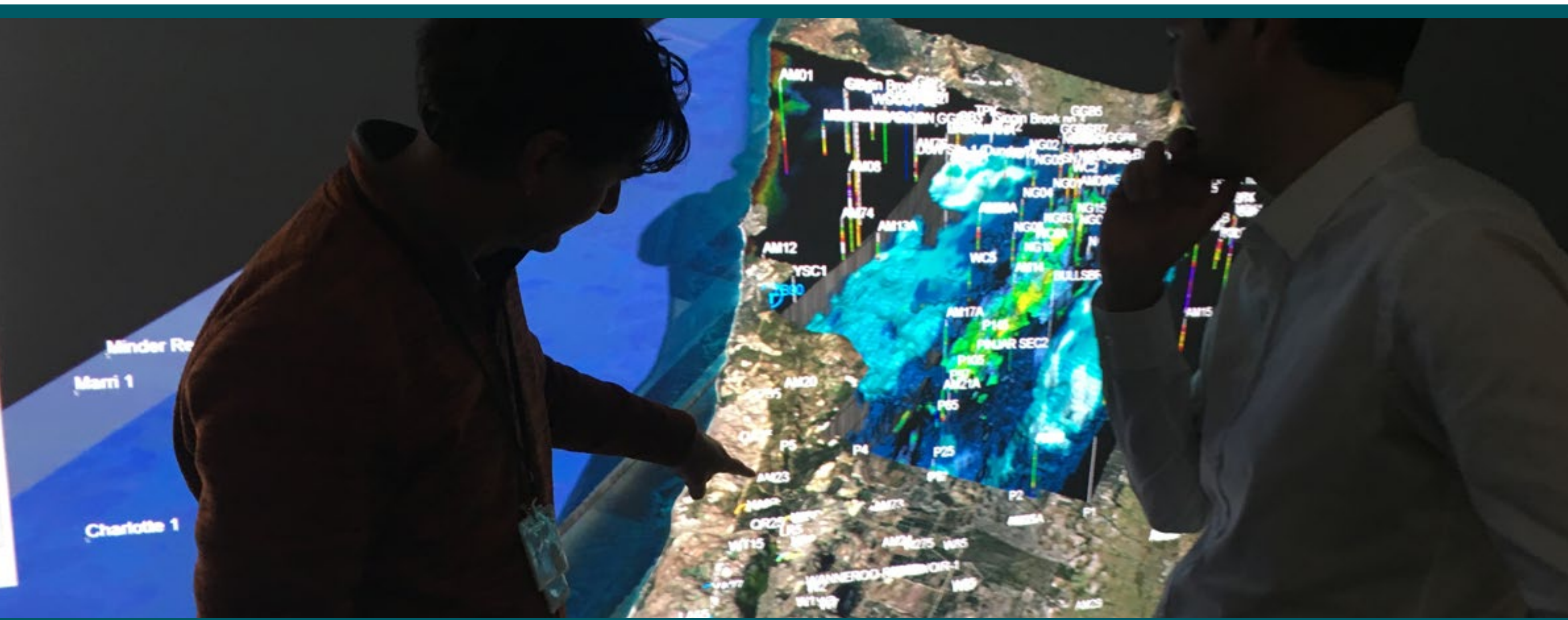
Government of **Western Australia**
Department of **Water and Environmental Regulation**

Studying Perth's deep aquifers to improve groundwater management

Findings from the Perth Region Confined Aquifer Capacity study



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Cover photograph: Brett Harris (Curtin University) and JP Pigois (DWER) viewing 3D hydrogeology under Perth at the Pawsey supercomputing centre.

Foreword

Science is the key to managing Perth's groundwater. Groundwater investigations provide the hydrogeological understanding that underpins the sustainable management of groundwater resources. Add new technologies to traditional groundwater science and we can understand complex aquifer systems better than ever.

This science comes at a critical time. There is demand for more precise information and management tools to balance the economic, social and environmental need for groundwater - in the context of climate change.

The $7 million study of Perth's deep aquifers was a four-year project to improve our certainty of how much groundwater we can abstract from these aquifers without impacting their long-term sustainability. The study combined conventional groundwater investigations, innovative science partnerships, and an ongoing collaboration with the Water Corporation. Partnering with leading research institutions enabled the Department of Water and Environmental Regulation to use the latest science and expertise in groundwater investigations and modelling.

With a sound scientific understanding behind how we manage groundwater, our deep aquifers can continue to play a crucial role in meeting Perth's water needs, now and into the future.

Contents

Figures

Tables

Summary and key findings

The Department of Water and Environmental Regulation completed the four-year, $7 million Perth Region Confined Aquifer Capacity (PRCAC) study in December 2016.

The study used robust, established science coupled with innovative research to improve the understanding of the deep Leederville and Yarragadee aquifers in the Perth region. The department worked with the Water Corporation to shape the study and share findings. The study has given us new insights into how the deep aquifers can be managed effectively.

The Leederville and Yarragadee aquifers are a vital part of Perth's total water supply. Groundwater from these aquifers is primarily accessed by the Water Corporation, under licence, for the Integrated Water Supply Scheme (IWSS) providing Perth's public water supply.

The study aimed to improve our understanding of how these aquifers interact, how groundwater is recharged, how it flows, and how groundwater abstraction and injection of recycled water impact on groundwater levels. In some parts of the system the deep aquifers are connected to the overlying Superficial aquifer or to each other. In some parts faults or other hydraulic property changes within aquifers also influence how groundwater moves through and between aquifers.

In areas where aquifers are connected, groundwater pumped from deep aquifers can draw down water levels in the overlying aquifer. Groundwater pumping from the deep aquifers can also influence the movement of seawater into the deep aquifers and the compression of the deep aquifers.

This summary report describes the main elements of the PRCAC study and the key findings and considerations for sustainably managing our deep aquifers. Related technical reports produced as part of the study are listed in section 1.3 and are available from the department on request.

Findings from the study (summarised below) are helping us to use and manage Perth's deep aquifers in the best way possible. The department is using this study and its findings to inform the next Gnangara groundwater allocation plan. Findings have and will continue to guide the location of future groundwater injection and recovery bores for Perth. For example, we have used the science to assist Water Corporation to identify locations for Beenyup Groundwater Replenishment Stage 2 injection and abstraction bores.

Abstraction volume is constrained mainly by connection to the Superficial aquifer

The deep aquifers are connected to the Superficial aquifer in some areas. Abstraction in or near connected areas causes drawdown in the Superficial aquifer and so impacts on groundwater-dependent ecosystems.

Generally, there is low risk of seawater intrusion in the deep aquifers

The risk of seawater intrusion restricts deep aquifer abstraction near the coast north of Perth, close to Mindarie, where the Leederville aquifer is connected to the Superficial aquifer. Modelling suggests that the risk of seawater intrusion to the deep aquifers is low elsewhere in Perth, even under current abstraction.

Subsidence from deep aquifer abstraction is minor compared with sea level rise

There is no risk of localised subsidence from deep aquifer abstraction, however minor subsidence over large areas is possible if the deep aquifers are drawn down further. This may bring forward the impacts of sea level rise, if not managed. A conservative estimate is that each metre of combined drawdown in the Leederville and Yarragadee aquifers could cause up to 1 cm of subsidence, bringing forward sea level rise by up to a year.

Groundwater replenishment can have many benefits for the whole system

Choosing optimal locations for injection (also known as replenishment) can bolster deep aquifer pressures, reduce leakage from the Superficial aquifer, help recover groundwater levels at high value groundwater-dependent ecosystems and in high value areas such as the Swan Valley, and allow for full recovery of injected water while maximising use of the deep aquifers for scheme supply. Modelling shows that an 'optimal pattern' of injection and abstraction will allow Water Corporation to abstract the total volume of Beenyup Stage 2 injected water. This compares with the originally proposed pattern where less than 80 per cent of reinjected water can be abstracted, with the same water resource and environmental outcomes.

New, additional water could be abstracted from the Leederville aquifer

The Leederville aquifer west of the Badaminna Fault (north of Yanchep) provides a potential groundwater resource in the future. Further work is needed to quantify sustainable abstraction limits and potential impacts of abstraction before this resource can be developed.

We can better interpret groundwater model outputs and improve future models

We now have a greater understanding of how groundwater moves around known or suspected faults and other restrictions to flow, and improved information on recharge and connection between aquifers to help us interpret model outputs and improve any new or revised models in the future. We will continue to enhance our understanding through an improved monitoring network and further work by the Water Corporation as part of Beenyup Groundwater Replenishment Stage 2.

1 Introduction to the study

1.1 Purpose and background

The purpose of the Perth Region Confined Aquifer Capacity (PRCAC) study was to find how and where to get the most benefit from using deep groundwater as a source for public water supply for Perth, with the least impact to the Gnangara groundwater system as a whole. The study aimed to develop the technical understanding needed to set out the best management options for the deep aquifers, assess potential water quality changes (such as from seawater intrusion), and evaluate injection of treated waste water to deep aquifers.

Most of the groundwater abstracted from the deep Leederville and Yarragadee aquifers has been, and continues to be, used to supply Perth's Integrated Water Supply Scheme (IWSS). The IWSS delivers drinking-quality water across Perth and Mandurah, and to much of the central wheatbelt and Kalgoorlie. The Leederville aquifer also supplies about 11 gigalitres per year (GL/year) of groundwater for horticulture, viticulture and public open space and other green space primarily for the iconic Swan Valley area.

As inflow to dams decreased in the 1980s, 1990s and 2000s groundwater was increasingly used to make up more and more of the scheme supply, while also maintaining supply for local, non-potable uses such as agriculture and irrigating public open space. By 2001, the ongoing effects of a drying climate along with this increased reliance on groundwater had negatively impacted on the groundwater system and the move to grow the scheme through alternative, climate-independent sources began.

Groundwater was relied on to maintain supply through this transition and, eventually, returning to a more sustainable level of groundwater abstraction became essential. The Department of Water and Environmental Regulation (formerly Department of Water) largely capped licensed groundwater abstraction for all purposes from 2009 and, with the Water Corporation, introduced sprinkler restrictions to scheme users and domestic garden bores and started staging down abstraction for scheme supplies.

Groundwater currently makes up almost half of the volume of water supplied for the IWSS. Over the last 10 years the deep Leederville and Yarragadee aquifers have each provided about 30 per cent of the total water supplied to the scheme. During very dry years when dam levels are low, IWSS customers have temporarily relied on greater volumes from the deep aquifers. The volume of water taken from the Leederville and Yarragadee aquifers for scheme supply increased over time, from around 31 GL/year in the early 1990s to a peak of 110 GL/year in 2011/12, with an average of over 95 GL/year since 2002 (Figure 1). A shift to a higher proportion of groundwater abstraction from the deep aquifers enabled some reduction in IWSS abstraction from the Superficial aquifer, helping to reduce direct impacts on other groundwater users and groundwater-dependent environments.

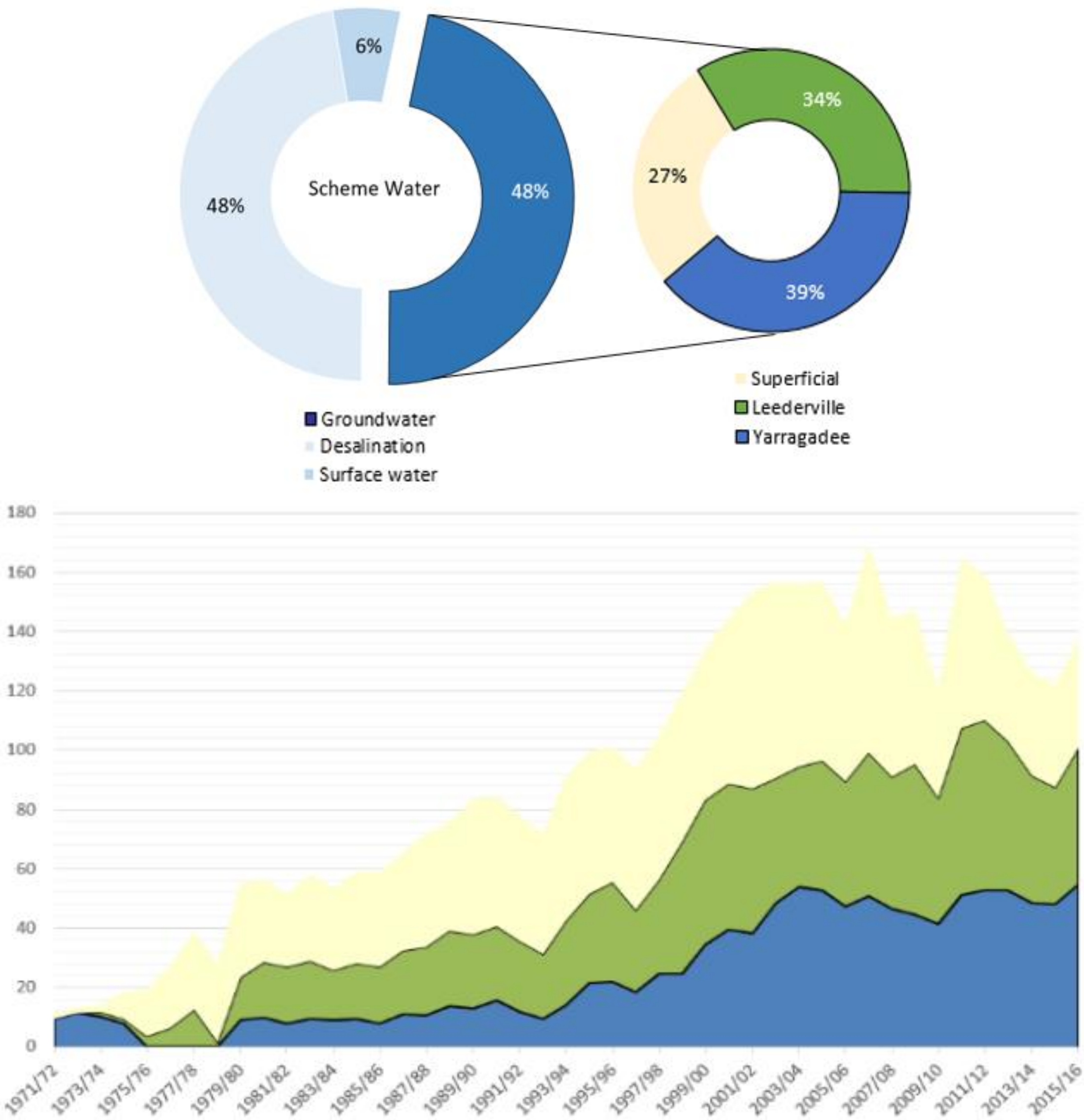


Figure 1 Breakdown of Integrated Water Supply Scheme supply (as at June 2016) and changes in groundwater supply over time

