TECHNICAL REPORT

IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

PHASE 3 VOLUME 3

ALINYTJARA WILURARA NATURAL RESOURCES MANAGEMENT REGION

2012/05

Government of South Australia

Department for Water

IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

PHASE 3 VOLUME 3

ALINYTJARA WILURARA NATURAL RESOURCES MANAGEMENT REGION

Darren Alcoe, Matt Gibbs and Graham Green

Science, Monitoring and Information Division
Department for Water

April 2012

Technical Report DFW 2012/05

Science, Monitoring and Information Division
Department for Water
25 Grenfell Street, Adelaide
GPO Box 2834, Adelaide SA 5001

Telephone	National	(08) 8463 6946
	International	+61 8 8463 6946
Fax	National	(08) 8463 6999
	International	+61 8 8463 6999
Website	www.waterforgood.sa.gov.au	

ISBN 978-1-921923-29-6

Preferred way to cite this publication

Alcoe, D, Gibbs, M and Green, G, 2012, *Impacts of Climate Change on Water Resources Phase 3 Volume 3: Alinytjara Wilur̲ara Natural Resources Management Region,* DFW Technical Report 2012/05, Government of South Australia, through Department for Water, Adelaide

Download this document at: http://www.waterconnect.sa.gov.au/TechnicalPublications/Pages/default.aspx

FOREWORD

South Australia's Department for Water leads the management of our most valuable resource—water.

Water is fundamental to our health, our way of life and our environment. It underpins growth in population and our economy—and these are critical to South Australia's future prosperity.

High quality science and monitoring of our State's natural water resources is central to the work that we do. This will ensure we have a better understanding of our surface and groundwater resources so that there is sustainable allocation of water between communities, industry and the environment.

Department for Water scientific and technical staff continue to expand their knowledge of our water resources through undertaking investigations, technical reviews and resource modelling.

Allan Holmes
CHIEF EXECUTIVE
DEPARTMENT FOR WATER

CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

The Department for Water's *Impacts of Climate Change on Water Resources* (ICCWR) project has undertaken an analysis of groundwater recharge and rainfall intensity data in the Alinytjara Wilu̲rara Natural Resources Management (AWNRM) Region to determine the potential impact of climate change on the principal known potable groundwater resources of the region.

This report is presented as Volume 3 of Phase 3 of the ICCWR project, with the intention that reports of numerical modelling of other regions in South Australia will comprise further volumes as the project progresses. Phases 1 and 2 of the ICCWR project reported on precursors to the detailed data-analysis phase, respectively the prioritisation of South Australia's water resources for climate change impact assessment and the selection of future climate change projections and downscaling methodology.

While the downscaling methodology is retained in this study, a new approach for selecting a suite of Global Climate Models (GCMs) has been adopted that is based on CSIRO's Climate Futures Framework (Clarke *et al*., 2011). Suppiah *et al*. (2006) identified 11 GCMs that were best suited to projections of South Australian climate and these were used, in addition to the CSIRO Mark 3.5 GCM, in the Climate Futures analysis for the AWNRM Region. The Climate Futures analysis aided in identifying the 'most likely', 'best' and 'worst case' projections and from the 12 possible GCMs, three GCMs were selected to represent each of these cases.

The climate and groundwater recharge processes of the arid areas of the AWNRM Region differ from the semi-arid and temperate areas of South Australia. Furthermore, limited rainfall and groundwater level data are available across the AWNRM Region. Consequently, an analysis of rainfall metrics was adopted to determine the impact of climate change on the capacity of the region's groundwater resources, rather than numerical hydrological models of the groundwater systems, which has been the approach taken in previous ICCWR assessments. The metrics selected are the change in:

- annual average rainfall, as an indicator of the overall projected change
- the first percentile daily rainfall, as an indicator of the change in the intensity of extreme rainfall events
- the number of events greater than 100mm/month, as an indicator of episodic large rainfall events that generate groundwater recharge in the arid north of the region

Regional climate data for the period 1970–99 was used as the historic climate baseline for the downscaling of projections of climate variables. Projected changes in annual average rainfall, first percentile rainfall and frequency of months with greater than 100mm rainfall compared to the baseline period were calculated for each cell on a regular grid across the study area. This process was undertaken for climate change scenarios for projected climates of 2030, 2050 and 2070 with high (A2) and low (B1) emission cases. Results of the analysis indicate the changes in each rainfall metric, for each future scenario.

The GCM selected to represent the 'most likely' future climate case projected that decreases in average annual rainfall is likely to range from 5% in a 2030 climate (irrespective of the emission scenario), to 14% in a 2070 climate with a high-emission scenario. Reductions in the magnitude of extreme rainfall events (i.e. the first percentile daily rainfall), compared to the 1990 historic baseline period, are projected for all combinations of Climate Futures cases and emissions scenarios across the whole AWNRM Region. When results are averaged across the whole AWNRM Region, a reduction in the frequency of rainfall events that are expected to lead to recharge (months of rainfall greater than 100 mm) is projected. However, these reductions are highly variable due to the very low frequency in much of the region of months with rainfall greater than 100 mm – in some cases less than once every 10 years on average. In the north of the region, where these large, recharge-generating rainfall events are the most frequent, the frequency of these events is projected (using the ‘most-likely’ GCM climate projection) to decrease by 22% under a low-emissions scenario for 2030 and 38% under a high-emissions scenario for 2070.

Based on these results, a risk-management analysis was conducted that aims to assist in the planning and adaptation of groundwater resources management in the AWNRM Region into the future. The risk analysis was based on two criteria; (1) whether the groundwater resources appear to be responsive to contemporary rainfall events; and (2) the projected change in the frequency of extreme rainfall events that lead to recharge. The groundwater resources that were identified as at the highest risk from impacts from climate change are located near the communities of Yunyarinyi (Kenmore Park), Pukatja (Ernabella) and Kaltjiti (Fregon).

1. INTRODUCTION

1.1. PROJECT BACKGROUND

Climate change is acknowledged as a potential threat to the future of South Australia's water security. The State's *Water for Good* plan identifies climate change as a major challenge to water resources in most of South Australia's Natural Resources Management (NRM) regions.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Bureau of Meteorology (BoM) have previously undertaken investigations which project the likely impacts of climate change on South Australia (Suppiah *et al.*, 2006; CSIRO & BoM, 2007). Their projections indicate that through the 21st century, South Australia may be subject to:

- increased temperatures
- reduced rainfall
- increased rainfall variability
- increased evaporation
- significantly increased frequency and severity of drought
- changes in the frequency of extreme weather events, including flooding.

Of immediate concern to South Australia will be the impacts of decreased rainfall and its increased variability. Along with higher temperatures, which increase potential evaporation, the combined impacts may have significant consequences for the State's natural water resources. With projected impacts of climate change leading to a generally drier outlook, the State may face reduced availability and increased risk to water resources that are of strategic and economic importance.

The Department for Water (DFW) project *Impacts of Climate Change on Water Resources* (ICCWR) was established in 2010 under the New Knowledge for the Future component of DFW's Groundwater Program. The Groundwater Program addresses Target 75 of South Australia's Strategic Plan 2011 which requires that "South Australia's water resources are managed within sustainable limits by 2018".

The studies conducted by the ICCWR project will ultimately fulfil Action 43 of the Water for Good plan: "Commission, where required, regional scale studies on the Impacts of Climate Change on Water Resources".

The Alinytjara Wiluṟara Natural Resources Management Board (AWNRMB) NRM Plan (AWNRMB, 2009) includes an action to "...support research on the impact of climate change on water resources (particularly its impact on recharge specific to the region)". This report provides details and results of the studies of the Alinytjara Wiluṟara Natural Resources Management (AWNRM) Region.

1.2. PREVIOUS WORK

This report is preceded by four related reports that have been completed by the ICCWR project. To enable the evaluation of climate change impacts on groundwater resources, a key foundation task was to identify the most appropriate climate change projections for use in these studies and to develop a method to down-scale these projections to create 'future climate' data sets that are representative of each study area location. This task was undertaken by the ICCWR project team and is described in the report *Impacts of Climate Change on Water Resources, Phase 2: Selection of Future Climate Projections and Downscaling Methodology* (Gibbs *et al*., 2011). However, while the downscaling methodology is retained in this study, a new approach for selecting a suite of Global Climate Models (GCMs) has been adopted that is based on CSIRO's Climate Futures Framework (Clarke *et al*., 2011), which is discussed in Section 3.1.

Two earlier reports on the impacts of climate change on water resources in the Northern and Yorke NRM region (Green *et al.,* 2011) and the Eyre Peninsula NRM Region (Green *et al.*, 2012) presented the results of numerical modelling of groundwater recharge and surface water runoff under a range of future regional climate scenarios. This report follows a similar structure, with the same climate downscaling methods applied to the region. However, numerical models of recharge were not developed in this study due to a paucity of the field data required for model calibration. Instead, this study has focussed on identifying changes in the frequency and magnitude of extreme rainfall events, which are understood to govern groundwater recharge in the arid areas of the AWNRM Region. This approach is based on evidence that in areas with an arid climate similar to the AWNRM Region (e.g. central Australia's Ti Tree Basin (Harrington, Cook & Herczeg, 2002) and Lake Eyre (Tweed *et al.*, 2011)), groundwater recharge occurs only after periods of extreme local rainfall, typically of greater than 100–200 mm/month.

1.3. AIMS AND OBJECTIVES

The objective of the AWNRM Region study is to provide, for water planning and adaptation policy purposes, an understanding of the likely changes to groundwater resource capacity specific to the region under a range of possible future climate scenarios. With some exceptions, the amount of water that is available from groundwater resources for cultural and environmental water provisions and human water uses is dictated by the volume of groundwater recharge. This study was focussed on the intensity and frequency of extreme rainfall events as these are likely to be the principal drivers of recharge and therefore determine the capacity of the water resources.

The majority of the population of the AWNRM Region resides near the Anangu Pitjantjatjara Yankunytjatjara (APY) (or Musgrave) Ranges. Recharge around the APY Ranges is thought to occur mainly via infiltration in areas of basement rock outcrop and adjacent alluvial outwash sediments following extreme rainfall events. Hence, knowledge of the changes in the frequency and magnitude of extreme rainfall events that may occur due to the impacts of climate change is essential for the planning and adaptation of water resources management in the AWNRM Region through the 21st century.

It is not the intention of this study to provide any guideline to the most likely climate change scenarios, nor to predict what changes in climate will occur. Rather, the intention has been to adopt an approach wherein the climate change projections of a range of existing GCMs are applied to rainfall intensity and frequency analyses that indicate possible changes in the frequency and magnitude of recharge events.

The objective of the study was achieved by completing five key activities:

1. Review of recharge studies conducted in the AWNRM Region and also in similar arid environments
2. Identification of the 'most likely', 'best' and 'worst' case climate projections and the selection of a suite of GCMs to represent each of these cases using the Climate Futures Framework
3. Downscaling to produce region-specific projections of changes to daily rainfall
4. Analysis of the changes in the frequency and magnitude of extreme rainfall events in projected future climate scenarios to provide a guide to potential future changes to the capacity of groundwater resources of the region

5. Risk management analysis for region's groundwater resources, based on (1) groundwater level response to contemporary rainfall; and (2) the projected percentage change in the frequency of large episodic rainfall (i.e. recharge) events.

