Government of **Western Australia**
Department of **Water**

Looking after all our water needs

Perth Region Aquifer Modelling System (PRAMS) scenario modelling for the Gnangara Sustainability Strategy

Hydrogeological record series

Report no. HG39
December 2009

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J De Silva

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Climate variability in the south-west of Western Australia has caused a significant decrease in rainfall, leading to a decrease in groundwater recharge to major groundwater systems such as the Gnangara Groundwater Mound. Coincident with rainfall decline is an increase in groundwater abstraction. Increased biomass of native vegetation and pine plantations in the Mound has further exacerbated the effects of rainfall decline on groundwater resources.

Groundwater resources in the Gnangara Groundwater Mound were evaluated for a number of climate, abstraction, land use and combined (or 'composite') scenarios using the Perth regional aquifer modelling system (PRAMS). The current version, PRAMS 3.2, is well calibrated to the Superficial aquifer. The modelling outcomes included the spatial and temporal variation in watertable, and the water balance. These outcomes agree well with each other, so the model can confidently be used to assess the impact of changes in individual modelling components. The results have been used to develop and support the Gnangara Sustainability Strategy (GSS) and the associated future governance framework for the groundwater resources of the Mound.

Modelling results based on GSS composite scenarios show that land-use management activities such as burning native vegetation at regular intervals and removing laminated veneer lumber (LVL) agreement (*Wood Processing (Wesbeam) Agreement Act 2002*) pine plantations, combined with reductions in both public and private abstraction, can arrest the current watertable decline. This will lead to a new hydraulic equilibrium where the recharge to the Superficial aquifer can be balanced with the water flowing out from the Gnangara Groundwater Mound, including discharge to the ocean and rivers. However, when a new hydraulic equilibrium is reached in 2030, the watertable will be lower over about 40% of the Mound compared to the watertable of 2008. The watertable will gradually start recovering around 2030 from increased recharge and gains in groundwater storage, assuming the current short-term (1997–2006) climate persists into the future. If it turns out that the climate is dryer than the short-term climate there will still be a new hydraulic equilibrium reached around 2030 but the watertable may then remain lower than the 2008 levels across nearly 50% of the Mound.

There are some uncertainties associated with the model predictions. These result from:

- the inclusion in the PRAMS abstraction database of licences that are no longer current
- underestimating the impact of urbanisation on the watertable
- possible future reductions in garden bore water use
- the tendency of the model to over-predict watertable decline.

There are also areas in the Mound that are less sensitive to the changes in climate due to groundwater flow characteristics, depth to watertable, and aquifer connectivity.

1 Introduction

1.1 Gnangara mound

The Gnangara Groundwater Mound is the most significant source of groundwater for the Perth region and is located on the Swan Coastal Plain. It is bounded by the coast line to the west, Gingin Brook to the North, Gingin Scarp and Darling Scarp to the east and the Swan River to the south. The Mound has an area of 2150 km^2.

1.2 Groundwater use

The Gnangara Groundwater Mound supports a variety of horticultural, agricultural, industrial, domestic and recreational needs with abstraction averaging 298 GL/yr for the period from 2004 to 2007 (Figure 1). The Superficial aquifer contributed 70% of total groundwater used. The average groundwater recharge for the same period was 360 GL/yr. After allowing for discharge to oceans and rivers the amount of this recharge available for use is only 160 GL/yr. The difference between the recharge and abstraction volumes is derived from depleting the groundwater storage and from the recirculation of irrigated groundwater.

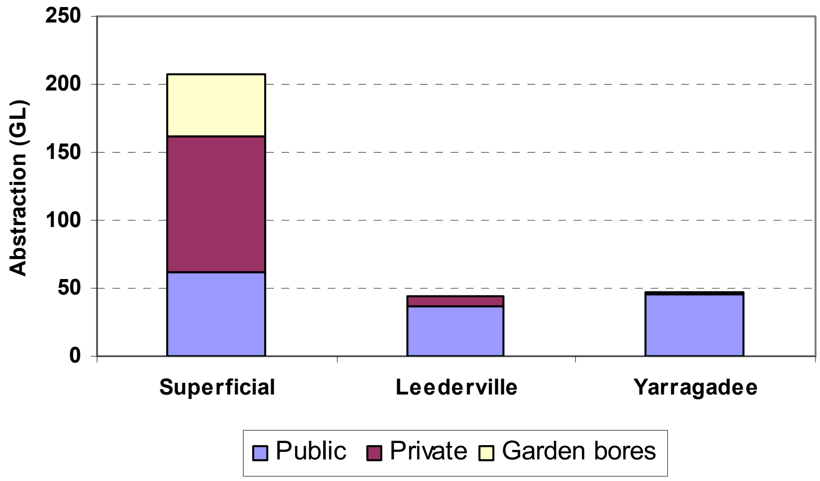


Figure 1 Groundwater use from the Superficial and confined aquifers in the Gnangara Groundwater Mound

1.3 Groundwater level decline

The Perth region has experienced a decade of significantly reduced rainfall which has affected groundwater levels in the Gnangara Groundwater Mound in two ways – by reducing recharge and by causing increased abstraction from groundwater to compensate for the reduced rainfall.

Reduction in recharge to the Superficial aquifer has resulted in a declining watertable (Figure 2). This reduction has not been offset by the increased recharge associated with urban development (Department of Water 2007). While it has been shown that climate is the most important factor, other factors that have contributed to the reduction in vertical recharge include the increased biomass of native vegetation and pine plantations that compete for dwindling water resources of the Mound.

Reduced rainfall and inflow to dams has reduced water availability from surface water sources for the Integrated Water Supply Scheme. This has coincided with a large increase in water demand associated with urban growth in Perth and has resulted in increased abstraction from the Gnangara Groundwater Mound to meet the shortfall in supplies (Department of Water 2007).

Past observations on the behaviour of the Gnangara Mound from 1979 to 2008 show that the two hydrogeological provinces within it react differently to climate, abstraction and pine plantations. This is consistent with the previous study (Yesertener 2007) based on cumulative deviation from mean (CDFM) analysis of past rainfall data (Table 1). One of the hydrogeological provinces is marked by the 'Leederville Window' which occupies the centre of the Mound. The other province is characterised by the presence of a confining layer of Kardinya Shale. The impact of climate has been offset in the Kardinya Shale province due to the increased recharge generated in the urbanised areas. Observations of past watertable declines were made at the Pinjar borefield (Leederville Window) and at the Mirrabooka borefield (Kardinya Shale).

Table 1 Past watertable declines in the Gnangara Mound

Study and factor affecting decline	Watertable decline m	
	Leederville Window	Kardinya Shale
CDFM study (1979–2004) Yesertener 2007		
Climate	3.0	0.0
Abstraction	1.5	1.0
Pine plantation	1.5	2.0
This study (1979–2008)		
Climate	3.0	0.0
Abstraction	2.0	1.5
Pine plantation	2.0	2.0

The decline in watertable due to abstraction is greater where the Kardinya Shale confining layer between the Superficial aquifer and the artesian aquifers is absent (Figure 2). This indicates that the cone of depression caused by the confined aquifer pumping is propagating into the Superficial aquifer. The maximum impact on the watertable from groundwater abstraction is in the area where Pinjar borefield is located. In addition, the state pine plantation, which occupies a large area in the centre of the Mound, also contributes to the groundwater decline by inhibiting rainfall recharge to the aquifers through interception of rainfall and the evapotranspiration of soil moisture.

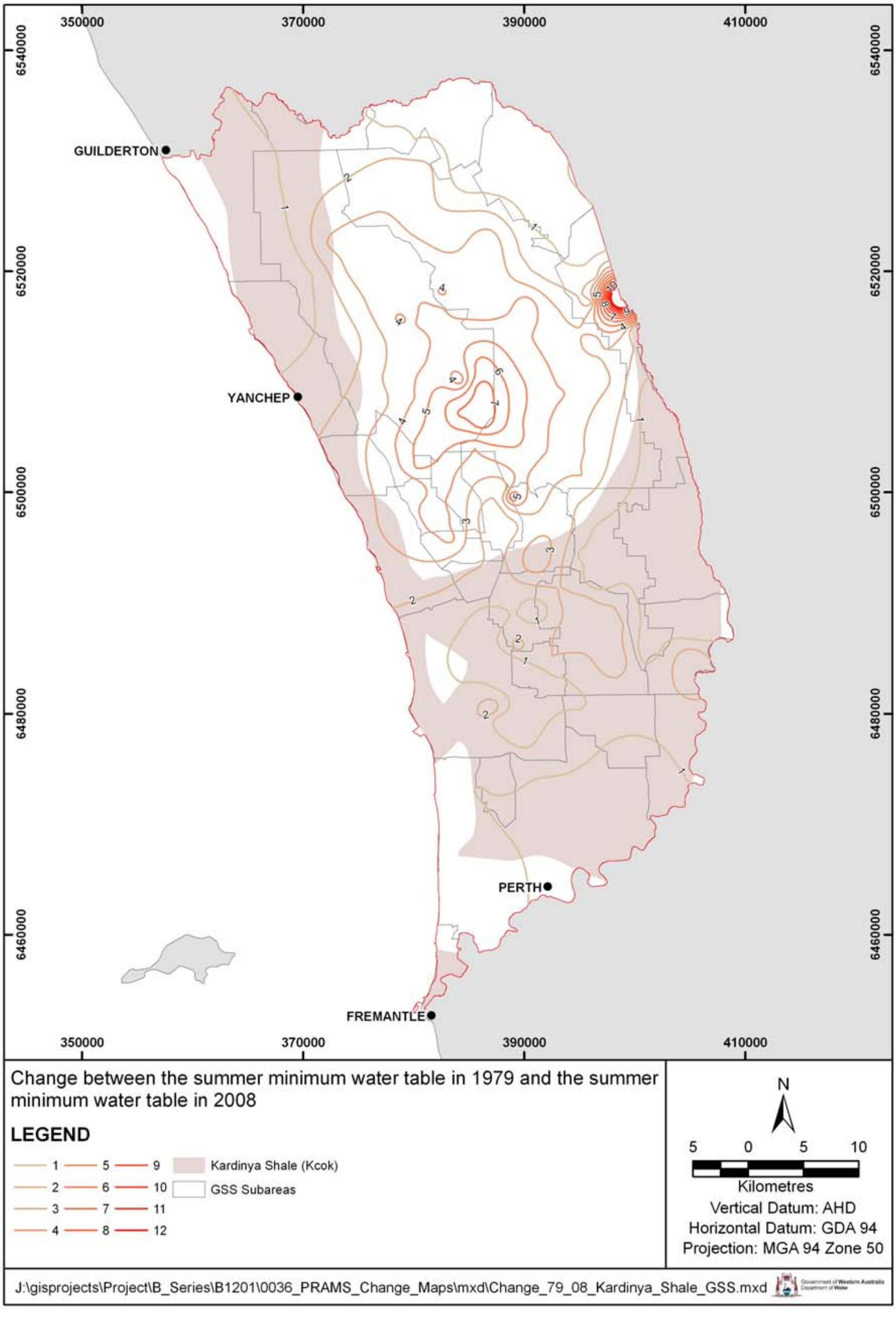


Figure 2 Watertable decline from 1979 to 2008

1.4 Implications for the environment

Water level criteria were set by the Environmental Protection Agency (EPA) to protect groundwater-dependent ecosystems on the Swan Coastal Plain (Arrowsmith and Carew-Hopkins 1994). These criteria, however, had not taken into account the short-term to medium-term climate change effects that had prevailed since the mid 1970s on the groundwater levels at the criteria sites. 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 to the EPA, under the *Environmental Protection Act 1986*, 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 and thereby to protect the environmental values of the Gnangara Groundwater Mound.

There are 40 Ministerial criteria sites spread within the Gnangara Groundwater Mound, of which 20 sites are classified as wetlands and the rest as terrestrial (groundwater monitoring bores). Each criteria site has either a ‘summer absolute minimum water level’, or a ‘summer preferable minimum water level’, or both. The current criteria sites are shown in Figure 3 and the breaches for the 2008–09 period in Figure 4. A summary of criteria breaches in the recent past is given in Table 2.

Table 2 Summary of Ministerial criteria breaches

Site type	Number of breached sites			
	2008–09	**2006–07**	**2004–05**	**2002–03**
Wetland	6	9	7	7
Terrestrial	7	7	5	3
Wetland (spring maxima)	4	4	3	3
Total	**17**	**20**	**15**	**13**

The reduced recharge and increased abstraction associated with demand for groundwater supplies have resulted in an increase in the number of sites at which ecological water requirements have not been met (Department of Water 2007). Ecological water requirements are defined as the water regimes needed to sustain key ecological values at a low level of risk.

Under the declining regional watertable conditions that prevail in the Gnangara Groundwater Mound, organic matter and chemical compounds containing reduced forms of iron, sulfur and nitrogen can be oxidised by exposure to atmospheric oxygen. This can cause acidity and allow nutrients and metals to be mobilised, thus causing environmental problems in groundwater-dependent wetlands and woodlands (Appleyard & Cook 2009). This can be further exacerbated if soils and aquifer sediments are sandy and have little or no carbonate content to buffer the acidification of soils and sediments.

Gnangara Lake, located close to the Mirrabooka borefield, was the first wetland in the area to acidify (in the late 1970s) but other lakes in the area are also showing similar trends of declining pH (Appleyard & Cook 2009). The acidity in these wetlands is attributed both to the oxidation of pyrite in lake bed sediments and the throughflow of acidic groundwater.

Groundwater has been pumped into Lake Jandabup to artificially maintain lake levels to prevent lake sediments drying out and acidifying and causing subsequent environmental damage. This artificial supplementation of Lake Jandabup commenced in 1999, and is continuing.

Exposure of peaty sediments to the atmosphere from the declining watertable has caused acidification which has been locally observed following dewatering at construction sites (Appleyard & Cook 2009).

Groundwater to meet environmental requirements needs to be of suitable quality and quantity. The occurrence of acid sulfate soils and acidic groundwater within the Gnangara Groundwater Mound demonstrates that these two aspects are closely linked. Changes to groundwater flow regimes caused by reduced rainfall and the impact of groundwater abstraction and land-use changes need to be managed to achieve social and economic goals with long-term environmental sustainability.

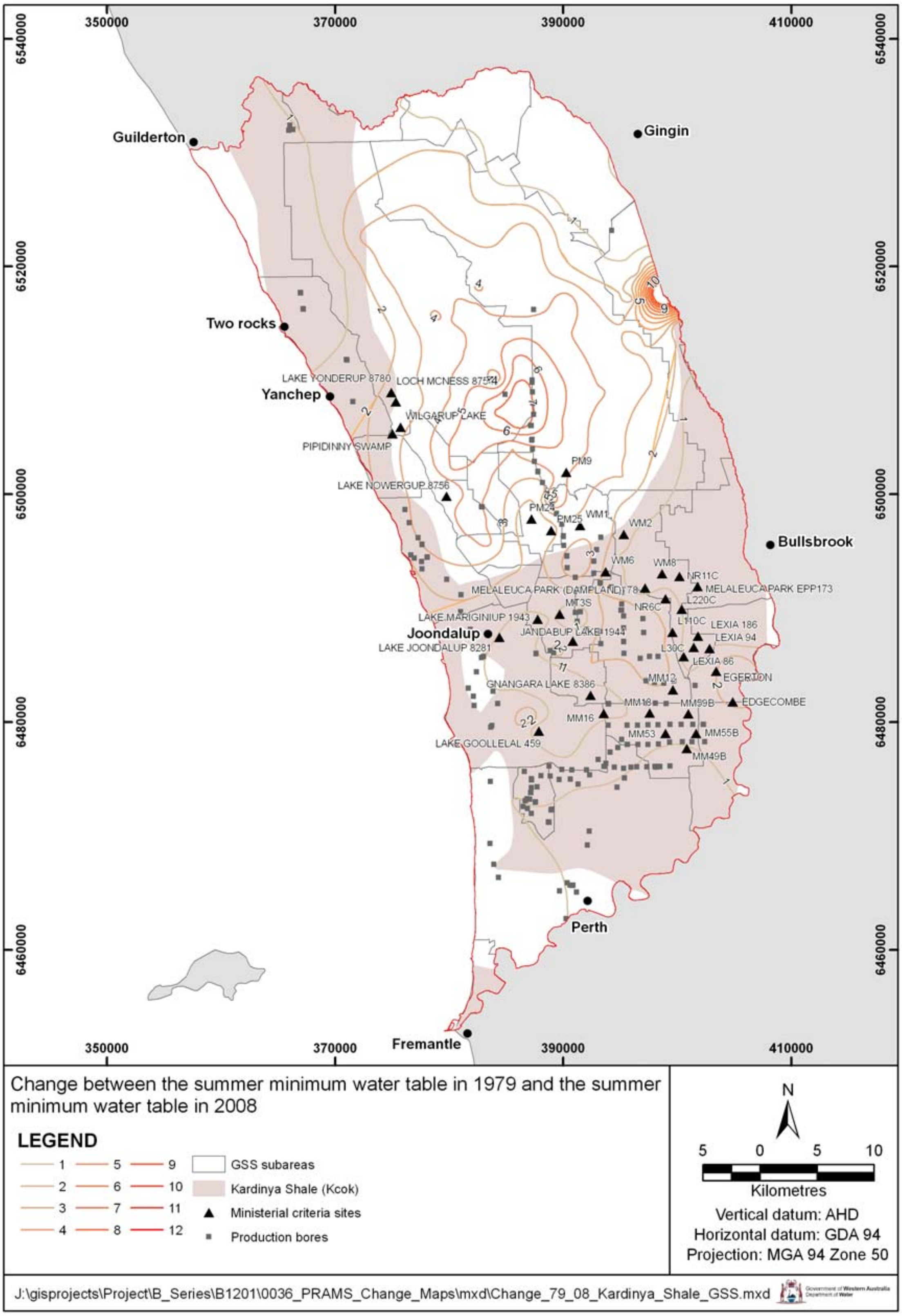


Figure 3 Location of Ministerial criteria sites, Water Corporation production bores and Kardinya Shale on a map of watertable decline

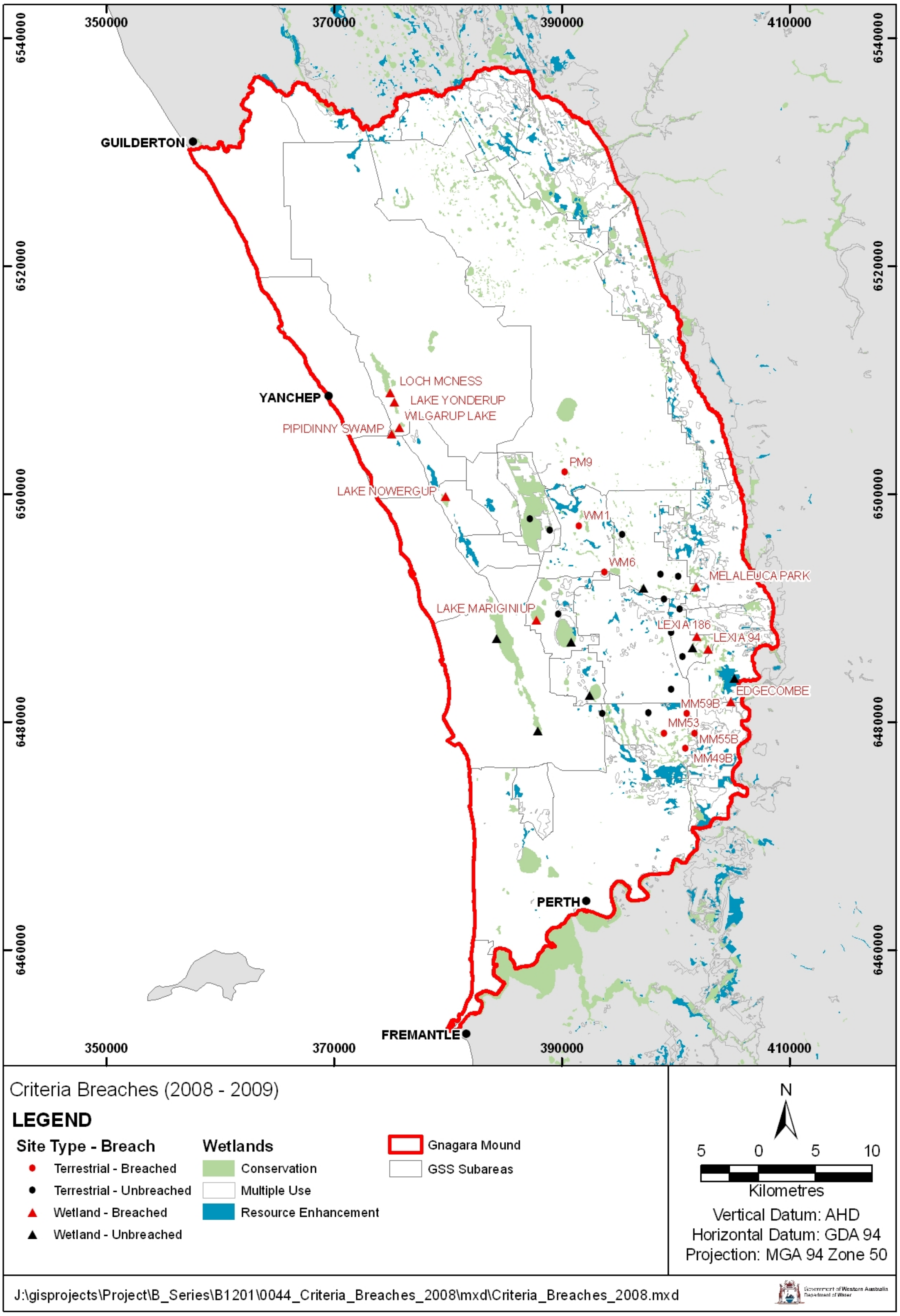


Figure 4 Ministerial criteria breaches on the Gnangara Groundwater Mound in 2007

1.5 Gnangara Sustainability Strategy

The Gnangara Sustainability Strategy is an 'across-government' initiative and involves all agencies responsible for the management of land and water within the Gnangara groundwater system. The initiative was set up to develop management options with a view to evaluating the impact of a drying climate in the year 2030 on the water balance of the Gnangara Groundwater Mound.

The strategy provides a framework to manage groundwater resources of the Gnangara Groundwater Mound in close association with other organisations associated with urban planning, management of native vegetation and biodiversity, commercial forestry operations and horticulture. Past land and water management practices, acting in isolation, have not addressed the wide ranging issues of this complex system.

1.6 Aims and objectives

The overall aim of this modelling study was to determine the relative impacts of land use, water use and climate variability, on the watertable and the water balance of the Gnangara Groundwater System. Specific objectives were to:

- model the impact of different climate regimes on groundwater recharge
- evaluate the effect of different land uses on the watertable
- assess the effect of groundwater abstraction on the watertable and storage capacity of the Superficial aquifer
- compare the relative effects of changes to each of the model components (land use, climate, and abstraction).

The results will be used to develop and support the Gnangara Sustainability Strategy and associated future governance framework for the groundwater resources of the Mound.

2 Hydrogeology

The hydrogeology of the Gnangara Mound is characterised by the occurrence of four major aquifers. These are the:

- Superficial aquifer
- Mirrabooka aquifer
- Leederville aquifer
- Yarragadee aquifer.

Stratigraphic details of these are outlined in the Table 3.

2.1 Superficial aquifer

From east to west on the Gnangara Groundwater Mound, the sediments of the Superficial aquifer (Figure 5) generally vary from being predominantly clayey (Guildford Clay) adjacent to the Darling Fault and Gingin Scarp, to a sandy succession (Bassendean Sand and Gnangara Sand) in the central coastal plain area, and to Tamala Limestone near the coastline.

Over most of the area the aquifer directly overlies sediments of Cretaceous age. In the Swan River estuary area, the Superficial aquifer overlies early Tertiary Kings Park Formation (Figure 5). Within the Gnangara Mound the Superficial aquifer has an average thickness of about 50 m.

Within the Gnangara Groundwater Mound area two hydrogeological provinces have been identified. They are the Leederville Window and Kardinya Shale area (Figure 5). In the Leederville Window hydrogeological province, the Superficial aquifer is in hydraulic connection with the Leederville and Yarragadee aquifers of the Gnangara Groundwater Mound. There is vertical leakage in the Kardinya Shale aquitard between the Superficial and confined aquifers. In the Kardinya Shale and Kings Park Formation area, the base of the Superficial aquifer acts as a no-flow boundary.

Lakes and wetlands of the Gnangara Groundwater Mound are surface expressions of the watertable. As a consequence of varying hydraulic conductivities, 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, and by less than 0.5 m in the limestone along the coast. The watertable is highest during September and October and lowest during April and May.

Groundwater flow is mainly towards the west and the south from the crest of the Mound and ultimately discharges to the ocean and the Swan River (Figure 6). The rate of groundwater flow ranges from 50 m/yr (Guildford Clay) to 1000 m/yr (Tamala Limestone). The occurrence of Tamala Limestone along the coastline has a draining effect on the Gnangara Mound, causing rapid groundwater movement through the limestone into the ocean.

The total available groundwater held in storage within the Superficial aquifer is about 60 000 GL. Estimated specific yields are 0.30 for the coastal belt of Tamala Limestone, 0.20 for the central area of Bassendean Sand and Gnangara Sand, and 0.05 for the area of Guildford Clay (Davidson & Yu 2008).

Depth to watertable (Figure 7) is one of the important factors that determines rainfall recharge to the Superficial aquifer. As depth to watertable increases, recharge to the aquifer decreases as a significant amount of infiltrating water is required to meet the water deficit within the unsaturated zone.

Table 3 Perth region stratigraphic units

Age	Stratigraphy	Symbol	Maximum thickness m	Lithology	Aquifer
Quaternary -Late Tertiary	Superficial formations	TQ	110	Sand, silt, clay, limestone	Superficial aquifer
Early Tertiary	Kings Park Formations	Tk	530	Shale, calcareous and glauconitic siltstone, minor sand	Confining layer
	Mullaloo Sandstone Member	Tkm	200	Sand, clayey and glauconitic	Minor aquifers
Cretaceous	Lancelin Formation	Kcl	120	Mudstone, silty, clayey and glauconitic	Local confining layer
	Poison Hill Greensand	Kcp	90	Sand, silty, clayey and glauconitic	Mirrabooka aquifer
	Gingin Chalk	Kcg	40	Chalk, sandy and glauconitic	Local confining layer
	Molecap Greensand	Kcm	80	Sand, clayey and glauconitic	Mirrabooka aquifer
	Osborne Formation	Kco	180	Sandstone, siltstone and shale	
	Mirrabooka Member	Kcom	160	Sandstone, siltstone and shale	Mirrabooka aquifer
	Kardinya Shale Member	Kcok	140	Shale, siltstone and minor sandstone	Confining layer
	Henley Sandstone Member	Kcoh	80	Sand, silty, clayey and glauconitic	Leederville aquifer
	Leederville Formation	Kwl	600	Sandstone, siltstone and shale	Leederville aquifer
	Pinjar Member	Kwlp	150	Sandstone, siltstone and shale	Leederville aquifer
	Wanneroo Member	Kwlw	450	Sandstone, siltstone and shale	Leederville aquifer

Age	**Stratigraphy**	**Symbol**	**Maximum thickness m**	**Lithology**	**Aquifer**
	Mariginiup Member	Kwlm	250	Sandstone, siltstone and shale	Leederville aquifer
	South Perth Shale	Kws	300	Shale, siltstone and minor sandstone	Confining layer
	Gage Formation	Kwg	350	Sandstone, siltstone and shale	Yarragadee aquifer
	Parmelia Formation	Kp	>287	Sandstone, siltstone and shale	
	Otorowiri Member	Kpo		Shale and siltstone	Confining layer
Jurassic	Yarragadee Formation	Jy	> 2000	Sandstone, siltstone and shale	Yarragadee aquifer

Source: after Davidson & Yu 2008

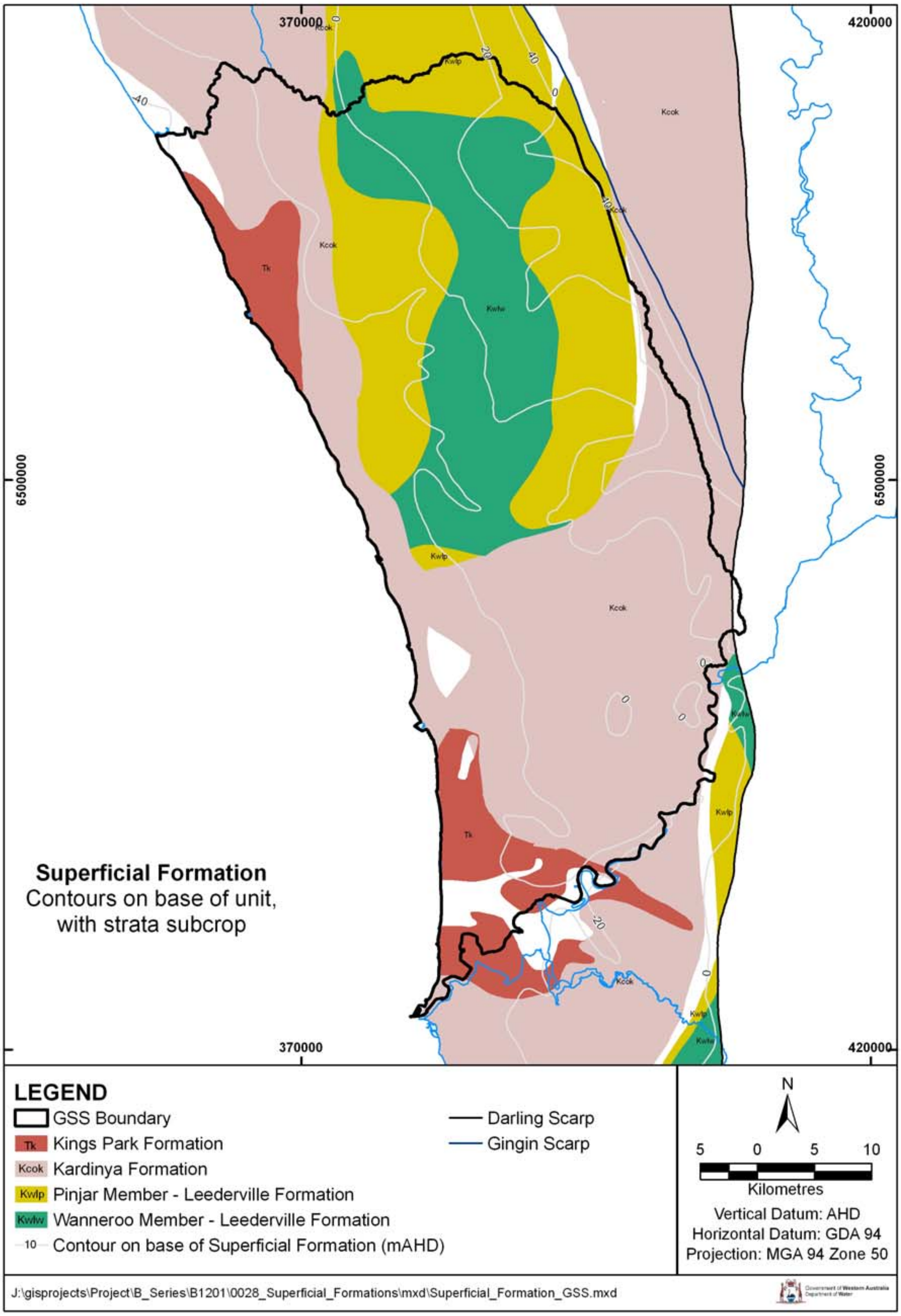


Figure 5 Superficial formation – contours on base of unit with strata subcrop

Source: Davidson & Yu 2008

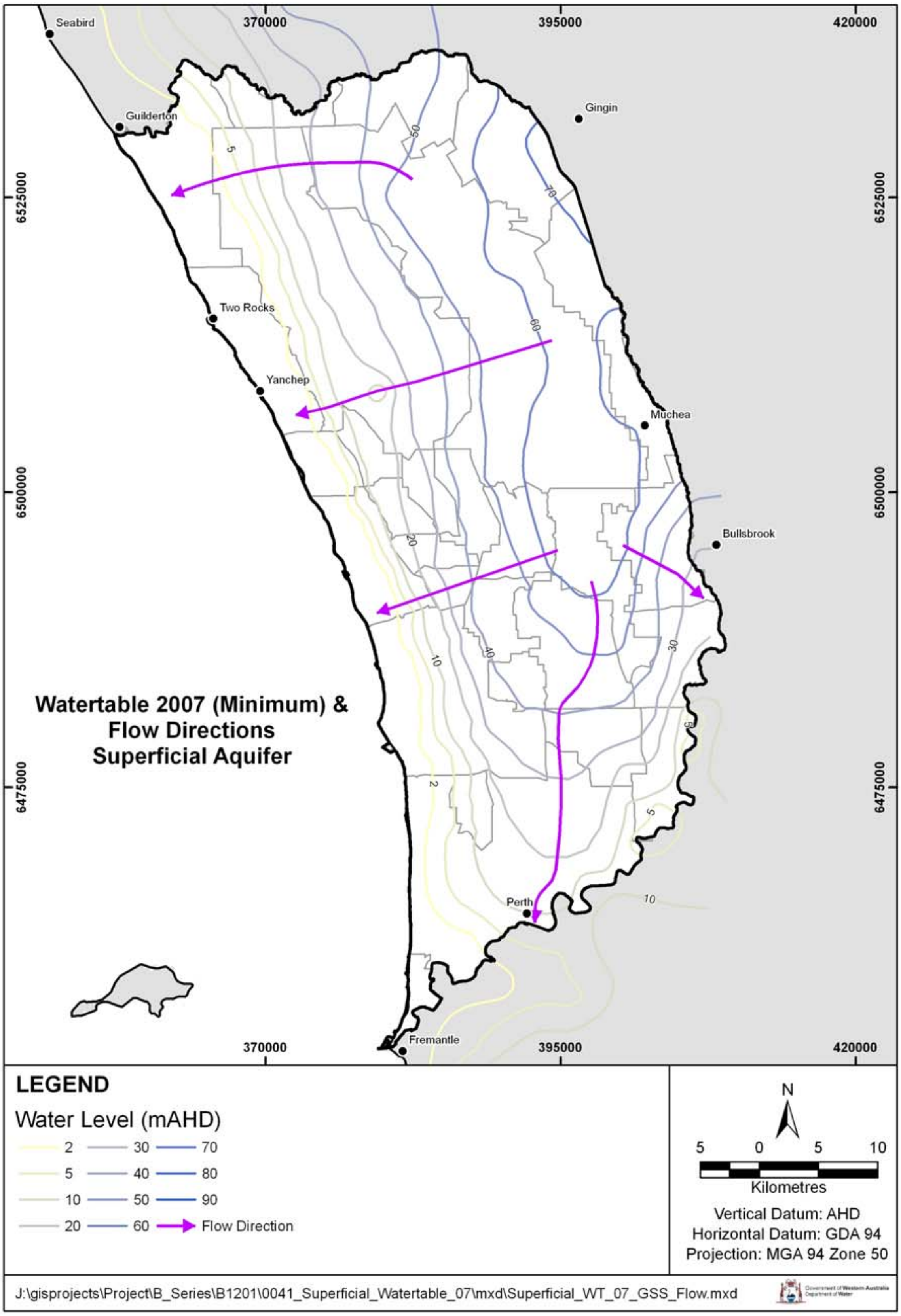


Figure 6 Watertable of the Superficial aquifer 2007

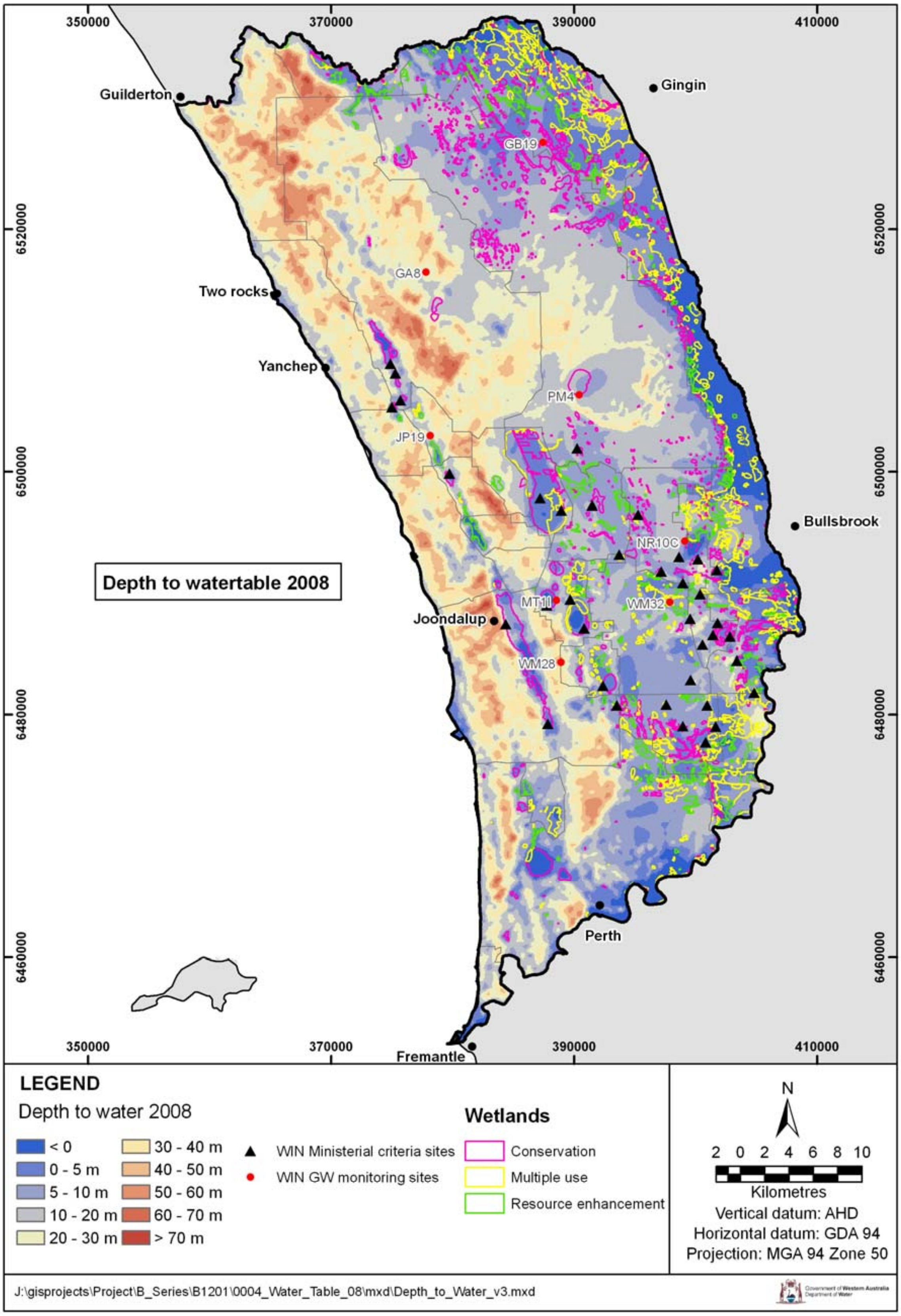


Figure 7 Depth to watertable 2008

2.2 Mirrabooka aquifer

The Mirrabooka aquifer comprises the Poison Hill and the Molecap Greensands, and the Mirrabooka Member.

The Mirrabooka aquifer is a semi-confined and locally confined aquifer that is present only in the northern Perth area, where it is confined by the Kardinya Shale. The potentiometric surface of the Mirrabooka aquifer is poorly defined within the metropolitan area. Sparse data from the Mirrabooka aquifer suggest that much of the groundwater throughflow eventually discharges by upward leakage into the Superficial aquifer (Davidson & Yu 2008).

2.3 Leederville aquifer

The Leederville aquifer (Figure 8) is a multilayered aquifer consisting of discontinuous interbedded sandstones, siltstones and shales in the general proportion of 50% sandstone to 50% siltstone and shale. The Leederville aquifer is hydraulically connected with the Superficial aquifer at the central part of the Gnangara Mound and is confined by the Kardinya Shale elsewhere. The Potentiometric surface map for summer 2007 (Figure 9) indicates that groundwater in the Leederville aquifer flows in a south-westerly direction from beneath the Dandaragan Plateau and eventually discharges into the ocean via the Superficial aquifer.

The total volume of groundwater in storage in the Leederville Aquifer beneath the Perth Region is about 280 000 GL. This estimation is based on an average storage coefficient of 0.0001 (Davidson & Yu 2008).