Management of the deep aquifers has adapted through a combination of responding to impacts and adjusting the volume and pattern of abstraction. Since capping abstraction in 2009, the department's approach to licensing IWSS abstraction has been to more precisely manage impacts at environmental criteria sites through adjusting volumes taken from each aquifer at each bore field from year to year. This work was informed by our understanding of where aquifers were connected, recognising that pumping from deep aquifers affected the Superficial aquifer in connected areas, and at other locations pumping had less impact. Along with the need to optimise abstraction, this highlighted the benefits of better understanding aquifer structure and led to an upgrade of the Perth Regional Aquifer Modelling System (PRAMS) and investment in the PRCAC study.

More recently, groundwater injection provides the opportunity to apply new science to further enhance groundwater management for sustainable, productive use of the deep aquifers as well as to benefit the system as a whole. Identifying the best locations for groundwater injection and abstraction is complex and relies on having a more precise understanding of the deep aquifers, which the PRCAC study has provided.

With decreasing inflow to dams, groundwater has become the most accessible and cost-effective water source for our potable public water supply. Using science to inform and continually improve management of the deep groundwater aquifers will support the groundwater system as a whole to continue to provide multiple benefits for water supply, water quality and groundwater dependent environments, culture and amenity.

1.2 What are the Leederville and Yarragadee aquifers?

Perth's groundwater system is made up of the unconfined Superficial aquifer (part of which is also known as the 'Gnangara mound' north of the Swan River), and the deeper Leederville and Yarragadee aquifers. The Superficial aquifer is mostly accessed to provide water for industry, horticulture, green space and garden bores, while the deep aquifers are primarily used by Water Corporation for scheme supply.

The Leederville and Yarragadee aquifers are referred to as 'confined' where shale layers (aquitards) above them prevent water from easily moving vertically, and water pressure builds up in the aquifers. Aquifers are connected to each other in areas where aquitards are not present, so water moves more freely between the Superficial, Leederville and Yarragadee aquifers in these areas. This connectivity occurs in large areas across the northern part of the Perth region, and increases the complexity and challenge of groundwater management.

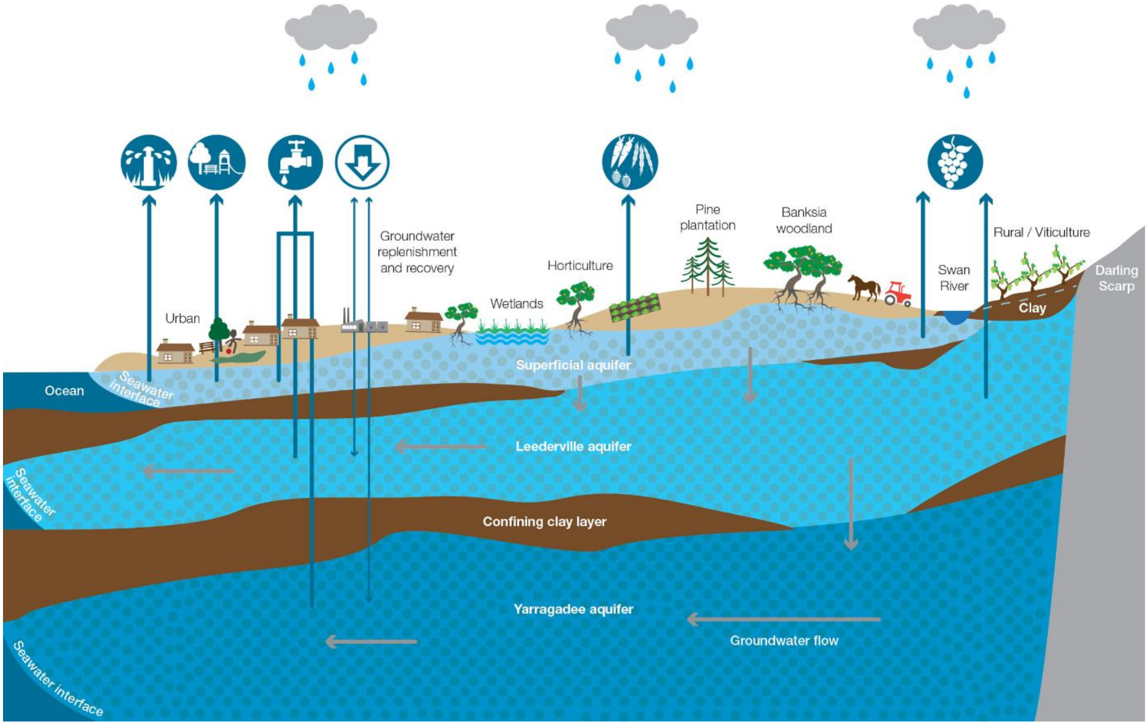


Figure 2 Cross-section showing the general structure of the Gnangara groundwater system, layering of aquifers and confining units, connection between aquifers, areas of recharge, directions of groundwater movement, and where aquifers are bounded by the saltwater interface and Darling Fault

Leederville aquifer

The Leederville aquifer is a major semi-confined aquifer, with a maximum thickness of about 550 m. It is present across the entire Perth region except where incised by the Kings Park Formation across the central Perth area (Figure 3). While often referred to as a confined aquifer, the Leederville aquifer is connected to a large area of the Superficial aquifer in the northern part of the Gnangara groundwater system. It is disconnected from the Superficial aquifer by the Kardinya Shale aquitard, a confining layer across about half of the Gnangara system (see Figures 2 and 3). Where it is connected, pumping from the Leederville aquifer can directly affect the Superficial aquifer and therefore can affect groundwater-dependent ecosystems, other groundwater users and the seawater interface.

Water quality in the Leederville aquifer is generally fresh (<500 mg/L TDS) across the Gnangara plan area (Figure 4), where there is a high level of connection with the Superficial aquifer. Salinity increases to between 500 and 1500 mg/L towards the edges of the Gnangara plan area. For groundwater to be used as a drinking water supply it generally needs to be taken from the area where is it less than about 500–600 mg/L.

Fresh groundwater moves in a general south-west direction from the recharge area in the north east of the system, and eventually out under the ocean where water becomes more saline at the seawater interface (see section 3.1).

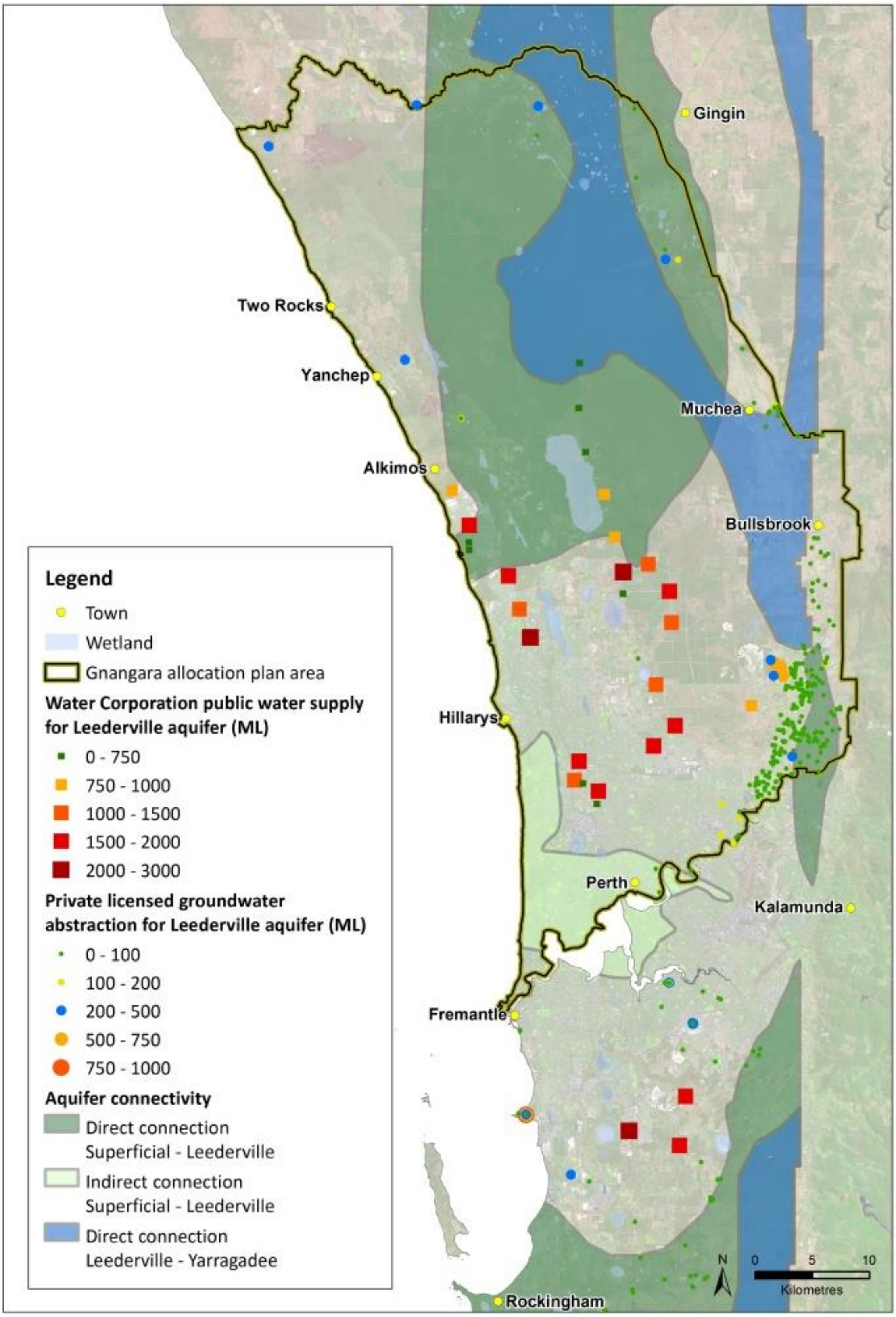


Figure 3 Groundwater connectivity of the Leederville aquifer, with abstraction locations and volumes for 2016 (note 'indirect connection' between aquifers is the Kings Park Formation)