2. THE ALINYTJARA WILURARA NATURAL RESOURCES MANAGEMENT REGION

The AWNRM Region covers more than 250 000 km^2 of the north-western corner of South Australia (Fig. 1). It is bounded by the Northern Territory and Western Australian borders and extends southward to the Great Australian Bight. The region is reserved largely for conservation and traditional Aboriginal use and occupation. It comprises the following parks and Aboriginal Lands (AWNRMB, 2009):

- Anangu Pitjantjatjara Yankunytjatjara Lands (vested in the Anangu Pitjantjatjara under the *Anangu Pitjantjatjara Yankunytjatjara Land Rights Act 1981*)
- Maralinga Tjarutja (MT) Lands (vested in the Maralinga Tjarutja under the *Maralinga Tjarutja Land Rights Act 1984*)
- Yalata (vested in the Aboriginal Lands Trust under the *Aboriginal Lands Trust Act 1966*)
- Areas adjoining the Yalata and Maralinga Tjarutja Lands, dedicated under the *South Australian National Parks and Wildlife Act 1972* and *Wilderness Protection Act 1992*, including:
  - Mamungari Conservation Park
  - Tallaringa Conservation Park
  - Yumbarra Conservation Park
  - Yellabinna Regional Reserve and Yellabinna Wilderness Area
  - Nullarbor Regional Reserve and Nullarbor National Park

The AWNRM Region has a population of around 2200, most of whom identify with the Pitjantjatjara, Yankunytjatjara, Ngaanyatjarra, Kokatha, Mirning or Wirangu peoples (AWNRMB, 2009). The size of the population tends to fluctuate with changing seasons and with the timing of community events and traditional ceremonies. Most of the population reside around the APY Ranges (Table 1).

The provision of potable water to communities and homelands within the AWNRM Region presents significant challenges due to limited supplies and competing demands. There are no large or permanent fresh surface water resources in the region and consequently, local groundwater is relied on for town water supply and stock and domestic purposes. Oak Valley is an exception with water pumped from wells located around 35 km from the settlement (Fig. 1) (AGT, 2010). Oak Valley's water supply is augmented by rainwater from a number of rainwater tanks that collect from rooves distributed across the area (DTEI, 2005). Groundwater and rainwater are transported to the community by tanker. Demand for water across the AWNRM Region includes human needs, pastoral (mainly cattle grazing) and mining (Sect. 2.3)

2.1. SURFACE GEOLOGY

The AWNRM Region comprises three distinct landscapes (Fig. 2); (1) the APY lands that are dominated by arid ranges that are collectively known and the APY Ranges (AWNRM 2009) – the APY Ranges include the Musgrave, Mann and Indulkana Ranges; (2) central to the AWNRM Region are the MT Lands and this area comprises the red sand dunes and stony plains of the Great Victoria Desert; and (3) to the south lies the vast, flat, limestone-dominated terrain of the Nullabor Plain that terminates at the Bunda Cliffs of the Great Australian Bight. The hydrogeology of these three different landscapes is correlated with geological provinces (Fig. 5) and is discussed further in Section 2.5.

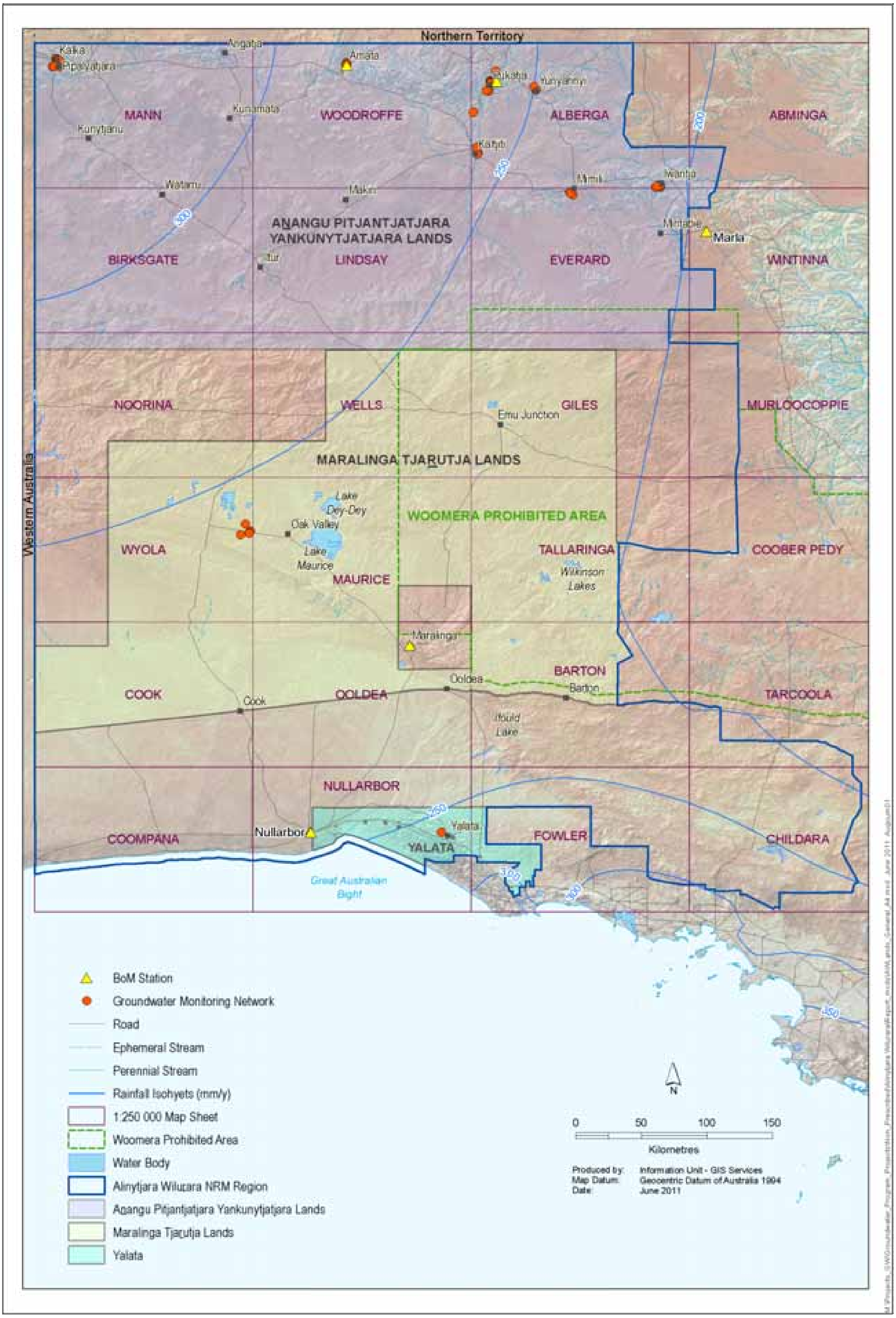


Figure 1. The Alinytjara Wilurara Natural Resources Management Region (Watt & Berens, 2011)

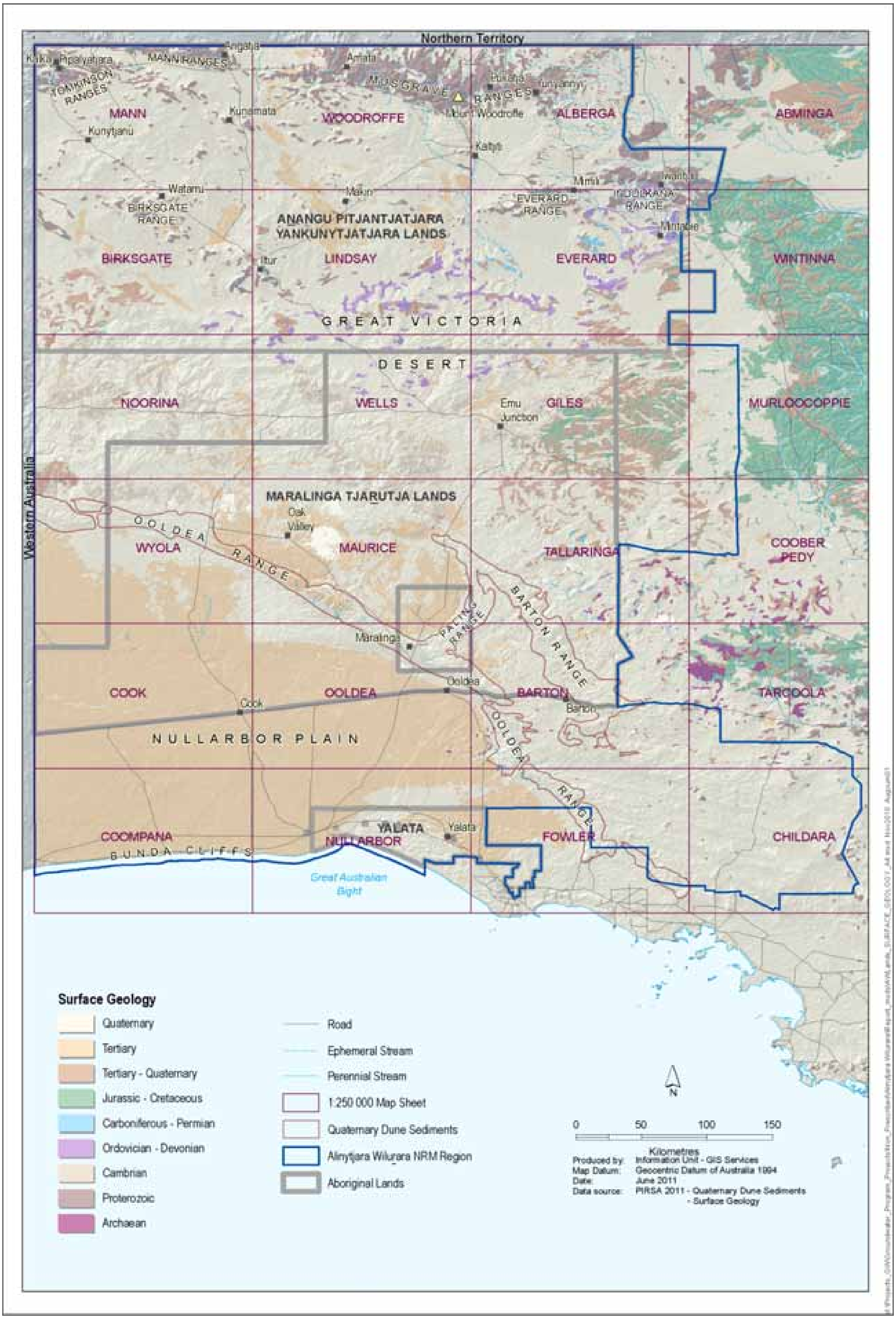


Figure 2. Surface geology of the Alinytjara Wilurara NRM Region (Watt & Berens, 2011)

Table 1. Towns and Aboriginal communities and homelands within the Alinytjara Wiluṟara NRM Region

Area	Town, Community or Homeland
APY Lands	Kalka, Pipalyatjara, Kunytjanu, Angatja, Kunamata, Iltur, Makiri, Amata, Pukatja (Ernabella), Kaltjiti (Fregon), Mimili, Yunyarinyi (Kenmore Park), Iwantja (Indulkana) and Mintabie
MT Lands	Oak Valley, Ooldea and Barton
Yalata	Yalata

2.2. CLIMATE

The AWNRM Region can be broadly described as having an arid climate. However, there are two distinct climate sub-zones within this broader arid zone (Fig. 4). Along the coast toward the south of the study area, the climate is described as 'cold steppe' (i.e. semi-arid). Further north, the climate shifts to 'hot desert'. These sub-zones have been delineated using the Köppen-Geiger climate classification system (Kottek *et al*., 2006), which is based on landscape signals of climate (particularly vegetation) and threshold values of mean annual precipitation and mean annual temperature.

