demonstrates that regionally climate is an important input component in a PRAMS scenario and that climate change is one of the main drivers of groundwater declines on Gnangara Groundwater Mound. The results of the base case scenario and the low-rainfall, short-term climate scenario (Scenario 2) predict that the watertable will continue to decline over large areas if all other components are held constant.

Contour analysis shows that across the Gnangara Groundwater Mound, the model is very sensitive to variations in rainfall, and the hydrograph analysis demonstrates that watertable fluctuations near the recharge area of the mound are primarily controlled by changes in rainfall, and to a lesser degree land-use. Similarly, volumetric analysis demonstrates that, in terms of storage changes, climate has a greater impact than the model components based on the limited set of modelling scenarios. However, the method of constructing the rainfall sequence used in the modelling may underestimate recharge and therefore overestimate the impact of rainfall decline.

Comparison of the base case with Scenario 2 (short-term, very dry climate) predicts a 2 to 4 m watertable level decline over much of the mound from a 10% rainfall difference. These results are in close agreement with previous hydrograph analyses (Yesertener, 2002, 2003, 2007) that identified climate change and increased vegetation density impacts as the dominant causes of watertable decline.

The areas of Gnangara Groundwater Mound, which have a limited sensitivity to climate are;

- The northern part of the mound where the very dense Yanchep pine plantation intercepts rainfall preventing recharge groundwater.
- The eastern area of the mound which is a discharge area and dominated by the Guildford Clay and has a shallow watertable.
- The western area of the mound, which is also a discharge area and dominated by the Tamala Limestone that has a very high transmissivity and a deep watertable.

The modelling results presented here improve on the previous work by incorporating the percentage area of native vegetation burning changes and differentiating between Water Corporation and pine related recharge declines in the southern part of the mound.

4.2 Abstraction

The PRAMS scenarios show the relative impact of reductions in Water Corporation and private licence allocations on groundwater levels on the Gnangara Groundwater Mound. The relationship between actual volumes of groundwater abstraction versus assumed allocations is still ambiguous in some of the high groundwater-use areas.

The impact of reducing Water Corporation abstraction is greatest at the Wanneroo and Pinjar borefields. Reductions in superficial aquifer Water Corporation abstraction will create a larger recovery over a smaller area near the bores. Reductions in confined aquifer Water Corporation abstraction will increase water levels over a smaller area in the superficial aquifer in the area of aquifer connectivity. However, volumetric analysis shows that abstraction reductions do not appear significant. This is primarily due to the comparatively small reduction in the Water Corporation superficial aquifer abstraction (i.e. 5GL). Impacts close to bores in the superficial aquifer can often be large and dominate the climate impacts. The impact of pumping the confined aquifer by the Water Corporation is important particularly in the Yeal and Pinjar zones, but not for Gnangara Groundwater Mound as a whole.

The predicted declines from private abstraction impacts in some parts of the model domain are unrealistic, particularly those near the Gwelup borefield and southern Wanneroo Groundwater Area. These unrealistic predictions are due to the uncertainty in the allocation database and are associated with areas of “phantom allocations” (areas that have been heavily allocated in the past, have been urbanised but the allocations remain). For more accurate modelling results, these phantom allocations should be removed. This will require on-the-ground surveys which may result in the recovery of substantial volumes of unallocated water for possible reallocation.

No garden bore manipulation scenarios were run as it is considered an unrealistic target for private abstraction reduction. One management option is to restrict the construction of new garden bores in areas of heavy allocation and large declines. Recent studies of the impacts of urbanisation (Vogwill, 2003) show that lot size, bore distribution and water trading need careful control to achieve planned reductions in abstraction.

4.3 Land-use

Modelling with PRAMS shows that land-use changes can increase recharge in some areas across the Gnangara Groundwater Mound. Changing native vegetation density by increasing the annual percentage area of burning is an effective method for increasing recharge, particularly in the northeast part of the Gnangara Groundwater Mound (i.e. Yeal Swamp). This is primarily due to the decrease in native vegetation burning over the past 25 years *(*Mattiske *pers. comm*., 2004). The pre-European burning frequency is believed to have been every 2 to 4 years (Kelly, 1999). However, large areas of the mound have not been burnt for at least 10 years with some areas up to 25 years (Paul Brown, *pers. comm.*). This burning regime over the last 25 years has reduced recharge, which has contributed to additional watertable decline. Unlike pine trees, which have a positive impact on groundwater recharge levels for the first 5 to10 years of growth following clearing, native vegetation density has increased (through a decrease in percentage area of native vegetation burning)and hence recharge has declined.

PRAMS modelling scenarios suggest that increases in recharge to the Gnangara Groundwater Mound can be achieved by increasing the percentage area of annual controlled burning. It should be acknowledged that the conversion of all high density *Banksia* woodland into low-density woodland would have biodiversity and conservation considerations, and a substantial increase in costs (Paul Brown, *pers. comm.*).

PRAMS modelling results also demonstrate that pine plantation clear-felling or thinning will increase water levels, primarily in the western part of the mound and particularly in the areas of heavy dense pine plantations, in the Pinjar and Yanchep management zones. The modelling results also show that a smaller water level increase is likely in areas that are not directly overlain by pine plantations (e.g. Wanneroo Groundwater Area). There has been a general expectation that removal of the pines would provide a large input of water, significant enough to facilitate continued and sustainable abstraction at current volumes. However, volumetric analysis indicates that this scenario would not produce large volumes of water in those subareas (i.e Wanneroo) where abstraction is greatest, for additional abstraction. Nevertheless, the increase in superficial aquifer storage is locally substantial (i.e. 256 GL over 10 years).