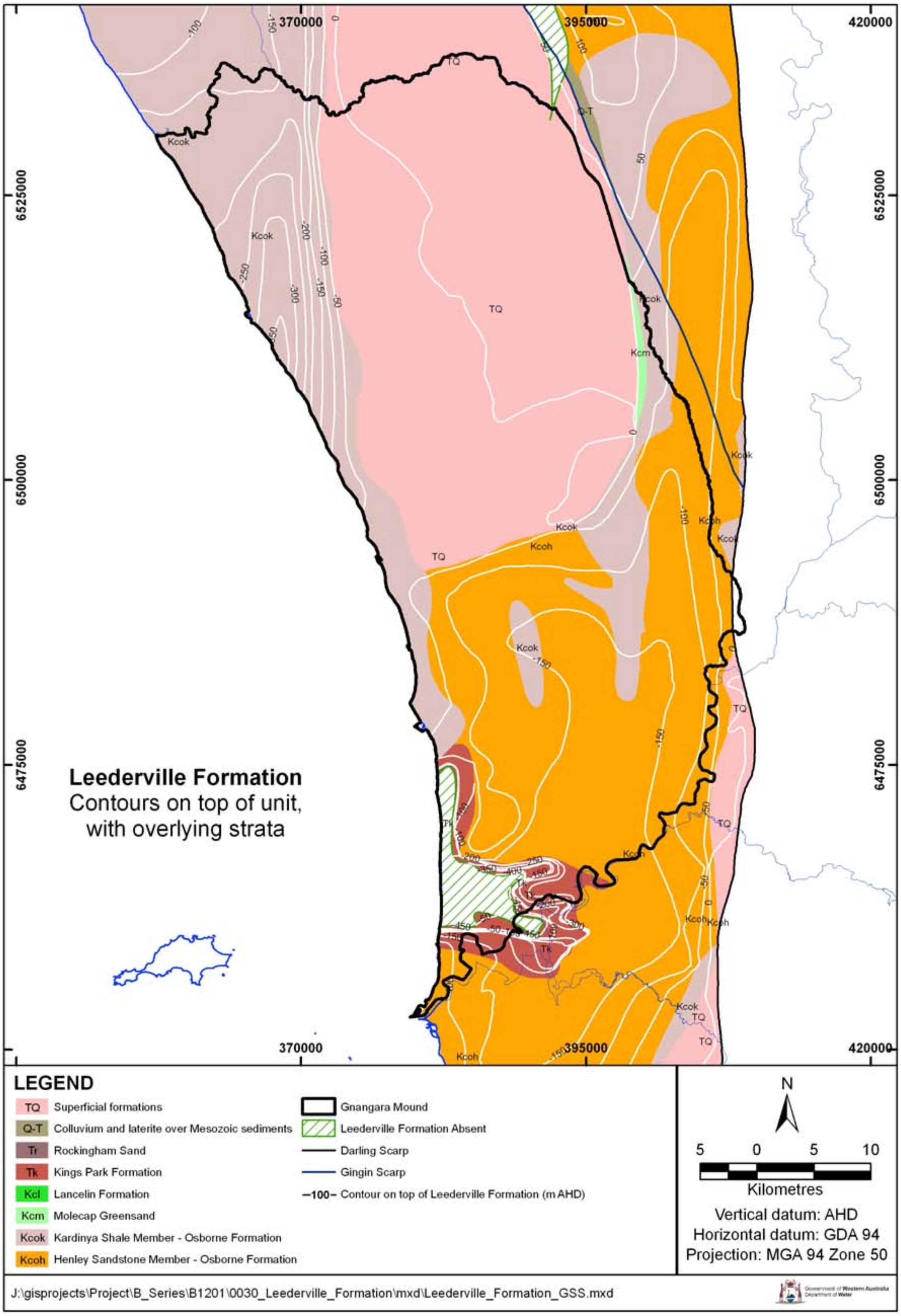


Figure 8 Leederville Formation – contours on top of unit, with overlying strata

Source: Davidson & Yu 2008

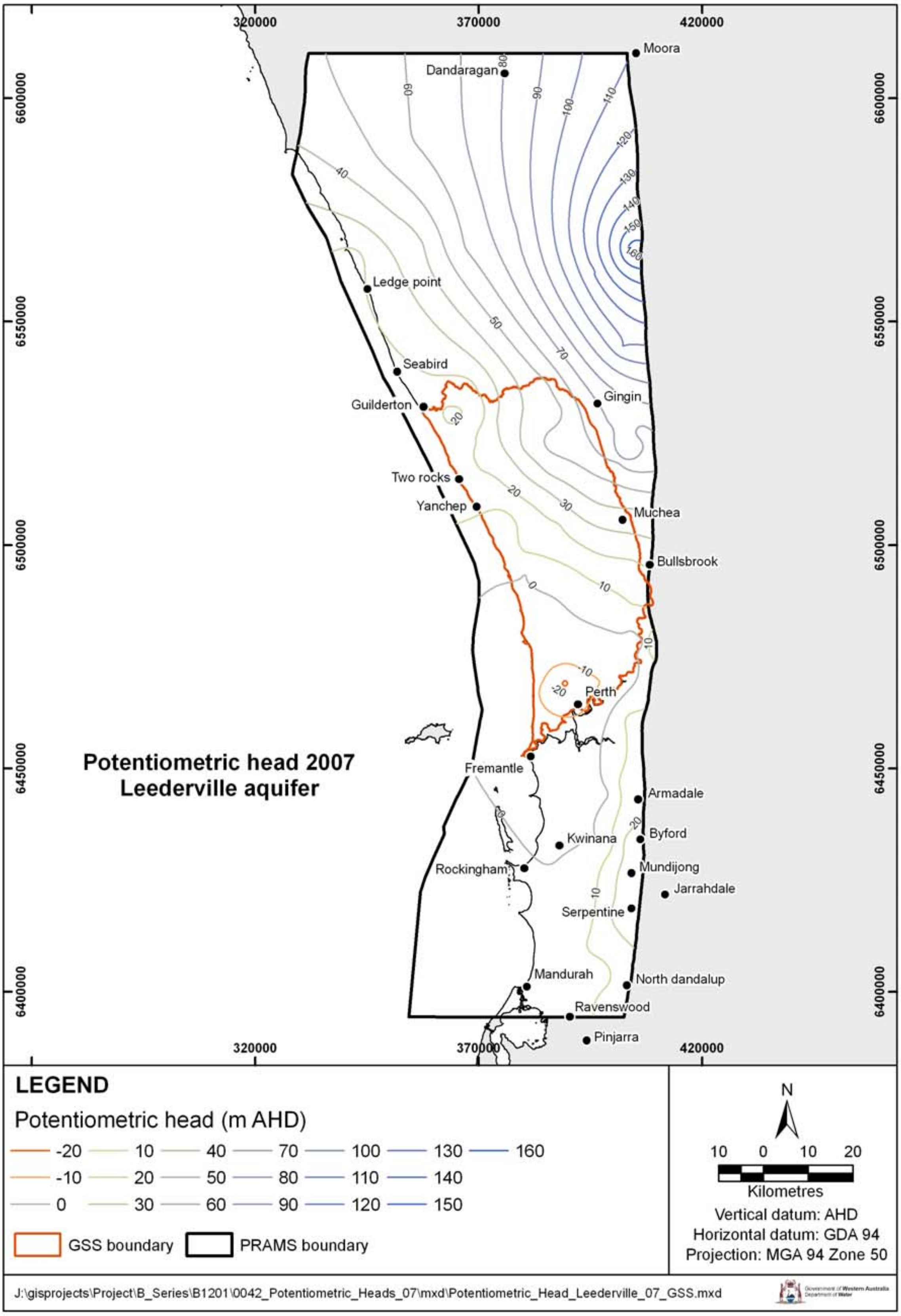


Figure 9 Potentiometric head surface – Leederville aquifer 2007

2.4 Yarragadee aquifer

The Yarragadee aquifer (Figure 10) is a major confined aquifer underlying the Perth region and extending to the north and south within the Perth Basin. It is a multilayered aquifer more than 2000 m thick. The aquifer consists of the Yarragadee Formation and Gage Formation. For more than half of the Gnangara Groundwater Mound, the Yarragadee aquifer is in direct hydraulic contact with the Leederville aquifer. It is confined either by the South Perth Shale or Otorowiri Member of the Parmelia Formation elsewhere. In a small part of the Northern Gnangara Mound the Yarragadee aquifer is directly overlain by the Superficial aquifer (locally known as the Yarragadee Window).

The Yarragadee aquifer consists of discontinuous interbedded sandstones, siltstones and shales in the general proportion of 50% sandstone to 50% siltstone and shale combined.

Groundwater recharge to the Yarragadee aquifer is by downward leakage of groundwater from the Leederville aquifer where the South Perth Shale is absent and where downward hydraulic head gradients occur. Groundwater recharge also occurs from the Superficial aquifer in the Yarragadee Window area. Groundwater discharges from the Yarragadee aquifer into the Leederville aquifer in areas where there are upward head gradients and South Perth Shale is absent. Groundwater flows in the Yarragadee aquifer in a south-westerly direction (Figure 11) and discharges offshore.

The Yarragadee aquifer contains a very large volume of fresh to saline groundwater in storage beneath the Perth region. However, groundwater is fresh only in the recharge area and down gradient from the recharge area, where groundwater salinity is less than 1000 mg/L TDS to depths of up to 500 m from the top of aquifer.

Based on a ratio of sandstone to siltstone and shale of 0.5, an assumed specific yield of 0.2 for the sandstone beds, and an average thickness of 1000 m for the aquifer, there is about 950 000 GL of groundwater storage (Davidson & Yu 2008).

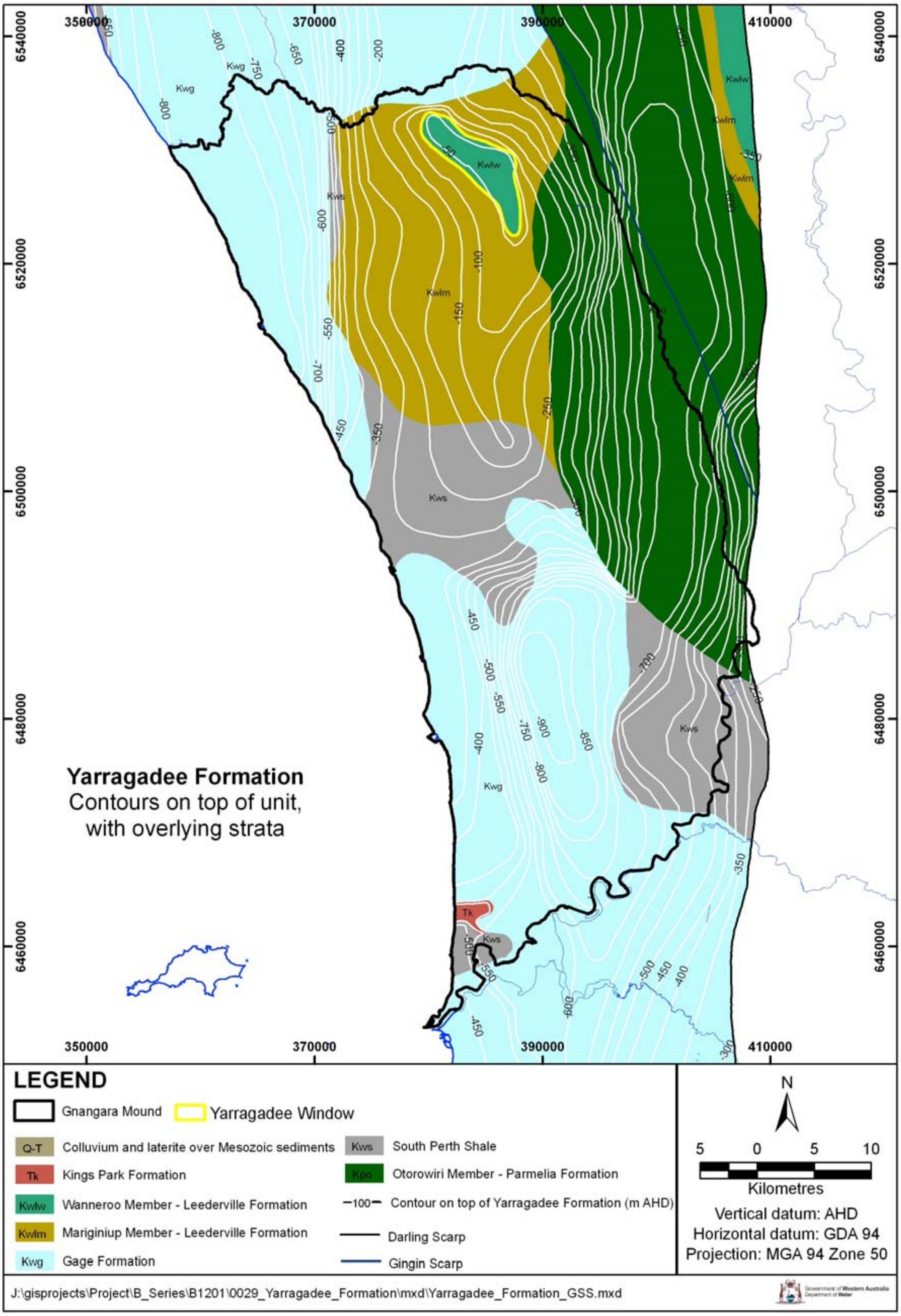


Figure 10 Yarragadee Formation – contours on top of unit, with overlying strata

Source: Davidson & Yu 2008

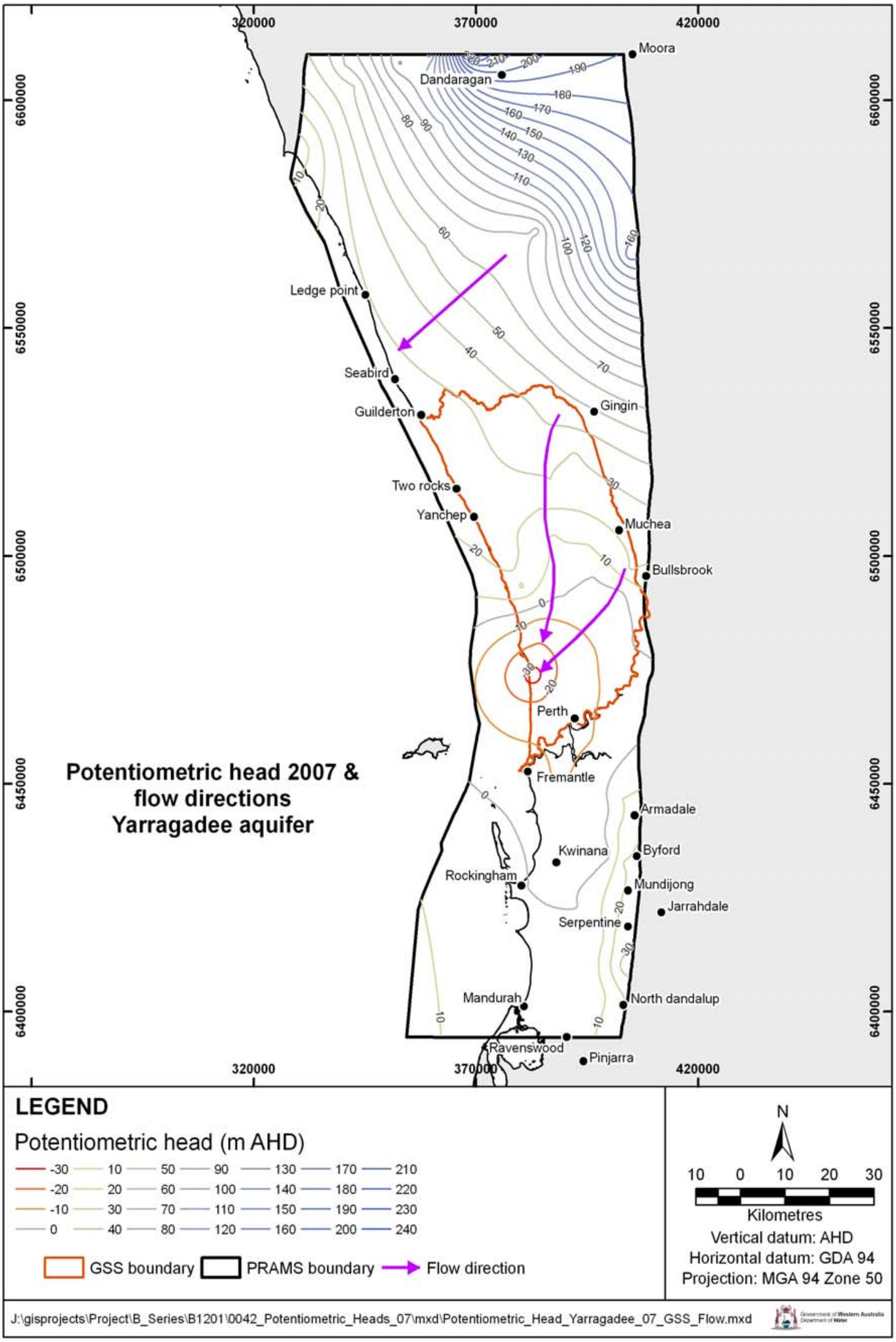


Figure 11 Potentiometric head surface – Yarragadee aquifer 2007

3 Groundwater model

3.1 Perth regional aquifer modelling system

PRAMS 3.2 comprises a vertical flux model (VFM) and a 13-layer saturated groundwater model based on MODFLOW 2000. A database has been developed that stores maps and data related to geology, topography, hydrogeology, land use, water use, monitoring and boundary conditions. The maps and attributes were used to generate input datasets for the numerical model.

PRAMS was developed using PMWIN (Chiang & Kinzelbach 2000). PRAMSView (Cymod Systems 2004) has been developed as a pre-processor to provide a link between the database and the model.

The main function of the PMWIN is to generate the ASCII MODFLOW files that are fed into the vertical flux model with major input files such as climate and land use. For running climate scenarios, climate files in the VFM need to be changed to represent the desired climate conditions. Likewise, for running land-use scenarios the VFM land-use files compiled as PMWIN matrix files need to be replaced with the new land-use files. However in abstraction simulations, the MODFLOW well package needs to change in PMWIN before running the VFM.

The VFM is integrated into the saturated model for calculating water balance components and recharge in the unsaturated zone. It links with GIS-based recharge units across the model domain.

3.2 Unsaturated model

Groundwater recharge to the Superficial aquifer was calculated with a specifically developed vertical flux model. 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 flow sources and sinks. The VFM model solves vertical flow only for subregions of the MODFLOW model. These subregions consists of representative recharge units 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 calculations, and empirical equations that correlate land-use with recharge rate. Table 4 lists land-use types where different recharge modules were used.

Table 4 Recharge conversion factors and modules for land-use types

VFM ID number	Land-use type	Recharge conversion factors/module	
		Rainfall	Evaporation
1	Banksia – high density	WAVES	WAVES
2	Banksia – medium density	WAVES	WAVES
3	Banksia – low density	WAVES	WAVES
4	Pasture	WAVES	WAVES
5	Market gardens	0.4	0.0
6	Parkland	0.4	0.0
17	Pines – high density	WAVES	WAVES
7	Pines – high/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

WAVES

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

Algebraic models

The vertical flux model also provides linear algorithms to calculate net recharge to the aquifer for representative recharge units 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 the general form of:

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

Where R = net recharge, P = precipitation, E = 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 (Barr et al. 2003).

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 5).

Table 5 Parameters for the algebraic recharge model

Land-use code	Description	VFM module	Rainfall coefficient α	EVT coefficient 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 and industrial	Linear	0.75	0.05	n/a

The VFM model uses the same domain and grid geometry as the saturated model to quantify data into model-referenced grid arrays.

The new model with its improved biophysical representation allows a more robust assessment of the 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.

3.3 Groundwater model

Horizontal discretisation

The north-west corner of the active model domain is at 315000E 6621000N (mGDA94), extending approximately 217 km south and from 20 to 107 km wide. The model consists of 500 m x 500 m finite-difference grids covering an area of 10 000 km^2. The use of 500 m x 500 m grid provides adequate resolution for allowing the accurate consideration of large wetlands, land-use changes, changes in surface elevation and hydraulic gradients within the model domain, while maintaining computational efficiency (Cymod Systems 2009).

Vertical discretisation

The model layers are defined by digital terrain models of the top and bottom aquifer and aquitard surfaces. The digital terrain models of each layer were constructed using available geological and geophysical logs and other drilling information, such as palynology.

The saturated component of the PRAMS is based on a 13-layer conceptual model (Table 6 and Figure 12) that was converted into a 13-layer numerical model based on MODFLOW 2000.

Table 6 Model layers of PRAMS 3.2

Aquifer or confining bed	Model layer
Superficial aquifer	1 to 3
Mirrabooka aquifer	4
Kardinya Shale	5
Leederville aquifer	6 to 8
South Perth Shale	9
Parmelia aquifer	10
Otorowiri Siltstone	11
Yarragadee aquifer	12 and 13

Model layer 1 is not based on a geological formation, but is defined as the watertable minus 10 m (top 10 m of saturated zone). The choice of a 10 m layer thickness was based on maximum observed watertable changes over the Swan Coastal Plain and also to prevent layer 1 from going dry during model simulations, especially near large production bores. The unsaturated zone or the vertical flux model layer is considered as layer 0. The top 100 metres of the Yarragadee aquifer, where most of the bores are, is represented by layer 12.

Boundary conditions

The rainfall recharge infiltrates the Superficial aquifer and vertically migrates to the confined aquifers through areas where no confining layer exists in between the Superficial and artesian aquifers. Groundwater flow is predominantly south or west and discharges into the ocean, Swan River and other drainages either at the coast or via offshore faults.

The coastline is considered as a constant head boundary for the Superficial aquifer (layer 1). Constant head is set as 0.5 m AHD to reflect the head difference between the fresh water in the Superficial aquifer and the ocean (Cymod Systems 2009). Groundwater in layer 2 preferentially flows upward and is discharged into layer 1 at the saltwater interface.

No-flow boundary conditions are assigned in the Leederville (layers 6, 7 and 8) and Yarragadee aquifers (layers 12 and 13). Outflow from these aquifers occurs as vertical flow via the offshore faults into layer 4. This vertical leakage occurs due to natural head difference between the Yarragadee, Leederville and the ocean.

The eastern boundary (Darling Fault), the northern boundary and the southern boundary are no-flow boundaries for all layers.

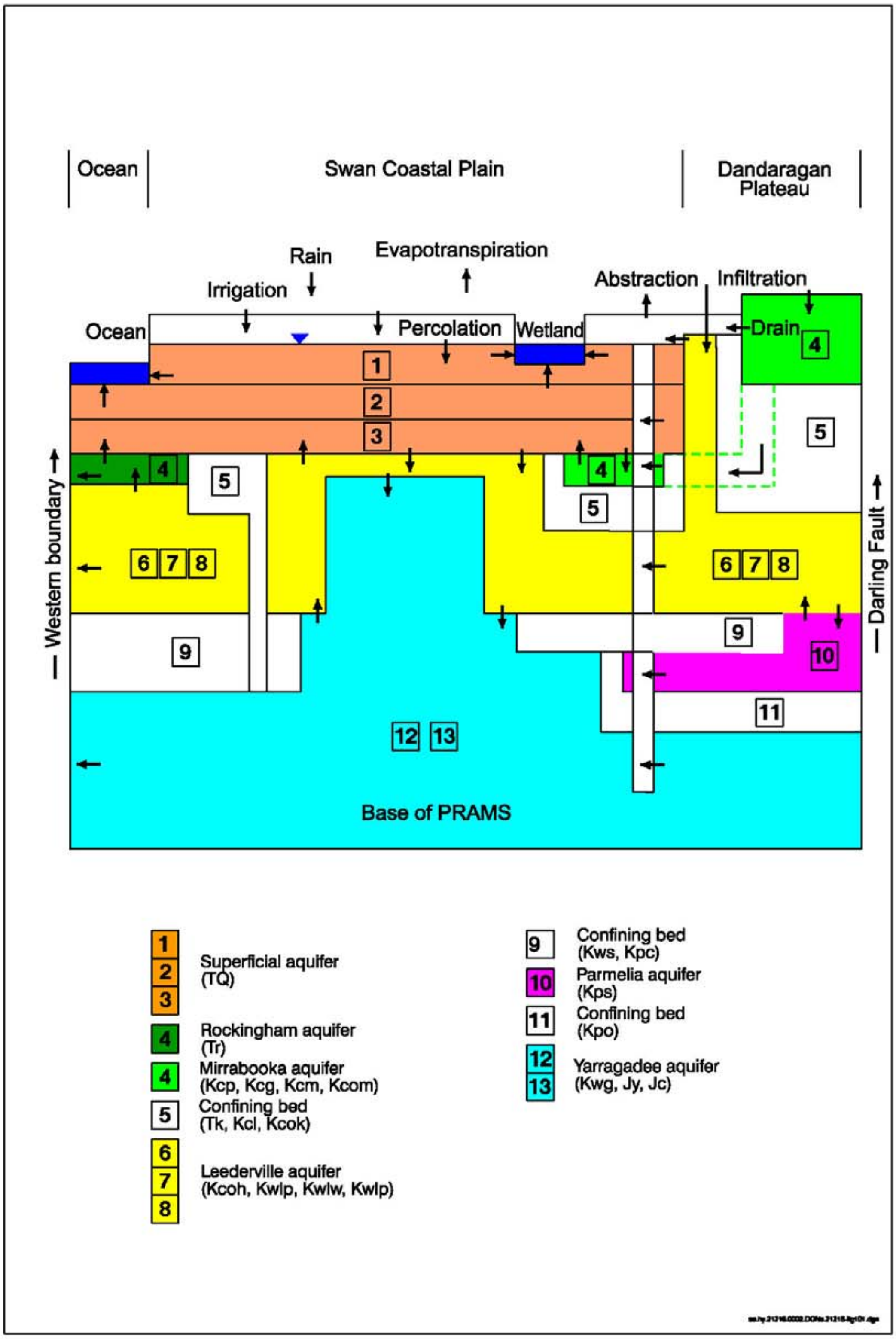


Figure 12 Conceptual model

3.4 Model calibration

The calibration of the groundwater model involves the iterative adjustment of selected aquifer parameters to minimise the error between the measured and simulated heads in all aquifers. Two types of calibration have been carried out – steady state, where input variables and boundary conditions are constant with time, and transient, where predicted hydrographs are compared to measured hydrographs over a selected period, and input variables vary with time (Cymod Systems 2009).

The calibration period for the PRAMS 3.2 transient model was from 1980 to 2000, encompassing 240 ‘stress periods’. Stress periods were defined as calendar months. Each stress period had between 4 and 8 time steps. PRAMS 3.2 was verified from 2000 to 2004. The steady state model was used to estimate the initial conditions in all layers of the transient model for 1980.

Most of the simulated heads at monitoring bores in the Superficial aquifer have a response consistent with the measured data. The monitoring bores maintain correct trends and the magnitude of error is constant, indicating the error stems from the initial conditions.

The calibration error is defined as the difference between the predicted and measured watertable levels. The spatial distribution of calibration error using the 1999 watertable of the Superficial aquifer is shown in Figure 13. The predicted watertable level is about 8 m lower than the measured in some parts of the Yeal area. Large parts of Yeal area are poorly calibrated in PRAMS 3.2, and it predicts levels much lower than those measured. This error could be inherited from PRAMS 3.0. Average calibration error of the Superficial aquifer is within one metre for 50% of the Gnangara Groundwater Mound and within two metres in 75% of the Mound (Figure 14). In general, the predicted watertable tends to be lower than the measured watertable. While some calibration error may be associated with hydraulic parameterisation in both MODFLOW and VFM, others could be attributed to non-hydraulic factors such as redundant water resource licensing allocations still forming a part of the PRAMS database.

The calibrated model was run for a further four-year period (2000 to 2004) for validation by comparing the predicted results with measured data. The validation results indicate that predictions within the validation period usually follow the observed trends, suggesting the model can be confidently used to predict the effects of various scenarios.

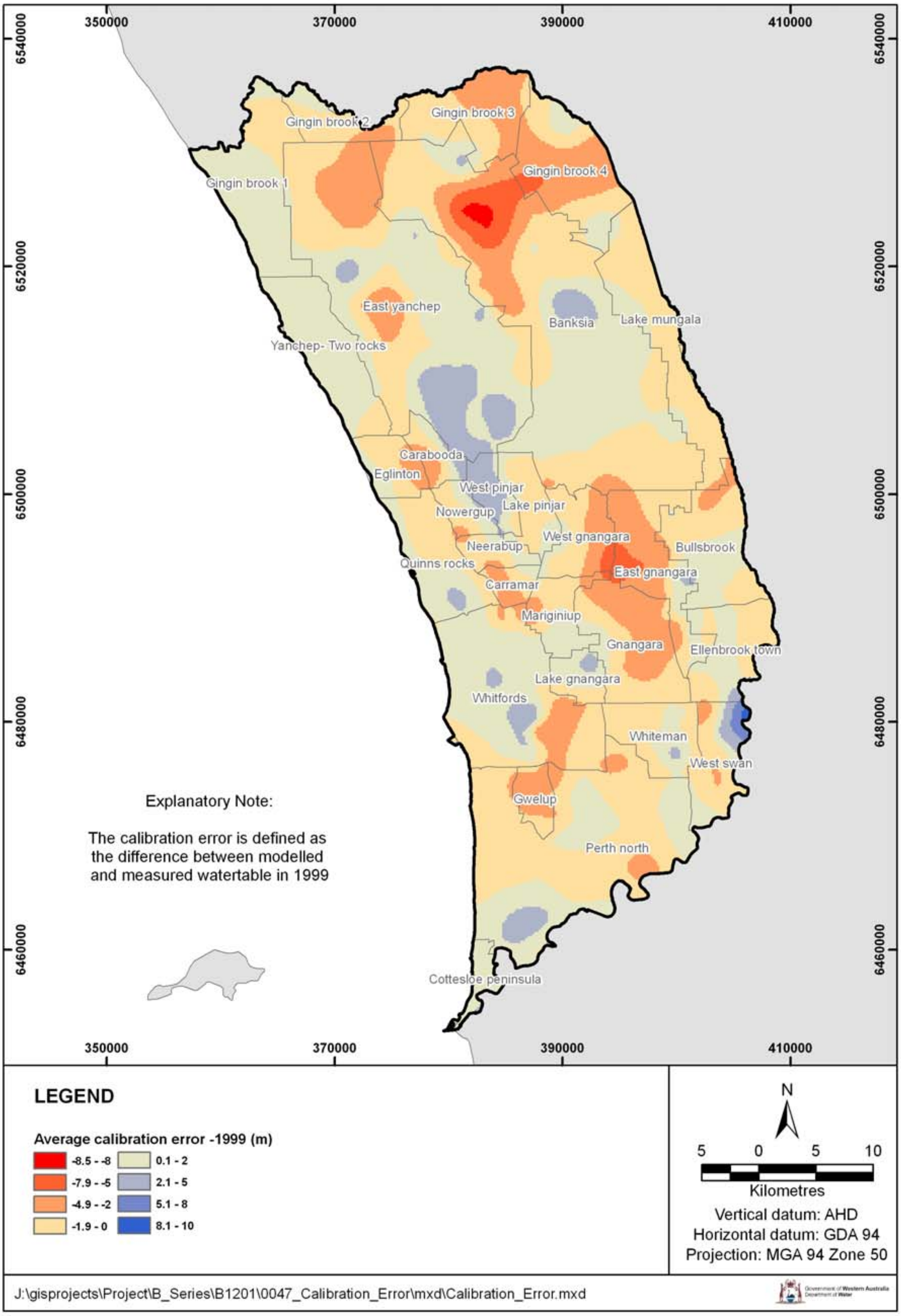


Figure 13 Calibration error of the Superficial aquifer

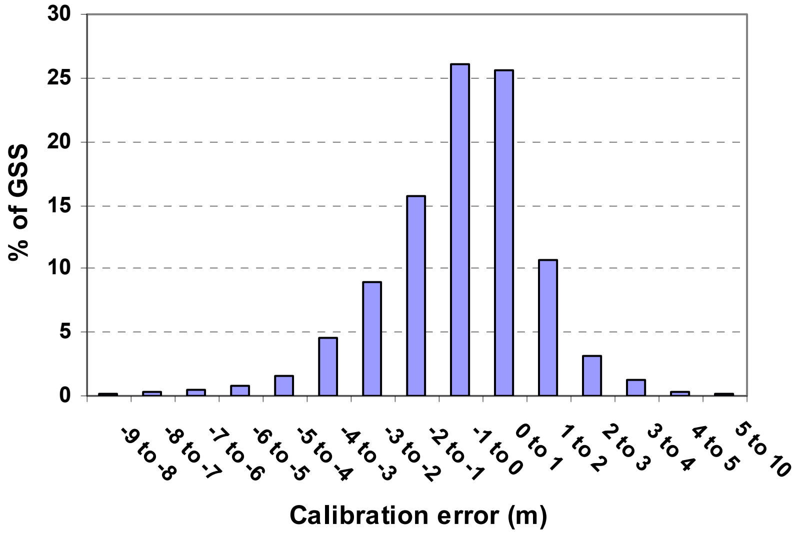


Figure 14 Distribution of calibration error in the Superficial aquifer

4 Scenario design

The scenario design is the first step in the process of developing various management options to optimise recharge to groundwater and hence control the watertable decline in the Gnangara Groundwater Mound. Each scenario is composed of a number of components that can be broadly categorised under climate, abstraction and land-use. These scenario runs using PRAMS 3.2 enable the impact or sensitivity of each component on the watertable to be individually assessed in reference to a particular benchmark scenario, termed here as the 'base case scenario'. In most of the scenarios only one of the modelling components has been changed from the base case to evaluate absolute and relative watertable changes. The scenarios chosen reflect the most likely and realistic water and land management options and likely climatic regimes based on the current understanding of regional climatic trends.

4.1 Scenario matrix

All the modelling scenarios (base case, climate, abstraction and land-use) are summarised in the scenario matrix (Table 7). This was developed by the GSS Task Force in consultation with major stakeholders such as the Water Corporation, the Forest Product Commission, the Department of Planning and the Department of Environment and Conservation. The crosses indicate which combination of factors were modelled in each scenario.

Table 7 Scenario matrix for GSS modelling

	Modelling components														
	Climate				**Abstraction**							**Land use**			**Composite**
Scenario name	Short-term	Dry	30-year ave	Wet	135 GL	120 GL	105 GL	0 GL	2007 pvt.al.[1]	Reduced horticulture	80% 2007 pvt.al.[1]	Pine removal as per LVL	Pine removal (2008)	LVL Banksia	GSS composite
Base case	X				X				X			X			
Dry		X			X				X			X			
30-year average			X		X				X			X			
Wet				X	X				X			X			
Reduced horticulture	X				X					X		X			
WC[3] 120 GL						X			X			X			
WC 105 GL	X						X		X			X			
WC 0 GL								X				X			
No private abstraction	X				X							X			
No abstraction	X											X			
LVL Banksia	X				X				X			X		X	
Pine removal (2008)	X				X				X				X		
GSS composite	X					X					X	X			X
GSS composite (dry)		X				X					X	X			X

[1]Pvt.al. – private allocation

4.2 Scenario components

Climate components

The two main climate inputs that are relevant to PRAMS modelling are rainfall and evapotranspiration. Climate is modelled in PRAMS using data from Wanneroo, Perth Airport, Lancelin, Chelsea and Jarrahdale. The three climatic zones that are relevant to the Gnangara Groundwater Mound are shown in Figure 15.

Annual rainfall at Perth airport for the last 120 years is given in Figure 16. The long-term average is about 820 mm/yr. However there is significant variation in rainfall amount and patterns. The 9-year moving average of rainfall indicates that there was significant decline in annual rainfall since 1968. Four climate modelling components have been used to evaluate the impact of climate on water levels and the water balance.

Climate 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 climate sequence is then repeated on an annual basis using the daily meteorological data for the duration of the model run. Details for setting up the scenarios are given in Water Corporation 2004.

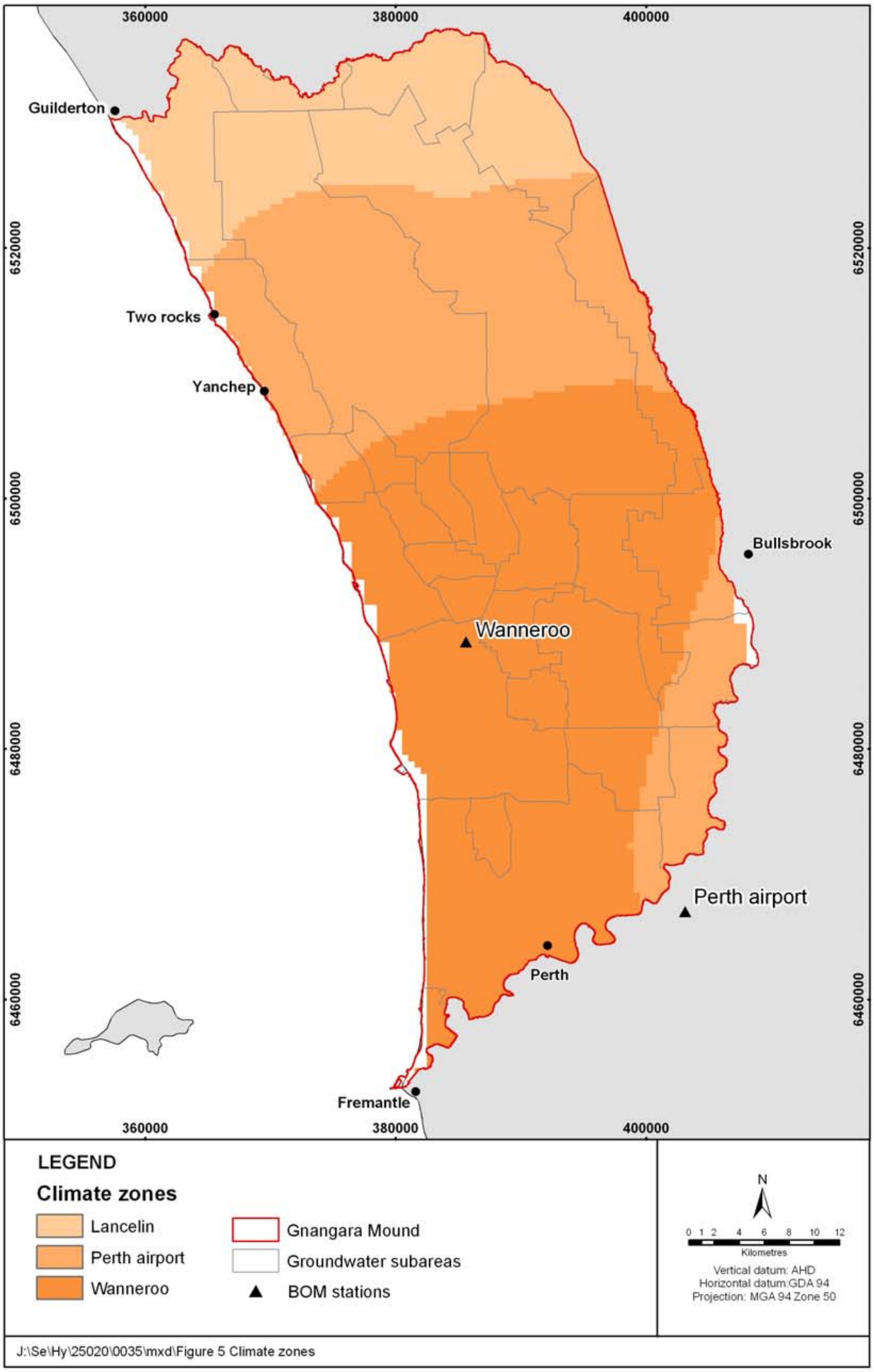


Figure 15 Climate zones used in PRAMS for the Gnangara Groundwater Mound

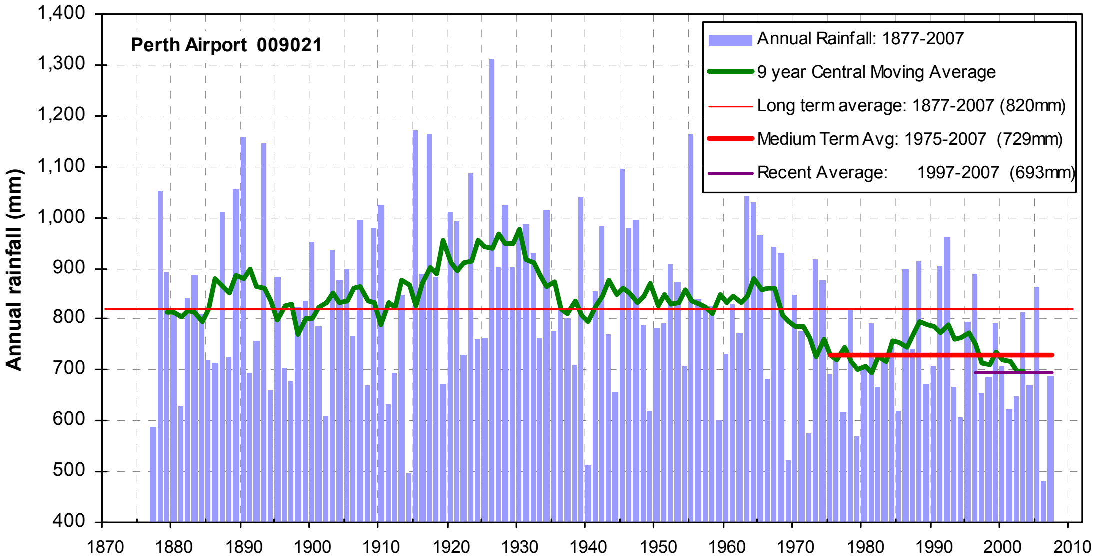


Figure 16 Annual rainfall for the Perth airport station from 1870 to 2004

Abstraction components

Abstraction is a significant component of the water balance in PRAMS. There are three types of groundwater abstraction: Water Corporation abstraction for public water supply (Figure 17), private licensed abstraction (Figure 18), and unlicensed abstraction for home gardens. In 2007, these three components accounted for 150 GL/yr, 200 GL/yr and approximately 112 GL/yr of abstraction respectively, from the Perth metropolitan area (Mandurah to Gingin Brook).

