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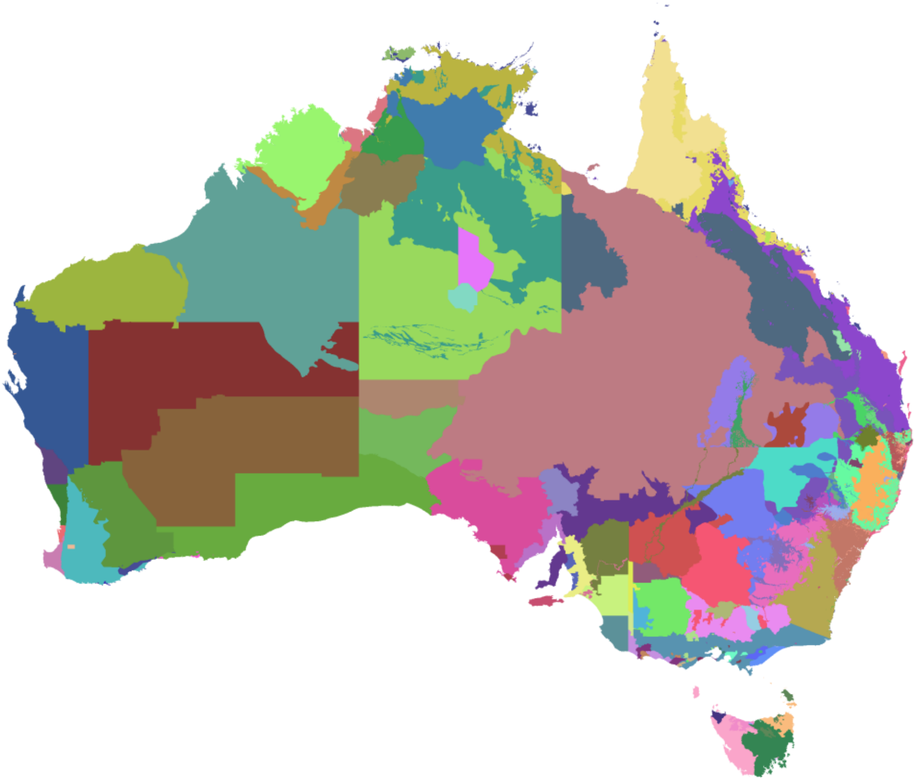

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Investigating the Impact of Climate Change on Groundwater Resources: Aquifer Characterisation

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ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

Two linked assessments have been conducted to characterise Australian aquifers in support of a broader project entitled *Investigating the Impact of Climate Change on Groundwater Resources*. First, a prioritisation scheme has been implemented to identify the most important and sensitive groundwater resources across Australia. Second, the recharge and discharge mechanisms of these priority systems have been assessed to characterise how they are sensitive to climate change.

The prioritisation scheme provides an objective basis to select priority aquifers that will become the focus of further activities in this project. Broad regional aquifers were defined by spatially combining groundwater management units (GMUs). Data was collated for each GMU which included groundwater extraction and sustainable yield volumes, and GDE occurrence. The aquifers were also characterised by their likely recharge to storage ratios.

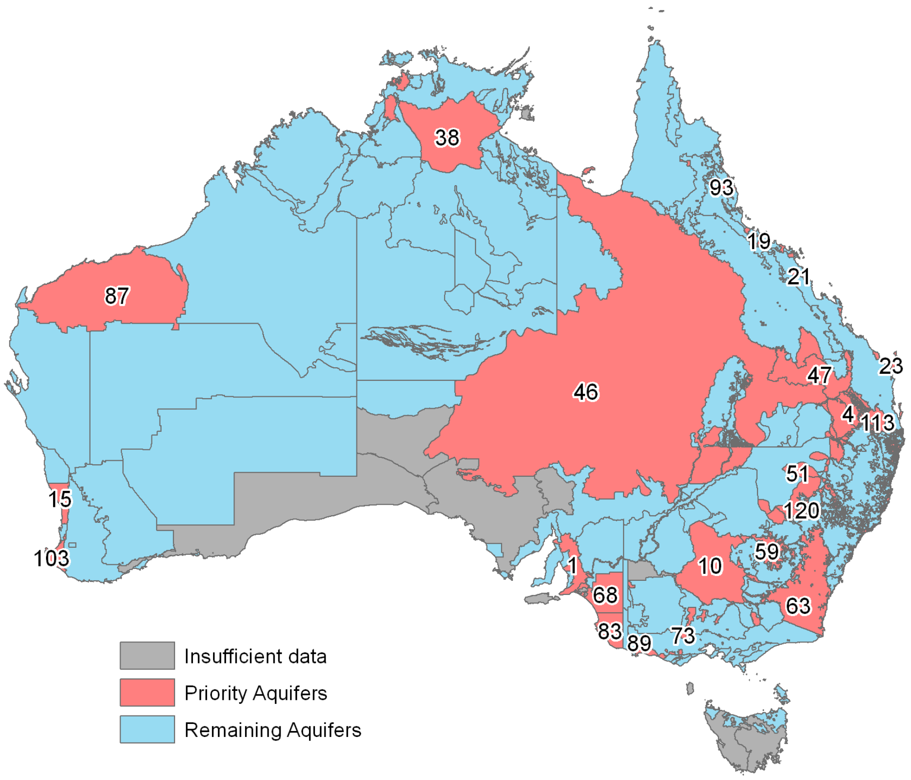
The scheme was developed by considering two broad questions: which aquifers are the most 'important' as water resources for consumptive use and for the environment; and which aquifers are the most 'sensitive' to climate change. Aquifers were scored according to their 'importance' and 'sensitivity', and these two factors were combined to generate a final list of aquifers that are both important and sensitive.

Twenty-two priority aquifers have been identified that cover a broad range of aquifer types and climate zones, as shown in Table 1-1. Their locations are shown in Figure 1-2.

1-1 Priority aquifers classified according to aquifer type and climate zone

Aquifer Type	1) Tropical[1]	2) Arid/Semi Arid	3) Mediterranean	4) Sub-tropical	5) Temperate
Alluvium				Gunnedah (NSW), Lachlan (NSW), Upper Condamine and Border Rivers Alluvium (Qld)	
Basalts				Atherton Tablelands(Qld), Toowoomba Basalts (Qld)	Newer Volcanics (Vic)
Carbonate	Daly Basin (NT)	Murray Group (SA,Vic)	Otway Basin (SA, Vic), Port Campbell Limestone (Vic)		
Coastal Alluvium	Coastal River Alluvium (Qld)			Coastal River Alluvium (NSW & Qld)	
Coastal Sands				Coastal Sands (NSW & Qld)	
Fractured Rock		Pilbara (WA)	Adelaide Geosyncline (SA)		Lachlan Fold Belt (NSW)
Riverine Plains		Calivil (NSW, Vic)			
Sedimentary Basin		GAB (NSW, NT, Qld, SA)	Central Perth Basin (WA), South Perth Basin (WA)	GAB (Qld, NSW)	
Upper Valley Alluvium				Upper Valley Alluvium (NSW)	

[1] Climate zone classification based on grouping Koppen-Geiger codes as follows: 1)Tropical = Af, Am, Aw; 2) Arid/Semi-Arid = BWh, BWk, BSh, BSk; 3) Mediterranean = Csa, Csb; 4) Humid subtropical = Cwa, Cfa; 5) Temperate = Cfb, Cfc, Dfb, Dfc



1-2 Location of priority aquifers

The priority aquifers have been assessed in terms of the sensitivity of their recharge and discharge processes. These processes control the availability of groundwater resources to both consumptive users and the environment, and the analysis highlights the potential pressure points and vulnerabilities of these aquifers to climate change. Each major recharge and discharge process has been examined using the following methodology:

1) The way in which the recharge/discharge process operates is described;
2) The factors controlling the process are examined to isolate the particular attributes of an aquifer that make the process either sensitive or less sensitive to climate change; and
3) The priority aquifers are analysed to highlight those that have attributes making them sensitive to climate change, and those that have attributes making them less sensitive to climate change.

The assessment findings for each recharge and discharge process has been compiled for every aquifer to illustrate the sensitivities of the priority systems. The results are summarised in Table 1-3.

Some of the aquifers display a broad range of ways in which they may be sensitive to climate change. For example, the Perth Basin, the Coastal Sands and Coastal Alluvial systems of NSW and Queensland, the Daly Basin, the Newer Volcanics and the Upper Valley Alluvial aquifers of NSW all have five or more recharge/discharge processes identified as being sensitive to climate change. Other aquifers have fewer categories of potential sensitivity. The analysis does not suggest such aquifers are less sensitive, merely that they are sensitive in fewer ways.

The key outcome of this work is that it provides a strategic focus for future activities and assessments investigating the impact of climate change on groundwater resources. Priority aquifers have been identified, and of these aquifers the ways in which they may be sensitive to climate change are highlighted.

1-3 Climate change sensitivity by recharge and discharge processes for priority aquifers

Aquifer	Recharge		Discharge				Storage dynamics	
	Diffuse recharge	Surface water recharge	Surface water discharge	Evapotranspiration	Coastal discharge (sea water intrusion)	Groundwater supply dependency (extraction)	Depth to watertable	R:S Ratio
Adelaide Geosyncline 3	🟦 *		🟦				🟦	🟦
Upper Condamine and Border Rivers Alluvium		🟦	🟦			🟦		
Calivil		🟦	🟦					
Central Perth Basin	🟦		🟦	🟦	🟦	🟦	🟦	
Coastal River Alluvium 1		🟦	🟦	🟦	🟦		🟦	🟦
Coastal River Alluvium 4		🟦	🟦	🟦	🟦		🟦	
Coastal Sands 4	🟦			🟦	🟦		🟦	🟦
Daly Basin	🟦	🟦	🟦	🟦			🟦	🟦
GAB 2		🟦	🟦			🟦	🟦	
GAB 4		🟦	🟦				🟦	
Gunnedah		🟦	🟦					
Lachlan		🟦	🟦				🟦	
Lachlan Fold Belt 5	🟦		🟦				🟦	🟦
Murray Group		▨				🟦	▨ #	
Newer Volcanics	🟦		🟦	🟦			🟦	🟦
Otway Basin	🟦			🟦			🟦	
Pilbara		🟦	🟦		🟦		🟦	
Port Campbell Limestone	🟦			🟦	🟦		🟦	
Atherton Tablelands	🟦		🟦				🟦	🟦
South Perth Basin	🟦		🟦	🟦	🟦		🟦	
Toowoomba Basalts	🟦					🟦		🟦
Upper Valley Alluvium 4		🟦	🟦	🟦		🟦	🟦	🟦

* Sensitive processes are shown with blue coloured cells

Highly insensitive due to deep water table

1. INTRODUCTION

This report describes an element of work that has been conducted to support a project for the National Water Commission (NWC) entitled *Investigating the Impact of Climate Change on Groundwater Resources*. The aims of the project are to provide a national snapshot of the potential impacts of climate change on groundwater resources for representative aquifer systems throughout Australia.

The impact of climate change on groundwater resources is likely to vary considerably across Australia. The impacts to a groundwater resource (or aquifer) will be determined by the changes in climate, which are likely to affect recharge, and the sensitivity of the aquifer to these disturbances. These aspects – climate, recharge and aquifer characterisation (in terms of sensitivity) – form the three major components of the overall project. Figure 1-1 illustrates how these components will interact and combine to provide a national snapshot of the potential impacts of climate change on groundwater resources. This report describes the aquifer characterisation component of the project.

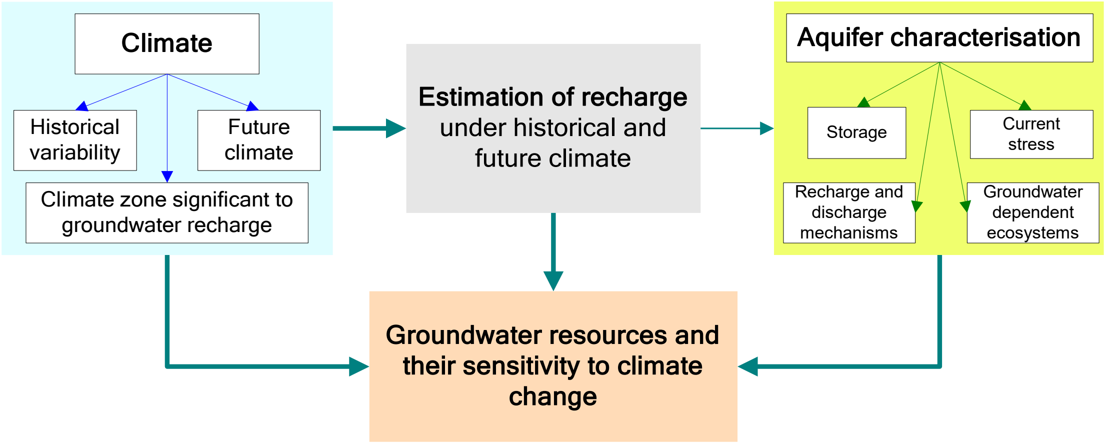


Figure 1-1 Project structure

There are two main objectives of the aquifer characterisation:

1) To identify which aquifers are the most important and sensitive water resources;
2) To identify how the priority aquifers may be sensitive to climate change by an assessment of their recharge and discharge mechanisms.

A prioritisation scheme will be developed to rank all of the aquifers throughout Australia with regards to their importance (as a resource for consumptive use and for the environment) and their sensitivity to disturbance. This will establish a list of priority aquifers that will become the focus of the project.

The recharge and discharge processes of the priority aquifers will be examined to identify their likely pressure points. For example, an aquifer may be particularly susceptible to changes in diffuse recharge or altered extraction pressures, but not to changes in surface water recharge. The assessment will provide a summary of the susceptibility to climate change for the priority systems.

The aquifer characterisation will ultimately be integrated with climate and recharge modelling components of the project to assess potential impacts in the priority systems.

2. AQUIFER PRIORITISATION

An aquifer prioritisation scheme has been developed to quantitatively identify the most important aquifers across Australia with regard to their sensitivity to climate change. The scheme has been developed by considering two broad questions: which aquifers are the most ‘important’ as water resources for consumptive use and for the environment; and which aquifers are the most ‘sensitive’ to climate change. Aquifers have been scored according to their ‘importance’ and ‘sensitivity’, and these two factors have been combined to generate a final list of aquifers that are both important and sensitive. The aquifers selected are to be used as the key sites for further analysis in this project – i.e. sites on which to focus for the discussion of recharge and discharge processes and their sensitivity to climate change, and sites where climate change and recharge modelling results should be analysed in detail.

The scheme has been developed to prioritise aquifers for the purposes of this project (i.e. an assessment of climate change priority) and does not represent a universal priority rating of Australia’s groundwater resources. Further work will be required for the methodology to be applied to aquifer prioritisation for other purposes.

2.1. Methods

2.1.1. Defining the major aquifers of Australia

The base spatial unit for the prioritisation of major aquifers of Australia is the Groundwater Management Unit (GMU). A GMU was defined by the 2000 National Land and Water Resources Audit as a ‘hydraulically connected groundwater system that is defined and recognised by Territory and State agencies’. There can be major differences in the nomenclature, definitions and sizes of these GMUs across various jurisdictions. Whilst GMUs can sometimes be based on cultural or arbitrary management boundaries as opposed to physical hydrogeological boundaries, they are often associated with geological units or aquifers and are the means by which groundwater use and management data are collated. Hence they have been used in this project to represent the major aquifers of Australia - either individually (where the GMU accurately represented an entire aquifer) or by assigning several GMUs to represent a larger regional aquifer (where the aquifer was represented by more than one aquifer).

An updated GMU coverage of Australia was sourced from the Bureau of Meteorology Interim Groundwater Geodatabase Project (draft). The following adjustments were made to provide a greater level of detail in areas coarsely represented by this coverage:

- The Murray Darling Basin (MDB) portion of Queensland was represented by incorporating spatial units derived through the MDBA sustainable diversion limit (SDL) project
- The Great Artesian Basin (GAB) portion of Queensland was represented by incorporating the GAB management zones as defined in the Hydrogeological Framework Report for the GAB WRP Areas (DERM, 2005)
- Northern Western Australia and the north east of the Northern Territory were represented by groundwater province boundaries.

The final dataset contains 385 GMUs across Australia, which are shown in Figure 2-1.

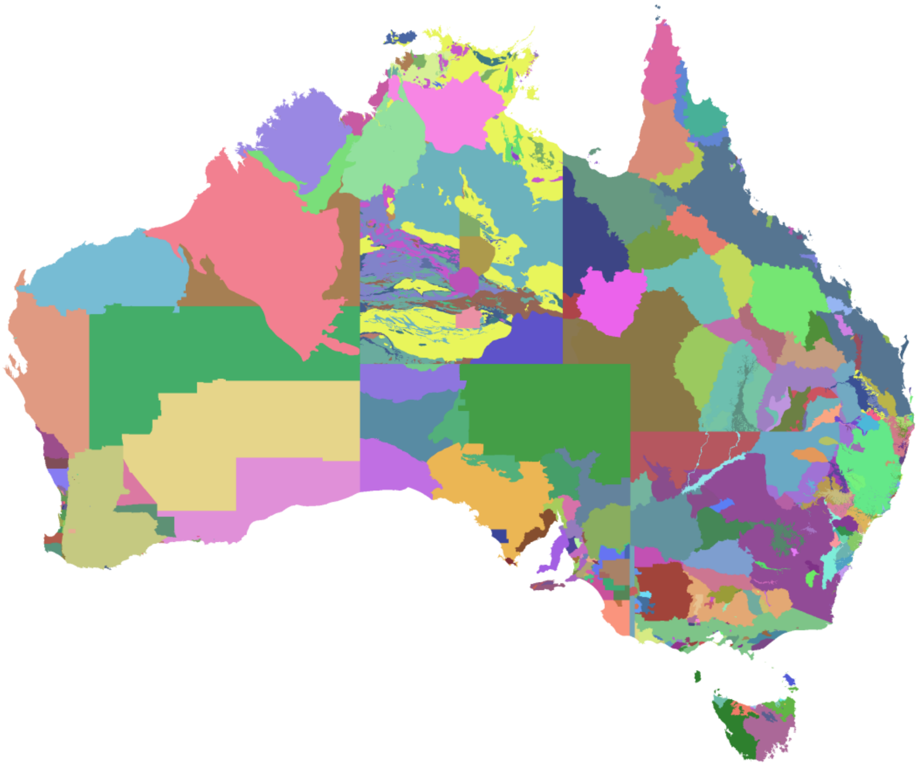


Figure 2-1 Groundwater Management Units (GMUs) used to define major Aquifer systems

GMUs were grouped to represent broad aquifer systems, which form the assessment unit for the prioritisation scheme. Where multiple layered aquifers occur at the one location – e.g. large sedimentary basins such as the Perth Basin – the GMUs were combined to represent one aquifer system as opposed to multiple aquifers. Where a number of smaller yet similar aquifers occur at separate locations within the same region (e.g. coastal sands along the East Coast), these aquifers were grouped into the one assessment unit. Aquifer systems were also split by climate zone[1] (Figure 2-2). For example the Lachlan Fold Belt in NSW covers several zones, so the aquifer system was split into each of those zones. The major aquifer systems are shown in Figure 2-3, and Appendix A details how GMUs were ascribed to aquifers.

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[1] Climate zone classification based on grouping Koppen-Geiger codes as follows: (1) Tropical = Af, Am, Aw; (2) Arid/Semi-Arid = BWh, BWk, BSh, BSk; (3) Mediterranean = Csa, Csb; (4) Humid subtropical = Cwa, Cfa; (5) Temperate = Cfb, Cfc, Dfb, Dfc. The Koppen-Geiger zones were delineated according to an historical climate: BAWAP data from 1970-2009

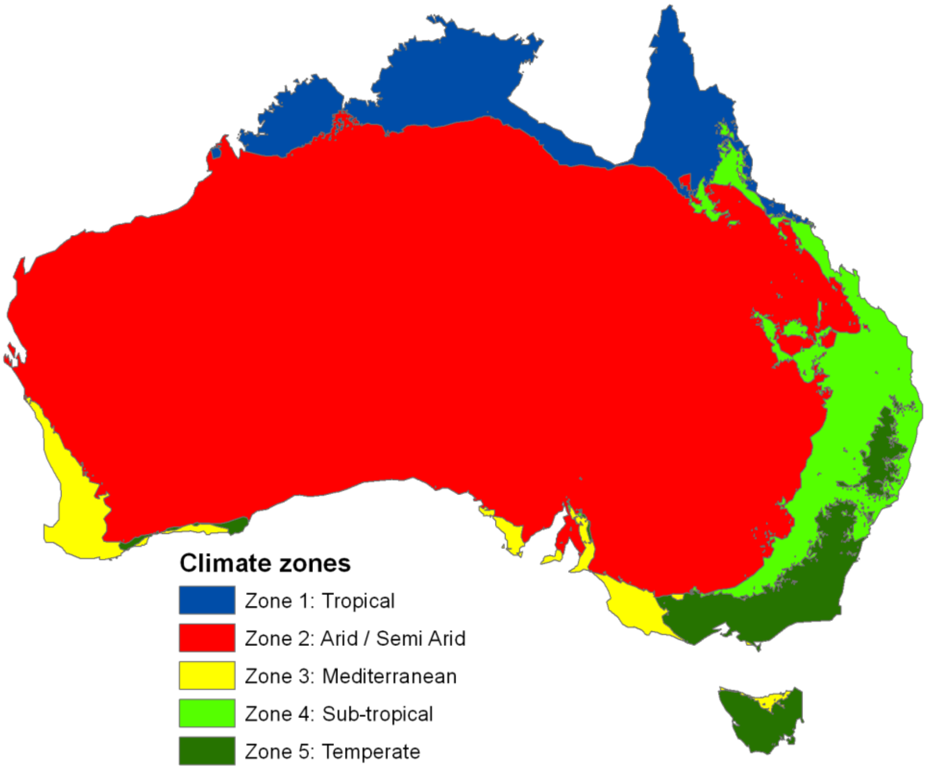

Figure 2-2 Climate zones used to classify aquifers

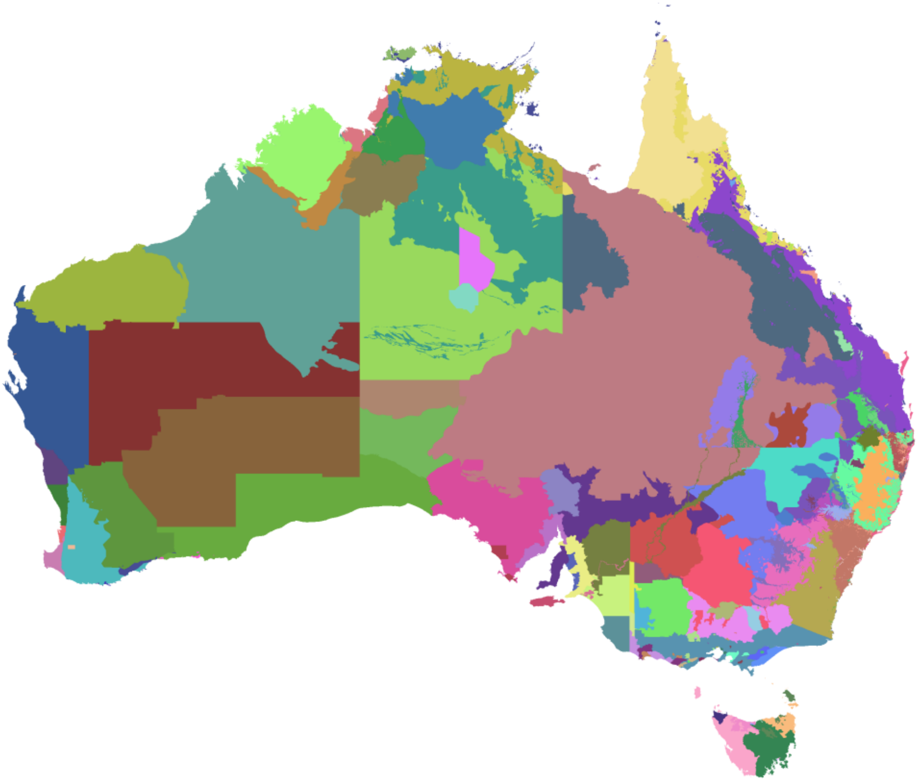

Figure 2-3 Major aquifer systems of Australia - the assessment units for prioritisation scheme

2.1.2. Prioritisation index for climate change sensitivity

The aquifer prioritisation scheme considers aquifer ‘importance’ and ‘sensitivity’ separately, and then combines these factors.

Aquifer importance index

Aquifer ‘importance’ is defined for the purposes of this project as the significance of the resource for consumptive use and for the environment. It is represented as a function of the current level of extraction, the volume of the resource and the presence of groundwater dependent ecosystems (GDEs). The index for aquifer importance is shown as follows:

$$I = \frac{E}{E_{max}} * \frac{SY}{SY_{max}} * f(baseflow\ GDEs) * f(other\ GDE\ types) \qquad [1]$$

Where, I is aquifer importance, E is the current level of extraction (ML/y), E_{max} is the highest level of extraction in the dataset (ML/y), SY is the sustainable yield (ML/y). and SY_{max} is the highest sustainable yield in the dataset. E/E_{max} is termed the ‘extraction metric’ and SY/SY_{max} is termed the ‘size of resource’ metric. The presence of GDEs is represented as separate functions for river baseflow GDEs and other GDE types (wetland or terrestrial vegetation GDEs), which are listed separately in the AWR2005 dataset. The rationale for treating river baseflow GDEs separately to other GDEs was to make an allowance for environmental baseflow as a particular factor of aquifer importance. The GDE functions are both defined numerically as follows:

$$f(GDEs) = \begin{cases} 0.85 & where\ GDEs\ identified \\ 0.15 & where\ no\ GDEs\ identified \end{cases} \qquad [2]$$

Where, 0.85 and 0.15 are dimensionless weighting factors arbitrarily selected to define to the presence or absence of GDEs. The sensitivity of these weighting factors is analysed in section 2.2.3.

Aquifer sensitivity index

The index for aquifer sensitivity is shown as follows:

$$Se = \frac{E}{SY} * f(R{:}S) \qquad [3]$$

Where. Se is aquifer sensitivity, E/SY is the ‘development metric’ for each aquifer – it being assumed that a high level of development (or stress) is indicative of a more sensitive aquifer. The $f(R/S)$ is a function describing the ratio between recharge (R) and storage (S). This is termed the ‘responsiveness metric’. A high level of recharge relative to storage is suggestive of greater sensitivity as there will be minimal buffering capacity (i.e. storage) if recharge rates are perturbed by climate change. For aquifers with a low R to S ratio there will be a much greater buffering capacity, and these aquifers will not be especially sensitive to climate change. Because there is significant uncertainty in deriving both R and S for all aquifers across Australia, a ranking function was introduced, which is summarised as follows:

$$f(R{:}S) = \begin{cases} 0.9 & high\ R{:}S \\ 0.3 & moderate\ R{:}S \\ 0.1 & low\ R{:}S \end{cases} \qquad [4]$$

Where $f(R/S)$ is given a weighting based on the likelihood of the aquifer having a high (0.9), moderate (0.3) or low (0.1) R to S ratio. Note that the values assigned for $f(R{:}S)$ are not equivalent to actual $R{:}S$ ratios, which are significantly lower (< 0.04). However, the relative difference between high and low scores is the same.

The relative difference in the weighting terms for the responsiveness metric was informed by an analysis of recharge to storage terms in the Murray Darling Basin, where there was less uncertainty regarding appropriate R and S values. The analysis estimated $R{:}S$ for the major aquifers in the Basin, and the results were summarised according to aquifer type (e.g.

fractured rock, alluvium etc) and climate zone as shown in Figure 2-4. Each aquifer type / climate zone combination was ranked as high, moderate or low based on the results obtained and the relative difference between the broad rankings was roughly equivalent to 'high' being three times greater than 'moderate' and nine time greater than 'low'. This relative difference has been preserved in the assumed weightings of the responsiveness metric.

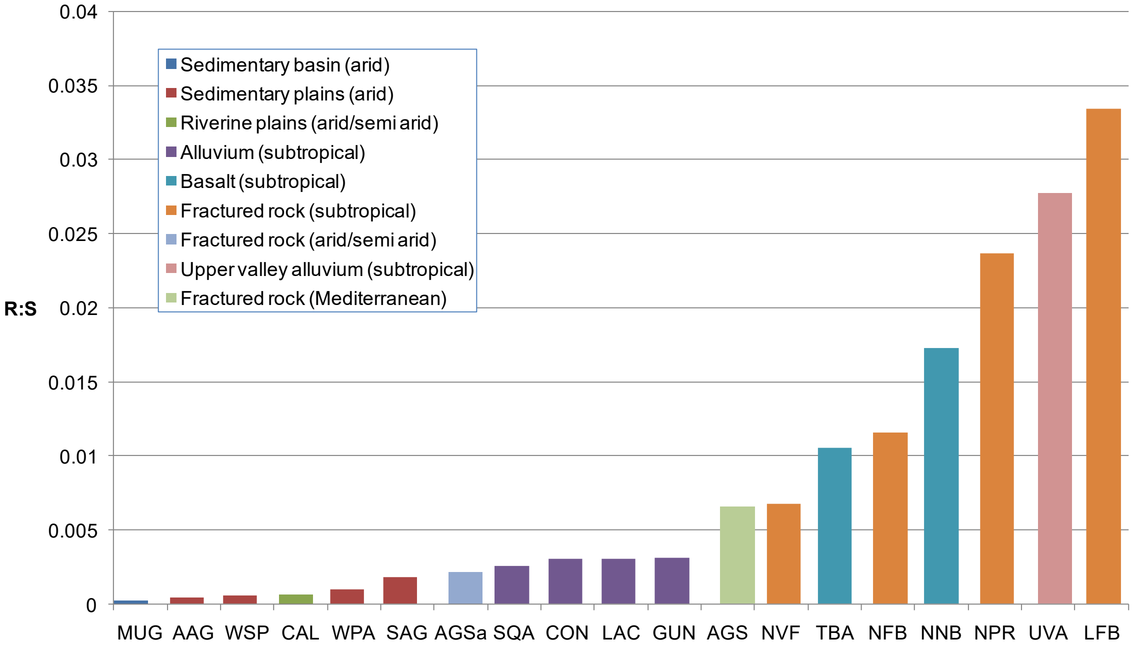

Figure 2-4 Recharge to storage ratios for major aquifer types in the Murray Darling Basin (see Appendix B)

Based on the results from the Murray Darling Basin, a matrix was developed to assign ratings of high, moderate or low according to aquifer type and climate zone (Table 2-1). The matrix was referenced to populate the responsiveness metric for all aquifers across Australia.

Table 2-1 Ratings of recharge to storage ratio based on aquifer type and climate zone (cells are empty where there are no instances of a particular aquifer type / climate zone combination)

Aquifer Type	Tropical[1]	Arid/Semi Arid	Mediterranean	Sub-tropical	Temperate
Alluvium	high	low	moderate	moderate	high
Basalts	high	moderate	high	high	high
Carbonate	high	low	moderate	moderate	high
Coastal Alluvium	high	low	moderate	moderate	high
Coastal Sands	high	moderate	high	high	high
Fractured Rock	high	moderate	high	high	high
Riverine Plains		low			moderate
Sedimentary Basin	low	low	low	low	low
Sedimentary Plains		low			moderate
Upper Valley Alluvium	high	moderate	high	high	high

[1] Climate zone classification based on grouping Koppen-Geiger codes as follows: Tropical = Af, Am, Aw; Arid/Semi-Arid = BWh, BWk, BSh, BSk; Mediterranean = Csa, Csb; Humid subtropical = Cwa, Cfa; Temperate = Cfb, Cfc, Dfb, Dfc. The Koppen-Geiger zones were delineated according to an historical climate: BAWAP data from 1970-2009

Carbonate aquifers are not represented in the analysis for the MDB, nor are tropical climates. There was no data available to widely characterise these aquifers. So in order to populate the remaining cells of the matrix (Table 2-1), the following assumptions have been made in the terms of R:S ratios: carbonate aquifers are assumed to be similar to alluvium aquifers; and tropical climates are assumed to be similar to a temperate climates (given that annual rainfall is high in both zones). An estimate of R:S for the Daly Basin (NT), which is comprised of fractured and carbonate rock, is consistent with these assumptions. The estimated R:S of 0.038 [based on Jolly (2001)] supports the assumption that fractured or carbonate rock aquifers in tropical settings have a high R:S.