Urbanisation is effective for increasing groundwater recharge on a local scale and represents a watertable decline mitigation tool. Mitigation is achieved by a combination of abstraction reduction and the increase in recharge from urbanisation. However, the benefits of urbanisation could be compromised if water trading agreements amount to “double-dipping”, where licences are transferred within the same groundwater area and large numbers of garden bores are installed in the new urbanised areas from which the water has been transferred.

4.4 PRAMS calibration

The PRAMS calibration has improved substantially since Stage 1 (Vogwill, 2004) and is now considered suitable for regional to subregional assessment (Merrick, 2006a, 2006b). The trends in the predicted and observed hydrographs match well and the water balance-storage change modelling agrees closely with the analysis of the observed storage declines.

The present calibration of the model is not sufficient to predict the watertable change near or within wetlands. Surface water bodies cannot be accurately modelled using a regional scale groundwater model with a cell size of 500 x 500 m. The use of

MODFLOW and the VFM overly simplifies the interaction of surface and groundwater.

The model has accurate, reliable water balances and is an excellent tool for looking at the area of influence of an individual model component. For example, the watertable difference map for the public water supply abstraction shows the likely extent of future impacts from public water supply abstraction. However, volumetric analyses need refinement and field verification, particularly the percentage area of native vegetation burning reduction scenarios.

Poor calibration of the model is identified in zones of high groundwater use by private licensees, due to uncertainties in the allocation database. It is likely that in some areas the licensed allocation is under-used, and in other areas over-used. This leads to under and over predictions of drawdown. The results from the Gnangara Mound Metering Program will be used to refine private abstraction input data for future PRAMS modelling.

5 Conclusions

This modelling study determines the relative impacts of land-use, water use and climate variability, on the watertable and storage capacity of the Gnangara Groundwater Mound under a limited set of scenarios. Scenario modelling results provided by contour, hydrograph and volumetric analyses indicate that:

- Climate is a dominant influence on superficial aquifer groundwater levels. PRAMS is very sensitive to variations in rainfall and the model predicts a continued decline in groundwater levels, under the medium-term, dry climate base case scenario (Scenario 1). Model sensitivity to rainfall may be a function of the method in which the rainfall sequence was derived, and as such recharge may be underestimated and watertable sensitivity to rainfall overestimated. Watertable declines are most evident on the recharge areas of the Gnangara Groundwater Mound. The short-term, very dry climate scenario (Scenario 2) predicts further declines. PRAMS predicts that groundwater levels will continue to decline unless annual rainfall increases by 100 to 200 mm/yr (i.e. to about 800 to 900 mm/yr).
- The predicted watertable rise in the southern part of the mound based on the medium-term dry climate scenario is mainly due to removal of the pine plantation under the current LVL agreement, and shows the potential impact of this type of land-use change on water levels.
- Land-use changes can increase groundwater levels, such that:
  - ➢ Thinning pine plantation density will increase groundwater levels with the greatest effect in areas directly overlain by pine plantations.
  - ➢ Increasing the burning area of native vegetation is also likely to increase groundwater levels over a similar area, but with a lower magnitude. The approach used to derive burning area-recharge relationships is somewhat simplified and needs refinement. This is essential given native vegetation covers 50% of Gnangara Groundwater Mound. The relationship between climate variation and vegetation change was not modelled.
  - ➢ Under the short-term, very dry climate scenario, the impact of vegetation density reduction may be minimal.
- PRAMS provides an indication of the impact of reducing groundwater abstraction on groundwater levels:
  - ➢ Reductions in superficial aquifer Water Corporation abstraction will create a larger magnitude of recovery over a smaller area near the bores. Reductions in confined aquifer Water Corporation abstraction will create greater recovery in the superficial area in areas of aquifer connectivity. More rigorous scenario modelling, including sensitivity

analysis is required for a more complete understanding of changes in abstraction and impact on the watertable.

  - The available records of private abstraction are inadequate, leading to poor calibration and intractable errors in some small, isolated parts of the PRAMS domain.

- A net recharge threshold has been identified by the use of the water balance of PRAMS. The threshold required to balance the cumulative effects of historical abstraction and rainfall on superficial aquifer storage ranges between 375 and 400 GL/yr. Groundwater storage will decline if net recharge is below 375 to 400 GL/yr and will increase if it is above the threshold, providing that 2003 conditions of abstraction and land-use are maintained. This threshold is also dependent on an annual rainfall of 788 mm/yr.

6 Recommendations and future work

Direct recommendations that arise from this modelling assessment are:

- The results generated (i.e. watertable difference, contour maps) should be incorporated into groundwater management plans and factored into groundwater management decisions.
- The modelling approach should be integrated in the EWP process as a tool to assess, evaluate and set realistic groundwater levels that take into consideration likely land-use and abstraction regimes and incorporate a drying climate. This should include a re-evaluation of current water level criteria, since PRAMS has shown that site-specific breaches of water level criteria are due to complex interactions of land-use change and abstraction, superimposed on the background of regional watertable decline due to climate variations.

To improve model results, further work is required to understand the influence of model inputs and components. This work should be undertaken in close co-operation with individual stakeholders to ensure that the scenarios are realistic, relevant and will provide a diverse range of modelling scenarios required for sustainable groundwater resource management.

