WATER FOR A HEALTHY COUNTRY
www.csiro.au

CSIRO

Climate change impact on groundwater resources in Australia

Summary Report

OV Barron, RS Crosbie, SP Charles, WR Dawes, R Ali, WR Evans, R Cresswell, D Pollock, G Hodgson, D Currie, F Mpelasoka, T Pickett, S Aryal, M Donn and B Wurcker

Australian Government
National Water Commission

Water for a Healthy Country Flagship Report series ISSN: 1835-095X

Australia is founding its future on science and innovation. Its national science agency, CSIRO, is a powerhouse of ideas, technologies and skills.

CSIRO initiated the National Research Flagships to address Australia's major research challenges and opportunities. They apply large scale, long term, multidisciplinary science and aim for widespread adoption of solutions. The Flagship Collaboration Fund supports the best and brightest researchers to address these complex challenges through partnerships between CSIRO, universities, research agencies and industry.

Consistent with Australia's national interest, the Water for a Healthy Country Flagship aims to develop science and technologies that improve the social, economic and environmental outcomes from water, and deliver $3 billion per year in net benefits for Australia by 2030.

For more information about Water for a Healthy Country Flagship or the National Research Flagship Initiative visit www.csiro.au/org/HealthyCountry.html

Important aspects of the work contained in this report were undertaken by Sinclair Knight Merz (SKM).

Citation

Barron OV, Crosbie RS, Charles SP, Dawes WR, Ali R, Evans WR, Cresswell R, Pollock D, Hodgson G, Currie D, Mpelasoka F, Pickett T, Aryal S, Donn M and Wurcker B (2011) Climate change impact on groundwater resources in Australia: summary report. CSIRO Water for a Healthy Country Flagship, Australia.

Copyright and disclaimer

Important disclaimer

Contents

Executive summary

Over the past few decades, much of Australia has experienced increasing demands on groundwater resources, largely due to a drier climate and/or increased pressure on surface water. In 2004, the National Water Initiative (NWI) was formed to ensure the implementation of a transparent planning framework that, amongst others goals, would avoid over-allocation of water resources, including groundwater. The NWI requires that risks associated with climate change and variability be incorporated in water management plans. In response to these issues, the National Water Commission commissioned the project, Investigating the impact of climate change on groundwater resources, within the National Groundwater Action Plan (NGAP), the primary objective of which was to determine how projected climate change will impact on groundwater recharge and groundwater resources across different aquifer types in different climate types across Australia. This report summarises the findings of the project.

Climate change generally impacts on renewable groundwater resources; resources that are fed by diffuse groundwater recharge (recharge associated with rainfall across the landscape) and localised groundwater recharge (recharge associated with water losses from rivers and floodplains), both of which are largely dependent on annual rainfall and its seasonal distribution.

The projection of future climates, inferred from 16 global climate models (GCMs) which were adopted in this project, is most consistent for south-west Western Australia and the southern Murray-Darling Basin, and projects a reduction in rainfall for 2050. There is a large range of rainfall projections between the GCMs; for example, across most of Australia the trend and magnitude of projected rainfall changes are not consistent, which limits the ability to provide confident assessments of likely impacts on groundwater resources.

The project found that the variability in recharge is magnified two to four times when compared to variability in rainfall. This so-called 'recharge elasticity' measure (where recharge is more sensitive to changes in rainfall) is higher in low recharge regions, i.e. arid zones, under tree land cover or heavier soils.

Using a range of future climate scenarios for diffuse recharge projections, we found that at the continental scale, the median diffuse recharge projection for a 2050 climate is 1 per cent less than the historical baseline and 15 per cent less for a dry future climate. However, the continental average does not reflect regional trends as under the median future climate a decrease in diffuse recharge is projected across most of the west, centre and south of Australia (where most groundwater extraction occurs) while increases in diffuse recharge are projected across northern Australia and areas of eastern Australia. For the median future climate, 79 per cent of the continent is projected to experience a reduction in recharge with 27 per cent of this area showing a reduction projected to be greater than 20 per cent. Only 21 per cent of the continent is projected to have an increase in recharge for the median future climate.

However, historical variability of diffuse recharge over 15-year periods (within the 80-year baseline) was found to be greater than the magnitude of modelled recharge change under the future climate scenarios over an equivalent 80-year average. This highlights the need for water-sharing plan flexibility, to account for the compounding effect of current climate variability and future climate change.

Changes in localised recharge due to climate change at a national scale can only be conceptualised generally. This is because climate change influences both river flow and groundwater level along with the nature of their interaction and the level of connectivity of rivers to shallow aquifers. All of these are highly site-specific. However, it was shown by this project that localised recharge is particularly sensitive to changes in high river flow rates leading to overbank floods.

It was found that land cover and land use changes may occur due to projected warming temperatures and rainfall decline, particularly where these factors lead to a shift in climate types. This is most relevant in the south-east and south-west regions of Australia, where areas currently used for annual cropping

are projected to become more arid. In such cases the reduction in recharge due to lower annual rainfall may be compounded by a land use changing away from annual cropping toward an increase in perennial vegetation (which further reduces recharge). The opposite could happen if a woodland environment succeeded to a grassland environment due to climate change, the reduction in deeper-rooted trees could increase recharge even if rainfall is reduced. While the impact on renewable groundwater resources caused by a reduction in rainfall alone may be significant, potential changes in land use could add greatly to it; this area requires further research.

The project found that projected changes in rainfall and renewable groundwater resources are likely to lead to changes in watertable elevation and have follow-on effects upon groundwater-dependent vegetation and other ecological communities that are directly or indirectly dependent on groundwater. Where aquifers are stressed, this will in turn lead to changes in water allocations of similar magnitude to the reduction in recharge. A detailed assessment of this analysis fell outside the scope of the project.

Sensitivity of groundwater systems to climate change is greatest for unconfined aquifers, particularly when they are stressed. The project assessed all groundwater management units or areas in Australia, combining them within their natural hydrogeological boundaries (known as aquifers), and 20 priority aquifers were identified as sensitive to climate change of national importance and where a projected reduction in renewable groundwater resources was most significant.

A significant risk (more than 25 per cent probability of more than a 20 per cent reduction in groundwater recharge) was projected for 13 priority aquifers. Among them were Otway Basin and Perth Basin, where the total current groundwater use is 295 GL/y and more than 1500 GL/y, respectively. A moderate risk (5 per cent to 25 per cent probability of more than a 20 per cent reduction in recharge) was estimated for a further six priority aquifers. Only one aquifer (Daly) had a low risk (less than 5 per cent probability of more than a 20 per cent reduction in groundwater recharge). Under the median future climate scenario, 15 priority aquifers were projected to have a reduction in recharge, and summed across all priority aquifers this reduction in recharge was projected to be 3000 GL/y.

This study was carried out at the regional scale and considered only gross consequences at the aquifer level and hence can only make broad recommendations. Further, and more detailed, analysis at a scale commensurate with resource use should be undertaken for the high priority aquifers. It showed that the tools currently available to support water resource planning are deficient for an adequate analysis of water resource availability under future climate conditions, neither are they adequate for accounting for climate variability in general. A key recommendation of this work is that all groundwater models used in water resource management in Australia should undergo a climate change audit to ensure that they are fit-for-purpose when proposing climate change adaptation strategies as this study has highlighted that some models are not suitable for this purpose.

Introduction

Over the past few decades, much of Australia has experienced increasing demands on groundwater resources, largely due to a drier climate and/or increased pressure on surface water. In 2004, the National Water Initiative (NWI) was formed to ensure the implementation of a transparent planning framework that, amongst others goals, would avoid over-allocation of water resources, including groundwater. The NWI requires that risks associated with climate change and variability be incorporated in water management plans.

Climate change generally impacts on renewable groundwater resources; resources that are fed by diffuse groundwater recharge (recharge associated with rainfall across the landscape) and localised groundwater recharge (recharge associated with water losses from rivers and floodplains), both of which are largely dependent on annual rainfall and its seasonal distribution.

Climate change is of most concern where aquifers are heavily allocated or particularly vulnerable to changes in recharge. In these systems a reduction in water availability due to climate change may impact on groundwater use and entitlements. In addition to consumptive use, a rich biodiversity associated with groundwater-dependant ecosystems may be impacted by changes to groundwater resources. The impacts of climate change are likely to be more profound for unconfined aquifer systems, which may respond rapidly to changes in the recharge regime.

Most groundwater is managed according to long-term average recharge to the system. The ability to incorporate risks associated with climate change and variability is limited by: sparse information on aquifers; poor understanding and quantification of recharge and discharge mechanisms; lack of spatial appreciation of the connectivity to streams; and unknown interactions with groundwater-dependent ecosystems. The effect of short- and long-term climate variability on groundwater resources is even less clear, both in terms of groundwater recharge and discharge.

In response to these issues, the National Water Commission commissioned the project, Investigating the impact of climate change on groundwater resources, within the National Groundwater Action Plan (NGAP), the primary objective of which was to determine how projected climate change will impact on groundwater recharge and groundwater resources across different aquifer types in different climate types across Australia. This report summarises the findings of the project.

The objective of this project was to determine how projected climate change would impact on groundwater recharge and groundwater resources across different aquifer types and climatic types across Australia. The project was undertaken by CSIRO in collaboration with Sinclair Knight Merz and was comprised of five major tasks:

i. Determine the effect of historical climate on diffuse recharge

ii. Determine the effect of future climate projections on diffuse and localised recharge

iii. Characterise aquifers in terms of their importance and sensitivity to climate change

iv. Review the capability of data and modelling to predict climate change impact on groundwater resources, and

v. Recommend improvements to groundwater management under changing climate conditions.

Groundwater management in Australia

One of the key issues for groundwater management in Australia is the establishment of groundwater extraction limits for groundwater management units (GMUs).

Groundwater models of varying complexity have been developed for a number of aquifers and used to assess the extraction limit using a range of sustainability criteria. Where groundwater models are not available (and that is in the vast majority of cases) extraction limits are commonly based on expert estimation of renewable groundwater resources, defined as:

- a proportion of rainfall – a constant proportion is commonly set for an aquifer regardless of inter-annual variation in rainfall, or
- a proportion of baseflow – assuming that groundwater discharge to a river on annual basis equals recharge to the system under steady-state conditions.

It is not a common practice to account for historical variability of climatic condition and its effect on renewable groundwater resources and changes in groundwater demands. Further, most extraction limits are defined for GMUs rather than at the aquifer scale.

Incorporating the impact of climate change and variability into groundwater management remains a challenge for water managers in Australia. Climate change is projected to lead to greater inter-annual climate variability, in addition to shifts in annual average rainfall and temperature. Our current approaches to groundwater management generally lack the sophistication to incorporate this increasing natural variability into the estimation of groundwater extraction limits.

Recommendations

The following recommendations are based on the analyses carried out in the National Groundwater Action Plan Project: 'Investigating the impact of climate change on groundwater resources'.