Climate statistics (Table 2) show that rainfall in the 'cold steppe' climate zone (i.e. Nullarbor) is winter dominant, whereas rainfall in the 'hot desert' climate zone is summer dominant. Rainfall in the 'hot desert' zone becomes increasingly episodic and unpredictable with decreasing latitude. The seasonal climate for the locations in Table 2 are shown in Figure 3, where the box plots represent the monthly rainfall and solid lines the average monthly potential evapotranspiration (PET). The whole period of the SILO rainfall record (1891–2011, inclusive) has been used to produce Figure 3. The black horizontal line within each box represents the median rainfall for each month and the lower and upper bounds of the box represents the 25^{th} and 75^{th} percentile monthly rainfall, respectively. The whiskers extending beyond each box represent 1.5 times the range of rainfall within the box and circles represent monthly rainfall totals that fall outside this range, which can be considered extreme events. The average monthly PET markedly exceeds the median monthly rainfall for all months at all locations (Fig. 3) and there are only a small number of extreme monthly rainfall totals that have exceeded the average monthly PET over the 121 years of climate data.

Importantly, in arid areas, rain may not fall for several years but conversely, intense rainfall can deliver total annual rainfall in a single event. Consequently, mean rainfall statistics are often misleading and care should be taken in their interpretation.

Table 2. Monthly climate statistics for the Alinytjara Wiluṟara NRM Region (BoM 2011, from Watt & Berens, 2011)

Locality	Mean annual maximum temp (^{0}C)	Mean annual minimum temp (^{0}C)	Mean summer maximum temp (^{0}C)	Mean summer minimum temp (^{0}C)	Mean winter maximum temp (^{0}C)	Mean winter minimum temp (^{0}C)	Period of record
Pukatja	27.1	13.0	34.3	20.2	18.9	5.0	1997–2011
Marla*	28.7	13.6	36.1	21.1	20.5	5.6	1985–2011
Maralinga	25.2	11.8	31.4	15.7	17.9	7.2	1955–1967
Nullarbor	23.7	10.6	27.5	15.2	18.8	5.7	1986–2011

Locality	Mean annual rainfall (mm)	Mean summer rainfall (mm)	Highest summer rainfall (mm)	Lowest summer rainfall (mm)	Mean winter rainfall (mm)	Highest winter rainfall (mm)	Lowest winter rainfall (mm)	Period of record
Amata	279.1	35.9	254.4	0	13.0	68.7	0	1962–2011
Marla*	240.0	29.4	128.2	0	12.3	88.4	0	1985–2011
Maralinga	224.4	19.9	142.1	0	17.8	95.0	0	1955–2011
Nullarbor	248.8	13.0	121.8	0	27.3	93.0	0	1888–2011

* Note that Marla lies just outside of the AWNRM Region

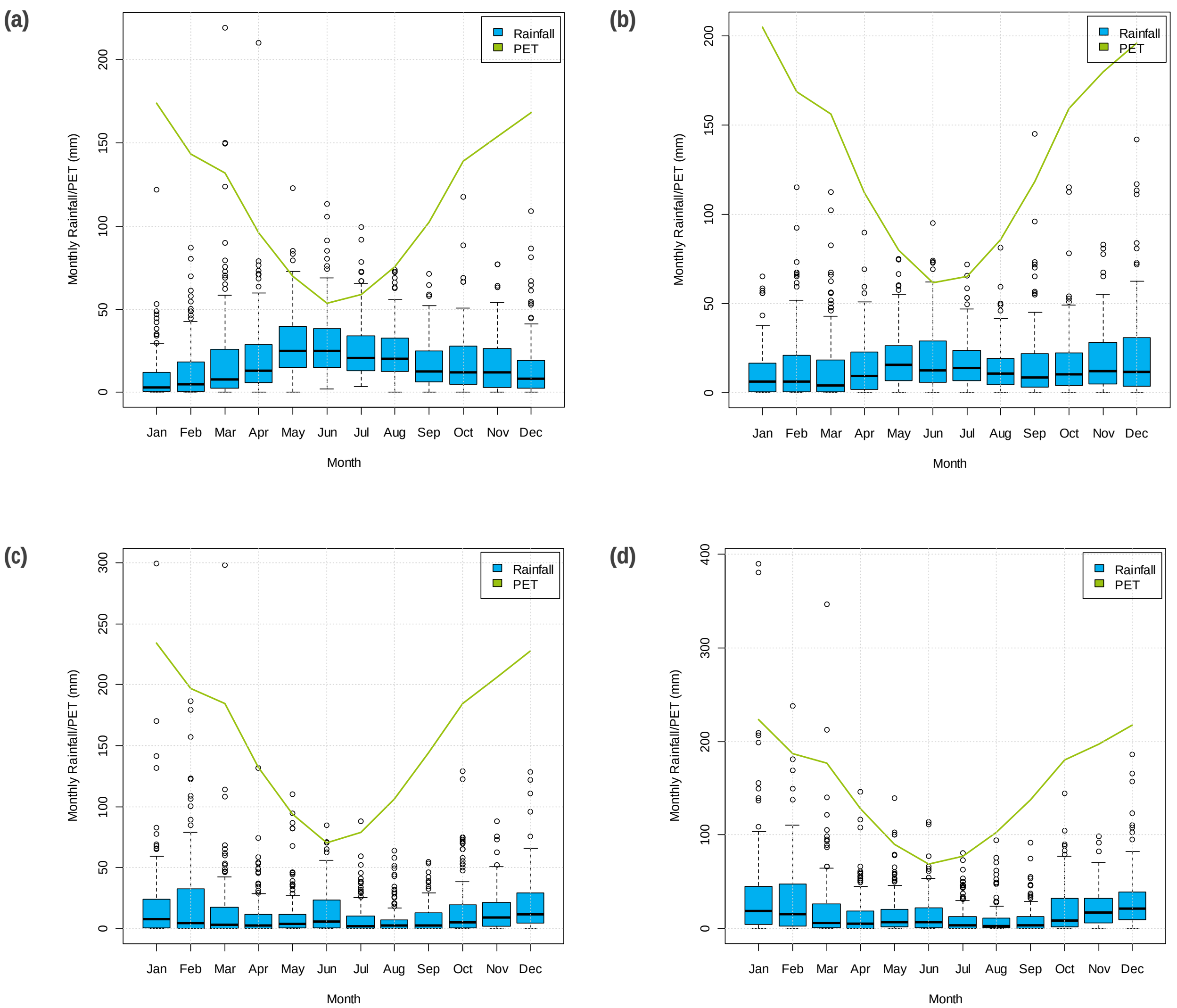


Figure 3. Monthly rainfall and potential evapotranspiration (PET) at the BoM rainfall stations (Fig. 1) (a) Nullabor, (b) Maralinga, (c) Marla and (d) Pukatja (Ernabella) (Jeffrey 2001). Note the different scales on the vertical axes. The whiskers extending beyond each box represent 1.5 times the range of rainfall within the box and circles represent monthly rainfall totals that fall outside this range, which can be considered extreme events.

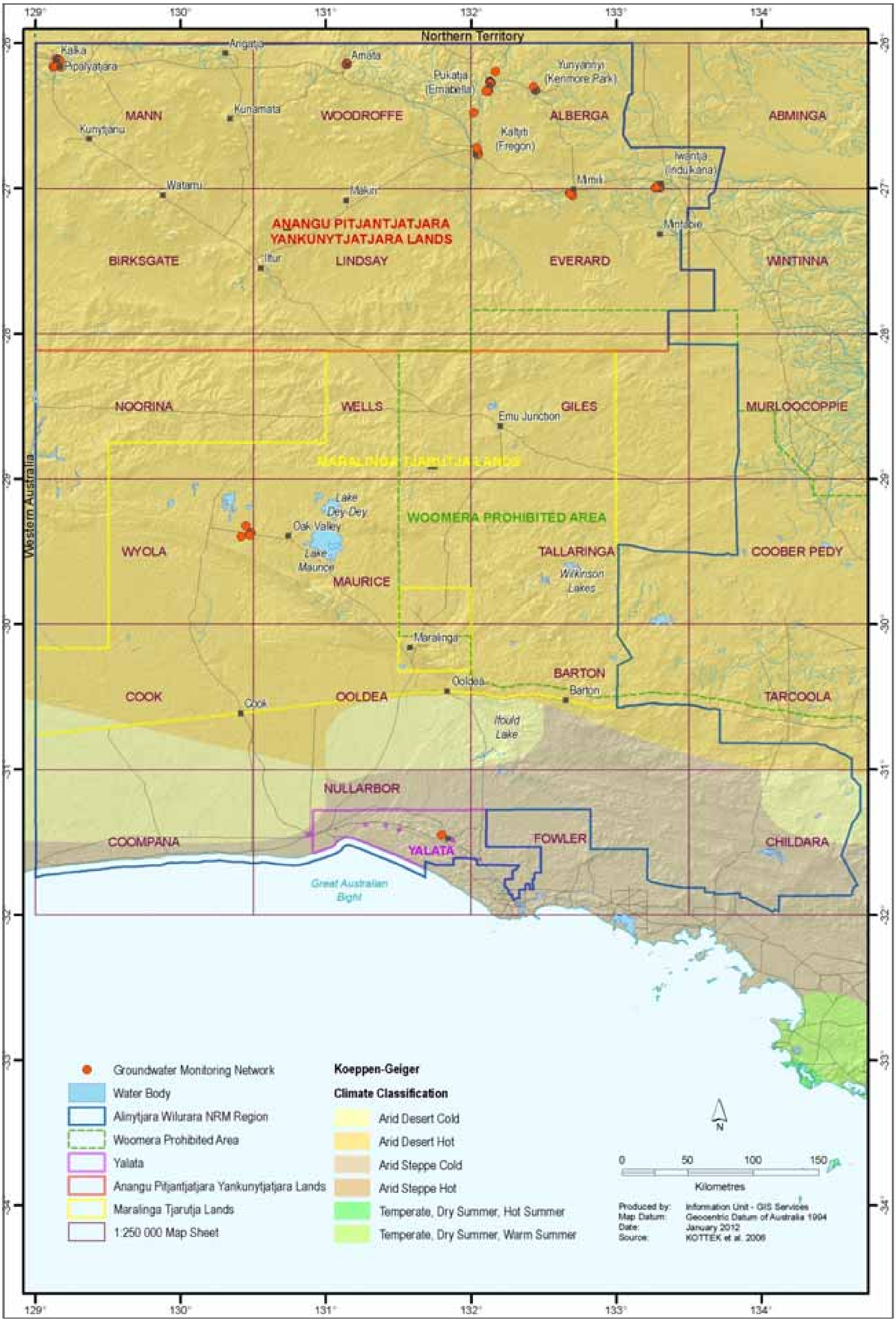


Figure 4. Climate zones based on the Koppen-Gieger climate classification system

2.3. DEMAND FOR GROUNDWATER

Groundwater has underpinned the viability of small communities and pastoral activities across the region for many years. Water use by the pastoral sector has been poorly documented. Feral animals such as camels, horses and donkeys are also impacting on the land and biodiversity of the region, including the water asset (AWNRMB, 2009), however the volume of water they consume is unknown.