Climate change prioritisation index

The final aquifer prioritisation score is obtained by the product of the Importance and Sensitivity indices, which are first standardised. This relationship is defined as:

$$Final\ prioritisation = \frac{I}{I_{max}} * Se_{standardised} \qquad [5]$$

Where, $Se_{standardised}$ is the standardised sensitivity score that is calculated using the below equations:

$$Se_{standardised} = 10^{Se_{alt}} \qquad [6]$$

$$Se_{alt} = \frac{Se_L * [\min(Se_L) - \min(I_L)]}{\min(Se_L)} \qquad [7]$$

$$Se_L = log_{10}\left(\frac{Se}{Se_{max}}\right) \qquad [8]$$

$$I_L = log_{10}\left(\frac{I}{I_{max}}\right) \qquad [9]$$

A scaling function [7] is applied to the log-transformed normalised scores of sensitivity [8] and importance [9] in order to scale sensitivity scores to match the range of the importance scores. The scaled and log-transformed values of the sensitivity index are converted back to equivalent terms by equation [6] and are then combined with importance scores to derive the final prioritisation score [5].

The standardisation procedure ensures that aquifer importance and sensitivity are given equivalent numerical weighting before being combined. The importance index has 4 individual metric terms in comparison to 2 in the sensitivity index; which means that the results obtained for the importance index range over 8 orders of magnitude in comparison to 4 orders of magnitude for the sensitivity index. To correct for this inequality, the standardisation procedure scales the results obtained from the sensitivity index to match the range of the importance index.

2.1.3. Data sources to populate prioritisation index

The base data required to populate the prioritisation index were current extraction, sustainable yield and the identification of GDEs. Much of this data was listed in the Australian Water Resources 2005 (AWR, 2005) datasets, which were obtained with permission from the jurisdictions. The AWR 2005 data were updated by the most recent estimates of extraction and sustainable yield volumes, which were either obtained from Sustainable Yield studies in relevant areas or sought from each jurisdiction. These data sources are summarised in Table 2-2. Where sustainable yield volumes were not available, groundwater allocations were used as a sustainable yield surrogate. This assumption is consistent with National Water Initiative (NWI) objectives that allocations should reflect sustainable yields. In addition to extraction and sustainable yield data, the AWR 2005 dataset lists the whether GDEs have been identified for each GMU. GDEs are listed according to GDE type, which allowed for the breakdown of River Baseflow, Wetland and Terrestrial GDEs to populate the relevant metrics in the aquifer importance index.

Table 2-2 Data sources for updated extraction and sustainable yield volumes

Jurisdiction	Data sources used to update AWR 2005 dataset
ACT	NSW Macro and WSP data 2004-05 provided by NSW Office of Water
NSW	NSW Macro and WSP data 2004-05 provided by NSW Office of Water. For the GAB, the GAB WSP was used to provide an updated SY.
NT	Water Allocation Plans as documented on NRETAS website[1]
Qld	■ The MDB portion of QLD was represented by MDBA sustainable diversion limit (SDL) units. Use based on 07/08 statistics, SY based on preliminary SDL volumes. ■ For the GAB portion of Queensland, GMUs were represented by GAB management areas and use, SY volumes were assigned according to Hydrogeological Framework Report for the GAB WRP Areas (DERM, 2005) ■ For remaining areas, NaSY borepoint data for whole of state was cut to GMUs. The following assumptions were made: ■ bores with 0 allocation (other than S&D) were removed ■ annual use volume of 1 ML assumed for bores with S&D allocation and no allocation ■ all bores with an allocation volume had use assumed to be 80% allocation.
SA	Updated use and SY volumes for prescribed water resource areas provided by SA DfW.
Tas	TasSY
Vic	Victoran Water Account data 06/07
WA	SWSY and NaSY

[1] http://www.nt.gov.au/nreta/water/plans/index.html

Data limitations

While up-to-date information has been obtained, there are various limitations associated with the data used to populate the prioritisation scheme. Extraction rates can vary significantly from year to year. The sustainable yield statistics are not likely to be terribly robust as they are subject to different definitions and interpretations across different jurisdictions and regions. And the GDE data is limited. It is based on existing data (AWR, 2005) which is poorly documented in terms of how GDEs were identified, what is their level of groundwater dependence (relative to the regional aquifer), how significant are they in a national context, and how susceptible are they to perturbations to the water balance. It is also possible that the dataset may not include several important GDEs.

2.2. Results and discussion

2.2.1. Individual metrics

The results obtained for the 6 individual metrics that combine to form the prioritisation scheme are shown in Figure 2-5. The first four maps [a) - d)] relate to the measure of aquifer importance. The last two maps [e) and f)] relate to the measure of aquifer sensitivity.

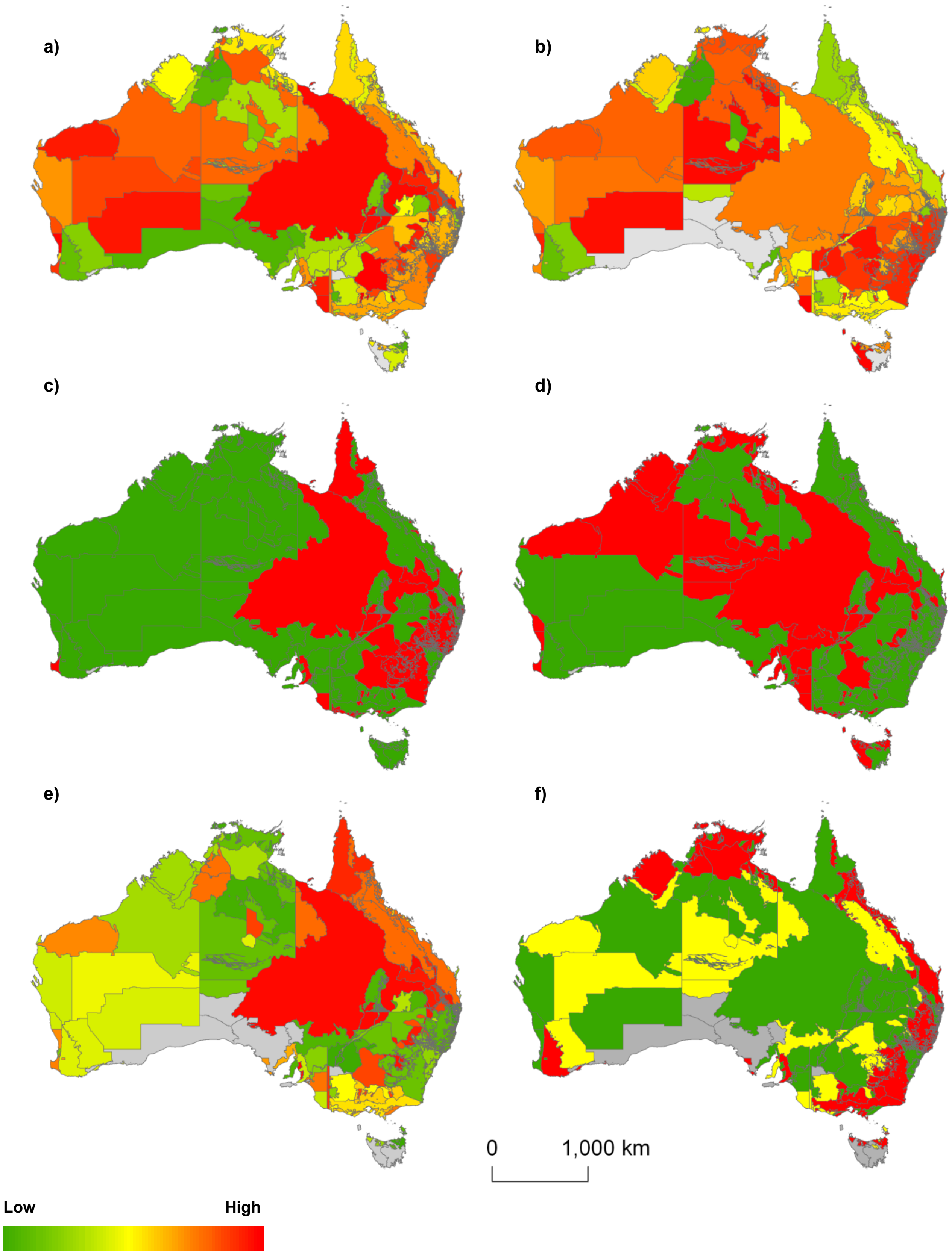

Figure 2-5 Aquifer prioritisation results for individual metrics: a) E/Emax; b) SY/SYmax; c) f(baseflow GDEs); d) f(other GDE types); e) E/SY; f) f(R:S)

2.2.2. Priority Aquifers

The prioritisation scheme has been used to identify important aquifers, sensitive aquifers, and aquifers that are both important and sensitive – i.e. the priority aquifers for this project. The cut-off for the aquifers defined as important, sensitive or priority was based on an analysis of the prioritisation scores, which were plotted against rankings. In each of the prioritisation categories, an inflection point was noted in the prioritisation score after which there was a less significant change in the score relative to ranking. This point corresponded to rank 22 for the aquifer importance score, rank 25 for the aquifer sensitivity score, and 22 in the overall prioritisation score.

Table 2-3 lists the priority aquifers, with their locations shown in Figure 2-6, Figure 2-7 and Figure 2-8. A complete summary of the prioritisation results is listed in Appendix C.

The aquifers defined as important are typically extensive systems with GDEs identified and high levels of groundwater extraction. The major aquifers of the Murray Darling Basin, the Perth Basin, the Otway Basin and the GAB are included. The list of important aquifers also includes some spatially extensive inland systems such as the Goldfields, the Canning Basin and the Pilbara in Western Australia, and fractured and weathered rock aquifers associated with Northern Territory interior. The inclusion of such aquifers is related to the coarse definition of management boundaries (i.e. extensive GMUs) that leads to the definition of extensive aquifer systems with accordingly high sustainable yield and extraction metrics.

The aquifers identified as sensitive are less extensive spatially and typically occur in the higher rainfall zones (Figure 2-7).

The priority aquifers include many of those listed as important or sensitive, but also comprise aquifers that scored consistently in both categories – e.g. the Adelaide Geosyncline in South Australia, and the Daly Basin in the Northern Territory (i.e. the Tindall Limestone Aquifer). Some aquifers appear as priority aquifers that may not be readily sensitive to climate change. The GAB and Murray Group Limestone are two such examples. Current recharge rates in these aquifers are minimal compared to storage volumes, and the time lags associated with altered recharge rates are vast. However, while it is unlikely that some priority aquifers will be especially sensitive to climate change, they are considered priority aquifers due to their importance.

Table 2-3 Priority aquifers as defined by the prioritisation scheme

Rank	Important Aquifers		Sensitive Aquifers		Priority Aquifers	
	Aquifer ID	Aquifer Name	Aquifer ID	Aquifer Name	Aquifer ID	Aquifer Name
1	10	Calivil	120	Upper Valley Alluvium 4	10	Calivil
2	83	Otway Basin	94	Quaternary Sand Dune Deposits	46	GAB 2
3	46	GAB 2	113	Toowoomba Basalts	51	Gunnedah
4	21	Coastal River Alluvium 4	2	Albany	83	Otway Basin
5	15	Central Perth Basin	43	Fractured rock	21	Coastal River Alluvium 4
6	23	Coastal Sands 4	22	Coastal River Alluvium 5	87	Pilbara
7	51	Gunnedah	121	Upper Valley Alluvium 5	59	Lachlan
8	47	GAB 4	93	Atherton Tablelands	47	GAB 4
9	103	South Perth Basin	36	Fractured Rock Aquifer 4	73	Newer Volcanics
10	87	Pilbara	33	Fractured Rock Aquifer 1	23	Coastal Sands 4
11	42	Fractured and weathered rock 2	81	Ord-Victoria 1	15	Central Perth Basin
12	68	Murray Group	56	Humevale Siltstone	93	Atherton Tablelands
13	50	Goldfields	31	Eyre Peninsula Limestone Lenses	113	Toowoomba Basalts
14	61	Lachlan Fold Belt 2	92	Quaternary Alluv associated with the Goulburn River	103	South Perth Basin
15	63	Lachlan Fold Belt 5	19	Coastal River Alluvium 1	4	Upper Condamine and Border Rivers Alluvium
16	75	North Perth Basin	73	Newer Volcanics	120	Upper Valley Alluvium 4
17	89	Port Campbell Limestone	59	Lachlan	89	Port Campbell Limestone
18	71	New England Fold Belt 4	4	Upper Condamine and Border Rivers Alluvium	68	Murray Group
19	59	Lachlan	116	Unincorporated Area GMW	19	Coastal River Alluvium 1
20	13	Canning	108	TLA 3	1	Adelaide Geosyncline 3
21	72	New England Fold Belt 5	27	Curlip Gravel	38	Daly Basin
22	62	Lachlan Fold Belt 4	118	Unincorporated Area SRW	63	Lachlan Fold Belt 5
23			9	Brighton Grp		
24			90	Prior Stream and Recent floodplain Deposits		
25			51	Gunnedah		

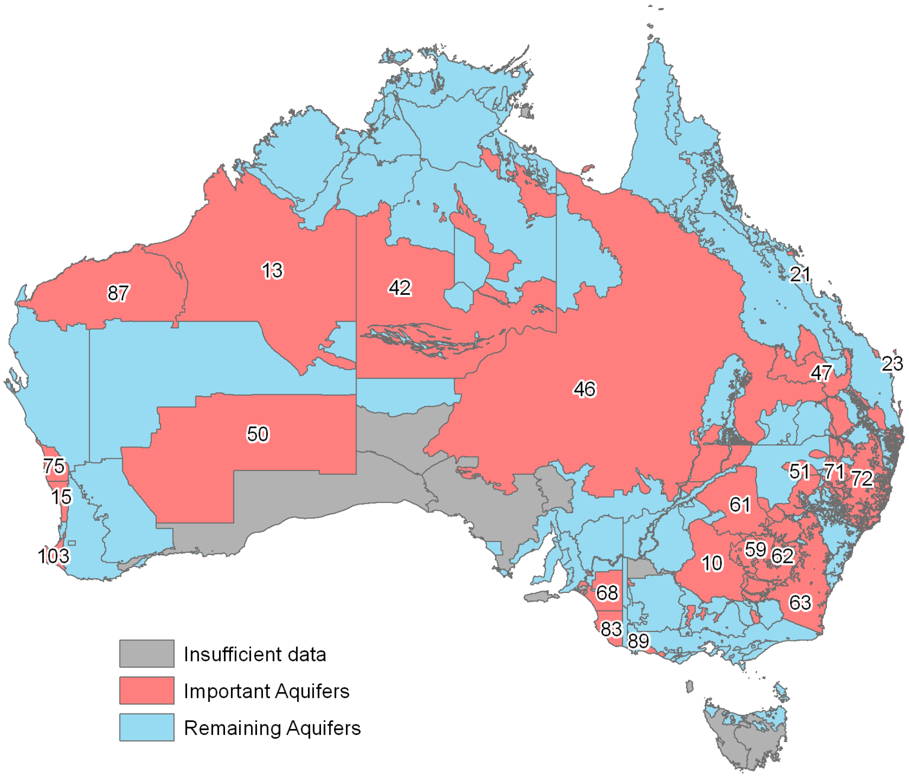

Figure 2-6 Important aquifers as defined by prioritisation scheme (numbers indicate aquifer ID codes)

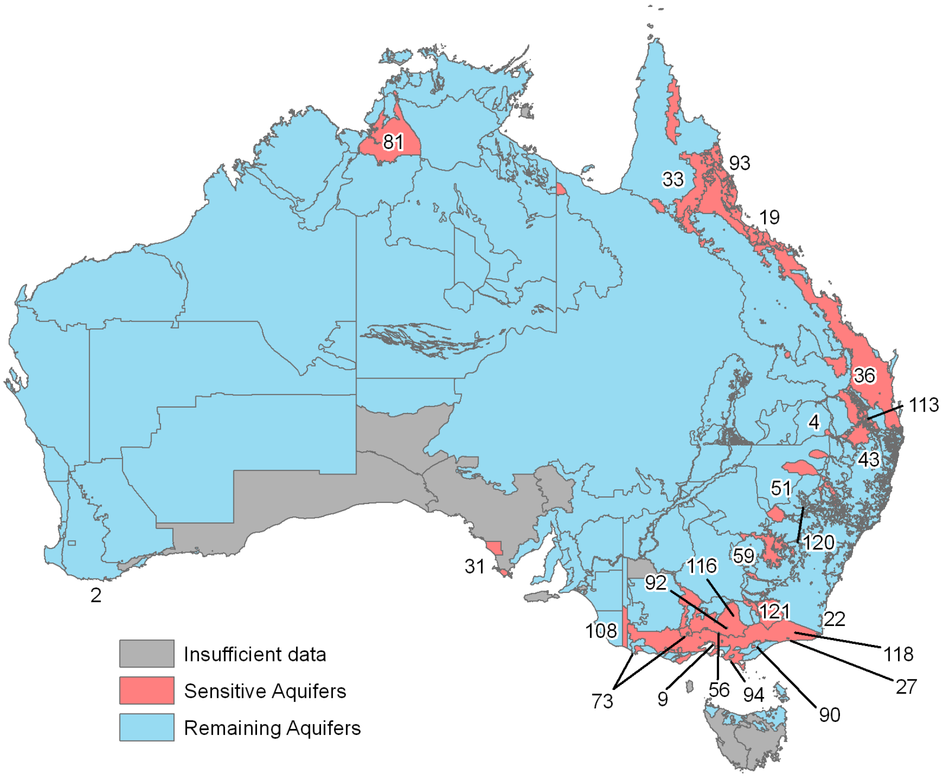

Figure 2-7 Sensitive aquifers as defined by prioritisation scheme (numbers indicate aquifer ID codes)

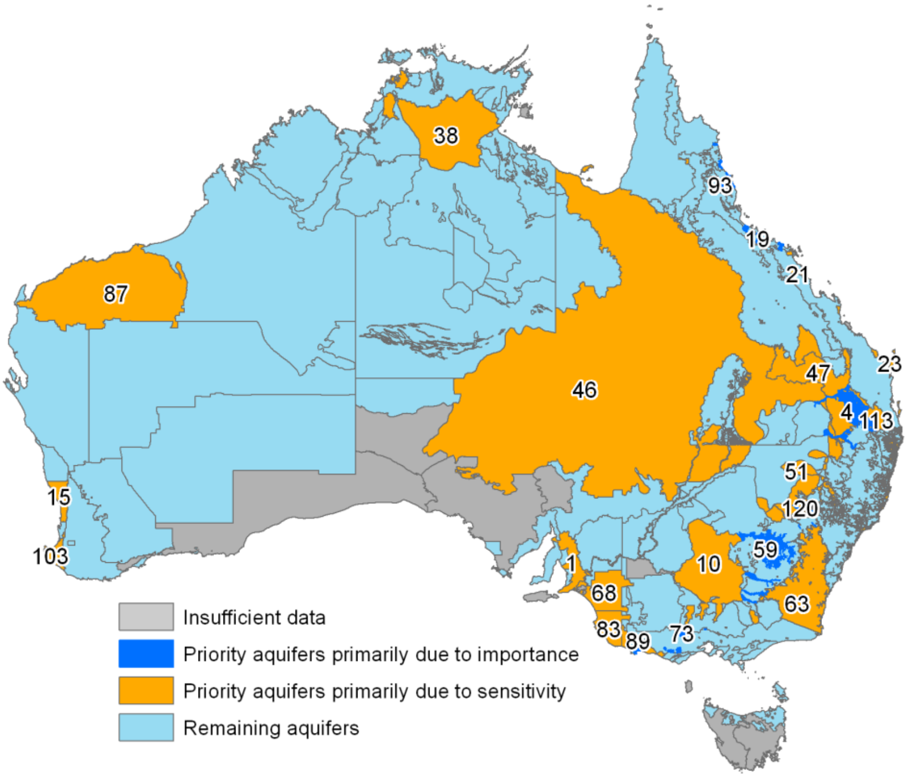

Figure 2-8 Priority aquifers due to a combination of importance and sensitivity (numbers indicate aquifer ID codes)

2.2.3. Sensitivity Analysis

The relative importance of each metric listed in the prioritisation scheme is determined by its range and variance not by its actual value. That is, the variance of scores in each of the metrics will determine how powerfully the metric will discriminate between aquifers. Table 2-4 lists some relative measures of range and variance for the prioritisation metrics.

Table 2-4 Relative measures of range and variance for prioritisation metrics

	Max/Min	95th percentile / 5th percentile	Coefficient of variation*
Aquifer Importance metrics#			
E/Emax	12,289	505	212%
SY/SYmax	2,947	459	164%
f(RB)	5.7	5.7	84%
f(GDE)	5.7	5.7	75%
Aquifer Sensitivity metrics#			
E/SY	1,682	88	119%
f(R:S)	9	9	79%

*Calculated as the standard deviation divided by the mean

#Note that the aquifer importance metrics are not directly comparable to the aquifer sensitivity index as the latter are scaled before being combined in the final prioritisation score

The ratio between the maximum and minimum score is a standardised measure of the range of the metric. A more robust measure of range is obtained by the ratio of the 95th to 5th percentile score, which is less skewed by outliers. Meanwhile, the coefficient of variation is a measure of relative dispersion in the dataset.

Regarding the aquifer importance index it is apparent that the extraction and resource size are more significant metrics in determining importance than the GDE metrics. For the aquifer sensitivity index the development metric is more significant that the responsiveness metric.

GDE metric sensitivity

With the exception of the GDE metrics, which were arbitrarily assigned, the range and variance for each of the prioritisation metrics was based on actual data (the responsiveness index was based on estimates of R:S from the MDB). A post-hoc analysis was performed to assess the sensitivity of the arbitrary values assigned to GDE metrics. Three scenarios were analysed:

- Scenario 1 (S1): f(GDE) = 0.75 where GDEs identified and 0.3 where GDEs not identified
- Scenario 2 (S2): f(GDE) = 0.6 where GDEs identified and 0.4 where GDEs not identified
- Scenario 3 (S3): f(GDE) = 0.9 where GDEs identified and 0.1 where GDEs not identified

Scenarios 1 and 2 analyse the impact of lessening the significance of the GDE metrics. Scenario 3 analyses the impact of strengthening the significance of the GDE metric. Table 2-5 summarises the results of the sensitivity analysis in terms of how the makeup of the top priority aquifers is altered. With only minor changes to the list of priority aquifers, the results suggest firstly that the GDE metrics are not especially sensitive. Second, that reducing the impact of the GDE metrics (i.e. scenarios 1 and 2) is not advisable given that this would result in the classification of large unincorporated areas as priority aquifers.

Table 2-5 Sensitivity analysis of GDE metric weightings

	S1: GDEs present = 0.75 GDEs absent = 0.3	**S2:** GDEs present = 0.6 GDEs absent = 0.4	**S3:** GDEs present = 0.9 GDEs absent = 0.1
Relative GDE weighting	reduced	Significantly reduced	increased
Priority aquifers redefined as low priority	▪ Lachlan Fold Belt 5 (NSW)	▪ Lachlan Fold Belt 5 (NSW) ▪ Port Campbell Limestone (Vic)	▪ Daly Basin (NT)
Low priority aquifers redefined as priority	▪ Goldfields (WA)	▪ Fractured Rock Aquifer 4 (Qld) ▪ Goldfields (WA)	▪ Eyre Peninsula Limestone Lenses (SA)

2.2.4. Comparison with other aquifer prioritisation results

The aquifer prioritisation presented is the first such scheme to be implemented nationally. Other aquifer ranking procedures have been conducted on a regional basis. In 1998, the NSW Government undertook a statewide aquifer risk assessment to guide water management activities (DLWC, 1998). Aquifers were also prioritised in the Murray-Darling Basin to guide project efforts for the MDB SY (Richardson et al., 2008). While these assessments were conducted on a smaller scale and were defined according to different objectives, there is alignment with the outputs of the prioritisation presented here. The 20 GMUs defined as highest priority in the Murray Darling Basin by Richardson et al. (2008) are all represented as priority aquifers in Table 2-3. Of the 36 aquifers listed as highest risk in

NSW in 1998 (DLWC, 1998), the majority (24) are defined as priority in Table 2-3[2]. The aquifers listed as high risk by DWLC (1998) that are not represented as such in this report tend to be small resources, many of which have been subject to changes in the management boundaries since 1998. It is also likely that the different classifications may result from the different criteria assessed (e.g. contamination risk). Despite these few discrepancies there is broad alignment between the outputs.

The priority aquifers (Table 2-3) also represent all areas listed as requiring reductions from current diversion limits in the Guide to the Proposed Basin Plan (MDBA, 2010).

A more recent prioritisation study of direct relevance has been conducted by the South Australian Department for Water (Wood and Green, 2011), where water resources (both surface water and groundwater) were prioritised according to the potential risks posed by climate change. The work was conducted independently of this project, yet shares a similar methodology in that resources were prioritised according resource ‘significance’ and ‘sensitivity’. The major difference was it also included a climate change risk rating based on previous climate change modelling. The results from this study support the findings of this project in that the highest priority groundwater resources for South Australia are in the Mount Lofty Ranges (Adelaide Geosyncline) and the limestone aquifers of south east South Australia (Otway Basin).

2.2.5. Limitations

The aim of the prioritisation scheme was to provide an objective basis to select priority aquifers across Australia to assess for climate change impacts. Whilst this aim has been achieved, there are a number of underlying assumptions and limitations to the aquifer prioritisation scheme that need highlighting as they affect the results obtained. These limitations are in addition to the data limitations described on page 8.

GMU classification

In some cases the classification of regional aquifers was based on one large GMU that in reality encompasses several aquifer systems. This limitation may overstate the importance of several inland aquifers, which are primarily defined as being large resources due to their size. Further efforts to prioritise Australian aquifers by these means should examine ways in these larger GMUs can be redefined with the associated data allocated more appropriately (e.g. to hotspot areas). The introduction of a metric focussed on the intensity of extraction (e.g. extraction per unit surface area) may offset this bias.

Sea-water rise

One aspect of climate change not assessed by the prioritisation scheme is the potential for sea-water ingress as a result of changing sea levels. The inclusion of sea-water ingress as a unique factor in the index was likely to skew the definition of priority aquifers to focus on coastal systems. It was also recognised that vulnerability of coastal aquifers is being assessed in a concurrent project[3]. Despite the absence of sea-water ingress in the prioritisation scheme, several coastal aquifers have been identified as priority systems and this process will be examined in more detail within the recharge / discharge discussion paper.

Groundwater dependency

The prioritisation scheme does not incorporate a metric for groundwater dependence – i.e. the importance of groundwater relative to total water use on an aquifer scale. It is reasonable to assume that regions more dependent on groundwater would be more sensitive to climate

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[2] The aquifers defined in DLWC (1998) represent smaller spatial units to those defined in this report. Hence many of the 24 aquifers that defined as highest risk by DWLW (1998) have been lumped together in the current assessment.

[3] National-Scale Vulnerability Assessment of Seawater Intrusion Project, Geoscience Australia

change compared to regions with similar attributes in the other prioritisation categories. The barrier to the inclusion of such a metric is its difficulty to populate: one would need to disentangle the complex overlap between surface water and groundwater management use areas. However future efforts to prioritise Australian aquifers may wish to persevere with this option.

Other applications

The methodology developed has been used to prioritise aquifers for the purposes of this project. Further work would be required to implement the methodology to prioritise aquifers for other purposes. While this work may be the first attempt to nationally prioritise aquifers by importance, the results should not be considered as a universal ranking of aquifers by importance outside the context of this project. Any further prioritisation activities need to be tightly defined according to relevant objectives. For instance in this project there is no value assigned to the use of groundwater – e.g. dollar value of agricultural production or ecological value of the GDEs present. The introduction of such metrics would significantly alter the results obtained.

2.3. Conclusion

Groundwater management units (GMUs) have been attributed and combined to define the major aquifers of Australia. The aquifers have been separated by climate zone, and existing data has been collated relating to groundwater extraction rates, sustainable yield volumes, the occurrence and types of GDEs present. Recharge to storage ratios are estimated based on aquifer type and climate. The aquifers have been ranked according to their importance and their sensitivity using a prioritisation scheme specifically designed for this project. The process provides an objective basis to select priority aquifers that will become the focus of further activities in this project.

2.4. Recommendations for further aquifer prioritisation

Further national aquifer prioritisation activities may proceed in the future that are either related or unrelated to this project. The following recommendations are made to assist with such activities:

- The relative weighting of the individual metric terms used in the prioritisation scheme is critical to the results obtained. Further prioritisation activities may wish to apply a more rigorous selection of the weightings using a formalised procedure and expert guidance (e.g. Raj and Kumar, 1999).
- The nationwide aquifer coverage developed is considered preliminary and would be enhanced by a formal review process, including the consultation with jurisdictions.
- An more accurate and better-defined nationwide GDE coverage is needed
- A separate prioritisation could be developed for coastal aquifers where the threat of sea-water ingress is included.
- The inclusion of surface water vulnerability to climate change could be added as a compounding factor if supported by data.
- It is likely that higher quality datasets will become available in the future (e.g. GDE Atlas) which will enhance the accuracy of further prioritisation activities.

3. PRIORITY AQUIFERS

The Aquifer prioritisation scheme (Chapter 2) identified the priority aquifers across Australia to be the focus of this study. This chapter presents summary descriptions for each of these aquifers. They are summarised in Table 3-1 below where they are classified according to aquifer type and climate. A broad range of aquifer types and climate zones are represented.

Table 3-1 Classification of priority aquifers according to aquifer type and climate zone

Aquifer Type	1) Tropical[1]	2) Arid/Semi Arid	3) Mediterranean	4) Sub-tropical	5) Temperate
Alluvium				Gunnedah (NSW), Lachlan (NSW), Upper Condamine and Border Rivers Alluvium (Qld)	
Basalts				Atherton Tablelands(Qld), Toowoomba Basalts (Qld)	Newer Volcanics (Vic)
Carbonate	Daly Basin (NT)	Murray Group (SA,Vic)	Otway Basin (SA, Vic), Port Campbell Limestone (Vic)		
Coastal Alluvium	Coastal River Alluvium (Qld)			Coastal River Alluvium (NSW & Qld)	
Coastal Sands				Coastal Sands (NSW & Qld)	
Fractured Rock		Pilbara (WA)	Adelaide Geosyncline (SA)		Lachlan Fold Belt (NSW)
Riverine Plains		Calivil (NSW, Vic)			
Sedimentary Basin		GAB (NSW, NT, Qld, SA)	Central Perth Basin (WA), South Perth Basin (WA)	GAB (Qld, NSW)	
Upper Valley Alluvium				Upper Valley Alluvium (NSW)	

[1] Climate zone classification based on grouping Koppen-Geiger codes as follows: 1)Tropical = Af, Am, Aw; 2) Arid/Semi-Arid = BWh, BWk, BSh, BSk; 3) Mediterranean = Csa, Csb; 4) Humid subtropical = Cwa, Cfa; 5) Temperate = Cfb, Cfc, Dfb, Dfc

3.1. Adelaide Geosyncline 3

The Adelaide Geosyncline is a major geolological feature extending from the Fluerieu and Yorke Peninsulas, through the Mount Lofty Ranges to the Northen Flinders Ranges. The focus of this study is the aquifers coincident with a Mediterranean climate - i.e. the southern extent of the Geosyncline. The region includes several GMUs as listed in Appendix A.

The region is characterised by steep and undulating terrain with predominately fractured-rock aquifers that form in Proterozoic metasediments. Sedimentary aquifers, such as the Permian sands of the Fleurieu Peninsula, can also provide significant local supplies of groundwater.

The fractured-rock aquifers present throughout the Mount Lofty Ranges are recharged predominantly via rainfall but may also accept some recharge from streams during periods of high flow. Discharge from this aquifer occurs through springs and seeps at the break of slope and as baseflow to streams. Discharge also occurs at depth (as groundwater through flow) to the adjoining sedimentary aquifers of the Adelaide Plains, particularly in faulted zones.

3.2. Upper Condamine and Border Rivers Alluvium

The Border Rivers Alluvium (QLD & NSW) and Upper Condamine Rivers Alluvium (QLD) are located on the border of New South Wales and Queensland, and to the north of the border on the western slopes of the Great Dividing Range.