Recommendations for improving groundwater management under changing climate conditions are:

- To develop risk-based or adaptive approaches to groundwater management which can account for both year-to-year variability in renewable groundwater resources and longer-term impacts from climate change.
- To collect the data required for risk-based or adaptive approaches to be undertaken. Critical to this approach are fundamental datasets that are not currently being collected; for example, the metering of groundwater extraction and water level fluctuations, including the areas of surface and groundwater interaction[1].
- To investigate the effect of climate change (CO_2 and temperature) on vegetation water-use efficiency and consequently, how vegetation management may impact on future groundwater resources. Climate impacts on vegetation and the indirect effect on the water balance is an important, but relatively unknown issue. In low rainfall regions (<700 mm/year) and in areas where climate types are projected to change, changes in vegetation may have a disproportionately large impact upon groundwater resources.
- To improve understanding and capability to model the interaction between surface water and groundwater (both at a local and at a national scale). Few models currently simulate sophisticated surface water – groundwater interactions and those that do require further development.
- Audit the groundwater models used for groundwater resource management in Australia to ensure they are fit-for-purpose where climate change adaptation strategies are being based upon the results of those models.

These recommendations are based on the results of analyses undertaken during the project and summarised in the following pages.

[1] Ali, et al., 2011

Historical climate and its effect on diffuse recharge

Key findings

- *Australian climatic trends over the past 80 years have led to shifts in climate types*
- *The intensity and seasonality of annual rainfall is the most important climate parameter for recharge estimation*
- *The effect of temperature, solar radiation and vapour pressure deficit on recharge is important in regions with low annual recharge and under climate types with summer-dominated rainfall*
- *Inter-annual rainfall variability is amplified 2- to 4-times in recharge variability (recharge elasticity)*

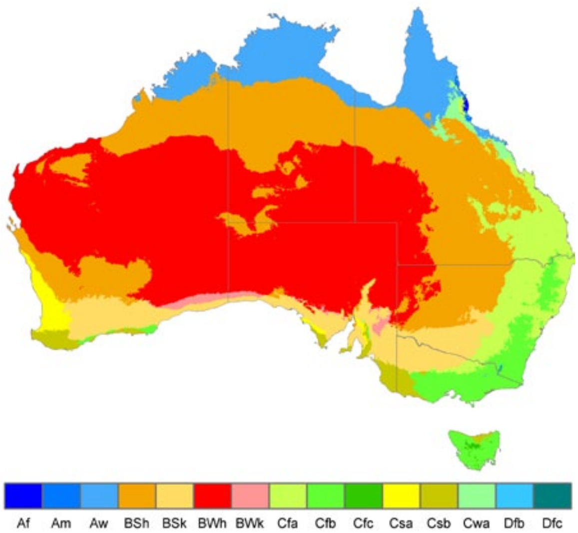


Figure 1: **Baseline Köppen-Geiger climate types across Australia for the 40 year period centred on 1990: A's types – tropical climate types; B's types – arid climate types, C's types – temperate climate types; D's types - cold climate types**

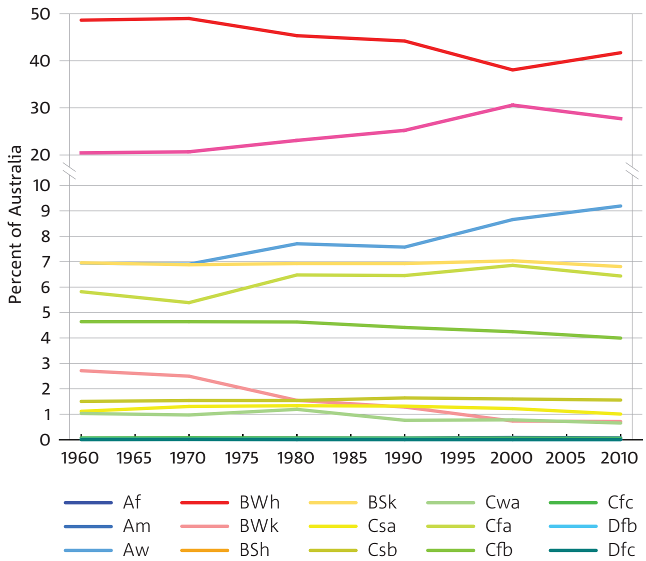


Figure 2: **Area (as percentage of Australia) of Köppen-Geiger climate types for 30 year time periods ending at the plotted year**

Distribution of climate types

Climate types are defined by seasonal patterns of rainfall and temperature that are also the dominant climate factors influencing recharge. Climate types reflect the spatial distribution of terrestrial ecosystems, which have a substantial effect on renewable water resources.

The observed time series of temperature and rainfall over the period from 1930 to 2010 indicates a warming trend over most of Australia (except for the inland northwest), increasing rainfall over northern, central and northwest Australia, and decreasing rainfall in eastern, southeast and southwest Australia[2]. These trends have resulted in decadal changes in the spatial distribution of the Köppen-Geiger climate types across Australia.

Figures 1 and 2 show a southerly extension of tropical types in the far north (Aw) with a corresponding contraction in the northern extent of arid types (BSh). The arid types (B) have expanded to the south and southeast, with corresponding contraction of temperate types (Cs and Cf). These changes indicate a possible contraction to the northern extent of the southern cropping zones.

Diffuse recharge estimation

Diffuse recharge (or deep drainage below 4 m) was estimated at a national scale using the WAVES model, which accounts for climate types, soils and vegetation. Modelled historical annual average recharge data are presented in Figure 3[3]. Diffuse recharge was found to be greater in high rainfall zones, under annual vegetation compared to native vegetation and under lighter textured soils compared to finer textured soils.

[2] Barron et al, 2010, 2011
[3] Crosbie, et al, 2011a, c

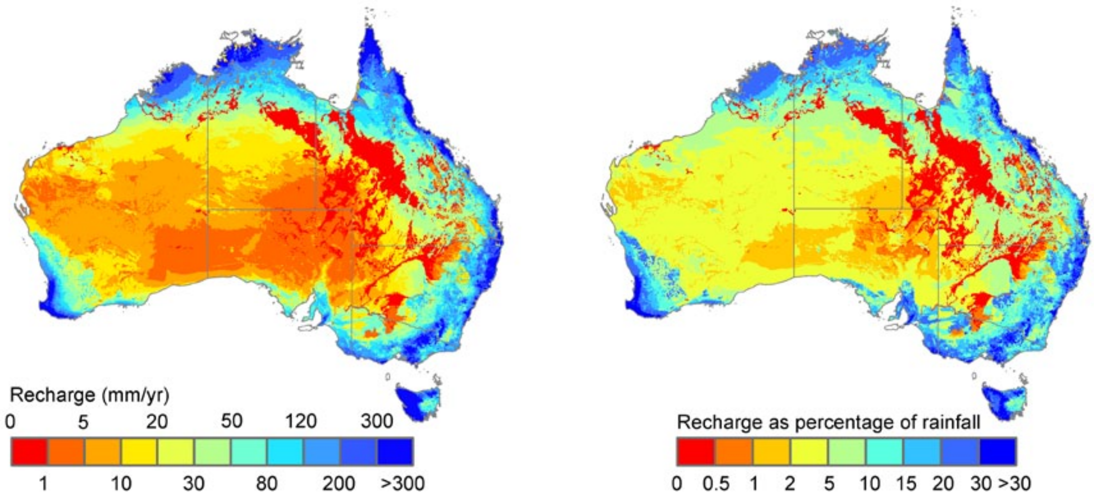


Figure 3: **Modelled historical annual average recharge across Australia for the period 1930–2009 expressed in mm/yr (left) and as a percentage of rainfall (right)**

Impact of climate parameters on diffuse recharge

Annual rainfall was found to be the most important parameter in recharge estimation overall (Figure 4a). However, its relative importance reduces in regions of lower rainfall (e.g. BSk), with an increase in the relative importance of other climate parameters (temperature, solar radiation and vapour pressure deficit) (Figure 4b). The effect of climate parameters, other than rainfall, on recharge is greater under climate types that have summer-dominated rainfall (Csa and Csb). The effect of temperature, solar radiation and vapour pressure deficit on recharge is largely indirect and associated with vegetation water use; this indicates the importance of vegetation in recharge estimation particularly in the regions with a lower rainfall (less than 700 mm/year)[4].

An increase in rainfall intensity or duration of consecutive days with rainfall leads to an increase in recharge and a higher proportion of rainfall becoming recharge. This also leads to an increase in the relative importance of rainfall and a reduction in the relative importance of other climate parameters in areas with higher rainfall intensity (such as the tropics, Aw)[5]. As a result there is a non-linear relationship between recharge and rainfall and the proportion of recharge to annual rainfall (R/P) is not likely to be a constant – even for the same land cover and soil type.

Relating the sensitivity of diffuse recharge to changes in annual rainfall – similar to the concept of the elasticity of runoff – annual changes in recharge were found to be proportional to annual changes in rainfall, by a factor of 2- to 4. This means that a 10 per cent reduction in rainfall is likely to result in a reduction to recharge of 20 to 40 per cent. The higher values in recharge sensitivity to rainfall changes were estimated for desert and arid climate types (i.e. BSk or BWh) (Figure 4c).

The variability of recharge in 15-year periods compared to the long-term average is greater in areas of low recharge whereas the range between wet and dry 15-year periods is comparatively smaller in high recharge areas[6].

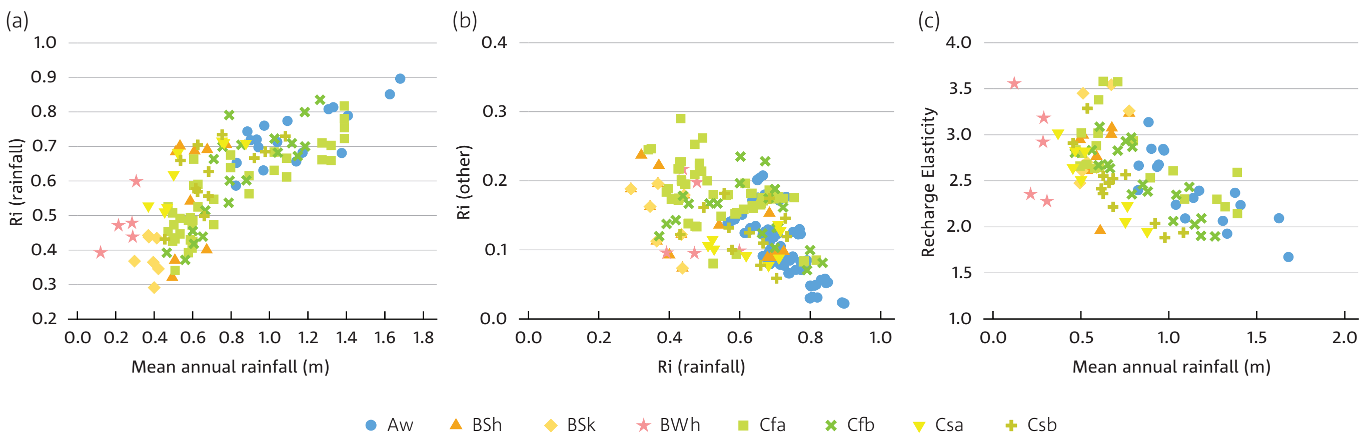


Figure 4: **Relationship between (a) relative importance of rainfall and mean annual rainfall; (b) relative importance of temperature, vapour pressure deficit (VPD) and solar radiation (cumulatively) and mean annual rainfall and (c) recharge elasticity and mean annual rainfall; all for perennial vegetation and soil with K~1 m/day**

4 Barron et al., 2011
5 Barron et al., 2011
6 Crosbie et al., 2011c

Future climate projection

Key findings

- ***There are large uncertainties in the modelling of the magnitude and direction of future rainfall projections***
- ***Climate change projections show a decrease in rainfall for Southwest Western Australia and the southern Murray-Darling Basin across all global warming scenarios***
- ***Projected future changes in the spatial distribution of climate types indicate a further increase in aridity at the expense of temperate climate types***

The projected future climates were inferred from 16 global climate models (GCMs) of the Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC AR4). The full range of IPCC AR4 future climate projections was accounted for by scaling these 16 GCMs results according to three global warming scenarios for both 2030 (+0.7°C, +1.0°C and +1.3°C) and 2050 (+1.0°C, +1.7°C and +2.4°C). Figure 5 shows the projected future changes in rainfall estimated relative to 80 years of baseline rainfall data from 1930 to 2010[7].