2.3.1. TOWN WATER SUPPLY

Estimates of groundwater consumed by the 11 main Aboriginal communities of the AWNRM Region have been calculated using pumping data collected between 1998–2007 (AGT, 2010) (Table 3). For some settlements and homesteads, the demand for water (as gauged by trends in usage) is projected to increase in the future, whilst trends in corresponding groundwater levels suggest that groundwater storages are either steady or decreasing.

Table 3. Groundwater use for the Alinytjara Wilurara NRM Region's main Aboriginal communities (AGT, 2010)

Community	Aquifer type	Groundwater use (ML/y)	Trend in usage	Trend in water levels
Kalka	Alluvium and fractured rock	18	Increasing	Rising
Pipalyatjara	Fractured rock	28	None	Rising
Amata	Alluvium and fractured rock	50	None	Declining
Umuwa	Fractured rock	6*	Decreasing	Declining
Pukatja (Ernabella)	Alluvium and fractured rock	99	Increasing	Declining
Yunyarinyi (Kenmore Park)	Fractured rock	15	None	Declining
Kaltjiti (Fregon)	Alluvium and fractured rock	59	None	Steady
Mimili	Fractured rock	30	Increasing	Steady
Iwantja (Indulkana)	Fractured sandstone	32	Increasing	Steady
Oak Valley	Fractured sandstone	50*	Unknown	Steady
Yalata	Quartz Sands	61	None	Declining

*Based on only two years' data

2.3.2. PASTORAL AND MINING SECTORS

Increasing pastoral and mining activity is reported to be one of the main influences on the region's water demand (AWNRMB, 2009). Whilst cattle grazing is the main land use around the APY Ranges, few records of pastoral activity exist. There are large uncertainties in stocking rates, groundwater extraction volumes and the status and condition of wells used for stock watering (Watt & Berens, 2011). Furthermore, the now former Department for Transport Energy and Infrastructure reported that pastoral activity was increasing around the eastern APY Lands in 2005 (DTEI, 2005).

The AWNRM Region is likely to be rich in minerals and/or petroleum resources (AGT, 2010). Exploration is active across the study area, although the only operational, large-scale mine is the Iluka Resources' Jacinth-Ambrosia Mineral Sands Project. This mine extracts groundwater at the rate of around 9500 ML/y (Parsons Brinkerhoff, 2008) from a high-salinity palaeovalley aquifer. The dynamics of the region's complex groundwater systems are poorly understood and consequently, it is difficult to project what impacts increasing pastoral and mining activity are likely to have on potable groundwater supplies.

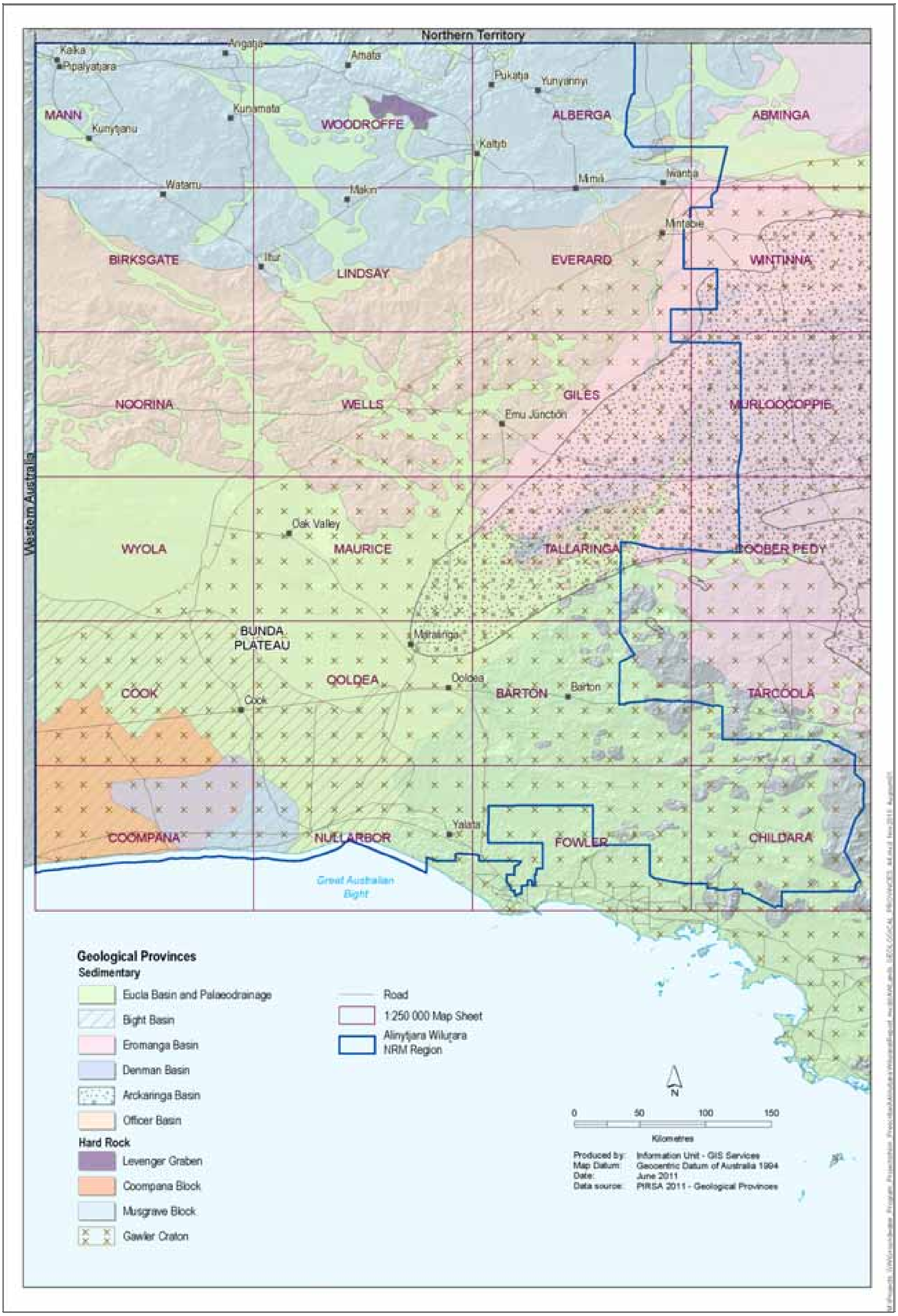


Figure 5. Geological provinces of the AWNRM Region (Watt & Berens, 2011)

2.4. GROUNDWATER RECHARGE IN ARID ENVIRONMENTS

Groundwater recharge to unconfined aquifers is a function of rainfall duration and intensity and also a function of topography, the type of vegetation and its extent, the nature of the soil profile and the underlying geology. The estimation of recharge rates to unconfined aquifers in arid environments can be especially challenging due to the episodic nature of rainfall and low fluxes to the water table.

Many arid-zone groundwater systems host groundwater that is very old and may have been recharged under a different climate to today's (Clarke *et al.*, 1987). These systems may contain 'fossil' water and some may not receive recharge from present-day rainfall. However, some groundwater systems in arid regions show water level responses to local rainfall events.

Many techniques are available to estimate contemporary rainfall recharge. However, the choice of technique is often difficult because the timing and location of recharge is variable (Scanlon, Healy & Cook, 2002). The hydrograph (or water table fluctuation) method is commonly used to estimate recharge rates due to its simplicity and because *a priori* knowledge of mechanisms by which water moves through the vadose zone is not required (Healy & Cook, 2002). This method is best applied to groundwater systems with shallow water tables which show sharp water level rises and recessions (e.g. ICCWR assessments of the Northern and Yorke and Eyre Peninsula NRM Regions). However, in arid areas, water fluxes are usually low and the water table deep. Consequently, the hydrograph technique is often not useful in these environments (Herczeg & Love, 2007). Instead, environmental tracer methods are often used.

Recharge rates have been estimated in the arid Ti-Tree Basin in central Australia using two environmental tracer methods – modelling and isotopic dating of groundwater by ^{36}Cl and ^{14}C (Harrington, Cook & Herczeg, 2002). Recharge from floodouts of ephemeral rivers in the region was found to be an important recharge mechanism. Recharge to fresh groundwater (salinity less than 1000 mg/L) via streambed floodout reportedly occurred at a mean rate of ~1.9 mm/y compared with a mean recharge rate of ~0.2 mm/y for the rest of the basin. Importantly, recharge appeared to occur rarely and only after the most intense rainfall events of greater than 150–200 mm/month. It is thought that water levels today are still responding to an extreme rainfall event that occurred in 1974.

Major-ion chemistry, stable isotopes, radiogenic isotopes and remote sensing data have been used to investigate groundwater recharge and salinisation processes in the Lake Eyre Basin in arid central Australia (Tweed *et al.,* 2011). A large and intense local rainfall event occurred in January 2007 that resulted in the flooding of the usually-dry Lake Eyre. Results from groundwater chemistry analysis showed no evidence of recharge from the floodwaters or the local rainfall, but recharge may not have yet been detected due to low transit times and low infiltrating volumes. The stable-isotope chemistry results derived from this study indicate that groundwater in this area is mainly recharged diffusely following local heavy rainfall events of 100–150 mm/month.

2.5. GROUNDWATER RESOURCES OF THE AWNRM REGION

Most communities within the study area are located in the APY Lands (Fig. 1). Consequently, groundwater investigations have been concentrated largely around the APY Ranges. Alluvial outwash sediments were the preferred groundwater targets during early groundwater exploration due to more favourable site selection and less challenging drilling conditions. However, hydrogeologists investigating groundwater occurrence later discovered that weathered and fractured bedrock hosted the lowest salinity groundwater (generally less than 800 mg/L) (Magee, 2009). Groundwater less than 1500 mg/L is often associated with the weathered zone overlying basement highs of the Gawler Craton (Martin, Sereda & Clarke, 1998). Lower salinities in fractured rock aquifers are likely to be governed by processes of localised recharge. It is surmised that in arid areas such as the Musgrave Province (Fig. 5), groundwater recharge occurs as a result of episodic, heavy summer rainfall events (Read, 1989).

Palaeovalley aquifers typically have greater storages of groundwater than fractured rock aquifers, but these are usually avoided in the AWNRM Region for potable supply due to high salinities (generally greater than 1500 mg/L) (Magee, 2009) and the potential for high levels of toxic elements such as sulfates, nitrates and fluoride. Furthermore, the region's palaeovalley aquifers (especially the Pidinga Formation) often have high levels of naturally occurring radionuclides (Buxton, 2005). Lower-salinity groundwater is likely to occur preferentially in calcrete aquifers (Magee, 2009), such as those occurring in the Oak Valley area.

Groundwater resources that are important for the AWNRM Region's town water supplies reside within a variety of geological environments. Regional groundwater systems are closely related to geological provinces (Fig. 5) (GHD, 2009b). Groundwater across the Musgrave Province and Officer Basin generally resides within three aquifer types (Miller, 1967; Tewksbury & Dodds, 1997; Dodds, 1997; Martin, Sereda & Clarke, 1998):

- *APY (Musgrave) Ranges* – weathered and fractured Precambrian rocks and Quaternary alluvial outwash aquifers (e.g. aquifers that provide town water supply for most APY communities and homelands)
- *Officer Basin* – Late-Proterozoic and Early-Palaeozoic sedimentary strata toward the southern part of the basin
- widespread Cenozoic palaeovalley sediments.

Oak Valley lies within the Eucla basin and the community's town water supply resides within an unidentified fractured sandstone aquifer. The Yalata community's domestic water supplies are sourced from deep Middle-Miocene quartz sands aquifers.