The alluvial units are associated with the current drainage system and aquifers range from 10 m thick in headwater regions to greater than 120 m in the central areas of the river valleys (DERM, 2009; Barret, 2009; CSIRO, 2007). In both the GMUs, groundwater is predominantly fresh to brackish (<3,000 mg/L TDS) and water tables are intersected 2 m to 20 m below surface (DEWHA, 2009). Localised areas of more saline groundwater (3,000 – 14,000 mg/L TDS) are found in the northern and western portions of the Upper Condamine Alluvium GMU (CSIRO/SKM, 2010).

Recharge to these alluvial aquifers occurs via diffuse rainfall recharge, inundation (flood) recharge and river leakage. In the Upper Condamine Alluvium GMU groundwater discharge to the Condamine River also occurs (CSIRO/SKM, 2010).

3.3. Calivil

The Calivil aquifer grouping represents the priority GMUs within the Riverine Plains of the Murray Darling Basin which utilise groundwater from the Renmark, Calivil and Shepparton Formations (Appendix A).

The Renmark Group is the basal aquifer within the Riverine Plains. It is composed of alluvial sands and gravels with inter-bedded carbonaceous clay-rich units, and is hydraulically connected with the overlying Calivil Formation. The Calivil Formation is up to 80 m thick and consists of quartz sand and gravel. Together these units are thickest where they overlie and infill paleovalleys and may exceed 300 m in thickness (CSIRO/SKM, 2010). The Shepparton Formation overlies the Calivil Formation and usually forms the watertable aquifer. It is a highly heterogeneous deposit of river and lake sediments (CSIRO, 2008).

Groundwater is extracted from each of these units but the Calivil Formation is the primary productive aquifer, supplying large scale irrigation, stock and domestic demands. Salinity is typically less than 3,000 mg/L TDS but is saline in some areas (CSIRO, 2008). Groundwater in the Shepparton Formation is generally more saline and used for irrigation only where water quality allows. Extraction has led to significant drawdown in the Calivil Formation and there is a risk to water quality from induced leakage from shallow saline watertable Shepparton Formation aquifers (CSIRO, 2008).

3.4. Central Perth Basin

The Central Perth Basin is considered one of Australia’s most important groundwater resources, supplying over half of the domestic water for the city of Perth and surrounds, as well as supplying water for industry and irrigation of parklands and gardens. The Basin was recently at the focus of a CSIRO Sustainable Yields project (CSIRO, 2009) and much of the background information presented here is derived from that report.

There are three main resource aquifers in the Central Perth Basin, namely the Superficial Alluvial, Leederville and Yarragadgee aquifers.

The Superficial Aquifer is the uppermost and primary production aquifer, providing around 66% of extracted groundwater supplies. It is a major multi-layered unconfined aquifer comprised of Tertiary to Quaternary sequences of sand, limestone, silt and clay, with a total thickness of up to 90 m. Recharge occurs via direct rainfall infiltration and via stormwater runoff, particularly in urban areas. Surface water drainage lines are also a potential source of recharge, although some also receive baseflow from groundwater. Some recharge also occurs by upward leakage from underlying aquifers.

Watertable elevations in this unconfined aquifer depend mainly on topography, the hydraulic conductivity of aquifer materials and distance from a discharge point. Variations in watertable elevation over time depend on storage properties and recharge – discharge changes which themselves depend on climate, land use and management practices and abstractions. Groundwater from the Superficial Aquifer unit discharges to the Indian Ocean, rivers, lakes, springs, and artificial and natural drains as well as by evapotranspiration. The groundwater from the Superficial Aquifer also drains into underlying aquifers where there are downward gradients and confining beds are absent.

The Leederville Aquifer is a shallow and extensive, confined to semi-confined aquifer that provides around 21% of groundwater for the Perth area. It is comprised of mainly discontinuous, interbedded sandstones, siltstones and shale with some conglomerates. Recharge to the Leederville Aquifer occurs via direct infiltration in outcrop areas (such as creek beds), and where confining layers are absent via upwards discharge from the underlying Yarradgee Aquifer and by downward leakage from the Superficial Aquifer. The Leederville discharges into the underlying Yarragadee Aquifer and into the surface water drainage lines. Groundwater salinity ranges from 180 to 2130 mg/L TDS with most having a salinity level of less than 1000 mg/L TDS.

The confined Yarragadgee Aquifer provides around 11% of groundwater supplies from the Central Perth Basin. It underlies the Leederville except where it outcrops or subcrops beneath the Superficial Aquifer (beneath the coastal plains). The stratified layers of the aquifer predominantly comprise sand and have a thickness that varies from 1000 to 2000 m. Recharge to this aquifer occurs via direct rainfall recharge where it outcrops, and were confining beds are absent, by downward leakage from the Superficial and Leederville aquifers. The groundwater from the Yarragadee discharges into the Indian and the Southern Ocean. A significant amount of groundwater also discharges into the Blackwood River where the river is incised into the Yarragadee Aquifer downstream of Darradup.

3.5. Coastal River Alluvium 1

The Coastal River Alluvium 1 grouping incorporates the alluvial (fluvial) aquifers on the tropical northeast coast of Queensland (as listed in Appendix A).The respective GMUs are moderately sized (113 km2 -1,340 km2) and three of the larger GMUs in this grouping -the Burdekin River Delta, Bluewater and Bowen -are characterised by moderate to high levels of development with groundwater extractions approaching or exceeding sustainable yields (AWR, 2005). Being of potable quality and easily accessible (i.e. shallow), extracted groundwater is used extensively for irrigation, town and domestic water supplies. Despite high levels of extraction, groundwater levels are reported to be stable in each of these highly developed GMUs although the Burdekin GMU will not sustain further development (DEWHA, 2009). Groundwater development is considered to be low in the remaining GMUs.

3.6. Coastal River Alluvium 4

The Coastal River Alluvium 4 grouping incorporates the alluvial (fluvial) aquifers on the sub-tropical northern New South Wales and southern Queensland coasts. The aquifers within this grouping comprise coarse Quaternary floodplain sediments, associated with the current drainage system. Hence, there is a high degree of surface water – groundwater connectivity. Depths to water table are typically 3-10 m below ground level and groundwater is mostly fresh to brackish (≤ 1,000 mg/L TDS). The GMUs within the Coastal River Alluvium 4 grouping are small to moderately sized (85 – 1,942 km2) and are characterised by low to moderate levels of groundwater development for irrigation, town supply and some industrial purposes (Appendix A). Over extraction has lead to water table declines and seawater intrusion in some areas (AWR, 2005) (NRMMC, 2002).

3.7. Coastal Sands 4

The Coastal Sands 4 grouping incorporates the numerous Quaternary sand aquifers on the sub-tropical, east coast of Australia (approximately central Queensland to central New South Wales). The GMUs within this grouping (listed in Appendix A) are small to moderately sized, ranging from 22 km^2 to 1970 km^2 and are comprised primarily of aeolian and marine sand dune deposits (AWR, 2005). Aquifers can be up to 100m thick and watertables are intersected 3-11 m below ground level (AWR, 2005). The aquifers are characterised by high infiltration rates and the main recharge mechanism is diffuse rainfall recharge (AWR, 2005).

Groundwater is generally of good quality (i.e. low salinity) in the sand aquifers, although in the majority throughout the Coastal Sands 4 GMUs the level of development is broadly characterised as ‘low level’ relative to sustainable yields. Localised areas of high level development do exist where groundwater water is extracted for municipal, commercial, stock watering and crop irrigation purposes (AWR, 2005).

In many of these GMUs there is no potential for future development due to the potential for seawater intrusion impacts. Additionally, many of the aquifers within this grouping, namely the Tomago Sandbeds, Macleay Coastal Sands, Richmond Coastal Sands, Botany Sandbeds and Bellinger Coastal Sands, have been classified as being at ‘high risk’ with respect to over extraction and land use threats (i.e. contamination) (DLWC, 1998).

3.8. Daly Basin

The Daly Basin aquifers refer to the thick (approaching 200 m) mid Cambrian to early Ordovician Tindall Limestone and Oooloo Dolostone aquifers (and equivalents) in the Northern Territory (Geoscience Australia, 2010). The aquifers are highly connected to the local surface water systems, providing the primary water source for baseflows and although there is the potential to reliably supply large volumes of water for extractive purposes, modelling suggests that current rates of extraction are close to or at the limits of recoverable groundwater extractions, particularly in irrigation areas (CSIRO, 2009). Recharge to the aquifers occurs via rainfall infiltration, either diffusely or direct through sink holes and dissolution hollows (Crosbie, McCallum, & Harrington, 2009).

3.9. The Great Artesian Basin

The Great Artesian Basin (GAB) is a large sedimentary basin located in central Australia. It is complex, geographically extensive system comprising multiple aquifers within a number of geological basins and sub-basins.

The GAB contains two major aquifer systems known and the J (Jurassic) and K (Cretaceous) aquifer systems (although the `Jurassic' grouping includes Triassic, Jurassic and Late Cretaceous units) (Habermehl, 2002). The Jurassic aquifers are typically low salinity (500-1500 mg/L TDS), high yielding sandstones under artesian to sub-artesian pressures. Formations are known variously (depending on geological basin or GMU jurisdiction) as the Pilliga Sandstone, Hooray Sandstone and Cadna-owie Formation. The Cretaceous aquifers are sub-artesian with typically higher salinities (Habermehl, 2002). Also included in the GAB 2 aquifer grouping is the GAB Cap Rock, which represents the surficial part of the GAB which is characterised by calcrete deposits or low permeable layers (Herczeg, 2008).

Recharge to the GAB occurs along the eastern and western margins of the basin where aquifer units (or `intake beds') are uplifted and exposed. Recharge occurs via direct infiltration to intake beds, and indirectly through creek channels and unconsolidated sediments (Herczeg, 2008). McMahon, et al. (2005) estimated that annual deep seepage into the north east part of the GAB is approximately 47,000 ML or <0.5% of incident rainfall. At the western margin, average annual recharge is estimated to be 0.6 mm/year which is less than 0.1% of precipitation (McMahon, et al., 2005). In the context of resource management time frames and sustainable yield determinations, the GAB is so large and groundwater flow so slow that recharge currently occurring in intake areas is considered to have no discernable effect on the total volume in storage (DNRM, 2005).

Discharge occurs from the GAB via both natural and artificial mechanisms. GAB aquifers have been exploited since the late 18th century by pastoralists, governments and mining interests and over extraction has led to the decline of the potentiometric surfaces across the basin. Several 'cap and pipe' programs have been instigated since 1989 with the aim of recovering water pressure, most of which have been successful (DNRM, 2005). Natural discharge from the GAB occurs via vertical leakage or diffuse discharge to the surface, particularly where confining layers are thin or absent, and at several artesian spring complexes which are typically associated with areas of faulting or outcrop. About 90% of the natural GAB discharge is thought to occur by diffuse upward leakage through the overlying water tables, and ultimately by evaporation though the soil (GABCC, 1998; Tweed, 2007). Permanent springs are found along the southern and western discharge margins of the GAB and 'overflow' springs are found in the eastern recharge zones where the local topography and aquifers intersect (Thomson & Barnett, 1985). The GAB also discharges via subsurface flow to adjoining basins and submarine discharge to the Gulf of Carpentaria (DNRM, 2005).

3.9.1. GAB 2

The GAB 2 aquifer grouping refers to areas within the semi- arid or arid climate zones of the State Government of Queensland Great Artesian Basin Water Resource Plan Area. Mostly this refers to aquifers spatially associated with all portions of the GAB other than those in the far south east of Queensland categorised into GAB 4. The GMUs incorporated into the GAB 2 category are listed in Appendix A.

The major productive aquifers in this grouping are equivalents of the Hooray, Hutton, Algebuckina and Clematis sandstones and Canda-owie Formation, with the Injune Creek Group and Precipice sandstones also accessed. The aquifers are generally confined and sub-artesian to artesian in nature and water quality is variable but is generally <1,000 µS/cm EC. Yields range from <1 L/s to 80 L/s (DNRM, 2005). The majority of water extracted from these aquifers is used for stock and domestic purposes with irrigation, town supply, intensive stock watering and mining (mine supply and dewatering) extractions in some of the more developed GMUs. Shallow aquifers associated with Willumbilla Group equivalents are also accessed across most of the GAB 2 area, however water quality is typically poor (i.e. EC >1,000 µS/cm) and yields are generally low (DNRM, 2005). As such, extracted water is used predominantly for stock and domestic purposes.

3.9.2. GAB 4

The GAB 4 aquifer grouping refers to aquifers that are within the State Government of Queensland Great Artesian Basin Water Resource Plan Area that are subject to a sub-tropical climate and the GAB New South Wales GMU. This includes the Mulgilde, Eastern Downs and Clarence Morton GMUs in south eastern Queensland on the basis that these basins correlate with that of the major GAB structural basins and the sedimentary sequences are of similar age and nature (DNRM, 2005).

The major productive aquifers in this grouping are the local equivalents to the Hutton Sandstone (fine to coarse grained quartzose sandstone, lithic sandstone, siltstone and mudstone deposited from rivers and lakes) and the basal Precipice Sandstone (comprised of quartzose sandstone and siltstones) (DNRM, 2005). These aquifers are artesian or sub-artesian and water quality mostly ranges between 100-2,000 µS/cm EC, but can be variable with conductivities in excess of 4,000 µS/cm EC in some areas. Typical flow or pump rates range from 10 L/s to 30 L/s and groundwater is used extensively for mining, industrial, intensive stock and town water supplies in addition to stock and domestic supply. Overlying aquifers are typically of poorer quality, are lower yielding and are often associated with coal seam deposits. Accordingly, where utilised, shallow groundwater use is mostly restricted to stock watering and some domestic use (DNRM, 2005).

Overall, productive aquifers within the GAB 4 group are considered to be highly developed and “high to very highly” committed, with localised drawdowns of up to 70 m recorded. Demand on groundwater supplies is expected to increase in the future, with increases in urban development and mining activities forecast. Even in the absence of climatic considerations, it is expected that this development will result in progressive storage depletion and groundwater head decline (DNRM, 2005).

Additional pressures of groundwater resources are likely to result from the development of the Coal Bed Methane reserves across the GAB 4 group. Development of this resource is likely to result in significant dewatering of shallow aquifers and reduction of this largely marginal stock and domestic groundwater source through dewatering will in turn increase pressures on other aquifers and water sources in the area.

While these areas are under a high degree of extraction pressure little is known about the condition of the aquifers as there is limited monitoring in these dominantly sub-artesian areas (DNRM, 2005).

3.10. Gunnedah

The Gunnedah grouping comprises those GMUs in northeast NSW that are associated with the sedimentary Gunnedah and Narrabri Formation aquifers, and contemporaneous equivalents (Appendix A).

The Narrabri and basal Gunnedah Formations are spatially associated with the current surface water drainage systems and are comprised primarily of unconsolidated, interbedded sands, gravels and clays (CSIRO/SKM, 2010). The 15-50 m thick Narrabri Formation comprises recent alluvial fan sediments and is found either at surface or at up to 10 m below ground level (CSIRO, 2007). Groundwater in the Narrabri Formation is mostly fresh to brackish, but can be saline, particularly away from surface water features (CSIRO/SKM, 2010). The underlying Gunnedah Formation ranges between 20 m and 45m thick and groundwater is typically fresher to brackish (CSIRO/SKM, 2010). Underlying the Gunnedah Formation, but spatially restricted to paleochannels, the deepest aquifers within parts of some of the GMUs in the Gunnedah grouping is the coarse grained Cubbarroo Formation (CSIRO, 2007).

Groundwater is hosted in both the Narrabri and Gunnedah Formations, which are hydraulically connected across most areas and act as one aquifer unit. The aquifers are mostly unconfined and the watertable is typically intersected at 10 m below ground level. In certain locations, the Gunnedah Formation is semi-confined to confined by clay layers (Barret, 2009).

Recharge to the Narrabri Formation occurs primarily through leakage from rivers and watercourses and is supplemented by infiltration of floodwaters, diffuse rainfall recharge and root zone drainage associated with irrigation activities (CSIRO/SKM, 2010). Recharge to the Gunnedah Formation occurs primarily by downwards infiltration from the Narrabri Formation (CSIRO, 2007).

The groundwater resources of the Gunnedah grouping are amongst the most intensively developed in New South Wales, with extracted water used for stock and domestic, irrigation and town water supply purposes (CSIRO, 2007). The Gunnedah Formation aquifers form the primary groundwater source and most of the high yielding extraction bores are constructed in this aquifer. This has led to large drawdowns near regional centres (up to 20 m) and has induced leakage from the overlying (and typically more saline) aquifer and in certain locations, has resulted in dewatering of the Narrabri Formation (CSIRO/SKM, 2010; CSIRO, 2007; Barret, 2009).

3.11. Lachlan

The Lachlan group comprises the Billabong Creek, Mid Murrumbidgee, Upper Lachlan and Upper Murray Alluvial GMUs on the western slopes of the Great Dividing Range in southern New South Wales. Each of these areas is characterised by relatively deep valleys that contain alluvial deposits associated with the current and prior drainage systems.

The main productive aquifer is the confined Lachlan Formation (or Calivil Formation), a Late Tertiary alluvium which is up to 80 m thick and comprised of well sorted clean quartz sand and gravel (CSIRO/SKM, 2010; BRS, 2001). Groundwater is predominantly fresh (150-950 µS/cm EC) but decreases in quality away from the current surface water drainage systems (CSIRO/SKM, 2010). Extraction from the Lachlan Formation aquifers is high, with groundwater used extensively for town supply and irrigation purposes. As a result, substantial drawdown (up to 20 m) is observed at many locations (CSIRO/SKM, 2010).

Overlying the Lachlan/Calivil Formation is the Quaternary Cowra Formation (contemporaneous with and sometimes referred to as the Shepparton Formation), which is comprised of unconsolidated gravels, silts and clays with shoestring sand lends. The Cowra Formation ranges in thickness from 35 m – 80 m (CSIRO/SKM, 2010). Groundwater in the Cowra Formation is typically of poorer quality than in the Lachlan at >1,000 µS/cm EC, but extraction has resulted in significant drawdown and dewatering of this unit (BRS, 2001).

3.12. Lachlan Fold Belt 5

The Lachlan Fold Belt covers an extensive region of NSW forming part of the western watershed of the Great Dividing Range. It includes mountainous to hilly erosive landscapes in the east, grading westwards into depositional plains with low to gentle slopes and some protruding relict mountain ranges. It is composed of a composite orogenic belt of Mid-Cambrian to Early Carboniferous age rocks, consisting of meta-sediments, meta-volcanics and granites. The region forms predominately fractured-rock aquifers that are not extensively utilised.

Owing to their much lower porosity, fold belt fractured-rock groundwater systems have a much smaller storage size than large sedimentary basins such as the Great Artesian Basin or the Murray Basin. Thus, they respond faster and with greater magnitude to changes in the water balance than large sedimentary basins (Rancic, 2009).

3.13. Murray Group Aquifers

The Murray Group Aquifers comprises the extensive Tertiary Limestone Aquifer (TLA) units of the Murray geological basin in South Australia and western Victoria. The TLA units can be up to 140 m thick particularly in the vicinity of regional depocentres and may out crop at the surface but are more commonly overlain by younger sedimentary units (Lewis, et al., 2008). The Prescribed Wells Areas and GMUs represented by the Murray Group Aquifer grouping are presented in Appendix A.

Water quality is highly variable through the Murray Group Aquifers. In some areas groundwater quality is suitable for town supplies and irrigation purposes and in other areas the groundwater quality inhibits its use (CSIRO, 2008). The TLA is the major aquifer in the Murrayville and Mallee Prescribed areas where extracted water is used for town supplies, stock and irrigation purposes (CSIRO, 2008). Good quality groundwater is essentially a fossil resource, recharged around 20,000 years ago, and not greatly influenced by current recharge events.

3.14. Newer Volcanics

The Newer Volcanics are basalt aquifers that form in broad, low volcanic plateaus throughout Western Victoria. Fractures in the basalt form the primary pathways for groundwater flow. The aquifers are recharged directly through numerous volcanic cones and via infiltration through fractures. Recharge occurs preferentially in areas of less weathered basalt, stony rises and eruption points. Outside of preferential recharge areas, there is a lower flux of water reaching the water table due to lower infiltration rates and increased evapotranspiration (Tweed, 2007). Groundwater from these basalts is used for stock and domestic purposes, irrigation, and town water supplies. Groundwater flow typically radiates outward from the elevated recharge sources into the plains. Groundwater quality of the Newer Volcanic aquifers is highly variable depending on proximity to the recharge area. Groundwater is of good quality (<560 mg/L TDS) around volcanic vents and increases to over 3360 mg/L TDS in low recharge areas. Groundwater quality of the basalt in the Daylesford area is good, averaging around 200 mg/L TDS (Heislers, 1993).

3.15. Otway Basin

The Otway Basin is a regional sedimentary basin extending from southeast South Australia along the south coast of Victoria to Melbourne. However in this project, the Otway Basin describes only the South Australian portion that comprises the Lower Limestone and Padthaway Coast Prescribed Wells Areas in southeast South Australia. The Otway Basin grouping contains two distinct, regionally extensive groundwater systems; the Tertiary Confined Sands Aquifer (TCSA) and the overlying, unconfined Tertiary Limestone Aquifer (TLA). The TLA forms the primary productive aquifer. Groundwater in the TLA is typically fresh to brackish and is used extensively for town, stock and domestic supplies, by commercial forestry and for the irrigation of crops and pasture (the latter, irrigation, responsible for up to 98% of groundwater use) (AWR, 2005). Commercial forestry plantations are also considered to use groundwater through infiltration interception and direct extraction where plantations overlie and access shallow groundwater. Direct extraction via this method accounts for approximately 7% of total available recharge (DWLBC, 2007).

Recharge to the TLA (and the TCSA) occurs via inflow from the adjoining Dundas Plateau in Victoria and the dominant flow direction is subsequently east to west (DWLBC, 2006). Recharge to the TLA in this area also occurs via diffuse rainfall infiltration and groundwater levels are responsive to changes in the precipitation regime. In general, rainfall has declined across the TLA and this has led to significant water table declines in over half of the management areas. This is due to the direct mechanism of decreased precipitation rates and the indirect mechanism of decreased precipitation rates leading to an increased demand for groundwater resources (DWLBC, 2006).

Compounding the effects of reduced precipitation are groundwater extractions that exceed the sustainable yield of the TLA resulting in widespread resource degradation, both in terms of availability (declining groundwater levels) and water quality (increased salinity from salt mobilisation) (DWLBC, 2007).

3.16. Pilbara

The hydrogeology of the Pilbara region is described by Johnson & Wright (2001), Haig (2009) and MWH (2009). The Pilbara grouping comprises three main aquifer groups; the unconsolidated sedimentary aquifers associated with valleys (alluvium and colluviums), chemically deposited aquifers (calcrete and pisolitic limonite) and fractured-rock aquifers. The valleyfill deposits are up to 200 m thick, comprise various sedimentary sequences of clay, sand and gravel, and form unconfined aquifers in connection with underlying basement rocks. The chemically-deposited aquifers form in Palaeochannels with groundwater flow predominately occurring through karstic features. Fractured- rock aquifers form in dolomitic formations and within the fractured and mineralised ore bodies. The iron-ore industry is the major groundwater user in the area for mine dewatering, dust suppression, and mineral processing (Johnson & Wright, 2001).

3.17. Port Campbell Limestone

The Port Campbell Limestone grouping incorporates the Glenelg and Hawkesdale GMUs and the Nullawarre and Yangery Groundwater Supply Protection Area located on the south west coast of Victoria. The mid to late Miocene Port Campbell Limestone is the primary productive aquifer in this region and is comprised primarily of marine calcerenite. Clay rich marl increasingly interfingers the calcarenite with depth, such that only the top 50 – 200 m of the Port Campbell Limestone is considered a productive aquifer. The Port Campbell Limestone is either found in outcrop or is overlain by hydraulically connected younger dune sands and volcanics and therefore it can be considered the water table aquifer (DEWHA, 2009). Groundwater is if of good quality (≤1,000 mg/L TDS approximately) and is used extensively for irrigation purposes.

The Port Campbell Limestone is part of the greater Otway Basin, but is distinguished from the South Australian potion of the Otway Basin as defined in this project. The distinction was made to isolate the carbonate/karstic aquifers of the broader Otway Group. In southeast South Australia, the major productive Tertiary limestone aquifer outcrops; whereas in Victoria, the productive Port Campbell limestone is partly overlain by basalt. The two aquifers are thus likely to exhibit a different response to climate change so they are separated in this project.

3.18. Atherton Tablelands

The Atherton Tablelands comprise the Pleistocene Basalt aquifers of the Atherton A and B GMUs, located on eastern slopes and tablelands of the Great Dividing Range in far north Queensland. This aquifer comprises numerous, multilayered basalt flows separated by palaeo-weathering surfaces and minor alluvial gravels of palaeo-drainage channels (Locsey, 2004). Basalt flow thicknesses range from 50-120 m; however groundwater is extracted primarily from the fractured and thinner weathered zones of basalt. Pump rates from range from 2 – 20 L/s up to 40 L/s (DEWHA, 2009; CSIRO, 2001).

The Quaternary Basalts are a highly dynamic system, characterised by high horizontal flow rates (approaching 10 m per year), and short groundwater residence times – mostly less than 30 years (CSIRO, 2001). Recharge is relatively high at 150-660 mm/year (or 16-33% of incident precipitation), but highly seasonal coinciding with the summer monsoon season (CSIRO, 2001). Diffuse rainfall infiltration is the primary recharge mechanism, but only occurs after the soil profile is fully wetted which is usually by December of each year (AGE, 2007). Minor recharge also occurs via stream leakage (AGE, 2007). The groundwater system is highly connected to the surface water drainage system and most recharge that is not extracted discharges to streams (CSIRO, 2001). As such, the aquifers are considered a seasonally finite resource (Balston & Turton, 2006).

The basalts are considered to be highly developed and extracted groundwater is primarily used for crop irrigation, town and industrial supply and stock and domestic applications. Extraction has increased by over an order of magnitude from approximately 3,000 ML/year in the mid 1980's to 14,000 ML/year (approaching the then sustainable yield of 15,000 ML/year) in 2001 (CSIRO, 2001). The sustainable yield has since been increased however the system remains currently over allocated and approaching extraction limits (DEWHA, 2009). Despite this, groundwater levels are stable and entitlements were 100% of allocations in the 2009/10 period (DERM, 2009).

3.19. South Perth Basin

The South Perth Basin grouping encompasses the Blackwood, Blackwood – Karri, Busselton Capel, Bunbury and Bunbury – Karri GMUs in the south west of Western Australia. The area is reliant on groundwater resources for irrigation purposes.

The main productive aquifers in this grouping are the sedimentary Yarragadee (in the Blackwood, Blackwood – Karri and Busselton Capel GMUs) and Cockleshell Gully Formations, the regionally extensive Leederville Formation, and the uppermost Superficial Aquifers. The hydrogeology of these units was reviewed in detail by (CSIRO, 2009) and much of the background information presented here is derived from that report.

The Yarragadee Formation is a thick (1,000-2,000 m) Jurassic sedimentary assemblage composed primarily of sand. The regional groundwater flow direction in this formation is from south to north and recharge occurs via direct rainfall recharge where the aquifers outcrop, and where confining beds are absent and downward vertical recharge from the overlying Leederville and Superficial aquifers occurs. The Yarragadee aquifers discharge directly to streams, and in the north of the Basin where vertical hydraulic gradients are reversed, to overlying aquifers and the Indian Ocean.

The Leederville Formation is a Cretaceous, multilayered sedimentary aquifer system comprising discontinuous sand beds and clay layers, up to 400 m thick. Aquifers within the formation are confined to unconfined and contain fresh to brackish groundwater (180 - 2,130 mg/L TDS). Recharge occurs via direct rainfall infiltration where the formation outcrops and via downwards leakage from the overlying Superficial Aquifer where present. Flow is directed away from the resultant localised recharge mounds in the centre of the basin to both the north and the south and groundwater discharges to streams, to the underlying Yarragadee Formation and to both the Southern and Indian Oceans.

The Superficial Aquifers are a Cainozoic collection of sand, clay and limestone and are spatially restricted to the coastal areas. Recharge occurs via direct rainfall infiltration and discharge occurs to streams, to both the Southern and Indian Oceans, and in the south of the basin where vertical hydraulic gradients allow, to the underlying Leederville and Yarragadee aquifers.

The depth to groundwater varies across the South Perth Basin area, from <3 m in coastal areas to greater than 10 m inland.

3.20. Toowoomba Basalts

The Toowoomba Basalts include the Toowoomba North, Toowoomba South, Toowoomba City, Warwick and Nobby Basalt GMUs in southeast Queensland. The basalts form part of the Tertiary Main Range Volcanics and groundwater is hosted in fractures, vesicle and weathered zones of these basalts. Aquifers are intersected anywhere between 2 m and 155 m below surface, are typically 10-30 m thick and may be confined, semi-confined or unconfined. Groundwater salinity ranges from fresh to brackish (DEWHA, 2009). Groundwater levels in the basalts are responsive to rainfall events and recharge occurs via direct infiltration where units outcrop or through overlying well drained soils. Sustainable yields from the Basalt GMUs have been established empirically (from historical data) or from recharge estimates derived from runoff and soil moisture models (DEWHA, 2009).

Natural discharge from the Toowoomba Basalts occurs via outflow to the Condamine Alluvium (to which it is hydraulically connected). Additionally, there is a high density of irrigation, stock and domestic, and municipal supply bores across the area with over 80% of groundwater extracted used for irrigation purposes (CSIRO/SKM, 2010).

3.21. Upper Valley Alluvium 4

The Upper Valley Alluvium 4 class comprises aquifers within the Belubula Alluvium, Cudgegong Alluvium, Bell Valley Alluvium, Castlereagh Alluvium and the Collaburragundry-Talbragar Valley alluvium located in central east New South Wales. The alluvial deposits are spatially associated with the current surface water drainage system and are typically thin (<15-30 m) and narrow. Sediments include gravels, sands, silts and clays (CSIRO/SKM, 2010). Groundwater is typically intersected within deeper coarse sand and gravel layers with water tables approximately 5 m below surface (DEWHA, 2009). Average groundwater salinities are in the range of 400-500 mg/L TDS but brackish conditions are experienced throughout the units (CSIRO/SKM, 2010).

Recharge to these aquifers occurs via diffuse rainfall infiltration either directly or through overlying permeable alluvial soils, results from infiltration of slope runoff or via leakage from associated rivers (CSIRO/SKM, 2010).

Groundwater extraction is a major discharge mechanism and there is a high density of stock and domestic, irrigation and high volume extraction (>100 ML/day) bores throughout the Upper Valley Alluvium 4 aquifers. Current levels of development are classified as high in the Collaburragundry-Talbragar Valley and very high in the Belubula, Cudgegong, Bell Valley and Castlereagh areas (CSIRO, 2008).

4. RECHARGE AND DISCHARGE PROCESSES

As part of the aquifer characterisation component of this project, the recharge and discharge processes for the priority aquifers will be examined to outline how these aquifers may be sensitive to climate change. Recharge and discharge processes are the primary determinants of groundwater availability, as described in the following equation for the water balance of a groundwater resource:

$$R - D = \Delta S \qquad [10]$$

Where *R* is groundwater recharge; *D* is groundwater discharge and *ΔS* is change in storage.

Recharge is the process by which groundwater is replenished. If it increases, more water becomes available for consumptive users or the environment. If it is diminished, less water becomes available. Discharge is the removal or loss of groundwater and has the opposite effect to recharge. An imbalance between recharge and discharge results in a change in groundwater storage. If recharge exceeds discharge, then groundwater levels rise. If recharge is less than discharge, then groundwater levels decline.

Climate change has the potential to alter both recharge and discharge and thereby perturb groundwater availability. The extent to which groundwater availability is altered for a particular aquifer system will be dependent on the nature of climate change at the relevant location, and the sensitivity of recharge and discharge processes to those changes in climate.

This chapter outlines the sensitivity of the recharge and discharge processes in the aquifer systems identified as being priority in Chapter 2 (Aquifer Prioritisation). The intention of this assessment is to highlight the potential pressure points and vulnerabilities of these aquifers to climate change.