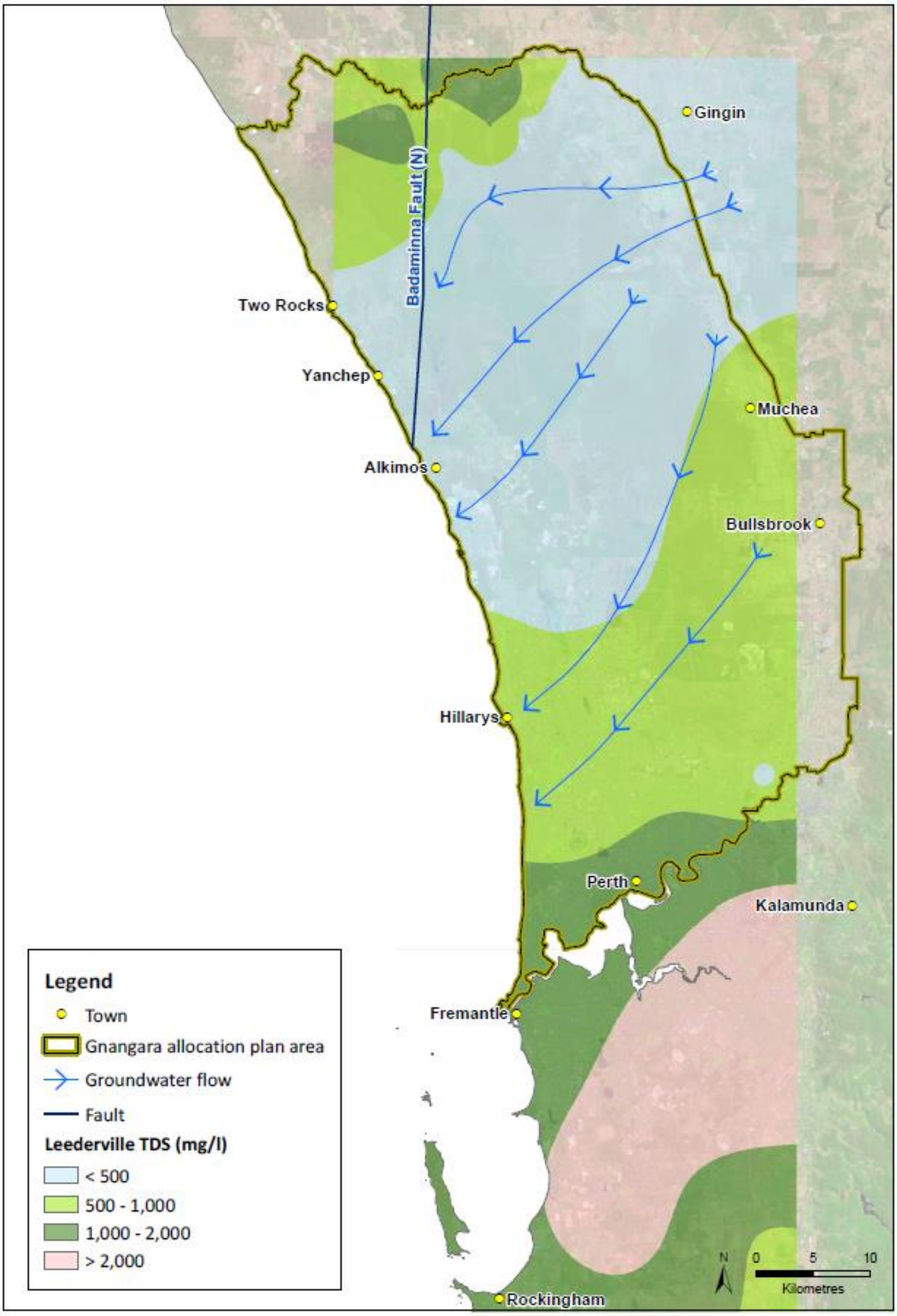


Figure 4 Groundwater quality in the Leederville aquifer

Yarragadee aquifer

The Yarragadee aquifer is a major, mostly-confined aquifer ranging up to more than 2000 m thick and is found across the entire Perth region. The Yarragadee aquifer is largely disconnected from the shallower Leederville aquifer by the South Perth Shale aquitard (confining layer) (see Figures 2 and 5). However, in the north of the Gnangara groundwater system there are areas where the confining shale layer is absent and the Yarragadee and Leederville aquifers are connected. There is also a small area at Yeal Nature Reserve where the Yarragadee aquifer is directly connected to the Superficial aquifer (Figure 5). Groundwater in the Yarragadee aquifer generally moves in a south to south-west direction, from the area where it receives recharge from the Superficial and Leederville aquifers in the north, and then out towards the ocean.

Water quality data for the Yarragadee aquifer reflects the level of connectivity with the Superficial and Leederville aquifers, with higher salinity water found where the aquifer is least connected and receives the least fresh water recharge (Figure 6). As with the Leederville aquifer, groundwater from the Yarragadee aquifer needs to be mostly fresh (<500–600 mg/L) to become part of our drinking water supply.

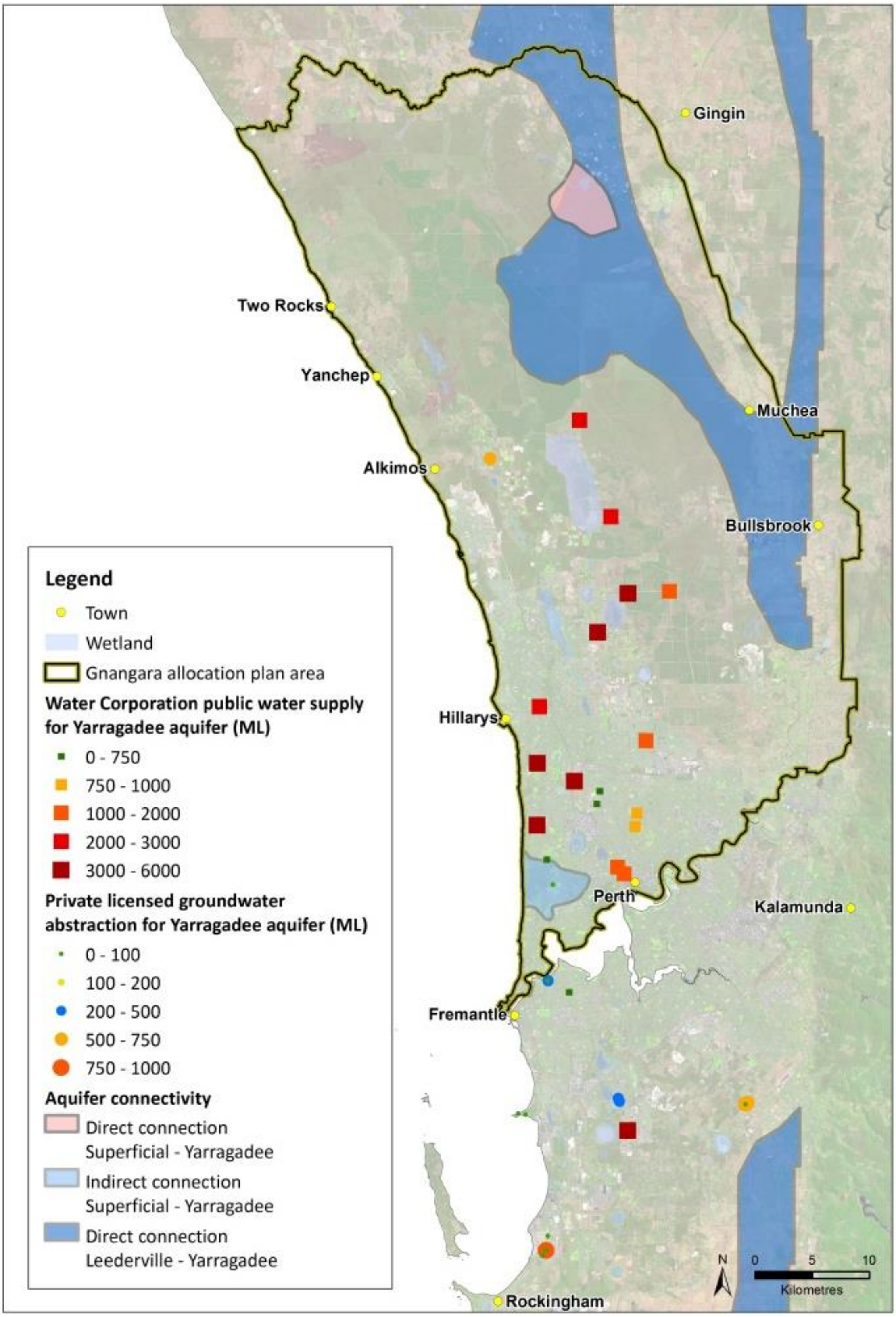


Figure 5 Groundwater connectivity of the Yarragadee aquifer, with abstraction locations and volumes for 2016 (note 'indirect connection' between aquifers is the Kings Park Formation)

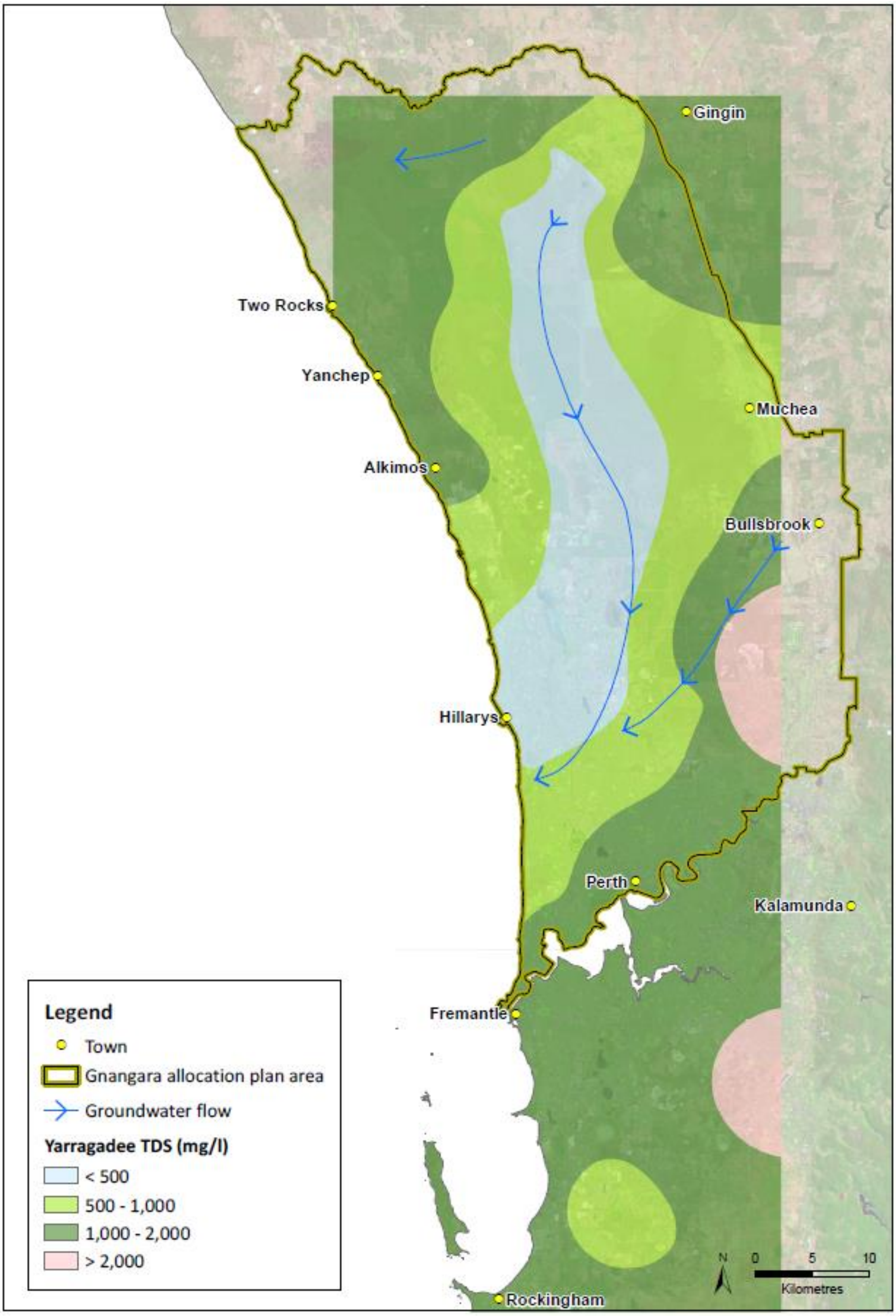


Figure 6 Groundwater quality in the Yarragadee aquifer

Managing abstraction and pressure levels

There is a large volume of water stored in the deep aquifers, but their connection to and impact on the groundwater level of the Superficial aquifer is a significant factor in managing abstraction and pressure.

Pressures in the Leederville and Yarragadee aquifers have declined since 1995 when groundwater abstraction increased from these aquifers. The rate of decline has eased in recent years with the aquifers approaching a new balance and some areas in the Leederville aquifer recovering where abstraction has been reduced. Positive water pressures in the Leederville and Yarragadee aquifer help support groundwater levels in the Superficial aquifer where connected, prevent the onshore movement of seawater into the deep aquifers, and prevent the deep aquifers from compacting, which may lead to subsidence of the land surface.

We have a good understanding of how the Kardinya Shale and South Perth Shale aquitards prevent vertical movement of water between the Superficial, Leederville and Yarragadee aquifers from many years of monitoring the response of aquifers to groundwater abstraction. In moving to more complex management of the deep aquifers by using optimal abstraction patterns and groundwater replenishment and recovery, we need a more detailed understanding of the groundwater flow system, particularly of the faults and discontinuities that may restrict groundwater movement in the Leederville and Yarragadee aquifers. More complex management also requires a better understanding of how changes to pressures in the deep aquifers from abstraction and injection effect the Superficial aquifer, the deep aquifer seawater interface, and potential subsidence.