Uncertainties in the direction and magnitude of regional rainfall changes are pervasive and limit our ability to assess likely impacts for many regions of Australia. Projections are most consistent for southwest Western Australia and the southern Murray-Darling Basin where even the wet future climate scenario projects a decrease in rainfall.

Impact of climate change on climate types

These projected changes in climatic conditions will also affect the spatial distribution of the Köppen-Geiger climate types across Australia[8]. The mode of the projections from the 16 GCMs indicate an increase in arid climate types (BSh) at the expense of temperate climate types in the east (Cfa), south and south-west of the continent (Csa and Csb) and an increase in tropical climate types (Aw) at the expense of temperate climate types for coastal Queensland (Cfa) (Figure 6). The temperate climate types (C) are associated with the most fertile agricultural land that currently have a large proportion of annual vegetation, a reduction in temperate climate types may precipitate some land use changes that have yet to be incorporated into the modelling of the impact of future climate impacts on recharge. Changes in vegetation type are known to be able to cause a change in recharge of up to two orders of magnitude, this is a much larger change in recharge than from the projections of a future climate alone. The indirect effects of climate change may impact upon water resources more than the direct effects of climate change, this area needs further research.

[7] Barron et al., 2011
[8] Barron et al., 2010

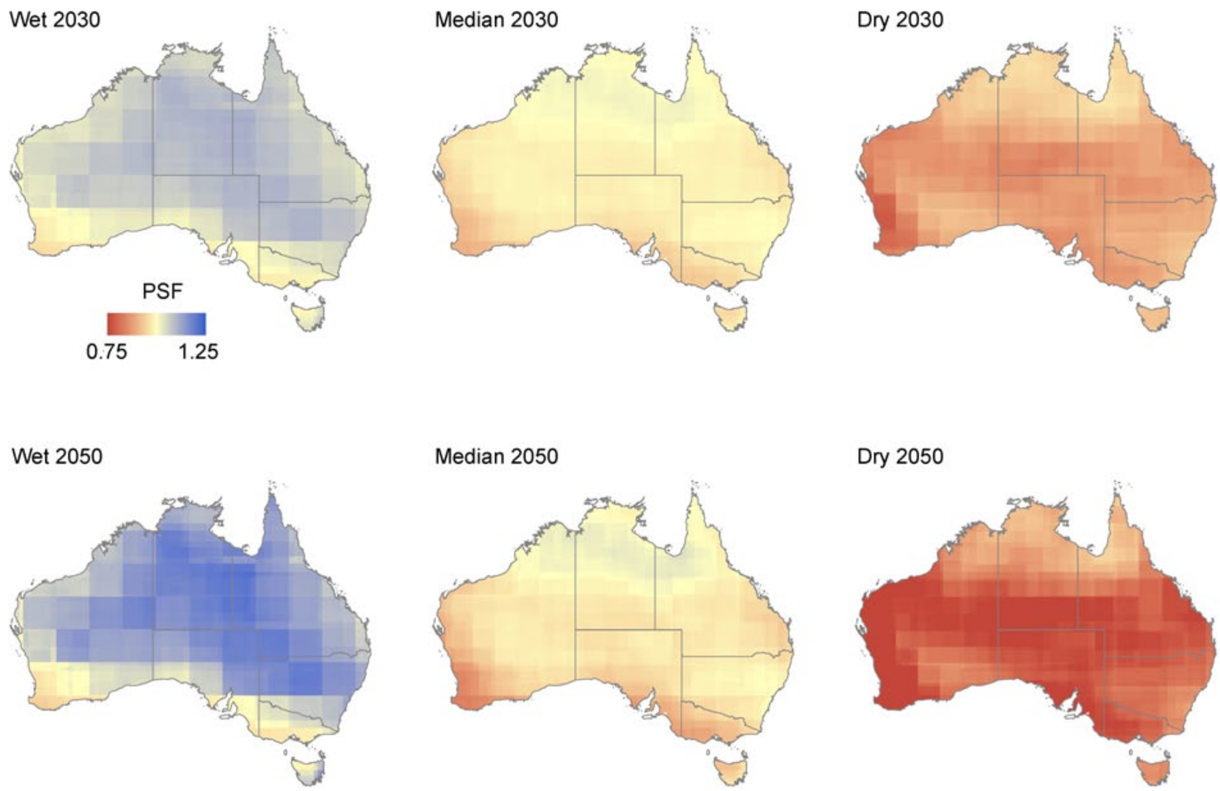


Figure 5: **Precipitation Scaling Factors (PSF): change in annual average rainfall projected for wet, median and dry future climate scenarios for 2030 (top row) and 2050 (bottom row) relative to baseline; Note the projections show a large uncertainty, except for a decrease in rainfall for southwest Western Australia and the southern Murray-Darling Basin across all global warming scenarios**

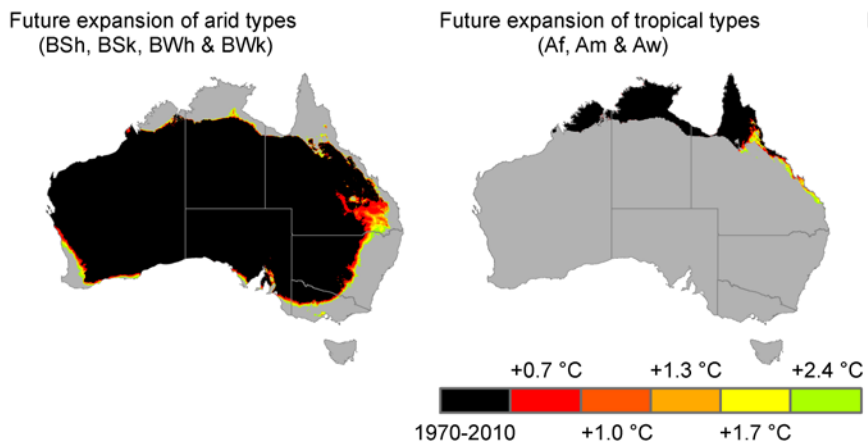


Figure 6: **The mode of the changes in (simplified) Koppen-Geiger climate types derived from 16 GCMs for five global warming scenarios; Note the projections show an increase in the areas of the arid (B's types) and tropic (A's types) climate types occurrence and corresponding reduction in the areas of temperate and cold (C's and D's types) climate types occurrence**

Effect of future climate projection on diffuse recharge

Key findings

- ***Median future climate projections for 2030 and 2050 show a decrease in recharge in the west, centre and south-east of Australia and increases in recharge in the northern Australia and a small area of eastern Australia***
- ***The sensitivity of recharge to changes in rainfall is relatively constant under all global warming scenarios***
- ***Historical variability of diffuse recharge is greater than the magnitude of modelled recharge change under all global warming scenarios***

The 16 GCMs used in the analysis do not produce consistent projections of recharge, except in southwest Western Australia where all GCMs project a decrease in rainfall and derived recharge[9]. For most of the country, the greater the projected warming the fewer projections that result in a decrease in recharge; an exception being parts of the south where all GCMs project a decrease in recharge (Figure 7).

Recharge projections are reported as a recharge scaling factor (RSF), the ratio of the future to the historical baseline scenario recharge. Thus a 50 per cent reduction in recharge will have a RSF of 0.5 and a 50 per cent increase in recharge will have a RSF of 1.5. The median future climate projects a decrease in recharge across most of the west, centre and southeast of Australia with increases across northern Australia and a small area of eastern Australia (Figure 8). The dry future climate projects a decrease in recharge everywhere. The wet future climate projects an increase in recharge everywhere except for southwest Western Australia and a few other localised areas of southern Australia.

The most extreme scenarios considered are a wet 15-year period within a wet future climate and a dry 15-year period within a dry future climate (Figure 8). At a GMU scale, the wet extreme can project increases in recharge of more than 300 per cent and the dry extreme decreases of more than 90 per cent[10]. The projections made for 2030 during the four CSIRO Sustainable Yields Projects in MDB, Tasmania, Northern Australia and South-West of Western Australia are generally consistent with the projections made for 2050 in the current project.

At the continental scale, the median diffuse recharge projection for a 2050 climate is 1% less than the historical baseline and for a dry future climate a 15% reduction is projected. However a continental average does not reflect the regional trends as under the median future climate a decrease in diffuse recharge is projected across most of the west, centre and south of Australia (where most of the groundwater extraction occurs) while increases in diffuse recharge are projected across northern Australia and areas of eastern Australia. For the median future climate 79% of the continent is projected to experience a reduction in recharge with 27% of this area where the reduction is projected to be greater than 20%. Only 21% of the continent is projected to have an increase in recharge for the median future climate.

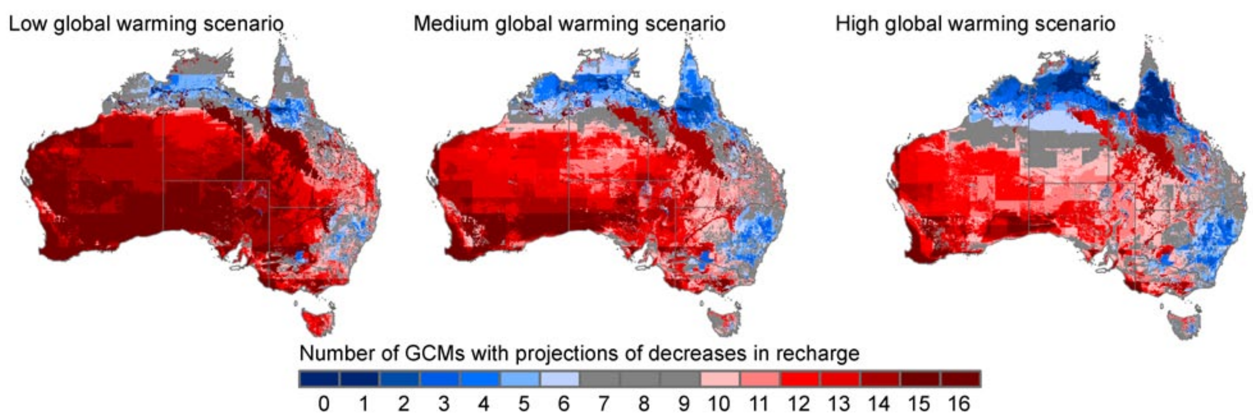


Figure 7: **Number of GCMs under which a decrease in recharge is projected (from the 16 GCMs for each global warming scenario)**