The total Perth metropolitan (including Jandakot Mound) Superficial aquifer abstraction from the Water Corporation borefields in 2006–07 was 65.99 GL, and was lower than the baseline allocation of 75.85 GL. For the GSS area, the total Water Corporation abstraction was 60.18 GL out of a baseline allocation of 68 GL (URS 2008). This was the highest level of abstraction from the Superficial aquifer since pumping began in the 1970s. Gnangara (Wanneroo, Pinjar and Lexia borefields) abstracted 21.05 GL/yr and Gwelup–Mirrabooka another 19.49 GL/yr. The Coastal Scheme (Yanchep–Two Rocks, Quinns and Whitfords) made up the remainder of 19.61 GL/yr. While abstraction was slightly increased in the Gwelup–Mirrabooka borefields, significant reduction was made in Gnangara and the Coastal Scheme compared to baseline allocation limits.

In 2007, it is estimated that a total of 200 GL/yr of groundwater was extracted from the Superficial and the confined aquifers for private abstraction. While horticulture and agricultural groundwater use is the most dominant, other uses include industry and services, park and recreation and domestic. There has been a rapid growth in licensed abstraction since 1999.

Licensed private abstraction is based on the licensed entitlement as stored in the Department of Water's water resource licensing database. Each abstraction bore (draw point) is in the MODFLOW well package. The monthly abstraction figure is derived using a scaling coefficient to reflect water use seasonality (Davidson & Yu 2008). The return of groundwater to the Superficial aquifer following irrigation is assumed to be 20%.

There are an estimated 135 000 unlicensed garden bores across the Perth metropolitan area that use around 112 GL/yr. This abstraction is represented in each model scenario as a density distribution and is assumed to grow at a rate of 3% per year. Almost all garden bores pump water from the Superficial aquifer. The return of groundwater to the Superficial aquifer following irrigation is assumed to be 30%.

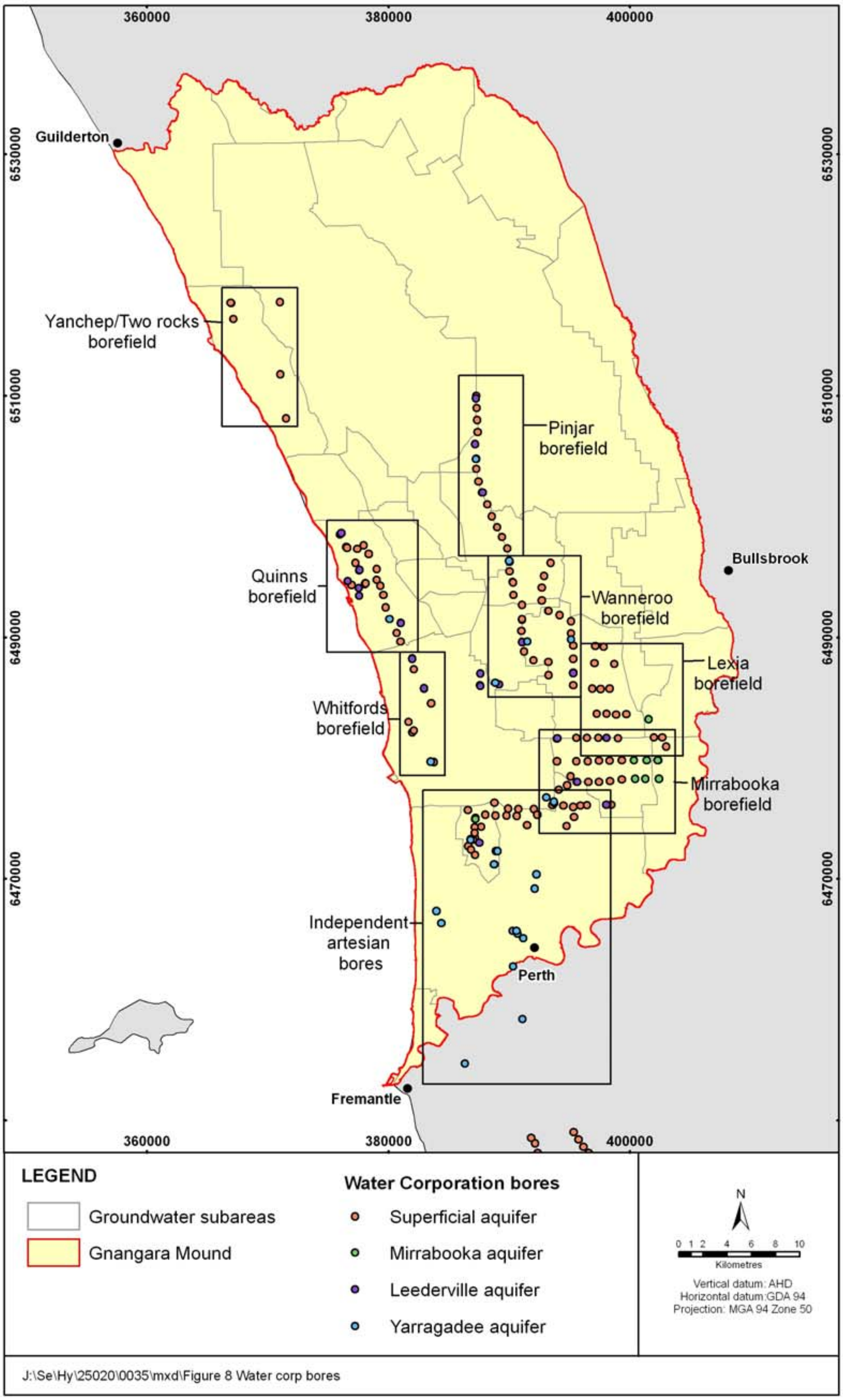


Figure 17 Distribution of Water Corporation borefields on the Gnangara Groundwater Mound, shown by aquifer

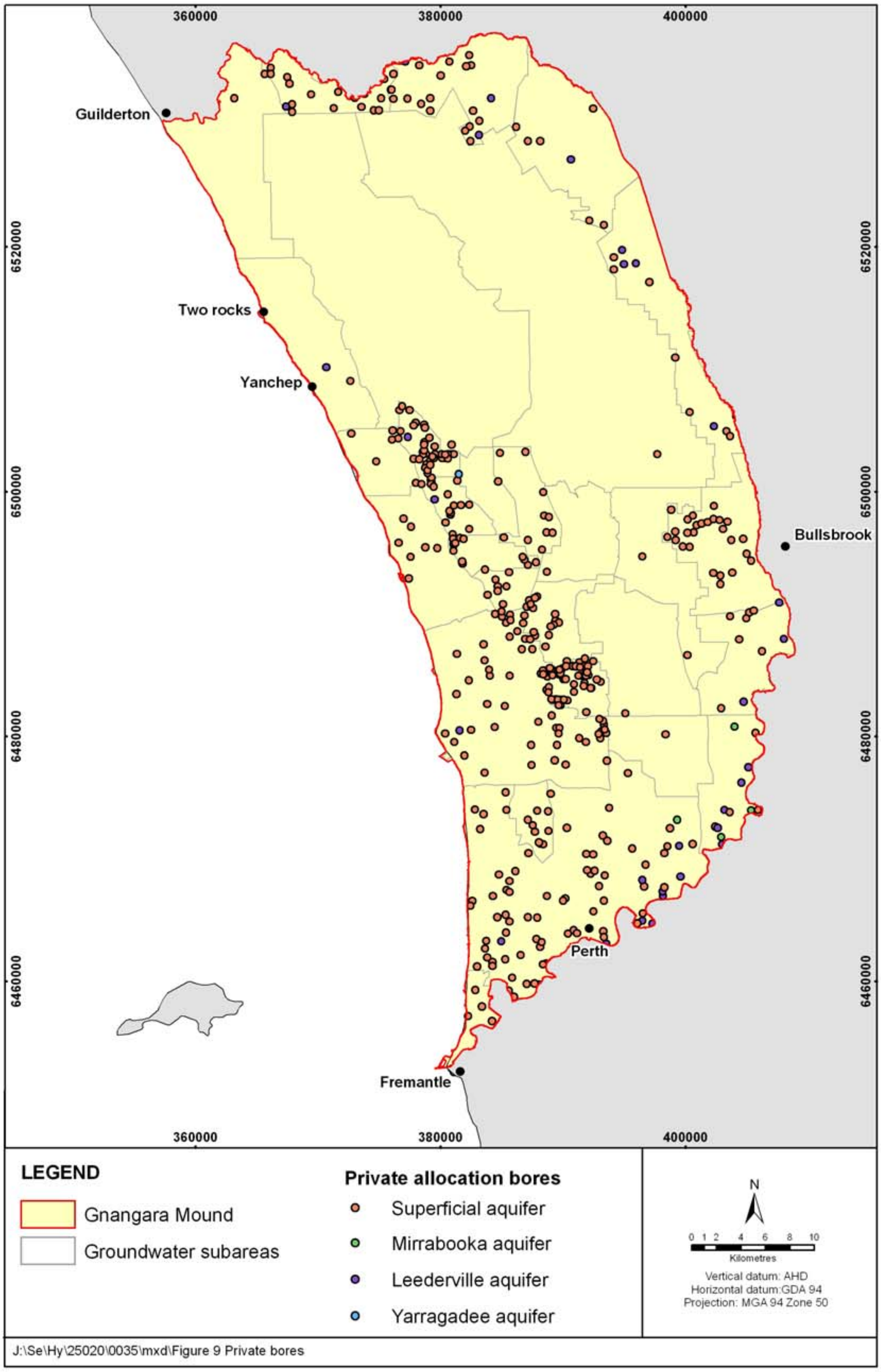


Figure 18 Private allocation (licensed) bores greater than 50 000 kL/yr

Land-use components

There are 14 land-use types used in PRAMS 3.2 (Table 8 and Figures 19 and 20). Groundwater recharge under different land-use types is modelled by the VFM and estimated recharge is fed into the saturated model. Land use is a dynamic data set that will change through the modelling period from 2008 to 2031. As pine plantations are gradually removed and certain areas of native vegetation are burnt there will be significant changes to the composition of the land-use component. After each burning episode, native vegetation cells grow back, for example, from low to medium density. After each burning episode, the leaf area index (LAI) of a particular area will be reduced by 50%. Growth factor that is used in the land use classification is 10 years. That is, the time taken for a Banksia cell with LAI of 0.55 to grow back to maximum LAI of 1.1 is 10 years (M Canci 2009 pers. comm.). Regeneration is also accounted for in the generation of time-series land use data. Some of the cells that are classified as grassland at the beginning of time-series may become Banksia as time progresses. Cleared pine areas are either replaced with pasture (grassland) or native vegetation – Banksia. Some of the current pine areas may also be developed into urban areas.

*Table 8 Land-use types used in PRAMS VFM module and recharge rates**

Description	GSS area km^2	Recharge mm	Recharge as % of rainfall
Banksia – high density	13.25	85	10
Banksia – medium density	672.50	135	18
Banksia – low density	157.43	300	38
Pasture	639.23	360	45
Market garden/parkland	6.25	320	40
Pine – high density	13.75	0	0
Pine- medium to high density	39.50	0	0
Pine – medium density	60.00	0	0
Pine – low to medium density	60.75	65	8
Pine – low density	39.50	220	28
Urban – residential	381.72	400	50
Urban – commercial	26.97	500	63
Lakes/wetlands	12.92	-500	-85

Source: after Xu et al. 2005

*Estimated annual recharge (based on Perth regional office – average rainfall is about 800 mm for the period 1980 – 2003, Bassendean Sand soil type, deep watertable)

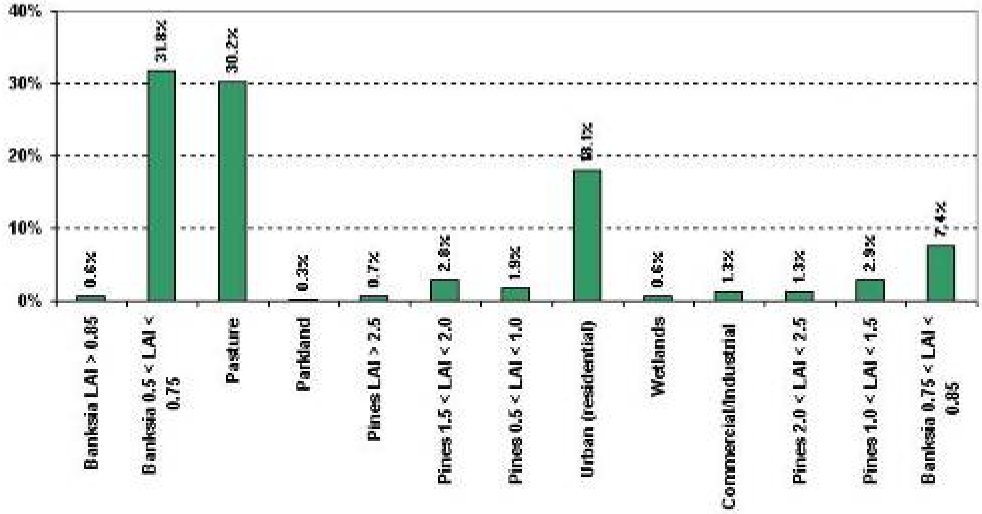


Figure 19 VFM Land-use breakdown for the Gnangara Mound (2007)

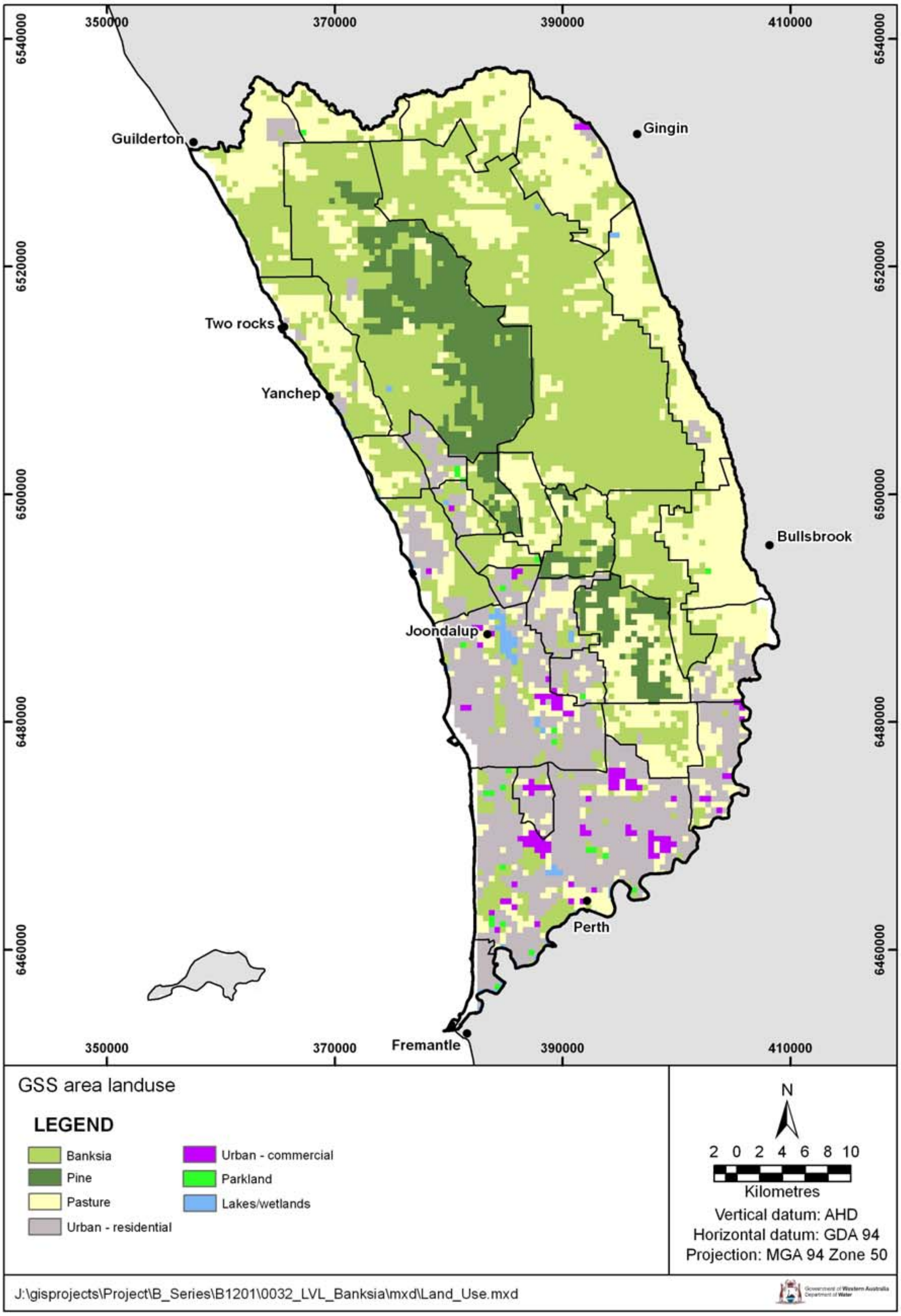


Figure 20 Land-use distribution used in PRAMS (2007)

4.3 Base case scenario

The base case is a groundwater modelling scenario that represents the conditions described below. Some of the land use changes in this scenario are aimed at increasing the groundwater recharge and thereby reducing the impact of watertable decline. The base case developed for this modelling study is founded on the following components:

- short-term climate (1997–2006), annual rainfall used in this scenario for the Perth airport climate zone is 680.8 mm/yr
- Water Corporation abstraction of 135 GL/yr (subarea breakdown of abstraction volumes are given in Table 9)
- private allocation at 100% of 2007 levels (from the Department of Water's Water Resource Licensing database) (subarea breakdown of abstraction volumes are given in Table 9)
- garden bores growth at 3% per year (subarea breakdown of abstraction volumes are given in Table 9)
- pines removed as per the Forest Products Commission laminated veneer lumber agreement (*Wood Processing (Wesbeam) Agreement Act 2002*). Pine area will be reduced to less than 100 ha (< 1 km^2) in 2031 from 9.6% of total GSS area (2007).
- laminated veneer lumber pines replaced with pasture (grassland). Pasture area will increase from 30.2% (2007) to 38.2% (2031) of the GSS area.
- native vegetation burning in 10-year rotations in 2008, 2018 and 2028. All native vegetation gets burnt once in 10 years. The area burnt in one particular year ranges from 2% to 26%. Total Banksia covers 39.8% of the GSS area, changes to Banksia from 2007 to 2031, as shown in Figure 21.
- additional urbanisation that will increase the total urban area from 19.4% (2007) to 21.7% (2031).

Projected land-use distribution and relevant area statistics are given in Figure 22 and Table 10.

Table 9 Licensed and unlicensed abstraction from the Superficial aquifer, used in base case scenario

Subarea	Name	Licensed abstraction		Garden bores GL/yr	Total GL/yr
		Public GL/yr	Private GL/yr		
1	Banksia	2.11	1.35	0.55	4.01
2	Bullsbrook	0	4.34	0.13	4.47
3	Carabooda	0	5.46	0.04	5.49
4	Carramar	0	1.16	0.03	1.18
5	Cottesloe Peninsula	0	0.46	0.46	0.92
6	East Gnangara	0	0.26	0.16	0.42
7	East Yanchep	1.38	0.49	0.59	2.46
8	Eglinton	0	0.46	0.09	0.55
9	Ellenbrook Town	0.43	2.27	0.59	3.28
10	Gingin Brook 1	0	1.44	0.01	1.46
11	Gingin Brook 2	0	4.74	0.00	4.74
12	Gingin Brook 3	0	4.77	0.00	4.77
13	Gingin Brook 4	0	2.93	0.00	2.93
14	Gnangara	7.51	1.08	0.43	9.02
15	Gwelup	7.27	1.16	1.02	9.45
16	Lake Gnangara	0	5.52	0.10	5.62
17	Lake Mungala	0	3.04	0.00	3.04
18	Lake Pinjar	0	0.82	0.06	0.87
19	Mariginiup	0	6.62	0.06	6.68
20	Neerabup	0	2.49	0.03	2.53
21	Nowergup	0	2.76	0.03	2.79
22	Perth North	6.03	14.74	25.21	45.98
23	Quinns Rocks	13.44	2.36	0.43	16.23
24	West Gnangara	1.68	0.19	0.08	1.95
25	West Pinjar	0.00	0.00	0.04	0.03
26	West Swan	0.75	4.07	0.66	5.48
27	Whiteman	2.15	0.29	2.65	5.09
28	Whitfords	3.07	13.08	7.62	23.76
29	Yanchep Two Rocks	1.03	0.75	0.13	1.91
Total		**46.85**	**89.07**	**41.19**	**177.11**

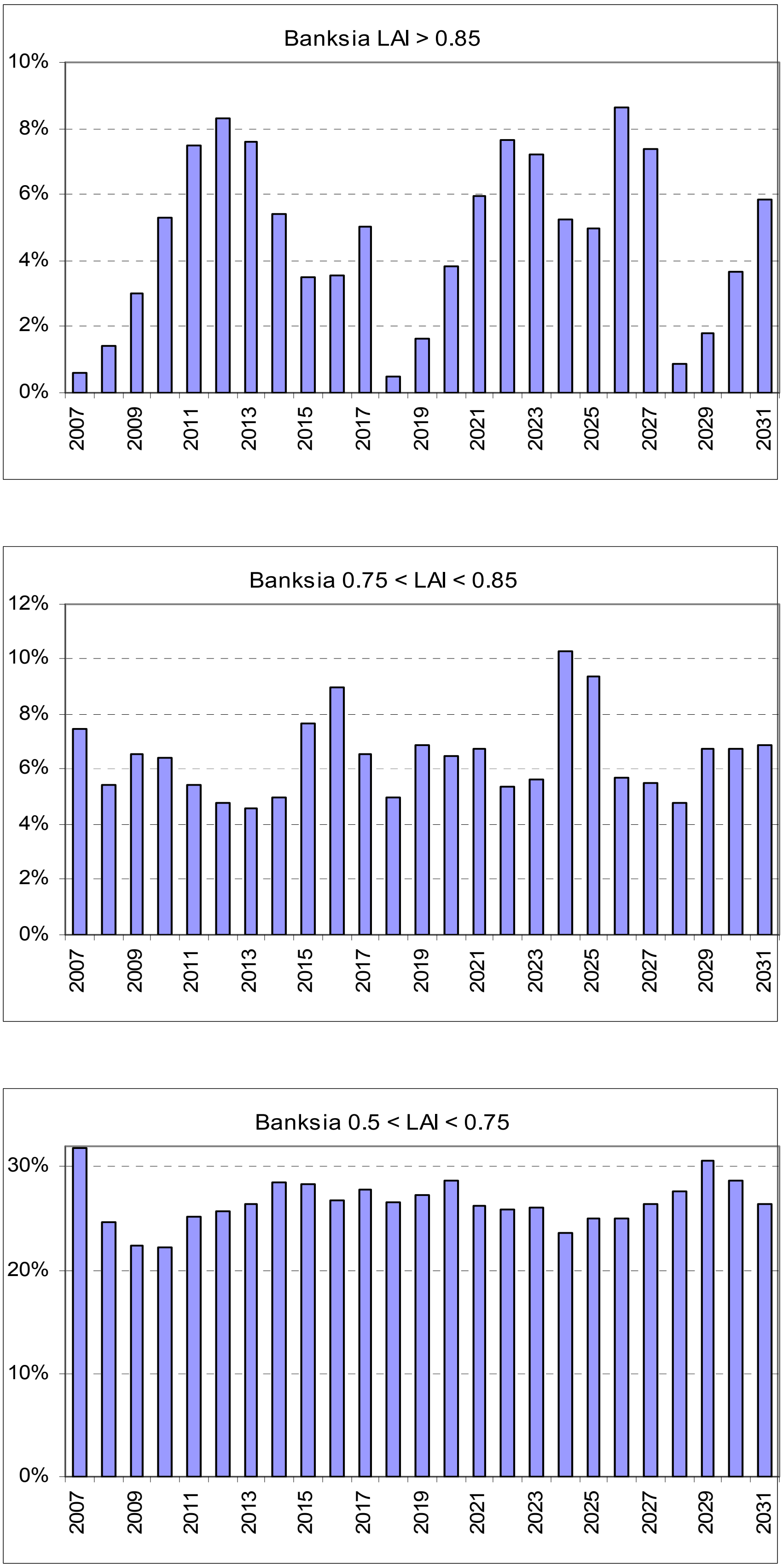


Figure 21 Banksia distribution changes due to burning regimes, used in base case scenario

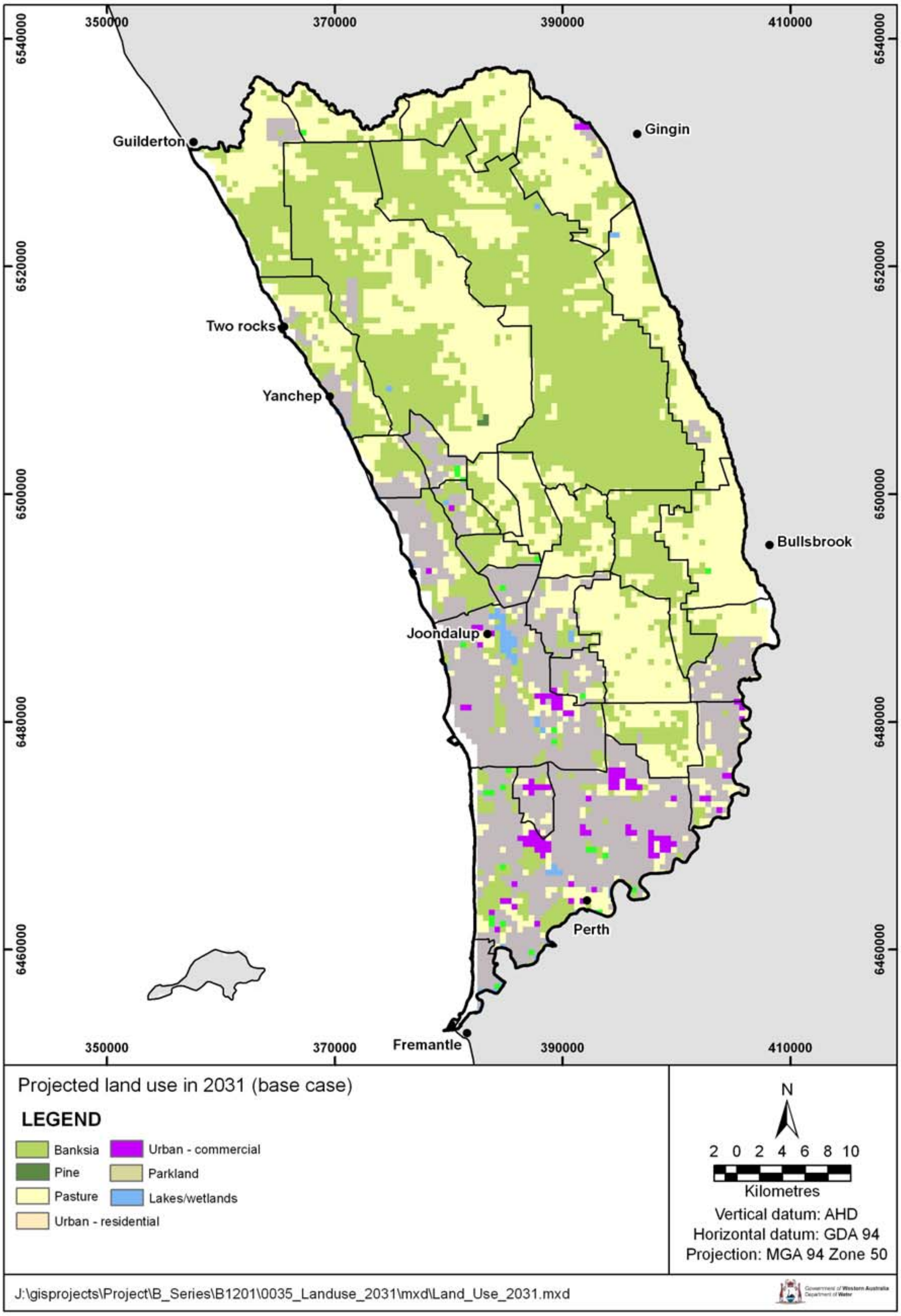


Figure 22 Projected land-use distribution in 2031, used in base case scenario

Table 10 Projected land-use distribution in 2031, used in base case scenario

Description	Area km^2	Area as % of GSS
Banksia – high density	124	5.9
Banksia – medium density	145	6.9
Banksia – low density	558.25	26.4
Pasture	807.25	38.2
Parkland	6.50	0.3
Pine – high density	0	0
Pine – medium to high density	0	0
Pine – medium density	0.25	0
Pine – low to medium density	0.25	0
Pine – low density	0.25	0
Urban – residential	434	20.5
Urban – commercial	26.25	1.2
Lakes/wetlands	12.75	0.6

4.4 Climate scenarios

In the climate scenarios only the climate component was changed, while all the other modelling components remained as in the base case. Three climate scenarios were modelled.

Dry climate scenario (11% less than mean from 1976-2006)

This climate scenario represents the dry climate condition in recent years. The annual rainfall used in this scenario for the Perth airport climate zone was 644.2 mm/yr. A synthetic climate year representing the dry climate was repeated from 2008 to 2031 in the model.

30-year average climate scenario (1976-2006)

This climate scenario represents the medium-term climate conditions in recent years. The annual rainfall used in this scenario for the Perth airport climate zone was 701.3 mm/yr. A synthetic climate year representing the 30-year average climate was repeated from 2008 to 2031 in the model.

Wet climate scenario (1950-1975)

This climate scenario is based on the wet climate condition in past years. The annual rainfall used in this scenario for the Perth airport climate zone was 860.9 mm/yr. A synthetic climate year representing the wet climate was repeated from 2008 to 2031 in the model.

4.5 Abstraction scenarios

Public abstraction scenarios

To assess the sensitivity of the watertable to a reduction in groundwater abstraction by the Water Corporation, the public abstraction component was reduced from the 135 GL/yr (base case) to the following three levels:

- 120 GL/yr
- 105 GL/yr
- 0 GL/yr

Note that in Table 11, the figures are abstraction from the Superficial component only. There are also abstraction components from confined aquifers inside the Mound and from the Superficial aquifer outside the Mound. This explains the apparent discrepancy between the figures in the column headings and the totals at the bottom. For instance, the 105 GL scenario consists of:

- 41.86 GL from the Superficial aquifer within the mound
- 53 GL – from confined aquifers within the mound
- 10 GL – from Superficial and confined, but outside the Mound.

All the other modelling components in the base case scenario remained the same. Yearly abstraction volumes used in these scenario for each subarea and the borefields are given in Table 11.

For all the scenarios there is a confined aquifer component but we are focussing in this study on the Superficial component only.

Table 11 Public abstraction scenarios volumes (Superficial aquifer only)

GSS subarea	Borefield	105 GL	120 GL	135 GL
Banksia	Pinjar	1.51	1.76	2.06
East Yanchep[1]	Yanchep Two Rocks	1.38	1.38	1.38
Ellenbrook Town[1]	Mirrabooka	0.45	0.45	0.45
Gnangara	Lexia and Wanneroo	6.84	6.84	7.14
Gwelup	Gwelup	7.02	7.02	7.24
Lake Pinjar[1]		0.01	0.01	0.01
Mariginiup[1]		0.00	0.00	0.00
Perth North	Mirrabooka	5.61	5.81	5.81
Quinns Rocks	Quinns	11.85	13.25	13.25
West Gnangara[1]	Wanneroo	1.69	1.69	1.69
West Swan[1]	Mirrabooka	0.65	0.65	0.65
Whiteman	Mirrabooka	0.97	1.67	1.92
Whitfords	Whitfords	2.85	3.05	3.05
Yanchep Two Rocks[1]	Yanchep Two Rocks	1.00	1.00	1.00
Total		**41.86**	**44.60**	**45.67**

Note: The majority of differences between these scenarios are in abstraction from the confined aquifers due to operational constraints on the borefields and treatment plants.

[1]These subareas showed no change between the different scenarios.

Private abstraction scenarios

To assess the sensitivity of the watertable to various levels of private abstraction, the following three scenarios were modelled. In each case, all the other modelling components remained the same as in the base case.

30% reduction in horticulture

In this scenario private allocation for horticulture purposes was reduced by 30%.

No private abstraction

In this scenario there was no private abstraction.

No abstraction

In this scenario both public and private abstraction components were set to zero, except unlicensed abstraction (garden bores).

4.6 Land-use scenarios

In these scenarios the land-use component was changed, while all the other modelling components remained same the as for the base case.

Laminated veneer lumber Banksia scenario

In this scenario laminated veneer lumber pine areas were replaced with Banksia native vegetation. This assessed the sensitivity of the watertable to changes in recharge caused by replacing pines with native vegetation instead of pasture (grassland). It also evaluated the impact of this on the water balance.

Immediate pine removal

In this scenario all the pine areas were removed in 2008 and replaced with pasture (grassland). This scenario helped to determine the impact of pine plantations on the watertable and the water balance, especially the recharge to the Superficial and confined aquifers.

4.7 GSS composite scenario

This scenario used a combination of abstraction and land-use changes. A comparison of land use with the base case scenario is shown in Figure 23 and the projected land-use distribution is in Figure 24 and Table 12. The following changes from the base case were made:

- Water Corporation abstraction at 120 GL/yr
- private allocation at 80% of 2007 levels (from the Department of Water's water resource licensing database)
- additional land-use changes expected by 2031:
  - market gardens increasing by 625 ha starting in 2023 following clearing of laminated veneer lumber pines, with no further growth in the area allocated for this land use
  - two more industrial areas in the West Pinjar and West Gnangara subareas occupying another 950 ha of cleared laminated veneer lumber pine areas
  - 3500 ha of laminated veneer lumber pine will be replaced by Banksia instead of grassland
  - pine area will be reduced to 1225 ha
  - an additional 6000 ha will be allocated to future urban residential growth.

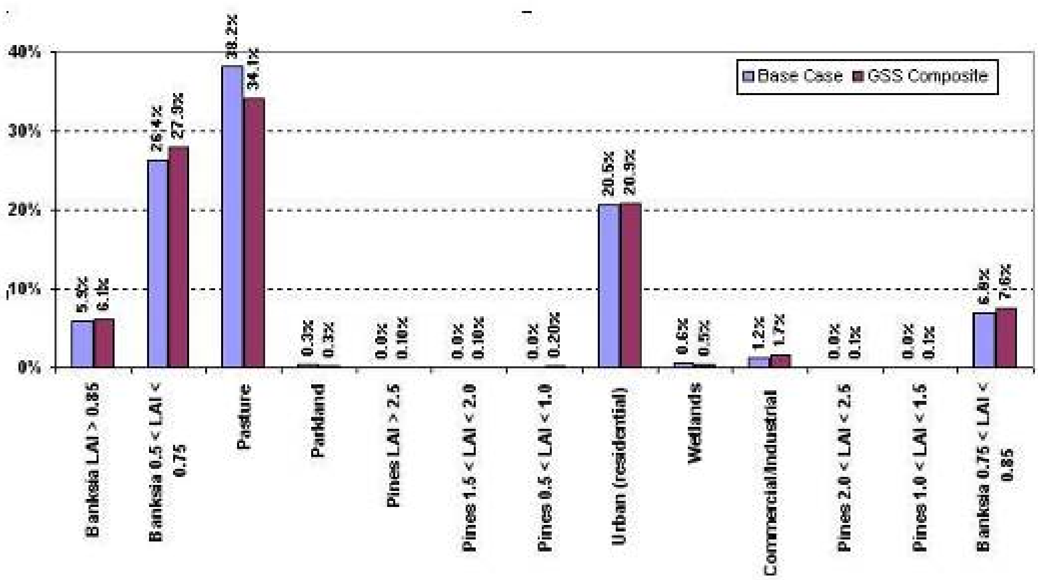


Figure 23 Comparison of land-use types for the base case and GSS composite scenarios in 2031

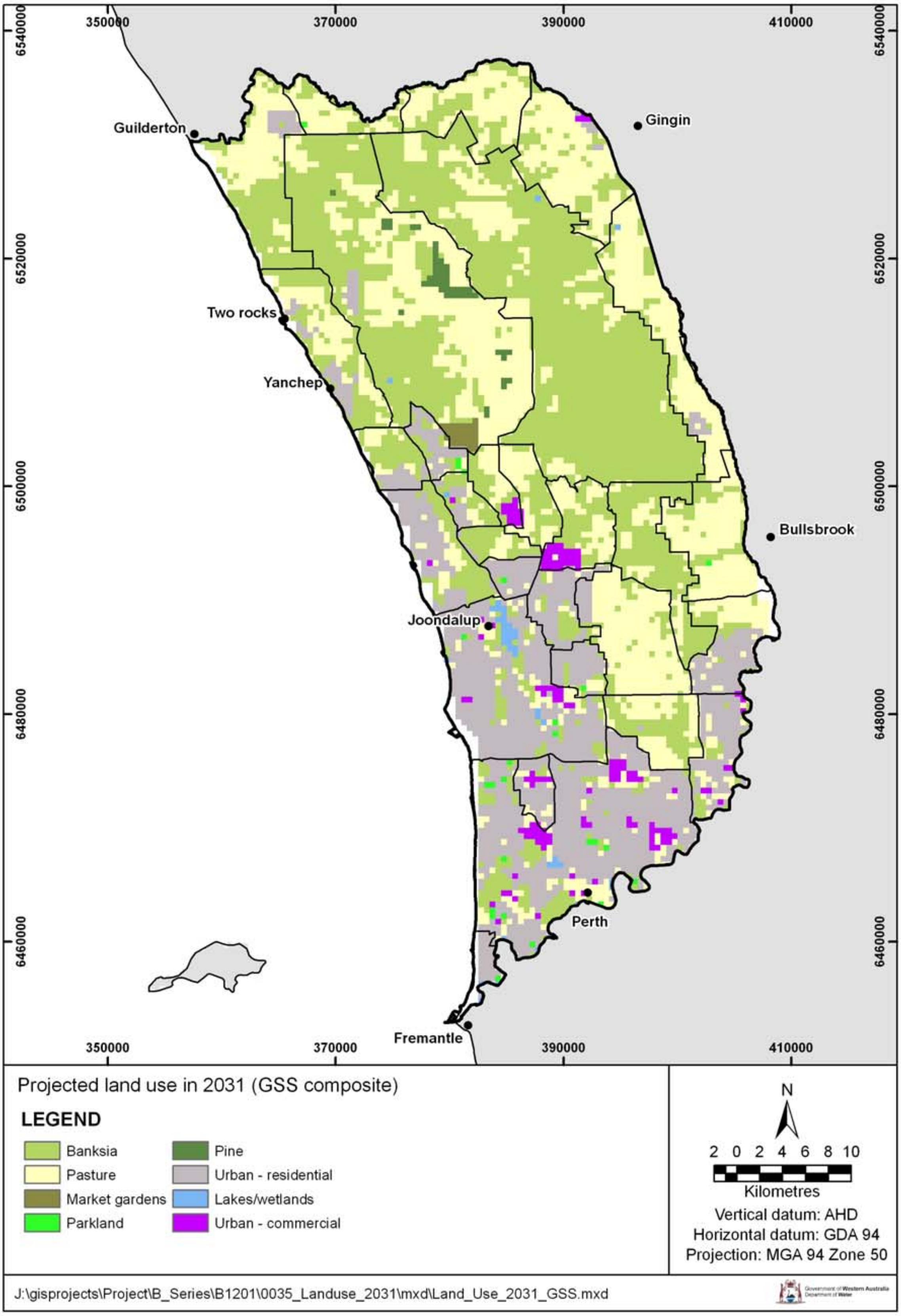


Figure 24 Projected land-use distribution in 2031, used in composite scenario

Table 12 Projected land-use distribution in 2031, used in composite scenario

Description	Area km^2	Area as % of GSS
Banksia – high density	129	6.1
Banksia – medium density	160	7.6
Banksia – low density	590.25	27.9
Pasture	720.50	34.1
Market Gardens	6.75	0.3
Parkland	6.25	0.3
Pine – high density	3	0.1
Pine- medium to high density	2.5	0.1
Pine – medium density	1.5	0.1
Pine –low to medium density	2	0.1
Pine – low density	3.25	0.2
Urban - residential	442.75	20.9
Urban - commercial	36.5	1.7
Lakes/wetlands	10.5	0.5

5 Scenario results

The results generated from modelling the different scenarios with PRAMS 3.2 fall into three categories:

- watertable and potentiometric heads of the Superficial aquifer and confined aquifers from 2008 to 2031
- water balance of the Superficial and confined aquifers from 2008 to 2031
- hydrographs for selected monitoring bores.