A detailed discussion of the regional geology and hydrogeology of the AWNRM Region is reported by Watt and Berens (2011). A summary of the current, albeit limited understanding of the groundwater systems upon which the settlements and homelands of the APY Lands, MT Lands and the Yalata regions rely for town water supplies follows, including a summary of rainfall-recharge relationships that have been reported in previous studies (Table 5).

2.5.1. ANANGU PITJANTJATJARA YANKUNYTJATJARA (APY) LANDS

The APY Lands are situated in the arid far-north of South Australia and extend to the South Australia–Northern Territory border (Fig. 1). These Aboriginal Lands host the vast majority of the AWNRM Region's population. At least nine APY communities rely on groundwater for domestic purposes. All of the sedimentary and fractured rock groundwater systems within the APY Lands are understood to be of limited extent (Dodds & Sampson, 2001; AGT, 2010).

Most of the town water supply wells are completed within fractured rock aquifers of the Musgrave Block. The Musgrave Block comprises Precambrian igneous and metamorphic rocks that outcrop as the APY Ranges along the northern border of the APY Lands. The Musgrave Block forms a regional fractured rock aquifer of variable yield (Watt & Berens, 2011). The Indulkana Range wells to the east are completed within an unidentified fractured sandstone aquifer.

Groundwater also resides within shallow Quaternary alluvial outwash aquifers that are located adjacent to basement outcrop in and near the APY Ranges. These small, localised occurrences of groundwater are understood to be recharged by direct infiltration of rainfall (Rowe *et al.*, 2006).

2.5.2. MARALINGA TJARUTJA LANDS (OAK VALLEY)

The Oak Valley community has a population of around 100 (AWNRMB, 2009) and is located within the Great Victoria Desert (Fig. 1). The community's town water supply wells lie within the Eucla Basin, which is underlain by Neoproterozoic rocks of the Gawler Craton.

The Oak Valley community's town water supply resides within unidentified fractured sandstone and siltstone aquifers occurring at between 2–30 m depth. The town water supply well field exists in five localised occurrences of brackish groundwater (300–3000 mg/L) with standing water levels of around 20 m. The well field is located around 35 km west of the community and the water is carted via tanker. Dodds (1997) reported that the current town water supply wells could run dry or turn saline at any time, particularly after an extended period (i.e. months or years) of locally dry weather. Dodds and Sampson (2002b) reported that the three town water supply wells that are monitored appear to be in a sustainable pumping routine, although they reiterated that the fragility of the resource means that careful monitoring is required. Fresh, potable groundwater also exists in valley calcrete palaeovalley deposits in the Oak Valley area (Dodds *et al.*, 1995), probably due to enhanced local recharge via runoff from hard calcrete surfaces. However, due to low rainfall and high evaporation, these resources are likely to always be of limited extent.

2.5.3. YALATA

The near-coastal Yalata community has a population of around 160 (AWNRMB, 2009) and is located between the eastern extent of the Nullarbor Plain and the south-eastern edge of the Great Victoria Desert (Fig. 1). The aquifer used for town water supply is the quartz sands Middle-Miocene Pidinga Formation, which occurs at a depth from around 60 m to greater than 75 m. This aquifer is overlain by the Late-Eocene Wilson Bluff Limestone and Early-Pliocene Nullarbor Limestone.

The town water supply wells have standing water levels of around 60 m but water levels have been gradually declining since monitoring began in 2000. There are no rainfall data available for the Yalata town water supply wells area, making an assessment of rainfall-recharge relationships difficult. However, Dodds and Sampson (2002b) reported that there had been no indication from standing water level data of recharge to the aquifer and that the gradual decline in water levels is likely to be attributable to natural processes of groundwater discharge to the adjacent marine environment. Further, Costar and Sampson (2004) reported that recharge to the aquifer appears not to occur locally but may be occurring as far away as the Ooldea Ranges or the Nullabor Plain (i.e. tens to hundreds of kilometres distant).

2.6. GROUNDWATER RECHARGE IN THE AWNRM REGION

In general, the source, extent, quality, connections and recharge mechanisms for groundwater resources in the region are poorly understood (AWNRMB, 2009). Environmental consultants GHD (2009a) identified numerous knowledge gaps, e.g. groundwater recharge rates, aquifer properties, hydraulic gradients, volumes of throughflow, indirect recharge rates (via stream losses) and groundwater quality.

Palaeovalley groundwater systems occurring in arid environments typically experience low recharge rates (Magee, 2009). Recharge involves a complex variety of sources that are poorly understood and not well quantified. Estimated recharge rates for palaeochannel and palaeovalley calcrete aquifers (such as those in the Oak Valley area) are typically based on assumed rates of rainfall infiltration efficiencies for given rainfall intensities and magnitudes (e.g. Tewkesbury & Dodds, 1997). However, uncertainties surrounding the contribution to recharge from overland flows led Magee (2009) to contend that these estimates are at best only educated guesses of actual recharge rates.

2.6.1. PREVIOUS GROUNDWATER RECHARGE STUDIES

A number of authors have undertaken qualitative groundwater recharge assessments of unconfined groundwater systems across the AWNRM region (Table 5). These assessments draw largely consistent conclusions with respect to water level response to local rainfall events, although some inconsistencies are apparent in fractured rock environments, particularly where there are disparate lengths of rainfall and water level records between studies. The discrepancies between the conclusions of various reports highlight the effects of rainfall episodicity and the spatial variability of recharge events in this arid environment. For example:

- Greater APY Lands
  - GHD (2009a) reported that monitoring data indicates relatively stable community water supply well water levels at Pipalyatjara, Kaltjiti (Fregon), Mimili, Yunyarinyi (Kenmore Park) and Iwantja (Indulkana), while water levels at Kalka and Amata are variable and levels at Pukatja (Ernabella) are showing marked declines
  - Costar and Sampson (2004) reported that water levels in APY Lands aquifers, at all communities except Fregon and the Indulkana Range wells, had showed recharge for the period October 2003–April 2004; while the declining water levels in the Indulkana Range wells was reported to be of short-term concern
- Yunyarinyi (Kenmore Park)
  - GHD (2010) reported that for the fractured rock aquifers in the Yunyarinyi (Kenmore Park) area, there is a strong correlation between water levels and rainfall for the period 2000–2008
  - Contrastingly, environmental consultants AGT (2008) reported that rainfall is seen to have no observable effect on groundwater levels for the same Yunyarinyi groundwater systems over the seasonal period April 2007–November 2007.

These comparisons illustrate that the timescale over which data is analysed can influence conclusions drawn regarding aquifer response to rainfall events. This is due to the episodic nature and spatial variation of rainfall events in arid areas.

Few studies have attempted to quantify groundwater recharge of the AWNRM region. AWNRMB (2009) estimated that for the APY Ranges, only 2% of rainfall occurred as deep drainage. This suggests that the potential for recharge is low. GHD (2010) produced quantitative estimates of the total water resource (i.e. both groundwater and surface water) within the region using a spatially-distributed rainfall– runoff–recharge modelling framework.

Rainfall–runoff–recharge modelling has previously been conducted to develop AWNRMB's understanding of water resources across the region (GHD, 2010). The aim of this modelling was to produce some initial estimates of groundwater recharge and runoff that results from effective rainfall. The study used PERFECT's simple water use (crop factor) modelling platform. PERFECT is a one-dimensional, biophysical model which simulates the plant–soil–water–management dynamics in agricultural systems (Littleboy *et al.*, 1989). As part of this study, the main groundwater and surface water flow processes of the AWNRM Region have been conceptualised (Fig. 6).

The results of the model suggest that rainfall recharge is a relatively insignificant component of the water balance across the AWNRM region (Table 4). Furthermore, the modelled estimates represent the upper bounds of available water resources because the model does not take into account any evapotranspiration, runoff or recharge subsequent to the initial rainfall event.

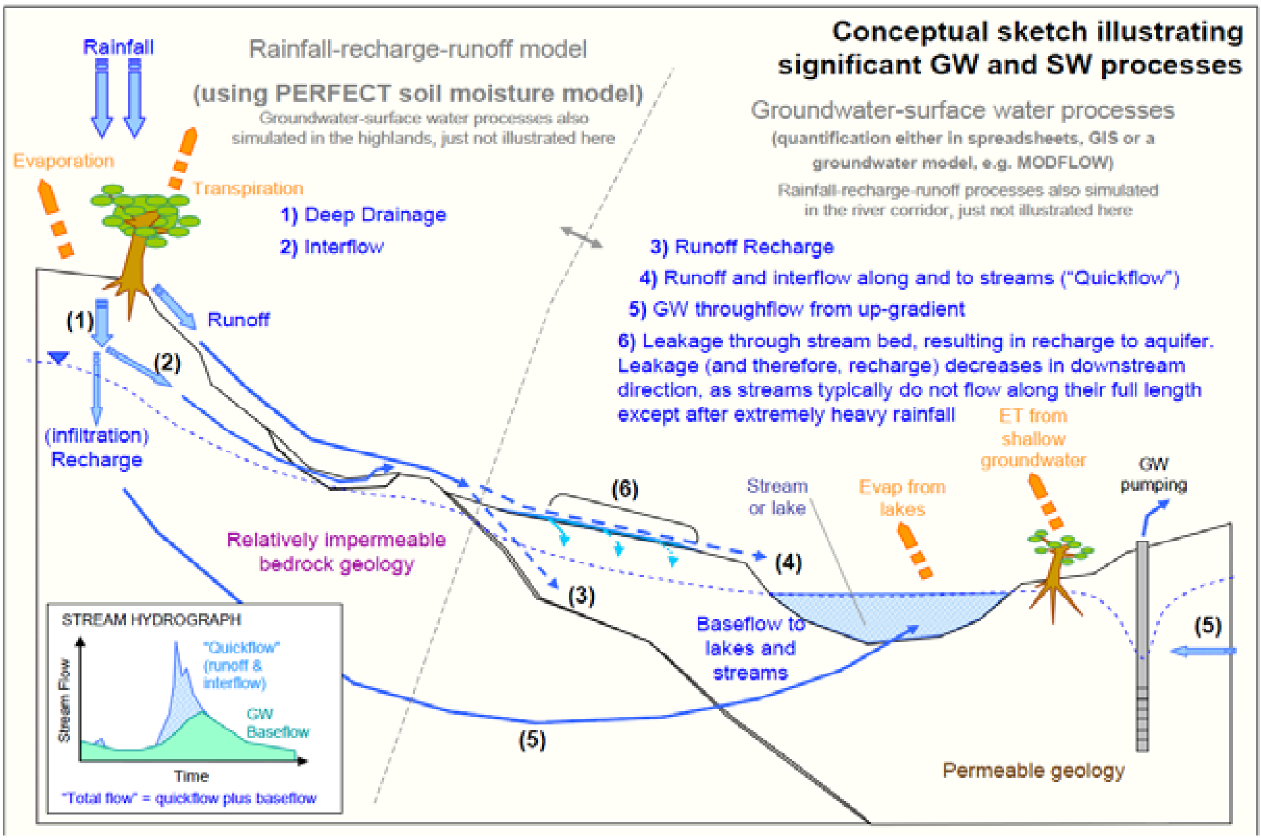


Figure 6. Conceptual model of recharge processes in the AWNRM region (GHD, 2010)

Table 4. PERFECT rainfall–runoff–recharge model results (GHD 2010)