Suggested focus areas of future work include:

- Detailed hydrogeological investigations of individual wetlands and other GDEs to determine the interaction of the regional groundwater flow regime with the local watertable. This should include determination of the palaeohydrology of wetlands, so that the observed and predicted groundwater declines can be evaluated over a much longer period than the currently monitored record allows. These long-term hydrological changes in wetlands can also be incorporated into the EWP process. The Investigation of the Sustainablity of Shallow Groundwater Systems in the Perth Region (Perth SGS Investigation Program) will provide this data and will be used to develop site-specific, local-scale groundwater models.
- Assessment of model components to improve calibration:
  - The allocation database needs refinement so that private allocation and actual abstraction are represented more accurately. This is required to be determined for the present, with the use of meters, and if possible the results of the metering should be extrapolated into the past to improve the model calibration.
  - The VFM requires an improved understanding of the different land-use types and the resulting groundwater recharge. The usual method of calibrating a groundwater model, by manipulating the recharge magnitude and location to improve the calibration and reduce the

residuals (difference between observed and predicted values), is not possible in PRAMS due to the VFM. The VFM can be changed to improve calibration but, with so many parameters, field observations are required to back up any changes in the model or VFM recharge relationships.

  - Studies are required to better determine pine plantation absolute water use and the ability of the pine trees on Gnangara Groundwater Mound to directly access groundwater under various climate regimes.
  - Studies are required to better estimate native vegetation absolute water use under various climate regimes.
  - Improved calibration of satellite imagery will reduce the error and LAI “drift” between satellite images. More ground measurements (under-storey verses canopy and ground base LAI determinations) are required to improve the modelling of LAI based PRAMS land-uses.
  - The impact of bush wild fires, controlled burns, and native vegetation thinning on groundwater recharge needs to be better understood.
  - The impact of an increased native vegetation-burning regime needs to be studied and evaluated from both a groundwater recharge and biological perspective.

- Future modelling work should include:
  - Specifically designed climate scenarios representing both increases and decreases in rainfall and that incorporate high rainfall events/years.
  - The likely range of watertable changes, based on the possible extent of future climate regimes. This is achievable with PRAMS but requires reliable local to regional scale predictions translated from Global Circulation Models (GCMs).
  - Local scale models that bridge the gap between PRAMS and the site-specific wetland criteria. These models need to include: detailed unsaturated zone moisture content modelling; watertable fluctuations and very accurate depth to water relationships; seepage face and drainage modelling; overland flow modelling; detailed evapotranspiration modelling.
  - Variation of Water Corporation abstraction through the entire possible range (e.g. 0 to 180 GL), to better evaluate the impact of abstraction on the watertable.

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Appendices

Appendix 1— GIS based vegetation (*Banksia*) burning and pines modelling methodology

The temporal distribution of both DEC controlled burns and wildfires is shown in Figures 1 to 4.

The distribution of pine plantation stands and the thinning regime as per the LVL agreement are shown in Figure 5.

GIS Methodology

The following outlines the GIS methodology used to set up, model and execute the *Banksia* / fire relationship for PRAMS modelling scenarios.

The WAVES 2002 land-use data was used as a base for native vegetation density changes and only the *Banksia* areas (low, medium, high) were altered.

Growth simulation was based on the following criteria:

- *Banksia* areas were based on WAVES 2002 land-use, designated as either low, medium or high density category.
- After 5 years of growth, a *Banksia* cell was changed to a higher density category.
- *Banksia* cells were “burned” according to the percentage burning scenario being modelled with areas based on the area of native vegetation (i.e. 2.5% - 102 cells or 7.5% - 307 cells).
- High density *Banksia* cells were always “burned” before medium density *Banksia* cells to try and replicate the mosaic of controlled burns for the mound.
- After burning, the cells were converted to a low density category.

Spatial analysis was conducted on the resulting grid data produced from the *Banksia* simulation analysis on a yearly basis. This included a correlation matrix (Table 1), and Moran’s I coefficient to determine mathematically the degree of heterogeneity of the growth on a cell by cell basis (Table 2). This was done to assess underlying trends and patterns produced by the algorithm.

Once the modelling simulations were produced a relevant transition change analysis was conducted. This determined the spatial interaction of *Banksia* growth. A land-use change detection script was used. This basically operates on a cell by cell basis and tracks the density changes in each cell. Finally table statistics analysis was conducted which computed the total number of each criteria change and relevant areas (Tables 3 and 4).

Table 1. Autocorrelation descriptions

Geary's C	Moran's I	Interpretation
0 < c < 1	I > 0	Similar, regionalized, smooth, clustered
c = 1	I = 0	Independent, uncorrelated, random
c > 1	I < 0	Dissimilar, contrasting, checkerboard

Table 2. Moran's I results for the *Banksia* simulated growth data

Simulation Date	Moran's Coefficient (I)
banksia2002	0.39775
banksia2003	0.39633
banksia2004	0.39633
banksia2005	0.39633
banksia2006	0.39633
banksia2007	0.49561
banksia2008	0.44748
banksia2009	0.44748
banksia2010	0.44748
banksia2011	0.44748
banksia2012	0.54533
banksia2013	0.57815
banksia2014	0.57909
banksia2015	0.57909
banksia2016	0.57909
banksia2017	0.39633
banksia2018	0.63646
banksia2019	0.60554
banksia2020	0.60554
banksia2021	0.60554
banksia2022	0.44748
banksia2023	0.44180
banksia2024	0.62777

Table 3. Summary of *Banksia* variations in <u>only</u> prescribed burn areas of the Gnangara Groundwater Mound. 1 = high density, 2 = low density and 22 = medium density.