This chapter mainly analyses and reviews the data relating to the Superficial aquifer that forms the top four layers of the PRAMS 3.2 (Cymod Systems 2009).

5.1 Spatial analysis

Changes to the watertable from 2008 to 2031 under 13 different scenarios are presented as maps of absolute change and change relative to the base case in Figures 25 to 51. The absolute change map for a particular scenario was prepared by subtracting the predicted watertable levels in 2031 from the predicted levels in 2008. Another watertable difference map was prepared by subtracting the watertable elevations predicted for a particular scenario in 2031 from the predicted watertable levels for the base case in 2031. The predicted effects on watertable levels of the various changes modelled in the scenarios is summarised in Table 13. Water level differences in metres between the base case and the scenario are divided into five groups: 0.1 to 1 m, 1 to 2 m, 2 to 5 m, 5 to 10 m and > 10 m. Most of the scenarios tend to have a significant effect within 0.1 to 1 m compared to water level groups of greater than 2 m.

Table 13 Watertable changes in relation to base case scenario

Scenario	Area affected by watertable level change km^2					Total area affected by up to 10m change* as % of GSS
	0.1 to 1 m	1 to 2 m	2 to 5 m	5 to 10 m	>10 m	
Climate						
Dry (decline in watertable)	626	399	387			66
30-year average	715	791	400			89
Wet	460	265	639	516	197	97
WC abstraction						
120 GL	952	41				46
105 GL	1136	262				65
0 GL	674	677	406	86		86
Private abstraction						
Reduced horticulture	327	198	14			25
No private abstraction	781	739	376	47		90
No abstraction	442	397	863	333		95
Land-use						
Laminated veneer lumber Banksia	69					3
Immediate pine removal 2008	934	200	151			60
GSS composites						
GSS composite	1336	326	13.9			78
GSS composite dry (decline in watertable)	650	348	90.5			51
GSS composite dry (rise in watertable)	445	17				21

*Total area of GSS is 2149 km^2

Note: Unless indicated, figures represent rises in watertable.

As can be seen in Table 13 scenario differences are likely to be influenced by a number of factors and not the climate alone. At the 0.1 to 1 m interval the watertable is likely to be influenced by groundwater abstraction, especially the Water Corporation's. The factors changed in the GSS composite scenario are also likely to have an impact in the 0.1 to 1 m range. The changes in the no private abstraction scenario and climate (30-year average) scenario have an equal influence on the 1 to 2 m interval. Again at greater than 2 m interval, climate and abstraction play a main role. The effect of switching off all pumping has similar effect in area to having a wet climate but the wet climate has more area with greater change. In both scenarios groundwater levels are predicted to show an increase in watertable across 95% of Gnangara Groundwater Mound. Thus PRAMS predicts that in 2031 that the area of influence across the Mound from climate and groundwater abstraction (both public and private) are similar but storage change is more for the wet climate. Thus in terms of area of influence and depth of watertable change the dominant effect in 2031 will be due to climate, followed by combined private and public abstraction and then land-use change.

The table indicates that:

- overall the areal effect of having a dry climate can be matched by reducing the Water Corporation abstraction to 105 GL (dry 66%, 105 GL 65%)
- reduced horticulture can only diminish the effect in area of a dry climate by 25% (dry 66%, reduced horticulture 25%);
- the outcome of the GSS composite scenario in terms of area of impact can be mainly attributed to the reduction in the public and private abstraction. Land-use changes only have a minor areal effect (GSS composite 78%, WC 120 GL 46%, reduced horticulture 25%)
- the no abstraction scenario has the same effect in area as the wet climate scenario (no abstraction 95%, wet climate 97%)
- immediate removal of pines in 2008 has a similar areal effect to the dry climate scenario (immediate pine removal 60%, dry climate 66%), but for immediate pine removal most of the water level rise is within 0.1 to 1 m range whereas for the dry climate more of the decrease is deeper.
- the effects of the laminated veneer lumber Banksia scenario are very similar to the base case scenario where cleared pines are replaced with pasture (grassland).

Base case scenario

The prediction of absolute changes in the watertable levels of the Gnangara Groundwater Mound is shown in Figure 25. This shows that the base case watertable is predicted to decline between 0.1 and 3 m over most of the Mound and up to 9 m in the Banksia subarea (Yeal) from 2008 to 2031. There is a small area of net watertable rise under the southern part of the pine plantations due to increased recharge from thinning and clear-felling of pines.

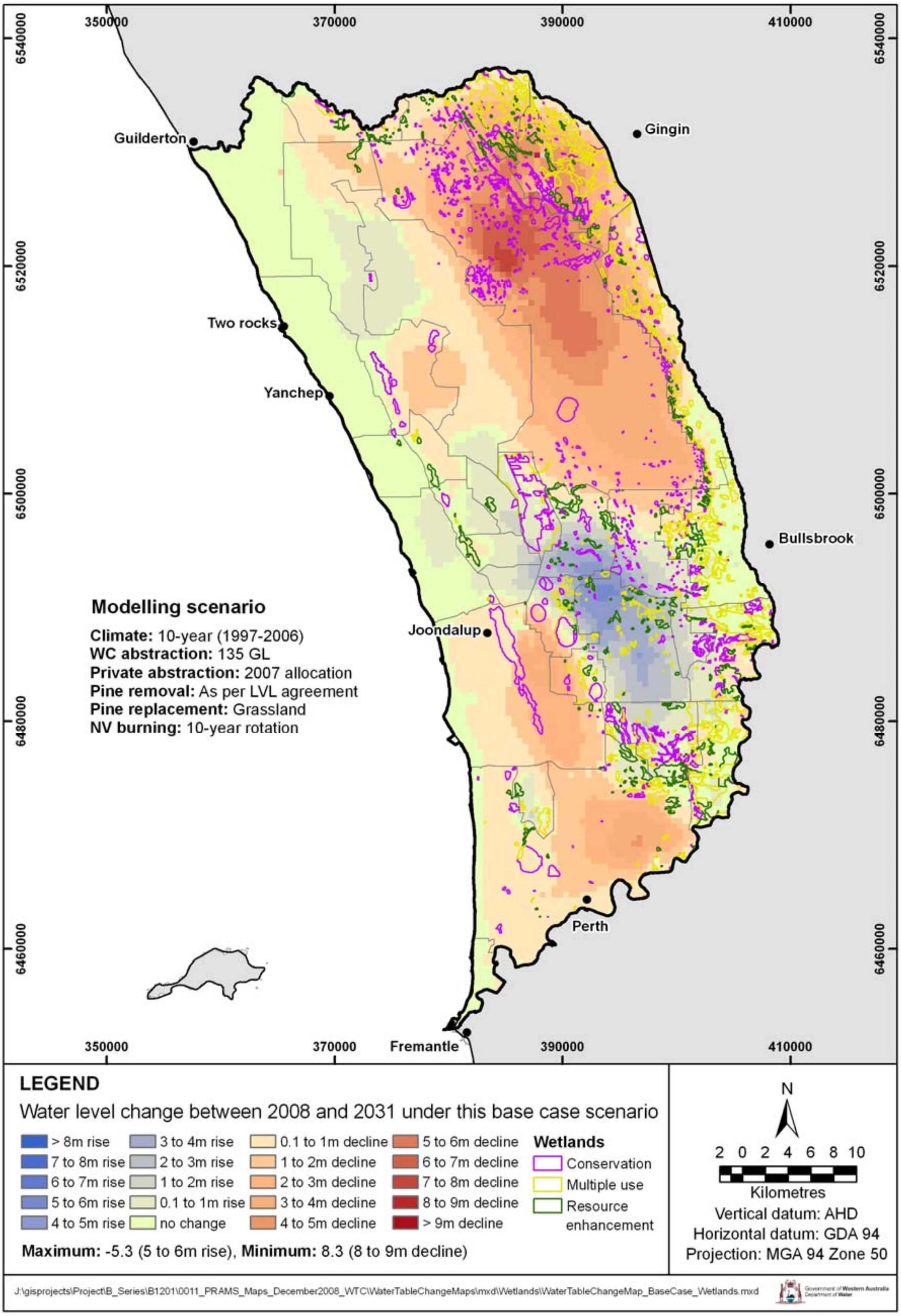


Figure 25 Base case scenario, showing predicted watertable change from 2008 to 2031

Under the base case, 22% of the area records no change in watertable between 2008 and 2031 (Table 14), while 59% of the area shows a decline in watertable and 19% of the area has a rise in watertable for the same period. The areas of watertable decline are mainly centred on the Banksia subarea and Perth North and Whitfords subareas where the majority of licensed and unlicensed abstraction continues from the previous 30 years (1979–2008). A rising watertable occurs where the southern pine plantation had been cleared in 1990s. There is also an effect from the proposed clearing of the northern pine plantation (East Yanchep) on recharge with the watertable starting to rise by 2031. There is a considerable area of no change in watertable, especially in subareas along the coast and in the eastern part of the Mound. These may be attributable to the presence of high permeability Tamala Limestone, with the decrease in throughflow being replaced by saline intrusion and the presence of low permeability Guildford clay in the discharge area in the east.

Table 14 Area statistics of watertable change for base case scenario

Level change m	Area km^2	% of GSS
No change	471	21.9
Rise		
0.1 to 1	240	11.2
1 to 2	65	3.0
2 to 3	47	2.2
> 3	52	2.4
Decline		
0.1 to 1	481	22.3
1 to 2	271	12.6
2 to 3	183	8.5
3 to 5	251	11.7
> 5	88	4.1

Climate scenarios

Dry climate

This scenario models the sensitivity of the watertable to a drying climate. Figure 26 shows modelled changes in watertable levels between 2008 and 2031. The difference between the base case and the dry climate scenario is shown in Figure 27. The results show substantial, additional declines of the watertable under a dry climate regime from 2008 to 2031. This suggests that rainfall reduction is the main cause of watertable trends across the Mound. These results are consistent with the hydrograph analysis undertaken by Yesertener (2007).

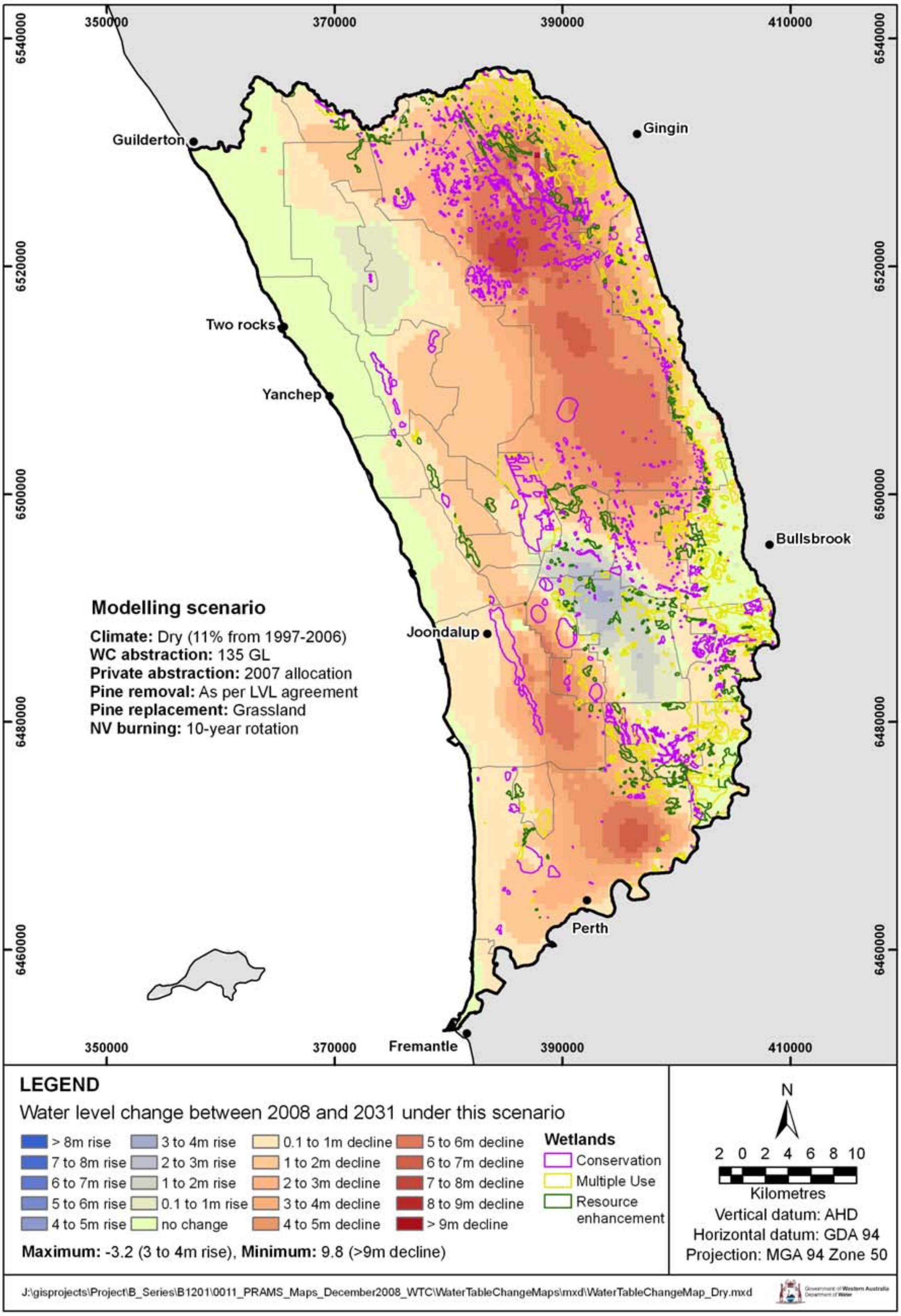


Figure 26 Dry climate scenario, showing predicted watertable change from 2008 to 2031

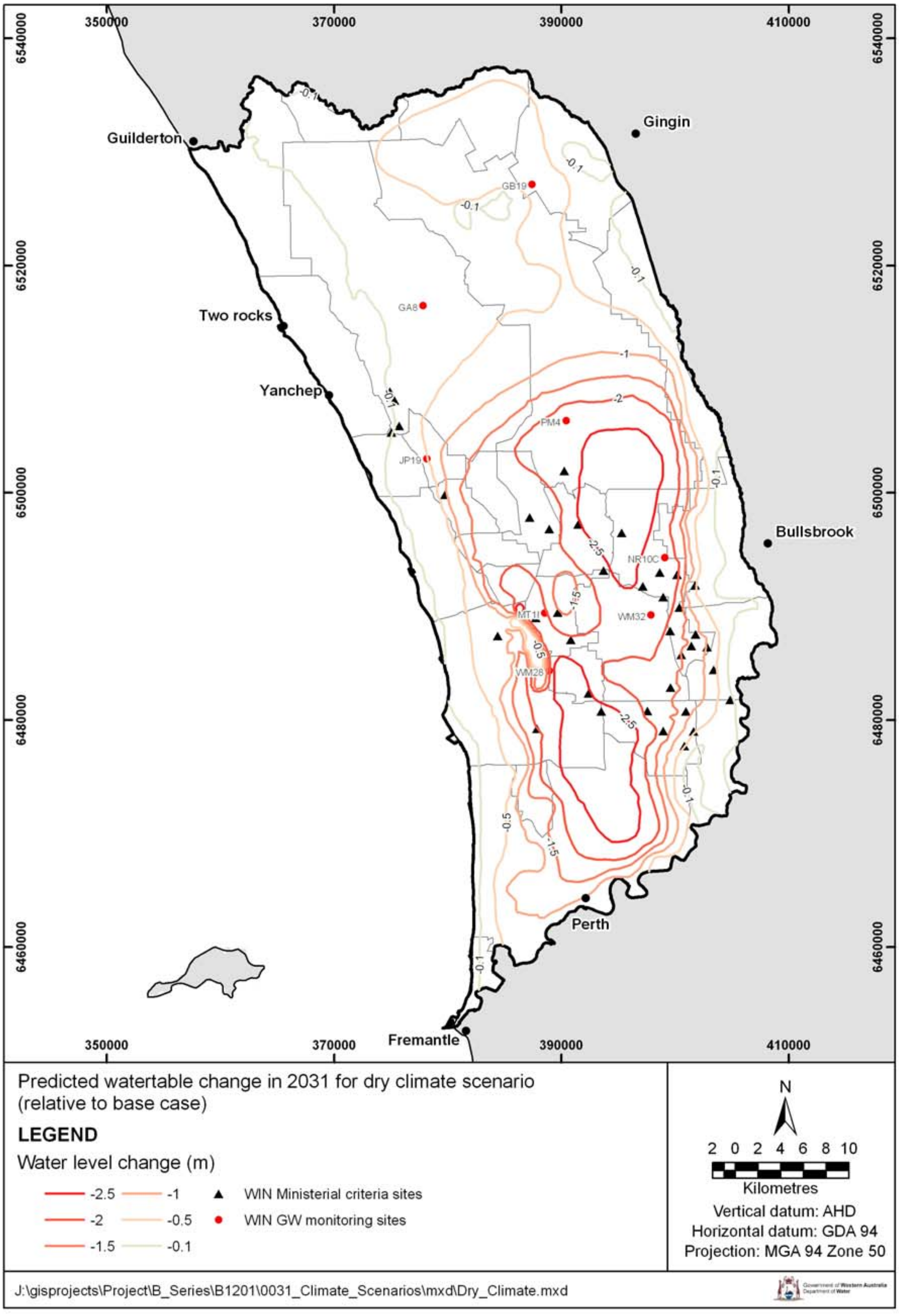


Figure 27 Watertable elevation difference in 2031 between the dry climate and the base case scenarios

30-year average climate

This scenario models the sensitivity of the watertable to a 30-year average climate (1976–2006). Figure 28 shows modelled changes in watertable levels between 2008 and 2031. The difference between the base case and the 30-year average climate is shown in Figure 29. The results indicate that under this scenario, which has a wetter climate than the base case, 89% of the Gnangara Mound is predicted to record significant increases in watertable ranging from 0.1 m to 2.5 m. The maximum increase is centred on the Lexia wetlands where sensitive wetlands and Ministerial criteria sites are located.

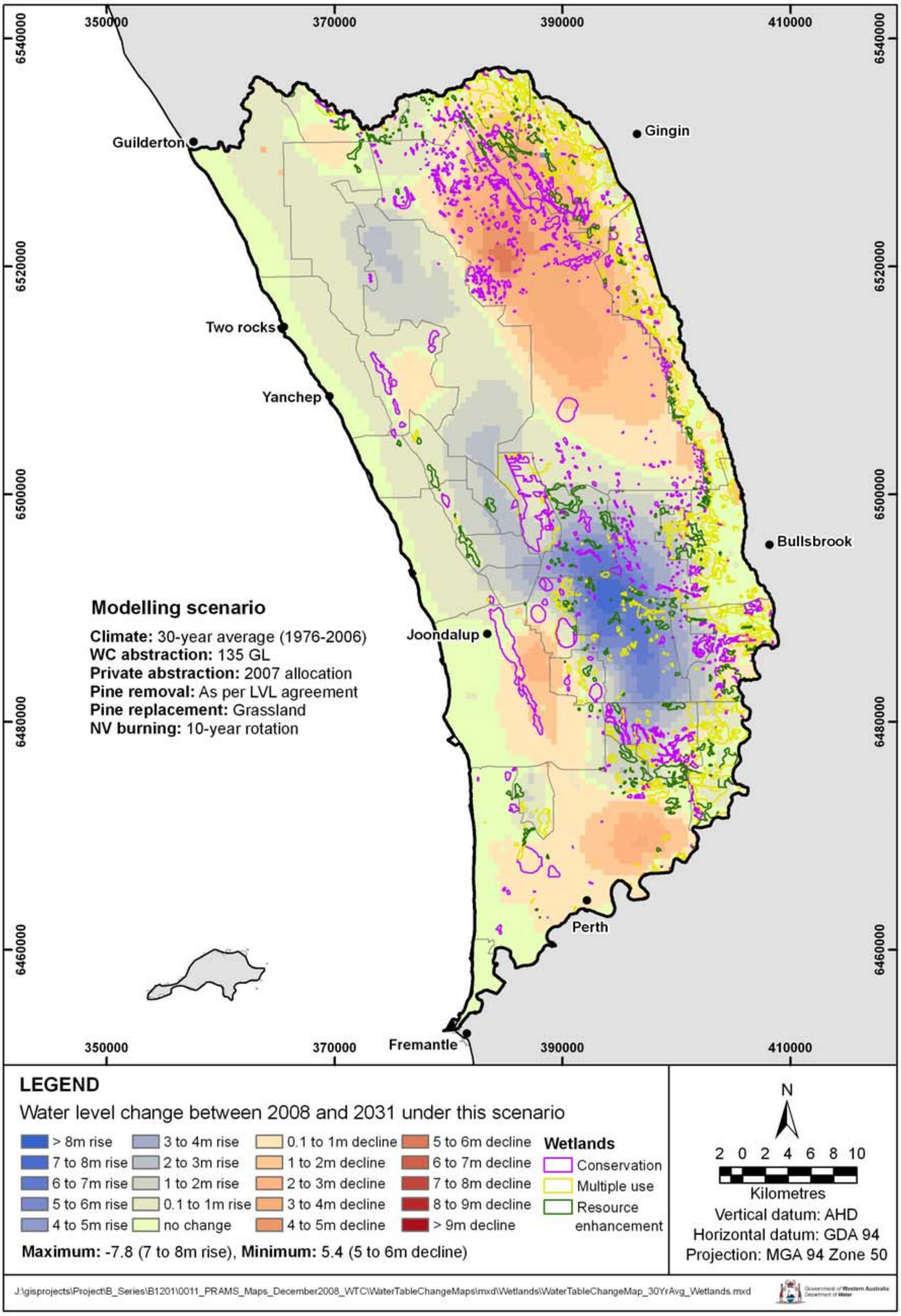


Figure 28 30-year average climate scenario , showing predicted watertable change from 2008 to 2031

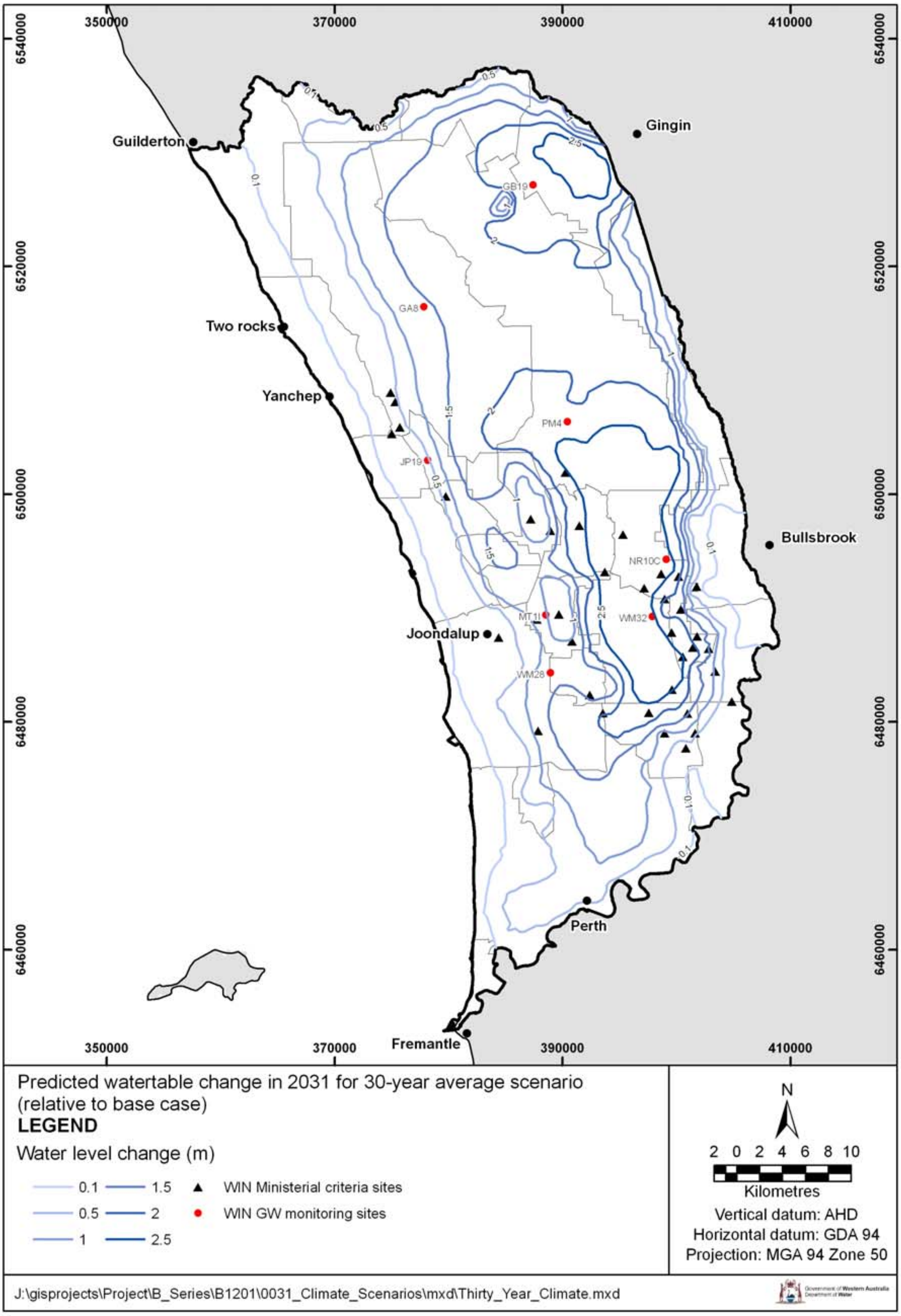


Figure 29 Watertable elevation difference in 2031 between the 30-year average climate and the base case scenarios

Wet climate

This scenario models the sensitivity of the watertable to a wet climate (1950–1975). Figure 30 shows modelled changes in watertable levels between 2008 and 2031. The difference between the base case and the wet climate scenarios is shown in Figure 31. The results show that under a much wetter climate than the base case climate, 97% of the Gnangara Mound is predicted to record significant increases in watertable levels, ranging from 0.1 m to more than 11 m. The maximum increase is centred on the Yeal area that provides recharge to the confined aquifers.

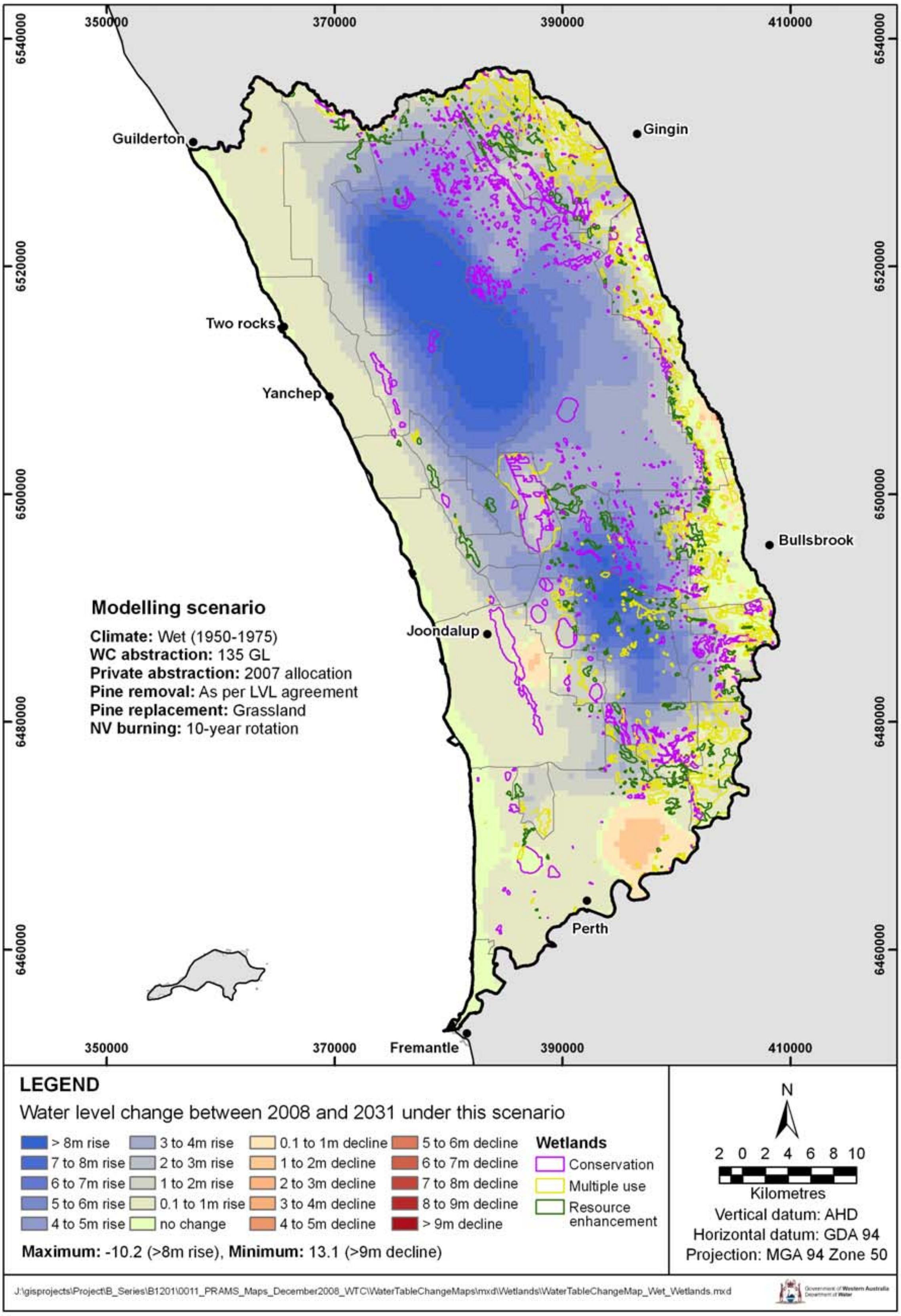


Figure 30 Wet climate scenario, showing predicted watertable change from 2008 to 2031

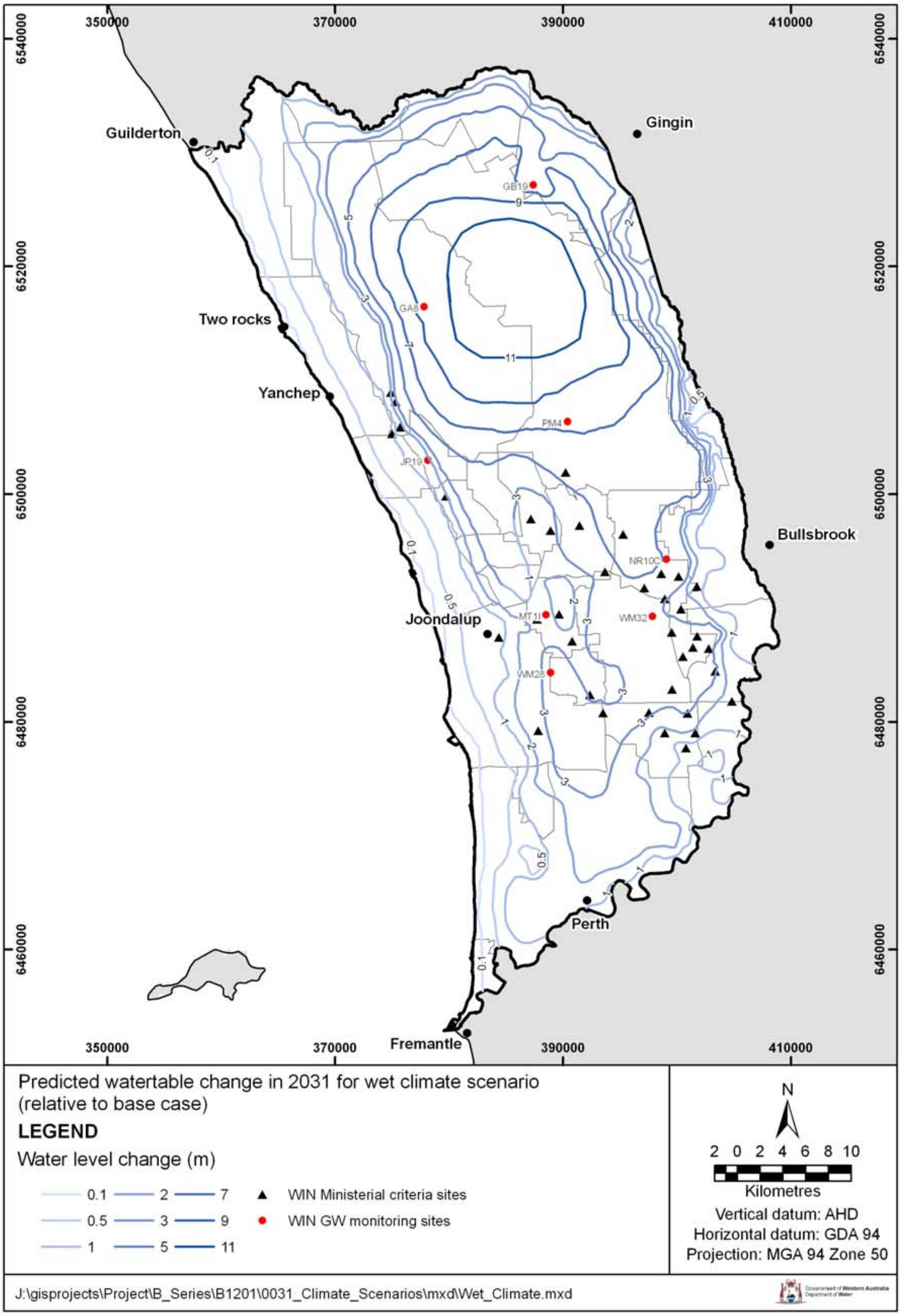


Figure 31 Watertable elevation difference in 2031 between the wet climate and the base case scenarios

Abstraction scenarios

Table 15 Breakdown by aquifer of Water Corporation abstraction scenarios

Aquifer	Total abstraction		
	105 GL	**120 GL**	**135 GL**
Superficial	36.52	39.27	40.40
Mirrabooka	3.18	3.18	3.18
Leederville	27.60	33.05	35.44
Yarragadee	30.18	35.90	47.44
Total Gnangara Mound*	**97.48**	**111.40**	**126.46**

* The totals do not add up to the column headings because there are some production bores outside the Mound which are not included in the totals here but which were included in the modelling.

Water Corporation 120 GL abstraction

There is only about 1.1 GL difference in abstraction between the 120 GL and the base case (135 GL) for the Superficial aquifer. Most of the reduction in abstraction was derived by reducing the abstraction in the Yarragadee aquifer from 47.44 GL to 35.9 GL (Table 15). Comparison of abstraction volumes from the Superficial aquifer for this scenario and the base case is given in Table 11 (Section 4, Scenario design) and Table 15 above. The greater portion of groundwater volumes (Superficial aquifer) were modelled as being pumped from the Water Corporation production bores in Quinns Rocks (29.7%), Gwelup (15.7%) and Gnangara (15.3%) subareas.

Under this scenario in 2031, 46% of the Gnangara Groundwater Mound shows a rise in watertable relative to the base case. However, most of the watertable rise is limited to the range of 0.1 to 1 m. The recovery in watertable levels under this scenario can be mainly attributed to the reduction in Yarragadee aquifer pumping. There is also good spatial correlation between the watertable recovery area and the area where the Leederville Formation and Yarragadee Formation subcrop beneath the Superficial Formation. Figures 32 and 33 show the absolute and relative watertable for this scenario respectively.