Water balance component	West Central SAAL region (29671 sq.km)	North East, around Ernabella (33077 sq.km)	Catchment to Oak Valley (43712 sq.km)	Catchment to Yalata (15156 sq.km)
Output Period	2000-2008	2000-2008	2000-2008	2000-2008
(INPUT) Rainfall	85.5 mm/a	314.7 mm/a	296 mm/a	346.3 mm/a
(INPUT) Pot. Evap.	3,067	3,067	2,740	2,391.2
Actual ET (soil zone)	81.9	287.3	284.7	335.8
Recharge	0.05	0.6	1.6	0.5
Lateral	0.001	0.2	0.2	0.03
Runoff	6.1	11.1	11.7	9.7
Total modelled yield (before any further ET)	**6.1** mm/a (rech + runoff + lat)	**12** mm/a	**13.5** mm/a	**10.2** mm/a
	~495 ML/d	~1,090 ML/d	~1,610 ML/d	~423 ML/d
'Excess PE'	2,985 mm/a	2,780 mm/a	2,455 mm/a	2,055 mm/a
Gauged yield	**N/A**	**N/A**	**N/A**	**N/A**

Table 5. Previous groundwater recharge assessments of unconfined groundwater systems across the AWNRM region (Watt and Berens, 2011)

Region	Aquifer type(s)	Comment	Period	Reference
Amata	Alluvium and fractured rock	Heavy rainfall in Amata results in long term recharge to the aquifer	1999–2008	AGT 2008/31, in AGT 2010
		Moderate correlation between SWL and climate (DFW pluviometer A0261001); rise in water level (~8 m) after heavy rain in 2001; drop in water level (~5 m) corresponding to low rainfall since 2003	2000–2008	GHD 2010
		It is evident from a continued rise in SWL for a year after a recharge event that recharge occurs both close to the wells and many kilometres away	1995–2002	Dodds & Sampson 2002b
Iwantja (Indulkana)	Fractured sandstone	Weak correlation between SWL and climate (DFW pluviometer A0051002); no apparent response to local rainfall	2000–2008	GHD 2010
		Heavy rainfall results in long-term recharge to aquifer	1999–2008	AGT 2008/31, in AGT 2010
		At IMB-19: recharge to the aquifer is occurring at a point close to the well, if not through the well itself	1998–2002	Dodds & Sampson 2002b
		At IMB-19A: no immediate obvious responses to potential recharge events although the steadily rising SWL probably results primarily from recharge	1998–2002	Dodds & Sampson 2002b
		At IMB-25: rainfall events do not likely have any immediate or dramatic effect on water levels; probably gradual recharge of the aquifer over months and years	1995– 2002	Dodds & Sampson 2002b
		At IMB-27: SWL suggests the well is near a point of recharge for the aquifer, but lacks the probability of direct recharge through the well itself	1998–2002	Dodds & Sampson 2002b

Region	Aquifer type(s)	Comment	Period	Reference
Iwantja (Indulkana)		**At IR-1 & IR–2**: authors uncertain about whether this aquifer is being recharged and, as there are no signs of recharge, they have assumed none	1999-2002	Dodds & Sampson 2002b
Kalka	Alluvium and fractured rock	Heavy rainfall resulted in little to no recharge to the aquifer, but recharge is likely occurring	1999–2008	AGT 2008/31, in AGT 2010
		Weak correlation between SWL and climate (DFW pluviometer A0231004)	2000–2008	GHD 2010
		No recharge can be seen in the SWL data for any well, in this or any of the monitoring periods	1998–2002	Dodds & Sampson 2002b
Kaltjiti (Fregon)	Alluvium and fractured rock	Moderate correlation between SWL and climate (DFW pluviometer A0231002); reasonable correlation of slightly declining groundwater and rainfall trend since mid-2002	2000–2008	GHD 2010
		No relationship between rainfall and recharge of aquifer has been identified	1999–2008	AGT 2008/31, in AGT 2010
		There is no evidence of recharge but nor has the rainfall ever exceeded 50 mm in a day, which appears to be the basic requirement for recharge in the Musgrave Block	1995–2002	Dodds & Sampson 2002b
Mimili	Fractured rock	Weak correlation between SWL and climate (DFW pluviometer A0231003); no apparent response to local rainfall	2000–2008	GHD 2010
		Heavy rainfall results in small short-term recharge to the aquifer	1999–2008	AGT 2008/31, in AGT 2010
		No indication that recharge of the aquifer(s) has taken place	1995–2002	Dodds & Sampson 2002b

Region	Aquifer type(s)	Comment	Period	Reference
Oak Valley	Fractured sandstone	Weak correlation between SWL and climate (DFW pluviometer A0231006); a well located adjacent to the rainfall station shows some correlation with rainfall	2000–2008	GHD 2010
		There appears to be no obvious relationship between rainfall and aquifer recharge	1999–2008	AGT 2008/31, in AGT 2010
		Rainfall figures show little precipitation (<16 mm over 2 hours); not enough to generate recharge	2001–2002	Dodds & Sampson 2002b
Pipalyatjara	Fractured rock	Moderate correlation between SWL and climate (DFW pluviometer A0231004); gradual increase in groundwater levels may be correlated with periodic significant rainfall events	2000–2008	GHD 2010
		Heavy rainfall results in long-term recharge to the aquifer	1999–2008	AGT 2008/31, in AGT 2010
		Exceptionally heavy rains in late November and December 2001 (749 mm); recharge is evident from the rise in SWL in both wells	1997–2002	Dodds & Sampson 2002b
Pukatja (Ernabella)	Alluvium and FRA	Heavy rainfall results in long-term recharge to the aquifer.	1999–2008	AGT 2008/31, in AGT 2010
		Strong correlation between SWL and climate (BoM station 016097); consistent correlation with rise in water level (~5 m) following heavy rainfall in 2001; steady decline in water level corresponding to low rainfall since 2003	2000–2008	GHD 2010
		Rainfall events of Dec 2001 & Feb 2002 had a more dramatic effect on SWL than earlier events (e.g. Feb 2000) of equal magnitude	1995–2002	Dodds & Sampson 2002b

Region	Aquifer type(s)	Comment	Period	Reference
Yalata	Quartz sands	Weak correlation between SWL and climate (SILO station 018106); stable rainfall but declining groundwater trend	2000–2008	GHD 2010
		No rainfall data exists for the Yalata area, so an assessment of recharge is not possible; no indications of recharge in the SWL data	1999–2002	Dodds & Sampson 2002b
Yunyarinyi (Kenmore Park)	Fractured rock	Strong correlation between SWL and climate (DFW pluviometer A0051001); consistent correlation with rise in water level (~5 m) following heavy rainfall in 2001; steady decline in water level corresponding to low rainfall since 2003	2000–2008	GHD 2010
		Rainfall is seen to have no recharge effect on the aquifer	Apr 2007–Nov 2007	AGT 2008/11, in AGT2010
		Heavy rainfall results in long term recharge to the aquifer	1999–2008	AGT 2008/31, in AGT 2010
		Recharge has clearly taken place in the aquifers at all three wells	1995–2002	Dodds & Sampson 2002b

There are a number of assumptions required in the rainfall–runoff–recharge model and the limitations that result have been acknowledged by the authors (GHD, 2010). A paucity of field observations that resulted in omission of model calibration is the principal limitation. The lack of data has also constrained the conceptual understanding of the system. Other model limitations include model domain discretisation (20 x 20 km cell size) and the use of very simple soil, vegetation rooting depth and crop models.

2.7. EVALUATING THE IMPACTS OF CLIMATE CHANGE

Previous DFW ICCWR projects have used daily time step rainfall–runoff–recharge models to assess the impacts of climate change projections on water availability (e.g. Green *et al.*, 2011; Green *et al.*, 2012). However, a rainfall–runoff–recharge modelling approach in the AWNRM Region is considered to be impractical due to a paucity of data and the high level of uncertainty in earlier rainfall–runoff–recharge modelling of this region (GHD, 2010). Consequently, the current study adopts an analysis of climate metrics which are likely to indicate a change in the occurrence of recharge, rather than a rainfall–runoff–recharge modelling approach .

2.7.1. METRICS OF CLIMATE CHANGE IMPACT

Under the effects of climate change, South Australia is likely to be subject to changes in both average annual rainfall amounts and the frequency of extreme weather events, including flooding (Suppiah *et al.*, 2006; CSIRO and BoM, 2007). If the frequency of extreme rainfall events increases, the frequency of episodic recharge events, which are driven by the extreme rainfall events, may also increase.

Measures of the frequency and magnitude of extreme rainfall events are likely to be the most important metrics in projecting changes in recharge due to the impacts of climate change in the AWNRM Region. However, this analysis is valid only where recharge is contemporary with rainfall. In some groundwater systems, the relationship between rainfall and recharge may not be clear (e.g. Oak Valley town water supply aquifers), while water levels in some aquifers may be entirely unresponsive to contemporary rainfall events.

Two rainfall metrics have been selected to provide an indication of the possible impacts of climate change on recharge. The first metric is the change in the magnitude of the first percentile daily rainfall, which is the amount of rainfall that is expected to fall in a day on the wettest days, occurring on only one in every 100 days, on average (i.e. the most intense *daily* rainfall events). Crosbie *et al*. (2012) found that episodic recharge in the Murray-Darling Basin was more strongly related to the change in first percentile rainfall compared to the change in total rainfall. Crosbie *et al*. (2012) also tested the threshold percentile to represent the extreme rainfall events and found that as the threshold was reduced to include more rainfall events, the discriminatory power of the rainfall metric to estimate change in recharge was reduced. As such, a threshold of 1% was found to be appropriate (Crosbie *et al*., 2012).

The occurrence of rainfall events leading to recharge in the AWNRM Region is expected to be less frequent than one in every 100 days, as recharge events occur only once every few years (on average) even in the areas in the AWNRM Region that experience the most frequent events. However, it is difficult to quantify the changes in very rare events such as these, even over a number of decades. Hence, the one in 100 day occurrence has been selected as a trade-off between representing the very rare events, while still having enough events within the data to provide confidence in the results.

The second climate metric is the number of months over a 30-year period that recorded a large amount of rainfall. Stable-isotope chemistry suggests that over the long term, diffuse recharge occurs predominantly after heavy local rainfall events of greater than 100–150 mm/month (Tweed *et* *al.,* 2011). As such, the number of months with rainfall greater than 100mm/month has been identified for each scenario to provide an indication of the expected change in the frequency of recharge events, based on the different GCM projections. The analysis has been based on rainfall totals in a calendar month as the calculation is much more computationally efficient compared to using a metric such as a rolling total of rainfall over a 30-day period. As over 10 000 pixels of daily rainfall have been included in the analysis for each time period, emission scenario and GCM considered, the computation gains using a monthly total were significant. There is the potential to miss recharge events that occur over the end of one month into the next month compared to using a 30-day rolling total, however an initial analysis revealed that the difference between the two approaches was negligible.

For consistency with previous ICCWR studies, changes in average annual rainfall have also been considered. However, average rainfall data provides little insight into the important aspect of rainfall for water resources in the study region, as the monthly average PET is greater than the monthly average rainfall in all months of the year (Fig. 3). Furthermore, there are distinct differences in rainfall patterns between the 'cold steppe' and 'hot desert' climate sub-zones (Sect. 2.2).