[9] Crosbie et al., 2011b
[10] Crosbie et. al., 2011a

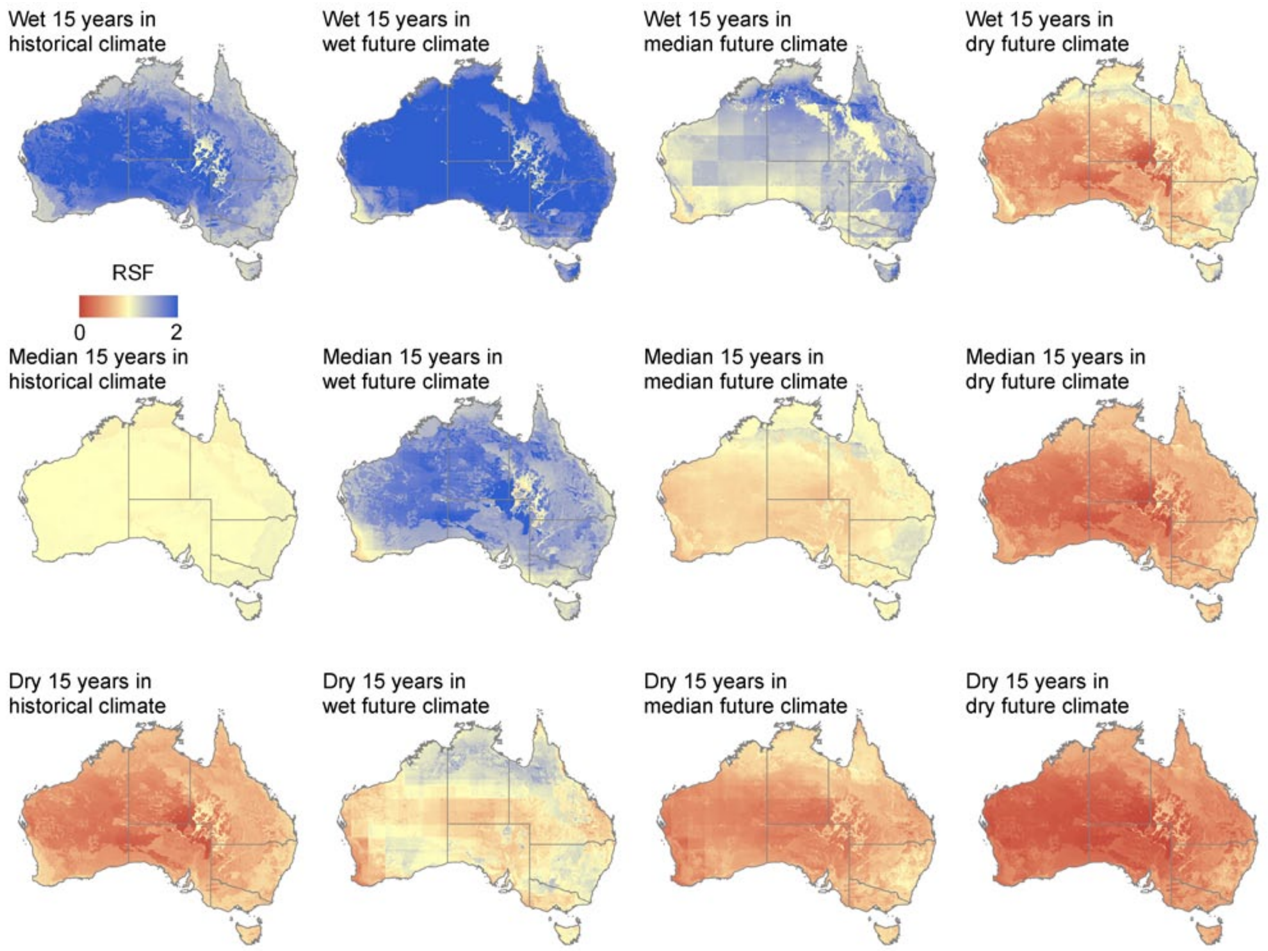


Figure 8: **Recharge scaling factor (RSF) for four climate scenarios (historical and wet, median and dry future climate) and 15-year variabilities (wet, median and dry) using a 80-year baseline (1930-2010)**

Results of future recharge modelling can also be presented in a risk analysis framework, requiring the quantification of the likelihood and consequences of a change in recharge[11]. From a water management perspective the consequences of an increase in recharge (RSF greater than 1.0) are not severe. The consequences of a decrease in recharge due to climate change is likely to have an impact on water allocations, a small decrease in recharge (1.0 greater than RSF greater than 0.8) might be able to managed through adaption, a large reduction in recharge (0.8 greater than RSF greater than 0.5) will likely lead to reductions in allocations while an extreme reduction in recharge (RSF less than 0.5) will likely have far more serious consequences. The likelihood of experiencing these recharge changes under a future climate can be evaluated by fitting the modelling results from the 16 GCMs and three global warming scenarios to a probability distribution to calculate the probability of exceedances (Figure 9).

Under all global warming scenarios the probability of an increase in recharge is quite low through most of the centre, west and south of the continent with some areas of the east and across the north having a high probability of exceeding a RSF of 1.0. Under all global warming scenarios the likelihood of a RSF greater than 0.8 (20 per cent reduction) is high for the east and north of the country, is uncertain for the centre and west of the continent and (particularly for the high global warming scenario) is highly unlikely for the southwest. The probability of exceeding a RSF of 0.5 (50 per cent reduction) is highly likely for most of the continent with only the southwest have a probability that is uncertain (0.33 to 0.67) for the high global warming scenario.

[11] Crosbie et al., 2012

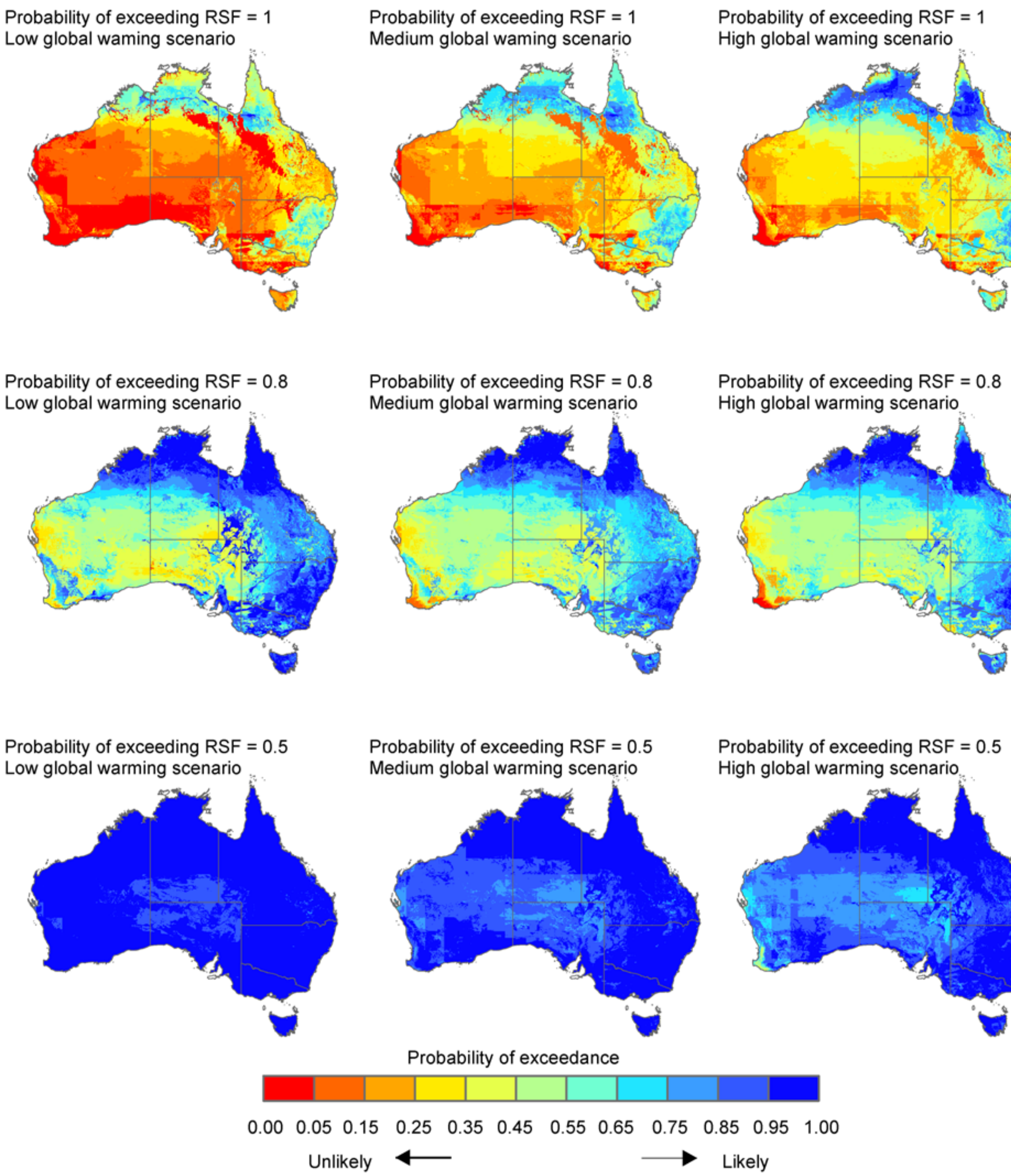


Figure 9: **Probability of exceeding a recharge scaling factor (RSF) of 1, 0.8 and 0.5 for the low, medium and high global warming scenarios for a 2050 climate relative to a 1990 climate**

Effect of future climate projection on localised recharge

Key findings

- *Climate change impact on localised recharge is dependent on the type and degree of river connectivity to the shallow aquifer*
- *Projected changes in localised recharge from disconnected losing streams are similar to projected changes in river flow*
- *Projected changes in localised recharge from connected losing streams are lower than the projected changes in river flow; sensitivity of localised recharge to changes in river flow reduces in areas with deeper groundwater*
- *Projected future, drier climates that result in deeper watertables lead to more localised recharge from connected losing streams even when river flow reduction is projected*
- *Projected changes in localised recharge from overbank floods are much greater than projected changes in river flows*

Changes in localised recharge due to projected climate change are related to changes in both the river flow and the depth to groundwater. Riverbed and river valley morphology may also influence the annual losses from a river to groundwater. In addition, losing rivers can be hydraulically connected to the river (water flow from the river into the aquifer in accordance with Darcy's Law) or can be disconnected (unsaturated flow processes define water losses from the river to the aquifer). Since only relative changes in localised recharge were considered the hydraulic properties and thickness of the fluvial sediments forming a riverbed are less important for this conceptual analysis[12].

[12] Barron et al., 2011

For disconnected streams: the changes in localised recharge are predominantly defined by the changes in an effective river width (ERW) as the river stage doesn't have an effect on water losses from such streams to groundwater. As a result greater sensitivity to changes in river flow is expected for wider rivers with flat riverbeds, where variation in river flow causes ERW changes. For such rivers, reduction or increase in localised recharge is likely to be similar to projected changes in river flow. In rivers with a narrow riverbed and steep banks, where variation in river flow does not significantly affect ERW, then changes in localised recharge as a result of changes in river flow are not likely.

For connected streams: the changes in localised recharge are dependent on changes in river stage and ERW as well as the depth to groundwater, in accordance with Darcy's Law. Reduction or increase in localised recharge from connected losing streams is likely to be lower than projected changes in river flow (Figure 10). The river flow is projected to reduce under the Dry and Median scenarios and to increase under the Wet scenario. However in all cases the corresponding changes in localised recharge are less in magnitude than the changes in river flow.