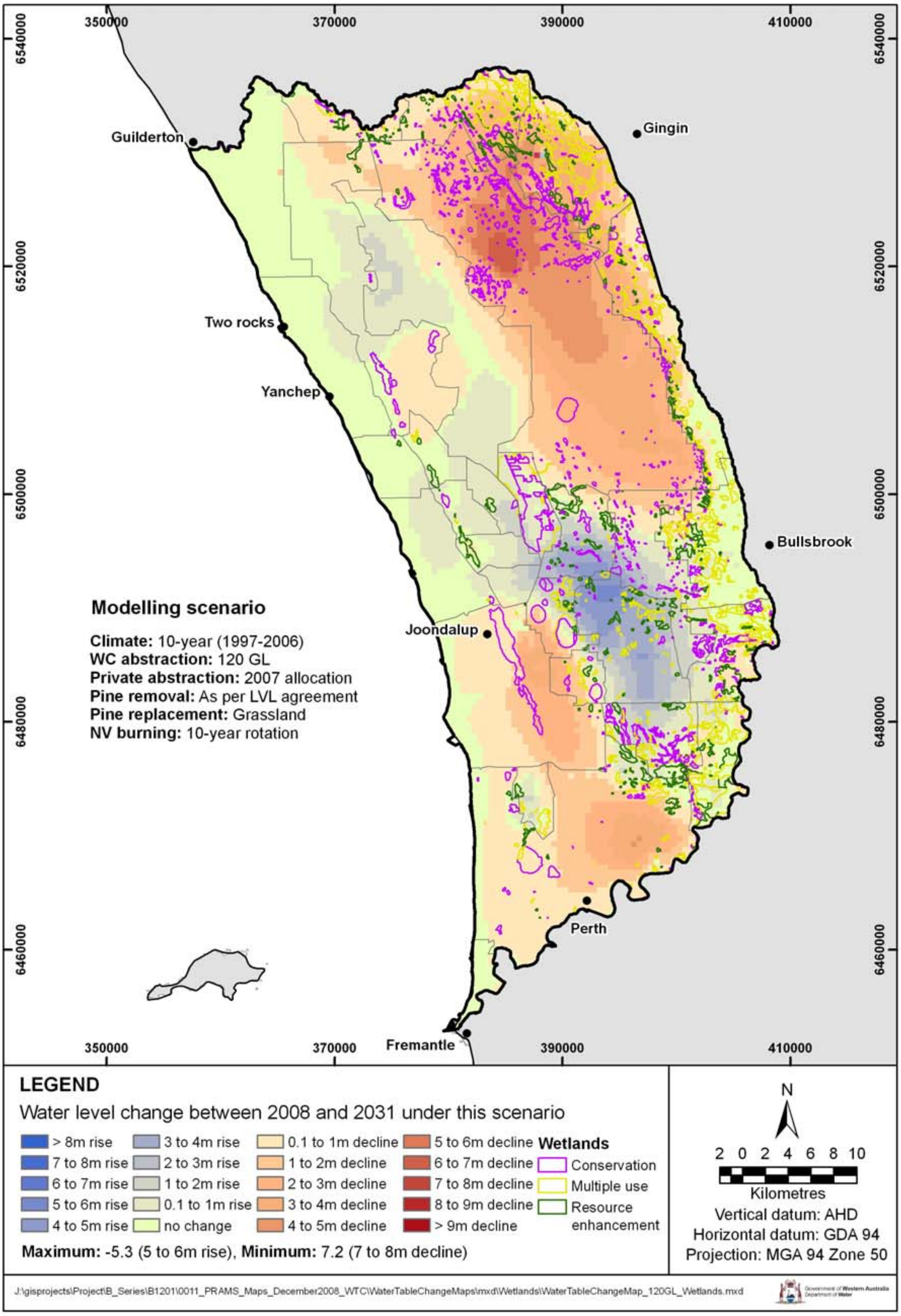


Figure 32 Water Corporation 120 GL abstraction scenario, showing predicted watertable changes from 2008 to 2031

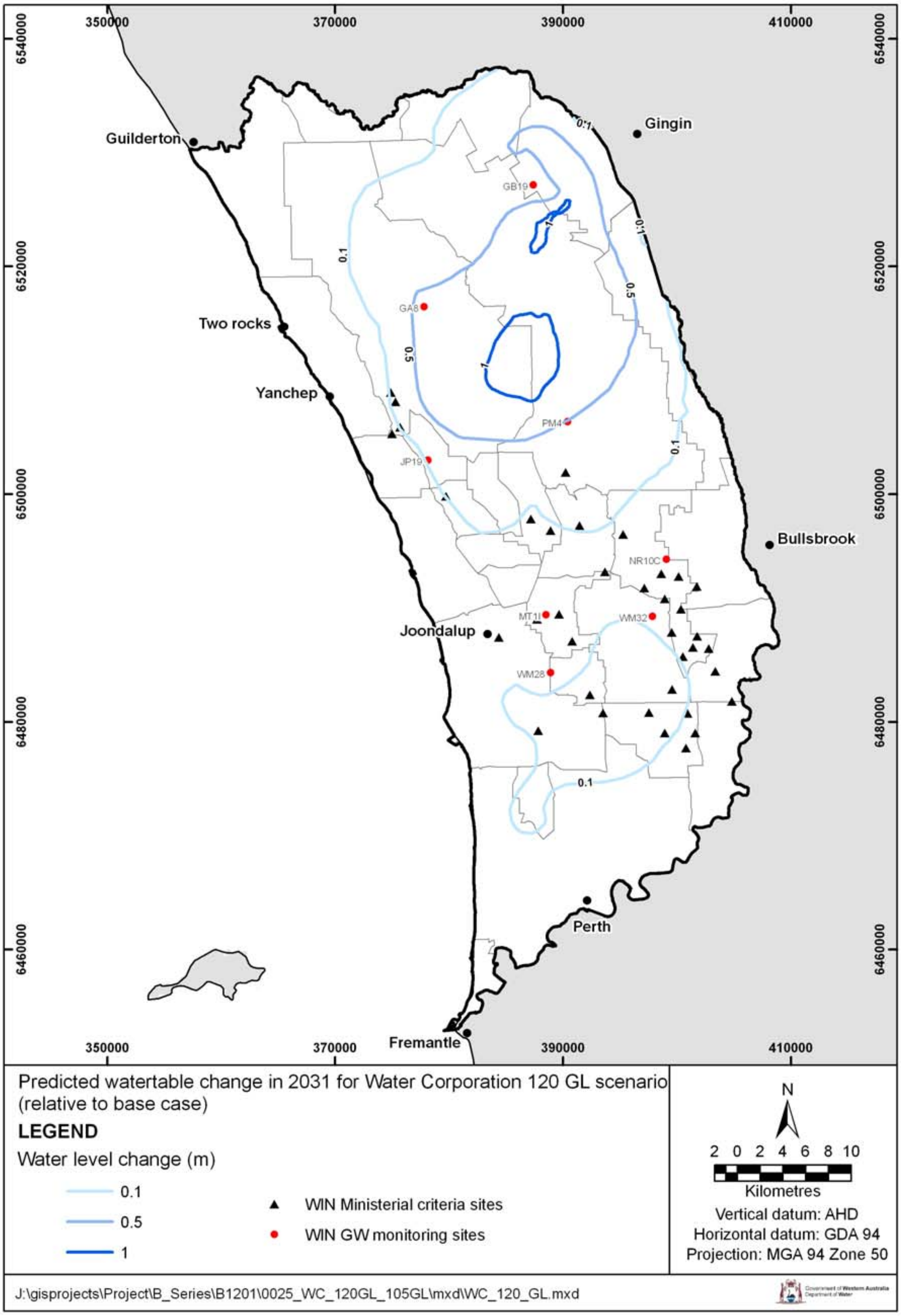


Figure 33 Watertable elevation difference in 2031 between the Water Corporation 120 GL abstraction scenario and the base case scenario

Water Corporation 105 GL abstraction

In this scenario, abstraction from the Superficial aquifer was reduced from 40.4 GL in the base case to 36.52 GL and from the confined aquifers by 25 GL. A comparison of abstraction volumes for this scenario and base case is given in Table 11 (Section 4, Scenario design). The greater portion of groundwater volumes (Superficial aquifer) were modelled as being pumped from the Water Corporation production bores in Quinns Rocks (28.3%), Gwelup (16.8%) and Gnangara (16.3%) subareas.

Under this scenario, in 2031 65% of the Gnangara Groundwater Mound shows some degree of recovery in watertable levels relative to the base case. However, most of this is limited to the range of 0.1 to 1 m. The 0.1 m contour expands to cover a large part of the Mound compared to the 120 GL scenario, thus improving the watertable conditions in a significant portion of Ministerial sites and sensitive wetlands. The recovery in watertable under this scenario can be mainly attributed to the reduction in Yarragadee aquifer pumping. There is also good spatial correlation between the watertable recovery area and the area where the Leederville Formation and Yarragadee Formation subcrop beneath the Superficial Formation. Figures 34 and 35 show the absolute and relative watertable changes for this scenario respectively.

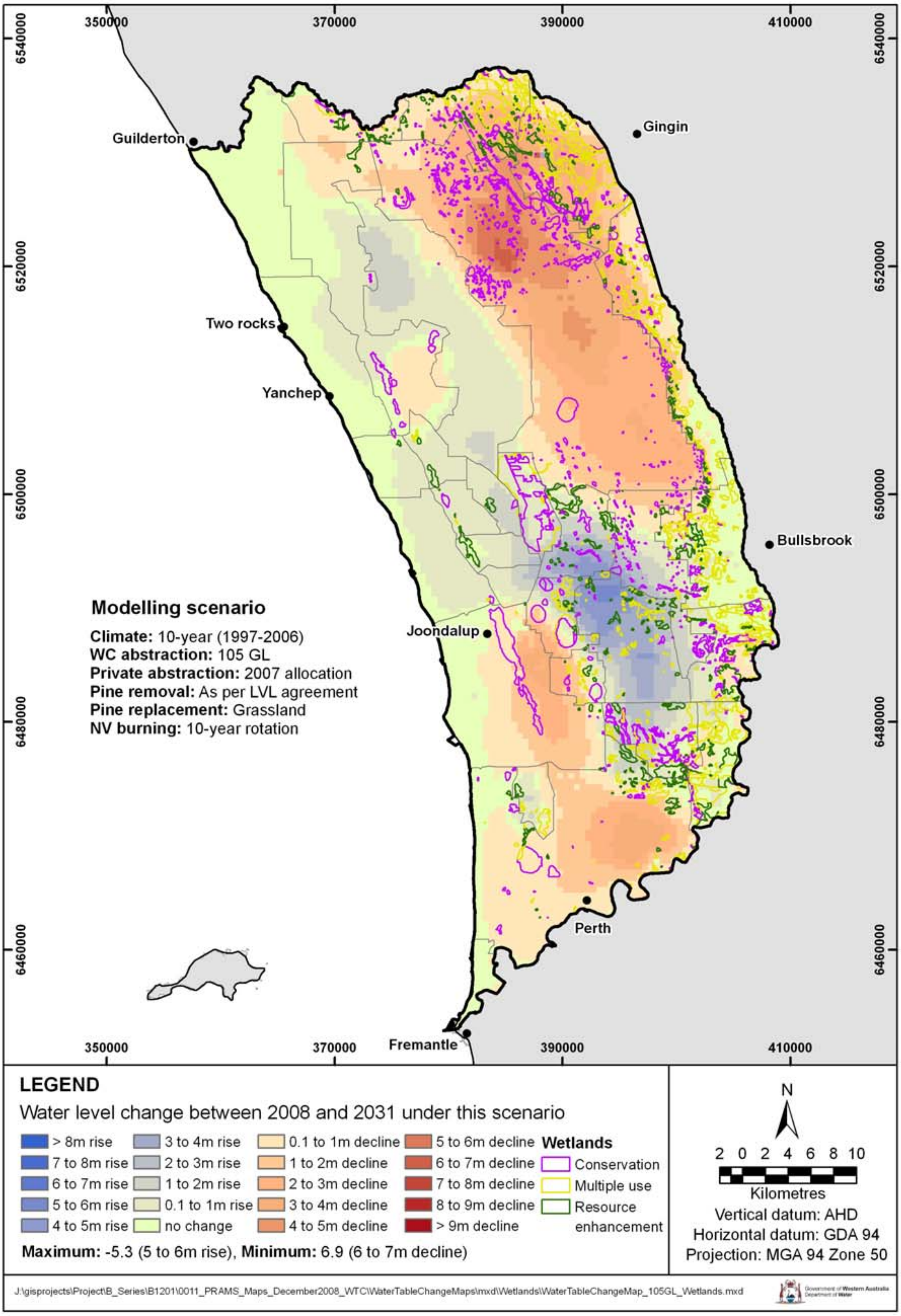


Figure 34 Water Corporation 105 GL abstraction scenario, showing predicted watertable change from 2008 to 2031

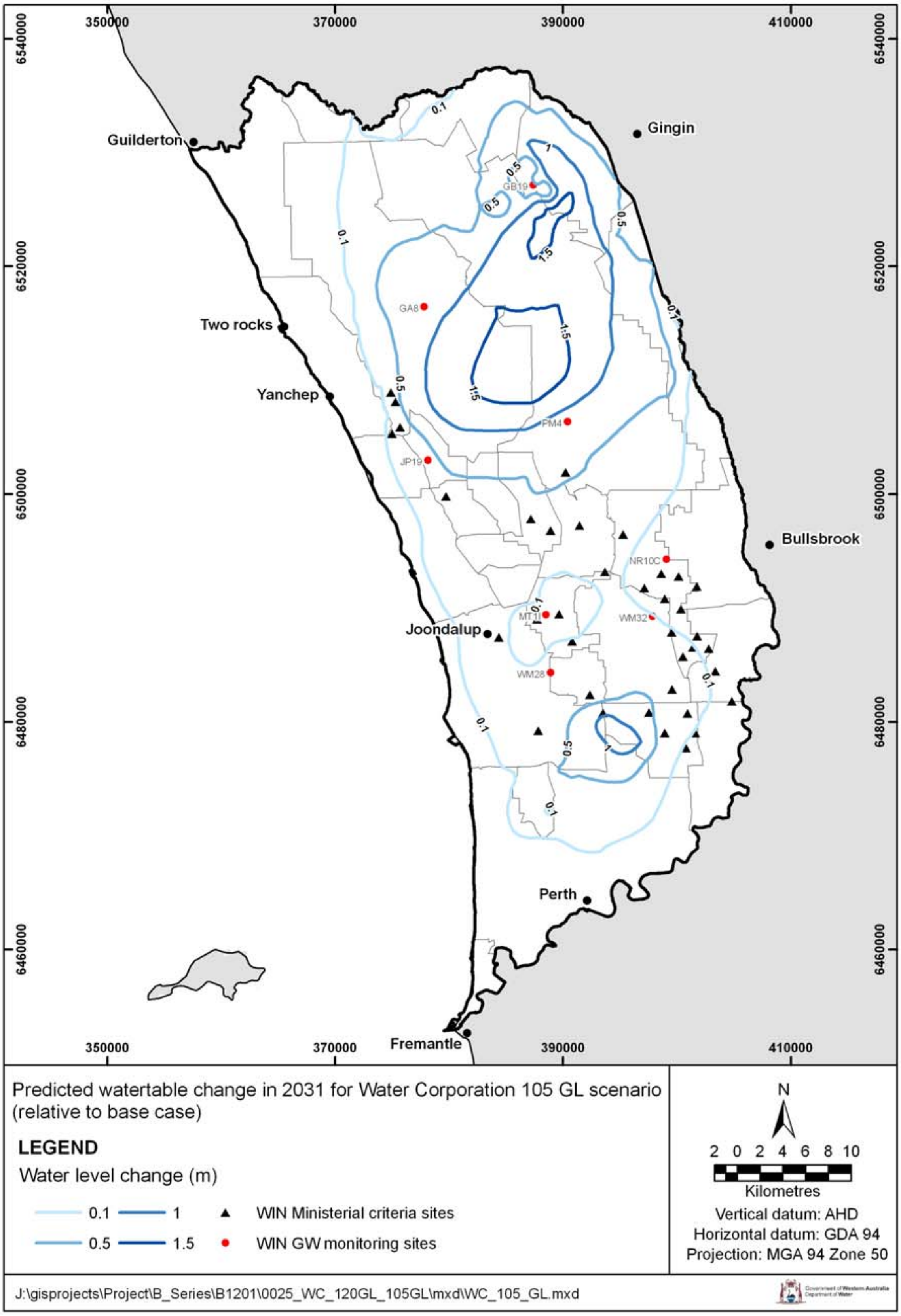


Figure 35 Watertable elevation difference in 2031 between the Water Corporation 105 GL abstraction scenario and the base case scenario

Water Corporation 0 GL abstraction

The modelling for no Water Corporation pumping (all the production bores shut down in 2008) showed that 86% of the Gnangara Groundwater Mound will recover to some extent in 2031. The majority of the watertable rises relative to the base case are in the 0.1 to 1 m group and the 1 to 2 m group. This recovery benefits all the sensitive wetlands and the designated Ministerial criteria sites. Some Ministerial criteria sites located in the southen part f the Mound are likely to show a recovery in the watertable of up to 3 m. The recovery in the southern area of the Mound may be due to a reduction in Superficial aquifer abstraction whereas the northern recovery area recovery is attributable to a reduction in confined pumping. The relative watertable maps show Water Corporation pumping in 2031 is likely to have a regional impact on the Mound, not a local impact restricted to the Water Corporation borefields. Figure 36 and 37 show the absolute and relative watertable level changes for this scenario respectively.

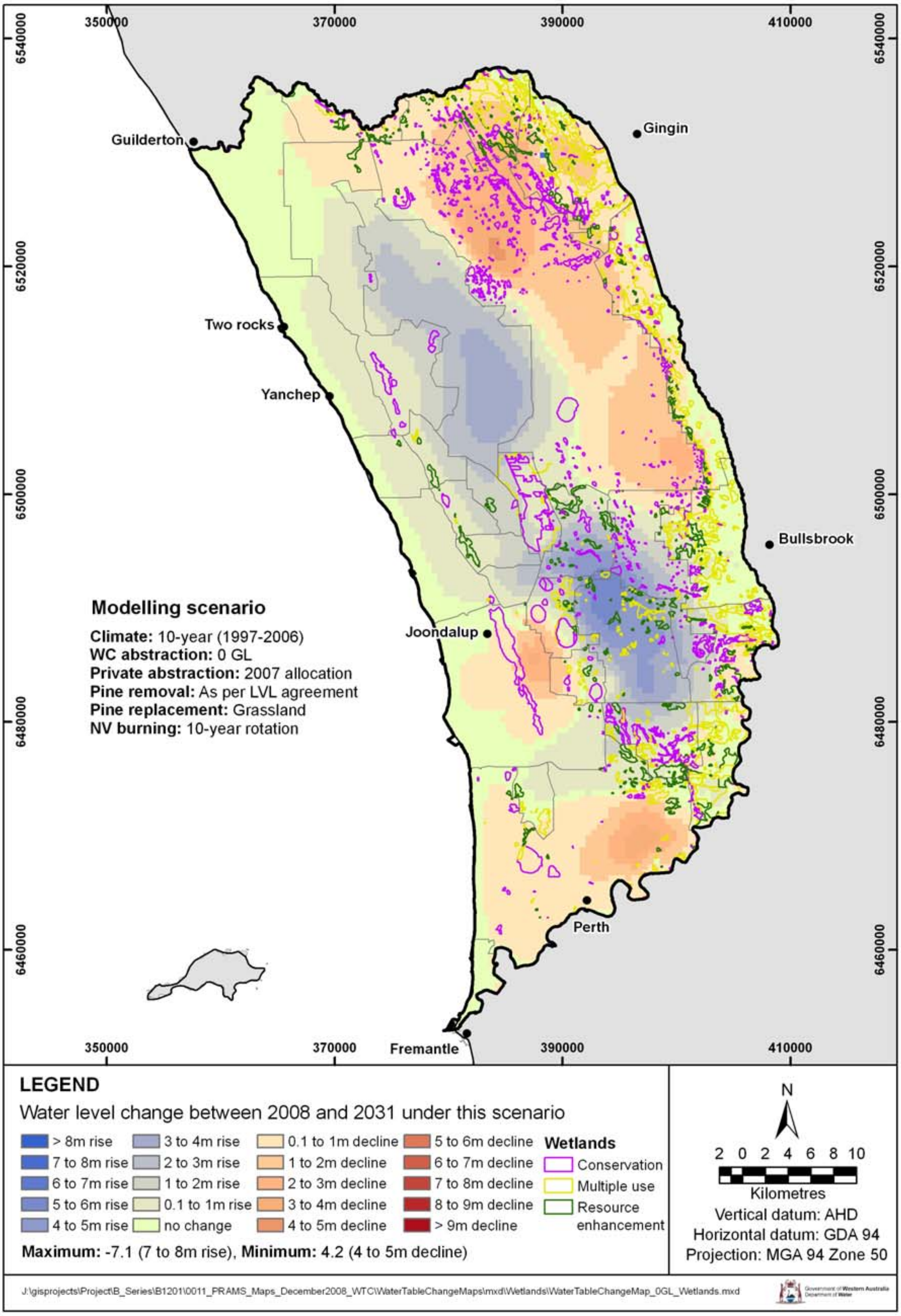


Figure 36 No Water Corporation (public) abstraction scenario, showing predicted watertable change from 2008 to 2031

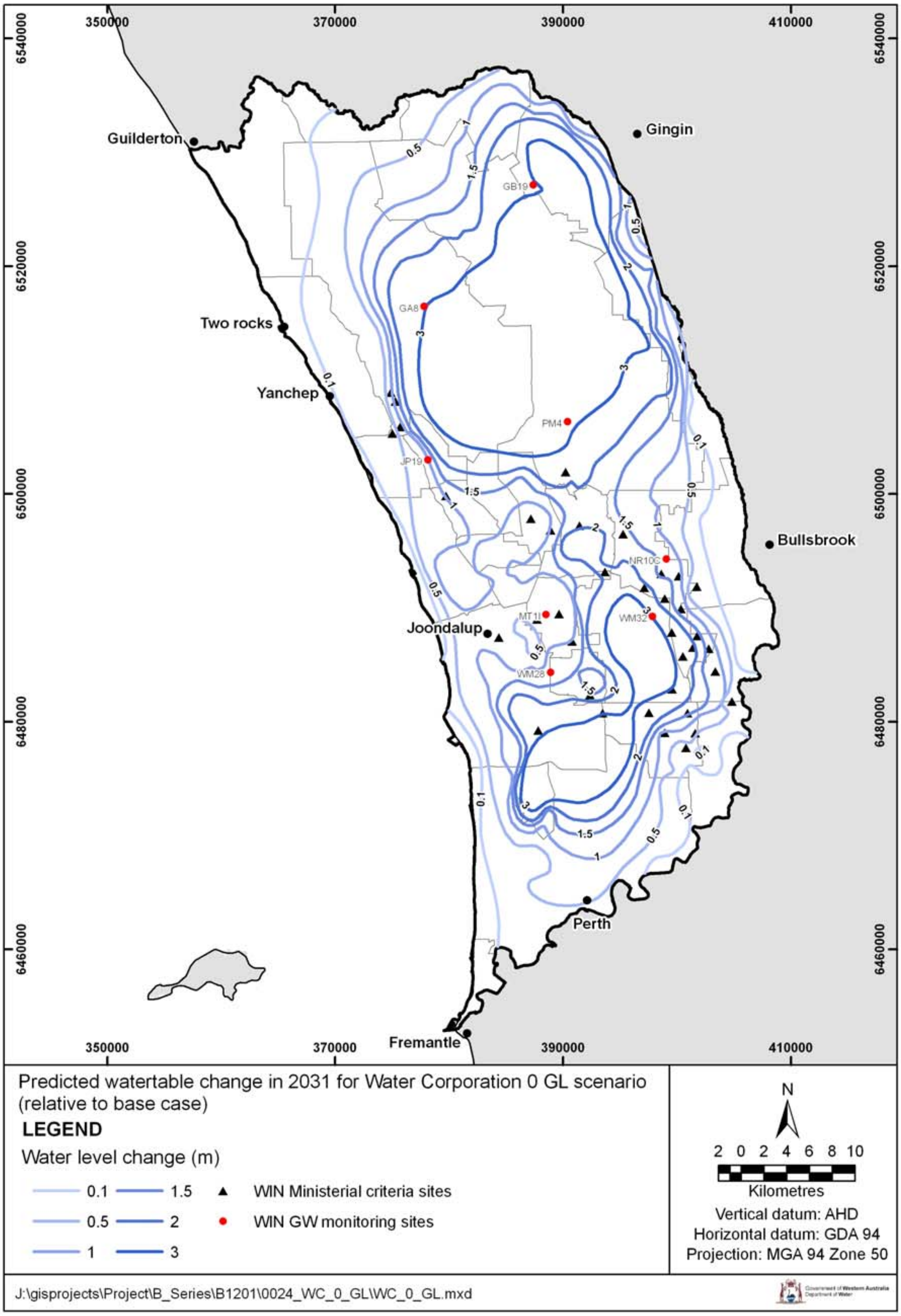


Figure 37 Watertable elevation difference in 2031 between the no Water Corporation (public) abstraction scenario and the base case scenario

Reduced horticulture (by 30%)

Modelling of this scenario shows a likely local effect centred on subareas extending from Carabooda to Lake Gnangara, where horticultural activities are the most dominant land use. Some of the major private pumping from this area includes:

- 6.62 GL/yr from Mariginiup
- 5.46 GL/yr from Carabooda
- 5.52 GL/yr from Lake Gnangara.

Under this scenario, following a 30% allocation reduction for horticulture in 2007, 30% of the Mound is modelled as showing recovery to some extent . Unlike public abstraction, private abstraction mainly relies on the abstraction from the Superficial aquifer. Figure 38 and 39 show the absolute and relative watertable for this scenario, respectively.

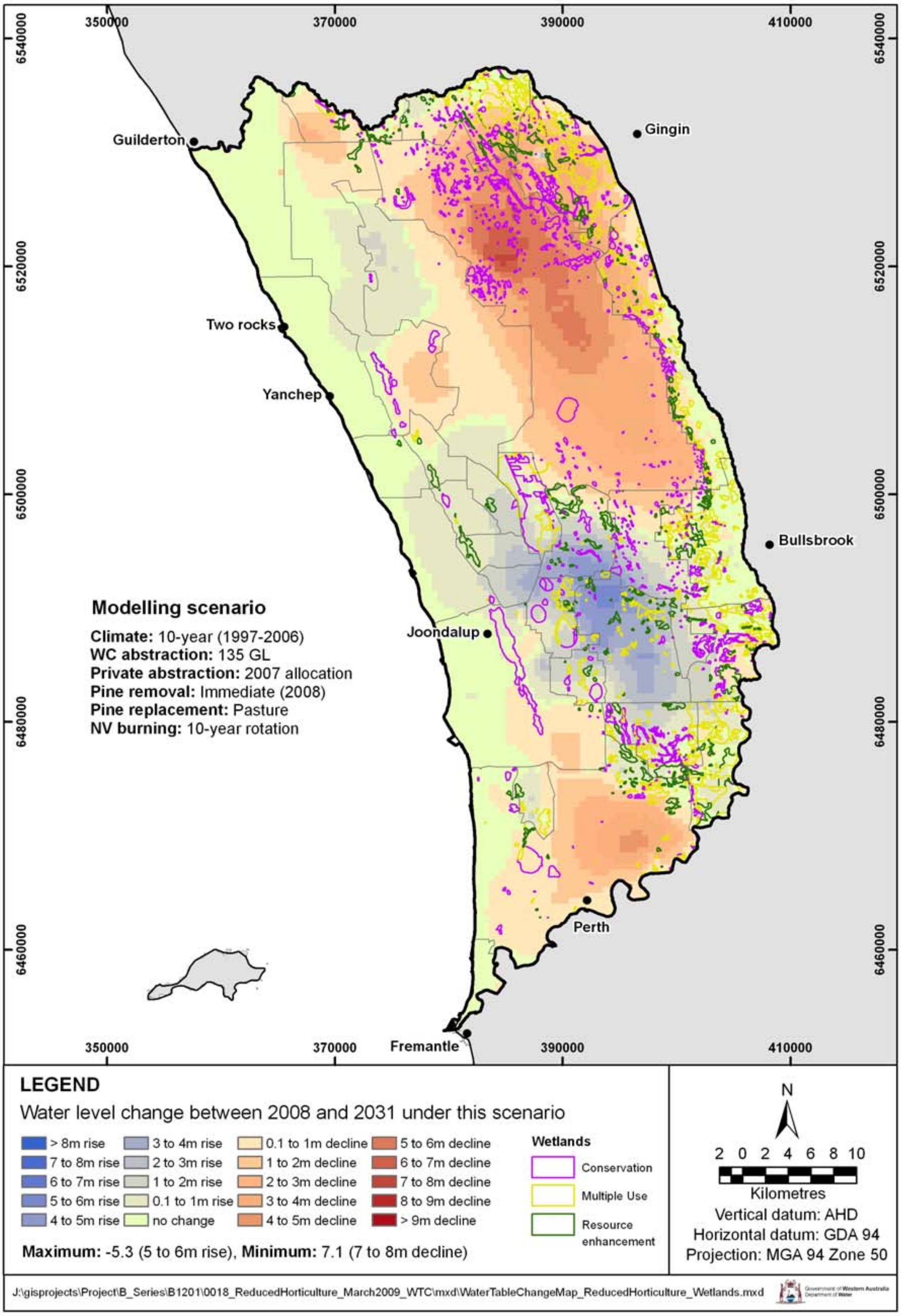


Figure 38 Reduced horticulture scenario, showing predicted watertable change from 2008 to 2031

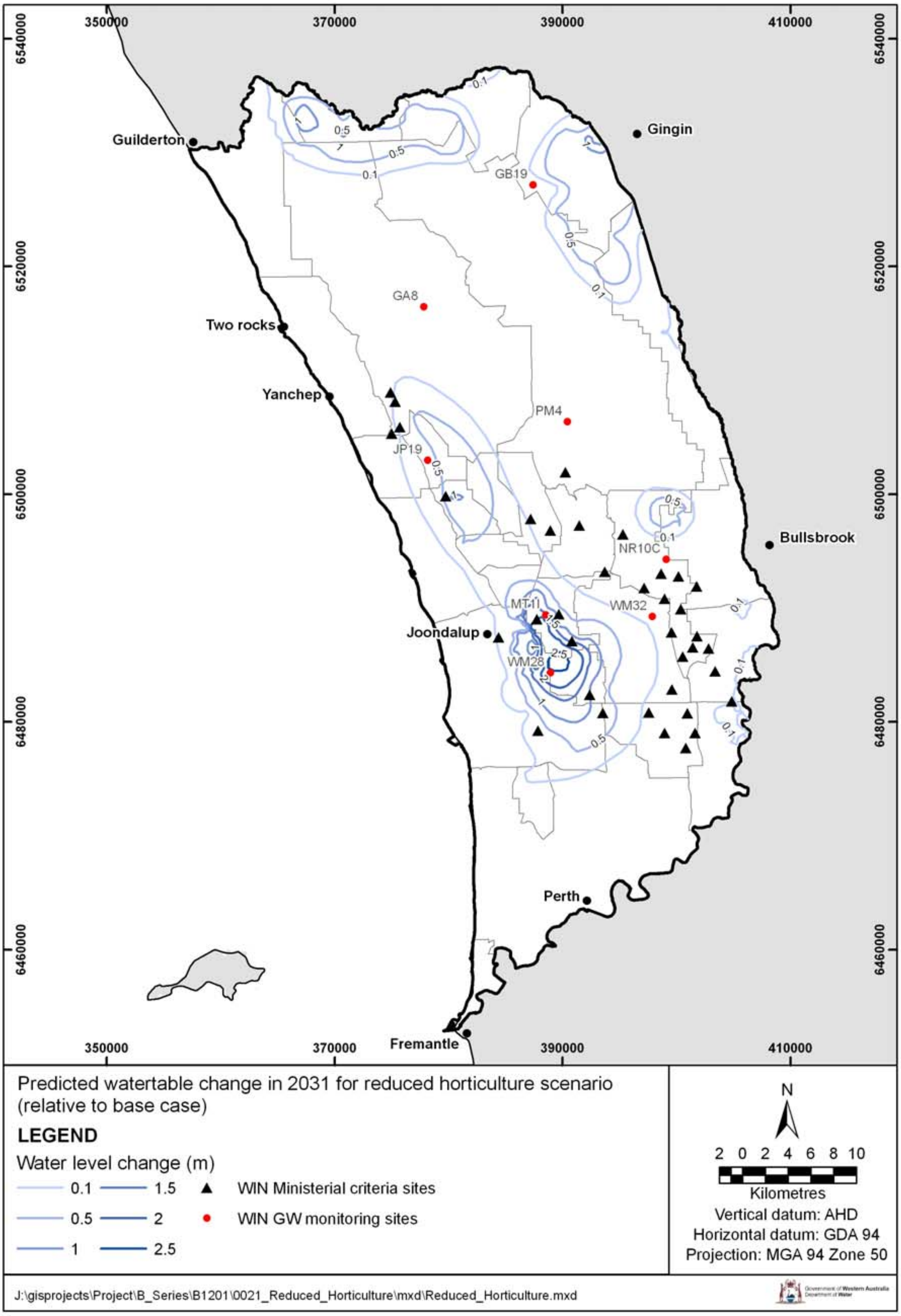


Figure 39 Watertable elevation difference in 2031 between the reduced horticulture scenario and the base case scenario

No private abstraction

This scenario looks at the impact of private abstraction (2007 allocation) on watertable levels. If there were no private pumping, modelling shows that 90% of the Mound will recover to some extent, indicating a regional impact similar to that of the no public abstraction scenario (Water Corporation 0 GL). The majority of watertable differences relative to the base case fall into the 0.1 to 1 m group and the1 to 2 m group. This recovery benefits most of the sensitive wetlands and the designated Ministerial criteria sites. Some Ministerial criteria sites located in the southen part of the Mound are likely to recover by up to 3 m. Figures 40 and 41 show the absolute and relative watertable for this scenario respectively.

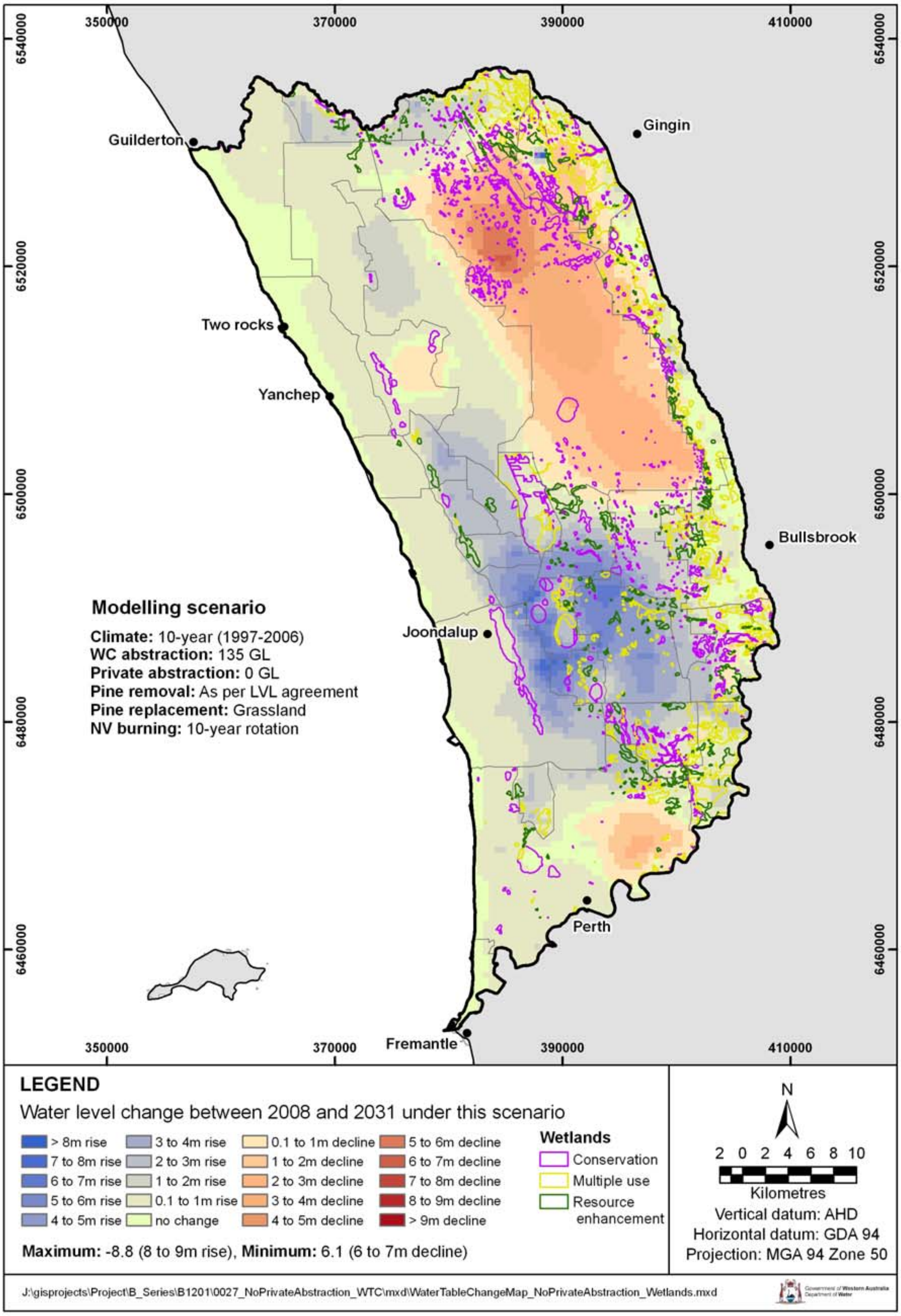


Figure 40 No private abstraction scenario, showing predicted watertable change from 2008 to 2031

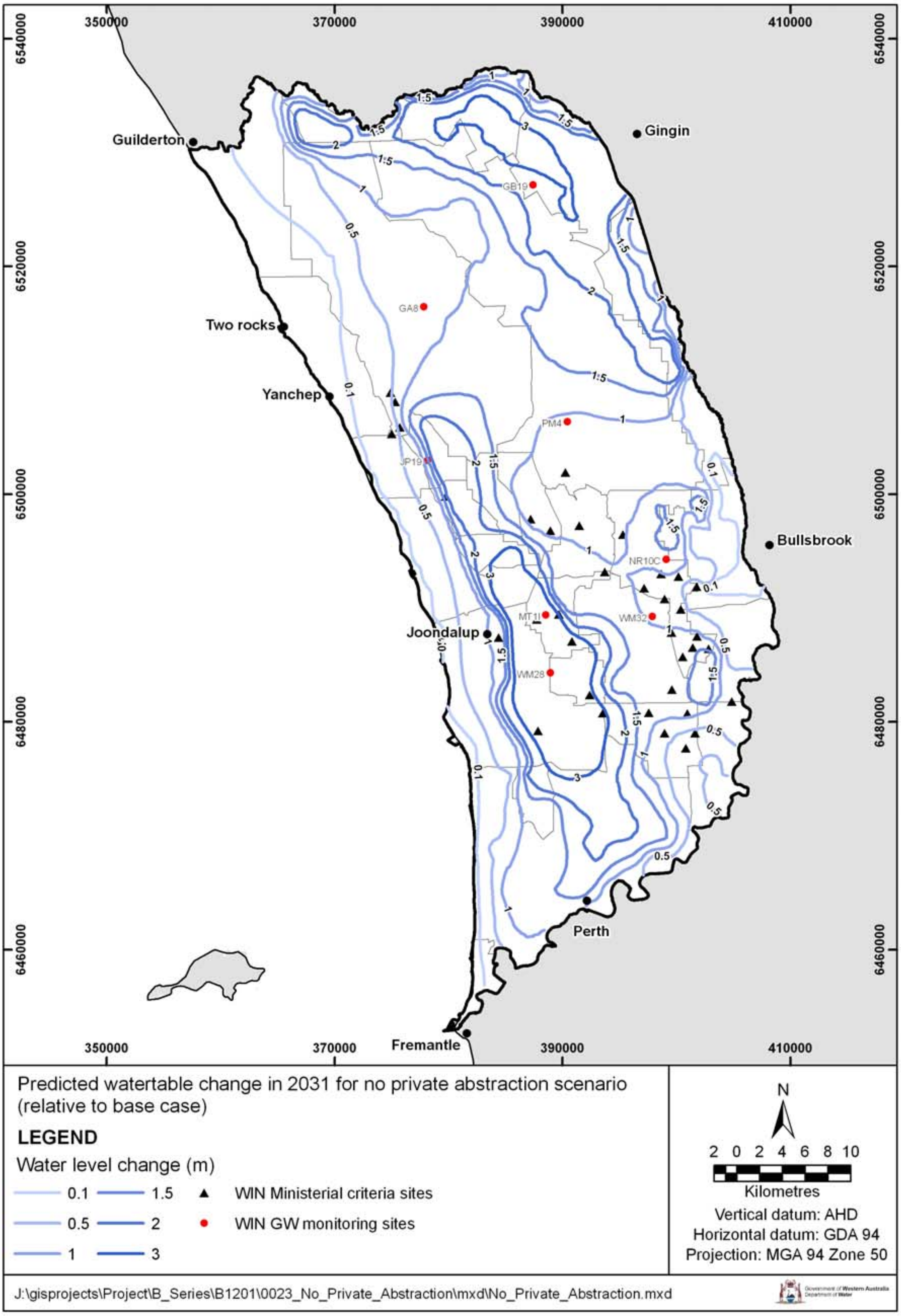


Figure 41 Watertable elevation difference in 2031 between the no private abstraction scenario and the base case scenario

No abstraction

This scenario models the effects of stopping both private and public abstraction and hence is primarily a combination of the scenarios above, that is, the no private abstraction and Water Corporation 0 GL scenarios. If there is no abstraction at all (except garden bores), modelling shows that 95% of the Gnangara Groundwater Mound will have recovery in watertable levels, indicating a major regional impact. The cessation of both private and public abstraction will have spatial effects comparable to that of the wet climate scenario, but there will be less storage gain. The majority of watertable differences relative to the base case fall into the 2 to 5 m group. This scenario will have significant impact benefiting all the sensitive wetlands and the Ministerial criteria sites. Figures 42 and 43 show the absolute and relative watertable for this scenario respectively.