3. CLIMATE CHANGE PROJECTIONS

The projections of climate change and their potential impacts on the water resources of the AWNRM Region are presented in this section. A new approach for representing the range of climate change projections has been applied to the region, called the "Climate Futures Framework". This approach identifies the 'most- likely', 'best' and 'worst' case projections for the future and provides a mechanism to select GCMs to represent each of these cases. This is followed by an analysis of the projections from the GCMs selected from the Climate Futures Framework analysis. Downscaling was undertaken to produce region-specific changes in daily rainfall and these are used with the two rainfall metrics in projecting possible changes to the capacity of water resources in the region.

3.1. CLIMATE FUTURES FRAMEWORK

The Climate Futures Framework has been developed to provide a simplified representation of GCM projections, while still addressing uncertainty and maintaining internally consistent combinations of climate variables from the different models (Clarke *et al.*, 2011). In this section, the approach used in the Climate Futures analyses in this study is outlined and then results are presented for a number of locations.

3.1.1. CLIMATE FUTURES FRAMEWORK APPROACH

The Climate Futures Framework approach involves classifying the projected changes in climate by the different GCMs into separate categories (termed Climate Futures) defined by two climate variables – typically, the change in annual mean surface temperature and the change in annual average rainfall are used. Each Climate Future is then assigned a relative likelihood, based on the number of climate models that fall within that category (e.g. Fig. 7) (Clarke *et al*., 2011). The different Climate Future categories can then be used as the basis for further impact assessment.

Clarke *et al*. (2011) define a number of Climate Futures categories, including the 'most-likely', 'best' and 'worst' cases. The 'most-likely' case is defined as the category which satisfies all of three criteria; (1) contains the greatest number of models; (2) contains one third of the total number of models; and (3) the number of models must be at least three greater than the next most populous Climate Future. By this definition, it may in some cases be impossible to describe any one of the projected Climate Futures as 'most likely'. The 'best' and 'worst' case Climate Futures definitions are based on the particular risk assessment being undertaken. For example, in an analysis of Perth's climate, Clarke et al. (2011) defined the 'best' case as the Climate Future that would result in the highest rainfall and smallest temperature increase (i.e. the wettest and coolest climate) and the 'worst' case was defined as the Climate Future that would result in the least rainfall and highest temperature increase (i.e. the driest and hottest climate). These Climate Futures definitions are considered appropriate for the AWNRM region.

Clarke *et al*. (2011) found a strong correlation between change in evapotranspiration and change in mean temperature (0.9 for the Australian region) and as such, it is considered appropriate in the current study to use change in average annual temperature and change in average annual rainfall as the Climate Futures classifying variables. This approach allows all GCMs to be included in the analysis, as all models project changes in temperature, whereas only nine of the 24 models project changes in evapotranspiration. By evaluating both variables concurrently, internal consistency is maintained between the model projections, such that comparisons between the rainfall and temperature changes projected by each GCM are made at the same time. In comparison, the common approach of considering only median, 10^{th} and 90^{th} percentile projections for each variable separately (e.g. CSIRO & BoM, 2007) is likely to be less robust.

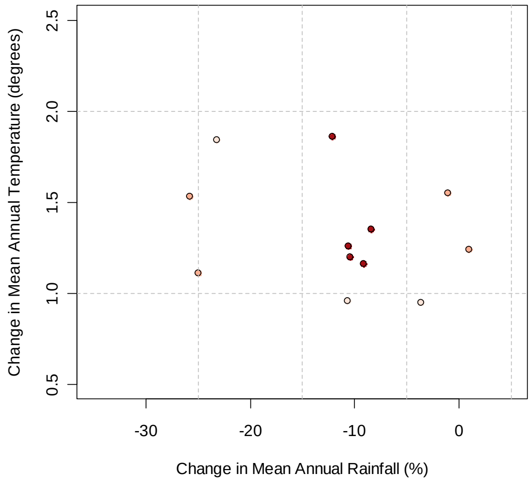
3.1.2. CLIMATE FUTURES FOR AWNRM REGION

Clarke *et al*. (2011) based their Climate Futures analysis on all 24 available GCMs (23 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007) models and the CSIRO Mark 3.5 GCM). However, the authors note that in some regions, some models may be rejected based on a multi-factor analysis of model performance. A multi-factor analysis was undertaken for South Australia by Suppiah *et al*. (2006), who considered the GCM outputs of temperature, rainfall and atmospheric pressure. Demerit points were accrued by models that performed poorly. While an accurate performance when simulating the current climate does not guarantee the same level of accuracy when the same model is applied to future climate projections, the approach taken by Suppiah *et al*. (2006) was to assess if current GCM climate errors were of a nature that significantly reduced the likelihood that the enhanced greenhouse simulation will be reliable. For example, Suppiah *et al*. (2006) found that 12 GCMs omitted key drivers of South Australia's climate system and consequently, the authors rejected these models as they were considered to be unsuitable for generating climate projections within South Australia. The remaining 11 GCMs, as well as the CSIRO Mark 3.5 GCM which was not assessed, have been selected to be used in the Climate Futures analysis for the AWNRM Region. It should also be noted that different metrics of GCM performance will result in different GCMs being identified as suitable for a region, for example another GCM comparison was undertaken by Smith and Chandler (2010) for the Murray-Darling Basin. However, to the authors' knowledge, Suppiah *et al*. (2006) is the only GCM performance analysis specific to South Australia and as such, has been used as the basis for GCM selection.

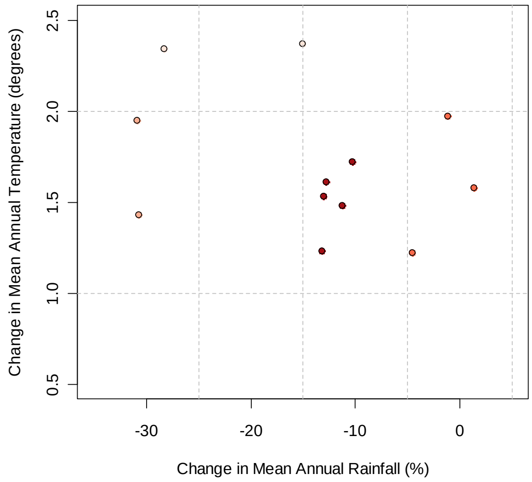
As 13 fewer models are used compared to Clarke *et al*. (2011), the criteria for the 'most-likely' scenario (i.e. containing at least three more GCMs than the next highest Climate Future) is unrealistically high. For the analysis in this study, the criterion for the 'most-likely' case has been reduced to containing at least two more models.

Three study site locations have been selected for the Climate Futures analysis that are representative of the AWNRM Region's different climate and hydrogeological zones. These sites are; (1) Pukatja in the North; (2) Nullarbor toward the south coast; and (3) Maralinga that is located approximately central to the study area (Fig. 1). The time horizon of 2050 has been used and both low (B1) and high (A2) emission scenarios have been investigated. For each of these locations and emission scenarios, projections from each of the 12 GCMs for the variables of (1) change in mean annual temperature (degrees) and (2) change in mean annual rainfall (percentage) were obtained from the OzClim website (CSIRO, 2012). The projected changes were calculated relative to the historic baseline period of 1975–2004.

The projections for temperature and rainfall have been plotted (e.g. Fig. 7), where each point represents a different GCM output and darker red colours are used to represent the more-likely Climate Futures. Regular division of the different Climate Futures categories were adopted, every one degree of change, and every 10% reduction in rainfall, starting from a "no change" category represented by a projected change in average annual rainfall less than ±5%.



Low Emissions



High Emissions

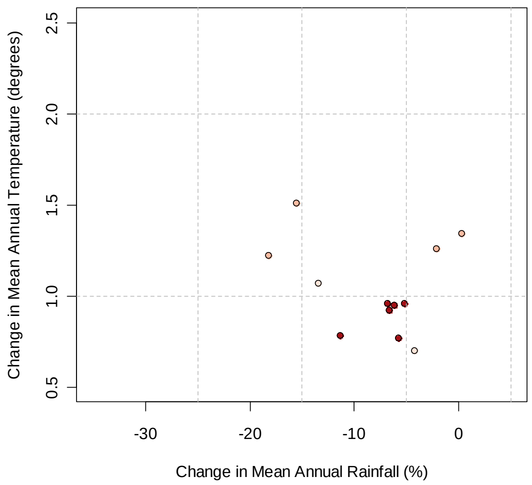
Figure 7. GCM Projections for Pukatja for 2050

Table 6. Climate Future matrix for Pukatja 2050 Low Emissions

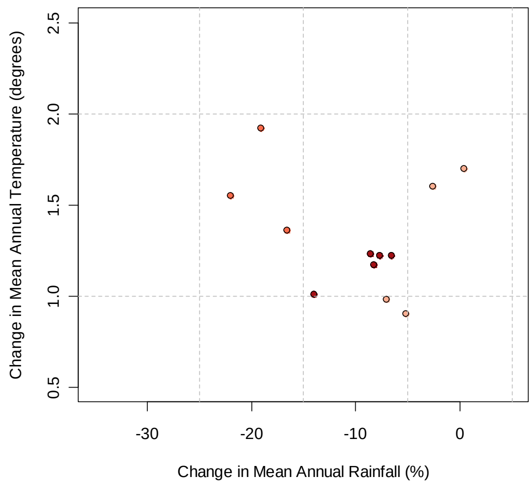
		Mean Annual Temperature (°C)		
		Slightly Warmer	Warmer	Hotter
Annual Rainfall (%)		0.5 to 1	1 to 2	2 to 3
Much Drier	More than -25		2 of 12 models (17%)	
Drier	-15 to -25		1 of 12 models (8%)	
Slightly Drier	-5 to -15	1 of 12 models (8%)	5 of 12 models (42%)	
Little Change	-5 to 5	1 of 12 models (8%)	2 of 12 models (17%)	

Table 7. Climate Future matrix for Pukatja 2050 High Emissions

		Mean Annual Temperature (°C)		
		Slightly Warmer	Warmer	Hotter
Annual Rainfall (%)		0.5 to 1	1 to 2	2 to 3
Much Drier	More than -25		2 of 12 models (17%)	1 of 12 models (8%)
Drier	-15 to -25			1 of 12 models (8%)
Slightly Drier	-5 to -15		5 of 12 models (33%)	
Little Change	-5 to 5		3 of 12 models (25%)	



Low Emissions



High Emissions

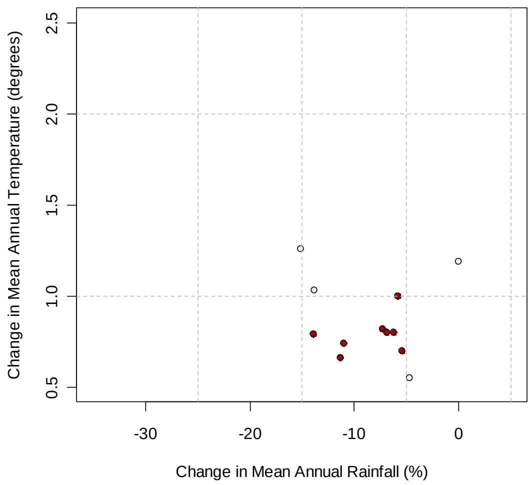
Figure 8. GCM Projections for Maralinga for 2050