Greater detail on the structure and hydrogeology of the deep aquifers can be found in 'Perth region Leederville and Yarragadee aquifers re-interpretation report' (Department of Water 2017c).

1.3 Scope of the study

The Perth Region Confined Aquifer Capacity (PRCAC) study completed several packages of work over four years to work out how to maximise use of the deep aquifers while balancing impacts to the groundwater system as a whole. The study:

- applied a range of investigation methods to improve our hydrogeological understanding of the deep aquifers and their connection with the Superficial aquifer
- developed methods to assess the impact of different groundwater management approaches on the groundwater resource and it's connected values, based on changes in water levels, and used these methods with the Perth Regional Aquifer Modelling System (PRAMS) to inform the next Gnangara groundwater allocation plan, IWSS abstraction, and Groundwater Replenishment locations.

Improved hydrogeological understanding

The PRCAC study provided an improved conceptualisation of how:

- water moves between aquifers
- the deep aquifers are recharged
- pressure changes in the deep aquifers impact the environment, other users and the deep aquifers themselves.

We used established, robust hydrogeological data collection and interpretation methods to characterise key aspects of the Leederville and Yarragadee aquifers. Through innovative research partnerships with Curtin University and the University of Western Australia we applied the latest data acquisition and modelling technology to refine this interpretation and improve how we use the PRAMS groundwater model.

PRAMS is the Department of Water and Environmental Regulation's most comprehensive and advanced numerical groundwater model. It has been built based on data and aquifer information from the department's extensive network of regional monitoring bores and long-term water level data in the Perth region. The most recent version of PRAMS (version 3.5, released in 2015) is a well calibrated model which is suitable for informing regional to sub-regional scale groundwater management decisions. PRAMS is not suitable for modelling small scale areas such as wetlands, surface water flow such as flow to drains, or short-term effects such as construction dewatering.

This summary document provides a high-level overview of the investigation work completed with a focus on how groundwater moves in key areas, including connectivity across faults (section 2).

For more detail on how the PRCAC study improved our broader understanding of the Leederville and Yarragadee aquifers, the department can provide the following unpublished reports on request:

- 'Perth region confined aquifer capacity study: aquifer assessment review and scoping report', report no. HR351, Department of Water 2014a.
- 'Groundwater chemistry and isotope survey of the Leederville and Yarragadee aquifers in Perth', report no. HR370, Department of Water 2017b.
- 'Perth region Leederville and Yarragadee aquifers re-interpretation report', report no. HR363, Department of Water 2017c.

Assessing the effects of deep aquifer abstraction

We used PRAMS to help answer the question of how best to maximise use of the deep aquifers without unacceptable impacts to:

- environmental and social value of groundwater-dependent ecosystems, such as wetlands and some threatened ecological communities
- the quality of water in the deep aquifers from seawater intrusion
- other users of the deep aquifers, or parts of the Superficial aquifer affected by deep aquifer abstraction
- settlement of the land surface due to subsidence.

We defined new impact assessment criteria (water level targets or changes) and tested them using both a conventional 'trial and error' modelling approach, and also with innovative modelling research with the University of Western Australia (section 3.2).

This new understanding and modelling have supported our work with the Water Corporation to test deep aquifer management strategies, using medium-term planning described in *Water Forever Whatever the Weather* (Water Corporation 2009) as a starting point. This work has guided injection and abstraction locations for the second stage of the Beenyup Groundwater Replenishment Scheme and provides a foundation for rebalancing the Gnangara groundwater system.

This summary document provides an overview of how we developed methods for using water level changes and targets with PRAMS to inform how we manage the deep aquifers.

For more detail, the department can provide the following unpublished reports on request:

- 'Assessment of the potential for saline intrusion into the Perth region Leederville and Yarragadee aquifers', report no. HR366, Department of Water 2016a.

- 'Method for assessing impacts at groundwater-dependent ecosystems on the Gnangara system from deep aquifer use', report no. HR368, Department of Water 2016b.
- 'Developing and assessing Leederville and Yarragadee aquifer modelling scenarios using PRAMS 3.5', report no. HR365, Department of Water, 2017a.

2 Improved hydrogeological understanding of the deep aquifers

Hydrogeological features such as faults and aquitards (confining layers) influence how pumping from parts of one aquifer can impact other parts of the aquifer, or connected aquifers. Before the Perth Region Confined Aquifer Capacity (PRCAC) study was completed, the Department of Water and Environmental Regulation and the Water Corporation had a good understanding of the extent and influence of the Kardinya Shale and South Perth Shale aquitards that separate the Superficial, Leederville and Yarragadee aquifers (section 1.2). The PRCAC study complemented this prior knowledge by providing a greater understanding of how groundwater moves around known or suspected faults, as well as improved information on recharge and connection between aquifers.

Detailed information on the investigations completed as part of the PRCAC study can be found in supporting technical documents which are internal, unpublished reports (section 1.3).

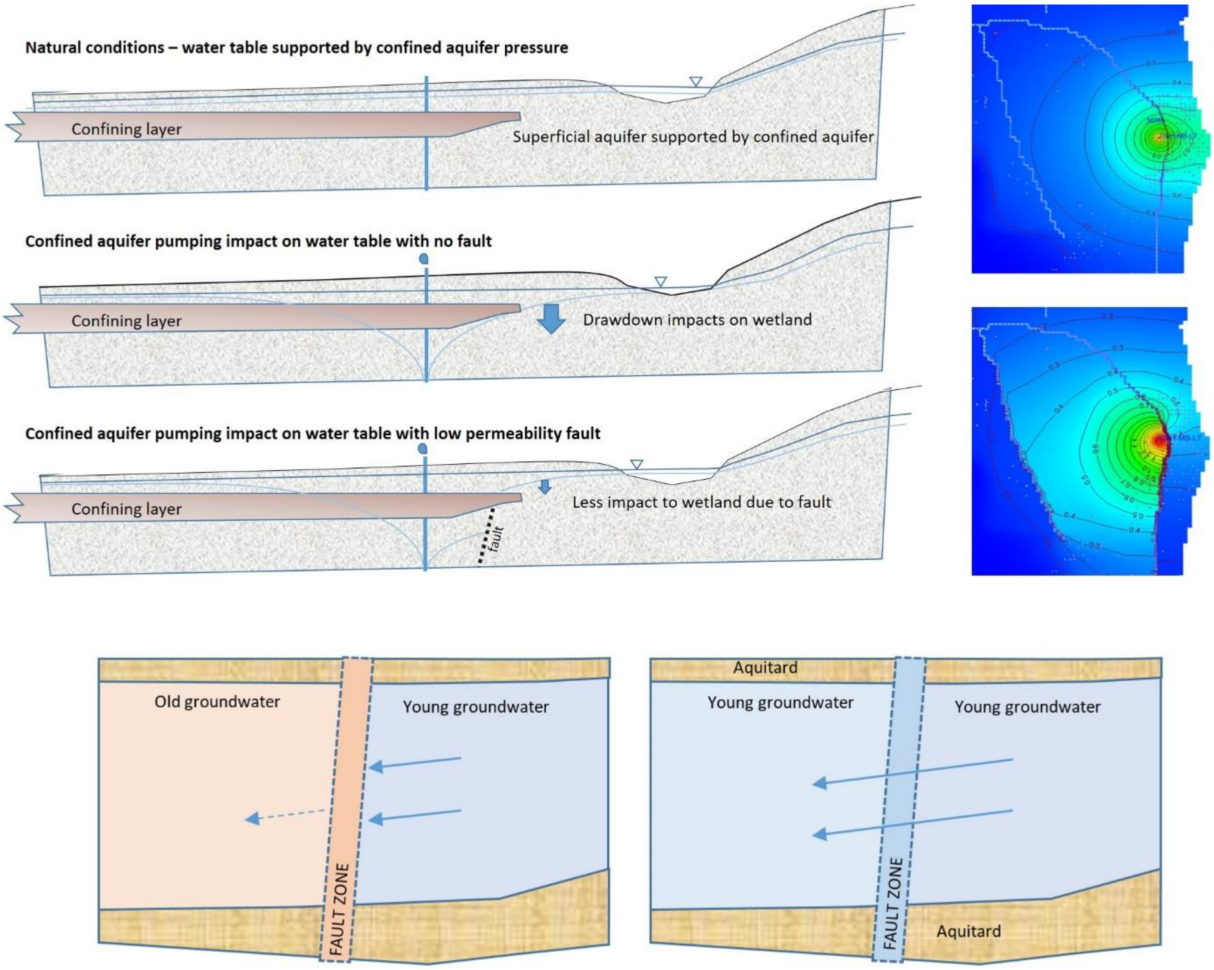
The sections below focus on how faults affect the movement of groundwater in the deep aquifers below Perth.

2.1 How faults affect groundwater movement

Faults or other deformations within an aquifer system can create a zone of low permeability, which means how much or how quickly water can move through an aquifer is limited. In faulted areas:

- aquifer and aquitard sediments may be mixed
- hydrogeological units may be offset such that highly permeable units (sands) are next to low permeability units (silts and clays)
- shearing along the fault may create a larger proportion of clay in the fault zone.

These hydraulic property changes can reduce the rate of groundwater flow through the aquifer, and can mean that pumping water from one side of the fault has a lesser impact on groundwater levels on the other side of the fault (Figure 7).



Top left – Cross-section view showing the impact of a fault on groundwater flow and a nearby wetland.
Top right – Modelled drawdown of a single 0.5 GL/year Leederville bore with no fault (top) and with a fault (bottom).
Bottom – How groundwater age can indicate connection across a fault.

Figure 7 How faults affect groundwater flow, impacts of abstraction and groundwater age

2.2 What work did we do to better understand faults?

The PRCAC study aimed to improve our hydrogeological understanding of the known Badaminna Fault and suspected Wanneroo and Joondalup faults in the Gnangara plan area (Figure 8). In the current version of PRAMS faults are used to restrict modelled groundwater flow to varying degrees (De Silva et al. 2013).

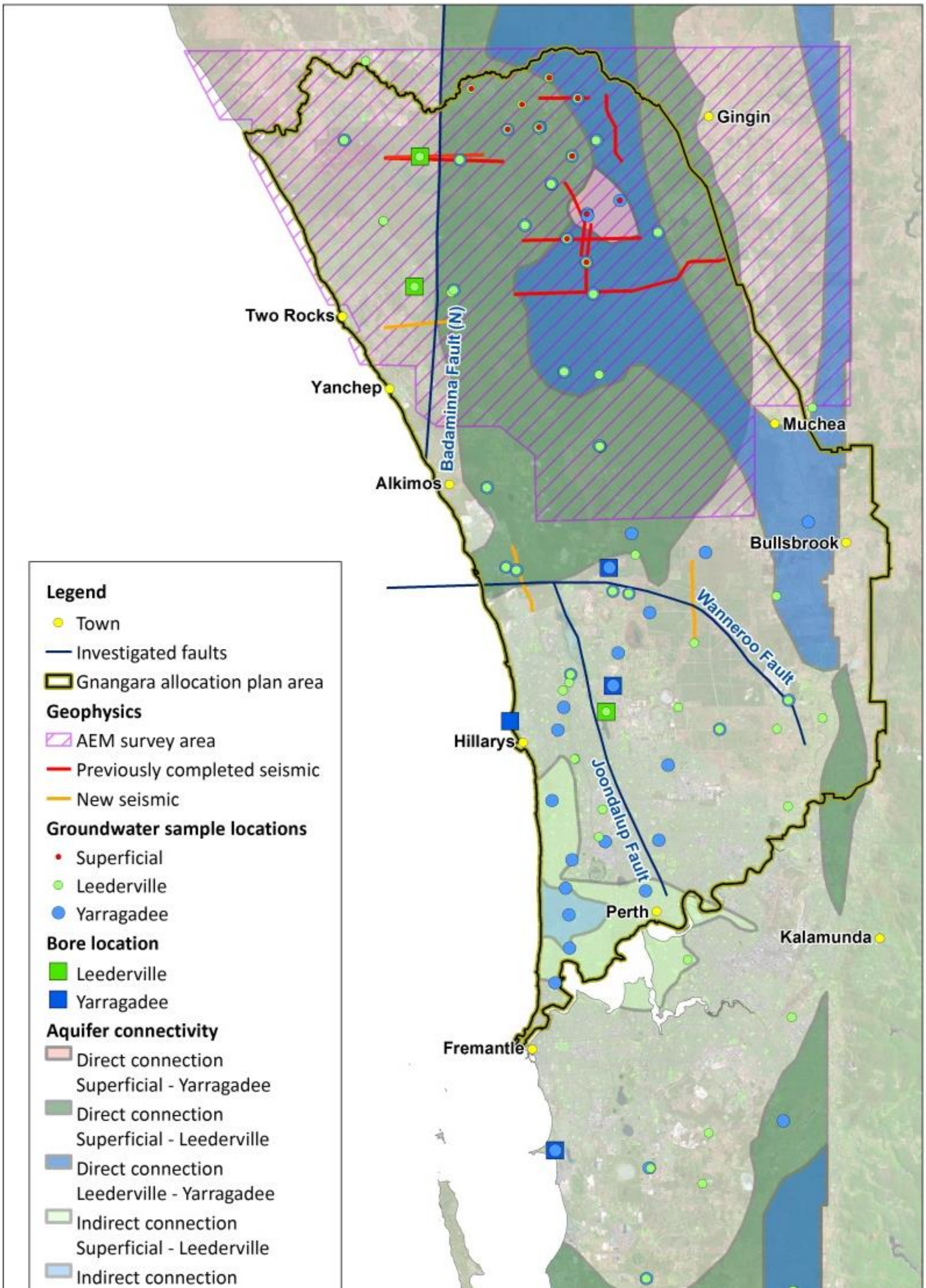


Figure 8 Locations of faults and investigation activities

We used a combination of the following established hydrogeological methods complemented by innovative research to better understand the deep aquifers:

- Constructed seven deep aquifer monitoring bores, to a maximum depth of around 900 metres.
- Collected information from the new monitoring bores to understand groundwater age, flow directions and connectivity across faults:
  - downhole geophysics
  - geological interpretation
  - water levels and water samples tested for standard chemistry as well as radiogenic and stable isotopes.
- Completed seismic surveys across previously inferred faults to determine their presence or structure.
- Flew an airborne electromagnetic (AEM) survey to identify faults and impermeable layers within the top few hundred metres to better understand the connection between aquifers.