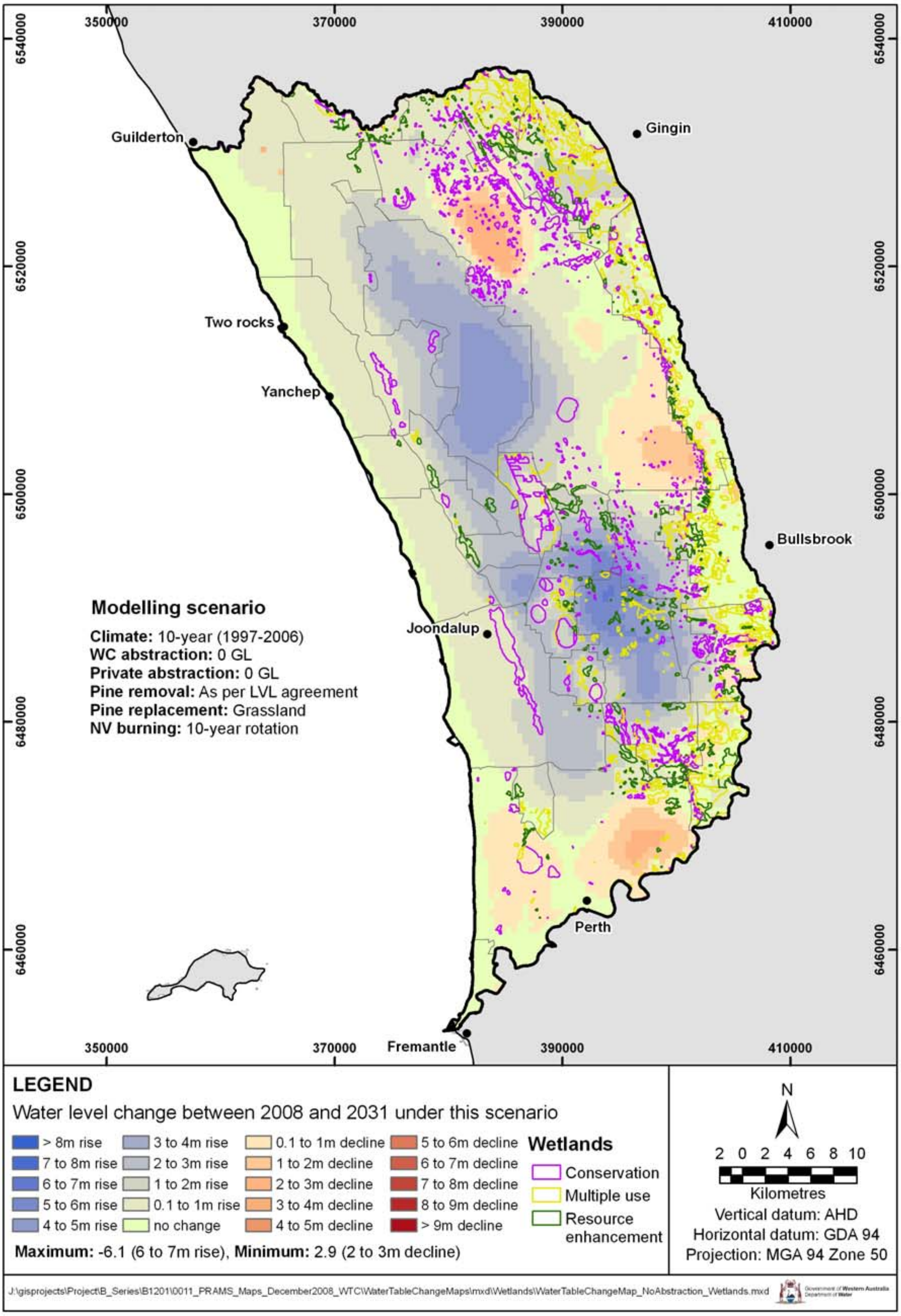


Figure 42 The no abstraction scenario, showing predicted watertable change from 2008 to 2031

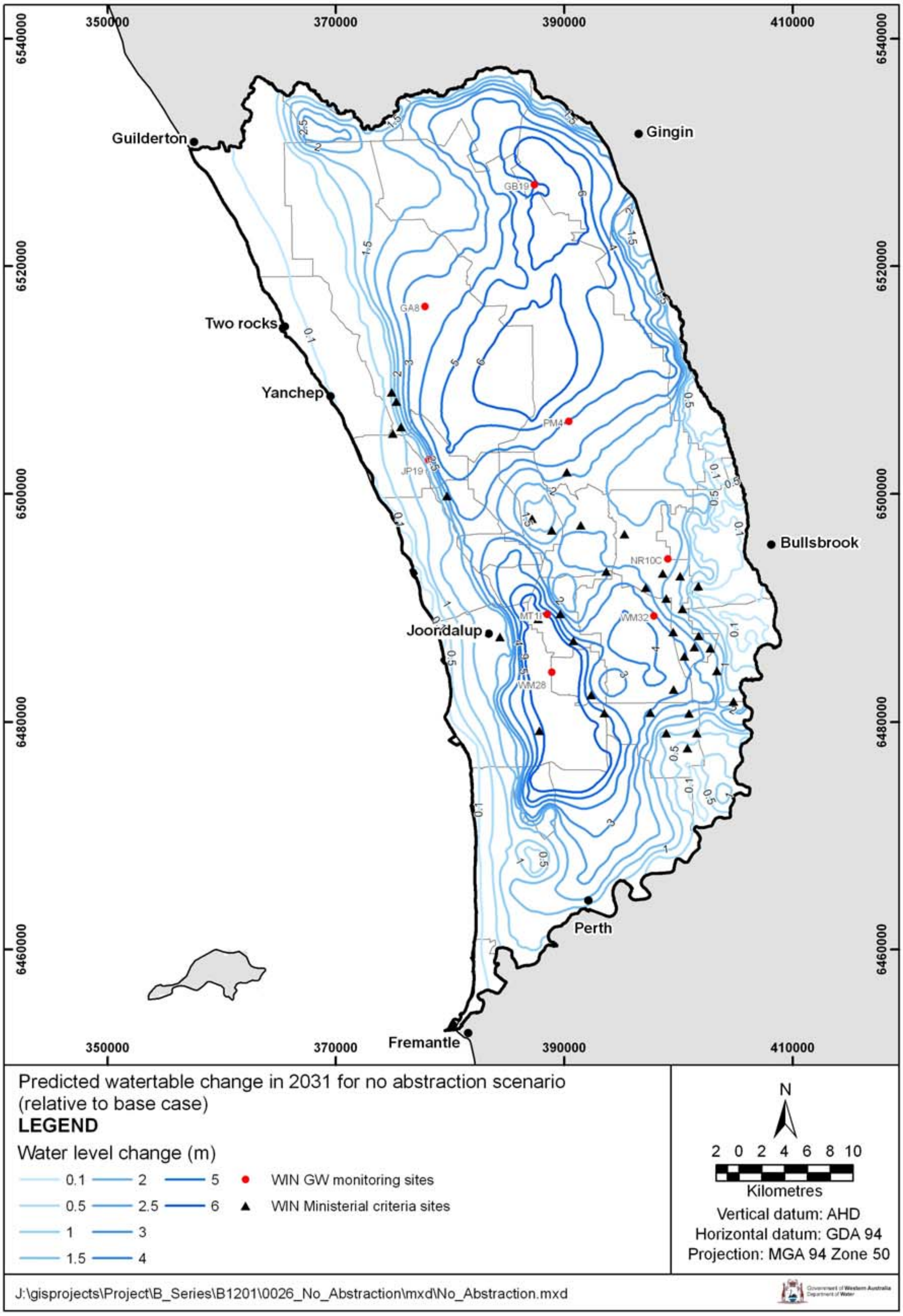


Figure 43 Watertable elevation difference in 2031 between the no abstraction scenario and the base case scenario

Land-use scenarios

The distribution of land use, together with climate and local additional storage capacity induced by abstraction, 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 under the densest of pine plantations (Xu et al. 2005).

Laminated veneer lumber Banksia

Modelling of this scenario indicates effects very similar to the base case, where cleared pines are to be replaced with pasture (grassland). Only 3% of the Mound area will show recovery in watertable levels under this scenario in 2031 if cleared pines are replaced with Banksia. Figures 44 and 45 show the absolute and relative watertable levels for this scenario respectively.

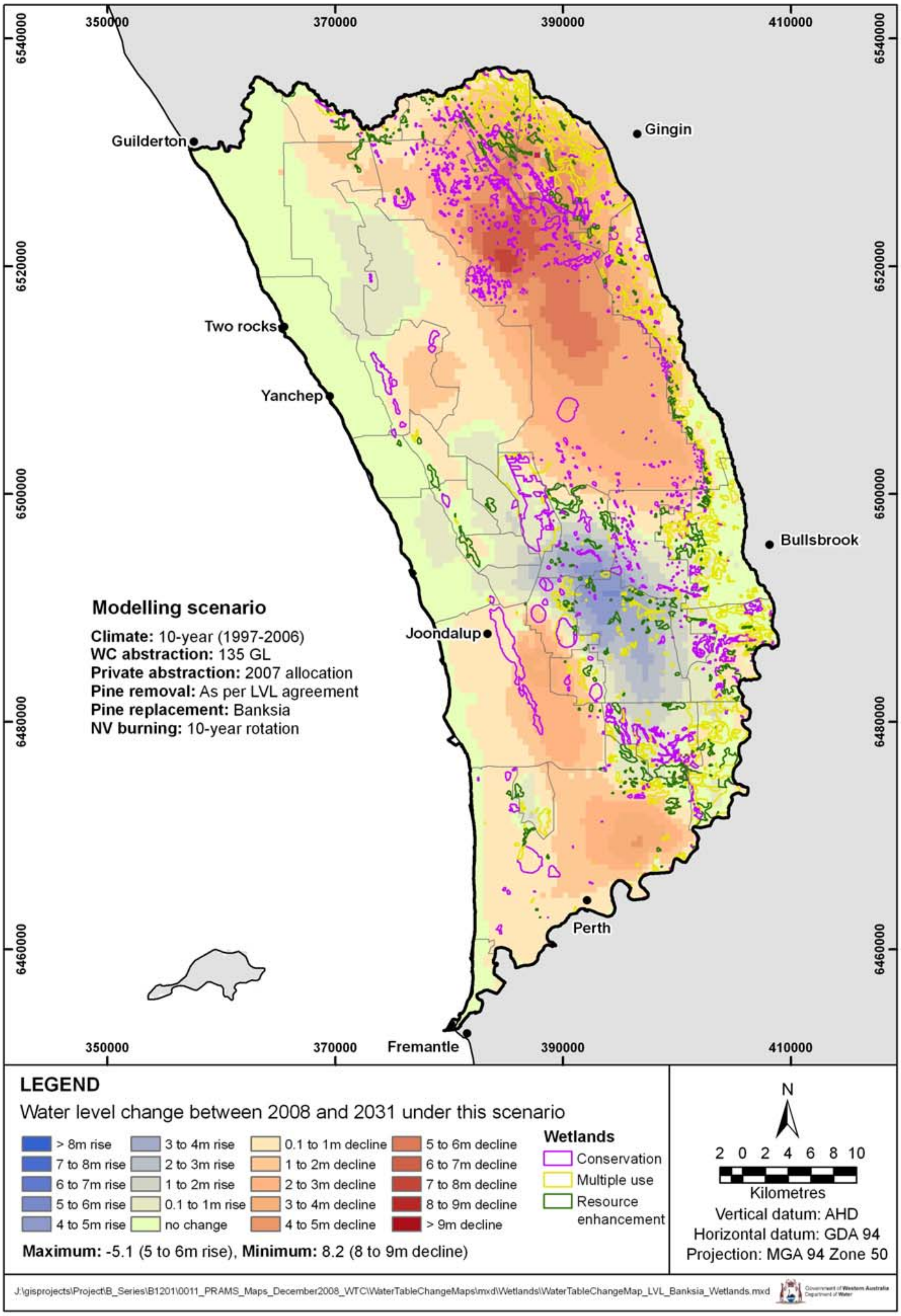


Figure 44 Laminated veneer lumber Banksia scenario, showing predicted watertable changes from 2008 to 2031

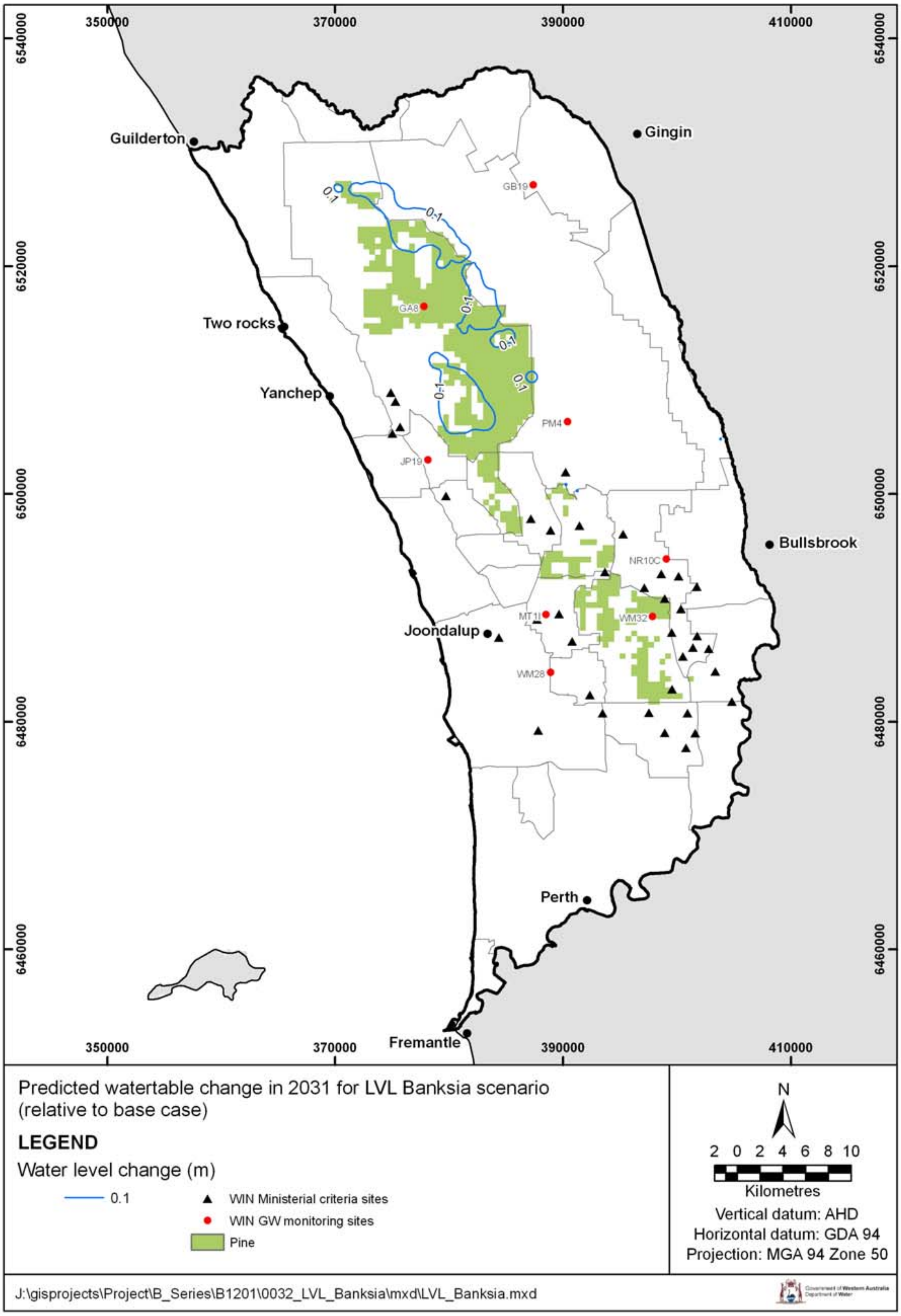


Figure 45 Watertable elevation difference in 2031 between the laminated veneer lumber Banksia and the base case

Immediate pine removal

If all the remaining pine plantations were cleared in 2008, modelling shows there would be watertable recovery over 60% of Gnangara Groundwater Mound area in 2031. Most of the watertable recovery is within the 0.1 to 1 m range. As a result of immediate pine removal, watertable conditions in a significant number of Ministerial criteria sites will recover by a minimum of 0.1 m and a maximum of 1 m. The recovery area is centred on the pine plantation with the maximum recovery to the east of Two Rocks. The maximum recovery area is also on the area where the Leederville Formation subcrops beneath the Superficial Formation. Figures 46 and 47 show the absolute and relative watertable for this scenario respectively.

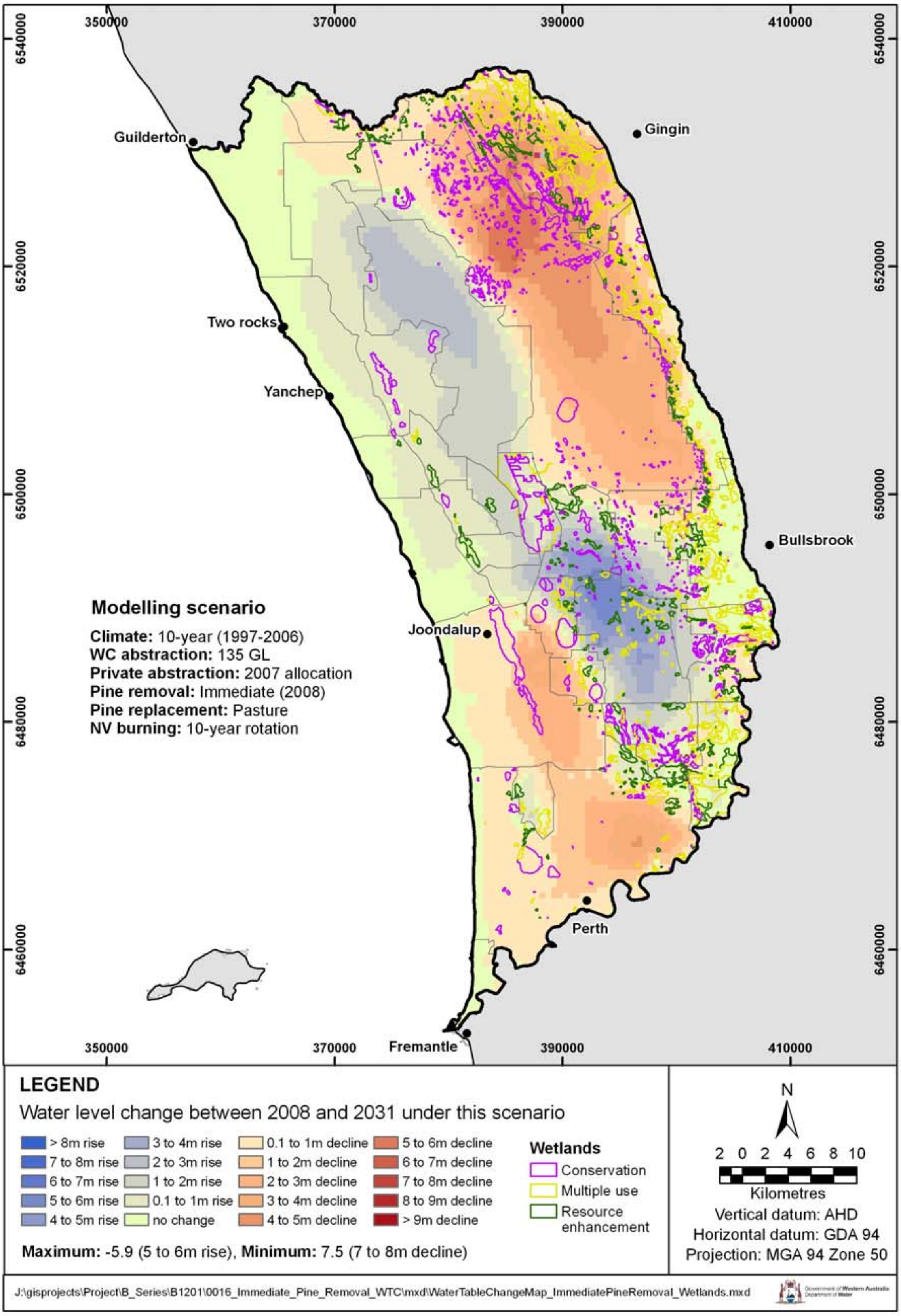


Figure 46 Immediate pine removal scenario, showing predicted watertable change from 2008 to 2031

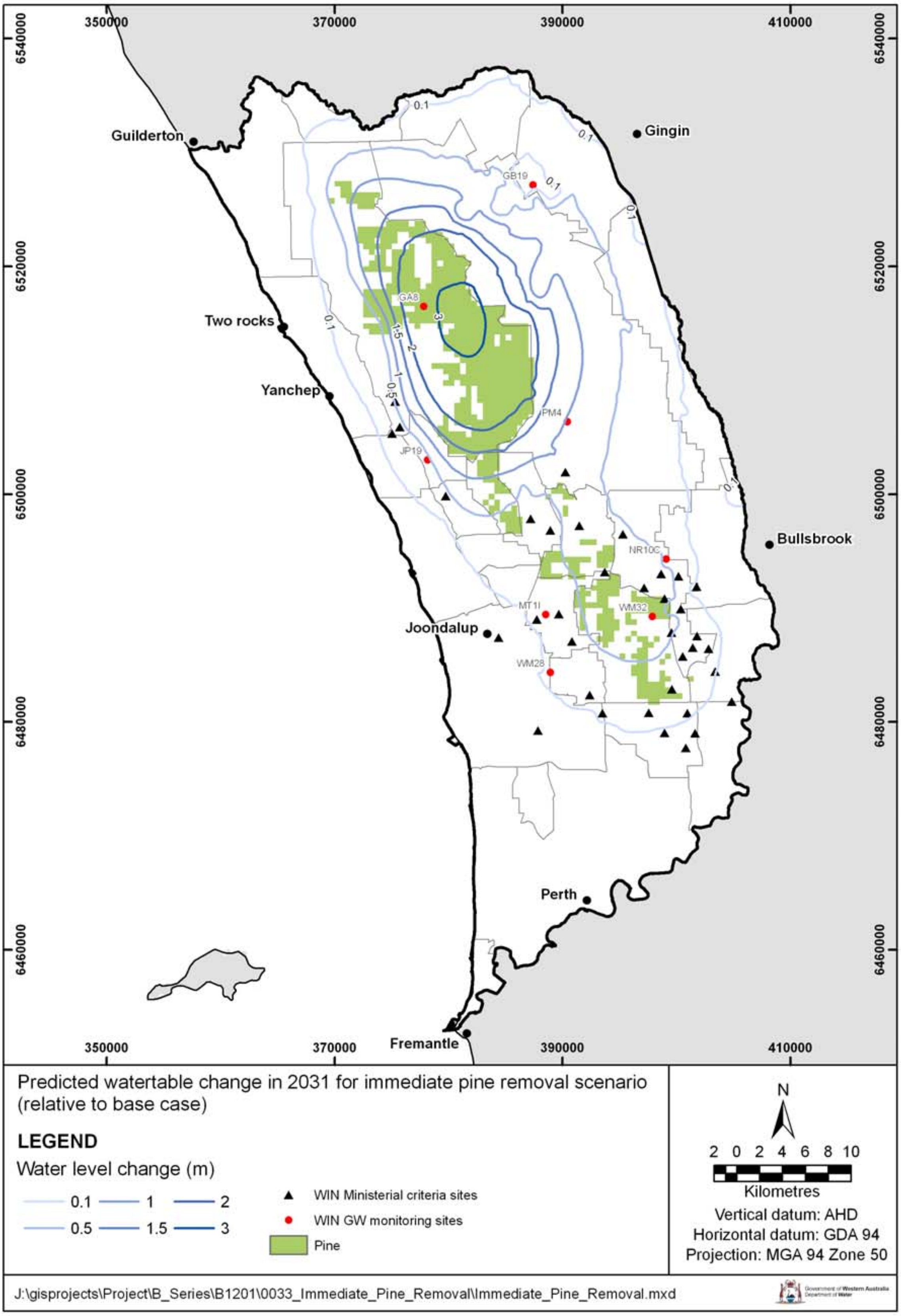


Figure 47 Watertable elevation difference in 2031 between the immediate pine removal scenario and the base case scenario

GSS composite scenario

Modelling of this scenario indicates there will be watertable recovery over 78% of the Gnangara Groundwater mound in 2031. The watertable differences (relative to the base case) are mainly within the 0.1 to 1 m group. As both private and public abstraction are reduced in the scenario, the watertable recovery can be linked mainly to reduction in abstraction. Some of the land-use changes considered here may have a minor impact as well. Figures 48 and 49 show the absolute and relative watertable for this scenario respectively.

The GSS composite scenario was also modelled with the dry climate. Watertable levels are likely to decline over 51% of the Mound by 2031 under this scenario. There will also be watertable recovery over 21% of the Mound (Table 13). The absolute and relative watertable changes for the dry climate composite are shown in Figures 50 and 51 respectively.

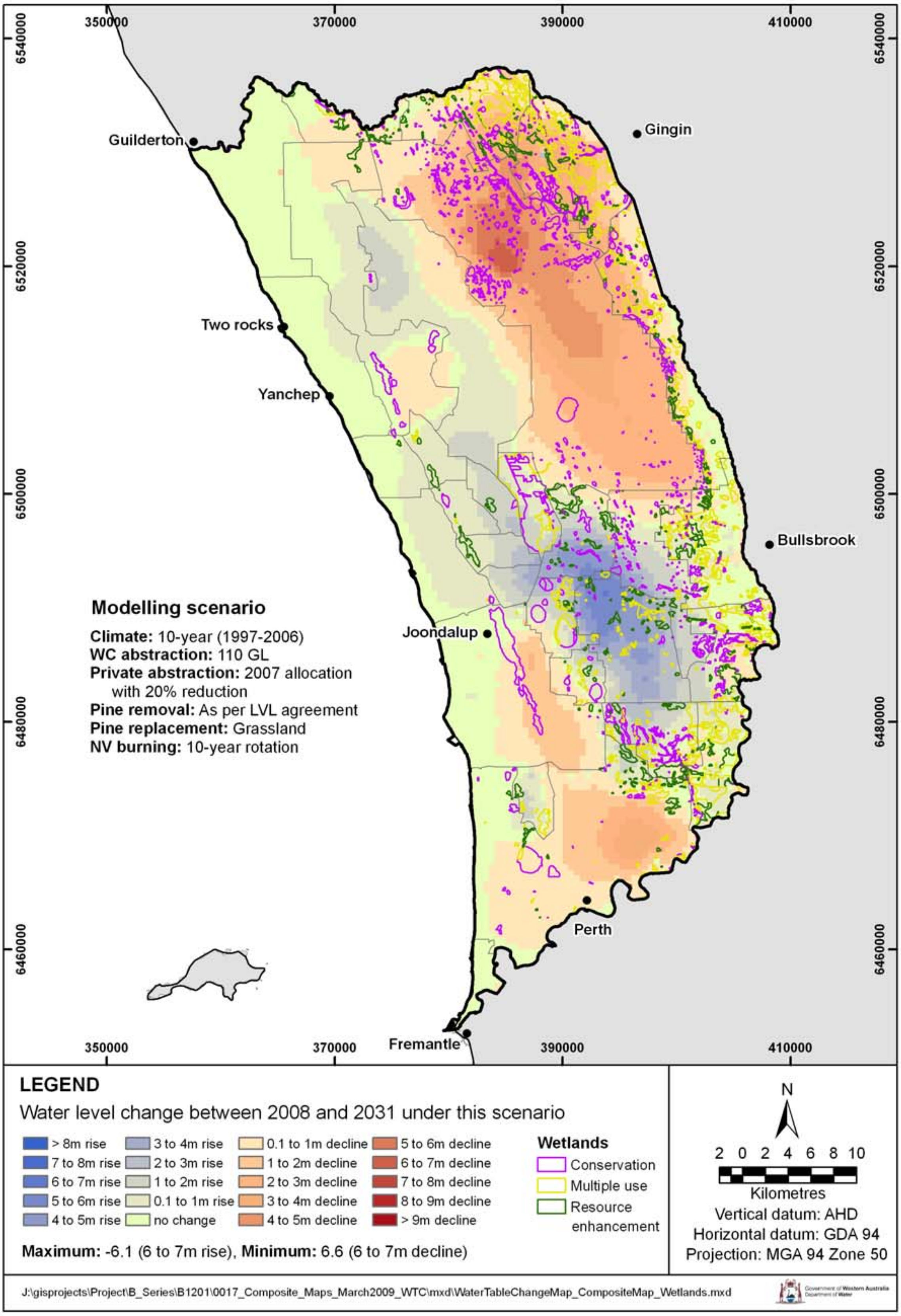


Figure 48 GSS composite, showing predicted watertable change from 2008 to 2031

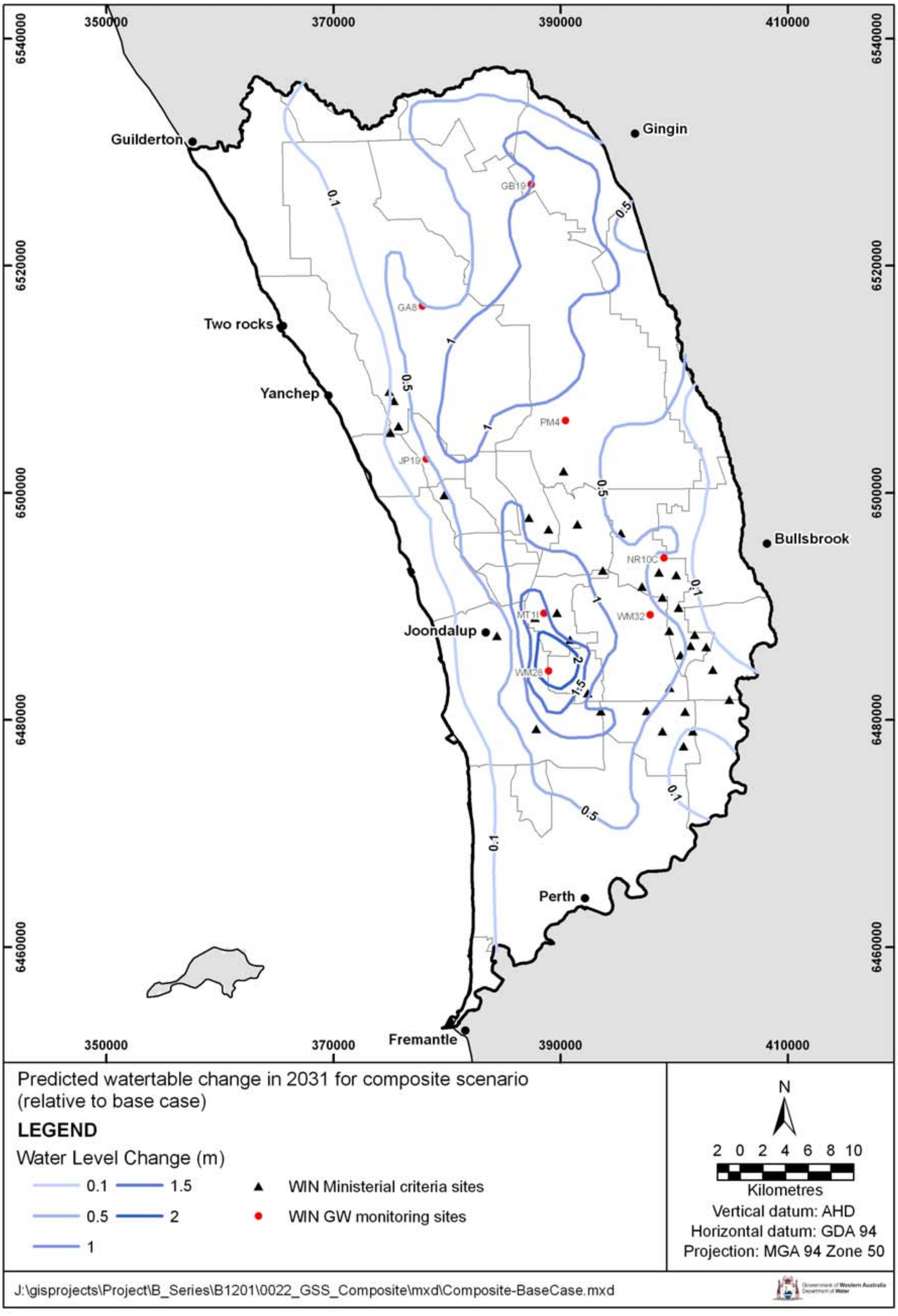


Figure 49 Watertable elevation difference in 2031 between the GSS composite and the base case scenarios

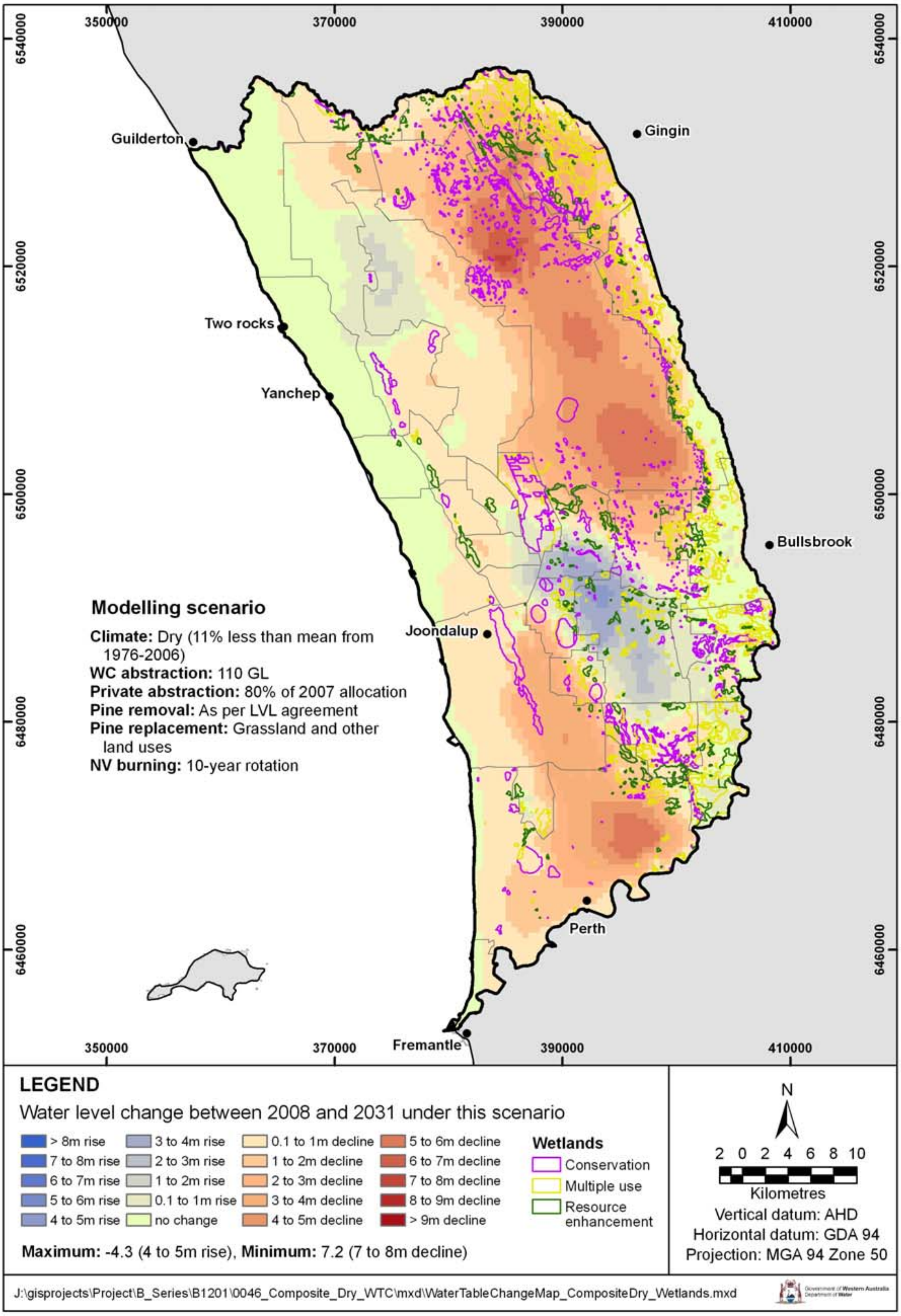


Figure 50 GSS composite (dry climate) scenario, showing predicted watertable change from 2008 to 2031

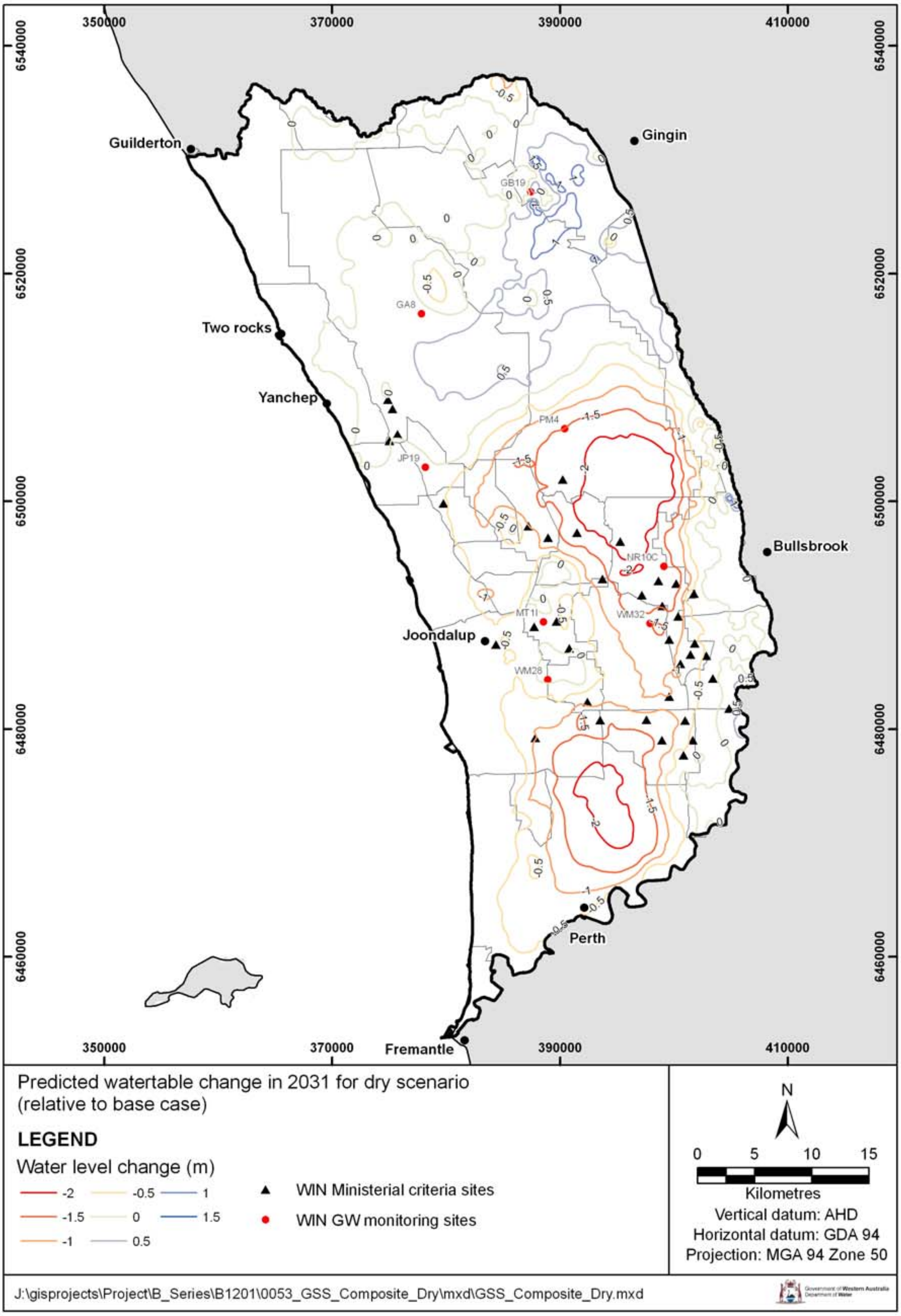


Figure 51 Watertable elevation difference in 2031 between the GSS composite (dry climate) scenario and the base case scenario

Climate sensitivity within the GSS area

The predicted watertable differences in 2031 between the extreme wet climate and dry climate scenarios are shown in Figure 52. The climate sensitivity derived from Figure 52 is summarised in Table 16. Climate scenario differences account for an effect on the watertable varying from 0 to more than 10 m. This reflects the degree of sensitivity to the climate within the GSS area. Higher watertable differences between the two extreme scenarios indicate a higher sensitivity to climate change. Topographically, sensitivity to the climate increases from low-lying areas along the coastline to the elevated areas of the Gnangara mound. That is the sensitivity decreases from groundwater recharge areas to discharge areas.

Table 16 Climate sensitivity within the GSS area

Watertable change m	Climate sensitivity	Area km^2	Percentage of GSS area
0 to 2	Low	650	30.2
2 to 5	Low to intermediate	460	21.4
5 to 10	Intermediate to high	788	36.7
>10	High	250	11.6

Coastal Tamala Limestone areas where groundwater within the Superficial aquifer discharges to the ocean have the lowest sensitivity to climate. The lowest sensitivity area forms about 30% of the GSS area.

The highest sensitivity area, about 11.6% of the GSS area, is located within the Banksia and East Yanchep GSS subareas where Banksia and pine forests are located. These are the groundwater recharge areas of the Gnangara Groundwater Mound and show more than 10 m change in watertable between the two extreme climate scenarios. Hence the management of these recharge areas is vital for both the Superficial and confined aquifers. Most of the Ministerial criteria sites including the Lexia wetlands fall within the intermediate to high category which accounts for 36% of the GSS area.