4.1. Outline and Methodology

Recharge and discharge can be broken down into several key processes. The major recharge processes are diffuse recharge from rainfall infiltration and localised recharge from surface water losses. The major discharge processes are discharge to surface water, evapotranspiration, groundwater extraction and outflows to the ocean. Locally important recharge and discharge processes include natural and induced inter-aquifer leakage and induced recharge.

A general methodology has been devised to ascertain how each of the above processes may be sensitive to climate change for the priority aquifers. Each major recharge and discharge process will be examined using the following methodology:

4) The way in which the recharge/discharge process operates will be described;
5) The factors controlling the process will be examined to isolate the particular attributes of an aquifer that make the process either sensitive or less sensitive to climate change; and
6) The priority aquifers will be analysed to highlight those that have attributes making them sensitive to climate change, and those that have attributes making them less sensitive to climate change.

The assessment findings for each recharge and discharge process will be compiled for every aquifer to illustrate the sensitivities of the priority systems. Emphasis is placed on the shallow unconfined aquifers as these are generally the most important with regard to climate impacts.

4.2. Recharge Processes

Groundwater recharge is defined as the entry of water into the saturated zone at the water table (Freeze and Cherry, 1979). While recharge can be defined more broadly as any water that reaches an aquifer from any direction (Lerner, 1997), this paper focuses on the downward movement to the water table.

Recharge occurs via two primary mechanisms; diffuse recharge and localised recharge.

Diffuse recharge refers to recharge that is relatively uniform across a given landscape and hence is generally derived from rainfall or irrigation and results from widespread percolation through the unsaturated zone.

Localised recharge refers to concentrated recharge; such as that from streams, which may occur either from within-bank recharge or over-bank recharge, or from point sources of water input, such as via dolines and caves. Within-bank recharge is the process of a stream recharging an aquifer through its banks and is often referred to as ‘bank storage’ because the water that moves from the stream bank to the aquifer is generally returned back to the river when the river levels fall. Over-bank floodplain recharge relates to the recharge of the groundwater through the soil surface after the stream has broken its banks.

4.2.1. Diffuse recharge

Diffuse rainfall recharge is the most prevalent form of recharge to Australian aquifers. The simplified process is illustrated in Figure 4-1 and is described as follows:

1) A portion of rainfall enters the soil profile as infiltration (some will be lost to interception, runoff or ponded evaporation). A number of factors influence the extent of infiltration during a rainfall event, including: the amount of rainfall, its intensity and duration; the nature and density of vegetation coverage; topographic slope and geomorphic controls; soil permeability, and the antecedent moisture content of the soil.

2) The soil profile is a storage that is filled by infiltration and depleted by soil evaporation and plant transpiration. Soil moisture storage is determined by soil and plant characteristics such as the depth of the soil profile, the rooting depth and soil hydraulic properties. Field capacity and permanent wilting point mark the upper and lower levels of water content of a soil which is available to plants. Soil moisture in excess of field capacity will typically drain rapidly under gravity and becomes deep drainage.

3) Deep drainage water may be perched (and transmitted laterally above the watertable to discharge at the surface), or it may percolate through the unsaturated zone and enter the watertable to become recharge. The transit time through the unsaturated zone depends on the permeability and thickness of the unsaturated zone. Where water tables are shallow, this process may take minutes. Where water tables are deep, the process may take decades or even several millennia.

4) In certain situations the soil storage can be bypassed by preferential flow and rapid recharge events can occur. Preferential flow can occur in a variety of ways (Hendricks and Flurry, 2001). Flow can be transmitted through large conduits such as macropores (e.g. old root channels), desiccation cracks or karstic channels. These conduits have a large diameter such that water drains freely under gravity and cannot be retained within the soil profile. Preferential flow can also occur when unstable wetting fronts develop. This mainly occurs in coarse textured soils and is sometimes called ‘fingering’ in reference to the concentration of flow in finger-like columns. Unstable wetting is related to air-entrapment and water repellency. Preferential flow can be an important component of groundwater recharge and will in some cases be the dominant recharge mechanism.

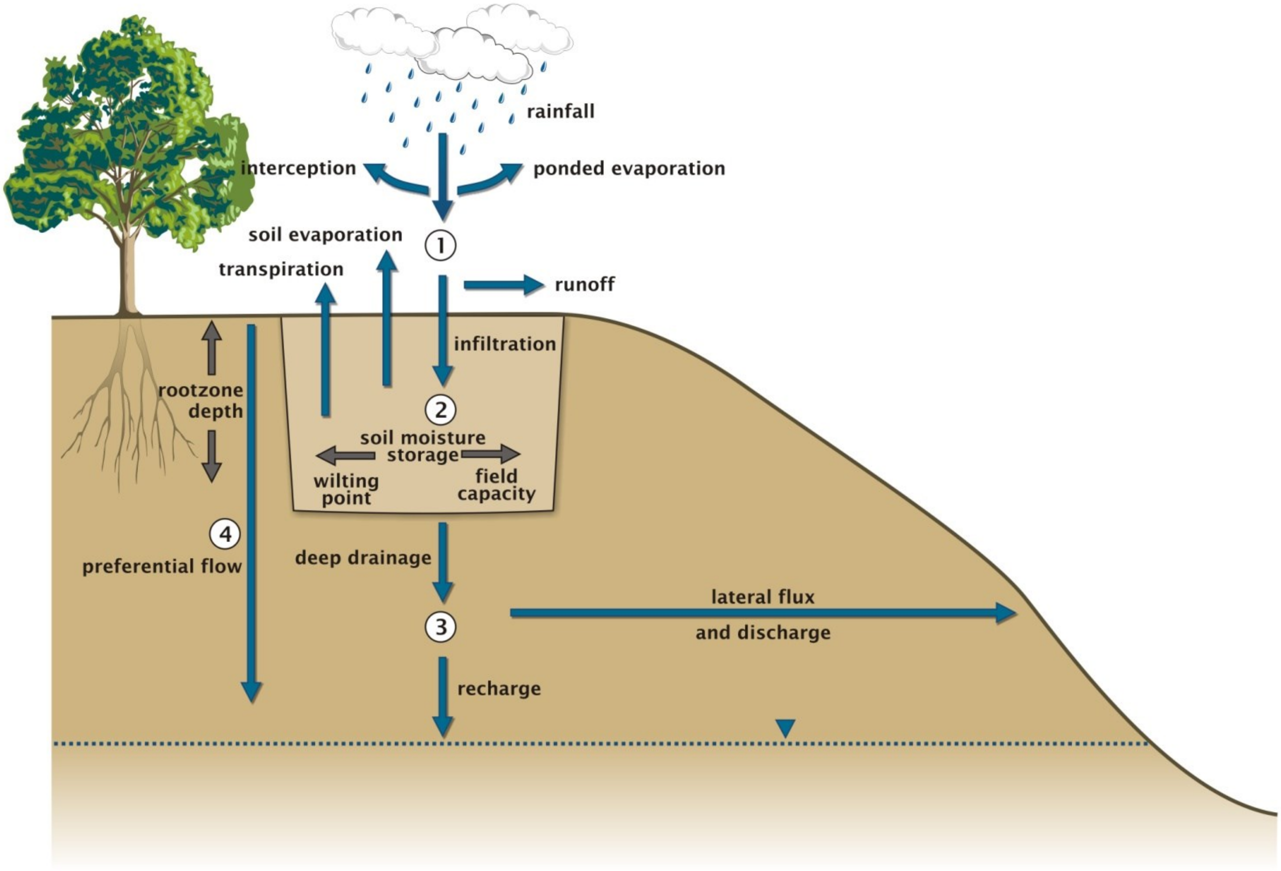

Figure 4-1 Diffuse rainfall recharge processes

Irrigation recharge generally follows more or less the same process as rainfall recharge, with the major difference being the source of water. The extent to which irrigation recharge enhances natural rainfall recharge is dependent on irrigation efficiency. Inefficient irrigation systems can cause significant deep drainage, which is limited in more efficient systems such as drip or trickle.

Factors influencing diffuse recharge

Diffuse recharge is influenced by climate, land use, land forms, soil properties and water table depth. It is closely related to climatic factors; particularly rainfall and evaporative demand. The timing and intensity of rainfall in relation to evaporative demand influences interception, runoff, infiltration, plant transpiration and soil moisture relations. Land use determines the nature and density of vegetation coverage - impacting interception, soil evaporation and transpiration – and includes irrigation activity leading to enhanced recharge rates[4]. Landforms influence runoff: a function of relief, land use and climate. Soil properties control the storage capacity of the soil, the potential for preferential flow, and the rate at which water can move through the unsaturated zone. The depth of the water table controls lag times between rainfall and recharge, and impacts net recharge – when the water table is shallow (i.e. within the root zone) there are losses to evapotranspiration which will limit net recharge.

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[4] The indirect implications of climate change on land use was recognised by Ficklin et al. (2010) who predicted that irrigators would respond with a change in planting regime in order to account for the increase in plant growth rates (given that crops grow faster under higher average daily temperatures). Although faster crop development would result in a reduced growing season water demand, it is likely that multiple cropping would occur and hence the annual water demand may increase. The indirect impacts of climate change on land use are recognised, yet they are not considered further as part of this work.

Aquifer characteristics that influence diffuse recharge sensitivity

Of the factors listed above that influence diffuse recharge, some are dynamic and controlled by external forces (e.g. climatic factors and land use / vegetation) while others are more fixed and more closely related to the physical attributes of a particular aquifer system (e.g. soil properties, land forms and water table depth). It is these fixed attributes that are the focus of this chapter as they will determine the potential sensitivity of a particular aquifer system to climate change. The variable and dynamic factors influencing recharge are being assessed in a separate component of the project where climatic and recharge modelling exercises are being undertaken. The integration of the two components of the project (fixed and dynamic assessments) will provide a combined picture as to the likely impact of climate change on the priority groundwater resources.

Before an assessment of the priority aquifer systems, it is first necessary to determine which physical attributes of aquifers are indicative of diffuse recharge being sensitive or insensitive to climate change. In broad terms, an aquifer is considered more sensitive to climate change impacts on diffuse recharge where it is a dominant component of the water balance and where it occurs rapidly (i.e. where it is promoted).

In the first instance, the extent to which rainfall is partitioned into runoff (surface drainage) and infiltration (potential recharge) may be an important indicator of recharge sensitivity. Aquifers associated with poor surface drainage features (e.g. few natural watercourses) will almost be entirely dependent on diffuse recharge as a source of recharge. Therefore changes in diffuse recharge in such aquifers are likely to have a more acute impact. Aquifers with poor surface drainage tend to occur where there is subdued topography and coarse-textured soils.

Soil properties that are influential for diffuse recharge are profile thickness, soil water storage, soil hydraulic conductivity and characteristics that encourage preferential flow. Soil profile thickness influences soil moisture storage and the transmission time for water to pass through the vadose zone. Soil moisture storage – also determined by soil texture and structure – is a buffer to rainfall becoming recharge. Hydraulic conductivity controls the rate at which water passes through the vadose zone. And preferential flow is a mechanism by which rapid recharge can occur.

The following soil characteristics are inferred for diffuse recharge sensitivity as they promote recharge: thin soil profiles, limited storage, high hydraulic conductivity and likely preferential flow.

Assessment of diffuse recharge sensitivity for priority aquifers

Soil and landform data was analysed for the high priority aquifer systems to assess their potential sensitivity to diffuse recharge changes. The Atlas of Australian Soils was obtained and soil property data attributed according to McKenzie et al. (2000). The soil property data was clipped to the extent of the priority aquifer systems. (In the case of the GAB, the data was clipped to defined recharge areas). The following soil property data was collated: soil and landform descriptions; soil profile depths, Plant Available Water Capacities (PAWC[5]), which are a measure of soil moisture storages; and saturated hydraulic conductivities for both the A and B horizons. Each aquifer comprised multiple soil mapping units with different soil types and associated properties. To summarise the data on an aquifer basis, the soil and landform descriptions were reviewed and summarised, and the numerical properties for the various soil mapping units were averaged on a spatially-weighted basis. For example if one soil mapping unit covered 80% of an aquifer's area, the soil depth, PAWC and Ksat were weighted by 0.8 and summed with the values from smaller units weighted by factors of less than 0.2.

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[5] The Plant Available Water Capacity (PAWC) is a parameter that quantifies soil water storage. It is calculated as the amount of water held between field-capacity and permanent wilting point, summed over the rooting depth.

The collated soil and landform property data is shown in Table 4-1 for the high priority areas.

The soil and landform descriptions demonstrate a variety of geomorphic settings for the priority aquifers. From the perspective of diffuse recharge, the key features are relief, soil type, soil texture and soil depth. The aquifers with poor surface drainage (few watercourses) have subdued topography and coarse-textured soils. The Perth Basin (North and South), the Otway Basin, the Port Campbell Limestone and the Murray Group all have poor surface drainage.

The numerical parameters in Table 4-1 have limited variability compared to expected field data. For instance, soil profile depths can vary from 0 to > 10m deep, and hydraulic conductivities tend to range over several orders of magnitude. The low variability is probably a result of aggregating large areas. Nevertheless, the data provides a broad regional summary from which relative differences between aquifers can be identified. A rating was assigned to each of the parameters as follows: 'high' or equivalent being > 75th percentile; 'moderate' or equivalent being between the 25th and 75th percentile; and 'low' or equivalent being < 25th percentile. (The percentiles were derived from the presented dataset).

Soil profile thickness unsurprisingly shows a close relationship to PAWC (Table 4-1) with the following aquifers identified as being sensitive in these categories: the Adelaide Geosyncline, Coastal Sands, Newer Volcanics, Toowoomba Basalts and Pilbara (moderate PAWC, yet shallow soils). The fractured rock and basalt systems tend to rank as sensitive in these categories, but there are some exceptions: the Atherton Tablelands basalt where deep loams are prevalent; and the Lachlan Fold Belt which covers an extensive area of highly variable soil types.

Saturated hydraulic conductivities (Ks) are listed in Table 4-1 for both A horizons (topsoil) and B horizons (subsoil). The A horizon Ks is probably more critical to diffuse recharge because it affects infiltration and this is where most evapotranspiration occurs in the unsaturated zone. Several aquifers are regarded as being more sensitive in terms of Ks. The Adelaide Geosyncline, Lachlan Fold Belt and South Perth Basin have comparatively high Ks in both the A and B horizons. The Central Perth Basin, Daly Basin and Port Campbell Limestone have comparatively high Ks in the A horizon and comparatively moderate Ks in the B horizon.

The likelihood of preferential flow is not included as an attribute in the Atlas of Australian Soils or ASRIS database. It is an attribute that is difficult to identify, yet is often associated with coarse-textured soils where uneven wetting fronts develop or with karstic systems (which also have coarse-textured soils) where dissolution features channel flow. It is documented as occurring in the coarse-textured soils covering the Gnangara mound in the Central Perth Basin (Salama et al., 2005) and in the karstic environs of the Oolloo Dolostone and Tindall Limestone (Daly Basin) (CSIRO, 2009). Based on this logic, the aquifers with coarse-textured soils and/or karstic features have been identified as aquifers where preferential flow is likely to be more prevalent. Other aquifer systems are included where the mechanism is documented – e.g. the Newer Volcanics (Tweed et al., 2007).

In summary, the aquifers rated as sensitive to changes in diffuse recharge are as follows: Adelaide Geosyncline, Central and South Perth Basins, Coastal Sands, Daly Basin, Newer Volcanics, Toowoomba Basalts, Otway Basin, Port Campbell Limestone and Lachlan Fold Belt. Despite not being rated as sensitive from the analysis of soil and land use properties, the Atherton Tablelands aquifer is also included due to its known relatively high recharge rates and dynamic fluctuations in groundwater levels (Cook et al., 2001; Locsey, 2004).

Table 4-1 Soil and landform property data

Aquifer	Aquifer type	Climate zone	Landscape and soil description	Surface drainage	soil profile thickness		PAWC		Ks			Preferential flow
					m	rating	mm	rating	A horizon (m/d)	B horizon (m/d)	rating	
Adelaide Geosyncline 3	fractured rock	3	Hills and valleys with shallow soil varieties	typical	0.79	shallow	67	low	0.88	0.80	high A, high B	less likely
Condamine and Border Rivers Alluvium	alluvium	4	Gentle slopes and plains with dark cracking clays	typical	1.20	deep	134	high	0.67	0.49	low A & B	less likely
Calivil	Riverine plains	2	Plains with low sand hills, prior streams and variable soils. Some gilgai plains with cracking clays	typical	1.13	deep	114	high	0.71	0.60	low A, moderate B	less likely
Central Perth Basin	sedimentary basin	3	Subdued dune/swale systems, plains and plateaus with deep sandy soils	poor	0.97	deep	130	high	0.93	0.70	high A, moderate B	likely
Coastal River Alluvium 1	coastal alluvium	1	Alluvial plains with loamy soils	typical	0.96	moderate	108	moderate	0.81	0.68	moderate A & B	less likely
Coastal River Alluvium 4	coastal alluvium	4	River terraces and floodplains with porous loams	typical	0.93	moderate	110	moderate	0.82	0.71	moderate A & B	less likely
Coastal Sands 4	coastal sands	4	dune/swale systems and sandy plains	poor	0.64	shallow	83	low	0.83	0.47	moderate A, low B	likely
Daly Basin	carbonate	1	Gently undulating terrain on sandstones, siltstones and limestones. Soils variable	typical	0.82	moderate	112	moderate	0.89	0.67	high A, moderate B	likely
GAB 2	sedimentary basin	2	Varied	typical	0.77	shallow	90	moderate	0.72	0.50	low A, low B	less likely
GAB 4	sedimentary basin	4	Varied	typical	0.88	moderate	89	low	0.78	0.51	low A, low B	less likely
Gunnedah	alluvium	4	Plains with cracking clays	typical	1.25	deep	138	high	0.61	0.45	low A & B	less likely
Lachlan	alluvium	4	Plains and river terraces with hard, red alkaline soils	typical	0.99	deep	90	moderate	0.83	0.73	moderate A, high B	less likely
Lachlan Fold Belt 5	fractured rock	5	Steep and undulating country with variable landscape and soils	typical	0.95	moderate	118	high	0.89	0.81	high A, high B	less likely
Murray Group	carbonate	2	Sandy plains and dunes	poor	0.87	moderate	92	moderate	0.88	0.68	moderate A & B	likely
Newer Volcanics	basalts	5	Stony rises with dark shallow porous loamy soils	typical	0.81	shallow	66	low	0.83	0.51	moderate A & B	likely
Otway Basin	carbonate	3	Plains with swamps, dunes. Limestone outcrops and typically sandy soil	poor	1.00	deep	92	moderate	0.83	0.51	moderate A & B	likely
Pilbara	fractured rock	2	Stony shallow soils with outcropping geology	typical	0.78	shallow	99	moderate	0.86	0.80	moderate A, high B	less likely
Port Campbell Limestone	carbonate	3	Plains with variable but often sandy soils	poor	0.84	moderate	95	moderate	0.91	0.60	high A, moderate B	likely
Atherton tablelands	basalts	4	Basaltic plateaus flanked by steep slopes. Soils are deep red friable earths	typical	1.38	deep	205	high	0.88	0.79	moderate A, high B	less likely
South Perth Basin	sedimentary basin	3	low relief plateaus and plains with sands	poor	0.94	moderate	125	high	0.90	0.79	high A, high B	likely
Toowoomba Basalts	basalts	4	Steep to hilly with shallow porous loamy soils	typical	0.64	shallow	85	low	0.71	0.40	low A &B	less likely
Upper Valley Alluvium 4	upper valley alluvium	4	River terraces and floodplains with variable soil types	typical	0.91	moderate	115	moderate	0.80	0.67	moderate A & B	less likely

4.2.2. Localised Recharge

Localised recharge refers to concentrated recharge, such as that from streams, which may occur either from within-bank recharge or over-bank recharge, or point sources of water input, such as via dolines and caves.

Localised recharge occurs where there is a hydraulic connection between the surface water and the groundwater system and where the groundwater level is lower than the stream elevation. In these situations water seeps from streams to recharge underlying aquifers. The rate at which surface water seeps into the aquifer is controlled by the difference in head between the aquifer and the stream. Streams that lose water to groundwater are called “losing streams”, and the recharge to the groundwater is called “surface water leakage” (SKM, 2006a).

Localised recharge first requires a hydraulic connection between streams and the groundwater system. Strong interactions between streams and the groundwater system are usually associated with shallow aquifers. The shallow aquifers are generally “unconfined”, but may be “semi-unconfined” (SKM, 2006b). Most groundwater systems are connected to surface water when the full extent of the system is taken into consideration. Streams and groundwater interact in all types of landscapes and, as there are many types of landscapes and geological settings, there is much variability in the nature and degree of connectivity between surface water and groundwater systems (Reid et al., 2009). Winter et al. (1998) describe interaction as occurring in three basic ways:

- streams gaining water from inflow of groundwater through the streambed;
- streams losing water to groundwater by outflow through the streambed; and
- streams that do both, gaining in some parts and losing in others, or perhaps alternating between gaining and losing depending on periodic changes in relative stream and groundwater levels.

Localised recharge is driven by river levels that are controlled by rainfall. Over-bank floodplain recharge is driven by the frequency and intensity of flooding events. Changes in temperature and precipitation are expected to alter groundwater recharge to aquifers, causing shifts in water table elevation in unconfined aquifers as a first response to climate trends (Scibek & Allen, 2006). Where an aquifer is hydraulically connected to the surface water, changes to the surface water regime also impact water table elevations. In this respect, climate change-induced changes to the frequency and intensity of rainfall and flooding events in particular may impact localised recharge.

Factors influencing localised recharge

Literature was reviewed to identify the factors that influence localised recharge and to isolate attributes that are indicative of sensitivity.

Allen et al. (2004) modelled the sensitivity of the Grand Forks aquifer in south-central British Columbia, to climate driven changes in recharge and river stage. The Grand Forks aquifer is a highly productive alluvial aquifer situated in a bedrock valley, approximately 4 km wide near its centre and narrower at both ends. The area is characterised by a semi-arid climate. Annual diffuse recharge to the narrow alluvial aquifer is limited and the simulations of high and low diffuse recharge rates showed there was little impact on changes to hydraulic head. However, an assessment of changes in river-stage elevation provided an insight into the process that controls recharge and the seasonal availability of groundwater in the valley, for this particular aquifer. The aquifer was highly sensitive to changes in river stage. For a scenario that simulated flood conditions of 50 % higher than average flows, the watertable averaged 3.5 m higher than current levels and there was an increase in surface water leakage to surrounding aquifers. These results are consistent with what is expected of a narrow alluvial valley aquifer situated in a bedrock valley, with river stage providing the dominant control on aquifer water levels.

A study of two aquifers in Denmark by Van Roosmalen et al. (2007) found that the magnitude of the hydrological response to projected climate change was highly dependent on the geological setting. Modelling projected a significant increase in mean annual rainfall, but with drier summers. The aquifer characterised by sandy soils and large interconnected aquifers indicated that surface water leakage increased significantly, resulting in higher groundwater levels and increased groundwater – river interactions. For the aquifer characterised by low-permeability soils and covered by clay-rich layers of regional extent, only minor changes in groundwater levels were predicted.

The results from Van Roomalen et al. (2007) suggest that aquifers with highly permeable stream beds or karstic features such as dolines will be more sensitive to changes in streamflow caused by climate change. Indeed climate change modelling conducted in the karstic Daly River catchment, Northern Territory, as part of the NASY project showed significant changes in aquifer-stream interactions as a results of varying rainfall (CSIRO, 2009b).

Scibek and Allen (2006) compared the response of two small aquifers to projected climate change. Both aquifers were unconfined, heterogeneous and highly permeable; typical of aquifers found in southern British Columbia. Climate modelling projected a shift in the hydrograph peak to an earlier date, but no change in the magnitude of the peak. For the aquifer in which diffuse recharge was the most significant recharge mechanism (compared to localised recharge), only minor changes to groundwater level were predicted. More significant changes to both groundwater levels and aquifer-stream interactions were predicted at the second aquifer, which was confined to a narrow river valley and recharged predominantly by surface water.

To summarise, the following aquifer attributes have been identified as indicators of localised recharge sensitivity: a high degree of river-aquifer connectivity; a high proportion of localised recharge relative to diffuse recharge; a geomorphic setting of narrow alluvial aquifers; and attributes which promote rapid recharge, such as coarse-textured stream-beds or karstic features. Also, aquifers that are recharged by ephemeral streams (as opposed to perennial streams) are considered more sensitive to climate change due to the likely impact of climate change on streamflow events and duration.

Assessment of sensitivity of priority aquifers to localised recharge

The process of groundwater discharge to surface water and of surface water leakage to aquifers, are intricately connected, which is why the two processes are typically discussed in terms of ‘groundwater and surface water interaction’. For this reason, an integrated assessment of the sensitivity of groundwater – surface water interactions has been conducted, as opposed to the examining the recharge and discharge processes separately. The assessment is discussed in section 4.3.1.

4.3. Discharge Processes

Groundwater discharge is the removal of water from the saturated zone across the water table surface, together with the associated flow toward the water table within the saturated zone (Freeze and Cherry, 1979). The major discharge mechanisms can be localised – such as discharge to springs, rivers, wetlands, lakes and to groundwater extraction bores – or more widespread, such as lateral discharge to oceans or evapotranspiration where watertables are shallow. The sensitivity of these mechanisms to climate change is discussed below.

4.3.1. Discharge to surface water

The discharge of groundwater to surface water occurs where there is a hydraulic connection between streams and aquifers, and where the water table is higher than the stream elevation. In this case the stream is defined as a “gaining stream”, and the groundwater discharge is called “base flow”.

During low flow conditions in a stream, baseflow can constitute a high proportion of the total streamflow.

Factors influencing discharge to surface water

The factors influencing groundwater discharge to streams are similar to those influencing localised recharge (stream leakage). The rate at which groundwater discharges into a stream is largely determined by the slope or angle of the watertable (hydraulic gradient) and the permeability (or hydraulic conductivity) of the adjacent aquifer (SKM, 2006a).

Scibek and Allen (2006) predicted that under a drying climate, lower groundwater levels would lead to altered groundwater - surface water interactions. The predicted lowering of groundwater levels in the vicinity of a gaining stream resulted in flattening the hydraulic gradient between the river and the aquifer such that a subsequent reduction in baseflow was noted, particularly in summer months.

Investigation of the Grand Forks aquifer by Allen et al. (2004) concluded that variations in river-stage elevation were the major driver of watertable elevation change. For a scenario under a drying climate; the watertable was predicted to be 2.1 m lower than current levels and a decreased rate of baseflow to streams was evident.

These studies illustrate that groundwater discharge processes will be sensitive to climate change where surface water and groundwater are well connected and where a change recharge rates may lead to significant changes in groundwater levels to affect hydraulic gradients.

Groundwater discharge to streams will be particularly sensitive in highly permeable settings. For instance in the karstic Daly River Basin where dolines channel stream-aquifer interactions, predictive modelling conducted for the NASY project showed that mean dry season flows (which are fed by groundwater discharge) increased by 35 % under a wetter climate scenario (CSIRO, 2009b).

Assessment of sensitivity of priority aquifers to river recharge/discharge

As noted, the processes of groundwater discharge to surface water and of surface water leakage to aquifers are intricately connected, and therefore the sensitivity to climate change of the groundwater and surface water interaction process has been considered holistically, as opposed to the sensitivity of the two processes separately.

Two primary factors were considered to determine the sensitivity of the process of groundwater and surface water interaction: whether groundwater and surface water interaction occurs in the aquifer system; and what the dominant recharge/discharge mechanism for that aquifer system is. The findings are summarised in Table 4-2.

Table 4-2 Summary of Priority Aquifer Sensitivity to Groundwater and Surface Water Interaction

Aquifer	Localised Recharge (i.e. stream leakage to aquifer)			Localised Discharge (i.e. baseflow to streams)		
	High degree of groundwater and surface water connectivity	Dominant recharge process	Sensitivity of localised recharge process to climate change	High degree of groundwater and surface water connectivity	Does groundwater discharge provide baseflow to rivers?	Sensitivity of groundwater discharge process to climate change
Adelaide Geosyncline 3	Yes	Diffuse	Low	Yes	Yes	High
Upper Condamine and Border Rivers Alluvium	Yes	Localised	High	Yes	Yes	High
Calivil	Yes	Localised	High	Yes	Yes	High
Central Perth Basin	Yes	Diffuse	Low	Yes	Yes	High
Coastal River Alluvium 1	Yes	Localised	High	Yes	Yes	High
Coastal River Alluvium 4	Yes	Localised	High	Yes	Yes	High
Coastal Sands 4	No	Diffuse	Low	No	No	Low
Daly Basin	Yes	Diffuse/ Localised	High	Yes	Yes	High
GAB 2	Yes	Localised	High	Yes	Yes	High
GAB 4	Yes	Localised	High	Yes	Yes	High
Gunnedah	Yes	Localised	High	Yes	Yes	High
Lachlan	Yes	Localised	High	Yes	Yes	High
Lachlan Fold Belt 5	Yes	Diffuse	Low	Yes	Yes	High
Murray Group	No	Neither	Low	No	No	Low
Newer Volcanics	Yes	Diffuse	Low	Yes	Yes	High
Otway Basin	No	Diffuse	Low	No	No	Low
Pilbara	Yes	Localised	High	Yes	Yes	High
Port Campbell Limestone	No	Diffuse	Low	No	No	Low
Atherton Tablelands	Yes	Diffuse	Low	Yes	Yes	High
South Perth Basin	Yes	Diffuse	Low	Yes	Yes	High
Toowoomba Basalts	No	Diffuse	Low	No	No	Low
Upper Valley Alluvium 4	Yes	Localised	High	Yes	Yes	High

Alluvial Aquifers

The alluvial aquifers associated with the Gunnedah, Calivil, Lachlan, and the Upper Condamine and Border Rivers alluvium are considered to be highly sensitive to climate change impacts on surface water – groundwater interaction. It is recognised that for these aquifers the dominant groundwater source is the deeper semi-confined aquifer, not the shallow watertable aquifer that is in direct contact with the river. However, the semi-confined aquifers are well connected with the shallow aquifer and increases in groundwater pumping regimes typically lead to a reduction in surface water flows.

Numerical modelling was conducted for parts of each of these aquifers and the mass balance results have been analysed to indicate the significance of surface water leakage relative to the overall recharge to the aquifer. The numerical modelling results from the Basin

Plan development modelling (unpublished) was used and the scenarios modelled included a historical climate and current groundwater use. The results indicate that:

- For the Gunnedah aquifer the mass balance results indicate that more than 60 % of the recharge to the groundwater system was sourced from the river (according to the Upper Namoi Alluvium numerical model);
- For the Calivil aquifer the mass balance results indicate that approximate 31 % of the recharge to the groundwater system was sourced from the river (according to the Lower Murrumbidgee Alluvium numerical model);
- For the Lachlan aquifer the mass balance results indicate that approximately 50 % of the recharge to the groundwater system was sourced from the river (according to the Upper Lachlan Alluvium numerical model);
- For the Upper Condamine and Border Rivers Alluvium aquifer the mass balance results indicate that approximately 53 % of the recharge to the groundwater system was sourced from the river (according to the Upper Condamine Alluvium numerical model).

These aquifers also receive considerable recharge from over bank flow or flooding events. Changes in the magnitude and frequency of flooding events as a result of climate change would alter this important recharge mechanism.

For the Upper Valley Alluvium 4 aquifer and the coastal river alluvium aquifer, numerical modelling results do not exist, however they are considered sensitive to climate change impacts on the groundwater and surface water interaction processes. This is supported by aquifers such as the Hunter River alluvium, which is managed via a water sharing plan that treats groundwater and surface water as a single water source, due to the very high connection between the two (NSW DWE, 2009).

Fractured Rock Aquifers

Streams associated with upland fractured rock aquifers are generally considered to be highly connected and typically gaining in nature (Braaten and Gates, 2002). This means that for many of the fractured rock aquifers, groundwater discharge to streams is a significant process and is likely to be at high risk to climate change impacts.

In support of this, Cook et al. (2001) found that the groundwater of the Atherton Basalts have similar chloride and stable isotope concentrations to the stream water. This was concluded to indicate that most of the river flow was from groundwater inflows rather than surface runoff.

DWLBC (2008) noted that in terms of the fractured rock aquifers associated with the Adelaide Geosyncline 3, although the flow from groundwater to surface water is only seasonal and is minimal, during summer this discharge has great significance for aquatic ecosystems at some locations, as this discharge allows for the persistence of water through dry summers.