The different information these investigation methods provided, and what they told us for the PRCAC study is described in Table 1.

Table 1 Groundwater investigation methods and what they told us

Investigation method	What information does this method provide?	What did it tell us about the deep aquifers?
Drilling groundwater monitoring bores	Geology and lithology of aquifers and aquitards from logging physical characteristics of sediments. Offsets and likely continuity of layers across faults, to help assess connectivity and pumping effects. Age of aquifers and aquitards from palynology (pollen spores) samples. Permeability and salinity from downhole geophysics. Response of aquifers to abstraction and injection from long-term water level monitoring, which can inform connectivity across faults and aquitards.	The depth and thickness of the Leederville and Yarragadee aquifers in key locations, how thick the confining shale units are, and the offset of aquifers between bores. Samples collected from bores installed either side of the Badaminna fault help tell us how connected aquifers are across the fault Two bores installed in the Yarragadee aquifer near the coast (Hillarys and Woodman Point) confirmed that the seawater interface is offshore, and the bores will be used for long-term seawater interface monitoring. Bores installed near the suspected Joondalup and Wanneroo faults are being monitored to assess aquifer properties around these features and we will continue to collect and analyse water level data in the long-term.
Groundwater sampling	Chemical and isotope signatures from adjacent bores tells us groundwater age, flow patterns and connectivity (such as across faults and aquitards).	The Leederville aquifer is mostly not connected across the Badaminna Fault, except near Yanchep. The Leederville aquifer west of the Badaminna Fault is connected to the Yarragadee aquifer east of the fault. Better understanding of the connectivity across the suspected Wanneroo and Joondalup faults in the deep aquifers.
Seismic surveys	2D geological structure, including faults and tops and bottoms of aquifers and aquitards, to several kilometres deep based on seismic reflections.	Supports interpretation on connectivity around the Badaminna Fault. The east to west trending flow restriction modelled in PRAMS as the Wanneroo Fault is actually a steep hill.
Airborne Electromagnetic (AEM) surveys	3D geological structure including faults and aquitards to a few hundred metres deep, based on electrical conductivity of sediments. AEM shows up either more clayey (aquitards) or higher salinity material.	Better conceptualisation of the structure of the Badaminna fault. Where the Yarragadee aquifer is directly connected to the Superficial aquifer in Yeal Nature Reserve. Where the Leederville aquifer is directly connected to the Superficial aquifer.

2.3 Badaminna Fault

The PRCAC study confirmed a potential source of additional groundwater in the Leederville aquifer to the west of the Badaminna Fault (Figure 8).

Investigations showed that the Leederville aquifer is almost entirely disconnected across the Badaminna Fault, except for some leakage near Yanchep. The Leederville aquifer on the western side of the fault was however found to be connected to the Yarragadee aquifer on the eastern side of the fault. This connectivity between the Yarragadee and Leederville aquifers is new information. The current interpretation in PRAMS is that there is no connection.

The Badaminna Fault means that groundwater abstraction from the Leederville aquifer to the west of the fault is unlikely to impact groundwater levels in the aquifer to the east of the fault, except possibly near Yanchep. However, abstraction from the Leederville aquifer west of the fault may affect the Yarragadee aquifer east of the fault, which may in turn affect the Leederville and Superficial aquifers where connected and the groundwater-dependent values these aquifers support.

The Kardinya Shale separates the Superficial and Leederville aquifers to the west of the Badaminna Fault, however is absent east of the Badaminna Fault. This means the Leederville and Superficial aquifers are not connected to the west of the Badaminna Fault. This is different to what is currently interpreted in PRAMS.

2.4 Suspected Wanneroo and Joondalup faults

The information collected during the PRCAC study shows some restriction in groundwater flow near where the Wanneroo and Joondalup faults are mapped in PRAMS; however, the study did not find that this restriction is caused by major faulting. The study did find that there is a large change in the thickness and depth of geological layers, particularly in the upper part of the Yarragadee aquifer. The change in thickness reduces the area in which water can flow through aquifers and causes deformations in aquifers that may restrict groundwater flow.

Groundwater chemistry and isotope data indicate that the Yarragadee aquifer is connected across the mapped location of the suspected Wanneroo and Joondalup faults, though there is some slowing of groundwater flow. Analysis of groundwater contour patterns also show some restriction in groundwater flow in the Yarragadee aquifer near the coast where the suspected Wanneroo Fault is interpreted.

The Leederville aquifer is also connected across the suspected Wanneroo and Joondalup faults as mapped in PRAMS, based on groundwater chemistry and isotope data. Though the aquifer is connected, the data shows slowing of groundwater flow near the northern and eastern parts of where the Wanneroo Fault is modelled in PRAMS. New seismic mapping across the suspected Wanneroo Fault and drilling near both faults did not show a major offset of geological layers, so these restrictions are more likely caused by smaller changes (or heterogeneities) within the Leederville aquifer itself.

3 Using water level targets to assess management options

To help answer the question of how to maximise use of the deep aquifers, the Department of Water and Environmental Regulation set strategic outcomes, developed quantitative objectives and targets, then assessed management options against these targets. This process was adapted from the National Water Commission's *Guidance for groundwater storage utilisation in water planning* (GHD et al. 2012, Figure 9). Management options focussed on the Integrated Water Supply Scheme, as the Water Corporation are the main users of the deep aquifers.

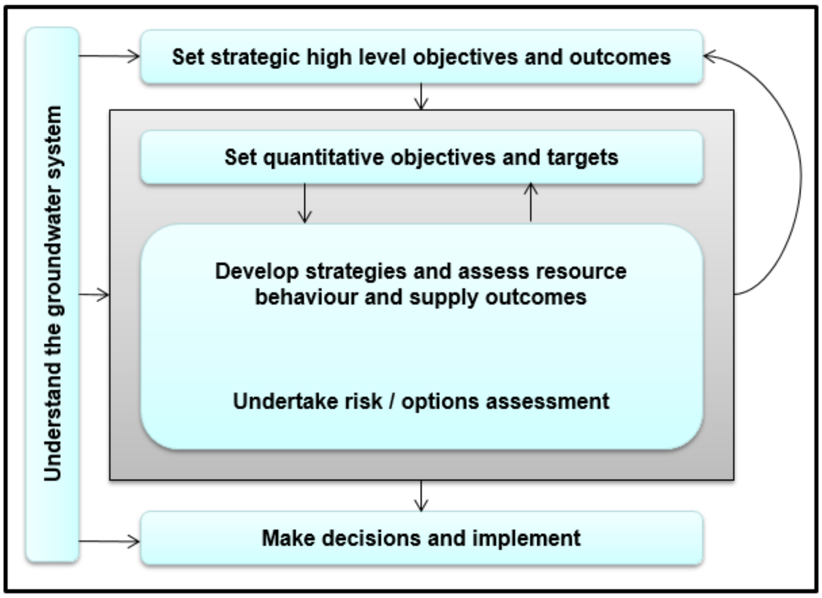


Figure 9 Process used to assess deep aquifer management options

Based on initial planning by the department and Water Corporation, the strategic outcome for the deep aquifers is to maximise abstraction from the Leederville and Yarragadee aquifers for public benefit, while maintaining sufficient pressures in the aquifers to:

- support the Superficial aquifer and its groundwater-dependent ecosystems
- prevent degradation of the deep aquifers from seawater intrusion
- ensure other groundwater users are not adversely impacted by deep aquifer abstraction
- prevent irreversible subsidence.

The following sections describe how we:

- set quantitative targets or water level changes to assess and interpret modelled aquifer pressure changes against the above objectives (section 3.1)

- developed management options and used the targets and changes to assess options in PRAMS (section 3.2).

3.1 Setting water level targets

Groundwater-dependent ecosystems

Abstraction from the deep Leederville and Yarragadee aquifers decreases pressure within these aquifers. This increases leakage from the Superficial aquifer where it connects to the deep aquifers (section 1.2), which lowers the watertable. Although the response is delayed, this impacts groundwater-dependent ecosystems such as wetlands and vegetation that rely on groundwater. Many groundwater-dependent ecosystems are impacted by deep aquifer abstraction because drawdown occurs over a large area.

To compare and assess the modelled impacts on groundwater-dependent ecosystems under different injection and abstraction scenarios we defined a set of groundwater level targets at key representative groundwater-dependent ecosystems (Figure 10). The targets matched existing environmental water provision criteria for groundwater-dependent ecosystems, set in *Ministerial Statement No. 819* under Part IV of the *Environmental Protection Act 1986* (Government of Western Australia 2009), including Lake Nowergup, Loch McNess, Lake Joondalup and Lake Jandabup. Sites with environmental water provision criteria in *Ministerial Statement No. 819* are known as criteria sites.

To improve spatial coverage, we also developed target levels for other high-value sites affected by deep aquifer pumping that were not well represented by criteria sites (Figure 10). These new targets for other representative sites were based on local studies that related groundwater levels to wetland levels (HR368, Department of Water 2016b).

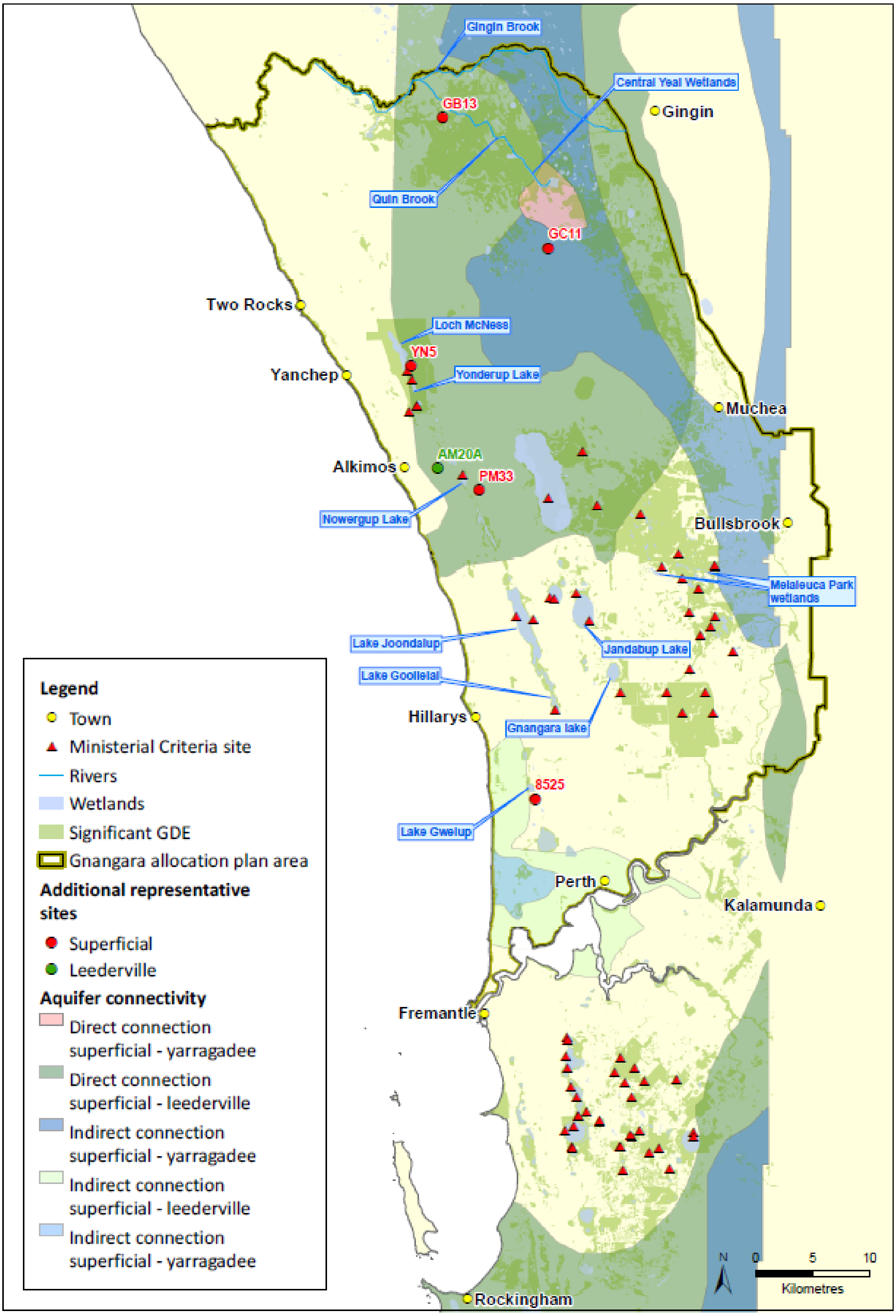


Figure 10 Groundwater-dependent ecosystems assessed as part of the study

Case study: Water level targets at Lake Nowergup and Loch McNess

Lake Nowergup and Loch McNess (Figure 11) are two highly valued wetlands affected by Leederville aquifer pumping. They are part of a linear chain of wetlands about 5 km from the coast extending from south of Lake Joondalup in the south to Loch McNess in the north. All the wetlands in this chain are surface expressions of the Superficial aquifer. Lake Nowergup is currently artificially supplemented by groundwater pumped from the Leederville aquifer.