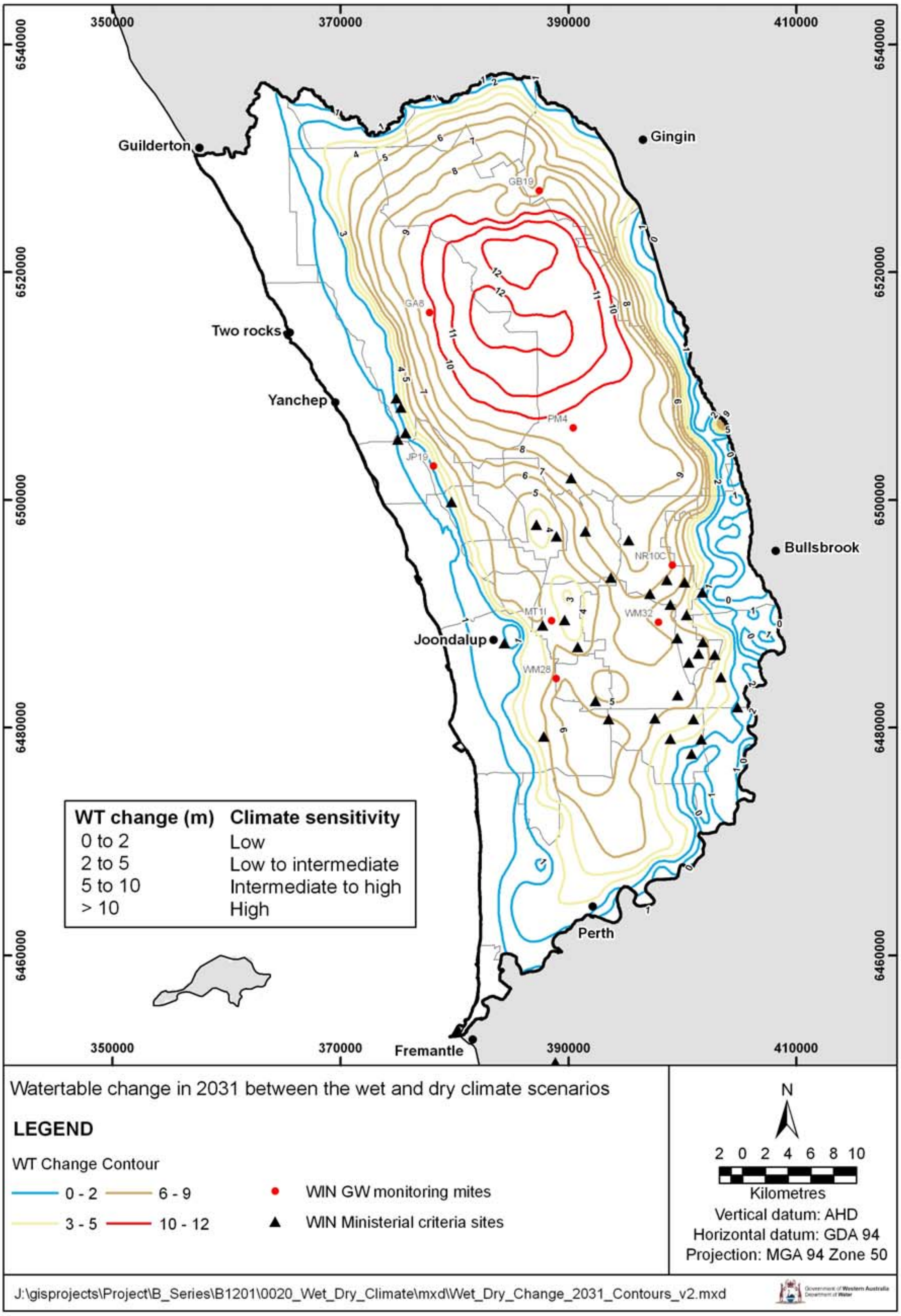


Figure 52 Climate sensitivity within the GSS area

Hydrogeological controls on future impacts

In order to study the effects of hydrogeology on the predictions of the modelling, the results for each modelling scenario for the two hydrogeological provinces of the Mound were determined using maps of watertable change relative to the base case. The Pinjar borefield was selected to represent the Leederville Window province and the Mirrabooka borefield to represent the Kardinya Shale areas (Table 17).

Table 17 Predicted changes by 2031 in the Gnangara Mound

Scenario	Watertable change m	
	Leederville Window	Kardinya Shale
Climate		
Dry	-0.5	-2.5
30-year average	+2.0	+2.5
Wet	+11.0	+3.0
Water Corporation abstraction		
120 GL	+1.0	+0.1
105 GL	+1.5	+0.5
0 GL	+3.5	+1.0
Private abstraction		
Reduced horticulture	0.0	+0.1
No private	+1.0	+1.5
No abstraction	+6.0	+2.0
Land use		
laminated veneer lumber Banksia	+0.1	0.0
Pine removal	+2.0	+0.5
GSS composite		
GSS composite	+1.0	+0.5

Groundwater monitoring shows that climate impact has been severe on the Leederville Window areas. In the Kardinya Shale areas the effect of climate has been offset by the excess recharge generated from the urbanised areas. This indicates that even with the current rainfall conditions, Kardinya Shale areas have been able to neutralise the effect of drying climate. In addition, groundwater throughflow from the centre of the Mound occurs in Kardinya Shale areas. Scenario modelling for a dry climate predicts that the watertable in the Kardinya Shale areas will decline by 2.5 m in 2031. Past effects in the Kardinya Shale areas suggests that this future impact may be an overestimation. If current climate conditions improve to the 30-year average conditions, Kardinya Shale areas will possibly be able to achieve the maximum possible rainfall recharge.

Further Kardinya Shale areas have more shallow watertable areas than the Leederville Window. This is another reason for the greater rainfall recharge to Kardinya Shale areas. However, under a wet climate scenario, the Leederville Window will have an 11 m increase in watertable whereas the Kardinya Shale area has only a 3 m increase. This is because the Leederville Window has a thicker unsaturated zone than the Kardinya Shale areas. As a result, under a wetter climate the Leederville Window area has the potential to absorb and store a significant amount of rainfall recharge without evapotranspiration loss or surface runoff. In contrast, in shallow water level areas such as Kardinya Shale, excess rainfall recharge is lost through evapotranspiration, surface runoff, and discharge to drains.

Vertical flux model recharge – spatial and temporal change

Rainfall recharge to the Superficial aquifer as estimated by the vertical flux model under the base case scenarios in 2007 and 2031 is shown in Figure 53. The spatial distribution of the rainfall recharge is illustrated in Figure 54. There are significant changes to the recharge under projected land-use changes in 2031. In 2007, the model estimates the maximum rainfall recharge to be in the range of 100 to 150 mm in nearly 25% of the Gnangara Groundwater Mound. As a result of land-use changes in 2031, the maximum recharge increases to 250 to 350 mm range covering 36% of the Mound. The maximum annual recharge, 450 mm, is under the urban-residential land.

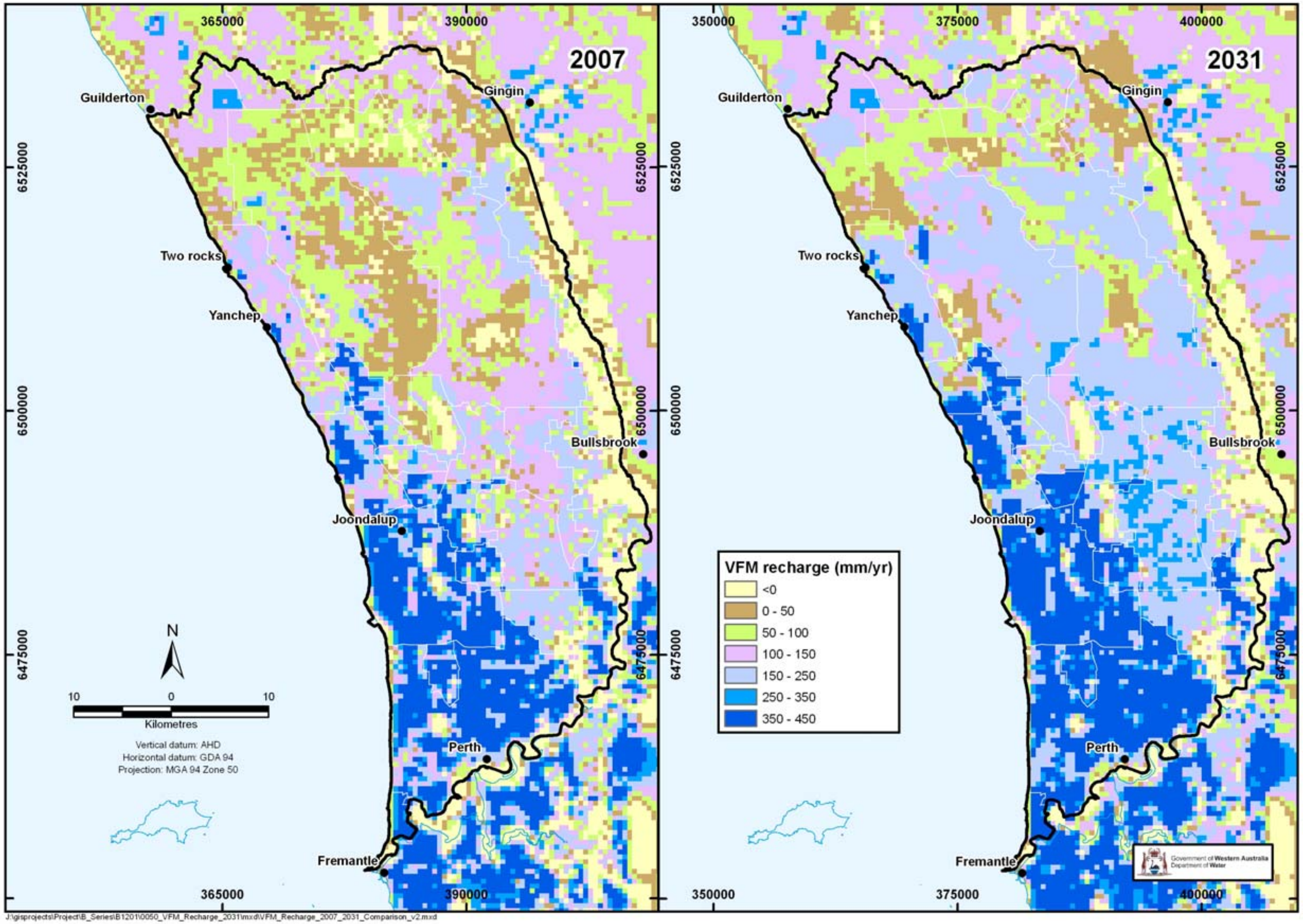


Figure 53 Rainfall recharge estimated by the vertical flux model under base case scenario – 2007 and 2031

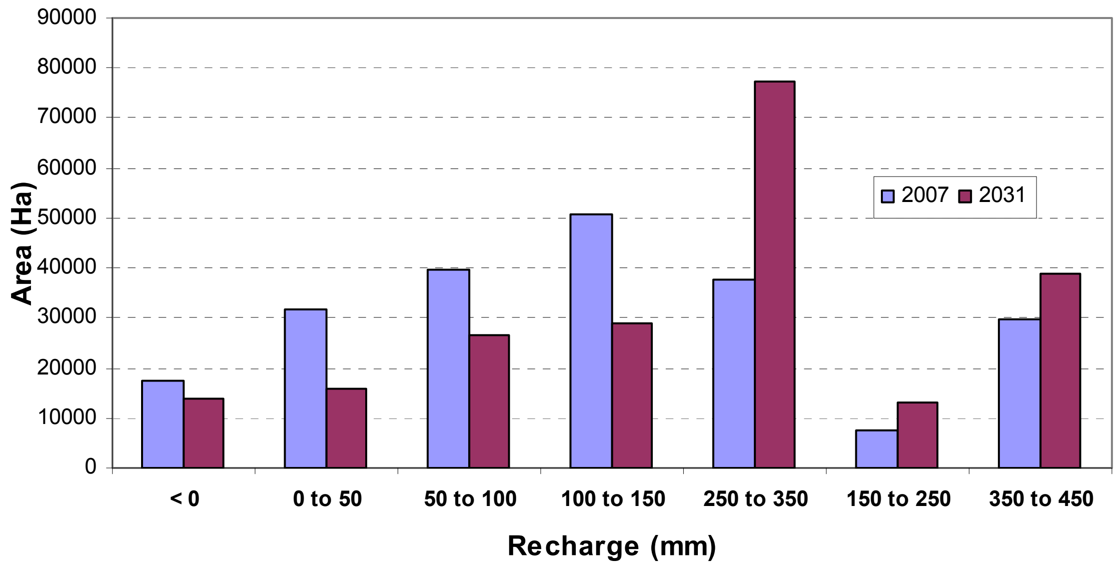


Figure 54 Spatial distribution of vertical flux model recharge under base case scenario – 2007 and 2031

5.2 Water balance analysis

The water balance is made up of a number of components. These include storage, discharge to oceans (discharge to constant head boundaries of the model domain), wells (both private and public abstraction), drains (discharge to drains and rivers), recharge, garden bores and flux (mainly leakage to confined aquifers). The only input component of the water balance is recharge and all the other components represent outputs. When the recharge is not enough to balance output components then the model takes out water from the aquifer storage, with a consequent fall in groundwater levels in the Superficial aquifer and in potentiometric heads in confined aquifers. When the recharge exceeds the sum of the output components, the excess results in a gain in aquifer storage and consequent rise in groundwater or pressure levels. In the water budget module of MODFLOW, any positive value of storage change indicates storage depletion whereas negative values are for the gain in groundwater storage.

As a check on the model, the difference between the sum of the input water balance components and the sum of the output water balance components should be within 2% of the total input or output. These differences are shown in the 'error' column in Table 18.

For the water balance calculations the nominated water balance zones are the GSS area representing the whole Gnangara Groundwater Mound and the 29 subareas, which are defined by various land uses. Water balance values can be extracted for all the 336 stress periods from 2004 to 2031. The stress period for the transient MODFLOW modelling is a calendar month. As extracting the water balance for each stress period is very time consuming, water balance estimates were extracted for four-year periods (48 stress periods) and then divided by four to get the average for each year of a particular period. The results are shown in the GSS summary (Table 18). Note that for storage, a *positive* value signifies *depletion*. For the other components, a *negative* value signifies *depletion*.

Table 18 Gnangara Mound water balance summary

Scenario	Period	Storage + is depletion	Ocean	Wells	Drains	Recharge	Garden bores	Flux	Error
		GL/yr	GL/yr	GL/yr	GL/yr	GL/yr	GL/yr	GL/yr	GL/yr
GSS base case	2008–2011	27.49	-169.61	-135.93	-22.88	402.55	-41.19	-60.52	-0.08
	2012–2016	30.32	-174.78	-134.42	-22.85	406.80	-46.14	-58.96	-0.04
	2017–2021	13.69	-172.34	-134.36	-21.57	427.50	-54.79	-58.17	-0.04
	2022–2026	19.96	-169.80	-134.36	-20.03	425.07	-63.64	-57.25	-0.04
	2027–2031	-3.33	-167.56	-133.81	-17.94	452.47	-73.31	-56.52	-0.02
Climate scenarios									
Dry	2008–2011	61.10	-157.16	-134.32	-20.68	358.09	-41.19	-65.95	-0.11
	2027–2031	16.32	-143.85	-132.16	-13.21	406.38	-73.31	-60.19	-0.02
30-year average	2008–2011	-14.54	-173.07	-134.32	-24.55	453.80	-41.19	-66.22	-0.10
	2027–2031	-21.96	-182.91	-132.16	-22.84	496.50	-73.31	-63.33	-0.01
Wet	2008–2011	-112.58	-197.64	-134.32	-32.42	586.66	-41.19	-68.56	-0.05
	2027–2031	-65.27	-245.11	-132.67	-38.25	625.82	-73.31	-71.21	-0.01

Note: For scenarios other than the base case, only the first and last four-year periods were extracted

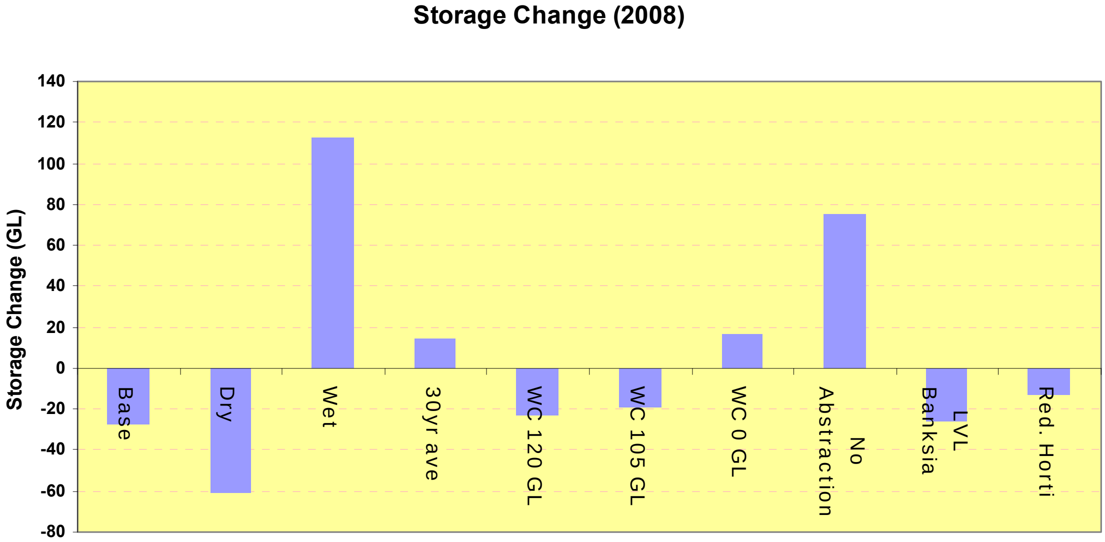
Scenario	Period	Storage + is depletion GL/yr	Ocean GL/yr	Wells GL/yr	Drains GL/yr	Recharge GL/yr	Garden bores GL/yr	Flux GL/yr	Error GL/yr
Water Corporation abstraction scenarios									
Water Corporation abstraction 120 GL	2008–2011	22.96	-166.27	-133.38	-22.46	402.61	-41.19	-62.43	-0.16
	2027–2031	-8.65	-167.05	-130.97	-18.40	451.41	-73.32	-53.05	-0.03
Water Corporation abstraction 105 GL	2008–2011	19.32	-168.65	-130.97	-22.53	402.32	-41.19	-58.53	-0.23
	2027–2031	-11.98	-173.03	-128.23	-18.81	450.28	-73.32	-44.94	-0.03
Water Corporation abstraction 0 GL	2008–2011	-17.06	-205.20	-89.80	-28.63	393.22	-41.19	-11.44	-0.09
	2027–2031	-25.05	-212.48	-88.69	-25.73	431.91	-73.32	-6.67	-0.03
Private abstraction scenarios									

Scenario	Period	Storage + is depletion	Ocean	Wells	Drains	Recharge	Garden bores	Flux	Error
		GL/yr	GL/yr	GL/yr	GL/yr	GL/yr	GL/yr	GL/yr	GL/yr
30% reduction in horticulture	2008–2011	12.98	-168.61	-115.69	-23.14	401.11	-41.19	-65.55	-0.10
	2027–2031	-8.36	-170.70	-114.05	-19.57	446.02	-73.32	-60.05	-0.03
No private abstraction	2008–2011	-30.46	-180.32	-54.80	-27.51	393.87	-41.19	-59.78	-0.19
	2027–2031	-23.13	-199.90	-43.50	-30.16	421.04	-73.32	-51.04	-0.01
No abstraction	2008–2011	-74.71	-201.77	-14.29	-30.00	391.28	-41.19	-30.02	-0.70
	2027–2031	-36.48	-246.60	0.00	-37.41	388.95	-73.31	4.85	0.01

Scenario	Period	Storage + is depletion	Ocean	Wells	Drains	Recharge	Garden bores	Flux	Error
		GL/yr	GL/yr	GL/yr	GL/yr	GL/yr	GL/yr	GL/yr	GL/yr
Land – use scenarios									
laminated veneer lumber Banksia	2008–2011	25.98	-168.06	-134.32	-22.78	402.91	-41.19	-62.62	-0.09
	2012–2017	29.23	-170.67	-132.77	-22.35	407.00	-46.14	-64.34	-0.04
	2018–2021	14.35	-169.09	-132.70	-21.07	426.65	-54.79	-63.39	-0.04
	2022–2026	21.85	-165.25	-132.70	-19.61	421.66	-63.64	-62.35	-0.04
	2027–2031	-0.16	-166.10	-132.16	-17.86	447.86	-73.31	-58.29	-0.02
Immediate pine removal	2008–2011	-8.26	-167.20	-134.32	-22.41	440.22	-41.19	-66.91	-0.08
	2027–2031	6.21	-171.83	-132.05	-18.29	452.12	-73.32	-62.88	-0.04

Scenario	Period	Storage + is depletion GL/yr	Ocean GL/yr	Wells GL/yr	Drains GL/yr	Recharge GL/yr	Garden bores GL/yr	Flux GL/yr	Error GL/yr
GSS composite scenarios									
GSS composite (short-term climate)	2008–2011	11.42	-169.46	-115.45	-23.61	399.11	-41.19	-61.00	-0.17
	2027–2031	-18.18	-172.09	-113.07	-20.31	448.76	-74.26	-50.88	-0.03
GSS composite (dry climate)	2008–2011	45.12	-160.82	-115.45	-21.84	354.84	-41.19	-60.85	-0.19
	2027–2031	2.92	-153.13	-113.25	-16.07	402.41	-73.32	-49.60	-0.04

Annual storage changes - all GSS scenarios



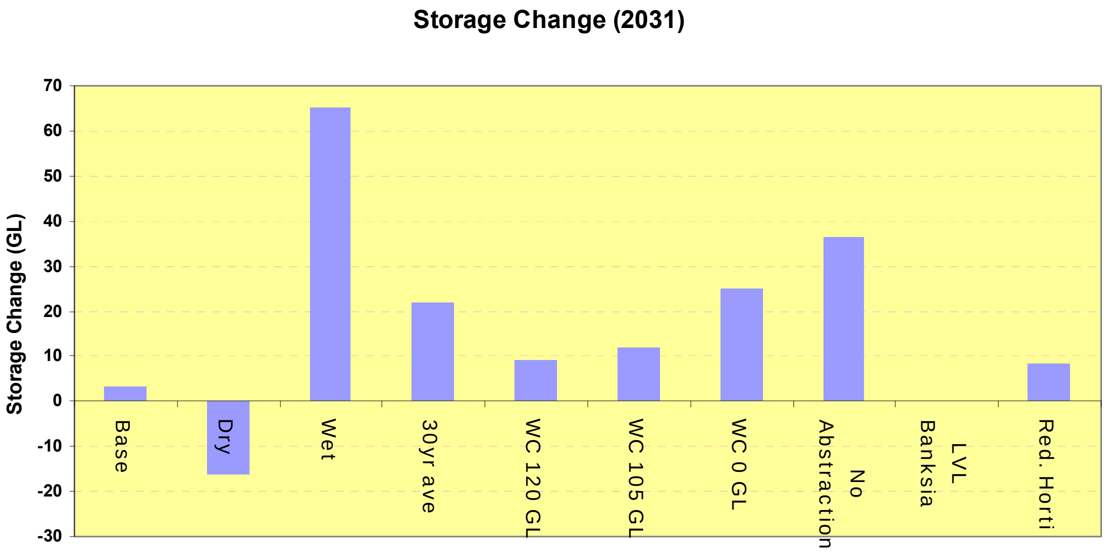


Figure 55 Storage changes for all GSS scenarios (2008 and 2031)

Figure 55 indicates that apart from the wet climate, 30-year average climate, Water Corporation 0 GL and no abstraction scenarios, all the other scenarios in 2008 show depletion in storage due to prevailing dry climatic conditions. However in 2031 water storage recovers for most of the scenarios. Thus in the long term the water balance analysis shows that groundwater in the Gnangara Mound will reach a new equilibrium in the most of the scenarios, including the base case.

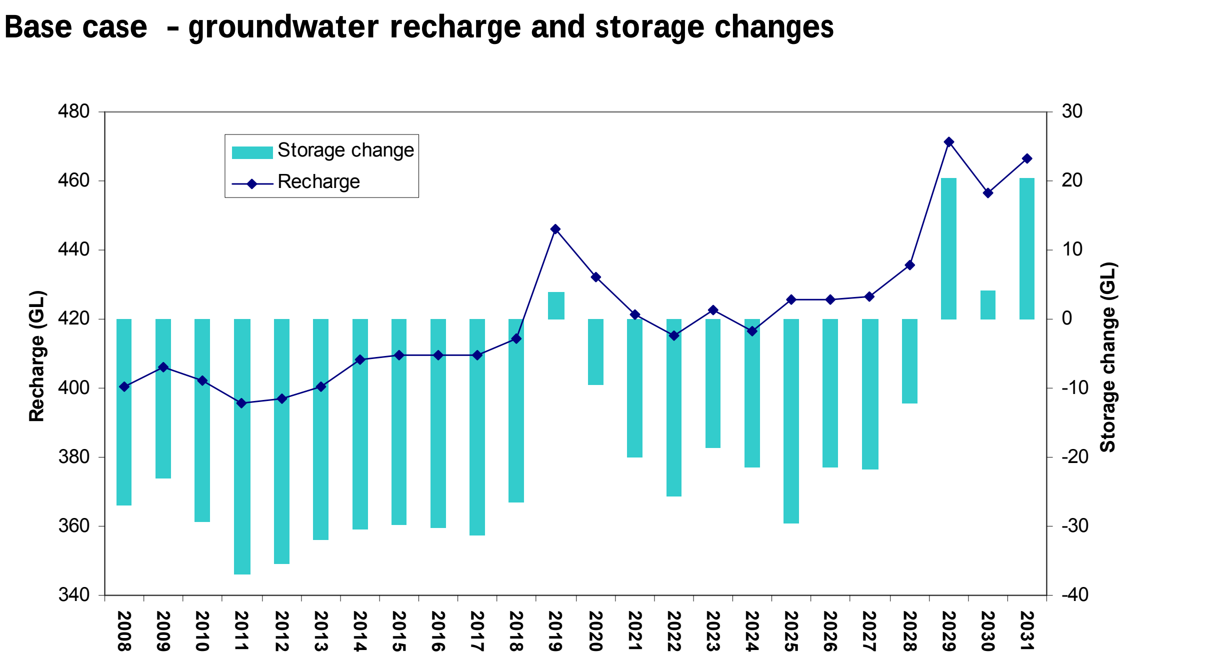


Figure 56 Relationship between annual recharge and storage change for the base case (2008 to 2031)

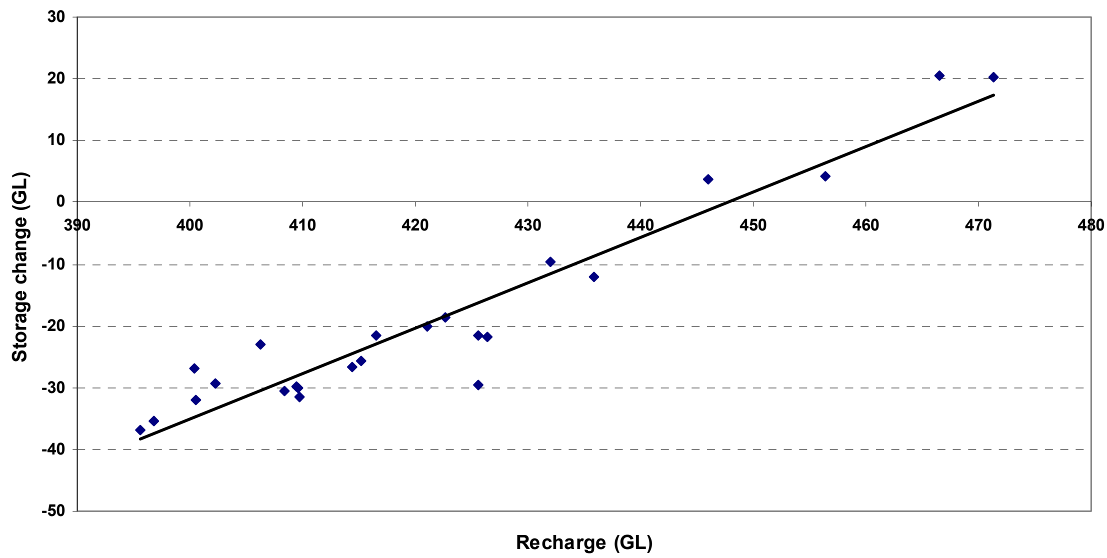


Figure 57 Recharge and storage change (base case)

Figure 56 shows the predicted time-series data of annual vertical recharge and the storage changes for the base case from 2008 to 2031. Recharge to the groundwater system varies from 400 GL in 2008 to 466 GL in 2031 with the minimum value of 396 GL occurring in 2011 and the maximum value of 471 GL occurring in 2029.

As shown in Figure 57, storage change varies from a storage loss of 27 GL in 2008 to a storage gain of 20 GL in 2031. The cumulative storage decline from 2008 to 2031 is estimated to be 464 GL.

The correlation between recharge and storage change (Figure 57) indicates that recharge of 450 GL is required to stop the decline of groundwater storage under current climatic, land use and abstraction conditions. The base case will only achieve such recharge rates on four occasions, that is, only after significant Banksia burning events and when all the laminated veneer lumber pine plantations are cleared. Recharge and storage change have a good correlation coefficient (R^2 = 0.91). This graph can be used to determine the recharge to groundwater if the annual storage change in the Superficial aquifer can be estimated from the groundwater monitoring data. However, this threshold recharge limit is much higher than the previous limit of 375 to 400 GL estimated by Vogwill et al. (2003) because they concluded that it was dependent on the 2003 conditions of abstraction and land use being maintained.

As shown in Figure 58, it was estimated that storage depleted by nearly 700 GL between 1979 and 2008. This is an average rate of 23.3 GL/yr. The GSS modelling base case scenario predicts a further 500 GL storage depletion, which only starts to recover in 2029 following proposed land use changes. Groundwater storage depletion until 2029 is predicted to occur at a similar rate to the 2008 rate of 25 GL/yr.

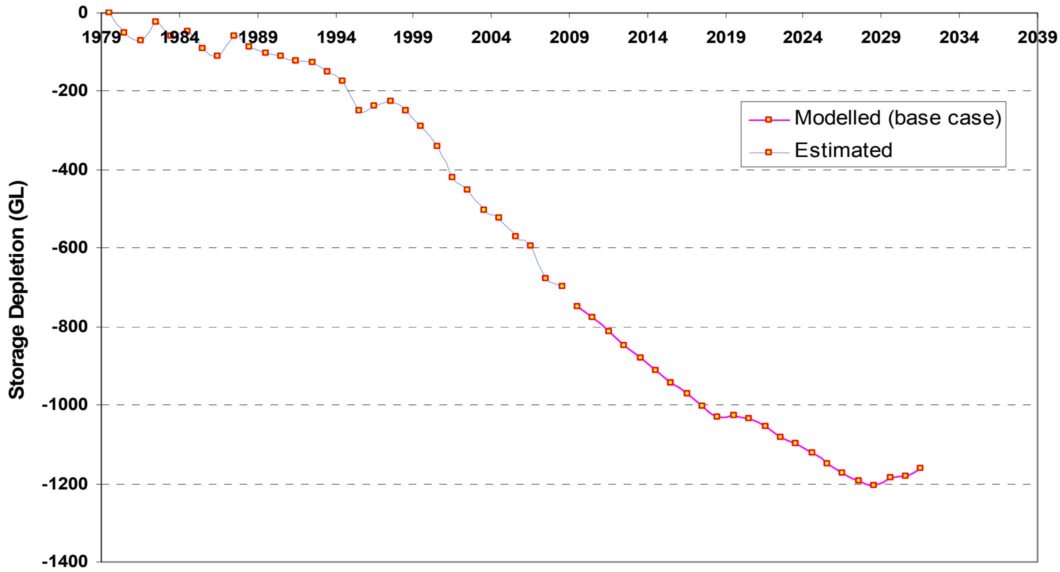


Figure 58 Estimated and predicted storage depletion in the Gnangara Mound since 1979

Wells and garden bores represent all the licensed and unlicensed abstraction from the Superficial aquifer. Apart from Water Corporation abstraction, these are net values after taking into account a 25% recirculation of irrigated water. In addition, there are minimum abstraction levels during the winter months of May, June and July. For the base case the total Superficial aquifer abstraction in 2008 was 136 GL of which 40 GL is public abstraction by the Water Corporation and the rest is 2007 private allocation (licensed). The total unlicensed abstraction (garden bores) from the Superficial aquifer was about 41 GL in 2008.

The vertical leakage from the Superficial to the confined aquifers is shown in the flux column in Table 18. Pumping from confined aquifers induces most of this vertical leakage. Flux also contains lateral throughflow coming in (positive values) or going out (negative values) of the water balance zone (GSS area). As shown in Table 16, flux is about 60 GL for the base case (135 GL Water Corporation abstraction). If there is no Water Corporation pumping, flux reduces to just 6 GL. Thus 54 GL out of 90 GL confined aquifer pumping is generated from induced vertical leakage.

In the base case for 2008 recharge is only 402 GL. However the total outputs (wells, ocean discharge, drains and garden bores and flux) amounts to 430 GL. This results in a water budget deficit of 27.5 GL. To balance this deficit PRAMS takes 27.5 GL from the storage. For the base case in 2031, recharge to groundwater is increased by 50 GL as a result of land use changes. Total outflow is 449 GL resulting in 3 GL of water being added to storage.

Abstraction scenarios

Note that storage change in the other abstraction scenarios are in proportion to the volume abstracted so we have only shown the 105 GL scenario.

Water Corporation 105 GL

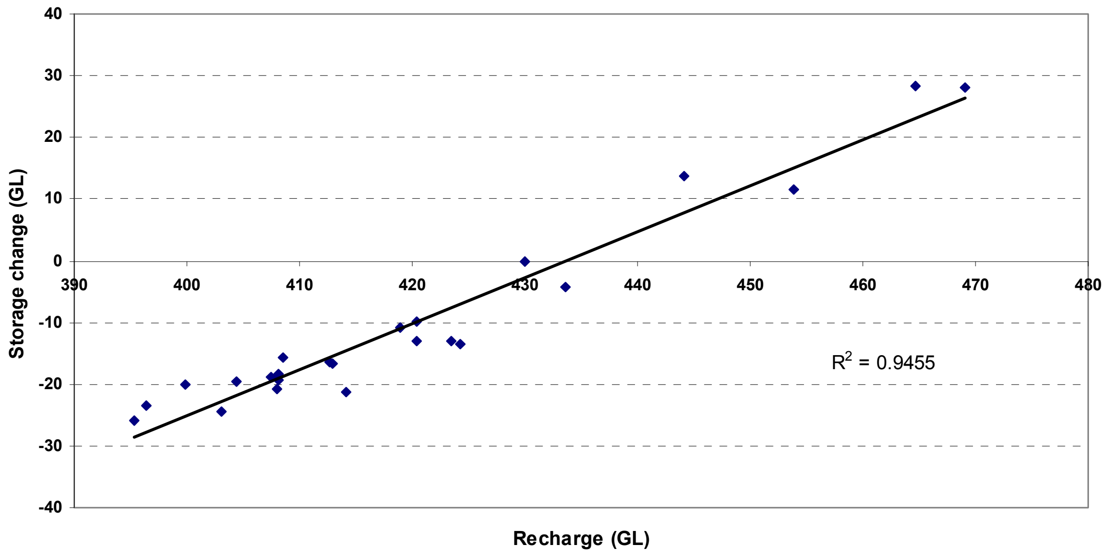


Figure 59 Recharge and storage change (Water Corporation 105 GL)

As with the base case scenario, predicted storage change is well correlated to the predicted rainfall recharge (R2 = 0.95). Under a reduced public abstraction scenario, threshold recharge where rainfall recharge is in equilibrium with the total outflow will be reduced from 448 GL in the base case to about 433 GL.

Land-use scenarios

Immediate pine removal

Under the immediate pine removal scenario, groundwater recharge increases to 436 GL in 2008 from 400 GL in the base case. This is about a 36 GL increase in recharge. Large scale burning in 2008 and 2018 would result in an increase in recharge to groundwater by 32 GL and 36 GL, respectively. The maximum recharge that can be achieved from vegetation management – immediate pine removal and large scale burning of Banksia – is about 469 GL.

An additional recharge of 69 GL will occur in 2029 due to immediate removal of pines. According to transient PRAMS modelling, this appears to have the benefit of arresting the rate of storage decline (Figure 60). The additional recharge will mainly occur in the East Yanchep and Gnangara subareas and will have the following benefits:

- increased discharge to oceans. This will reduce the risk of salt water intrusion into the Superficial aquifer near the coast.
- decrease in depth to watertable. This will have a positive impact by recovering water levels in environmentally sensitive wetlands including Yanchep Caves. Decreasing depth to watertable will increase the vertical recharge to the confined aquifers.
- As a result of early removal of pines there is a net cumulative effect of recharge on storage depletion. Under the base case scenario where there is a gradual removal of pines, storage will decline by another 500 GL before it starts to recover. Under the immediate pine removal storage decline is only another 230 GL (Figure 60).
- increased discharge to groundwater-dependant wetlands
- increased induced recharge due to confined aquifer pumping
- additional recharge to the Leederville aquifer.

A disadvantage of this scenario is that if the watertable recovers to within 2 m below ground level there will be increased evapotranspiration loss from groundwater. Thus the additional recharge, instead of replenishing storage, is lost through evapotranspiration.

The subareas that benefit under the immediate pine removal scenario are Perth North, West Swan, Mariginiup, Lake Mungala, Whitfords and Ellenbrook Town which benefit due to increased recharge and recovery of the watertable.

LVL Banksia

There was only a minor effect on the water balance and watertable levels of the Superficial aquifer relative to the base case.

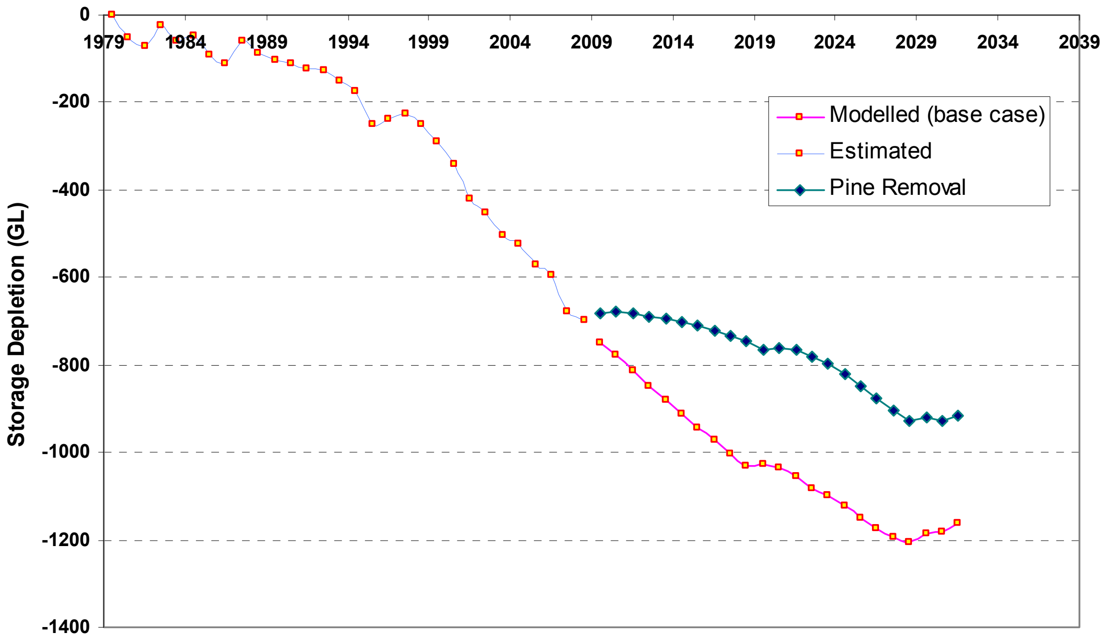


Figure 60 Storage depletion for the base case and immediate pine removal scenarios

GSS composites

A summary of groundwater recharge for GSS composite scenarios are given in Table 19. A further breakdown of groundwater recharge on the basis of GSS subareas for each hydrogeological province (Kardinya Shale and Leederville Window) is given in Tables 20 and 21. There is about 46 GL reduction in rainfall recharge when climate is changed from short term to dry. The majority of the reduction in recharge, 67%, occurs in the Kardinya Shale area, which shows less sensitivity to the climate in the past due to urbanisation and groundwater throughflow moving from the centre of the Mound. This suggests the impact of climate on this scenario may not be severe as modelling predictions. This may also be due to redundant water resource licensing allocations and garden bore water use that may be less than what the model estimates, due to smaller lot sizes. In Kardinya Shale areas these factors relevant to urbanisation are much more prevalent than the Leederville Window.