Year	Change	Number	Sum Area (m2)	Proportion (%)
1980 - 1985	Area was 22 and is 2 now	54	8731470.312	69.231%
	Area was 1 and is 22 now	22	3889706.839	28.205%
	Area was 1 and is 2 now	2	500000.000	2.564%
1985 -1990	Area was 1 and is 22 now	15	3112499.981	60.000%
	Area was 22 and is 2 now	10	525454.659	40.000%
1990 - 1992	Area was 22 and is 2 now	21	2210338.279	56.756%
	Area was 1 and is 22 now	14	2140911.673	37.838%
	Area was 1 and is 2 now	2	250247.987	5.405%
1992 - 1994	N.A.	N.A	N.A.	N.A.
1994 - 1996	Area was 22 and is 2 now	40	6066095.415	78.431%
	Area was 1 and is 22 now	8	446898.929	15.686%
	Area was 1 and is 2 now	3	551093.168	5.882%
1996 - 1998	Area was 1 and is 22 now	3	294862.502	2.439%
	Area was 22 and is 2 now	118	15789539.649	95.934%
	Area was 1 and is 2 now	2	477686.694	1.626%
1998 - 2000	Area was 22 and is 2 now	20	3502471.855	76.923%
	Area was 1 and is 22 now	4	784089.993	15.384%
	Area was 1 and is 2 now	2	385119.671	1.626%
2000 - 2002	Area was 1 and is 22 now	37	4933050.171	37.755%
	Area was 1 and is 2 now	8	1767388.890	8.163%
	Area was 22 and is 2 now	53	5543476.453	54.081%

Table 4. Summary of *Banksia* variations in only wildfire burn areas of the Gnangara Groundwater Mound. 1 = high density, 2 = low density and 22 = medium density.

Year	Change	Number	Sum Area (m2)	Proportion (%)
1980 - 1985	Area was 22 and is 2 now	14	2603990.205	87.500%
	Area was 1 and is 22 now	2	387974.659	12.500%
1985 -1990	Area was 1 and is 22 now	25	5328198.294	26.320%
	Area was 22 and is 2 now	68	16301682.180	71.560%
	Area was 1 and is 2 now	2	500000.000	2.105%
1990 - 1992	Area was 22 and is 2 now	144	28224339.323	60.000%
	Area was 1 and is 2 now	60	13997637.488	25.000%
	Area was 1 and is 22 now	36	5421654.558	15.000%
1992 - 1994	Area was 22 and is 2 now	85	11572494.502	88.540%
	Area was 1 and is 22 now	6	123343.280	6.250%
	Area was 1 and is 2 now	5	1136042.059	5.263%
1994 - 1996	Area was 1 and is 22 now	25	3237462.582	11.467%
	Area was 22 and is 2 now	163	30058460.283	74.770%
	Area was 1 and is 2 now	30	6287702.146	13.761%
1996 - 1998	Area was 1 and is 22 now	2	22161.206	33.333%
	Area was 22 and is 2 now	4	17005.325	66.666%
1998 - 2000	N.A.	N.A.	N.A.	N.A.
2000 - 2002	Area was 1 and is 2 now	9	1481299.836	18.367%
	Area was 22 and is 2 now	31	4487992.906	63.265%
	Area was 1 and is 22 now	9	745307.029	18.367%