Figure 11 Photos of Loch McNess

The department recently studied why water levels were declining at Loch McNess (Kretschmer and Kelsey 2016). We found that watertable decline to 2012 to the east of the lake was mostly because of abstraction from the Leederville aquifer, with the remaining watertable decline to the east attributed to decreasing rainfall. To the west of the lake watertable decline was attributed to a combination of abstraction from the Superficial aquifer and climate.

To assess the modelled impacts of deep aquifer management options at Loch McNess, we set a water level target at Superficial monitoring bore YN5 that, if achieved, would likely result in meeting the environmental water provision criteria for the lake set in *Ministerial Statement No. 819*.

Similarly, the department recently commissioned a study to work out how much the water level declines at Lake Nowergup are caused by climate, local Superficial aquifer use for horticulture, or public water supply pumping from the Leederville aquifer at the Quinns and Pinjar bore fields. The study ranked the contribution of climate and groundwater abstraction to watertable changes at the lake since 1973. This study showed that local Superficial aquifer use for horticulture had the greatest impact on lake levels, followed by reduced rainfall, then Leederville aquifer pumping from Quinns and Pinjar bore fields (Global Groundwater 2015).

To assess the relative impacts of different deep aquifer management options we set the target for Lake Nowergup at nearby Superficial aquifer bore PM33 and Leederville aquifer bore AM20A. The targets were based on meeting the environmental water provision criteria for Lake Nowergup. Using these targets, we can see from PRCAC modelling using PRAMS, that while reduced Leederville abstraction would help improve Superficial aquifer levels at Lake Nowergup, horticulture abstraction would also need to be reduced to restore Lake Nowergup to a permanent flow-through lake without artificial supplementation.

Case study: Developing a water level target for Yeal Nature Reserve

The regional Superficial aquifer is directly influenced by water levels in the Leederville and Yarragadee aquifers near Yeal Nature Reserve, which has several high conservation value wetlands, including Yeal Lake and Quin Brook (Figure 12).

The department's study of the local hydrogeology of the Yeal wetlands found that there is variable connectivity between the watertable that supports the wetlands and the regional Superficial aquifer. We found that Yeal Lake is perched, which means it is disconnected from the regional Superficial aquifer and not influenced by deep aquifer pumping (Degens, Hammond & Bathols 20121.

In contrast, further downstream along Quin Brook the wetlands are influenced by water levels in the regional Superficial aquifer (Degens, Hammond & Bathols 20121. Superficial aquifer levels in this area have declined from 1995 to 2008 and groundwater discharge to the brook increasingly became seasonally intermittent. After 2008, it is unlikely there has been any Superficial aquifer discharge along the reach of Quin Brook within the Yeal Nature Reserve.

To assess impacts of deep aquifer pumping on Superficial aquifer levels at Quin Brook and other groundwater-dependent ecosystems in the northern part of the Gnangara plan area we set a target level at bore GC11. This bore is located near the centre of the Yeal Nature Reserve and about 5 km south of Quin Brook, and serves as a regional indicator of levels at groundwater-dependent ecosystems. The level is based on a groundwater level from when there was still groundwater discharge into Quin Brook in the early 2000's (Degens, Hammond & Bathols 20121. Recovery to this level would restore intermittent discharge from the Superficial aquifer to Quin Brook and restore the ecological values, which require periodic inundation.

This target water level improves the spatial coverage so that we could assess the relative effect of different deep aquifer abstraction and injection options on groundwater-dependent ecosystems in the northern part of the Gnangara plan area.

Figure 12 Quin Swamp (left) and Quin Brook downstream of Yeal Lake when it last flowed (2008)

Case study: Banksia woodland ecological community

The Gnangara system supports extensive areas of phreatophytic vegetation that uses groundwater to meet at least part of its water needs. This groundwater-dependent vegetation includes large areas of Banksia woodlands of the Swan Coastal Plain ecological community, which is listed as endangered under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).

Banksia woodlands provide vital habitat for over 20 nationally threatened species – such as Carnaby's and forest red-tailed black cockatoos, chuditch (western quoll) and western ringtail possum – as well as many wildflowers unique to the South West region and other animals that depend on them, such as the honey possum. They also provide ecosystem services and contribute to the health and wellbeing of local residents such as cooling temperatures in surrounding regions, storing carbon, filtering water that recharges our drinking water supplies from aquifers, and providing scenic recreation areas.

Hydrological degradation from groundwater abstraction is a threat to the protection of the community and so abstraction needs to be managed to make sure we minimise adverse impacts to the community.

Groundwater-dependent Banksia woodlands occur where depth to the watertable is less than 10 m and are extensive across northern areas of the Gnangara system where Superficial aquifer levels are influenced by deep aquifer abstraction.

To assess the impacts of deep aquifer abstraction on groundwater-dependent Banksia woodlands, we assessed modelling results against environmental water provision criteria set in *Ministerial Statement No. 819* for phreatophytic vegetation sites. These criteria, which are water levels suitable for protecting the environmental values, are set at 16 representative phreatophytic vegetation sites.

Salinity in the deep aquifers

The PRCAC study investigated and assessed two salinity issues that could potentially result from deep aquifer abstraction:

- Seawater from the offshore parts of the Leederville and Yarragadee aquifers may move inland and impact the accessible, on-shore parts of the aquifer.
- Brackish water surrounding the fresh water areas of the aquifer may move in as water is abstracted and reduce the volume of fresh water available (see groundwater quality maps, section 1.2).

Seawater intrusion

The seawater interface – the natural interface at the coast between high salinity groundwater and freshwater – is typically much further offshore in the confined aquifers, compared to the Superficial aquifer. Abstracting groundwater can reduce groundwater flow to the ocean and cause the interface to move landward, making bores near the coast go saline if the interface comes onshore. While this is relatively well understood in the Superficial aquifer, the location and potential movement of the seawater interface in the deep aquifers and how to manage this was not well known before the PRCAC study.

For this study, the department used both analytical and numerical density modelling, compared with measured salinity from offshore petroleum wells, to understand how far fresh water extends under the ocean in the deep aquifers, and how it moves over time (Department of Water 2016a). This provided estimates based on simplified, horizontal and homogenous representations of the aquifers and aquitards.

This work suggests that during the last ice age fresh water moved out to the offshore parts of the Leederville and Yarragadee aquifers and confining units prevented seawater from entering the deep aquifers when the sea level rose at the end of the ice age. Fresh water was previously thought to only extend to an offshore fault (10–20 km offshore), but this new work shows that relatively fresh water likely extends offshore many tens of kilometres. This means that there is a large, offshore, fresh-to-marginal quality groundwater resource that can buffer the inland movement of seawater.

There is generally minimal risk that water quality will be degraded in the deep aquifers because of the seawater interface moving, even under an unrealistically high abstraction scenario modelled with PRAMS (Figure 13). An exception to this is near Mindarie, where we need to maintain pressures in the locally unconfined Leederville aquifer to minimise the potential for seawater intrusion moving down through the base of the Superficial aquifer to the Leederville aquifer. We set a target at monitoring bore AM20A, near Mindarie, to prevent seawater intrusion in this area (Department of Water 2016a, Department of Water 2017a).

The department installed two deep bores where the Yarragadee has been drawn down the most to test how saline the water is at depth and to provide seawater interface monitoring infrastructure. Sampling found fresh to marginal salinity groundwater in the Yarragadee aquifer in bores at Pinnaroo Point and Woodman Point at 870 m and 555 m below ground level respectively, which does not indicate presence of the seawater interface. This supports the conclusion from modelling that the seawater interface is many kilometres offshore in the Leederville and Yarragadee aquifers.

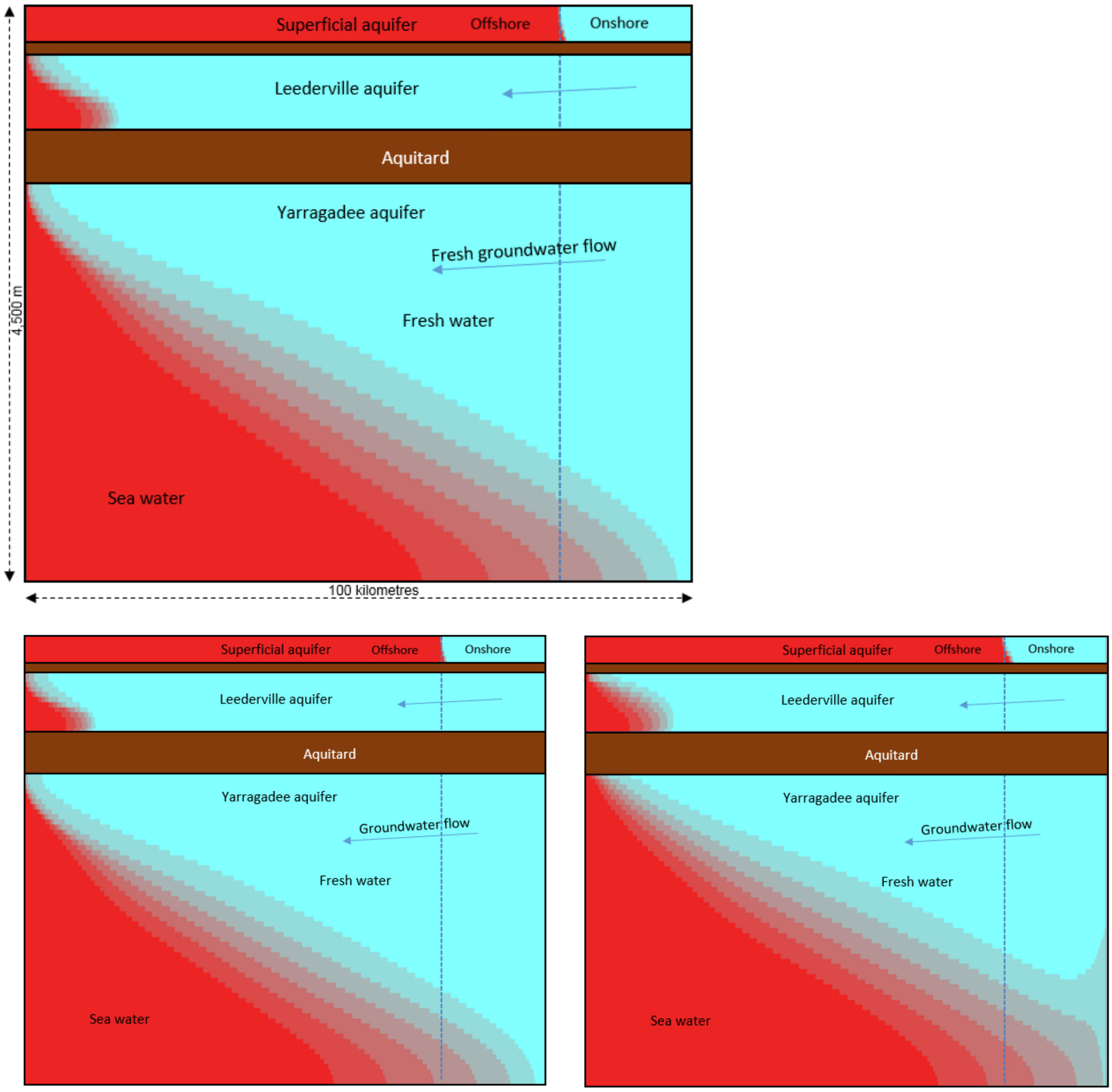


Figure 13 Modelled cross-section of the seawater interface in the deep aquifers at present (top) and under a high abstraction scenario after 30 years (bottom left) and 5000 years (bottom right) (note: not to scale)

Onshore fresh water depletion

Most deep abstraction bores are in areas where the aquifers are fresh (see quality maps in Section 1.2). Changes to groundwater movement because of abstraction may cause brackish or saline water to move into fresh water areas, gradually degrading water quality over time. We assessed the movement of brackish water into the areas of fresh water using 'particle tracking' modelling in PRAMS.