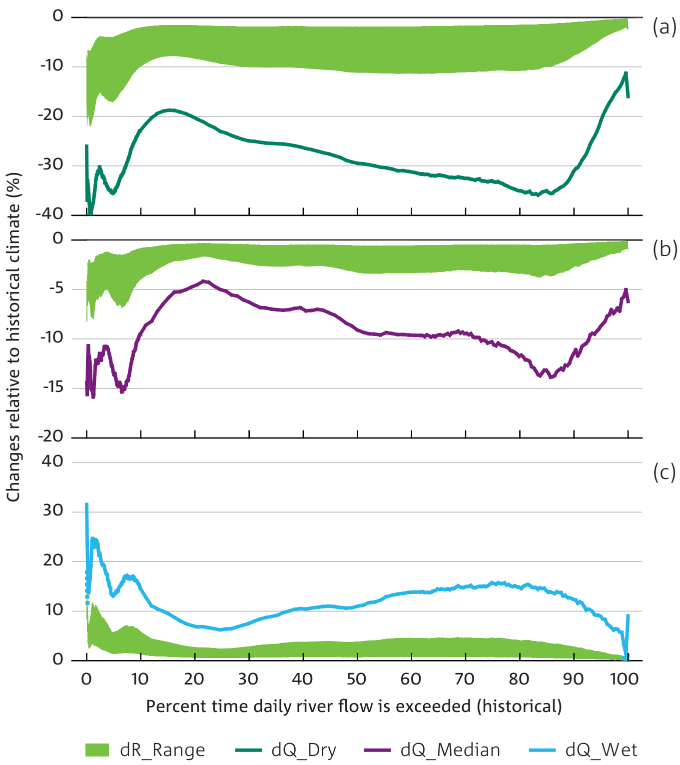


Figure 10: **Changes in the Murrumbidgee river flow (solid line) and the range of changes in localised recharge for (a) dry, (b) median and (c) wet future climate scenarios; the green area represents a range of various river morphologies: results for the narrowest channels are closer to the horizontal axis**

The impact on localised recharge is also greater for rivers with wide flat channels (Figure 11a), as the water losses are proportional to the infiltration front area. The sensitivity of localised recharge to the changes in the river flow is also greater in the lower reaches of a river valley, where slopes along the river channel are smaller (Figure 11b). Here the changes in the river stage are greater for the same changes in the river flow rate compared to steeper values with the same river morphology.

Localised recharge is less sensitive to changes in river flow in areas with deeper groundwater that remains unchanged under the future climate scenarios (Figure 12a). In such conditions, the effect of the river stage on the hydraulic gradient defining the infiltration rate from the river to an aquifer is lower and the changes in the river flow are likely to have less effect on losses from the river.

An increase in groundwater depth under future climate scenarios will likely cause an increase in localised recharge from connected losing streams even when a reduction in river flow is projected (Figure 12b) due to an increase in the hydraulic gradient controlling the infiltration rate from the river to the aquifer. This means that proportionally more of the surface water would be lost to groundwater recharge.

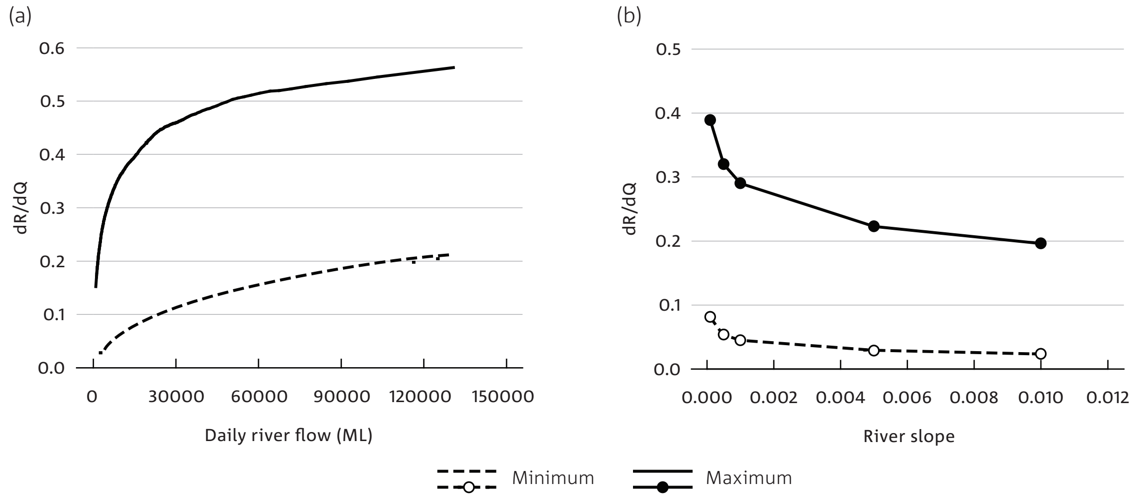


Figure 11: **Sensitivity of localised recharge to changes in river flow (dR/dQ) (a) to daily river discharge under historical climate conditions and (b) to river slopes (both plots are for the Murrumbidgee River)**

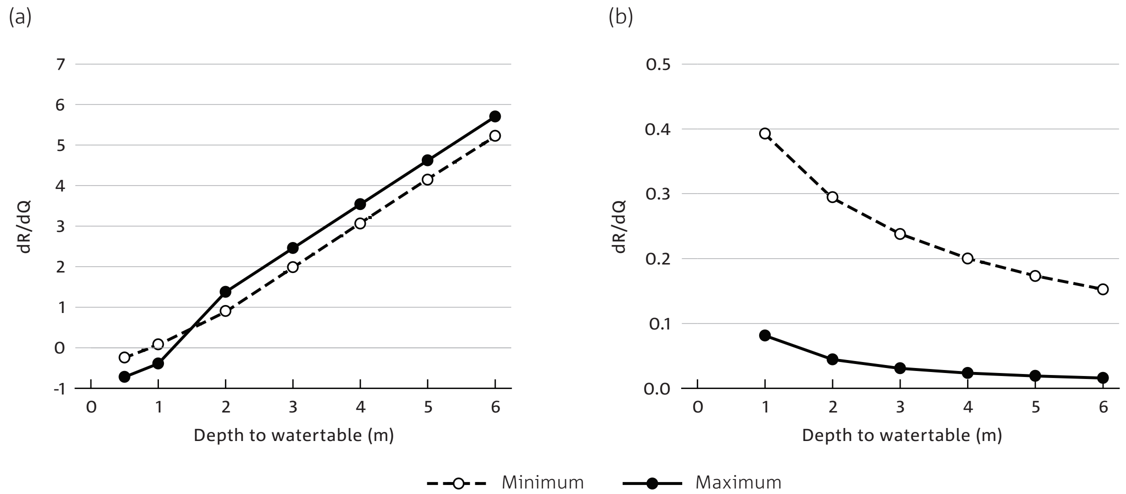


Figure 12: **Sensitivity of localised recharge to changes in river flow (dR/dQ) (a) to initial depths to groundwater, which remain unchanged under the future scenarios and (b) to changes in depth to groundwater, assuming a 1 m watertable depth for the historical scenario (both plots are for the Murrumbidgee River)**

For overbank flooding: For overbank flooding (as an extreme case of ERW increase), the changes in localised recharge may become much greater than projected due to variation in river flow. For example, in the Chowilla floodplain recharge volumes may increase up to 100 per cent for a 20 per cent increase in river flow (Figure 13).

The above conceptual analysis only provides a framework for an assessment of climate change impacts on localised recharge, and can not replace more detailed modelling of river and groundwater interactions in specific aquifers. However, for such anlaysis the required data on riverbed morphology, river flow, depth to groundwaterwater and sensitivity to climate are not widely available.

Projected changes in rainfall and renewable groundwater resources are likely to lead to changes in watertable elevation and have a follow-on effect upon groundwater dependent vegetation and other ecological communities directly or indirectly dependent on groundwater. Where aquifers are stressed, this should in turn lead to changes in water allocations of similar magnitude to the reduction in recharge. A detailed assessment of this fell outside the scope of the project.

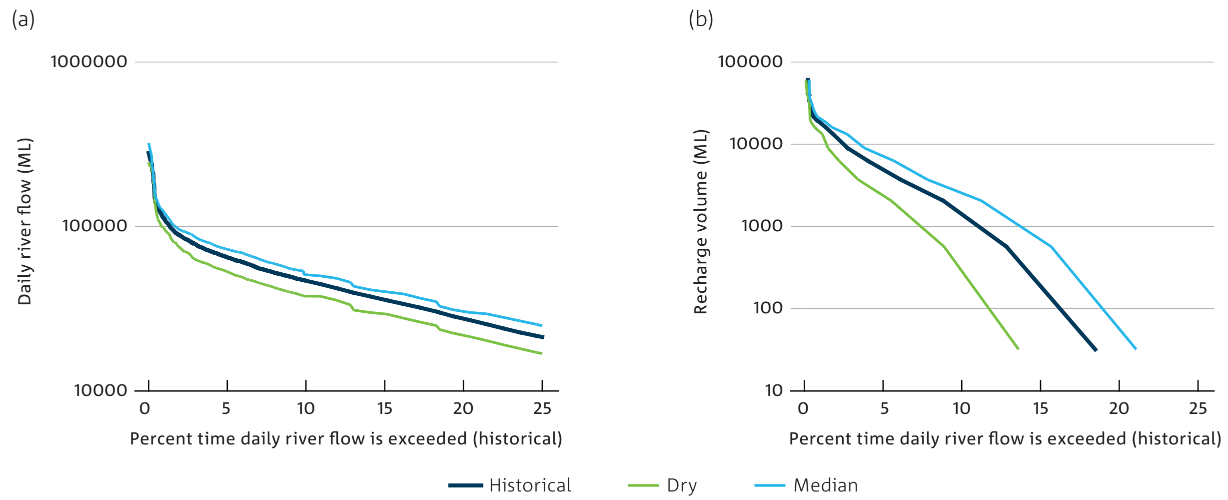


Figure 13: **Duration curves for (a) Chowilla daily river flow (426510) for historical, future dry and future median climate scenarios and (b) estimated recharge volumes from floodplain inundation under those climate scenarios**

Aquifer characterisation

Key findings

- *The effect of climate change on groundwater resources is influenced by the hydrogeological setting of an aquifer*
- *Fourteen priority aquifers were identified as both sensitive to climate and nationally important*
- *In addition, six aquifers in southwest Western Australia were also included in our high priority list as this region is projected to experience the greatest reduction in diffuse recharge under a median or dry future climate*

Not all groundwater systems are equally sensitive to variations in climatic conditions. Groundwater systems with small storage volumes, a rapid response to changes in recharge, with high transmissivity and stressed are likely to experience the greatest climate change impact in the next few decades. To facilitate a comparative analysis of Australian aquifers, the aquifer prioritisation framework was developed to define aquifers that are sensitive to climate change and those that are important as a groundwater resource at a national scale. A set of criteria were designed to address the specific purposes of this project and a national scale of the assessment, which were adopted within the framework.[13].

Aquifer sensitivity to climate change: An aquifer sensitivity rank was calculated by multiplying two factors: the level of development within an aquifer (E/SY; where E is the current level of extraction (ML/year) and SY is the reported sustainable yield of the aquifer (ML/year)) and aquifer responsiveness as a function of recharge (R) to storage (S) ratio,

$$Sensitivity = \frac{E}{SY} \times f\left(\frac{R}{S}\right)$$

The E/SY ratio defines a level of aquifer development with high values corresponding to a greater degree of sensitivity to climate changes. Because there is significant uncertainty in deriving both recharge and storage for all aquifers across Australia, the rating function (f) used was 0.9 for high ratio, 0.3 for moderate ratio and 0.01 for low ratio.