Table 19 Summary of groundwater recharge (modelled) under composite scenarios

Hydrogeological province	Short-term climate		Dry climate	
	2008–2011	2027–2031	2008–2011	2027–2031
	Recharge GL	Recharge GL	Recharge GL	Recharge GL
Leederville Window	129	163	116	148
Kardinya Shale	270	285	239	254
Gnangara Mound total	**399**	**448**	**355**	**402**

Table 20 Groundwater recharge (modelled) in the Leederville Window hydrogeological province under GSS composite scenarios

Subarea	Short-term climate		Dry climate	
	2008–2011	2027–2031	2008–2011	2027–2031
	Recharge GL	Recharge GL	Recharge GL	Recharge GL
Banksia	60.72	62.25	54.11	52.6
Carabooda	6.40	6.48	5.78	5.76
East Yanchep	24.78	54.92	23.77	52.96
Gingin Brook 3	7.96	6.91	7	6.17
Gingin Brook 4	8.29	8.18	7.74	7.98
Lake Mungala	2.30	4.30	2.51	5.01
Lake Pinjar	2.74	0.75	1.6	1.24
Neerabup	2.90	3.01	2.36	2.36
Nowergup	4.60	4.83	4.02	3.9
West Gnangara	8.28	11.52	6.89	9.94
Total Leederville Window recharge	**128.97**	**163.15**	**115.78**	**147.92**

Table 21 Groundwater recharge (modelled) in the Kardinya Shale hydrogeological province under GSS composite scenarios

Subarea	**Short-term climate**		**Dry climate**	
	2008–2011	**2027–2031**	**2008-2011**	**2008–2011**
	Recharge GL	**Recharge GL**	**Recharge GL**	**Recharge GL**
Bullsbrook	2.37	2.59	2.37	2.92
Carramar	5.07	5.88	4.42	5.17
Cottesloe Peninsula	3.31	3.38	2.86	2.91
East Gnangara	15.32	14.54	12.86	11.19
Eglinton	4.99	5.64	4.66	5.07
Ellenbrook Town	4.75	5.12	4.74	5.08
Gingin Brook 1	10.10	10.31	9.27	9.21
Gingin Brook 2	3.47	3.31	3.04	2.81
Gnangara	17.19	22.09	15.13	20.27
Gwelup	6.07	6.36	5.33	5.72
Lake Gnangara	6.67	6.52	5.82	6.14
Mariginiup	8.12	4.31	6.94	5.07
Perth North	81.58	86.13	71.40	75.72
Quinns Rocks	15.47	17.17	13.53	14.32
West Pinjar	2.58	5.60	2.15	4.61
West Swan	3.42	4.12	3.63	4.40
Whiteman	8.30	8.16	7.11	7.17
Whitfords	56.72	58.50	49.61	51.31
Yanchep Two Rocks	14.64	15.89	14.19	15.40
Total Kardinya Shale recharge	**270.14**	**285.60**	**239.05**	**254.50**

5.3 Hydrograph analysis

Hydrograph analysis summarises the modelled changes in water levels at selected sites, under the different scenarios. Sites for this analysis have been selected from well-calibrated bores from the PRAMS modelling (Figure 61). This analysis allows the relative impact of different scenarios to be compared at a particular site. The impact of locally significant scenarios relative to the base case in 2031 can be determined from these hydrographs and results. The hydrograph information is the same as that given in the watertable maps provided in the previous section, but is more detailed at the chosen locations. Hence, studying the hydrographs and the watertable maps will help in providing the spatial interpretation of the modelling.

In the following hydrograph analysis the observed data is shown together with the PRAMS simulated hydrograph from 2008 to 2031. The individual scenarios show how the base case would change if particular action was 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 options on the base case and the impact of climate variability.

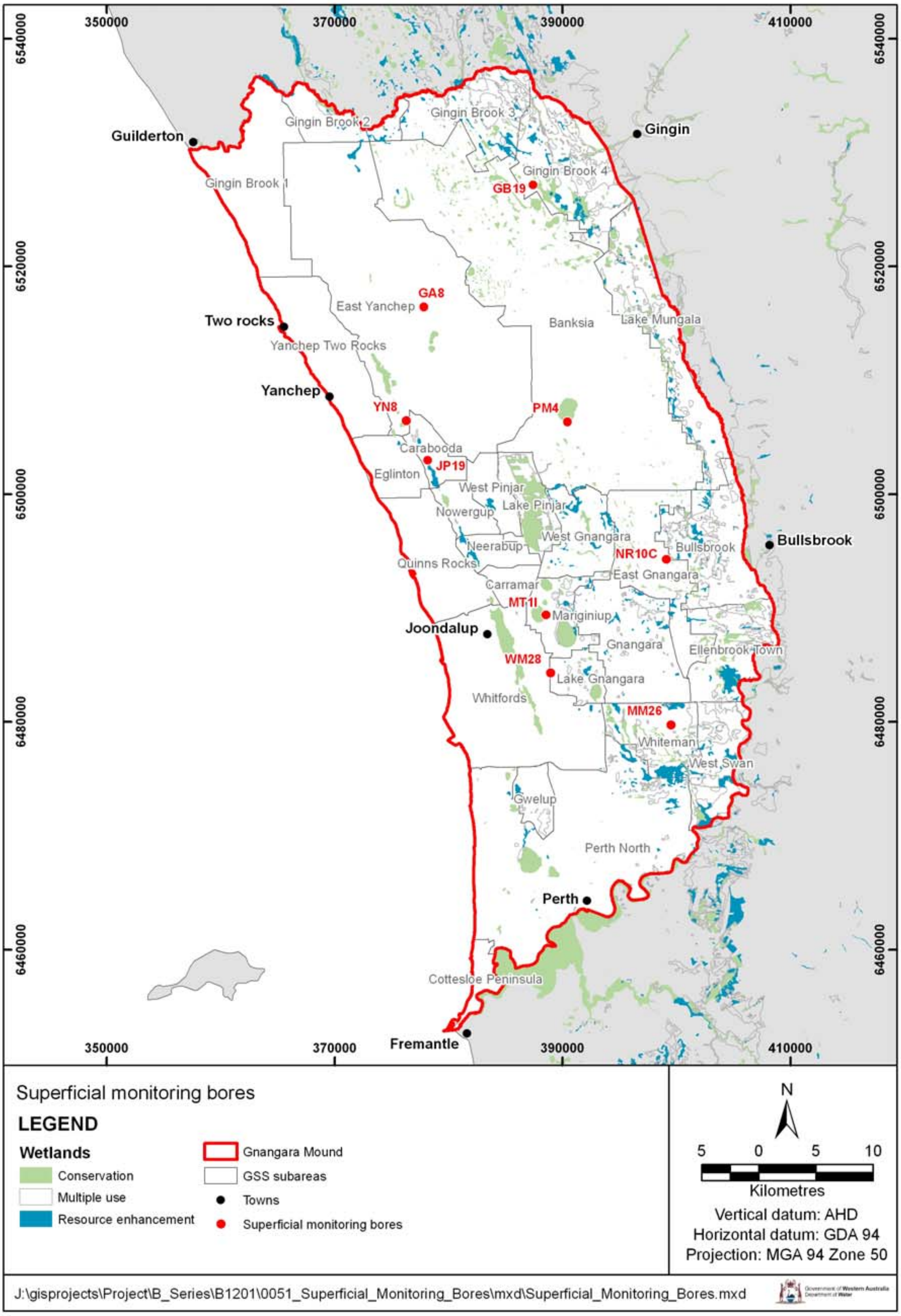


Figure 61 Superficial monitoring bores used in the hydrograph analysis

Hydrograph – bore GA8

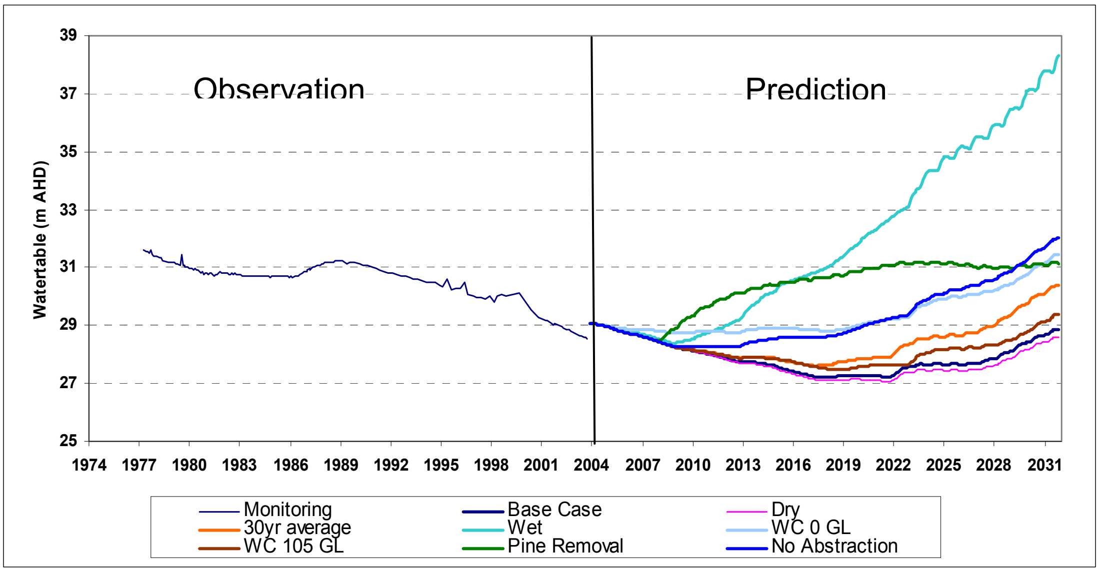


Figure 62 Observed and predicted hydrographs for eight modelling scenarios at monitoring bore GA8

Bore GA 8 is located in the middle of the Yanchep pine plantation. The observed hydrographs (Figure 62) show a declining trend, which has accelerated since 1996. The lack of seasonal fluctuations shown by the hydrographs is due to the dense vegetation and pine litter intercepting rainfall. The deep watertable (25 m) could also be attenuating the seasonal recharge resulting in a more constant vertical flux.

The base case predicted hydrograph shows continued declines, until the gradual removal of pines has a significant impact on recharge in 2023. From 2023 to 2031 there would be about 2 m increase in groundwater levels. The immediate removal of pines in 2008 and replacement with pasture would increase water levels by 3 m in 2020 and then groundwater levels reach equilibrium. The maximum recovery in groundwater level that can be obtained under the pine removal scenario is similar to the groundwater levels of 1980.

Predicted hydrographs for climate scenarios (dry, 30-year average and wet) indicate that this site is highly sensitive to climate change. Although there is not much difference between dry and the base case, and dry and 30-year average, the difference between dry and the wet scenario is about 10 m by 2031. This may reflect the potential to capture and store excess recharge in the depleted aquifers under the pine plantation.

The no abstraction scenario and Water Corporation 0 GL scenario achieve slightly higher groundwater levels than the pine removal scenario. There will be less than a metre difference between the no abstraction and Water Corporation 0 GL scenarios, indicating that most of the abstraction impact is caused by the Water Corporation confined aquifer pumping. The dominant impacts at this site, in order of greatest to least, are: climate, Water Corporation confined pumping and pines equally and private abstraction.

Hydrograph – bore GB19

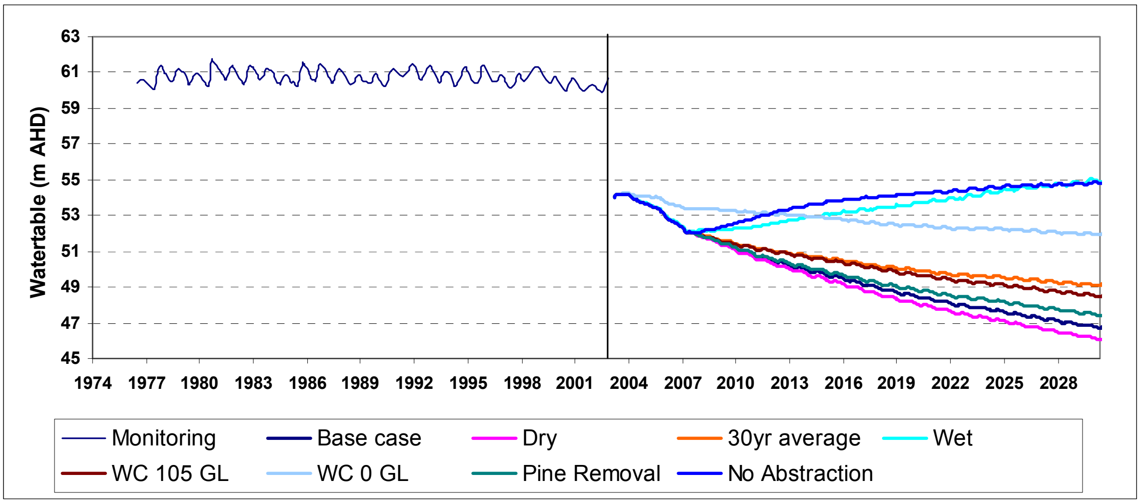


Figure 63 Observed and predicted hydrographs for eight modelling scenarios at monitoring bore GB19

Bore GB19 is located in the northern part of the Mound in an area of native vegetation. The observed hydrograph shows a fairly stable trend from 1978 to 2000. From 2000 to 2008 watertable levels have declined by 1 m (Figure 63). This decline in the watertable can be attributed to reduced rainfall and an increase in Water Corporation confined pumping. The predicted rapid decline from 2003 to 2008 is probably due to newly licensed private abstraction (which was used in the modelling) being significantly higher than actual new private abstraction. This results in the predicted hydrograph from 2003 to 2008 being considerably steeper than the measured hydrograph.

Note that the apparent sudden drop between the observed and modelled figures is due to calibration error as discussed in Section 3.4.

The predicted hydrographs show that this site has high sensitivity to climate and groundwater abstraction. The watertable difference between the wet and dry climate is 8 m. No abstraction also has similar levels of impact with the dominant impact, 5 m, resulting from the Water Corporation confined pumping and about 3 m from private abstraction, assuming licensed private abstraction matches actual abstraction. The recovery from the 2008 current actual level of private bore abstraction, if all private pumping ceased, would be about 3 m. Under the Water Corporation 105 GL scenario, the watertable is likely to recover by 1 m in 2031 as most of the reduction from the 135 GL/yr scenario is achieved from the confined aquifers. This implies that at GB19 the impacts on future groundwater levels, in order of greatest to least are: climate, Water Corporation confined aquifer pumping, private abstraction and pine removal.

Although not modelled here frequent burning regimes are likely to have similar effects to the Water Corporation pumping.

Hydrograph – bore PM 4

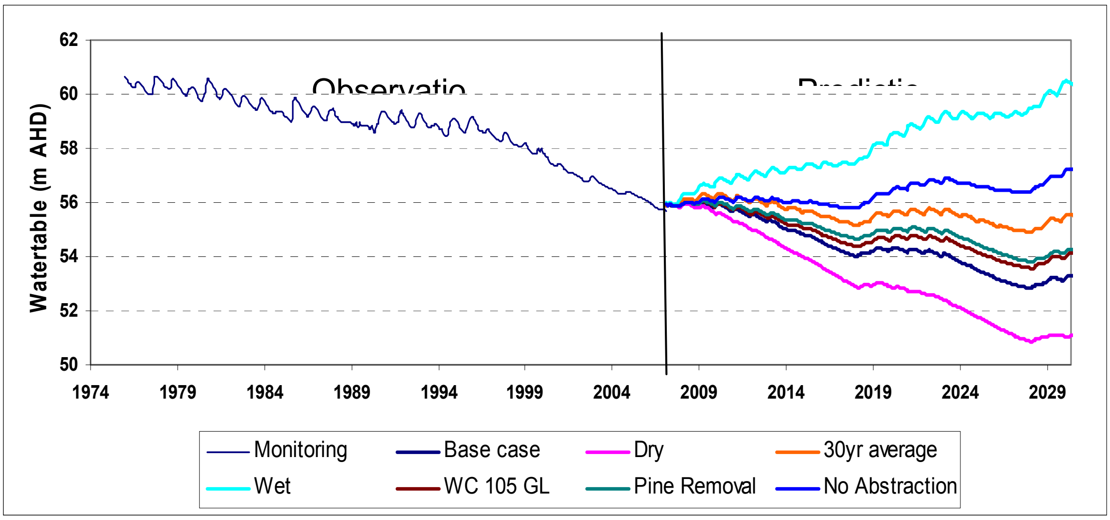


Figure 64 Observed and predicted hydrographs for seven modelling scenarios at monitoring bore PM4

Bore PM4 is located near the crest of the Gnangara Mound. The 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 12 years (1996 to 2008), have been recorded (Figure 64). The lack of distinct seasonal fluctuations indicates that little water infiltrates from the unsaturated zone to the watertable.

The predicted hydrographs show that under the current rainfall and current vegetation density the observed declines are likely to continue before stabilising around 2028 following the burning of Banksia and removal of pine plantations. The base case hydrograph shows an additional decline of 3 m. Under a dry climate condition there will be another 2 m decline relative to the base case. Both pine removal and Water Corporation 105 GL scenarios predict 1 m recovery in watertable levels by 2031. The impact of reductions in Water Corporation abstraction in this locality is mainly due to the proximity of the Pinjar borefield. Under the wet climate scenario groundwater level recovery is 7 m whereas the no abstraction scenario predicts 4 m recovery of which 3 m recovery is due to public abstraction by the Water Corporation. The impact of reduced horticulture is negligible and hence not shown in the hydrograph. This implies that the dominant impacts on future groundwater levels at PM4 are, in order of greatest to least impact: climate, Water Corporation confined aquifer pumping, pine removal and private abstraction equally and finally reduced horticulture.

Hydrograph – bore JP19

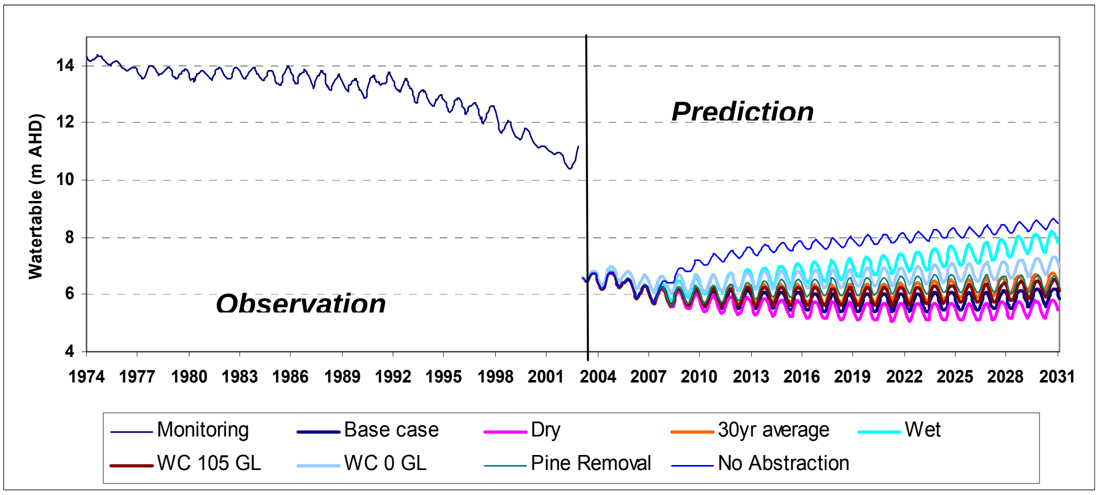


Figure 65 Observed and predicted hydrographs for eight modelling scenarios at monitoring bore JP19

Bore 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 shows an accelerated declining trend from 1999 onwards (Figure 65). Modelling indicates that this declining trend is likely to continue until 2012 when some degree of stabilisation is likely, due to the proximity of this area to the discharge flanks of the Gnangara Groundwater Mound system. The scenario difference between the dry climate and wet climate in 2031 is only 3 m, showing the limited sensitivity of the climate within the discharge flanks of the Mound.

The model results indicate that the dominant impacts at JP19 on future groundwater levels are in order of greatest to least impact: climate, private abstraction, Water Corporation pumping and pines. However, private and public groundwater abstraction combined have a greater impact than climate at JP19.

Hydrograph – bore YN08

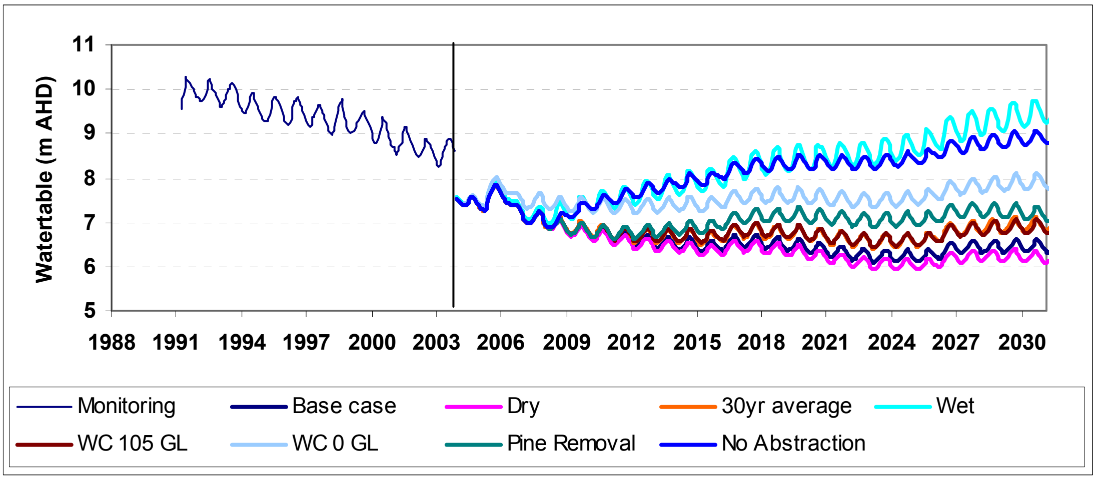


Figure 66 Observed and predicted hydrographs for eight modelling scenarios at monitoring bore YN08

Bore YN8 is located on the western margin of the Northern Wanneroo Groundwater Area at the boundary between the Bassendean Sand and Tamala Limestone. This site is close to the discharge area of the Mound. The observed hydrograph shows a steadily declining trend since the bore was constructed in the early 1990s (Figure 66).

The predicted hydrographs for the base case show a continued declining trend followed by a hydrologic equilibrium after 2025. Under a dry climate there will still be an equilibrium but at a slightly lower level than the base case. The watertable difference between the wet and dry climate is only 3 m, indicating limited sensitivity to the climate change due to the bore's close proximity to the groundwater discharge zone. The immediate pine removal scenario has about 0.8 m impact at YN08.

The no abstraction scenario has slightly less effect compared to the wet climate scenario. If there is no private or public pumping the watertable is likely to recover by 2.8 m. The impact of public pumping by the Water Corporation is 1.8 m. This implies that the dominant impacts on future groundwater levels at YN08 are, in order of greatest to least impact: climate, Water Corporation abstraction, private abstraction and pines. Although not modelled here, frequent burning regimes are likely to have a greater impact than the immediate pine removal at both this site and at Crystal Caves located further down gradient from YN08.

Hydrograph – bore MM26

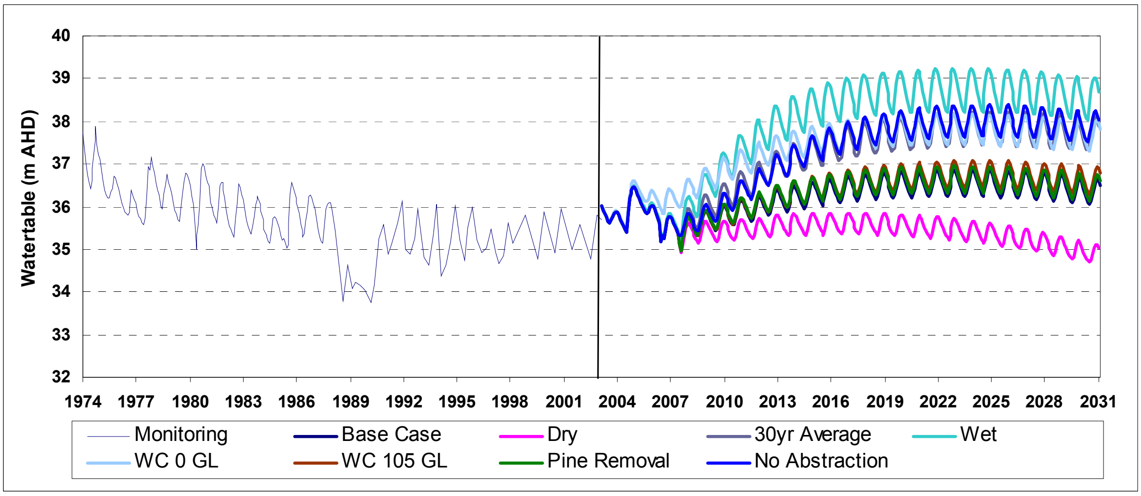


Figure 67 Observed and predicted hydrographs for eight modelling scenarios at monitoring bore MM26

Bore MM26 is located in the Mirrabooka Groundwater Area, south of the pine plantations in Whiteman Park. The observed hydrograph show a gradual declining trend in water levels compared to hydrographs at the other sites (Figure 67). MM26 is located near the discharge flanks of the Mound, close to the Swan River which has a relatively constant head, so long-term watertable fluctuations are attenuated.

The predicted hydrographs indicate that the watertable is only slightly sensitive to changes in climate. The watertable difference between the wet and dry climate scenarios is less than 4 m. There is negligible watertable difference between the 30-year average climate and the base case. Under a dry climate the watertable is likely to fall by another 1.5 m in 2031 compared to the base case. Immediate pine removal will have no effect at MM26.

Abstraction effects at MM26 are caused mainly by Water Corporation pumping. Under the no abstraction scenario the watertable would rise to slightly lower levels, about I m less, than would have occurred under the wet climate scenario. Reduction in Water Corporation pumping to 105 GL would have no impact at MM26 due to the fact that the Superficial aquifer here is fully separated from the confined aquifers by the Kardinya Shale. This is generally true for confined aquifer pumping in the southern part of the Mound.

Hydrograph – bore MT1I

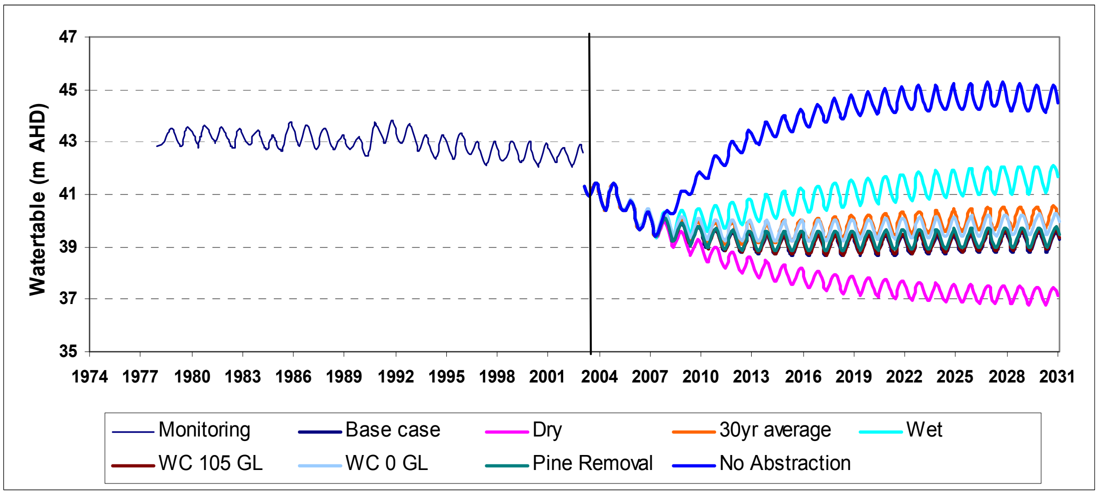


Figure 68 Observed and predicted hydrographs for eight modelling scenarios at monitoring bore MT1I

MT1I is located in the north-eastern 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 68) show a fairly stable trend from 1978 to 1994, with a declining trend since then. The watertable has declined by 1 m over the last 15 years (1994 to 2008).

The predicted rapid decline from 2003 to 2008 is probably primarily due to licensed private abstraction being significantly higher than actual private abstraction. This results in the predicted hydrograph from 2003 to 2008 being considerably steeper than the measured hydrograph (extrapolated from 2003 to 2008). The predicted hydrographs show watertable decline is likely to continue until 2012 before reaching a hydrologic equilibrium under base case conditions. In a dry climate, the watertable declines a further 2 m. This site has low to intermediate sensitivity to the scenario runs, with a watertable range of 4 m. Water Corporation pumping or immediate pine removal has limited or no impact at MT1I. Assuming licensed allocation matches actual abstraction then private abstraction has the greatest impact of 6 m relative to the base case, exceeding the impact of the wet climate by 4 m.

In practice, because of the recent trend of land-use change from horticulture to urban development the level of actual abstraction is significantly less than has been modelled. The impact of private abstraction relative to the base case would therefore be about 4.5 m, exceeding the impact of the wet climate by 2.5m.

Hydrograph – bore NR10c

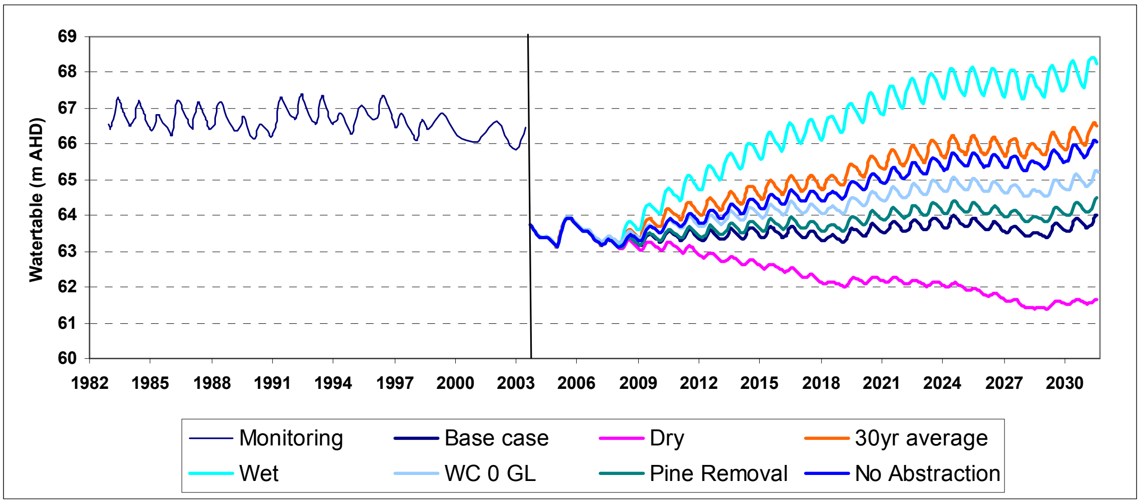


Figure 69 Observed and predicted hydrographs for seven modelling scenarios at monitoring bore NR10c

Bore NR10c is located in the Lexia area to the east of the pine plantation in an area of native vegetation. The Lexia area contains abundant wetlands, many of which have dried over recent years. The observed hydrograph has a relatively stable trend initially but shows a decline of less than 1 m from 1996 to 2008 (Figure 69).

Note that the apparent sudden drop between the observed and modelled figures is due to calibration error as discussed in Section 3.4.

The predicted hydrographs indicate that from 2008 to 2031 the base case hydrograph is stable with a minor response of up to 0.5 m from the ten-year burning regimes scheduled in 2008, 2018 and 2028. After each of the burning episodes the watertable rises and stabilises before slightly declining. However, under a dry climate the watertable will further decline by more than 2 m relative to the base case. The site is sensitive to climate change, with the watertable difference between the wet and dry climate scenarios being nearly 7 m The impact of immediate pine removal is about 0.5 m and is not enough to neutralise the effect of climate change.

Both the Water Corporation 105 GL and 120 GL scenarios have no impact at NR10c as there is no significant reduction in Superficial aquifer pumping in these scenarios and also there is no impact from confined pumping by the Water Corporation, due to the occurrence of the Kardinya Shale aquitard between the superficial and confined aquifers. The no abstraction scenario has 2 m impact on watertable equally shared by private and public abstraction. This implies that at NR10c the dominant impacts on future groundwater levels are, in order of greatest to least impact; climate, Water Corporation and private abstraction equally and then pines. More frequent burning may have a significant impact at NR10c but it is not possible to quantify this as a burning more frequently than on a 10-year rotation scenario was not modelled in this study.

Hydrograph – bore WM28

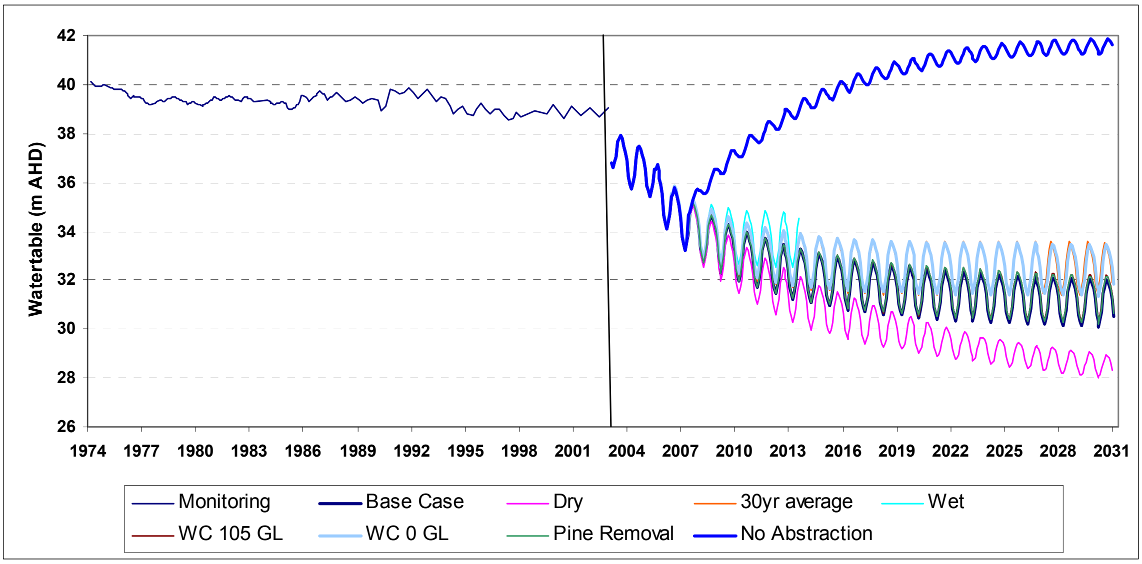


Figure 70 Observed and predicted hydrographs for eight modelling scenarios at monitoring bore WM28

Bore WM28 is located in the southern part of the Southern Wanneroo Groundwater Area, a region of high private abstraction. The observed hydrograph (Figure 70) indicates that the watertable has declined about 1 m since the groundwater monitoring began in 1974 (for 35 years). The predicted hydrograph for the base case indicates there will be a further 6 m decline by 2031. This will be a significant decline considering that there was only 1 m decline for the last 35 years. The predicted rapid decline from 2003 to 2008 is probably primarily due to licensed private abstraction being significantly higher than actual private abstraction. This results in the predicted hydrograph from 2003 to 2008 being considerably steeper than the measured hydrograph (extrapolated from 2003 to 2008).

Predicted hydrographs for the climate scenarios indicate a low to intermediate sensitivity at this site, with 4 m watertable difference between dry and wet climate scenarios (Figure 70). Under a dry climate the watertable is likely to fall by another 2.5 m relative to the base case. Pine removal has no impact on the watertable at the site.

Assuming licensed allocation matches actual abstraction then the no abstraction scenario has about 11 m impact at the site. Most of the watertable recovery under this scenario is attributable to private abstraction. Under the no abstraction scenario the watertable will recover exceeding the groundwater levels of 1974. In practice, because of the recent trend of land-use change from horticulture to urban development the level of actual abstraction is significantly less than has been modelled. The impact of private abstraction relative to the base case would therefore be about 6 m, exceeding the impact of the wet climate by about 4 m.

6 Conclusions

6.1 Base case scenario

Under the base case scenario, rainfall recharge to the Superficial aquifer is predicted to increase from 402 GL/yr (averaged over the 2008 to 2011 period) to 452 GL/yr (averaged over the 2027 to 2031 period). As a result, there is predicted to be a storage gain of 3 GL/yr in 2031. If the current short-term climate persists, proposed land-use changes are predicted to bring the Superficial aquifer to a new hydraulic equilibrium in 2031. However, the watertable will still remain lower than the levels of 2008 in nearly 60% of the Mound.

6.2 Climate scenarios

Climate modelling scenarios show that climate is the most significant factor determining the spatial distribution and magnitude of groundwater storage effects on the Superficial aquifer. If future climate is similar to the 30-year average climate, within a short period of time, the Superficial aquifer is predicted to reach a new hydraulic equilibrium where the aquifer gets rainfall recharge that balances out water demands on the Mound.

Under the future dry climate scenario over more than 20 years, recharge is predicted to improve slightly to 406 GL in 2031 compared to 2008, and groundwater storage is predicted to decrease at a rate of 16 GL/yr from the Superficial aquifer. This improvement is due to the land-use changes that are part of this scenario.

6.3 Public abstraction scenarios

The abstraction modelling scenarios predict that under reduced abstraction there will be a storage gain in the Superficial aquifer. If abstraction is reduced by 15 GL/yr, the resulting storage improvement is predicted to be 12 GL/yr. Reducing abstraction by this amount still falls short of neutralising the impact of a dry climate by 4 GL/yr because the storage loss is about 16 GL/yr in 2031 under the dry climate.

6.4 Private abstraction scenarios

If the private water allocation for horticulture is reduced by 30%, groundwater storage will be improved by 8 GL/yr in 2031. This storage improvement alone will not be able to counter the impact of a drying climate.

6.5 Land use scenarios

If the laminated veneer lumber pines are replaced by native vegetation (Banksia), rainfall recharge is predicted to be enough to balance out the water demands on the Mound. However, there will be no net storage gain to the already depleted groundwater storage and hence there will not be a sufficient buffer to stop the declining watertable if the climate gets dryer.

If the laminated veneer lumber pines are to be cleared immediately, rainfall recharge is predicted to increase by 38 GL/yr, resulting in a storage gain of 8 GL/yr. In the long term, rainfall recharge is predicted to be increased by another 12 GL/yr to a maximum of 452 GL/yr. However, the increased recharge will not replenish groundwater storage of Superficial aquifer as discharge to the ocean and leakage to confined aquifer increases.

Overall, land-use options are important for managing the water resources of the Gnangara Groundwater Mound, as improvements to recharge mainly occur in the Leederville Window hydrogeological province where the Superficial aquifer is hydraulically connected to the confined aquifers. This area also has a high potential to store more rainfall recharge than the other parts of the Mound. Hence, land-use management in the Banksia, East Yanchep and West Gnangara GSS subareas, which are located in the Leederville Window, is vital for managing water resources in the Mound.

6.6 GSS composite scenarios

The GSS composite (short-term climate) scenario indicates that the Superficial aquifer is predicted to reach a new hydraulic equilibrium where rainfall recharge is sufficient to maintain the water requirements of the Mound. The modelling predicts a storage gain of 18 GL/yr, mainly attributable to the reductions in private and public abstractions. This storage gain is enough to neutralise the impact of a dry climate (under the dry climate scenario the storage loss is about 16 GL/yr in 2031). Groundwater recharge under the GSS composite (short-term climate) is predicted to be 448 GL/yr and 36% of this is generated within the Leederville Window, which is more sensitive to climate change than the Kardinya Shale area.

When the GSS composite scenario was modelled with the dry climate, water balance results show that predicted storage loss is 3 GL/yr in 2031. The GSS composite scenarios are mainly designed to optimise groundwater management by carefully selecting land use and water management strategies in the current uncertain climatic environment.

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