The modelling indicated that there is very little regional horizontal movement of brackish water due to the slow rate of flow in the deep aquifers. Any depletion of the onshore fresh water resource will be more from lowering water levels rather than lateral movement of brackish water.

Subsidence

Lowering of groundwater levels from abstraction decreases the pore pressure in aquifers which can lead to land subsidence. Around the world, places that have been affected by subsidence include the San Joaquin Valley (USA), Tokyo, Shanghai and Bangkok, with lowering of the ground surface by several metres in some cases (PSM 2017).

Subsidence can be:

- either localised or over a large area
- irreversible and of relatively high magnitude when pore pressure decreases below the compressive strength of the aquifers
- of relatively low magnitude and reversible if pressures recover in aquifers if drawdown and decreased pore pressures remain within the compressive strength of the aquifers.

Through the PRCAC study, the department completed two key pieces of work to assess and manage the potential impacts of subsidence from deep aquifer abstraction:

- A collaborative research partnership (ARC Linkage) with the Curtin University on monitoring land surface movement using a range of surveying methods.
- A study that assessed potential subsidence from deep aquifer depressurisation (PSM 2017).

Although there are few geotechnical measurements of sediments in the Perth Basin and modelling was limited, PSM (2017) found that:

- there is little risk of significant subsidence from decreasing pressures past the compressive strength of the aquifers because the groundwater system has already been over-compressed from the sea level being 150 metres lower than it is today
- any subsidence that occurs will be elastic and directly related to the amount of drawdown in the aquifers
- under a high abstraction scenario, the worst-case modelled subsidence at the land surface was up to 237.8 mm.

Any potential subsidence would occur over a large area rather than causing localised subsidence (PSM 2017). This widespread lowering of the land surface would accelerate the impacts of sea level rise on coastlines and the Swan River during floods, though the amount of subsidence would be relatively small compared with sea level rise. The level of subsidence that might be expected from deep aquifer abstraction would range between:

- 0.2 cm per metre of combined deep aquifer drawdown, based on historic observations comparing subsidence to drawdown (Featherstone et al. 2015).

- 1 cm per metre of combined deep aquifer drawdown, based on predicted settlement rates, which would accelerate expected sea level rise impacts by one year.

With the above information, we used modelled water level changes from PRAMS to assess the relative potential for subsidence under different abstraction and injection scenarios, considering both the magnitude and extent of drawdown (HR365, Department of Water 2017a). The impact rating was based on:

- the worst case predicted settlement rate
- *Swan River flood damage assessment study* (Department of Water 2014b)
- *State planning policy no. 2.6 – State coastal planning policy* (Department of Planning 2006)
- *Sea level change in Western Australia – application to coastal planning* (Department of Transport 2010)
- various coastal hazard-risk assessments completed by local governments.

This assessment is considered conservative because there are few measured geotechnical properties of deeper aquifers, and actual subsidence is likely to be less than calculated.

Further work to manage any risk of subsidence includes ongoing monitoring of land surface changes as established by the research partnership with Curtin University, monitoring of land surface movement directly above the Beenyup injection bores, and collection of direct geotechnical properties of the deeper aquifers.

Other users affected by deep aquifer abstraction

Perth's deep aquifers are large and robust, and until recently have provided a significant water supply buffer. However, the resulting storage loss and, in particular, the effect of abstraction from the Leederville aquifer on the overlying Superficial aquifer, can potentially impact self-supply users of the Leederville and Superficial aquifers. Drawdown can increase capital, maintenance and energy costs for pumping. As well as making access to groundwater more expensive, persistent drawdown can increase the risk of local water quality issues such as acidification or saline intrusion in the Superficial aquifer, which may affect the use of this groundwater.

In addition to the impacts of drying climate, established self-supply groundwater users may be partially impacted on from deep aquifer drawdown because of proximity or connectivity between aquifers:

- Superficial aquifer users in the Carabooda horticulture area, where the Superficial aquifer is directly impacted by both Superficial abstraction and Leederville aquifer drawdown.

- Horticulture, viticulture and agri-tourism businesses in the Swan Valley who use both the Leederville and Superficial aquifers. The Superficial aquifer is impacted by Leederville aquifer pumping in parts of the Swan Valley where confining units are absent.
- Councils in the western suburbs who use the Superficial aquifer mainly for maintenance of public open space. The Superficial aquifer is relatively thin in this area and can become saline from being close to the ocean and river. Modelling currently shows that the Superficial aquifer is impacted by Leederville and Yarragadee aquifer drawdown through the potentially leaky Kings Park Formation (Figure 3). However, it should be noted that the properties of the Kings Park Formation are very uncertain and require further investigation.

Other users outside of the Gnangara plan area might be affected by pressure changes in the Leederville and Yarragadee aquifers; however, these were not covered by this study.

We set groundwater level targets at several Superficial and Leederville aquifer locations to assess the relative impact of different abstraction scenarios on groundwater users (Figure 14). These levels align with sector-based recovery strategies being developed as part of the next Gnangara groundwater allocation plan.

The following targets were set to help assess impacts on groundwater users:

- Carabooda horticulture area – We set a target at Leederville bore AM20A where the aquifer is connected to the Superficial aquifer. This target supports the recovery of Lake Nowergup and will help protect against further drawdown caused by Leederville aquifer abstraction for scheme supply which could also be impacting on self-supply users in the area.
- Swan Valley – We set a target at Leederville bore AM30B where the aquifer is confined, between the main scheme supply drawdown area and the Swan Valley. An investigation is planned in this area to refine this target and assess whether alternative non-potable supplies in the area (e.g. Managed Aquifer Recharge) could offset historic impacts.
- The Superficial aquifer in the western suburbs area – This target considers reports of water quality issues, a modelled impact on Superficial aquifer water levels from deep aquifer pumping, and proactive plans by the Western Suburbs Regional Organisation of Councils (WESROC) to invest in feasibility studies for alternative water supplies to maintain public open space. An investigation is underway to understand if PRAMS modelling correctly represents deep aquifer pumping impacts on Superficial aquifer water levels in this area.

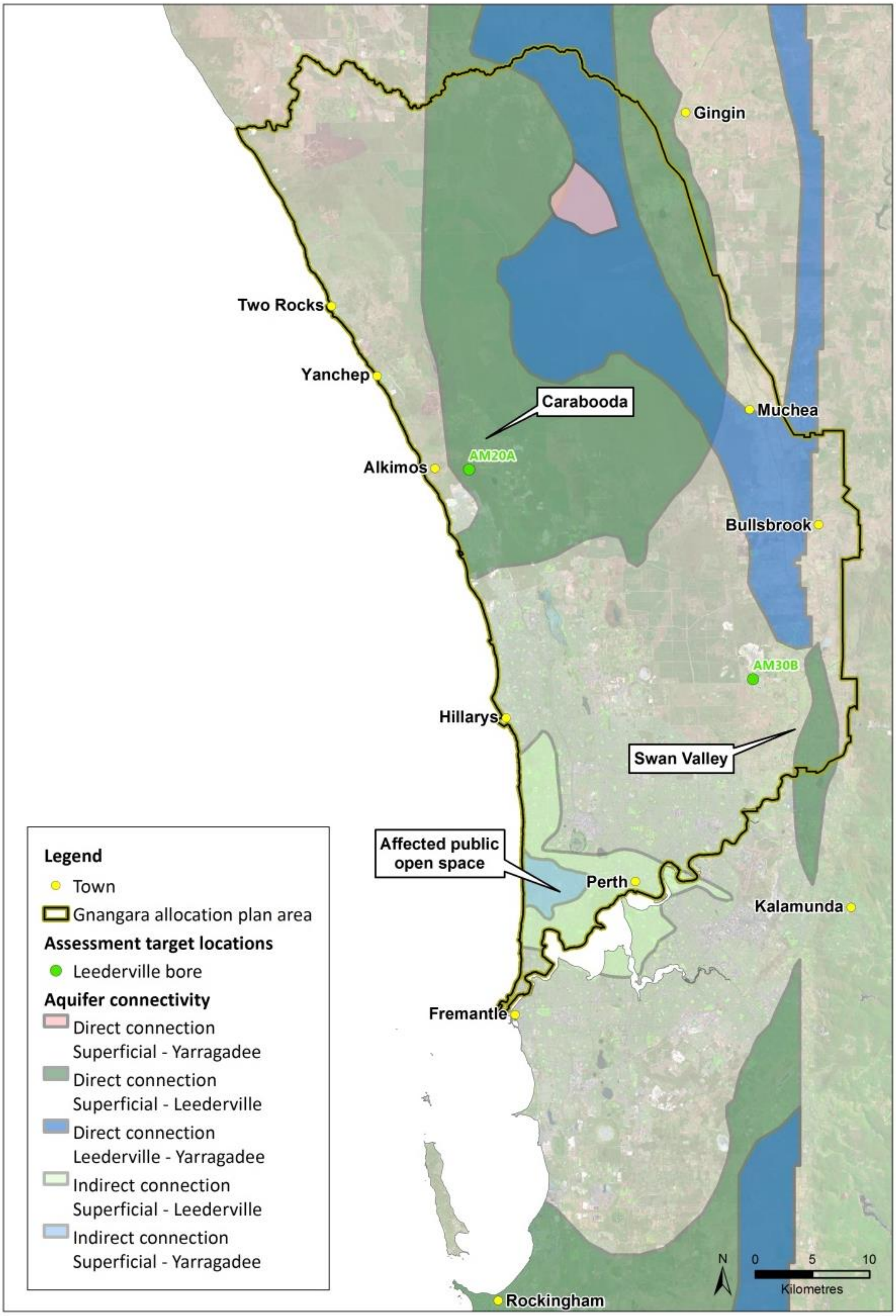


Figure 14 Targets to assess potential effects of deep aquifer abstraction on other users

3.2 Using targets to test management options

We used the quantitative targets and water level changes (section 3.1) to assess a range of management options. Two different groundwater modelling approaches were used:

- A standard 'trial and error' modelling approach, where different patterns of abstraction and injection were tested with PRAMS.
- An advanced optimisation modelling approach, by extending PRAMS capabilities through collaborative research with the University of Western Australia.

Trial and error modelling

The conventional trial and error approach involve modelling a range of management options of different volumes and patterns of abstraction and injection, assessing the outputs, and refining and remodelling the options. To develop abstraction and injection options we:

- reviewed known aquifer connectivity and historic abstraction impacts
- held internal workshops with department hydrogeologists, engineers and planners
- consulted Water Corporation on proposed strategies.

We modelled management options using PRAMS and assessed the outputs against the water level targets and changes described in this document. The process of developing and assessing the different management options is detailed in PRCAC modelling report HR365 (Department of Water, 2017a).

Some questions posed as part of this work were:

- How can we maximise Integrated Water Supply Scheme abstraction with the current Leederville and Yarragadee abstraction network with minimal (or acceptable) impacts?
- What effect do we see from different configurations of Stage 2 of the Water Corporation's Beenyup Groundwater Replenishment Scheme injection and abstraction?
- What is the impact of using new water sources, including the Leederville aquifer to the west of the Badaminna Fault, or moving a portion of the Carabooda horticulture allocation to the Yarragadee aquifer?

Optimisation modelling

To complement and improve the time and resource intensive 'trial and error' approach, the department completed a modelling research partnership with the University of Western Australia. This research developed and used innovative methods for parameter uncertainty analysis, calibration, optimal data collection, and resource optimisation. This provided the ability to select a set of targets and constraints (water levels, quality, and operational targets), set a question that we wished to answer, and run the model thousands of times by using 'particle swarm optimisation' with different abstraction and injection patterns to determine an optimal configuration (Figure 15).