Aquifer national importance: An aquifer importance rank, covering both consumptive groundwater use and the environmental demands, was calculated by multiplying four factors: the current level of extraction (E) proportional to the maximum in the country (Emax), the volume of the resources defined as "sustainable yield" (SY) proportional to the maximum in the country (SYmax) and the presence of groundwater-dependent ecosystems (baseflow and other GDEs):

$$Importance = \frac{E}{E_{max}} \times \frac{SY}{SY_{max}} \times f(baseflowGDEs) \times f(otherGDEs)$$

where 0.85 and 0.15 are weighting factors applied to the presence or absence of the two GDEs types.

The majority of the information required for aquifer prioritisation is associated with groundwater management units (GMUs); these were used to represent the major aquifers of Australia – either individually (where a GMU accurately represented an entire aquifer) or by aggregating several GMUs to represent a larger regional aquifer (where the aquifer was represented by more than one GMU). Where multiple layered aquifers occur at one location – e.g. a large sedimentary basin such as the Perth Basin – the GMUs have been combined to represent one aquifer system. 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 have been grouped into the one assessment unit.

Combined consideration of these two indices identifies the 14 most sensitive and nationally important high priority aquifers. Overall the fractured rock, alluvium and coastal aquifers show higher sensitivity to climate change. 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.

In addition the sedimentary basin aquifers in southwest Western Australia, where the largest proportionate reduction in recharge under a future climate was projected, were included in a high priority list. They are generally layered aquifer systems with a broad unconfined aquifer at the surface. A future climate may result in a 50 per cent reduction in recharge, causing significant watertable decline and impact on groundwater-dependent ecosystems. However overall impacts on total water resources were estimated to be negligible due to limited impacts of climate change on groundwater response in the areas outside the water supply mounds. The resulting map of regional aquifers prioritisation is shown in Figure 14.

[13] Currie et. al., 2010

Of the 14 high priority aquifers, diffuse recharge is the dominant recharge process in seven and localised recharge is the main process in the remaining seven (Table 1). The projected change in diffuse recharge is highly variable (Figure 15, a, b), ranging from an increase in recharge under the wet future climate in most high priority aquifers to substantial reductions under a dry future climate in all high priority aquifers. There will be changes in localised recharge, but these can't be quantified at this time due to lack of available information related to fluxes to and from groundwater as well as the changes in rivers flow under future climate scenarios.

Groundwater discharge to surface water systems is important in 10 of the 14 high priority aquifers where watertables are shallow (Table 1). The groundwater discharge to surface water systems is likely to reduce due to projected reduction in recharge under the drier climates and therefore expected drawdown of the watertable.

The groundwater use is variable across the high priority aquifers (Figure 16a); it is above the sustainable yield in some, e.g. Upper Condamine and Border Rivers Alluvium, and relatively low in others, e.g. Otway Basin[14].

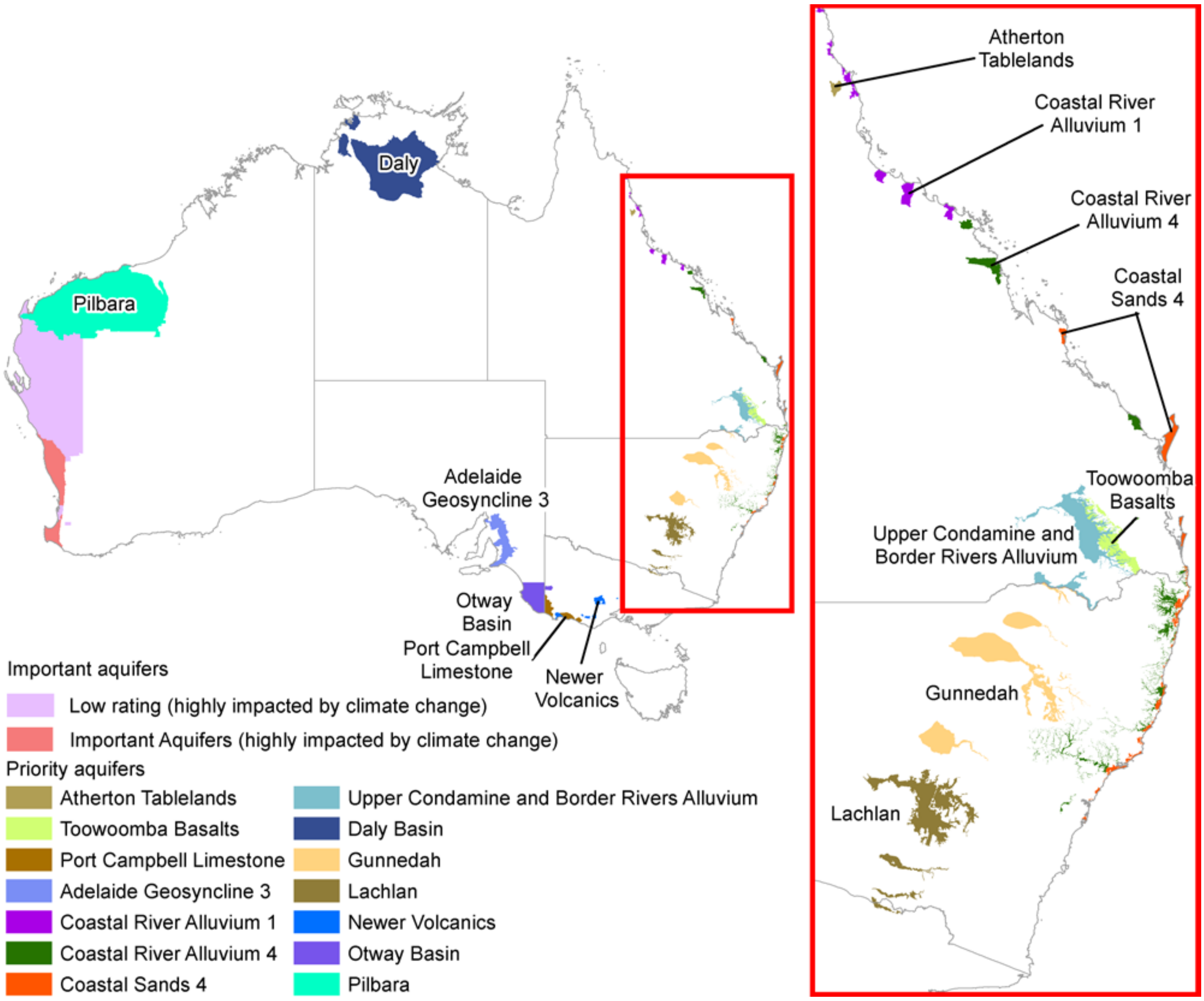


Figure 14: **Map showing location of high priority aquifers**

[14] Barron et. al., 2011

Agriculture is the largest groundwater user followed by domestic and town water supplies and commercial and mining industries – except in the Pilbara where the mining industry is the largest user. Groundwater use as a percentage of the total water extraction is above 50 per cent in 12 priority aquifers and more than 80 per cent in six, highlighting the importance of the groundwater resource for various industries (Figure 16b).

As inferred from these analyses, the impacts due to a reduction in recharge on agriculture, domestic and town water supplies, commercial and mining industries, utilising groundwater from the high priority aquifers, and the environment are not likely to be detrimental under a wet future climate. There are possible adverse effects in seven aquifers under a median future climate. The impacts are expected to be detrimental under a dry future climate.

Table 1: **Recharge, discharge mechanisms and storage dynamics in high priority aquifers**

AQUIFER	RECHARGE		DISCHARGE				STORAGE DYNAMICS	
	DIFFUSE RECHARGE	SURFACE WATER RECHARGE	SURFACE WATER DISCHARGE	EVAPO-TRANSPIRATION	COASTAL DISCHARGE (SEAWATER INTRUSION)	GROUNDWATER SUPPLY DEPENDENCY (EXTRACTION)	DEPTH TO WATERTABLE	S:R RATIO
Adelaide Geosyncline 3	*							
Upper Condamine and								
Coastal River Alluvium 1								
Coastal River Alluvium 4								
Coastal Sands 4								
Daly Basin								
Gunnedah								
Lachlan								
Newer Volcanics								
Otway Basin								
Pilbara								
Port Campbell Limestone								
Atherton Tablelands								
Toowoomba Basalts								

*Sensitive processes are shown with shaded cells.

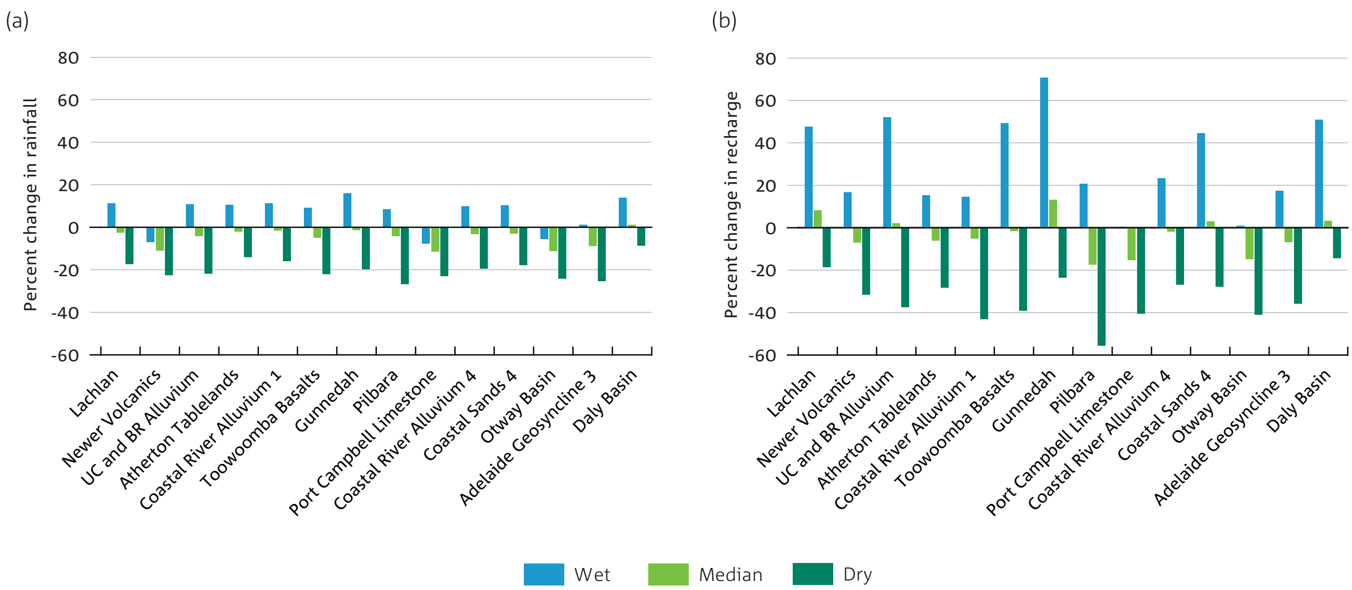
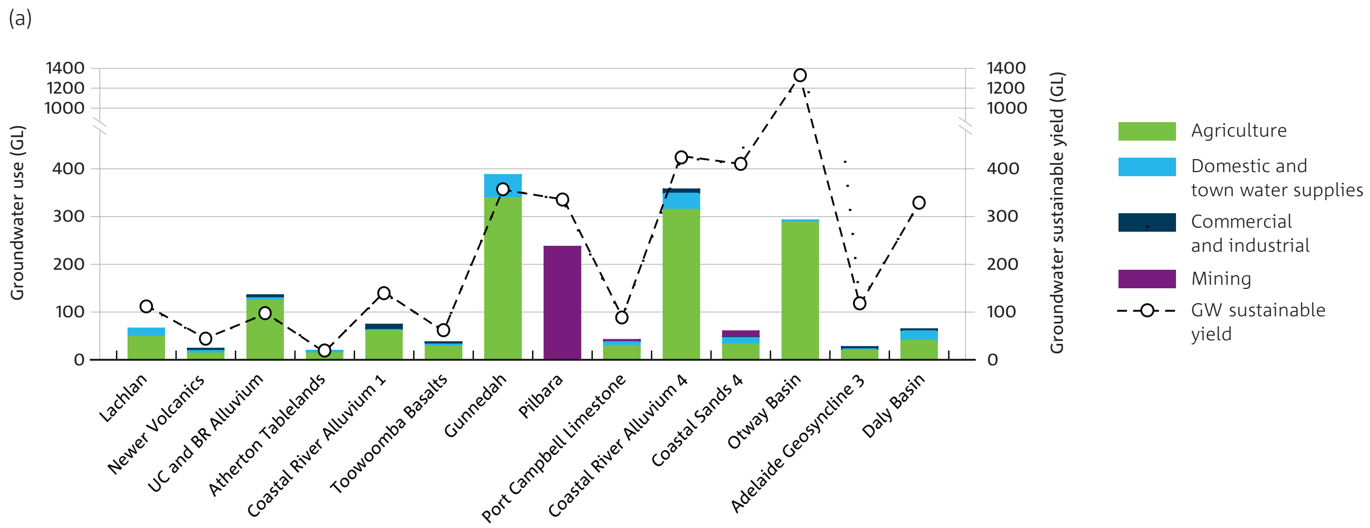