In terms of the fractured and karstic rock aquifers associated with the Daly Basin, both aspects of groundwater and surface water connectivity (i.e. groundwater discharge to streams and stream leakage to groundwater) are significant components of the water balance.

The Tindall Limestone is recharge via both diffuse mechanisms and localised indirect recharge. Localised recharge occurs where surface water is channelled into karstic features such as dolines (i.e. a closed depression in karstic topography) where it recharges the groundwater with virtually no interaction with the unsaturated zone. Considerable recharge occurs during exceptionally wet years when surface water flow is intercepted by the numerous dolines in the Katherine River area (CSIRO, 2009).

Groundwater within the Tindall Limestone discharges to the Katherine River, Flora River, Douglas River and Daly River along the bed of rivers and via discrete springs. Major discharges occur along the Flora River as it intercepts the much larger groundwater flows from the Wiso Basin (CSIRO, 2009).

The Toowoomba Basalts are considered to have a low sensitivity to climate change impacts on groundwater and surface water interaction. According to Free (2004) the basalts are readily recharged from rainfall through well drained porous soils, which suggest that groundwater recharge via stream leakage is not likely to be a significant recharge mechanism. Furthermore as part of the Basin Plan development (CSIRO/SKM, 2010) indicated that in the pre-development state, tributaries of the Condamine River associated with the basalt were maintained by groundwater discharge. However, large-scale groundwater extraction has degraded this process over the last 50 years, to the point where most streams no longer receive significant groundwater discharge. This means that the groundwater discharge to streams is not a significant process for the Toowoomba Basalts.

Layered Sedimentary Aquifers

Great Artesian Basin

While the Great Artesian Basin (GAB) as whole is not considered particularly sensitive to changes in modern-day recharge, there are some local groundwater flow systems associated with GAB recharge areas that are considered sensitive to climate change impacts on groundwater and surface water interaction. Figure 4-2 indicates the location of spring groups and river reaches that are fed by groundwater discharge from recharge areas in the GAB, where the streams incise the GAB aquifers (DERM, 2005). Spring discharge and groundwater discharge to streams occur during large recharge events where the infiltration capacity of the GAB intake beds is exceeded resulting in rejected recharge. Climate change impacts to these springs and watercourses could thus be significant.

Pilbara

The primary aquifers in the Pilbara are the Cainozoic valley fill alluvium, the underlying chemically deposited aquifers of calcrete/pisolitic limonite and the underlying fractured rock aquifers. The alluvial aquifer is recharged mostly by leakage from streambeds during high rainfall periods and to a lesser extent by direct infiltration of rainfall over the surface (Johnson and Wright, 2001). Groundwater discharges to river springs and pools. The underlying fractured rock aquifer is also recharged via river leakage into outcropping basement rocks or indirectly, via the overlying Cainozoic alluvium. Due to the ephemeral nature of streamflow in this region, these aquifers are considered highly sensitive to climate change impacts on groundwater and surface water interactions.

Perth Basins

The impacts of climate change on groundwater and surface water interaction were modelled for the South and Central Perth Basins as part of the South-West Western-Australia Sustainable Yields Project (CSIRO, 2009b). For the South Perth Basin the Blackwood and Capel Rivers usually receive around 33 GL/yr groundwater baseflow, however under the climate change scenario this is reduced by between 3 % and 27 %, relative to the historical climate.

For the Central Perth Basin groundwater discharge usually accounts for about 67 % of total flows of the Gingin Brook. Under the dry extreme future climate, groundwater discharge to the brook may reduce by 48 % relative to the historical climate.

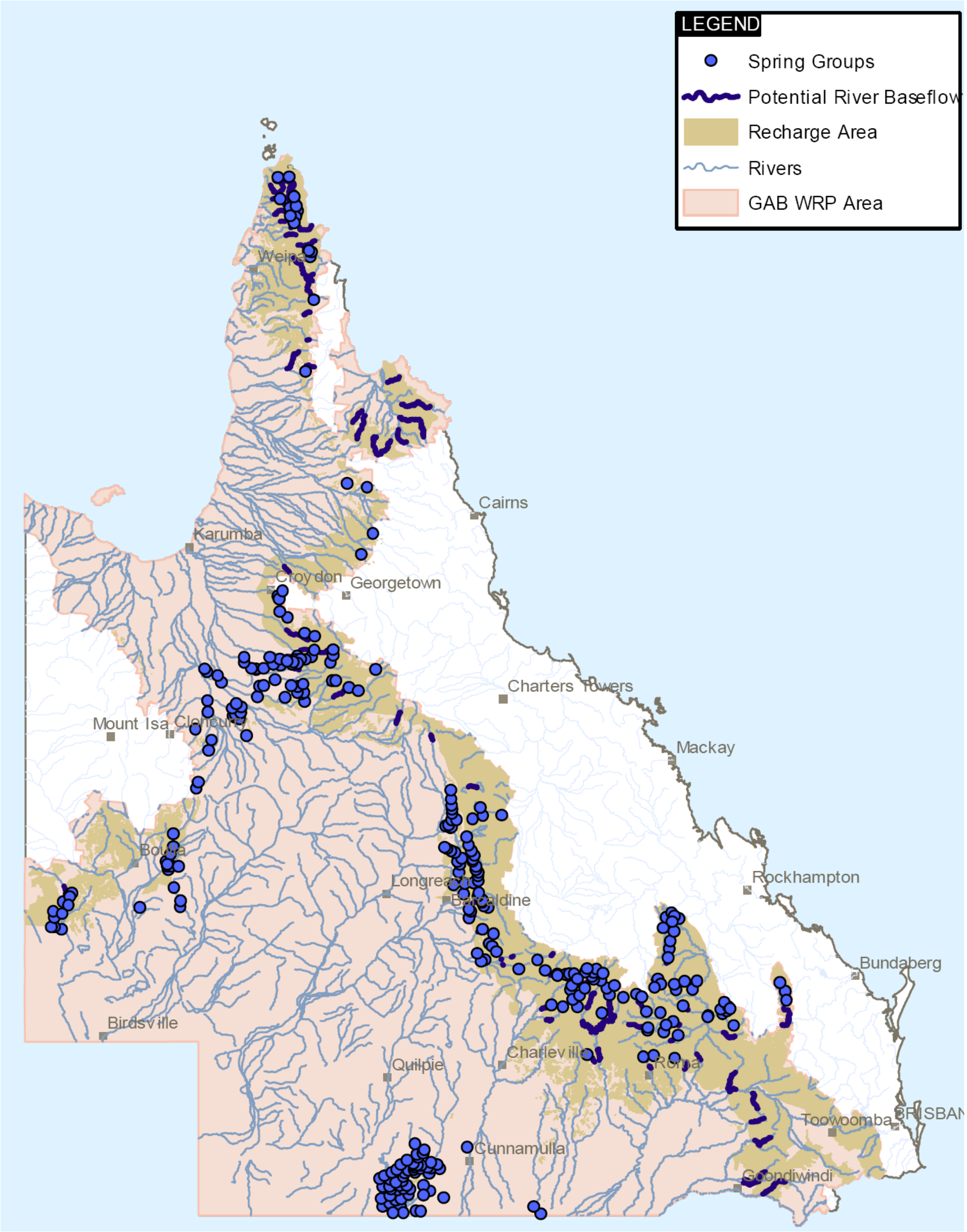

Figure 4-2 Locations of springs and potential baseflow for the Great Artesian Basin (From DNRM (2005))

4.3.2. Evapotranspiration

Evapotranspiration is the removal of water from the saturated zone via evaporation (from the land surface and near surface) or transpiration (water uptake by plant roots). In this context, evapotransipration relates only to direct losses from the watertable.

Factors influencing evapotranspiration

Evapotranspiration is controlled by climatic conditions, land use and vegetation, soil hydraulic properties and the depth of the water table. Climatic conditions (temperature, wind speed, relative humidity and radiation) control the intensity and timing of potential evapotranspiration, which drives the process. Land use and vegetation determine plant water requirements and rooting depths that define the limit of the evapotranspiration zone. Soil hydraulic properties (most importantly the soil water characteristic and unsaturated hydraulic conductivity) control soil evaporation depths, the thickness of the capillary fringe (a zone of near-saturation above the watertable), and the rate of fluxes to plant roots or to the soil evaporation zone. The depth of the watertable affects the occurrence and the rate of evapotranspiration; there being no evapotranspiration where watertables are deeper than the root zone (nominally 10m), increasing evapotranspiration rates as the watertable becomes shallower, and maximum rates occurring when the watertable intersects the land surface.

Climate change may alter evapotranspiration demand and thereby perturb groundwater discharge. As with other recharge and discharge processes, the magnitude of this impact for a particular aquifer is a result of the nature of climate change at the relevant location and the sensitivity of the process. There are a number of aquifer characteristics that determine the sensitivity of evapotranspiration; the depth of the watertable being the most critical characteristic.

Land use and vegetation factors will play a large role in influencing evapotranspiration – indeed land use change is likely to affect evapotranspiration more significantly than climate change – however these factors are dynamic, highly dependent on human factors, not closely linked to aquifer characteristics, and as such they will not be considered in this project. Soil hydraulic properties will play some role in influencing the sensitivity of an aquifer to climate-induced changes in evapotransipiration. For example coarse-textured soils in arid and semi-arid regions have been linked to deeper soil evaporation fronts than lighter textured soils (Gowing et al., 2006) and may therefore be more susceptible to climate change. But the impact of soil properties is regarded as secondary in comparison to the depth of the watertable for influencing climate change susceptibility.

Assessment of sensitivity of priority aquifers to evapotranspiration

Significant evapotranspiration losses have been reported to occur from groundwater when the watertable is less than 6 m deep (Salama, 1998). Such aquifers are regarded as being most susceptible to climate change-induced changes in evapotranspration. They include (as shown in Table 4-3) the Central and South Perth Basins, Coastal Alluvium and Sand aquifers, the Newer Volcanics, the Otway Basin and Port Campbell limestone and the Daly Basin. Regarding the GAB, the regional water table is also quite shallow and 90% of its natural discharge is via upward leakage and evaporation from the water table (Herczeg and Love, 2007). However this process is predominately driven by the head of the Jurassic aquifer and the potential impacts associated with changes in evapotranspiration from the water table are considered minor by comparison to factors that influence the pressure of the deeper aquifer (e.g. pumping activities).

Table 4-3 Watertable depth of the priority aquifers

Aquifer	Aquifer type	Climate zone#	Depth of Watertable (m bgl*)	Source
Adelaide Geosyncline 3	fractured rock	3	Generally > 10m, some areas 2-10m	PIRSA state DTW (depth to water) coverage
Upper Condamine and Border Rivers Alluvium	alluvium	4	> 10m	MDBC (2000)
Calivil	Riverine plains	2	Generally > 10m, some areas 2-10m and < 2m	MDBC (2000)
Central Perth Basin	sedimentary basin	3	extensive areas < 3m	CSIRO (2009b)
Coastal River Alluvium 1	coastal alluvium	1	likely shallow	
Coastal River Alluvium 4	coastal alluvium	4	likely shallow	
Coastal Sands 4	coastal sands	4	likely shallow	
Daly Basin	carbonate	1	regionally < 10m in wet season, ~10m in dry season	CSIRO (2009a)
GAB 2	sedimentary basin	2	Over most of the GAB the developed aquifers are artesian and occur several hundred meters below the surface. The pressure head of the confined aquifer is above the ground surface.	
GAB 4	sedimentary basin	4	Over most of the GAB the developed aquifers are artesian and occur several hundred meters below the surface. The pressure head of the confined aquifer is above the ground surface.	
Gunnedah	alluvium	4	> 10m	MDBC (2000)
Lachlan	alluvium	4	5-10m	Kulatunga (2009); Mitchell (2009)
Lachlan Fold Belt 5	fractured rock	5	variable	Rancic et al.(2009)
Murray Group	carbonate	2	> 10m	MDBC (2000)
Newer Volcanics	basalts	5	variable, but extensive areas < 5m	Tweed et al (2007)
Otway Basin	carbonate	3	Generally < 10m, with extensive areas < 3m	PIRSA state DTW (depth to water) coverage
Pilbara	fractured rock	2	likely variable but mostly deep	
Port Campbell Limestone	carbonate	3	likely shallow	
Atherton Tablelands	basalts	4	seasonal range of 6m, likely to be variable	Cook et al (2001)
South Perth Basin	sedimentary basin	3	extensive areas < 3m	CSIRO (2009b)
Toowoomba Basalts	basalts	4	> 10m	MDBC (2000)
Upper Valley Alluvium 4	upper valley alluvium	4	likely shallow	

Climate zones: 1) tropical; 2) arid/semi arid; 3) mediterranean; 4) sub-tropical; 5) temperate

*m bgl - metres below ground level

4.3.3. Discharge to Oceans

Water naturally flows in the direction of minimal stress, influenced by the pulling force of gravity. Thus, the oceans mark the ultimate fate of most water systems on earth. Exceptions being surficial depressions, such as the Dead Sea and Lake Eyre, which form internally draining surface water systems and groundwater discharge zones caused by impervious sub-surface structural highs. When coastal aquifers are in hydraulic contact with seawater, an interface exists whereby less dense freshwater sits above and adjacent to a denser seawater wedge. The position of this seawater-freshwater interface shifts in response to changes in flow conditions between the aquifer and the sea.

There is a ‘transition zone’ of salinity at the interface. A change in the hydraulic head difference between freshwater and seawater is the principal driver for movement of the transition zone. The transience and position of the interface is controlled by a number of factors, including sea-level rise and recharge/discharge variations, which are both affected by climate change.

Factors influencing sea water intrusion

The recharge-discharge rate of an aquifer can contribute to salt-water intrusion. The rate at which recharge occurs is important, given that it increases the hydraulic gradient and forces the saltwater wedge seaward, it also flushes out accumulated salts and dilutes saline water.

Conversely, reduced recharge rates allow the salt to accumulate in the aquifer, the water to become more saline, and the transition zone to penetrate further inland (Werner and Lockington, 2006). Low recharge rates have become an issue in Australia due to ongoing drought conditions and are expected to be intensified by a reduction in rainfall due to climate change (Pittock, 2003).

Sea-level rise, in response to a changing global climate, can also change the dynamic balance of the transition zone. Climate change predictions indicate a possible rising sea level of 59 cm (plus 10-20 cm for ice sheet melt) by 2100 (IPCC, 2007), which would lead to the inland migration of the freshwater-saltwater interface (Werner and Simmons, 2009). To re-establish equilibrium with fresh groundwater in response to rising sea-levels, the transition zone is predicted to move landward and intrude coastal aquifers.

In addition to the subsurface impacts, sea-level rise may also result in the permanent surface inundation of low-lying coastal regions and increase the frequency and intensity of temporary inundation through the occurrence of storm surges. This could result in the intrusion of saltwater into freshwater reserves through downward seepage. The impacts of sea-level rise are site-specific, and the response of the transition zone during sea-level rise will depend on the hydrogeology of the system, including the aquifer type and its geometry, aquifer parameter values (e.g. hydraulic conductivity), and system boundary conditions such as whether the aquifer is head-controlled or flow-controlled beyond the coastal fringe (Werner and Simmons, 2009).

Dixon-Jain et al. (2010) expect that Australia’s coastal aquifer systems are likely to become more vulnerable to salt-water intrusion in the future. Reasons for this include an expansion in groundwater development in coastal regions, as well as a drying climate characterised by periods of below-average rainfall and reduced groundwater recharge (and therefore reduced discharge) and climate change induced sea level rise. Each of these factors will contribute to putting increased pressures on the available fresh groundwater resources in coastal areas.

Voice et al. (2006) conducted a national scale assessment of the potential impacts of climate change on coastal systems as a consequence of sea-level rise. This assessment indicated that the impact of sea-level rise will vary for different types of beaches. For example open coast beaches backed by sand dunes have a natural buffer for responding to sea-level rise and increased erosion. This is not the case for artificially protected metropolitan beaches where the beach width is maintained by sand replenishment and backed by hard rock protection.

An unpublished report by Nation et al (2008) (as cited in Dixon-Jain et al. (2010)) used a GIS-based approach to analyse the current extent of salt-water intrusion and potential future threats associated with sea-level rise in Australia’s coastal irrigation areas. This included a GIS analysis of groundwater elevation data and maximum TDS (mg/L) values for individual coastal aquifers. These analyses indicated that the vulnerability to salt-water intrusion was greatest in the Queensland coastal irrigation areas, with smaller areas also identified in Victoria, South Australia, and Western Australia.

Assessment of sensitivity of priority aquifers to extraction

The sensitivity of the high priority aquifers to climate change impacts on the process of groundwater discharge to the ocean has been evaluated based upon the vulnerability of the aquifer system to sea water intrusion.

Characterisation of the high priority aquifers as having a high sensitivity to climate change impacts on the process of groundwater discharge to the ocean is largely based on previous investigations of sea water intrusion potential and/or occurrence. This includes various groundwater studies, resource appraisals and also the national scale vulnerability assessment of seawater intrusion that was undertaken by Dixon-Jain et al. (2010). This study included a stakeholder workshop with representatives from each of the State and Territories. This allowed for the establishment of a national perspective of jurisdictional views on seawater intrusion, including the threat of seawater intrusion, the extent of vulnerability and discussion of any investigations that had already been undertaken. In summary the following aquifers have been identified as highly sensitive and each is discussed briefly below;

- Central Perth Basin;
- South Perth Basin;
- Coastal River Alluvium (1 and 4);
- Coastal Sands 4;
- Port Campbell Limestone; and
- Pilbara.

Central Perth and South Perth Basin

Seawater intrusion has been identified at several locations throughout the Perth metropolitan area and other parts of the Swan Coastal Plain (Dixon-Jain et al., 2010). Increased groundwater salinity has also been noted in the Bunbury area (within the South Perth Basin) and DoW has installed a monitoring bore to monitor the saltwater – freshwater interface. Further, modelling conducted as part of the SW Western Australia Sustainable yields project predicted that under a drying climate scenario there are likely to be significant reductions in groundwater discharge to the oceans, which would increase the risk of seawater intrusion (CSIRO, 2009).

Coastal River Alluvium and Coastal Sands 4

For the Coastal River Alluvium aquifers (1 and 4) and the Coastal Sands 4 Aquifer, Dixon-Jain et al. (2010) identified a number of groundwater management areas that have reports of seawater intrusion. This included the Burdekin, Bowen, Pioneer, Bundaberg and Botany Sandbeds areas. While these examples of sea-water intrusion may not be directly related to climate-induced changes to the ocean discharge (more so extraction), there is potential for climate change to alter extraction patterns and thereby affect the risk of sea water intrusion.

The Burdekin area has been subjected to low rainfall and intense groundwater pumping, which has resulted in watertables dropping below sea level during drought periods (McMahon, 2004). In response to this the aquifers in this area have artificially recharged with surface water, which has resulted in reducing the over use of groundwater, however the system remains at threat from seawater intrusion. Tidal barrages have also been constructed on the lower delta to restrict the effects of seawater intrusion.

The Bowen Irrigation Area is regularly affected by drought and the volume of groundwater used for irrigation far exceeds that of surface water because of the low reliability of stream flows. The potential for over pumping leading to seawater intrusion has been identified as a major groundwater management issue (Welsh, 2002). A network of about 260 piezometers has been established by the Queensland Department of Natural Resources and Mines (QDNRM) to monitor watertable and salinity levels, including multi-piped bores near the coast to monitor seawater intrusion. Baskeran et al. (2001) reviewed hydrogeological, hydrochemical and isotopic information recorded in the area and concluded that the highly saline groundwaters near the coast were of seawater origin.

Groundwater use in the Pioneer Valley is dominantly for irrigation of sugarcane, for the sugar-milling industries and for urban water supply, stock water and for domestic supply. Many observation bores in the area have a minimum water level record that is below mean sea level and thus indicates the susceptibility of the aquifers to seawater intrusion (Werner and Gallagher, 2006; Murphy and Sorensen, 2000). The large tides (6 m range in spring) and flat topography of the coastal plain have resulted in the tidal limits extending up to 16.5 km inland, and as a result estuarine seawater intrusion contributes significantly to coastal aquifer salinisation (Werner and Gallagher, 2006).

The Bundaberg irrigation scheme was established in 1970 to provide water to areas within the defined Bundaberg Management Area in order to reduce the amount of groundwater use. However, although the scheme meant that additional surface water supplies were provided and there was an overall reduction in groundwater use, groundwater levels were (and currently are) still being pumped below sea level in some areas, resulting in the continuing risk of seawater intrusion (Bajracharya et al., 2006).

Production bores extracting groundwater for industrial purposes from the Botany Sands Quaternary aquifer (near Sydney airport), were reported as having experienced seawater intrusion in the 1960s (Timms et al., 2008). These bores were decommissioned shortly after and new production bores in the Quaternary aquifer were installed further inland.

Port Campbell Limestone

SKM (2007) conducted a groundwater resource appraisal for the Hawkesdale Management Area. The potential for sea water intrusion associated with bore interference and cumulative aquifer waterlevel drawdown was recognised in the coastal areas around Yambuk and between Warrong and Toolong. To investigate this risk a simple numerical groundwater model was built. The model was developed upon the concept of a single aquifer system for the Port Campbell Limestone aquifer and was used to assess the impact of granting a number of groundwater licence applications. The model results indicated that sea water intrusion was very sensitive to extraction. Given that climate change may influence extraction behaviours as well as more directly affecting coastal discharge, the model results suggest that the Port Campbell Limestone aquifer should be regarded as highly sensitive to climate change impacts on groundwater discharge to the ocean.

Pilbara

Haig (2009) indicated that a major constraint on groundwater development along the Pilbara coast is the potential for increases in groundwater salinity. Coastal aquifers in the Pilbara, while only part of the overall groundwater resources in this area, have to be managed very carefully to avoid seawater intrusion.

4.3.4. Extraction

Groundwater extraction (or abstraction, take, diversion or use) is traditionally defined as the deliberate removal of water from a groundwater resource via a bore, well or spring. Groundwater may be pumped to surface for use or captured at surface from artesian sources.

In Australia, groundwater is extensively used for irrigation of crops and pasture, intensive stock watering, industrial, mining and commercial needs, municipal (town) supplies and stock and domestic purposes, particularly so in arid and semi-arid regions where surface water is not readily available or unreliable.

Groundwater resources are generally managed at the state or local scale in Australia. In moderately and highly developed areas the amount of groundwater that can be extracted from an aquifer is determined by local management plans. In these plans the definition of extraction can be extended to include groundwater take by commercial forestry which can be direct (via transpiration where plantations overlie and access shallow groundwater) or indirect (through interception of precipitation that would otherwise result in recharge) (DWLBC, 2007). Dewatering associated with mining activities may also be considered groundwater use. In areas of low groundwater development, groundwater take is not necessarily controlled or monitored (AWR 2005).

Ideally, groundwater allocations (and subsequent take) in each groundwater management area is determined on the basis of environmentally sustainable levels of extraction, defined as the level of water extraction from a particular system that would compromise key environmental assets, or ecosystem functions and the productive base of the resource, if it were exceeded (AWR 2005).

In practice, the environmentally sustainable level of extraction may be unknown or poorly defined. Consequently, groundwater allocations are often determined: (i) by recharge rates (either estimated or modelled) where the best practice is to allocate only a fraction of recharge, in order to allow a significant fraction to supply the environment, (ii) empirically (from long term data) or, (iii) in situations where modern recharge is not a useful indicator, the maintenance of a groundwater pressure (e.g. the Great Artesian Basin, (DNRM, 2005)). Adding to uncertainties in water resources management is that actual extraction rates and volumes may be unknown or poorly estimated. For example, extractions may not be directly monitored but determined by proxy, say by equivalent irrigation areas (DWLBC, 2007). Additionally, take from stock and domestic bores, prevalent across most groundwater management areas, is not typically monitored.

Factors influencing groundwater extraction behaviours

At a fundamental level, groundwater yield and water quality are the primary determinants of groundwater use. Following from this, the main factor influencing the groundwater extraction behaviours is water availability (supply) and demand. Conjunctive water use is widely practiced throughout Australia, which means that groundwater resource utilisation will often increase when surface water resources become scarce (for whatever reason). Conversely, when surface water stores are adequate or plentiful, reliance on groundwater typically decreases.

Public perception can also influence groundwater extraction behaviours. For example, a proposal to meet extreme water shortages by the Toowoomba Regional Council (then Toowoomba City Council) with alternate water supply strategies - in this case through waste water treatment and reuse - was rejected by plebiscite (Council, undated). This outcome resulted in further extraction from already stressed groundwater resources.

Under climate change scenarios, in many areas across Australia, access to reliable surface water supplies may be decreased due to increased variability in precipitation. Under these circumstances, it can be beneficial to take advantage of the storage capacity of groundwater and increase groundwater withdrawals. However, this is unlikely to ease water stress in those areas where climate change is projected to decrease groundwater recharge such as south east Australia (Kundzewicz & Doll, 2009; Doll, 2009; BRS, 2007).

Assessment of sensitivity of priority aquifers to extraction

Extraction data, both surface water and groundwater, for each of the prioritised aquifers is presented in Table 4-4 as obtained from AWR (2005). The amount of surface water extraction apportioned to each GMU was determined using a GIS based approach. Surface water management areas (SWMAs) are laid over groundwater management units and the coincident area (i.e. proportion of each SWMA that overlies the aquifer) is determined. The equivalent surface water extraction amount (in ML/yr) for each SWMA is taken as the reported water extraction for that SWMA multiplied by the proportion of the SWMA that overlies the aquifer (assumption of even spatial distribution for extraction). The given surface water extraction (in ML/yr) for each aquifer presented in Table 4-4 is the sum of take for each coincident SWMA. The groundwater extraction data and sustainable yield volumes is identical to that presented in Chapter 2.

To identify groundwater demands, assess current stress in groundwater resources and identify potential changes under future climate scenarios for each of the prioritised aquifer groupings, two water use indicators are presented in Table 4-4.

First, groundwater extraction as a percentage of total (groundwater plus surface water) extractions is used to provide information as to the recent water use strategies in each prioritised aquifer grouping. Aquifer groupings with higher percentage values are highly dependent on groundwater resources for water resource needs. Aquifer groupings with lower percentage values are less reliant on groundwater and more reliant on surface water resources.

Second, total extraction as a percentage of total sustainable yield is used to provide information as to available water assets in each aquifer grouping under current conditions. This measure provides indicative information as to potential outcomes (in terms of water resource availability) due to changes in water use strategies, and the flexibility and resilience of the prioritised aquifer grouping. Aquifer groupings with higher percentage values are potentially less resilient to change brought about by water scarcity as take (surface water and groundwater) already approach or exceed sustainable yield limits. Aquifer groupings with lower percentage values are potentially more resilient to change as take is less than 100% of the total sustainable yield.

Table 4-4 Comparison of groundwater extractions to surface water extractions and total water availability. SW extraction is the maximum of actual water extractions and surface water sustainable yield for the relevant surface water management area. Data source: AWR (2005).

Aquifer Name	SW extraction (ML/yr)	SW sustainable yield (ML/yr)	GW extraction (ML/yr)	GW sustainable yield (ML/yr)	GW extraction as % of total extraction	Total extraction as % of total sustainable yield
Adelaide Geosyncline 3	61,297	93,012	26,691	117,421	30%	42%
Upper Condamine and Border Rivers Alluvium	60,076	42,490	130,502	96,600	68%	137%
Calivil	2,605,913	3,867,160	614,440	636,708	19%	72%
Central Perth Basin	46,819	58,118	496,500	771,130	91%	66%
Coastal River Alluvium 1	3,057	3,057	67,850	138,616	96%	50%
Coastal River Alluvium 4	46,804	95,254	168,160	423,593	78%	41%
Coastal Sands 4	31	18,221	53,477	410,011	100%	12%
Daly Basin	23,656	2,166,241	49,790	328,500	68%	3%
GAB 2	76,935	174,256	416,380	218,889	84%	125%
GAB 4	235,092	302,844	172,542	124,296	42%	95%
Gunnedah	156,716	451,385	342,897	356,688	69%	62%
Lachlan	92,472	175,412	157,128	111,145	63%	87%
Lachlan Fold Belt 5	11,698	458,402	35,359	727,721	75%	4%
Murray Group	2,001	2	206,174	268,195	99%	78%
Newer Volcanics	18,422	25,674	20,643	43,271	53%	57%
Otway Basin	5,115	50,165	291,249	1,326,146	98%	22%
Pilbara	20,325	177,422	236,894	334,930	92%	50%
Port Campbell Limestone	28,006	68,518	39,111	88,024	58%	43%
Atherton Tablelands	13,223	13,223	16,106	18,356	55%	93%
South Perth Basin	20,558	222,089	121,122	169,302	85%	36%
Toowoomba Basalts	8,301	8,301	76,100	61,100	90%	122%
Upper Valley Alluvium 4	271	2,029	23,290	4,852	99%	342%

Analysis of the first groundwater use measure indicates that vast majority (20 of 23) of the prioritised aquifer groupings are mostly dependent on groundwater resources (i.e. greater than 50% of extracted water is supplied by groundwater). The average groundwater dependency for the whole of the prioritised group is 73% and only the Calivil, Adelaide Geosyncline 3 and GAB 4 areas have a higher reliance on surface water than groundwater resources. The most highly groundwater dependent areas are the Coastal Sands 4, Murray Group, Upper Valley Alluvium 4, Otway Basin and Coastal River Alluvium 1 areas, each deriving >95% of extractions from groundwater sources. Groundwater dependence is also considered ‘high’ (as being >75th percentile of the presented dataset) in the Pilbara region (92% groundwater dependence).

Analysis of the groundwater extraction as a percentage of total sustainable yield metric shows that many of the prioritised aquifer groupings extract more water than is defined by the total sustainable yield; namely the Toowoomba Basalts, GAB 2, Upper Condamine and Border Rivers Alluvium and Upper Valley Alluvium 4 aquifers. The Atherton Tablelands and

GAB 4 areas also approach limits, utilizing greater than 90% of sustainable yields and round out those considered to be ‘high’.

When the two indices (level of groundwater dependency and total level of development) are combined, the aquifers that rank most highly are the Upper Valley Alluvium 4, Toowoomba Basalts, GAB2, Upper Condamine and Border Rivers Alluvium, Murray Group and Central Perth Basin. These are regarded as the most sensitive aquifers in this category.

Sensitive Aquifers

Upper Valley Alluvium 4

While the Upper Valley Alluvium 4 grouping is highly dependent on groundwater resources, the apparently high ratio of extraction to sustainable yield is misleading because the groundwater sustainable yield was derived from diffuse recharge only and does not include the considerable stream recharge rates that occur here. Indeed there is no evidence of unsustainable extraction in terms of groundwater storage with groundwater levels stable. It is however expected that extraction levels will increase in all Upper Valley Alluvium 4 aquifers in the future and water balance models run under different climate scenarios for 2030 indicate that this is likely to increase resource stress (CSIRO, 2008).

Toowoomba Basalts

The Toowoomba Basalts rank highly in terms of the two water use indicators with extraction greater than 100% of sustainable yield and groundwater take comprising 90% of extractions and ranks second highest overall (Table 4-4). Under recent use strategies, localised and significant drawdowns are observed across the Toowoomba Basalt GMU areas and there have been moratoriums for groundwater extractions from the Toowoomba City GMU.

GAB 2

The GAB2 aquifers rate third overall in terms of relative groundwater use and potential water stress. Reliance on groundwater is high (84% of total water use) and extractions in excess of sustainable yield are all attributed to groundwater. Current surface water extractions comprise only 44% of surface water sustainable yields, whereas groundwater extractions are 190% of groundwater sustainable yields (Table 4-4). Like the GAB as a whole, historical extractions have lead to broad scale potentiometric surface declines.

In the future, a drying climate across much of the GAB 2 area is expected to heighten dependence on groundwater across all users. This is recognised by the GAB Coordinating Council and water reform and investment actions are targeted around managing prolonged drought and climate change (GABCC, 2009).

Upper Condamine and Border Rivers Alluvium

The Upper Condamine and Border Rivers Alluvium GMUs rank fourth overall, as despite an only moderately high dependence of groundwater relative to surface water (68%) overall, extractions in excess of total sustainable yield are high and split fairly equally between surface water and groundwater (140% and 135% of sustainable yields respectively).