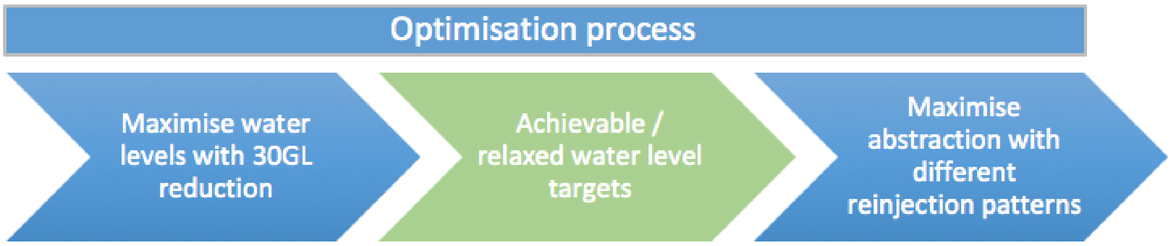


Figure 15 Optimisation approach

The following questions were posed as part of the optimisation scenarios:

- What is the highest water level that can be achieved at all water level targets, while taking 80 GL/year of water for public supply from all aquifers in Gnangara? (this volume would represent a 30 GL/year reduction to current abstraction). This step was required to determine the maximum achievable level across all water level targets as a starting point.
- If we set the water levels achievable with the 80 GL/year scenario as revised targets, what is the maximum volume that can be abstracted in Stage 2 of the Beenyup Groundwater Replenishment Scheme:
    - with all 28 GL/year reinjected on-site at Beenyup with new abstraction assets installed in South Wanneroo (the originally proposed option)
    - with 14 GL/year reinjected on-site at Beenyup (as per approved Stage 1) and 14 GL/year reinjected off-site, with new abstraction assets installed in locations to maximise recovery of recharge water (expected to be the more optimal option).

This research partnership is one of the first examples of using optimisation and high-performance computing (supercomputers) in a practical way to guide resource decisions. With this application, PRAMS is one of the most advanced and unique decision-supporting groundwater models in the world. This research was completed at the end of the PRCAC study, so its application was limited to the optimisation scenarios as described above. We aim to complete more research in the future in partnership with Water Corporation to further advance and use PRAMS as an optimisation tool to aid in decision making.

Summary of findings from modelling

Three broad management options for the deep aquifers can be considered as part of the wider Gnangara groundwater allocation planning. These scenarios are based on the findings of the modelling and assessment above, completed for the PRCAC study. This work was carried out relatively early in the allocation planning process, and findings will be applied as necessary to final allocation options. Adjusting deep aquifer abstraction volumes and patterns is only one component that can help rebalance the Gnangara groundwater system against the effects of drying climate between now and 2030, and modelling is only one tool that the department uses to inform management of the groundwater system.

1 Ongoing abstraction from the deep aquifers at current rates to 2030 (a 'do nothing' scenario) would contribute to:
   - ongoing decline of Superficial aquifer water levels and about 80 per cent of representative groundwater-dependent ecosystems below target levels, compared to about 50 per cent of target levels being met currently
   - risk of seawater intrusion where the Leederville aquifer is connected to the Superficial aquifer near the coast
   - ongoing risk of impact to self-supply groundwater users in western suburbs and Carabooda
   - sea level rise impacts 10–15 years earlier along the entire Perth metropolitan coastline and Swan River, as a worst-case estimate of land subsidence from deep aquifer depressurisation.

2 Reducing deep aquifer abstraction by about 15 GL/year to 2030 (10 GL/year from the Leederville aquifer and 5 GL/year from the Yarragadee aquifer) would result in:
   - improved water levels at representative groundwater-dependent ecosystems by up to 0.8 m compared with the no reduction scenario (while this would not increase the numbers of sites where levels meet the targets, the relative improvement in levels would have measurable benefits)
   - no significant risk of seawater intrusion in the Leederville aquifer where connected to the Superficial aquifer
   - no change in risk of impact to self-supply groundwater users in the western suburbs
   - sea level rise impacts 5–10 years sooner from Fremantle to Hillarys and along the Swan River from Fremantle to the Causeway (note that most of the sea level rise impact due to higher Swan River flood levels is upstream of the Causeway).

3 Reducing IWSS abstraction by 30 GL/year to 2030 in a pattern optimal for managing the system (groundwater aquifers, groundwater use and groundwater-

dependent environment), comprised of reductions of about 7 GL/year, 16 GL/year and 7 GL/year from the Superficial, Leederville and Yarragadee aquifers respectively and redistributing the abstraction pattern, leads to:

- no significant risk of seawater intrusion in the Leederville aquifer where connected to the Superficial aquifer
- improved water levels at representative groundwater-dependent ecosystems by up to 2.4 m compared to the no reduction scenario, with target levels met at about 50 per cent of sites (similar to current levels)
- further reduced potential for land subsidence
- reduced impacts to Superficial aquifer water levels in the western suburbs area
- recovery of pressures in the Leederville aquifer by up to about 4–5 m in the high value Swan Valley area, benefiting Superficial and Leederville aquifer self-supply users.

Strategic and targeted injection for the IWSS (and for local managed aquifer schemes) placed in optimal locations can:

- further bolster deep aquifer pressures
- reduce leakage from the Superficial aquifer
- help recover levels at high value groundwater-dependent ecosystems and high value areas such as the Swan Valley
- allow full recovery of reinjected water, and
- maximise use of the deep aquifers for scheme supply.

A more 'optimal' pattern can allow the total volume of reinjected water to be abstracted, compared with less than 80 per cent with the originally proposed injection and abstraction pattern, with the same resource and environmental outcomes.

4 Improving how we manage the deep aquifers

The Department of Water and Environmental Regulation will use the improved understanding of the deep aquifers gained through this study to help rebalance water entering and leaving the Gnangara groundwater system, manage the deep aquifers across the Perth region in the longer term, and guide future groundwater replenishment projects.

This study provides the knowledge and tools to help manage the deep aquifers:

- Improved understanding of groundwater flow around faults (and other partial groundwater flow barriers) to help interpret outputs from the current version of PRAMS (version 3.5), for the current round of groundwater allocation planning (section 2).
- Water level targets for groundwater-dependent ecosystems, seawater intrusion and impact to other users that can be used to assess the relative merits of future management options (section 3.1). The effect of deep aquifer pumping on subsidence in the deep aquifers can also be considered when assessing different management options.
- Advanced parameter uncertainty, predictive uncertainty and groundwater optimisation modelling tools that were tested as part of this study can be further developed and refined to improve how modelling is used in decision making (section 3.2).
- New hydrogeological information on aquifer connectivity, recharge, and movement of groundwater around faults will be used to improve future versions of PRAMS.
- Monitoring bores installed as part of the study will allow us to collect water level data in response to abstraction and injection, which will be used to improve our conceptual understanding of the groundwater system and improve PRAMS.

This study suggests that:

- reducing the volume of deep aquifer groundwater abstraction over time in targeted locations will contribute significantly to rebalancing the Gnangara groundwater system
- abstraction should first be reduced in parts of the deep aquifers near where they are connected to the Superficial aquifer
- an optimal pattern of abstraction and injection will limit the amount that deep aquifer abstraction needs to be reduced
- local managed aquifer recharge water supply schemes should be further investigated to offset some of the historic impacts of deep aquifer abstraction.

Figure 16 shows the current management direction that this study has informed, including areas to concentrate deep aquifer abstraction and areas where the project guided Water Corporation's Beenyup Groundwater Replenishment Stage 2 injection and abstraction bore locations. Future management directions informed by the study that should be investigated further are also shown on Figure 16, including where local managed aquifer recharge schemes might be considered to bolster local supply, and where the Leederville aquifer might provide a future water source north of Yanchep.

The PRCAC study shows that introducing science-based management changes for the deep aquifers would provide the following benefits for the Gnangara groundwater system and the people of Perth:

- Improved water levels at high-value groundwater-dependent ecosystems and in large areas of the Superficial aquifer, including the iconic Lake Nowergup and Loch McNess in Yanchep National Park.
- Recovery of water levels in the Carabooda and Swan Valley horticulture areas.
- Prevent risk of degradation of water quality in the Leederville aquifer from seawater intrusion near Mindarie.
- Reduce the risk of further land subsidence from deep aquifer pumping accelerating the impacts of sea level rise.
- Allow existing scheme assets to be used as much as possible, abstracting as much groundwater as possible, and supporting Superficial water levels for environmental benefit.

These benefits could come at the cost of needing an additional, alternative water source to replace up to 30 GL/year of public water supply. However, the increase in abstraction from the deep aquifers over the past 15 years has provided a useful source to meet shortfalls in public water supply under a drying climate, has delayed the impacts on the Superficial aquifer and provided time to implement demand management strategies and invest in alternative sources.

While the deep aquifers will continue to be an essential resource for Perth's water supply, the next stage in the groundwater story for Perth is to reduce and rebalance abstraction through the Gnangara groundwater allocation plan and licensing for the IWSS. This would help secure and prolong the abstraction of groundwater from Perth's largest, lowest cost water source – the Gnangara groundwater system – and support a healthy environment for our communities now and in the future.

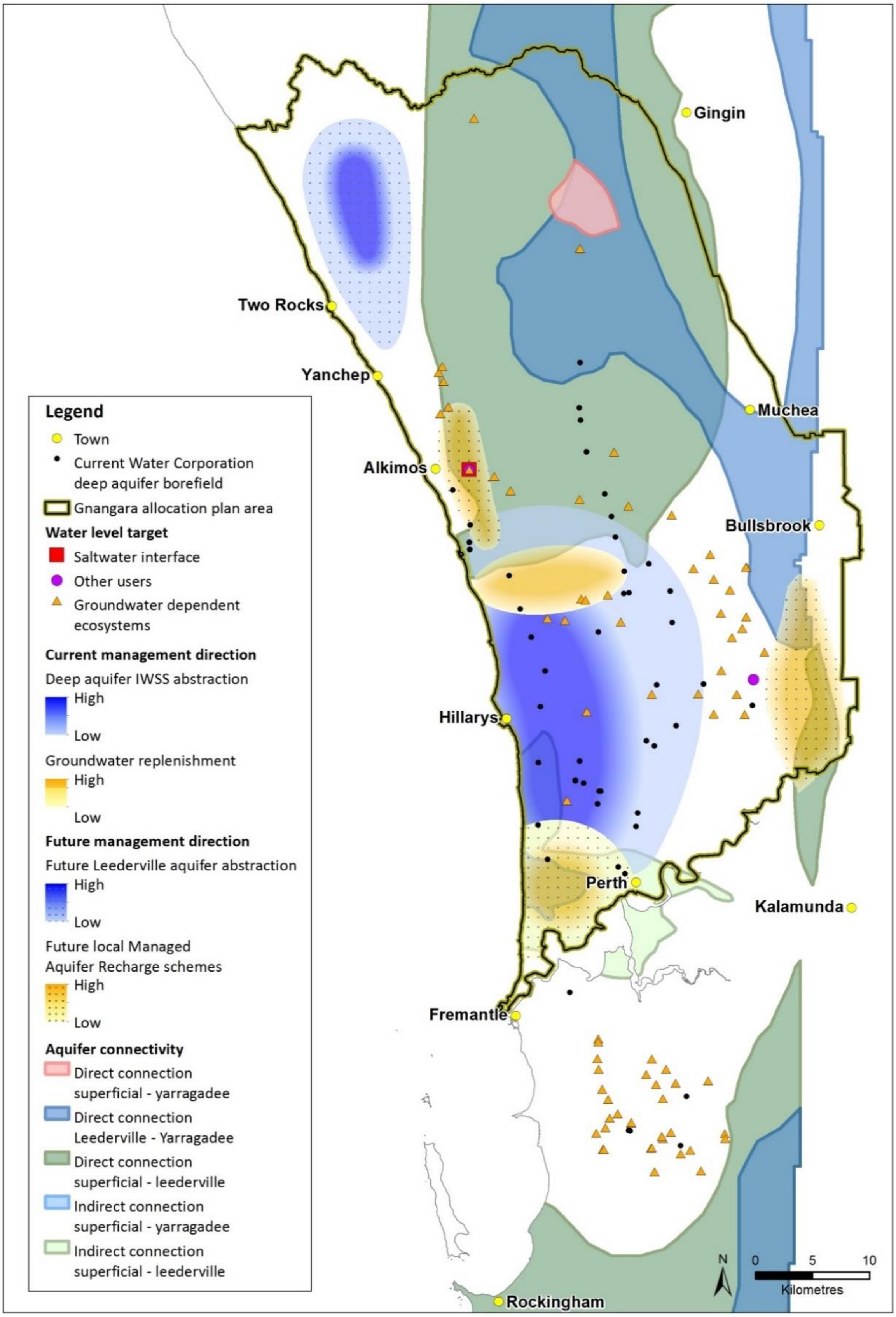


Figure 16 Conceptual representation of management direction for Perth's deep aquifers and locations of management targets

Shortened forms

DWER	Department of Water and Environmental Regulation
GL	Gigalitre/s
IWSS	Integrated water supply scheme
PRAMS	Perth regional aquifer modelling system
PRCAC	Perth region confined aquifer capacity study
PSM	Pells Sullivan Meynink
SWI	Seawater interface
TDS	Total dissolved solids

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