Figure 15: **Precipitation (rainfall) scaling factors, (a), and recharge scaling factors (b) under the wet, median and dry future climates in the high priority aquifers from baseline 80 years historical period rainfall**



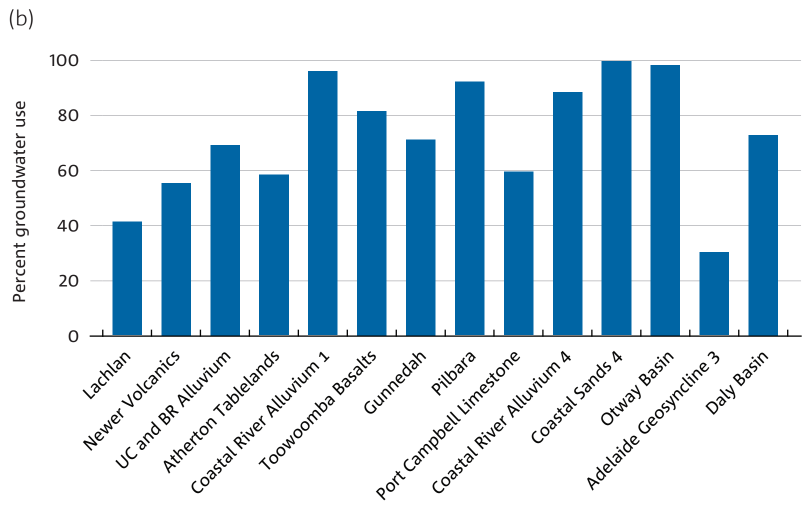


Figure 16: **Groundwater use by agriculture and others: total use and sustainable yield (a); and groundwater use as per cent of total water use (both from groundwater and surface water resources) in the region of the high priority aquifers (b)**

The probability of exceeding a specified RSF was estimated for each of the priority aquifers from the information provided in Figure 9. The probabilities chosen for analysis are exceeding a RSF of 1.0 (an increase in recharge), exceeding a RSF of 0.8 (a small reduction in recharge), exceeding an RSF of 0.5 (a large reduction in recharge) and not exceeding a RSF of 0.5 (an extreme reduction in recharge). Figure 17 shows that there is a significant risk (Probability less than 25%) of a large reduction (RSF greater than 0.8) in recharge for seven priority aquifers (Port Campbell Limestone, Otway Basin, Pilbara, Newer Volcanics, Toowoomba Basalts, Upper Condamine and Border Rivers Alluvium and Adelaide Geosyncline 3), a moderate risk (25% greater than Probability greater than 5%) for a further six priority aquifers (Coastal Sands 4, Coastal River Alluvium 1, Coastal River Alluvium 4, Gunnedah, Atherton Tablelands and Lachlan) while only one priority aquifer (Daly) has a small risk (Probability less than 5%) of a large reduction in recharge.

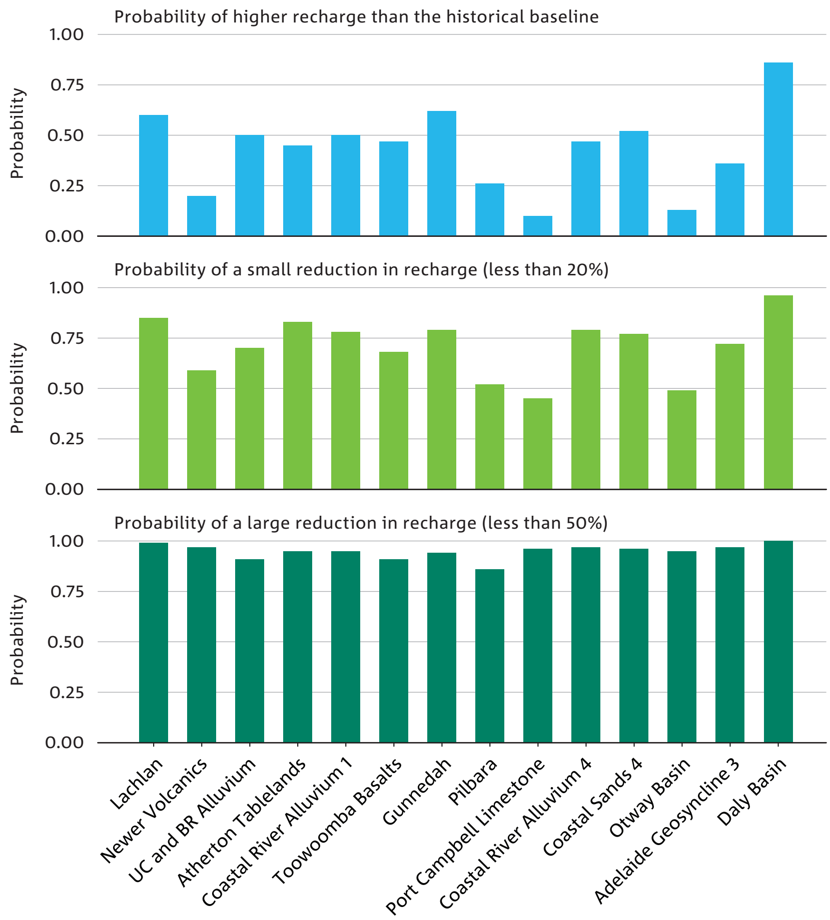


Figure 17: **Probability of excceding an RSF of 1.0, 0.8 and 0.5 for the high global warming scenario for the 14 priority aquifers.**

What limits our ability to adequately predict climate changes impact on groundwater resources?

Key findings

- *Differences between GCMs are the largest source of uncertainty in recharge projections; the choice of downscaling method is also a significant source of uncertainty*
- *Most of the reviewed groundwater models, used to investigate changes in the groundwater resources, were found to be inadequate in assessing the future impacts of climate change, particularly in their representation of surface and groundwater interaction*
- *Modelling approaches, model designs and the criteria used to define groundwater resources sensitivity to climate change vary substantially between the reviewed models*

The results of this investigation into projected future climate changes and possible impacts on groundwater resources are dependent on our understanding of the main governing processes influencing the projected changes and their representation in the currently available models and their ability to adequately simulate them. A synthesis of the analysis and observations of the project is presented in this section.

Future climate modelling: GCM results are too coarse for direct use in hydrological analysis and so some form of scaling or downscaling is required. To compare the daily scaling approach, as used in the majority of the investigations undertaken in this project, with other downscaling methods, a limited comparison of three methods was undertaken. The methods were: (1) daily scaling (DAILY), (2) stochastic downscaling (ST), and (3) dynamic downscaling (CCAM). Five GCMs were used to drive the different methods (CSIRO Mk3.5 (CSIRO), GFDL 2.0 (GFDL20), GFDL 2.1 (GFDL21), MIROC 3.2 midres (MIROC), and MPI-ECHAM5 (ECHAM). The methods were applied using a common baseline period (observed data) of 1981–2000 and a projection period of 2046–2065 (IPCC A2 scenario) for three study sites.

Figure 17 shows the range in uncertainty of projected rainfall changes due to GCMs and downscaling techniques, for one of these sites. At Livingstone Creek the change in future rainfall projections ranged from -32 per cent to +8 per cent with a median of -13 per cent. The daily scaling represents the percentage change in rainfall from the GCM outputs; at this site they encompass both increases and decreases in rainfall. The dynamic downscaling and stochastic downscaling do not use the rainfall from the GCMs and at this site produce very different projections. Additionally four hydrological models were used to assess the differences in projected recharge change (Figure 18). For Livingstone Creek the recharge projections ranged from -68 per cent to +101 per cent with a median of -7 per cent.

Across all three sites[15] it was shown that GCMs account for the largest uncertainty in recharge projections (53 per cent of historical recharge), downscaling methods are nearly as uncertain (44 per cent of historical recharge) and recharge models comparatively less (24 per cent of historical recharge).

Groundwater model projections: Computer models are simplifications of reality based on limited observation and groundwater system understanding. This is the case both in conceptualising the model domain, and in estimating and distributing the various hydrogeological properties, recharge and discharge fluxes and fluxes associated with boundary conditions. This project reviewed 21 models[16], that have been used for analysis of climate change effects on groundwater resources in various regions of Australia. This project identified a number of limitations in these models applicability to investigation of climate change impacts on groundwater resources, which are briefly described below.

Definition of 'Groundwater resources': Groundwater resources were defined differently in the reviewed modelling. In the MDBA studies, the groundwater resource was an amount of groundwater, which could be abstracted without changing groundwater storage. In other models the change in storage was a measure of climate impact on resources. This made the comparison of the model projections difficult.