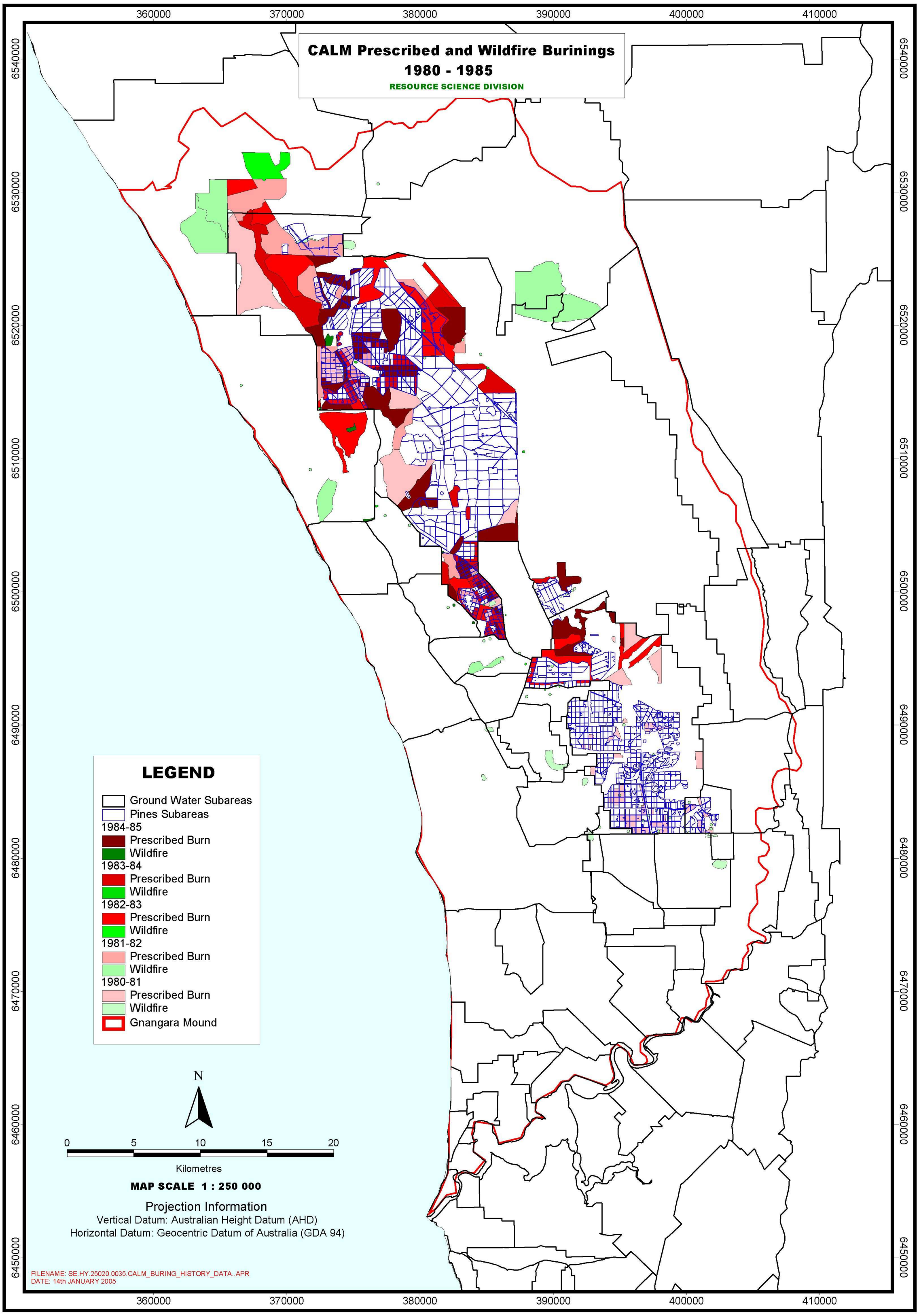

Figure 1. Areas of DEC prescribed burns and wildfires on the Gnangara Groundwater Mound 1980-1985.

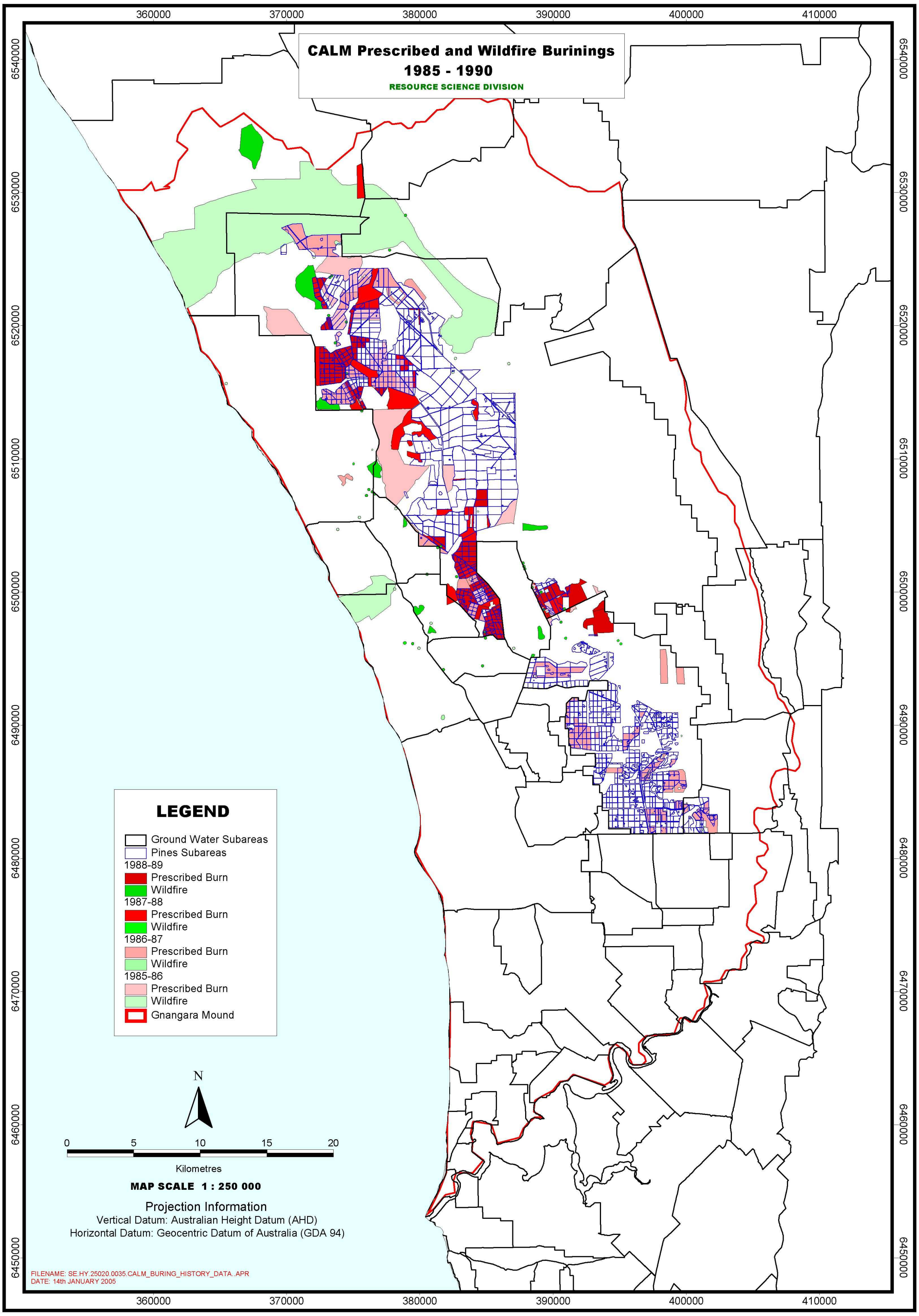

Figure 2. Areas of DEC prescribed burns and wildfires on the Gnangara Groundwater Mound 1985-1990.