Currently, in the Upper Condamine Alluvium, extraction is the most significant discharge mechanism with groundwater used extensively for irrigation, and to a lesser extent for stock and domestic purposes. Extraction activities are concentrated around the central valley and eastern headwaters of the GMU and this has resulted in significant drawdown (10-20 m) in the central valley area. Conversely, in the Border Rivers, surface water is more readily available and groundwater is used only to supplement town and irrigation supplies during drier periods.

Murray Group

The Murray Group aquifers rank 5th overall with a very high reliance on groundwater (99%) but moderate extractions in comparison to sustainable yields[6] (78%) (Table 4-4).

Climate models predict a future drying trend for the Murray Group with +5% to -10% changes in runoff by 2030 (relative to the current climate) and 10-30% reductions in groundwater recharge by 2050 (Chiew, et al., 2008; Doll, 2009). Additionally, groundwater extractions within the Murray Group area are forecast to grow in the future (Chiew, et al., 2008).

As noted in Chapter 3, groundwater in the Murray Group area is essentially a fossil resource. As such, future changes in precipitation regimes are not likely to impact on groundwater resource replenishment in the area directly, but indirectly as surface water becomes increasingly scarce and reliance on groundwater further increases.

Central Perth Basin

The Central Perth Basin grouping ranks 6th overall, weighted by a high reliance on groundwater (91%) (Table 4-4). Demand on groundwater supplies is expected to increase in the future in the Central Perth Basin by 114%-450% and this has been assessed in the context of local groundwater management planning (CSIRO, 2009b). With regards to potential impacts of climate change on abstraction amounts, as surface water is only used to supplement groundwater supplies it is unlikely that groundwater resources will be further stressed with additional demand in the event of a reduction in surface water availability. Modelling by (CSIRO, 2009b) indicates that under a range of future climate scenarios there will be only minimal changes to groundwater resourcing as abstraction is already at maximum limits and because groundwater storage volumes are predicted to be stable when averaged over large area. Localised changes to water tables however are likely to be observed with rises up to 6 m in some areas with falls up to 10 m in others. Whether a rise or fall is predicted is largely dependent on soil type and vegetation cover.

4.4. Storage changes

Climate-induced perturbations to the balance between recharge and discharge for an aquifer will result in changes to groundwater storage (equation 10). The way in which storage changes are likely to manifest is an important determinant of sensitivity to climate change. The intensity and timing of storage changes and the feedback mechanisms triggered will differ between aquifers. These aspects are discussed in the following sub-sections.

4.4.1. Watertable depth

The depth of the water table is an important aquifer characteristic that controls lag times between a change in recharge and a change in groundwater storage. The depth to the water table is essentially the thickness of the unsaturated zone through which water must pass to enter the aquifer; the thicker the unsaturated zone, the longer the lag time from a significant rainfall event to recharge.

Aquifers with shallow water tables will respond more rapidly to changes in climate compared to those with deep water tables. It is thus an important consideration regarding climate change sensitivity.

Water table depths are not well defined across Australia. Broad, documented ranges for water table depths of the priority aquifers are shown in Table 4-3. The aquifers with shallow water tables (< 10m) will be most sensitive. Those with deeper water tables will be less

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[6] Becasue the Mallee groundwater resources of the Marry Group are a ‘fossil’ resource, then obviously extraction rates cannot be sustained indefinitely. In this context, ‘sustainable yield’ refers to an annual extraction limit documented in the water sharing plan that was set to prolong the lifetime of the resource.

sensitive. However despite having water tables deeper than 10 m, it unlikely that lag times will be excessive for most of these aquifers (Gunnedah, Calivil, Condamine Alluvium and Toowoomba basalts).

The exception is the Murray Group Limestone where the water table depth is in the order of 60 m in the major developed zones (e.g. Mallee Prescribed Wells Area). Lag times of several decades to more than 100 years are thought to operate in this system. Moreover, modern recharge is thought to be negligible and the fresh water resources are thought to be a result of prehistoric recharge in wetter times approximately 20,000 years ago (MWRPC, 2000). It is therefore likely that climate change-induced recharge changes will have little impact for this resource within a timeframe that is meaningful for a management response.

4.4.2. Recharge to storage ratios

The importance of aquifer responsiveness to climate change is illustrated by Wilkinson and Cooper (1993), who analysed the response of idealised aquifer systems to climate change. They found that for slowly responding aquifers, an increase in the volume of winter recharge may result in increased baseflow to rivers throughout the year, even when there is a reduction in the period of recharge. Conversely, for quickly responding aquifers there may be a reduction in baseflow to rivers if the period of recharge is reduced, even if the annual volume of recharge increases. The responsiveness of aquifers is related to aquifer hydraulics and the most rapid responses to perturbations occur where there is high transmissivity, low storage and short flow paths (Alley et al., 2002).

The ratio of groundwater recharge to storage is an indirect measure of aquifer responsiveness and an inverse measure of the buffering capacity of an aquifer to disturbance. The recharge to storage metric should also bear a close relationship to the classification of groundwater flow systems. The groundwater flow system concept has been used by hydrogeologists to explain the relationship between recharge and groundwater behaviour (Walker et al., 2003) with the response times most rapid for local flow systems and most delayed for regional flow systems. The relationship between R:S and groundwater flow systems is as follows: high R:S corresponds to local flow systems; moderate R:S corresponds to intermediate flow systems; and low R:S corresponds to regional flow systems.

The R:S metric was used as part of the aquifer prioritisation task describes in Chapter 2. The results for the priority aquifers are summarised in Table 4-5.

Table 4-5 Relative recharge to storage ratios for priority aquifers

Low R:S	Moderate R:S	High R:S
Calivil	Gunnedah	Newer Volcanics
GAB 2	Otway Basin	Coastal Sands
GAB 4	Coastal River Alluvium 4	Atherton tablelands
Central Perth Basin	Pilbara	Toowoomba Basalts
South Perth Basin	Lachlan	Upper Valley Alluvium
Murray Group	Upper Condamine and Border Rivers Alluvium	Coastal River Alluvium 1
Calivil	Port Campbell Limestone	Adelaide Geosyncline
GAB 2		Daly Basin
GAB 4		Lachlan Fold Belt

The aquifers listed as having high R: S ratios in Table 4-5 will respond most rapidly and exhibit more extreme changes in groundwater conditions in response to climate change. The responsiveness of groundwater levels to climate variations over historical records for many of these aquifers is well documented (e.g. Rancic et al. 2009; CSIRO, 2009a).

At the other end of the spectrum, the aquifers regarded as being more insensitive are the Calivil, GAB, Central and South Perth Basins, and the Murray Group. Whilst these aquifers are lumped together in the simplified analysis presented in Table 4-5, there are some important distinctions within the grouping. The GAB is regarded as having substantial groundwater storage volume and the changes in recharge, discharge and groundwater storage rarely occur in concert due to very long flow paths and complex flow systems that propagate changes in rainfall to recharge and then through the aquifer (Herczeg and Love, 2007). It is therefore classed as insensitive. The Murray Group has large storage and is essentially a fossil resource (MWRPC, 2000). The Calivil aquifer has large groundwater storage and low diffuse recharge but is also supported by river leakage from regulated rivers. The exception to the insensitive classification is the Central and South Perth Basins. Whilst these are large sedimentary basins comprising several aquifers, if the uppermost superficial aquifer is treated separately then it would be regarded as having a moderate to high R:S and hosting local to intermediate flow systems. Indeed the sensitivity of the superficial aquifer to altered recharge has been witnessed in declining groundwater levels since the 1970s as rainfall has declined (CSIRO, 2009b).

4.5. Summary and conclusions

4.5.1. Recharge processes

Groundwater recharge is the process of aquifer replenishment and it occurs via two primary mechanisms; diffuse recharge and localised recharge.

Diffuse recharge refers to recharge derived from rainfall or irrigation and results from widespread percolation through the unsaturated zone. An aquifer is sensitive to climate change impacts on diffuse recharge, where the diffuse recharge component of recharge is dominant (i.e. areas where the potential for surface water drainage is poor) and occurs rapidly. Diffuse recharge rates are controlled by; profile thickness, soil water storage, soil hydraulic conductivity and preferential flow. The following characteristics of these properties are considered to indicate high recharge sensitivity: thin soil profiles, limited soil moisture storage, high soil hydraulic conductivity and likely preferential flow.

Localised recharge refers to concentrated recharge from streams and can occur either from within-bank recharge or over-bank recharge. Within-bank recharge is the process of a stream recharging an aquifer through its banks and is often referred to as ‘bank storage’ because the water that moves from the stream bank to the aquifer is generally returned back to the river when the river levels fall. Over-bank floodplain recharge relates to the recharge of the groundwater through the soil surface after the stream has broken its banks.

Localised recharge is driven by high river stage which is associated with high rainfall events. This means that localised recharge is more sensitive to the impact of climate change on the frequency of high rainfall events than it is to the impact of climate change on annual precipitation rates.

Groundwater aquifers most sensitive to climate change impacts on localised recharge are narrow alluvial valley aquifers that have a low surface area to intersect precipitation (i.e. low reliance on diffuse recharge) and strong connection with the river.

4.5.2. Discharge processes

Groundwater discharge is the removal of water from the saturated zone and can occur via a number of processes including; discharge to surface water (i.e. baseflow), evapotranspiration, groundwater pumping and flow to the ocean.

In terms of the baseflow process, this discharge mechanism is most sensitive to climate change impacts on watertable elevation. A lowering of water table elevation will coincide with a reduced rate of groundwater discharge to streams. The aquifers most sensitive to climate change impacts on this discharge mechanism are those with high connection to surface water.

Evapotranspiration is the direct loss from the watertable. This form of discharge is controlled by climatic conditions, land use and vegetation, soil hydraulic properties and the depth of the water table. The depth of the watertable is the most important driver of evapotranspiration rates. For example, there is no evapotranspiration where the watertable is deeper then the root zone.

Groundwater extraction is the deliberate removal of water from a groundwater resource via a bore, well or spring. The impact of climate change on surface water sources is likely to be a reduced reliability, which has the potential to increase the demand on the groundwater resource. This will have particular implications where groundwater recharge is predicted to decrease and the groundwater resource is already fully allocated.

The implication of climate change impacts on the process of groundwater discharge to the ocean is the subsequent increased threat of sea water intrusion that coincides with the reduction in discharge. A reduced discharge rate implies a lessening of the horizontal hydraulic gradient that is driving the groundwater flow to the ocean, which again, indicates that a reversal of flow towards the land is potential. This threat is greatest where aquifers reside along the coastline and the hydraulic gradient is shallow. It is exacerbated where excessive groundwater development is occurring.

4.5.3. Storage changes

An imbalance between recharge and discharge can result in changes to groundwater storage. The way in which an aquifer responds to changes in recharge or discharge is an important determinant of climate-change sensitivity. Some aquifers will respond rapidly and exhibit large storage changes. The ratio of storage to recharge is a metric by which the sensitivity of aquifers to storage changes can be gauged. A low S;R is indicative of sensitive aquifer that responds rapidly to changes in the recharge or discharge.

Prolonged lag-times associated with deep water tables in zones of recharge are suggestive of insensitivity to climate change.

4.5.4. Sensitivity of priority aquifers

Table 4-6 summarises which recharge and discharge processes are sensitive for the priority aquifers. The table provides a guide as to how an aquifer may be vulnerable to climate change.

All of the priority aquifers show at least some form of sensitivity to climate change. For instance even the Murray Group, which is essentially a fossil resource and not impacted by current recharge, is indirectly sensitive to climate change due its dependence on groundwater as a water resource.

There are other aquifers that have numerous processes considered sensitive. The aquifers with most number of sensitive processes (5 or more) are the Perth Basin, the Coastal Sands and Alluvial systems of NSW and Queensland, the Daly Basin, the Newer Volcanics and the Upper Valley Alluvial aquifers of NSW. A fewer number of sensitive classifications does not mean that the aquifer is less sensitive to climate change, only that is sensitive in fewer ways.

The identification of the potential pressure points to climate change has implications for management and water resource assessments. For instance, to appropriately assess water resource availability under climate change scenarios in aquifers that are more dependent on surface water recharge, then it is be necessary to focus assessment efforts on analysing how surface-groundwater interactions may change as a result of climate change. As well, integrated water management (of groundwater and surface water) is more critical in these systems.

Table 4-6 Climate change sensitivity by recharge and discharge processes for priority aquifers

Aquifer	Recharge		Discharge				Storage dynamics	
	Diffuse recharge	Surface water recharge	Surface water discharge	Evapotranspiration	Coastal discharge (sea water intrusion)	Groundwater supply dependency (extraction)	Depth to watertable	R:S Ratio
Adelaide Geosyncline 3	🟦 *		🟦				🟦	🟦
Upper Condamine and Border Rivers Alluvium		🟦	🟦			🟦		
Calivil		🟦	🟦					
Central Perth Basin	🟦		🟦	🟦	🟦	🟦	🟦	
Coastal River Alluvium 1		🟦	🟦	🟦	🟦		🟦	🟦
Coastal River Alluvium 4		🟦	🟦	🟦	🟦		🟦	
Coastal Sands 4	🟦			🟦	🟦		🟦	🟦
Daly Basin	🟦	🟦	🟦	🟦			🟦	🟦
GAB 2		🟦	🟦			🟦	🟦	
GAB 4		🟦	🟦				🟦	
Gunnedah		🟦	🟦					
Lachlan		🟦	🟦				🟦	
Lachlan Fold Belt 5	🟦		🟦				🟦	🟦
Murray Group		▨				🟦	▨ #	
Newer Volcanics	🟦		🟦	🟦			🟦	🟦
Otway Basin	🟦			🟦			🟦	
Pilbara		🟦	🟦		🟦		🟦	
Port Campbell Limestone	🟦			🟦	🟦		🟦	
Atherton Tablelands	🟦		🟦				🟦	🟦
South Perth Basin	🟦		🟦	🟦	🟦		🟦	
Toowoomba Basalts	🟦					🟦		🟦
Upper Valley Alluvium 4		🟦	🟦	🟦		🟦	🟦	🟦

* Sensitive processes are shown with blue coloured cells

Highly insensitive due to deep water table

5. CONCLUSIONS

This report has described two linked assessments that were conducted to characterise Australian aquifers by their sensitivity to climate change. A prioritisation scheme was implemented to identify the most important and sensitive groundwater resources across Australia. The recharge and discharge mechanisms of these priority systems were assessed to characterise how they are sensitive to climate change.

The prioritisation scheme provides an objective basis to select priority aquifers that will become the focus of further activities in this project. Twenty-two priority aquifers have been identified that cover a broad range of aquifer types and climate zones.

The priority aquifers have been assessed in terms of the sensitivity of their recharge and discharge processes. These processes control the availability of groundwater resources to both consumptive users and the environment, and the analysis highlights the potential pressure points and vulnerabilities of these aquifers to climate change. Some of the aquifers display a broad range of ways in which they may be sensitive to climate change. For example, the Perth Basin, the Coastal Sands and Coastal Alluvial systems of NSW and Queensland, the Daly Basin, the Newer Volcanics and the Upper Valley Alluvial aquifers of NSW all had five or more recharge/discharge processes identified as being sensitive to climate change. Other aquifers had fewer categories of potential sensitivity. The analysis does not suggest such aquifers are less sensitive, merely that they are sensitive in fewer ways.

The key outcome of this work is that it provides a strategic focus for future activities and assessments investigating the impact of climate change on groundwater resources. Priority aquifers have been identified, and of these aquifers the ways in which they may be sensitive to climate change are highlighted.

APPENDICES

APPENDIX A: ASCRIPTION OF GROUNDWATER MANAGEMENT UNITS TO AQUIFERS

Aquifer ID	Aquifer	Groundwater Management Unit	State or Territory	Priority Aq
0	Adelaide Geosyncline 2*	Adelaide Fold Belt	NSW	FALSE
0	Adelaide Geosyncline 2	Kanmantoo Fold Belt	NSW	FALSE
0	Adelaide Geosyncline 2	Northern Flinders	SA	FALSE
0	Adelaide Geosyncline 2	Willochra Creek	SA	FALSE
0	Adelaide Geosyncline 2	Yorke Peninsula	SA	FALSE
1	Adelaide Geosyncline 3	Barossa Prescribed Water Resources Area	SA	TRUE
1	Adelaide Geosyncline 3	Broughton River	SA	TRUE
1	Adelaide Geosyncline 3	Burra Creek	SA	TRUE
1	Adelaide Geosyncline 3	Clare Valley Prescribed Water Resources Area	SA	TRUE
1	Adelaide Geosyncline 3	Eastern Mount Lofty Ranges Prescribed Water Resources Area	SA	TRUE
1	Adelaide Geosyncline 3	Gawler	SA	TRUE
1	Adelaide Geosyncline 3	Light	SA	TRUE
1	Adelaide Geosyncline 3	Marne River and Saunders Creek Prescribed Water Resources Area	SA	TRUE
1	Adelaide Geosyncline 3	Southern Eastern Mount Lofty Ranges	SA	TRUE
1	Adelaide Geosyncline 3	Western Mount Lofty Ranges Prescribed Water Resources Area	SA	TRUE
2	Albany	Albany	WA	FALSE
3	Allluvium associated with the Warrego River	Warrego Alluvium	QLD	FALSE
4	Upper Condamine and Border Rivers Alluvium	Border Rivers Alluvium (Qld)	QLD	TRUE
4	Upper Condamine and Border Rivers Alluvium	Upper Condamine Alluvium	QLD	TRUE
5	Boisdale Fmn	Giffard	VIC	FALSE
5	Boisdale Fmn	Sale	VIC	FALSE
6	Bonaparte	Bonaparte	WA	FALSE
7	Bremer Basin	Bremer Bay	WA	FALSE
7	Bremer Basin	Condingyup	WA	FALSE
7	Bremer Basin	Esperance	WA	FALSE
7	Bremer Basin	Gibson	WA	FALSE
7	Bremer Basin	Hopetoun	WA	FALSE
8	Bridgewater Fmn	Nepean	VIC	FALSE
9	Brighton Grp	Frankston	VIC	FALSE
9	Brighton Grp	Moorabbin	VIC	FALSE
10	Calivil	Lower Lachlan Alluvium (downstream of Lake Cargelligo)	NSW	TRUE
10	Calivil	Lower Murray Alluvium (downstream of Corowa)	NSW	TRUE
10	Calivil	Lower Murrumbidgee Alluvium (downstream of Narrandera)	NSW	TRUE
10	Calivil	Campaspe Deep Lead	VIC	TRUE
10	Calivil	Katunga	VIC	TRUE
10	Calivil	Mid Goulburn	VIC	TRUE
10	Calivil	Mid Loddon	VIC	TRUE

Aquifer ID	Aquifer	Groundwater Management Unit	State or Territory	Priority Aq
10	Calivil	Mullindolingong	VIC	TRUE
10	Calivil	Southern Campaspe Plains	VIC	TRUE
10	Calivil	Upper Ovens	VIC	TRUE
11	Calivil (some outcropping basement)	Lower Ovens	VIC	FALSE
12	Canarvon Basin	Gascoyne	WA	FALSE
13	Canning	Broome	WA	FALSE
13	Canning	Canning	WA	FALSE
13	Canning	Derby	WA	FALSE
13	Canning	Canning-Kimberley	WA	FALSE
14	Carnarvon Alluvium	Carnarvon	WA	FALSE
15	Central Perth Basin	Cockburn	WA	TRUE
15	Central Perth Basin	Gingin	WA	TRUE
15	Central Perth Basin	Gnangara	WA	TRUE
15	Central Perth Basin	Gwelup	WA	TRUE
15	Central Perth Basin	Jandakot	WA	TRUE
15	Central Perth Basin	Mirrabooka	WA	TRUE
15	Central Perth Basin	Perth	WA	TRUE
15	Central Perth Basin	Rockingham	WA	TRUE
15	Central Perth Basin	Serpentine	WA	TRUE
15	Central Perth Basin	Stakehill	WA	TRUE
15	Central Perth Basin	Swan	WA	TRUE
15	Central Perth Basin	Wanneroo	WA	TRUE
15	Central Perth Basin	Yanchep	WA	TRUE
16	Childers Fmn	Corinella	VIC	FALSE
16	Childers Fmn	Kooweerup	VIC	FALSE
16	Childers Fmn	Moe	VIC	FALSE
17	Clarence Morton Basin	Clarence-Moreton Basin	NSW	FALSE
18	Clifton Fmn	Condah	VIC	FALSE
19	Coastal River Alluvium 1	Bluewater	QLD	TRUE
19	Coastal River Alluvium 1	Bowen	QLD	TRUE
19	Coastal River Alluvium 1	Burdekin	QLD	TRUE
19	Coastal River Alluvium 1	Cairns Coast	QLD	TRUE
19	Coastal River Alluvium 1	Cairns Northern Beaches	QLD	TRUE
19	Coastal River Alluvium 1	Duck Farm	QLD	TRUE
19	Coastal River Alluvium 1	Mossman	QLD	TRUE
20	Coastal River Alluvium 2	Callide	QLD	FALSE
20	Coastal River Alluvium 2	Cattle Creek	QLD	FALSE
20	Coastal River Alluvium 2	Monto	QLD	FALSE
21	Coastal River Alluvium 4	Bellinger Alluvium	NSW	TRUE
21	Coastal River Alluvium 4	Brunswick Alluvium	NSW	TRUE
21	Coastal River Alluvium 4	Clarence and Coffs Alluvium	NSW	TRUE
21	Coastal River Alluvium 4	Goulburn River Alluvium	NSW	TRUE
21	Coastal River Alluvium 4	Hastings River Alluvium	NSW	TRUE
21	Coastal River Alluvium 4	Hawkesbury Alluvium	NSW	TRUE
21	Coastal River Alluvium 4	Hunter River Alluvium	NSW	TRUE

Aquifer ID	Aquifer	Groundwater Management Unit	State or Territory	Priority Aq
21	Coastal River Alluvium 4	Karuah Alluvium	NSW	TRUE
21	Coastal River Alluvium 4	Macleay River Alluvium	NSW	TRUE
21	Coastal River Alluvium 4	Manning Alluvium	NSW	TRUE
21	Coastal River Alluvium 4	Nambucca Alluvium	NSW	TRUE
21	Coastal River Alluvium 4	Richmond River Alluvium	NSW	TRUE
21	Coastal River Alluvium 4	Tweed River Alluvium	NSW	TRUE
21	Coastal River Alluvium 4	Bundaberg	QLD	TRUE
21	Coastal River Alluvium 4	Clarendon	QLD	TRUE
21	Coastal River Alluvium 4	Cressbrook Creek	QLD	TRUE
21	Coastal River Alluvium 4	Pioneer	QLD	TRUE
21	Coastal River Alluvium 4	Proserpine	QLD	TRUE
22	Coastal River Alluvium 5	Bega River Alluvium	NSW	FALSE
22	Coastal River Alluvium 5	Towamba Alluvium	NSW	FALSE
22	Coastal River Alluvium 5	Tuross Alluvium	NSW	FALSE
23	Coastal Sands 4	Bellinger Coastal Sands	NSW	TRUE
23	Coastal Sands 4	Botany Sandbeds	NSW	TRUE
23	Coastal Sands 4	Brunswick Coastal Sands	NSW	TRUE
23	Coastal Sands 4	Clarence Coastal Sands	NSW	TRUE
23	Coastal Sands 4	Coffs Harbour Coastal Sands	NSW	TRUE
23	Coastal Sands 4	Great Lakes Coastal Sands	NSW	TRUE
23	Coastal Sands 4	Hastings Coastal Sands	NSW	TRUE
23	Coastal Sands 4	Hawkesbury to Hunter Coastal Sands	NSW	TRUE
23	Coastal Sands 4	Macleay Coastal Sands	NSW	TRUE
23	Coastal Sands 4	Manning Coastal Sands	NSW	TRUE
23	Coastal Sands 4	Nambucca Coastal Sands	NSW	TRUE
23	Coastal Sands 4	Richmond Coastal Sands	NSW	TRUE
23	Coastal Sands 4	Stuarts Point Sandbeds	NSW	TRUE
23	Coastal Sands 4	Tomago-Tomaree-Stockton Sandbeds	NSW	TRUE
23	Coastal Sands 4	Tweed Coastal Sands	NSW	TRUE
23	Coastal Sands 4	Farnborough	QLD	TRUE
23	Coastal Sands 4	Fraser Island	QLD	TRUE
23	Coastal Sands 4	Moreton Island	QLD	TRUE
23	Coastal Sands 4	North Stradbroke Isl	QLD	TRUE
24	Coastal Sands 5	Metropolitan Coastal Sands	NSW	FALSE
24	Coastal Sands 5	South East Coastal Sands	NSW	FALSE
25	Coffs Harbour Metasediments	Coffs Harbour Metasediments	NSW	FALSE
26	Collie Basin	Collie	WA	FALSE
27	Curlip Gravel	Orbost	VIC	FALSE
28	Dilwyn	Paaratte	VIC	FALSE
28	Dilwyn	Portland	VIC	FALSE
29	Eastern View Grp	Jan Juc	VIC	FALSE
30	Eucla Basin	Eucla	SA	FALSE
30	Eucla Basin	Nullabor	WA	FALSE
31	Eyre Peninsula Limestone Lenses	County Musgrave Prescribed Wells Area	SA	FALSE
31	Eyre Peninsula Limestone Lenses	Southern Basins Prescribed Wells Area	SA	FALSE

Aquifer ID	Aquifer	Groundwater Management Unit	State or Territory	Priority Aq
131	fractured and karstic rock	Unincorporated Area_30000445_NT	NT	FALSE
131	fractured and karstic rock	Unincorporated Area_30000447_NT	NT	FALSE
131	fractured and karstic rock	Unincorporated Area_30000448_NT	NT	FALSE
131	fractured and karstic rock	Unincorporated Area_30000455_NT	NT	FALSE
131	fractured and karstic rock	Unincorporated Area_30000460_NT	NT	FALSE
131	fractured and karstic rock	Unincorporated Area_30000471_NT	NT	FALSE
38	Daly Basin	Daly Roper	NT	TRUE
38	Daly Basin	Darwin Rural	NT	TRUE
39	Fractured and Karstic rock 2	Tennant Creek	NT	FALSE
39	Fractured and Karstic rock 2	Western Davenport	NT	FALSE
42	Fractured and weathered rock 2	Alice Springs	NT	FALSE
#N/A	Fractured and weathered rock	Unincorporated Area_30000444_NT	NT	FALSE
#N/A	Fractured and weathered rock	Unincorporated Area_30000446_NT	NT	FALSE
#N/A	Fractured and weathered rock	Unincorporated Area_30000449_NT	NT	FALSE
42	Fractured and weathered rock 2	Unincorporated Area_30000450_NT	NT	FALSE
42	Fractured and weathered rock 2	Unincorporated Area_30000451_NT	NT	FALSE
42	Fractured and weathered rock 2	Unincorporated Area_30000452_NT	NT	FALSE
42	Fractured and weathered rock 2	Unincorporated Area_30000453_NT	NT	FALSE
#N/A	Fractured and weathered rock	Unincorporated Area_30000454_NT	NT	FALSE
42	Fractured and weathered rock 2	Unincorporated Area_30000456_NT	NT	FALSE
42	Fractured and weathered rock 2	Unincorporated Area_30000457_NT	NT	FALSE
#N/A	Fractured and weathered rock	Unincorporated Area_30000459_NT (GMU split into several aquifers across climate zones)	NT	FALSE
#N/A	Fractured and weathered rock	Unincorporated Area_30000461_NT	NT	FALSE
#N/A	Fractured and weathered rock	Unincorporated Area_30000462_NT	NT	FALSE
41	Fractured and weathered rock 1	Unincorporated Area_30000463_NT	NT	FALSE
41	Fractured and weathered rock 1	Unincorporated Area_30000464_NT	NT	FALSE
#N/A	Fractured and weathered rock	Unincorporated Area_30000466_NT	NT	FALSE
#N/A	Fractured and weathered rock	Unincorporated Area_30000468_NT	NT	FALSE
#N/A	Fractured and weathered rock	Unincorporated Area_30000472_NT	NT	FALSE
43	Fractured rock	Border Rivers Fractured Rock	QLD	FALSE
43	Fractured rock	Condamine Fractured Rock	QLD	FALSE
44	Fractured rock and unconsolidated sediments	Ti-Tree	NT	FALSE
33	Fractured Rock Aquifer 1	Cook	QLD	FALSE
34	Fractured Rock Aquifer 2	Fitzroy	QLD	FALSE
34	Fractured Rock Aquifer 2	Highlands	QLD	FALSE
34	Fractured Rock Aquifer 2	Mount Isa	QLD	FALSE
36	Fractured Rock Aquifer 4	Unincorporated Area_30000316_QLD	QLD	FALSE
#N/A	Fractured Rock Aquifer	Unincorporated Area_30000334_QLD	QLD	FALSE
#N/A	Fractured Rock Aquifer	Unincorporated Area_30000337_QLD	QLD	FALSE
45	GAB 1	Cape Mgmt Area 1 of the GABWRP	QLD	FALSE
45	GAB 1	Gulf East Mgmt Area 4 of the GABWRP	QLD	FALSE
45	GAB 1	Gulf Mgmt Area 3 of the GABWRP	QLD	FALSE
45	GAB 1	Laura Mgmt Area 2 of the GABWRP	QLD	FALSE
46	GAB 2	GAB Cap Rock	NSW	TRUE

Aquifer ID	Aquifer	Groundwater Management Unit	State or Territory	Priority Aq
46	GAB 2	Unincorporated Area_30000467_NT	NT	TRUE
46	GAB 2	Barcaldine East Mgmt Area 13 of the GABWRP	QLD	TRUE
46	GAB 2	Barcaldine North Mgmt Area 12 of the GABWRP	QLD	TRUE
46	GAB 2	Barcaldine South Mgmt Area 14 of the GABWRP	QLD	TRUE
46	GAB 2	Barcaldine West Mgmt Area 11 of the GABWRP	QLD	TRUE
46	GAB 2	Carpentaria East Mgmt Area 6 of the GABWRP	QLD	TRUE
46	GAB 2	Carpentaria Mgmt Area 5 of the GABWRP	QLD	TRUE
46	GAB 2	Central Mgmt Area 16 of the GABWRP	QLD	TRUE
46	GAB 2	Flinders East Mgmt Area 8 of the GABWRP	QLD	TRUE
46	GAB 2	Flinders Mgmt Area 7 of the GABWRP	QLD	TRUE
46	GAB 2	Mimosa Mgmt Area 22 of the GABWRP	QLD	TRUE
46	GAB 2	North West Mgmt Area 10 of the GABWRP	QLD	TRUE
46	GAB 2	Surat Mgmt Area 19 of the GABWRP	QLD	TRUE
46	GAB 2	Warrego East Mgmt Area 18 of the GABWRP	QLD	TRUE
46	GAB 2	Warrego West Mgmt Area 17 of the GABWRP	QLD	TRUE
46	GAB 2	Western Carlo Mgmt Area 9 of the GABWRP	QLD	TRUE
46	GAB 2	Western Mgmt Area 15 of the GABWRP	QLD	TRUE
46	GAB 2	Far North Prescribed Wells Area	SA	TRUE
46	GAB 2	Unincorporated Area - Eromanga	SA	TRUE
47	GAB 4	Great Artesian Basin	NSW	TRUE
47	GAB 4	Clarence Moreton Mgmt Area 25 of the GABWRP	QLD	TRUE
47	GAB 4	Eastern Downs Mgmt Area 24 of the GABWRP	QLD	TRUE
47	GAB 4	Mulgildie Mgmt Area 23 of the GABWRP	QLD	TRUE
47	GAB 4	Surat East Mgmt Area 21 of the GABWRP	QLD	TRUE
47	GAB 4	Surat North Mgmt Area 20 of the GABWRP	QLD	TRUE
48	GAB ALLUVIAL	GAB Alluvial	NSW	FALSE
49	Gawler Craton	Gawler Craton	SA	FALSE
50	Goldfields	Goldfields	WA	FALSE
51	Gunnedah	Border Rivers Alluvium	NSW	TRUE
51	Gunnedah	Lower Gwydir Alluvium	NSW	TRUE
51	Gunnedah	Lower Macquarie Alluvium (downstream of Narromine)	NSW	TRUE
51	Gunnedah	Lower Namoi Alluvium	NSW	TRUE
51	Gunnedah	Miscellaneous Alluvium of Barwon Region	NSW	TRUE
51	Gunnedah	Peel Valley Alluvium	NSW	TRUE
51	Gunnedah	Upper Macquarie Alluvium (upstream of Narromine)	NSW	TRUE
51	Gunnedah	Upper Namoi Alluvium	NSW	TRUE
52	Gunnedah Basin	Gunnedah Basin	NSW	FALSE
53	Halls Creek	Halls Creek	WA	FALSE
54	Haunted Hill Formation	Wy Yung	VIC	FALSE
55	Haunted Hills Gravel	Wa De Lock	VIC	FALSE
56	Humevale Siltstone	Kinglake	VIC	FALSE
57	Kangaroo Island	Cygnet River	SA	FALSE
57	Kangaroo Island	Kangaroo Island	SA	FALSE
57	Kangaroo Island	Middle River	SA	FALSE