Diffuse recharge: Prior knowledge of the relationship and elasticity between rainfall and recharge is required to adequately implement climate change in a groundwater model where it is represented as a fraction of total rainfall. The simplistic model input describing net recharge as a fixed percentage of total rainfall would underestimate

[15] Crosbie et al. 2011b
[16] Chapter 5 in Barron et al., 20011

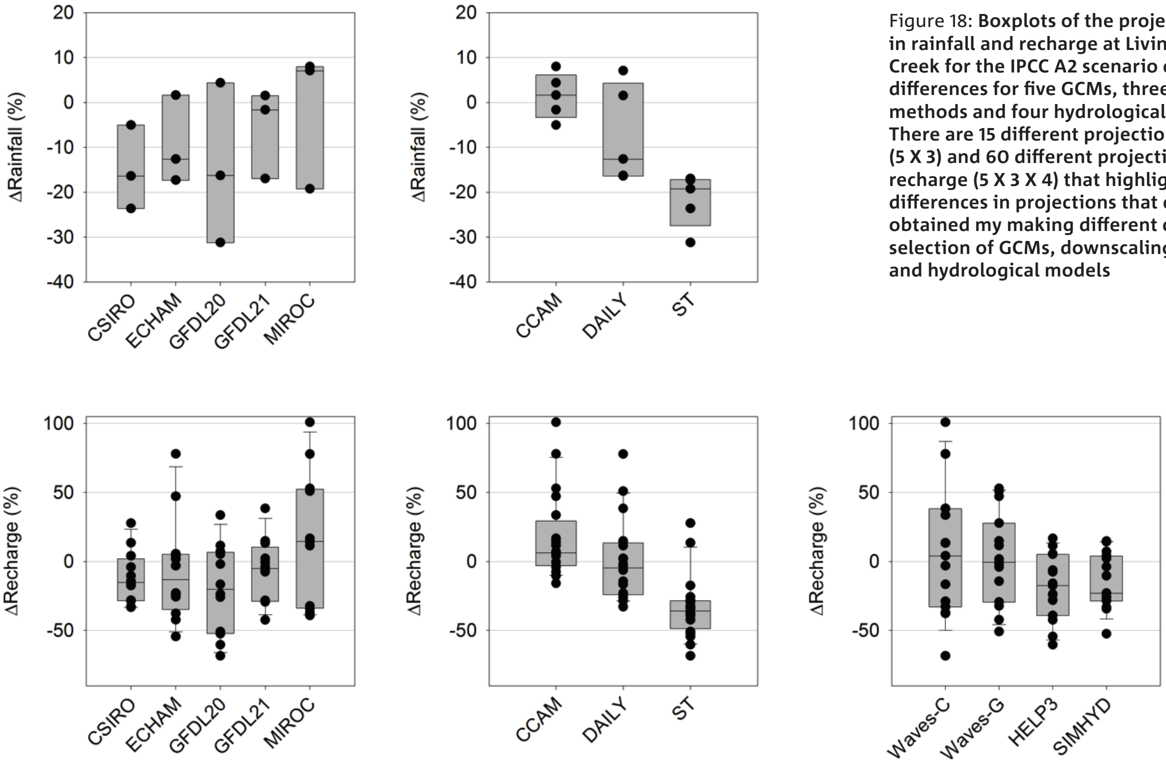


Figure 18: **Boxplots of the projected change in rainfall and recharge at Livingston Creek for the IPCC A2 scenario comparing differences for five GCMs, three downscaling methods and four hydrological models. There are 15 different projections of rainfall (5 X 3) and 60 different projections for recharge (5 X 3 X 4) that highlight the differences in projections that can be obtained my making different choices in the selection of GCMs, downscaling methods and hydrological models**

the changes in recharge, as it was shown that 10 per cent decrease in future rainfall is likely to lead to a 20 to 40 per cent decrease in recharge in contrast with the simplistic translation of a 10 per cent change in recharge.

Localised recharge, including floodplains: Processes associated with fluxes from and to rivers are not well represented in all reviewed models. Estimating the flux between the river and groundwater is commonly simplified. Changes in the river flow, surface water regulation measures and river morphology are not commonly included in analysis. The specifics of stream and aquifer connectivity (connected or disconnected stream) are not commonly addressed, while the localised recharge and its changes under future climate conditions are also rarely addressed. An additional limitation is related to the misrepresentation of the effective river width, which in many low valley rivers is the dominating factor in localised recharge changes under changing flow conditions. Moreover, flood and irrigation recharge are usually handled by the diffuse recharge simulation, and are mostly subjective in terms of their spatial and temporal patterns.

Diffuse discharge: Evapotranspiration losses are often linked with net recharge modelling. The mechanism for extracting groundwater by evapotranspiration, when modelled in addition to net or gross recharge, generally specifies a maximum rate at the surface with a linear decrease to an extinction depth. A lack of knowledge of changes in vegetation water use in response to rising temperature and CO_2 concentrations (and therefore vegetation water use efficiency) makes it difficult to incorporate these processes into numerical groundwater models.

Boundary conditions: Climate change effects on model boundary conditions are not commonly considered. No-flow boundary conditions are likely to provide the least effect on the model fluxes as these are least likely to change and do not contribute a flux to the model. Since many models are developed for only a part of an aquifer system (i.e. GMUs), this type of the boundary conditions may not be applicable.

Groundwater use data is limited: In 15 out of the 21 models groundwater abstraction comprised more than 50 per cent of the water balance; however availability of data on groundwater extraction is often a limited in many situations.

Process-based coupled surface water – groundwater models appear to be most suitable for simulation of climate change impacts on groundwater resources. Recently, a number of models (e.g. MIKE SHE, InHM, MODHMS or GSFLOW) have become available for the simulation of fully coupled surface water – groundwater systems. The challenge in using these physically based distributed coupled models is their large data requirements. Each individual process (e.g. channel flow, overland flow, unsaturated zone and saturated flows) requires a specific set of distributed parameters. The coupling of surface water and sub-surface water processes is also computationally expensive as the spatial and temporal scales for the individual components are different.

Conclusion

The outcomes of this project contribute to our understanding of the potential impact of climate change on groundwater management by quantifying the possible consequences of climate change on groundwater resources across the country.

The project provides the first continental scale analysis of climate change impacts on groundwater resources. Although the future climate projections have a large range, they provide opportunities to identify (i) the regions where all results are in an agreement (e.g. drying trends in the south and southwest of the country), and (ii) the range of potential changes in renewable groundwater resources. The latter was predominately related to diffuse groundwater recharge under the different climate types, but also some analysis was undertaken for localised groundwater recharge.

The project demonstrated that the effect of climate change on groundwater resources is influenced by the hydrogeological setting of an aquifer and current groundwater use. Fourteen priority aquifers were identified as both sensitive to climate and regionally important; they occur across all climate types and include most aquifer types. In addition to the 14 priority aquifers, six aquifers in south-west Western Australia were also included in our high priority list, as they are in the region projected to experience the greatest reduction in diffuse recharge under a median or dry projected future climate.

Glossary

Groundwater resources	Water resources that are held in aquifers and can be exploited for various uses by humans, usually to generate wealth
Groundwater management unit	An administrative area within which the groundwater resource is managed
Recharge	Recharge is the addition of water to the groundwater store, most commonly applied to water that crosses the plane of the water table
Diffuse recharge	Groundwater recharge due to rainfall that is distributed over a wide area
Localised recharge	Groundwater recharge that is focused on a small area such as river leakage
Deep drainage	Deep drainage is water that passes below the root zone of the vegetation. If there are no impeding layers it will become recharge after some time delay
Aquifer	An underground layer or geological formation that can yield groundwater to wells or bores. It can include one or more groundwater management units or be a part of groundwater management unit, along with other aquifers
High Priority Aquifers	Aquifers which are sensitive to climate change and are nationally important for consumptive and environmental use as a significant part of the water available
Storage	Groundwater storage is the total volume of water held in the pores of an aquifer
Discharge	The process whereby groundwater leaves an aquifer; a volumetric flux of water moving out of an aquifer
GCM	Global Climate Model
Stochastic downscaling	Generic term referring to any technique that relates local scale climate variables ('predictants') to large-scale climate forcing ("predictors"), through empirical-statistical relationships that capture the synoptic processes and moisture sources which influence local climate. Stochastic downscaling techniques can produce multiple realisations of predictant series, conditional on a single predictor series
Dynamic downscaling	Using a climate model at a higher spatial resolution (10 to 100 km) to better represent finer scale meteorological processes. Either a regional climate model (RCM) or limited-area model (LAM) can be nested in a host GCM that provides lateral boundary conditions or a 'stretched grid' model can run at a higher resolution over a region of interest with nudging from a host GCM
Pattern downscaling	Empirical scaling methods that scale historical climate series, such as daily rainfall, according to the relative difference between current and future GCM simulations of the climate variable

Project publications

Technical reports

Ali, R., Barron, O., Evans, R. and Dawes, W. (2011). Cost of model development and quantitative investigations in high priority aquifers of Australia. A report to the National Water Commission from Water for a Healthy Country National Research Flagship. 22pp

Barron OV, Crosbie RS, Charles SP, Dawes WR, Ali R, Evans WR, Cresswell RG, Pollock D, Hodgson G, Currie D, Mpelasoka FS, Pickett T, Aryal S, Donn M, Wurcker B (2011) Climate change impact on groundwater resources in Australia. Waterlines Report No 67, National Water Commission, Canberra, http://nwc.gov.au/publications/waterlines/climate-change-impact-on-groundwater-resources-in-australia

Barron O, Crosbie R, Dawes W, Pollock D, Charles S, Mpelasoka F, Aryal S, Donn M, Wurcker B (2010) Investigating the Impact of Climate Change on Groundwater Resources. CSIRO: Water for a Healthy Country, http://www.clw.csiro.au/forms/publications/details.aspx?ID=21662

Crosbie R, Pickett T, Mpelasoka F, Hodgson G, Charles S, Barron O (2011a) Diffuse recharge across Australia under a 2050 climate: Modelling results. CSIRO: Water for a Healthy Country National Research Flagship, http://www.clw.csiro.au/forms/publications/details.aspx?ID=21208

Crosbie RS, McCallum JL, Walker GR (2011c) The impact of climate change on dryland diffuse groundwater recharge in the Murray–Darling Basin. Waterlines report No 40, National Water Commission, Canberra, http://www.nwc.gov.au/publications/waterlines/the-impact-of-climate-change-on-dryland-diffuse-groundwater-recharge-in-the-murray-darling-basin

Currie DE, Wiltshire E, Irvine E, Evans WR, Barron O, Cresswell RG (2010) Investigating the impact of climate chnage on groundwater resources: aquifer characterisation. Sinclair Knight Merz and CSIRO: Water for a Healthy Country National Research Flagship.

Journal papers

Barron OV, Crosbie RS, Pollock D, Dawes WR, Charles SP, Pickett T and Donn M (2012) Climatic controls on diffuse groundwater recharge across Australia. *Hydrology and Earth System Sciences*, http://www.hydrol-earth-syst-sci-discuss.net/9/6023/2012/

Crosbie RS, Dawes WR, Charles SP, Mpelasoka FS, Aryal S, Barron O, Summerell GK (2011b) Differences in future recharge estimates due to GCMs, downscaling methods and hydrological models. Geophys Res Lett 38 (11):L11406

Crosbie RS, Pickett T, Mpelasoka FS, Hodgson G, Charles SP, Barron OV (2012) An assessment of the climate change impacts on groundwater recharge across Australia using a probabilistic approach with an ensemble of GCMs. Climatic Change

Conference papers

Charles SP, Mpelasoka FS, Crosbie RS, Dawes WR (2011) A multi-model comparison of daily precipitation projections using different downscaling techniques and their impact on modelled groundwater recharge. Paper presented at Greenhouse2011: The Science of Climate Change, Cairns, 4-8 April 2011

Crosbie RS, Pickett T, Mpelasoka FS, Hodgson G, Charles SP, Barron O (2011d) A continental scale assessment of the impact of climate change on groundwater recharge Paper presented at the MODFLOW and More, Golden, Colorado, USA.

CONTACT US
t 1300 363 400
+61 3 9545 2176
e enquiries@csiro.au
w www.csiro.au

YOUR CSIRO
Australia is founding its future on science and innovation. Its national science agency, CSIRO, is a powerhouse of ideas, technologies and skills for building prosperity, growth, health and sustainability. It serves governments, industries, business and communities across the nation.

CS ACT 2012 • BJ120225_WfHC_ClimateChangeImpactGroundwaterReport.indd