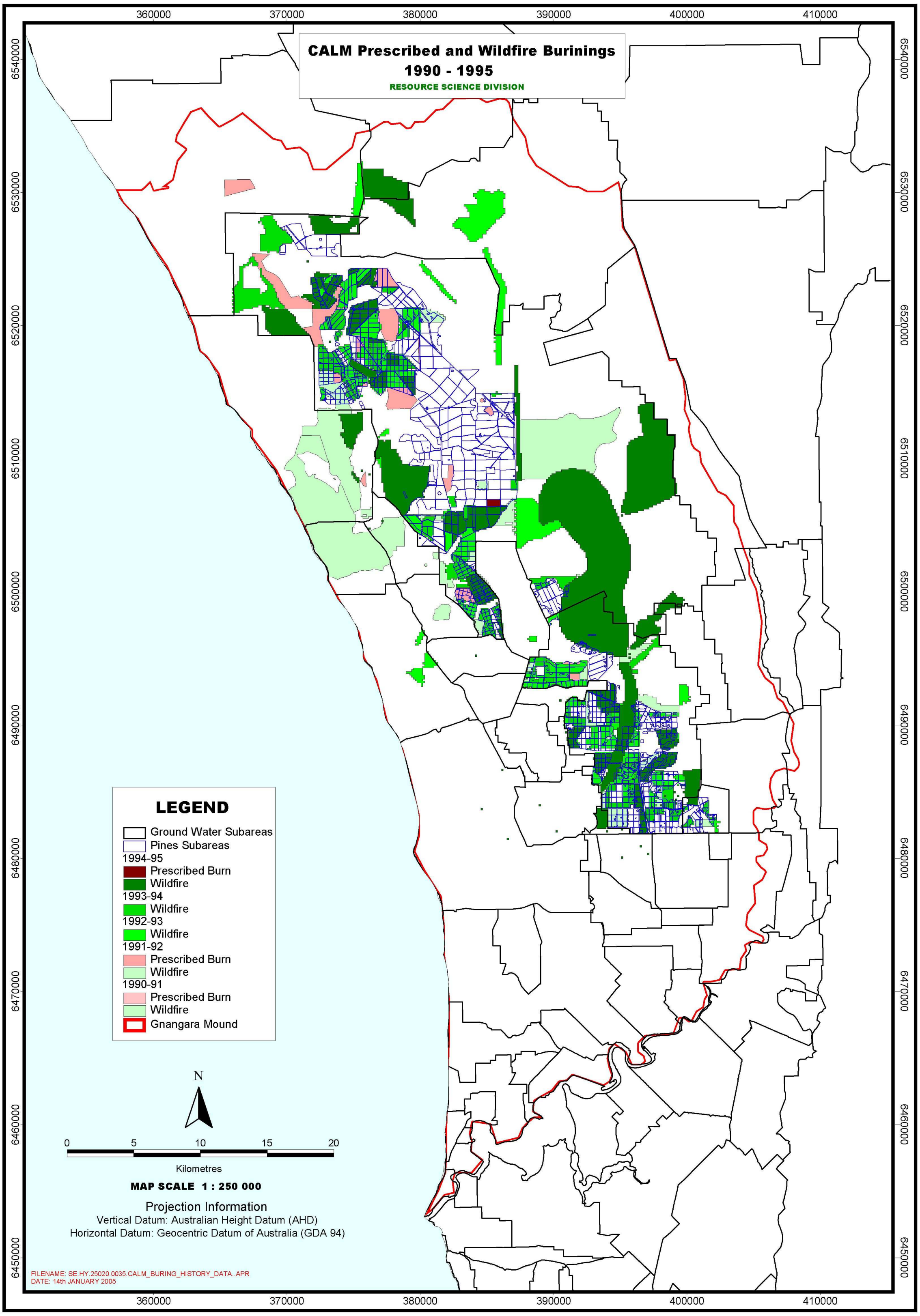

Figure 3. Areas of DEC prescribed and wildfire burns on Gnangara Groundwater Mound 1990 – 1995.