Aquifer ID	Aquifer	Groundwater Management Unit	State or Territory	Priority Aq
57	Kangaroo Island	Rocky River	SA	FALSE
58	Kimberley	Kimberley	WA	FALSE
59	Lachlan	Billabong Creek Alluvium (upstream of Mahonga)	NSW	TRUE
59	Lachlan	Mid Murrumbidgee Alluvium (upstream of Narrandera)	NSW	TRUE
59	Lachlan	Upper Lachlan Alluvium (upstream of Lake Cargelligo)	NSW	TRUE
59	Lachlan	Upper Murray Alluvium (upstream of Corowa)	NSW	TRUE
63	Lachlan Fold Belt 5	ACT	ACT	TRUE
63	Lachlan Fold Belt 5	Coxs River Fractured Rock	NSW	TRUE
63	Lachlan Fold Belt 5	Goulburn Fractured Rock	NSW	TRUE
#N/A	Lachlan Fold Belt	Lachlan Fold Belt (GMU split into several aquifers across climate zones)	NSW	FALSE
63	Lachlan Fold Belt 5	Yass Catchment	NSW	TRUE
62	Lachlan Fold Belt 4	Young Granite	NSW	FALSE
64	Latrobe Grp	Stratford	VIC	FALSE
64	Latrobe Grp	Yarram	VIC	FALSE
65	Latrobe Valley Coal Measures	Rosedale	VIC	FALSE
66	Mathinna	North East	TAS	FALSE
67	Mepunga Fmn	Gellibrand	VIC	FALSE
68	Murray Group	Angas-Bremer Prescribed Wells Area	SA	TRUE
68	Murray Group	Coorong	SA	TRUE
68	Murray Group	Ferries-McDonald	SA	TRUE
68	Murray Group	Kakoonie	SA	TRUE
68	Murray Group	Mallee Prescribed Wells Area	SA	TRUE
68	Murray Group	Peake, Roby and Sherlock Prescribed Wells Area	SA	TRUE
68	Murray Group	Tatiara Prescribed Wells Area	SA	TRUE
68	Murray Group	Tintinara-Coonalpyn Prescribed Wells Area	SA	TRUE
68	Murray Group	Kaniva	VIC	TRUE
68	Murray Group	Murrayville	VIC	TRUE
69	Musgrave Block	Mackay	SA	FALSE
69	Musgrave Block	Musgrave	SA	FALSE
69	Musgrave Block	Musgrave	SA	FALSE
71	New England Fold Belt 4	Bulahdelah Sandstone	NSW	FALSE
71	New England Fold Belt 4	Gloucester Basin	NSW	FALSE
71	New England Fold Belt 4	Lorne Basin (GMU split into several aquifers across climate zones)	NSW	FALSE
#N/A	New England Fold Belt	New England Fold Belt	NSW	FALSE
71	New England Fold Belt 4	North Coast Fractured Rock	NSW	FALSE
72	New England Fold Belt 5	Peel Valley Fractured Rock	NSW	FALSE
73	Newer Volcanics	Bungaree	VIC	TRUE
73	Newer Volcanics	Cardigan	VIC	TRUE
73	Newer Volcanics	Lancefield	VIC	TRUE
73	Newer Volcanics	Spring Hill	VIC	TRUE
73	Newer Volcanics	Upper Loddon	VIC	TRUE
73	Newer Volcanics	Warrion	VIC	TRUE
73	Newer Volcanics	Colongulac	VIC	TRUE

Aquifer ID	Aquifer	Groundwater Management Unit	State or Territory	Priority Aq
73	Newer Volcanics	Glenormiston	VIC	TRUE
73	Newer Volcanics	Heywood	VIC	TRUE
75	North Perth Basin	Arrowsmith	WA	FALSE
75	North Perth Basin	Jurien	WA	FALSE
76	Northern NSW Basalts 4	Alstonville Basalt	NSW	FALSE
76	Northern NSW Basalts 4	Galarganbone Tertiary Basalt	NSW	FALSE
76	Northern NSW Basalts 4	Inverell Basalt	NSW	FALSE
77	Northern NSW Basalts 5	Dorrigo Basalt	NSW	FALSE
77	Northern NSW Basalts 5	Liverpool Ranges Basalt	NSW	FALSE
77	Northern NSW Basalts 5	Orange Basalt	NSW	FALSE
78	Officer	Warburton	SA	FALSE
79	Older Volcanics	Leongatha	VIC	FALSE
79	Older Volcanics	Wandin Yallock	VIC	FALSE
#N/A	Ord-Victoria	Ord-Victoria (groundwater province split into several aquifers across climate zones)	NT	FALSE
83	Otway Basin	Lower Limestone Coast Prescribed Wells Area	SA	TRUE
83	Otway Basin	Padthaway Prescribed Wells Area	SA	TRUE
83	Otway Basin	Neuarpur	VIC	TRUE
84	Oxley Basin	Oxley Basin	NSW	FALSE
85	Pebble Point Fmn	Gerangamete	VIC	FALSE
85	Pebble Point Fmn	Newlingrook	VIC	FALSE
86	Peel Harvey Area	Murray	WA	FALSE
86	Peel Harvey Area	South West Coastal	WA	FALSE
87	Pilbara	Pilbara	WA	TRUE
88	Pirie Basin	Baroota	SA	FALSE
88	Pirie Basin	Mambray Coast	SA	FALSE
88	Pirie Basin	Spencer Gulf	SA	FALSE
89	Port Campbell Limestone	Glenelg	VIC	TRUE
89	Port Campbell Limestone	Hawkesdale	VIC	TRUE
89	Port Campbell Limestone	Nullawarre	VIC	TRUE
89	Port Campbell Limestone	Yangery	VIC	TRUE
90	Prior Stream and Recent floodplain Deposits	Denison	VIC	FALSE
91	Quat alluvial and Tertiary seds above GAB	Sediments above GAB: Border Rivers	QLD	FALSE
91	Quat alluvial and Tertiary seds above GAB	Sediments above GAB: Condamine-Balonne	QLD	FALSE
91	Quat alluvial and Tertiary seds above GAB	Sediments above GAB: Moonie	QLD	FALSE
91	Quat alluvial and Tertiary seds above GAB	Sediments above GAB: Warrego-Paroo-Nebine	QLD	FALSE
92	Quaternary Alluv associated with the Goulburn River	Alexandra	VIC	FALSE
95	Quaternary alluvium and colluvium	Merrimu	VIC	FALSE
93	Atherton Tablelands	Atherton Area A	QLD	TRUE
93	Atherton Tablelands	Atherton Area B	QLD	TRUE
94	Quaternary Sand Dune Deposits	Tarwin	VIC	FALSE
96	Renmark Grp	Balrootan	VIC	FALSE
96	Renmark Grp	Goroke	VIC	FALSE
96	Renmark Grp	Kaniva TCSA	VIC	FALSE

Aquifer ID	Aquifer	Groundwater Management Unit	State or Territory	Priority Aq
96	Renmark Grp	Little Desert	VIC	FALSE
96	Renmark Grp	Nhill	VIC	FALSE
97	River Murray	River Murray Prescribed Water Course	SA	FALSE
98	SE Tas fractured rock	Central South East	TAS	FALSE
100	Sedimentary Rock	Gove Water	NT	FALSE
101	Shepparton Formation	Barnawartha	VIC	FALSE
101	Shepparton Formation	Shepparton Irrigation	VIC	FALSE
102	Smithton Dolomite	Smithton	TAS	FALSE
103	South Perth Basin	Blackwood	WA	TRUE
103	South Perth Basin	Blackwood-Karri	WA	TRUE
103	South Perth Basin	Bunbury	WA	TRUE
103	South Perth Basin	Bunbury-Karri	WA	TRUE
103	South Perth Basin	Busselton-Capel	WA	TRUE
104	St George Alluvium	St George Alluvium: Condamine-Balonne	QLD	FALSE
104	St George Alluvium	St George Alluvium: Moonie	QLD	FALSE
104	St George Alluvium	St George Alluvium: Warrego-Paroo-Nebine	QLD	FALSE
105	St Vincent Basin	Adelaide	SA	FALSE
105	St Vincent Basin	McLaren Vale Prescribed Wells Area	SA	FALSE
105	St Vincent Basin	Northern Adelaide Plains Prescribed Wells Area	SA	FALSE
105	St Vincent Basin	Wakefield	SA	FALSE
99	SW Tas	West	TAS	FALSE
106	Sydney Basin	Maroota Tertiary Sands	NSW	FALSE
106	Sydney Basin	Sydney Basin - Blue Mountains Sandstone	NSW	FALSE
106	Sydney Basin	Sydney Basin - Coxs River Sandstone	NSW	FALSE
106	Sydney Basin	Sydney Basin - Macquarie Bogan	NSW	FALSE
106	Sydney Basin	Sydney Basin - Mangrove Mountain Sandstone	NSW	FALSE
106	Sydney Basin	Sydney Basin - Nepean Sandstone	NSW	FALSE
106	Sydney Basin	Sydney Basin - North	NSW	FALSE
106	Sydney Basin	Sydney Basin - Richmond Sandstone	NSW	FALSE
106	Sydney Basin	Sydney Basin - South	NSW	FALSE
106	Sydney Basin	Sydney Basin - Upper Hunter	NSW	FALSE
106	Sydney Basin	Sydney Basin Central	NSW	FALSE
106	Sydney Basin	Sydney Sandstone Central Coast	NSW	FALSE
106	Sydney Basin	Sydney Sandstone South Coast	NSW	FALSE
109	Tas Coastal Sands	Llandherne	TAS	FALSE
110	Tas Permo-triassic sediments	Spreyton	TAS	FALSE
111	Tas Tertiary Basalt	Burnie	TAS	FALSE
111	Tas Tertiary Basalt	Sorell	TAS	FALSE
111	Tas Tertiary Basalt	Wesley Vale	TAS	FALSE
112	Tas Tertiary Sediments	Flinders Island	TAS	FALSE
112	Tas Tertiary Sediments	Legerwood	TAS	FALSE
112	Tas Tertiary Sediments	Longford	TAS	FALSE
112	Tas Tertiary Sediments	Ringarooma	TAS	FALSE
112	Tas Tertiary Sediments	Scottsdale	TAS	FALSE
112	Tas Tertiary Sediments	St Marys	TAS	FALSE

Aquifer ID	Aquifer	Groundwater Management Unit	State or Territory	Priority Aq
112	Tas Tertiary Sediments	Tomahawk	TAS	FALSE
112	Tas Tertiary Sediments	Winnaleah	TAS	FALSE
108	TLA 3	Apsely	VIC	FALSE
#N/A	TLA	SA/VIC Border (GMU split into several aquifers across climate zones)	VIC	FALSE
107	TLA 2	Telopea Downs	VIC	FALSE
113	Toowoomba Basalts	Upper Condamine Basalts	QLD	TRUE
114	Torrens Basin	Lake Torrens	SA	FALSE
115	Unconsolidated Sediments	Unincorporated Area_30000458_NT	NT	FALSE
115	Unconsolidated Sediments	Unincorporated Area_30000465_NT	NT	FALSE
115	Unconsolidated Sediments	Unincorporated Area_30000469_NT	NT	FALSE
115	Unconsolidated Sediments	Unincorporated Area_30000470_NT	NT	FALSE
116	Unincorporated Area GMW	Unincorporated Area_30000586_VIC	VIC	FALSE
117	Unincorporated Area GWMW	Unincorporated Area_30000587_VIC	VIC	FALSE
118	Unincorporated Area SRW	Unincorporated Area_30000588_VIC	VIC	FALSE
119	Unincorporated Area SUN	Unincorporated Area_30000589_VIC	VIC	FALSE
120	Upper Valley Alluvium 4	Bell Valley Alluvium	NSW	TRUE
120	Upper Valley Alluvium 4	Belubula Valley Alluvium	NSW	TRUE
120	Upper Valley Alluvium 4	Castlereagh Alluvium	NSW	TRUE
120	Upper Valley Alluvium 4	Collaburragundry-Talbragar Valley	NSW	TRUE
120	Upper Valley Alluvium 4	Cudgegong Valley Alluvium	NSW	TRUE
121	Upper Valley Alluvium 5	Araluen Alluvium	NSW	FALSE
121	Upper Valley Alluvium 5	Bungendore Alluvium	NSW	FALSE
122	Werribee Delta and underlying newer volcanics	Deutgam	VIC	FALSE
123	Werribee Fmn	Cut Paw Paw	VIC	FALSE
124	Western Plains Alluvium	Lower Darling Alluvium	NSW	FALSE
124	Western Plains Alluvium	Upper Darling Alluvium	NSW	FALSE
124	Western Plains Alluvium	Mallee	SA	FALSE
124	Western Plains Alluvium	Murraylands	SA	FALSE
124	Western Plains Alluvium	Mypolonga Flat	SA	FALSE
124	Western Plains Alluvium	Noora Prescribed Wells Area	SA	FALSE
125	Western Sedimentary Plains	Western Murray Porous Rock	NSW	FALSE
126	Yilgarn-North	East Murchison	WA	FALSE
129	Yilgarn-South West 3	Bolgart	WA	FALSE
129	Yilgarn-South West 3	Bolgart East	WA	FALSE
129	Yilgarn-South West 3	Dwellingup	WA	FALSE
129	Yilgarn-South West 3	Happy Valley	WA	FALSE
#N/A	Yilgarn-South West	Karri (GMU split into several aquifers across climate zones)	WA	FALSE
128	Yilgarn-South West 2	Kondinin-Ravensthorpe	WA	FALSE
129	Yilgarn-South West 3	New Norcia	WA	FALSE
128	Yilgarn-South West 2	Westonia	WA	FALSE
129	Yilgarn-South West 3	Yenart	WA	FALSE
129	Yilgarn-South West 3	Yerecoin	WA	FALSE

*Number as suffix relates to climate zone: 1 = tropical; 2 = arid / semi arid; 3 = mediterranean; 4 = sub-tropical; 5 = temperate

APPENDIX B AQUIFER CODES LISTED IN FIGURE 2-4

Aquifer Code	Aquifer Name
MUG	Murray Group
AAG	Alluvium above GAB
WSP	Western NSW Sedimentary Plains
CAL	Calivil
WPA	Western Plains Alluvium
SAG	Sediments above GAB
AGSa	Adelaide Geosyncline (Arid Zone)
SQA	Southern Queensland Alluvium
CON	Condamine Alluvium
LAC	Lachlan
GUN	Gunnedah
AGS	Adelaide Geosyncline (Mediterranean Zone)
NVF	Northern Victoria Fractured Rock
TBA	Toowoomba Basalts
NFB	New England Fold Belt
NNB	Northern NSW Basalts
NPR	NSW Porous Rock
UVA	Upper Valley Alluvium
LFB	Lachlan Fold Belt

APPENDIX C: AQUIFER PRIORITISATION RESULTS

Aquifer details				Base Data				Aquifer Importance Index							Aquifer Sensitivity Index					Final Result	
Name	Aquifer ID	Aquifer Type	Climate Zone	Extraction (ML/y)	SY (ML/y)	Number of river baseflow GDEs identified	Number of wetland or terrestrial vegetation GDEs identified	E/Emax	SY/SYmax	f(RB)	f(GDE)	*I*	I/I_{max}	Importance Rank	*E/SY*	*f(R:S)*	*Se*	$Se_{standardised}$	Sensitivity Rank	Final prioritisation score	Rank
Calivil	10	Riverine plains	2	614,440	636,708	2	2	1.000	0.480	0.85	0.85	3.5E-01	1.0E+00	1	0.965	0.1	9.7E-02	5.3E-04	52	5.3E-04	1
GAB 2	46	sedimentary basin	2	416,380	218,889	16	1	0.678	0.165	0.85	0.85	8.1E-02	2.3E-01	3	1.902	0.1	1.9E-01	2.0E-03	32	4.8E-04	2
Gunnedah	51	alluvium	4	342,897	356,688	2	0	0.558	0.269	0.85	0.15	1.9E-02	5.5E-02	7	0.961	0.3	2.9E-01	4.7E-03	25	2.6E-04	3
Otway Basin	83	carbonate	3	291,249	1,326,146	1	1	0.474	1.000	0.85	0.85	3.4E-01	9.9E-01	2	0.220	0.3	6.6E-02	2.5E-04	65	2.5E-04	4
Coastal River Alluvium 4	21	coastal alluvium	4	168,160	423,593	10	2	0.274	0.319	0.85	0.85	6.3E-02	1.8E-01	4	0.397	0.3	1.2E-01	8.1E-04	45	1.5E-04	5
Pilbara	87	fractured rock	2	236,894	334,930	0	1	0.386	0.253	0.15	0.85	1.2E-02	3.6E-02	10	0.707	0.3	2.1E-01	2.5E-03	29	9.1E-05	6
Lachlan	59	alluvium	4	157,128	111,145	1	0	0.256	0.084	0.85	0.15	2.7E-03	7.9E-03	19	1.414	0.3	4.2E-01	1.0E-02	17	7.9E-05	7
GAB 4	47	sedimentary basin	4	172,542	124,296	5	1	0.281	0.094	0.85	0.85	1.9E-02	5.5E-02	8	1.388	0.1	1.4E-01	1.1E-03	38	6.0E-05	8
Newer Volcanics	73	basalts	5	28,956	59,031	4	4	0.047	0.045	0.85	0.85	1.5E-03	4.4E-03	24	0.477	0.9	4.3E-01	1.0E-02	16	4.5E-05	9
Coastal Sands 4	23	coastal sands	4	53,477	410,011	1	12	0.087	0.309	0.85	0.85	1.9E-02	5.6E-02	6	0.130	0.9	1.2E-01	7.9E-04	46	4.4E-05	10
Central Perth Basin	15	sedimentary basin	3	496,500	771,130	0	9	0.808	0.581	0.15	0.85	6.0E-02	1.7E-01	5	0.644	0.1	6.4E-02	2.4E-04	66	4.1E-05	11
Atherton Tablelands	93	basalts	4	16,106	18,356	2	2	0.026	0.014	0.85	0.85	2.6E-04	7.6E-04	35	0.877	0.9	7.9E-01	3.4E-02	8	2.6E-05	12
Toowoomba Basalts	113	basalts	4	76,100	61,100	0	0	0.124	0.046	0.15	0.15	1.3E-04	3.7E-04	45	1.245	0.9	1.1E+00	6.9E-02	3	2.5E-05	13
South Perth Basin	103	sedimentary basin	3	121,122	169,302	1	1	0.197	0.128	0.85	0.85	1.8E-02	5.2E-02	9	0.715	0.1	7.2E-02	2.9E-04	63	1.5E-05	14
Upper Condamine and Border Rivers Alluvium	4	alluvium	4	130,502	96,600	0	0	0.212	0.073	0.15	0.15	3.5E-04	1.0E-03	33	1.351	0.3	4.1E-01	9.2E-03	18	9.2E-06	15
Upper Valley Alluvium 4	120	upper valley alluvium	4	23,290	4,852	0	0	0.038	0.004	0.15	0.15	3.1E-06	9.0E-06	83	4.800	0.9	4.3E+00	1.0E+00	1	9.0E-06	16
Port Campbell Limestone	89	carbonate	3	39,111	88,024	1	1	0.064	0.066	0.85	0.85	3.1E-03	8.8E-03	17	0.444	0.3	1.3E-01	1.0E-03	40	8.9E-06	17
Murray Group	68	carbonate	2	206,174	268,195	0	4	0.336	0.202	0.15	0.85	8.7E-03	2.5E-02	12	0.769	0.1	7.7E-02	3.4E-04	61	8.5E-06	18
Coastal River Alluvium 1	19	coastal alluvium	1	67,850	138,616	0	0	0.110	0.105	0.15	0.15	2.6E-04	7.5E-04	36	0.489	0.9	4.4E-01	1.1E-02	15	8.1E-06	19
Adelaide Geosyncline 3	1	fractured rock	3	26,691	117,421	3	0	0.043	0.089	0.85	0.15	4.9E-04	1.4E-03	27	0.227	0.9	2.0E-01	2.4E-03	31	3.3E-06	20
Daly Basin	38	carbonate	1	49,790	328,500	0	0	0.081	0.248	0.15	0.15	4.5E-04	1.3E-03	30	0.152	0.9	1.4E-01	1.1E-03	39	1.4E-06	21
Lachlan Fold Belt 5	63	fractured rock	5	35,359	727,721	1	0	0.058	0.549	0.85	0.15	4.0E-03	1.2E-02	15	0.049	0.9	4.4E-02	1.1E-04	75	1.3E-06	22
Fractured Rock Aquifer 4	36	fractured rock	4	17,926	21,310	0	0	0.029	0.016	0.15	0.15	1.1E-05	3.0E-05	75	0.841	0.9	7.6E-01	3.2E-02	9	9.6E-07	23
Tas Tertiary Basalt	111	basalts	5	18,200	140,274	0	3	0.030	0.106	0.15	0.85	4.0E-04	1.2E-03	31	0.130	0.9	1.2E-01	7.8E-04	48	8.9E-07	24
Eyre Peninsula Limestone Lenses	31	shallow coastal sedimentary	3	8,467	13,882	0	1	0.014	0.010	0.15	0.85	1.8E-05	5.3E-05	68	0.610	0.9	5.5E-01	1.7E-02	13	8.9E-07	25
Goldfields	50	fractured rock & sedimentary basin	2	263,636	1,013,000	0	0	0.429	0.764	0.15	0.15	7.4E-03	2.1E-02	13	0.260	0.1	2.6E-02	4.0E-05	85	8.4E-07	26
Unincorporated Area SRW	118	fractured rock	5	23,497	58,742	0	0	0.038	0.044	0.15	0.15	3.8E-05	1.1E-04	58	0.400	0.9	3.6E-01	7.2E-03	22	8.0E-07	27
St Vincent Basin	105	sedimentary basin	3	41,504	22,970	0	1	0.068	0.017	0.15	0.85	1.5E-04	4.3E-04	43	1.807	0.1	1.8E-01	1.8E-03	34	7.9E-07	28
Lachlan Fold Belt 4	62	fractured rock	4	26,136	537,895	1	0	0.043	0.406	0.85	0.15	2.2E-03	6.3E-03	22	0.049	0.9	4.4E-02	1.1E-04	76	7.0E-07	29
Yilgarn-North	126	fractured rock	2	71,622	238,010	0	0	0.117	0.179	0.15	0.15	4.7E-04	1.4E-03	28	0.301	0.3	9.0E-02	4.7E-04	54	6.3E-07	30
TLA 3	108	carbonate	3	33,063	26,546	0	0	0.054	0.020	0.15	0.15	2.4E-05	7.0E-05	62	1.245	0.3	3.7E-01	7.8E-03	20	5.4E-07	31
Unincorporated Area GMW	116	fractured rock	5	18,971	45,208	0	0	0.031	0.034	0.15	0.15	2.4E-05	6.8E-05	63	0.420	0.9	3.8E-01	8.0E-03	19	5.4E-07	32
Smithton Dolomite	102	carbonate	5	11,500	60,000	0	1	0.019	0.045	0.15	0.85	1.1E-04	3.1E-04	48	0.192	0.9	1.7E-01	1.7E-03	35	5.2E-07	33
Northern NSW Basalts 4	76	basalts	4	11,638	68,843	3	0	0.019	0.052	0.85	0.15	1.3E-04	3.6E-04	46	0.169	0.9	1.5E-01	1.3E-03	36	4.7E-07	34
Quaternary Sand Dune Deposits	94	coastal sands	3	1,718	1,300	1	1	0.003	0.001	0.85	0.85	2.0E-06	5.7E-06	89	1.322	0.9	1.2E+00	7.7E-02	2	4.4E-07	35
Fractured Rock Aquifer 2	34	fractured rock	2	35,612	42,336	0	0	0.058	0.032	0.15	0.15	4.2E-05	1.2E-04	56	0.841	0.3	2.5E-01	3.6E-03	27	4.3E-07	36
Kimberley	58	fractured rock	1	11,102	75,637	0	1	0.018	0.057	0.15	0.85	1.3E-04	3.8E-04	44	0.147	0.9	1.3E-01	9.9E-04	41	3.8E-07	37

Aquifer details				Base Data				Aquifer Importance Index							Aquifer Sensitivity Index					Final Result	
Name	Aquifer ID	Aquifer Type	Climate Zone	Extraction (ML/y)	SY (ML/y)	Number of river baseflow GDEs identified	Number of wetland or terrestrial vegetation GDEs identified	E/Emax	SY/SY max	f(RB)	f(GDE)	*I*	I/I_{max}	Importance Rank	*E/SY*	*f(R:S)*	*Se*	$Se_{standardised}$	Sensitivity Rank	Final prioritisation score	Rank
New England Fold Belt 4	71	fractured rock	4	23,211	759,244	1	0	0.038	0.573	0.85	0.15	2.8E-03	7.9E-03	18	0.031	0.9	2.8E-02	4.4E-05	83	3.5E-07	38
Northern NSW Basalts 5	77	basalts	5	12,981	133,208	1	0	0.021	0.100	0.85	0.15	2.7E-04	7.8E-04	34	0.097	0.9	8.8E-02	4.4E-04	55	3.4E-07	39
North Perth Basin	75	sedimentary basin	3	70,094	280,650	0	1	0.114	0.212	0.15	0.85	3.1E-03	8.9E-03	16	0.250	0.1	2.5E-02	3.7E-05	86	3.2E-07	40
Fractured rock	43	fractured rock	4	8,922	8,900	0	0	0.015	0.007	0.15	0.15	2.2E-06	6.3E-06	87	1.003	0.9	9.0E-01	4.5E-02	5	2.8E-07	41
New England Fold Belt 5	72	fractured rock	5	20,816	680,913	1	0	0.034	0.513	0.85	0.15	2.2E-03	6.4E-03	21	0.031	0.9	2.8E-02	4.4E-05	83	2.8E-07	42
Brighton Grp	9	shallow coastal sedimentary	5	2,358	5,900	2	2	0.004	0.004	0.85	0.85	1.2E-05	3.6E-05	74	0.400	0.9	3.6E-01	7.2E-03	23	2.6E-07	43
Lachlan Fold Belt 2	61	fractured rock	2	45,274	931,776	1	0	0.074	0.703	0.85	0.15	6.6E-03	1.9E-02	14	0.049	0.3	1.5E-02	1.3E-05	93	2.4E-07	44
Fractured Rock Aquifer 1	33	fractured rock	1	8,618	10,246	0	0	0.014	0.008	0.15	0.15	2.4E-06	7.0E-06	85	0.841	0.9	7.6E-01	3.2E-02	9	2.2E-07	45
Boisdale Fmn	5	sedimentary basin	5	15,411	26,877	1	1	0.025	0.020	0.85	0.85	3.7E-04	1.1E-03	32	0.573	0.1	5.7E-02	1.9E-04	70	2.0E-07	46
Fractured and weathered rock 2	42	fractured rock	2	46,136	1,314,946	0	1	0.075	0.992	0.15	0.85	9.5E-03	2.7E-02	11	0.035	0.3	1.1E-02	6.6E-06	99	1.8E-07	47
Shepparton Formation	101	Riverine plains	2	87,152	223,294	0	0	0.142	0.168	0.15	0.15	5.4E-04	1.5E-03	26	0.390	0.1	3.9E-02	8.8E-05	78	1.4E-07	48
Pebble Point Fmn	85	sedimentary basin	5	12,677	21,977	1	1	0.021	0.017	0.85	0.85	2.5E-04	7.1E-04	38	0.577	0.1	5.8E-02	1.9E-04	69	1.4E-07	49
Coastal River Alluvium 2	20	coastal alluvium	2	48,134	36,970	0	0	0.078	0.028	0.15	0.15	4.9E-05	1.4E-04	54	1.302	0.1	1.3E-01	9.6E-04	43	1.4E-07	50
Childers Fmn	16	sedimentary basin	5	12,351	23,665	2	2	0.020	0.018	0.85	0.85	2.6E-04	7.5E-04	37	0.522	0.1	5.2E-02	1.6E-04	72	1.2E-07	51
Fractured and weathered rock 1	41	fractured rock	1	12,299	350,524	0	1	0.020	0.264	0.15	0.85	6.7E-04	1.9E-03	25	0.035	0.9	3.2E-02	5.8E-05	80	1.1E-07	52
Humevale Siltstone	56	fractured rock	5	1,236	2,015	1	1	0.002	0.002	0.85	0.85	2.2E-06	6.4E-06	86	0.613	0.9	5.5E-01	1.7E-02	12	1.1E-07	53
Albany	2	shallow coastal sedimentary	3	5,036	4,210	0	0	0.008	0.003	0.15	0.15	5.9E-07	1.7E-06	97	1.196	0.9	1.1E+00	6.4E-02	4	1.1E-07	54
TLA 2	107	carbonate	2	43,037	34,554	0	0	0.070	0.026	0.15	0.15	4.1E-05	1.2E-04	57	1.245	0.1	1.2E-01	8.8E-04	44	1.0E-07	55
Latrobe Valley Coal Measures	65	sedimentary basin	5	11,580	22,313	1	1	0.019	0.017	0.85	0.85	2.3E-04	6.6E-04	40	0.519	0.1	5.2E-02	1.6E-04	73	1.0E-07	56
Coastal River Alluvium 5	22	coastal alluvium	5	5,317	5,540	0	0	0.009	0.004	0.15	0.15	8.1E-07	2.3E-06	93	0.960	0.9	8.6E-01	4.1E-02	6	9.6E-08	57
Canning	13	sedimentary basin	2	46,982	311,697	0	1	0.076	0.235	0.15	0.85	2.3E-03	6.6E-03	20	0.151	0.1	1.5E-02	1.3E-05	90	8.9E-08	58
Older Volcanics	79	basalts	5	1,913	9,424	1	1	0.003	0.007	0.85	0.85	1.6E-05	4.6E-05	70	0.203	0.9	1.8E-01	1.9E-03	33	8.7E-08	59
Prior Stream and Recent floodplain Deposits	90	alluvium	5	7,062	17,743	0	0	0.011	0.013	0.15	0.15	3.5E-06	1.0E-05	82	0.398	0.9	3.6E-01	7.2E-03	24	7.2E-08	60
Quaternary Alluv associated with the Goulburn River	92	alluvium	5	1,042	1,937	1	1	0.002	0.001	0.85	0.85	1.8E-06	5.2E-06	90	0.538	0.9	4.8E-01	1.3E-02	14	6.7E-08	61
GAB 1	45	sedimentary basin	1	12,836	9,733	4	0	0.021	0.007	0.85	0.15	2.0E-05	5.6E-05	66	1.319	0.1	1.3E-01	9.9E-04	42	5.6E-08	62
Sedimentary Rock	100	sedimentary basin	1	10,100	4,860	1	0	0.016	0.004	0.85	0.15	7.7E-06	2.2E-05	76	2.078	0.1	2.1E-01	2.4E-03	30	5.4E-08	63
Sydney Basin	106	sedimentary basin	4	97,324	805,826	0	0	0.158	0.608	0.15	0.15	2.2E-03	6.2E-03	23	0.121	0.1	1.2E-02	8.6E-06	97	5.4E-08	64
Latrobe Grp	64	sedimentary basin	5	39,183	52,960	0	0	0.064	0.040	0.15	0.15	5.7E-05	1.7E-04	51	0.740	0.1	7.4E-02	3.1E-04	62	5.2E-08	65
Dilwyn	28	carbonate	3	3,417	10,606	2	2	0.006	0.008	0.85	0.85	3.2E-05	9.3E-05	60	0.322	0.3	9.7E-02	5.3E-04	51	4.9E-08	66
Haunted Hills Gravel	55	sedimentary basin	5	8,785	30,084	1	1	0.014	0.023	0.85	0.85	2.3E-04	6.8E-04	39	0.292	0.1	2.9E-02	5.0E-05	81	3.4E-08	67
Collie Basin	26	sedimentary basin	3	33,727	55,500	0	0	0.055	0.042	0.15	0.15	5.2E-05	1.5E-04	52	0.608	0.1	6.1E-02	2.1E-04	67	3.2E-08	68
Carnarvon Alluvium	14	coastal alluvium	2	10,612	11,100	0	1	0.017	0.008	0.15	0.85	1.8E-05	5.3E-05	67	0.956	0.1	9.6E-02	5.2E-04	53	2.8E-08	69
Bridgewater Fmn	8	sedimentary basin	5	4,281	6,013	1	1	0.007	0.005	0.85	0.85	2.3E-05	6.6E-05	64	0.712	0.1	7.1E-02	2.9E-04	64	1.9E-08	70
Eastern View Grp	29	sedimentary basin	5	3,663	4,250	1	1	0.006	0.003	0.85	0.85	1.4E-05	4.0E-05	72	0.862	0.1	8.6E-02	4.3E-04	56	1.7E-08	71
Calivil (some outcropping basement)	11	Riverine plains	5	9,858	25,200	0	0	0.016	0.019	0.15	0.15	6.9E-06	2.0E-05	77	0.391	0.3	1.2E-01	7.8E-04	47	1.6E-08	72
Curlip Gravel	27	shallow coastal sedimentary	5	498	1,200	1	1	0.001	0.001	0.85	0.85	5.3E-07	1.5E-06	98	0.415	0.9	3.7E-01	7.8E-03	21	1.2E-08	73
Canarvon Basin	12	sedimentary basin	2	31,872	138,360	0	0	0.052	0.104	0.15	0.15	1.2E-04	3.5E-04	47	0.230	0.1	2.3E-02	3.1E-05	87	1.1E-08	74
Bremer Basin	7	shallow coastal sedimentary	3	2,513	8,540	0	0	0.004	0.006	0.15	0.15	5.9E-07	1.7E-06	96	0.294	0.9	2.6E-01	3.9E-03	26	6.7E-09	75

Aquifer details				Base Data				Aquifer Importance Index							Aquifer Sensitivity Index					Final Result	
Name	Aquifer ID	Aquifer Type	Climate Zone	Extraction (ML/y)	SY (ML/y)	Number of river baseflow GDEs identified	Number of wetland or terrestrial vegetation GDEs identified	E/Emax	SY/SY max	f(RB)	f(GDE)	*I*	I/I_{max}	Importance Rank	*E/SY*	*f(R:S)*	*Se*	$Se_{standardised}$	Sensitivity Rank	Final prioritisation score	Rank
Upper Valley Alluvium 5	121	upper valley alluvium	5	1,339	1,454	0	0	0.002	0.001	0.15	0.15	5.4E-08	1.5E-07	107	0.920	0.9	8.3E-01	3.8E-02	7	5.9E-09	76
Oxley Basin	84	sedimentary basin	4	15,385	192,488	1	0	0.025	0.145	0.85	0.15	4.6E-04	1.3E-03	29	0.080	0.1	8.0E-03	3.8E-06	103	5.1E-09	77
Unincorporated Area GWMW	117	fractured rock	2	5,642	15,754	0	0	0.009	0.012	0.15	0.15	2.5E-06	7.1E-06	84	0.358	0.3	1.1E-01	6.6E-04	49	4.7E-09	78
Halls Creek	53	fractured rock	2	3,648	24,853	0	1	0.006	0.019	0.15	0.85	1.4E-05	4.1E-05	71	0.147	0.3	4.4E-02	1.1E-04	74	4.6E-09	79
Fractured rock and unconsolidated sediments	44	fractured rock	2	2,700	10,200	0	1	0.004	0.008	0.15	0.85	4.3E-06	1.2E-05	79	0.265	0.3	7.9E-02	3.6E-04	59	4.5E-09	80
Yilgarn-South West 3	129	fractured rock	3	1,254	4,745	0	0	0.002	0.004	0.15	0.15	1.6E-07	4.7E-07	104	0.264	0.9	2.4E-01	3.2E-03	28	1.5E-09	81
Coffs Harbour Metasediments	25	fractured rock	4	1,835	20,401	0	0	0.003	0.015	0.15	0.15	1.0E-06	3.0E-06	92	0.090	0.9	8.1E-02	3.8E-04	57	1.1E-09	82
St George Alluvium	104	alluvium	2	10,750	60,800	0	0	0.017	0.046	0.15	0.15	1.8E-05	5.2E-05	69	0.177	0.1	1.8E-02	1.8E-05	89	9.6E-10	83
Coastal Sands 5	24	coastal sands	5	2,689	87,438	0	0	0.004	0.066	0.15	0.15	6.5E-06	1.9E-05	78	0.031	0.9	2.8E-02	4.5E-05	82	8.4E-10	84
GAB ALLUVIAL	48	alluvium	2	17,230	350,414	0	0	0.028	0.264	0.15	0.15	1.7E-04	4.8E-04	42	0.049	0.1	4.9E-03	1.5E-06	106	7.0E-10	85
Pirie Basin	88	sedimentary basin	2	2,170	3,815	0	1	0.004	0.003	0.15	0.85	1.3E-06	3.7E-06	91	0.569	0.1	5.7E-02	1.9E-04	71	7.0E-10	86
Tas Tertiary Sediments	112	sedimentary plains	5	3,069	106,339	0	8	0.005	0.080	0.15	0.85	5.1E-05	1.5E-04	53	0.029	0.3	8.7E-03	4.5E-06	102	6.6E-10	87
Ord-Victoria 1	81	carbonate	1	478	598	0	0	0.001	0.000	0.15	0.15	7.9E-09	2.3E-08	113	0.800	0.9	7.2E-01	2.9E-02	11	6.5E-10	88
Peel Harvey Area	86	sedimentary basin	3	12,400	142,500	0	0	0.020	0.107	0.15	0.15	4.9E-05	1.4E-04	55	0.087	0.1	8.7E-03	4.5E-06	101	6.3E-10	89
Werribee Fmn	123	coastal sands	5	245	3,650	1	1	0.000	0.003	0.85	0.85	7.9E-07	2.3E-06	94	0.067	0.9	6.0E-02	2.1E-04	68	4.8E-10	90
Yilgarn-South West 2	128	fractured rock	2	2,014	7,620	0	0	0.003	0.006	0.15	0.15	4.2E-07	1.2E-06	101	0.264	0.3	7.9E-02	3.6E-04	60	4.4E-10	91
Western Plains Alluvium	124	alluvium	2	3,701	36,537	0	1	0.006	0.028	0.15	0.85	2.1E-05	6.1E-05	65	0.101	0.1	1.0E-02	6.1E-06	100	3.7E-10	92
Adelaide Geosyncline 2	0	fractured rock	2	2,864	154,906	0	1	0.005	0.117	0.15	0.85	6.9E-05	2.0E-04	50	0.018	0.3	5.5E-03	1.8E-06	105	3.7E-10	93
Gunnedah Basin	52	sedimentary basin	4	6,165	193,400	1	0	0.010	0.146	0.85	0.15	1.9E-04	5.4E-04	41	0.032	0.1	3.2E-03	6.2E-07	107	3.3E-10	94
Musgrave Block	69	fractured rock	2	1,330	19,860	0	1	0.002	0.015	0.15	0.85	4.1E-06	1.2E-05	80	0.067	0.3	2.0E-02	2.4E-05	88	2.8E-10	95
Clifton Fmn	18	sedimentary basin	3	3,011	7,437	0	0	0.005	0.006	0.15	0.15	6.2E-07	1.8E-06	95	0.405	0.1	4.0E-02	9.5E-05	77	1.7E-10	96
Fractured and Karstic rock 2	39	carbonate	2	1,800	1,860	0	0	0.003	0.001	0.15	0.15	9.2E-08	2.7E-07	106	0.968	0.1	9.7E-02	5.4E-04	50	1.4E-10	97
Quaternary alluvium and colluvium	95	alluvium	5	75	450	1	1	0.000	0.000	0.85	0.85	3.0E-08	8.6E-08	108	0.167	0.9	1.5E-01	1.3E-03	37	1.1E-10	98
Bonaparte	6	sedimentary basin	1	1,380	9,400	0	1	0.002	0.007	0.15	0.85	2.0E-06	5.9E-06	88	0.147	0.1	1.5E-02	1.3E-05	92	7.4E-11	99
Tas Permo-triassic sediments	110	sedimentary basin	5	800	2,500	0	1	0.001	0.002	0.15	0.85	3.1E-07	9.0E-07	102	0.320	0.1	3.2E-02	6.0E-05	79	5.4E-11	100
Ord-Victoria 2	82	carbonate	2	821	1,026	0	0	0.001	0.001	0.15	0.15	2.3E-08	6.7E-08	110	0.800	0.1	8.0E-02	3.7E-04	58	2.5E-11	101
Mathinna	66	fractured rock	5	500	175,191	0	1	0.001	0.132	0.15	0.85	1.4E-05	4.0E-05	73	0.003	0.9	2.6E-03	4.0E-07	108	1.6E-11	102
Western Sedimentary Plains	125	sedimentary plains	2	4,778	790,772	0	0	0.008	0.596	0.15	0.15	1.0E-04	3.0E-04	49	0.006	0.1	6.0E-04	2.3E-08	113	6.8E-12	103
fractured and karstic rock	131	carbonate	2	3,350	330,400	0	0	0.005	0.249	0.15	0.15	3.1E-05	8.8E-05	61	0.010	0.1	1.0E-03	6.4E-08	111	5.6E-12	104
Haunted Hill Formation	54	sedimentary basin	5	941	7,426	0	0	0.002	0.006	0.15	0.15	1.9E-07	5.6E-07	103	0.127	0.1	1.3E-02	9.5E-06	96	5.3E-12	105
Unconsolidated Sediments	115	coastal sands	1	360	46,760	0	0	0.001	0.035	0.15	0.15	4.6E-07	1.3E-06	100	0.008	0.9	6.9E-03	2.9E-06	104	3.8E-12	106
Renmark Grp	96	sedimentary basin	2	792	7,122	0	0	0.001	0.005	0.15	0.15	1.6E-07	4.5E-07	105	0.111	0.1	1.1E-02	7.3E-06	98	3.3E-12	107
Quat alluvial and Tertiary seds above GAB	91	alluvium	2	1,663	81,400	0	0	0.003	0.061	0.15	0.15	3.7E-06	1.1E-05	81	0.020	0.1	2.0E-03	2.5E-07	110	2.7E-12	108
Clarence Morton Basin	17	sedimentary basin	4	2,768	430,883	0	0	0.005	0.325	0.15	0.15	3.3E-05	9.5E-05	59	0.006	0.1	6.4E-04	2.6E-08	112	2.4E-12	109
Tas Coastal Sands	109	coastal sands	5	50	3,039	0	1	0.000	0.002	0.15	0.85	2.4E-08	6.9E-08	109	0.016	0.9	1.5E-02	1.3E-05	91	8.9E-13	110
Allluvium associated with the Warrego River	3	alluvium	2	679	26,600	0	0	0.001	0.020	0.15	0.15	5.0E-07	1.4E-06	99	0.026	0.1	2.6E-03	4.0E-07	109	5.7E-13	111
Werribee Delta and underlying newer volcanics	122	coastal sands	5	72	5,100	0	0	0.000	0.004	0.15	0.15	1.0E-08	2.9E-08	111	0.014	0.9	1.3E-02	9.6E-06	94	2.8E-13	112
Newer Volcanics and Calivil	74	basalts	5	72	5,100	0	0	0.000	0.004	0.15	0.15	1.0E-08	2.9E-08	112	0.014	0.9	1.3E-02	9.6E-06	94	2.8E-13	113

Aquifer details				Base Data				Aquifer Importance Index							Aquifer Sensitivity Index					Final Result	
Name	Aquifer ID	Aquifer Type	Climate Zone	Extraction (ML/y)	SY (ML/y)	Number of river baseflow GDEs identified	Number of wetland or terrestrial vegetation GDEs identified	E/Emax	SY/SYmax	f(RB)	f(GDE)	*I*	I/I_{max}	Importance Rank	*E/SY*	*f(R:S)*	*Se*	$Se_{standardised}$	Sensitivity Rank	Final prioritisation score	Rank
Eucla Basin	30	sedimentary basin	2	500	0	0	0	0.001	0.000	0.15	0.15	insufficient data									
Gawler Craton	49	fractured rock	2	500	0	0	0	0.001	0.000	0.15	0.15	insufficient data									
Kangaroo Island	57	fractured rock	3	1,500	0	0	0	0.002	0.000	0.15	0.15	insufficient data									
Mepunga Fmn	67	sedimentary basin	5	4	0	1	1	0.000	0.000	0.85	0.85	insufficient data									
Officer	78	sedimentary basin	2	500	0	0	0	0.001	0.000	0.15	0.15	insufficient data									
River Murray	97	alluvium	2	0	0	0	0	0.000	0.000	0.15	0.15	insufficient data									
SE Tas fractured rock	98	fractured rock	5	6,800	0	0	0	0.011	0.000	0.15	0.15	insufficient data									
SW Tas	99	fractured rock	5	0	1,315,046	0	1	0.000	0.992	0.15	0.85	insufficient data									
Torrens Basin	114	sedimentary basin	2	500	0	0	0	0.001	0.000	0.15	0.15	insufficient data									
Unincorporated Area SUN	119	sedimentary basin	2	0	0	0	0	0.000	0.000	0.15	0.15	insufficient data									

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6. ADDENDUM

6.1. Introduction

The prioritisation scheme presented in this report has been adjusted and reinterpreted to derive an adjusted priority aquifer listing for the final project report to the NWC. The weighting factor for 'aquifer responsiveness' – based on recharge to storage ratios – has been adjusted as it was seen to overestimate the sensitivity of large, sedimentary basin aquifers such the Great Artesian Basin. Further, the results have been reinterpreted using an ordination procedure to define three priority groupings:

> Priority aquifers – those which are both sensitive and important;
>
> Sensitive Aquifers – those which are classed as sensitive, yet rank as less important;
>
> Important Aquifers – those which are classed as important, yet rank as less sensitive.

The priority listing comprises 14 aquifers. All of these aquifers are included in the initial group of priority aquifers outlined in this report.

6.2. Changes to responsiveness metric

The altered aquifer responsiveness metric is shown in the following equation:

$$Aquifer\ responsiveness = f(R{:}S) = \begin{cases} 0.9 & high\ R{:}S \\ 0.3 & moderate\ R{:}S \\ 0.01 & low\ R{:}S \end{cases}$$

The only change is that to the value assigned to a low responsiveness rating has been revised down to 0.01 (from 0.1) as it was seen to overestimate the sensitivity of these aquifer types, particularly the large sedimentary basins like the GAB. The same matrix is used to assign ratings of high, moderate and low responsiveness according to their generic aquifer type and the climate zone where they are located (Table 2-1).

6.3. Revised method to define priority aquifers

Priority aquifers are defined as those which are both sensitive and important. A revised procedure has been developed to combine the aquifer sensitivity and importance scores. Previously, the two scores were multiplied to define an overall priority score. This has been superseded by an ordination approach.

Aquifers have been ranked according to their sensitivity and importance scores. The top twenty aquifers from each category define the aquifers that are most sensitive and those which are most important.

An ordination procedure has been used to define the priority grouping. The sensitivity rank is plotted against the importance rank (Figure 6-1). There is a relatively even scattering of points and, as expected, there is no relationship between the variables. Aquifers that fall close to the origin (i.e. are high ranking in terms of sensitivity and importance) are deemed priority. Classifications are also provided for the groups of aquifers that rank in the top twenty for either sensitivity or importance, but not very highly in the other category - a ranking of greater than 50. These aquifers are termed sensitive aquifers (of low importance rating) and important aquifers (of low sensitivity rating).

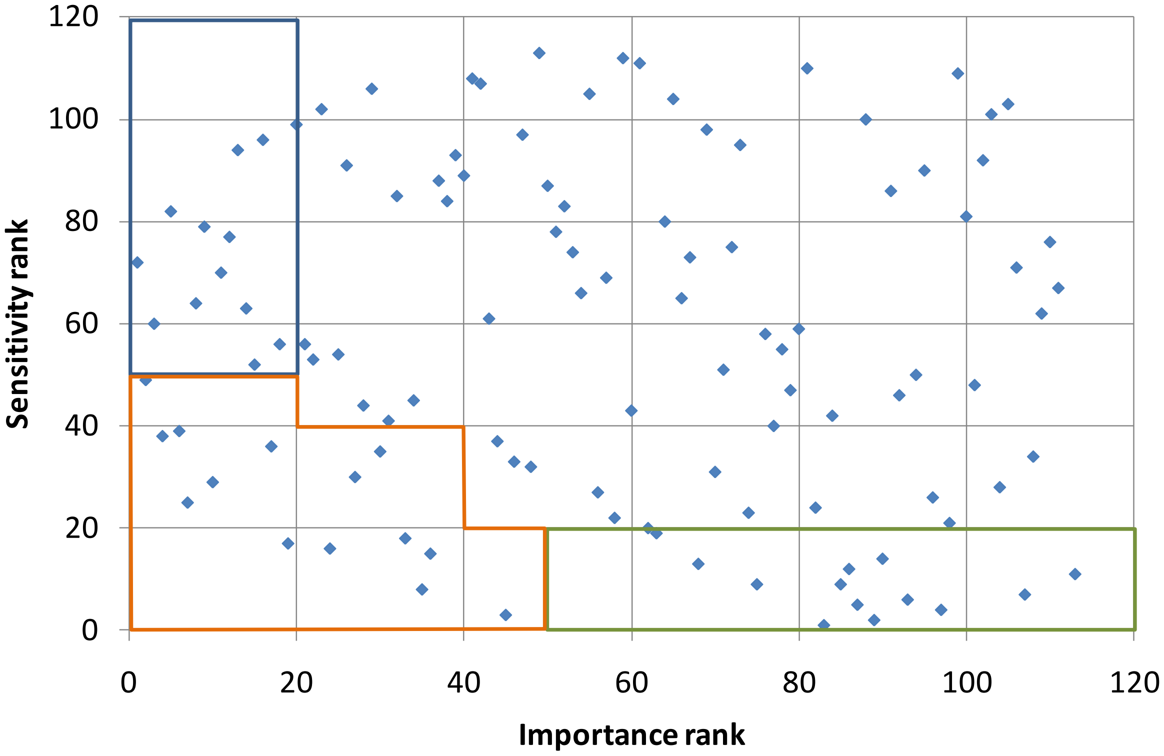

Figure 6-1 Plot of aquifer sensitivity rank versus importance rank. Orange line indicates selection of priority aquifers, green line indicates selection of sensitive aquifers (of low importance rating), blue line indicates selection of important aquifers (of low sensitivity rating)

6.4. New priority listing

The key results from the revised prioritisation scheme are summarised in Table 6-1. The table lists the twenty most sensitive aquifers, the twenty most important aquifers, and the three priority groupings. Their location is shown in Figure 6-2.

The 14 priority aquifers were all previously listed as priority aquifers. Hence they have all been characterised by the sensitivity of their recharge and discharge processes.

The aquifers no longer defined as priority (but were such under the previous scheme) are predominantly large sedimentary basins (GAB 2, GAB 4, Central and South Perth Basins) or other aquifers with low recharge relative to storage (Murray Basin, Calivil), which are regarded as lower priority due their relative insensitivity. The alteration to the aquifer responsiveness term has generated this demotion. The Upper Valley Alluvium 4 and Lachlan Fold Belt are the remaining aquifers no longer considered to be priority. Their demotion is related to the new selection approach, where aquifers that score highly in one category but not the other are not considered as priority.

Table 6-1 Prioritisation results: sensitive, important and priority aquifers the highly sensitive or highly important aquifers that do not score highly in the other categories.

There are a number of small yet sensitive systems listed as sensitive aquifers (of low importance). While these aquifers are not rated as important on a national scale, they may have significant local importance. The upper valley alluvial aquifers of NSW occur within this group and include the Belubula and Cudgegong GMUs, which are both highly developed aquifers and rated by the MDB SY as priority GMUs (Richardson et al., 2008). Similarly, some of the coastal sand aquifers are listed that are prescribed groundwater resources and support groundwater dependent ecosystems (e.g. Eyre Peninsula limestone lenses and Albany).

The aquifers listed as important (of low sensitivity rating) may also be sensitive to climate change at a local level. These aquifers include large sedimentary basins (e.g. Perth Basin, GAB), and riverine plains (e.g. Calivil). While the large storage volumes present in these systems is not suggestive of high level of sensitivity to climate change, there are local aspects of these aquifers that may be sensitive. For example the superficial aquifer of the Perth Basin supports a number of groundwater dependent ecosystems, and the thin nature of this aquifer suggests it will be sensitive to changes in climate.

Many of the other aquifers listed in the important (of low sensitivity) category are large unincorporated areas (e.g. Lachlan Fold Belt, New England Fold Belt, Goldfields). It is probable that the prioritisation scheme has overestimated their importance due to their substantial spatial extents.

Table 6-1 Prioritisation results: sensitive, important and priority aquifers

20 most sensitive aquifers listed in order of decreasing importance	Importance, sensitivity ranks	20 most important aquifers listed in order of decreasing sensitivity	Importance, sensitivity ranks	Aquifers with both moderately high sensitivity and importance	Importance, sensitivity ranks
Lachlan	19, 17	Lachlan	19, 17	Adelaide Geosyncline 3	27, 30
Newer Volcanics	24, 16	Gunnedah	7, 25	Daly Basin	30, 35
Upper Condamine and Border Rivers Alluvium	33, 18	Pilbara	10, 29		
Atherton Tablelands	35, 8	Port Campbell Limestone	17, 36		
Coastal River Alluvium 1	36, 15	Coastal River Alluvium 4	4, 38		
Toowoomba Basalts	45, 3	Coastal Sands 4	6, 39		
TLA 3	62, 20	Otway Basin	2, 49		
Unincorporated Area GMW	63, 19	Lachlan Fold Belt 5	15, 52		
Eyre Peninsula Limestone Lenses	68, 13	New England Fold Belt 4	18, 56		
Fractured Rock Aquifer 4	75, 9	GAB 2	3, 60		
Upper Valley Alluvium 4	83, 1	Lachlan Fold Belt 2	14, 63		
Fractured Rock Aquifer 1	85, 9	GAB 4	8, 64		
Humevale Siltstone	86, 12	Fractured and weathered rock 2	11, 70		
Fractured rock	87, 5	Calivil	1, 72		
Quaternary Sand Dune Deposits	89, 2	Murray Group	12, 77		
Quaternary Alluv associated with the Goulburn River	90, 14	South Perth Basin	9, 79		
Coastal River Alluvium 5	93, 6	Central Perth Basin	5, 82	**Legend**	
Albany	97, 4	Goldfields	13, 94	Priority Aquifers: sensitive & important	
Upper Valley Alluvium 5	107, 7	North Perth Basin	16, 96	Sensitive aquifers (low importance rating)	
Ord-Victoria 1	113, 11	Canning	20, 99	Important aquifers (low sensitivity rating)	

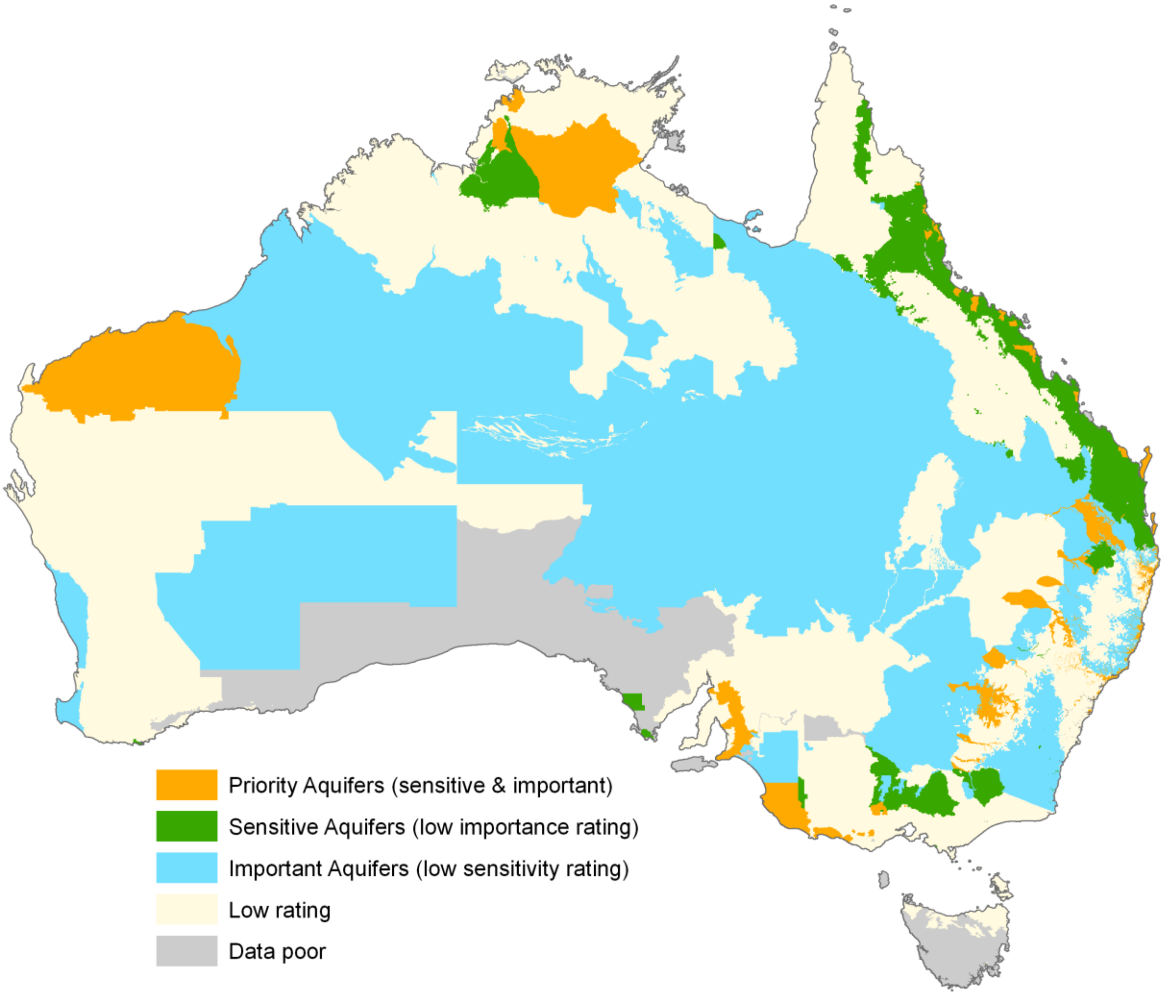

Figure 6-2 Map showing location of priority aquifers

6.5. Trends by aquifer type and climate zone

The plot of aquifer sensitivity versus importance ranks is reproduced in Figure 6-3 where it is shown by aquifer type and climate zone. The notable trends from this plot are summarised in Table 6-2. The analysis identifies some biases inherent in the prioritisation scheme. For instance on close analysis, a number of background trends are evident in the sensitivity index because aquifer type and climate zone were used to define the level of aquifer responsiveness. In the case of alluvium aquifers, a large proportion are shown to be sensitive to climate change yet those present in the arid-semi arid climate zone are calculated as having low sensitivity largely because they are assigned a low rating for the aquifer responsiveness metric. This highlights how some of the assumptions used in populating the metrics influence the results obtained.

Fewer trends are noted for the importance ranks. Sedimentary basins tend to be rated as important – most probably due to the large size of these resources in terms of current extraction rates and sustainable yields. By contrast, coastal sands are mostly considered to be rated as less important due to their limited size; the exception being the Coastal Sands 4 aquifer which comprises an amalgam of coastal sand GMUs in NSW and Qld.

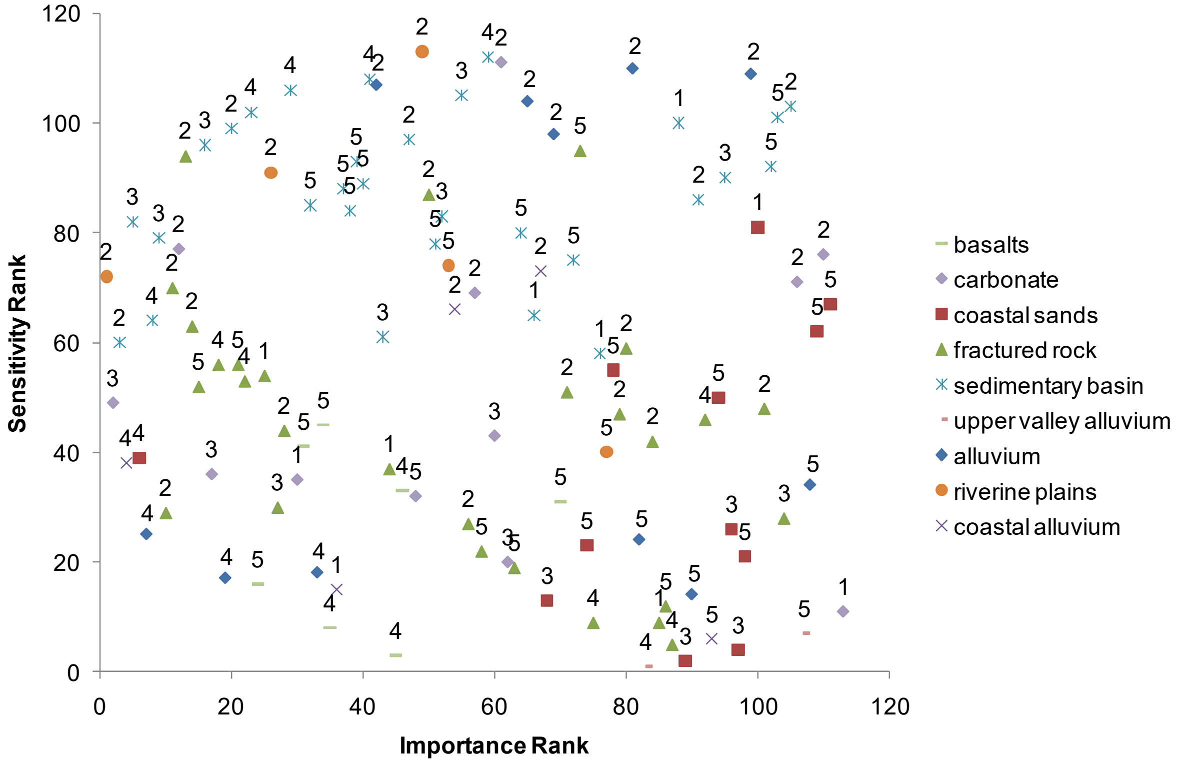

Figure 6-3 Plot of prioritisation ranks shown by aquifer type and zone. Climate zone classification based on grouping Koppen-Geiger codes as follows: (1) Tropical = Af, Am, Aw; (2) Arid/Semi-Arid = BWh, BWk, BSh, BSk; (3) Mediterranean = Csa, Csb; (4) Humid subtropical = Cwa, Cfa; (5) Temperate = Cfb, Cfc, Dfb, Dfc

Table 6-2 Trends noted in Figure 6-3

Aquifer type	Trends
Basalts	Tend to more sensitive with even importance distribution
Carbonate/Karstic	Even distribution
Coastal Sands	Tend to be sensitive and of low importance rating, with the exception of one prioirty aquifer (coastal sands 4) that is listed in the top 20 for importance
Fractured Rock	Tend to more sensitive with even importance distribution
Sedimentary Basins	Tend to be important but not sensitive
Alluvial Aquifers	
Upper Valley Alluvium	Only 2 examples, yet shown to be very sensitive but not important
Alluvium	Shown to be either sensitive or insensitive, with no intermediate sensitivity scores.
Riverine Plains	Tend to be not especially sensitive
Coastal Alluvium	Tend to be sensitive with and even importance spread

6.6. Conclusion

The revision of the prioritisation scheme and results has produced a refined list of priority aquifers where those that are relatively insensitive due to their large storage volumes in comparison to recharge have been excluded. The resulting 14 aquifers were all included in the original priority listing presented in the body of this report. Hence the analysis of recharge and discharge processes remains pertinent as it captures all of the final priority aquifers.

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