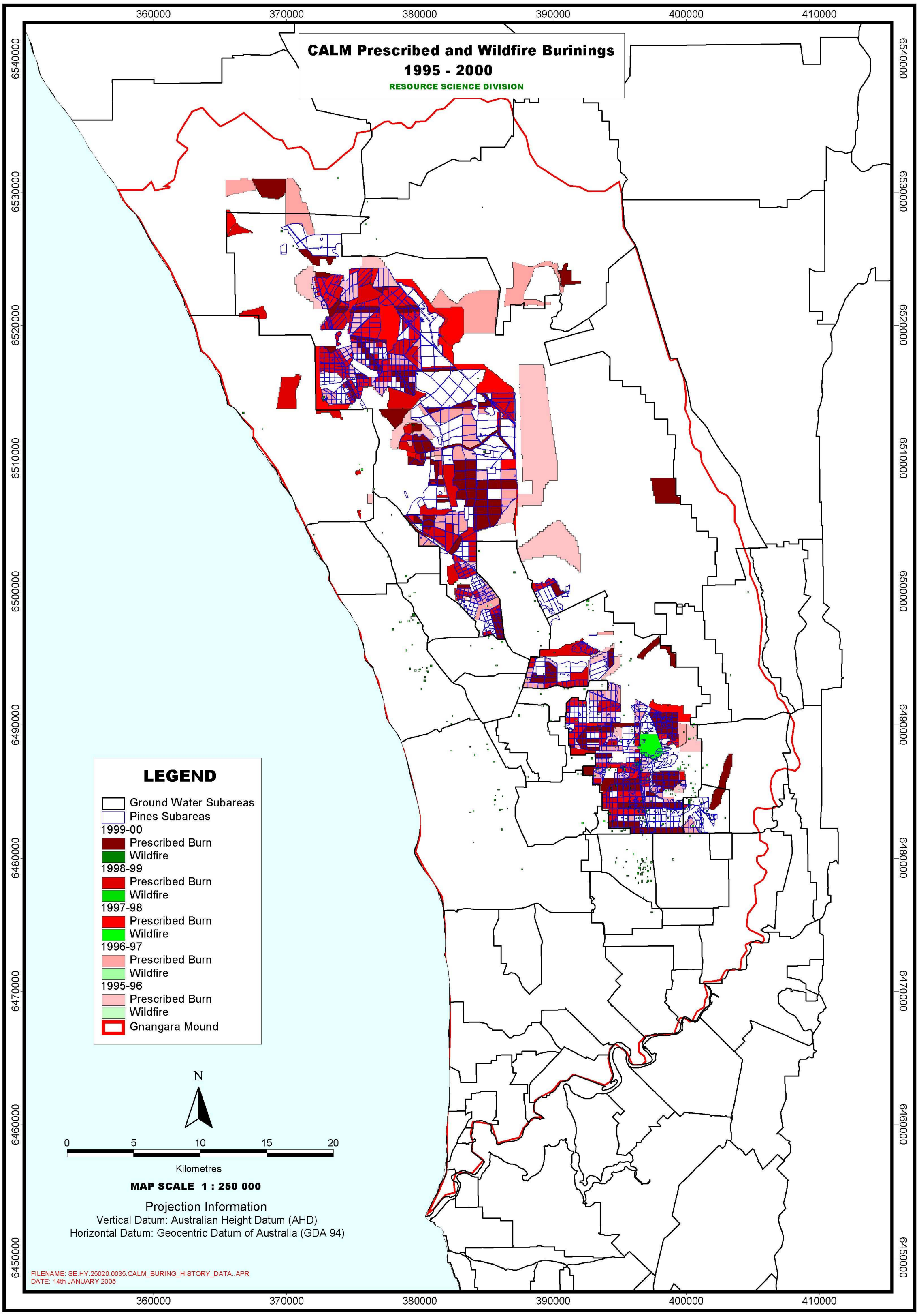

Figure 4. Areas of DEC prescribed and wildfire burns on Gnangara Groundwater Mound 1995 – 2000.

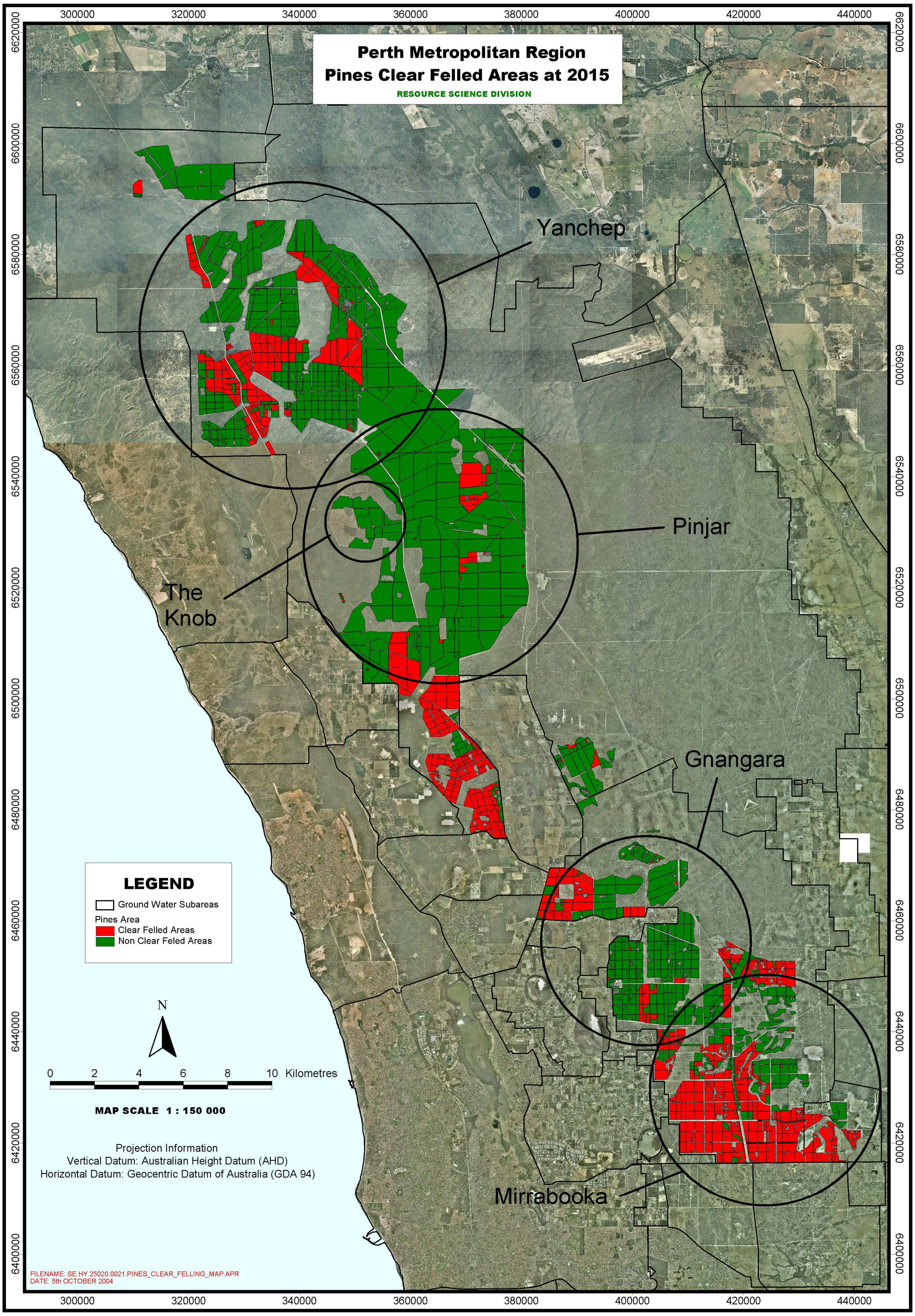

Figure 5. Pine plantation stands, which will be clear felled by 2015 (in red) in the pine removal (as per LVL Agreement) component.

Arc-Info banksia subarea / fire relationship script

```
/*************************************************************************************************
/**    General Algorithim                                                                        *
/**                                                                                              *
/**    for each year incremented                                                                 *
/**    &run in Arc                                                                               *
/**    test only for first 10 years initially                                                    *
/**     1. check 2002                                                                            *
/**         repeat >5.....yes, go &r a.aml                                                       *
/**     1). Total > 102, reselect random 102, H-->L, repeat = 1; rest, keep, repeat = 1; *
/**     2). Total <=102, eg. xx, reselect random xx, H-->L, repeat = 1; reselect random
(102-xx), medium, M-->L (2003),                                                                  *
/**         repeat = 1; rest, keep, repeat = 1                                                   *
/**        NT: repeat = 1;                                                                       *
/**     2. copy to 2003, repeat = repeat + 1                                                     *
/**        repeat >5....., yes, go &r a.aml                                                      *
/**     3. check 2003,                                                                           *
/**      1). Total > 102, reselect random 102, H-->L(2003), repeat = 1; rest, keep,
repeat;                                                                                          *
/**      2). Total <=102, eg. xx, reselect random xx H, H-->L (2003), repeat = 1;
reselect random (102-xx), medium, M-->L (2003),                                                  *
/**         repeat = 1; rest, keep, repeat;                                                      *
/**      4.copy to 2004, repeat = repeat + 1                                                     *
/**         repeat >5.....yes, go &r a.aml                                                       *
/**      5. check 2004,                                                                          *
/**        1). Total > 102, reselect random 102, H-->L(2004), repeat = 1; rest, keep,
repeat;                                                                                          *
/**        2). Total <=102, eg. xx, reselect random xx H, H-->L (2004), repeat = 1;
reselect random (102-xx), medium, M-->L (2004),                                                  *
/**          repeat = 1; rest, keep, repeat;                                                     *
/**                                                                                              *
/*************************************************************************************************
```

```
tables
sel banksubfin.pat
calc repeat = 1
q

&do i = 2 &to 12
   &s w = %i% + 1
      tables
      sel banksubfin.pat
      calc Z0%w% = Z0%i%
      calc repeat = repeat + 1
      q

arcplot
 clearselect
 resel banksubfin.pat info repeat > 5
 &s num = [extract 1 [show select banksubfin.pat info]]
 &if %num% eq 0 &then &goto check
  &else
     &do
          clearselect
        resel banksubfin.pat info repeat > 5 and Z0%w% = 'Low'
         &s num = [extract 1 [show select banksubfin.pat info]]
              &type repeat gt 5 and 'Low' is %num%
              &if %num% eq 0 &then &goto Medium
          Calculate banksubfin.pat info Z0%w% = 'Medium'
          Calculate banksubfin.pat info repeat = 1

          &label Medium
         Clearselect
         resel banksubfin.pat info repeat > 5 and Z0%w% = 'Medium'
            &s num = [extract 1 [show select banksubfin.pat info]]
                     &type repeat gt 5 and 'Medium' is %num%
                     &if %num% eq 0 &then &goto High
```

```
        Calculate banksubfin.pat info Z0%w% = 'High'
            Calculate banksubfin.pat info repeat = 1

        &label High
      Clearselect
         resel banksubfin.pat info repeat > 5 and Z0%w% = 'High'
         &s num = [extract 1 [show select banksubfin.pat info]]
           Calculate banksubfin.pat info Z0%w% = 'Low'
        Calculate banksubfin.pat info repeat = 1
     &type High 5-year is %w%!!!!!
    &end

  &label check
    clearselect
       resel banksubfin.pat info Z0%w% = 'High'
        &s num = [extract 1 [show select banksubfin.pat info]]
      &if %num% gt 102 &then
        &do
          reselect banksubfin.pat info RANDOM 102
          Calculate banksubfin.pat info Z0%w% = 'Low'
          Calculate banksubfin.pat info repeat = 1
        &end
      &else    /** assume high value more than 0
        &do
          &type checking year is %w%!!!!! %num%
          Calculate banksubfin.pat info Z0%w% = 'Low'
          Calculate banksubfin.pat info repeat = 1

          Clearselect
          reselect banksubfin.pat info Z0%w% = 'Medium'
          &s num-m = 102 - %num%
          &s m-sel = [extract 1 [show select banksubfin.pat info]]
          &if %m-sel% le %num-m% &then
            &do
```

```
            &type checking medium year is %w%!!!!! %m-sel% < %num-m%
            Calculate banksubfin.pat info Z0%w% = 'Low'
            Calculate banksubfin.pat info repeat = 1
        &end
       &else
        &do
            reselect banksubfin.pat info RANDOM %num-m%
              &type checking medium year is %w%!!!!! %num-m%
            Calculate banksubfin.pat info Z0%w% = 'Low'
            Calculate banksubfin.pat info repeat = 1
        &end
      &end
   q

&end
```