Table 8. Climate Future matrix for Maralinga 2050 Low Emissions

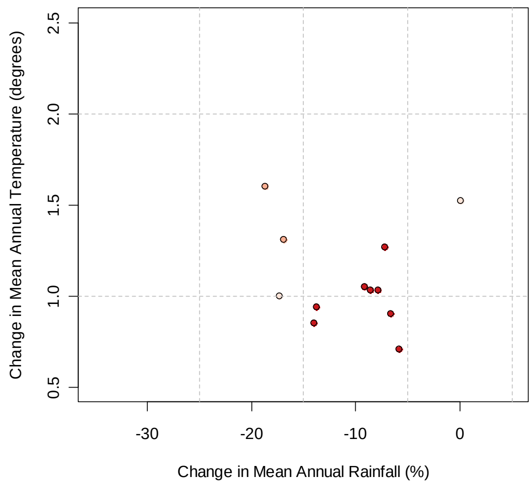
		Mean Annual Temperature (°C)		
		Slightly Warmer	Warmer	Hotter
Annual Rainfall (%)		0.5 to 1	1 to 2	2 to 3
Much Drier	More than -25			
Drier	-15 to -25		2 of 12 models (17%)	
Slightly Drier	-5 to -15	6 of 12 models (50%)	1 of 12 models (8%)	
Little Change	-5 to 5	1 of 12 models (8%)	2 of 12 models (17%)	

Table 9. Climate Future matrix for Maralinga 2050 High Emissions

		Mean Annual Temperature (°C)		
		Slightly Warmer	Warmer	Hotter
Annual Rainfall (%)		0.5 to 1	1 to 2	2 to 3
Much Drier	More than -25			
Drier	-15 to -25		3 of 12 models (25%)	
Slightly Drier	-5 to -15	2 of 12 models (17%)	5 of 12 models (42%)	
Little Change	-5 to 5		2 of 12 models (17%)	



Low Emissions



High Emissions

Figure 9. GCM Projections for Nullarbor for 2050

Table 10. Climate Future matrix for Nullarbor 2050 Low Emissions

		Mean Annual Temperature (°C)		
		Slightly Warmer	Warmer	Hotter
Annual Rainfall (%)		0.5 to 1	1 to 2	2 to 3
Much Drier	More than -25			
Drier	-15 to -25		1 of 12 models (8%)	
Slightly Drier	-5 to -15	8 of 12 models (67%)	1 of 12 models (8%)	
Little Change	-5 to 5	1 of 12 models (8%)	1 of 12 models (8%)	

Table 11. Climate Future matrix for Nullarbor 2050 High Emissions

		Mean Annual Temperature (°C)		
		Slightly Warmer	Warmer	Hotter
Annual Rainfall (%)		0.5 to 1	1 to 2	2 to 3
Much Drier	More than -25			
Drier	-15 to -25	1 of 12 models (8%)	2 of 12 models (17%)	
Slightly Drier	-5 to -15	4 of 12 models (33%)	4 of 12 models (33%)	
Little Change	-5 to 5		1 of 12 models (8%)	

The naming of the different Climate Futures have been included to provide some indication of the impacts of the projections however, the names themselves have been selected subjectively and qualitatively. Projections of (1) less than one degree of warming have been categorised as 'slightly warmer'; (2) between one and two degrees of warming have been defined as 'warmer'; and (3) two degrees of warming or more have been termed 'hotter'. Similarly for the rainfall variable, a projection indicating (1) a change in annual rainfall less than 5% has been termed 'little change'; (2) up to a 15% reduction 'slightly drier'; (3) up to 25% reduction 'drier'; (4) and greater than 25% reduction 'much drier'.

Based on changes to the average annual rainfall and average annual mean daily temperature, the GCMs project that for 2050 the climate is likely to be warmer and drier in the North of the region (based on the projections at Pukatja) (Fig. 7). Moving further south across the region, the magnitude of the projected changes decreases, with the projections for Maralinga classified as slightly drier and slightly warmer for the low emission case and increasing to the warmer category for the high emission case. The remainder of the GCMs can also be seen to fall toward the less extreme categories compared to the changes projected for the north of the region. For Nullarbor in the South of the region, the GCMs representing the 'most likely' case project a slightly drier and slightly warmer climate for 2050 for the low emissions case. For the high emissions case, the four of the eight models that were in the 'most-likely' case can be seen to move across from the slightly warmer climate future to the warmer climate future, while still corresponding to a slightly drier (5 to 15% reduction in rainfall) climate.

An extended Climate Futures analysis, conducted at the same three locations and for high and low-emission scenarios at the time horizon of 2050, but derived from all 24 GCMs (herein termed the '24-GCM analysis') is shown in Appendix A. The inclusion of all 24 models in the 24-GCM analysis do not change the most likely Climate Futures for each location and emission case considered compared to the 12-GCM analysis (i.e. the analysis based on 12 GCMs best suited to South Australian climate projections (Suppiah *et al.* 2006)). The greatest difference is that the 'wettest' GCMs (i.e. those that project a slight increase in average annual rainfall) tend to be absent from the 12-GCM analysis, whilst the driest and hottest GCMs remain in the Climate Futures analysis in both cases.

It is important to acknowledge that the individual GCM results represent one simulation of a possible future climate. The GCMs attempt to simulate the long-term variability in the observed climate and hence another simulation may produce different periods of wet and dry climates, potentially influencing the exact values used to represent the magnitude of change projected. In order to reduce the influence of the simulated future climatic variability, the projections provided on the OzClim website are derived from a relationship between each variable (temperature and rainfall in this case) and the global change in temperature projected, to smooth out the impact of this variability on the regional projections produced.

3.2. CLIMATE CHANGE PROJECTIONS FOR AWNRM REGION

The Climate Futures Framework analysis has been used to select three GCMs that represent the (1) 'best'; (2) 'worst'; and (3) 'most likely' cases of the future climate for both low and high-emission scenarios. The projections from these three GCMs have been downscaled to provide daily-time-step rainfall for the whole AWNRM region. The downscaled rainfall data have then been used in an analysis of climate metrics (Sect. 2.7.1) that provide an indication of the possible impacts of climate change on groundwater recharge and possible subsequent changes in the capacity of groundwater resources in the region.

3.2.1. SELECTION OF GLOBAL CLIMATE MODELS

Results of the Climate Futures Framework presented in the previous section provides an overview of the range of current projections for the AWNRM region, based on the suitable GCMs identified by Suppiah *et al*. (2006). To select a range of GCMs to infer the range of projected changes in water resources, the change in rainfall has been identified as the variable of interest. For this region with high PET and low rainfall it is likely that the change in temperature (and in turn evapotranspiration) will have little influence on the change in recharge, as PET is already in the order of 10 times greater than the rainfall.

It is not necessarily the case that the change in the average annual rainfall will be related to the change in the rainfall metrics selected to be important for recharge events (i.e. the change in the first percentile daily rainfall and the change in the number of months with more than 100 mm of rainfall). A subset of GCMs has been selected in order to reduce the amount of downscaling required, as it is a time consuming procedure. Changes in average annual rainfall are readily available from the OzClim website (CSIRO, 2012), however changes in the rainfall metrics of interest first require each GCM to be downscaled at the daily time step to the NRM region. Hence, it is not possible to select GCMs to be downscaled based on the important rainfall metrics identified without first downscaling the projections. Therefore, the selection process has been based on the available changes in average annual rainfall and it is acknowledged that these values may not directly relate to the rainfall metrics that are important to episodic recharge.

The Climate Future Framework analysis showed that the CSIRO Mark 3.5 GCM was generally found to lie within the ‘worst’ case category (i.e. the top left of the Climate Future plots (Figs 7–9), or top right cell of the tables (Tables 6–11)). The only exception to this was the Pukatja low-emission case, where the two GFDL (Geophysical Fluid Dynamics Laboratory) GCMs projected a slightly larger reduction in rainfall compared to the CSIRO Mark 3.5 GCM (Fig. 7). However, the difference is only small and as such, the CSIRO Mark 3.5 GCM has been selected to represent the ‘worst’ case climate future.

For the ‘best’ case climate future, the BCCR (Bjerknes Centre for Climate Research) GCM was often located toward the bottom right of the Climate Future plots, or the ‘best’ case box of the tables, along with the ECHAM5 (Max Planck Institute for Meteorology) GCM and the MIROC-H (Centre for Climate Research) GCM. Across the six scenarios considered, the BCCR GCM was present in the ‘best’ case climate future when considering the projected change in rainfall in all but one of these cases and as such, has been selected to represent the ‘best’ case.

Within the ‘most-likely’ GCMs, the LASG-IAP (Institute of Atmospheric Physics), HADGEM1 (Hadley Centre for Climate Prediction and Research) and NCAR-CCSM3 (National Center for Atmospheric Research) GCMs were always present for all locations and emission scenarios. The HADGEM1 GCM does not generate daily rainfall outputs and as such, cannot be used with the downscaling methodology in this study. The NCAR-CCSM3 GCM has been selected to provide a representation of the ‘most-likely’ case over the LASG-IAP GCM, as it provides daily projections for the whole future period from 2000–2100, whereas the LASG-IAP GCM provides daily projections for the future periods 2046–65 and 2081–2100 only.

3.2.2. DOWNSCALING METHODOLOGY

The daily scaling approach used for all previous ICCWR projects (Gibbs *et al.,* 2011) has also been used in this study. This approach adopts different scaling amounts for different seasons and for different rainfall percentiles and as such, provides a mechanism to demonstrate the difference between the projected changes in the mean rainfall, as well as the first percentile rainfall. However, as it is based on scaling observed data, the sequence of days during which rainfall occurs does not change for the future projection cases, only the amount of rainfall changes. It has been assumed that this will not have a large impact on the modelling results. More sophisticated downscaling approaches, such as the Non-homogenous Hidden Markov Models (NHMMs) currently being developed as part of the Goyder Institute Climate Change Project, would be required to consider temporal changes in the rainfall pattern for a future climate.

The daily-scaling approach adopted here requires projections of daily rainfall from the GCMs to calculate the different adjustment factors for the different rainfall percentiles (Gibbs *et al.,* 2011). The NCAR-CCSM3 and CSIRO Mark 3.5 GCMs provide daily rainfall projections for the whole 1961–2100 period (and in some cases runs earlier than 1961), whereas the BCCR GCM only provides daily rainfall projections for the future periods 2046–65 and 2081–2100, as well as the 1961–2000 historic period. In order to use the BCCR GCM for this study, the change in rainfall distribution for each season comparing the 1970–99 and 2046–65 periods of GCM data has been used to generate rainfall distributions for both the 2030 and 2050 projections reported later in this section. As the total for each 5% percentile range in rainfall are compared, the 20 and 30-year periods can be compared to each other. The adjustments were then scaled to ensure that the average rainfall change for the time horizon and season corresponds to the seasonal change projections provided by OzClim (CSIRO, 2012) for 2030 and again for 2050. Similarly, the change in rainfall distribution between the 1970–99 and the 2081–2100 BCCR GCM projections was used for the 2070 projections, again with the adjustment factors scaled to ensure the overall changes in rainfall resulting from the downscaling process correspond to the seasonal change projections provided by OzClim for 2070. Further details on the downscaling approach can be found in Gibbs *et al*. (2011).To provide a representation of the projected changes in the selected rainfall metrics for the AWNRM Region, the downscaling method has been applied to the whole region. The Australia-wide SILO gridded daily rainfall product (Jeffrey *et al*., 2001) has been used as the historical rainfall input for the basis of the downscaling method. The data is provided as a grid of 0.05° by 0.05° grid cells (approximately 5 km by 5 km) for each day. For each cell in the AWNRM region, data for the period 1975–2004 has been used as the historic baseline period for the daily-scaling approach and the resulting annual average rainfall, first percentile rainfall and number of months with greater than 100mm rainfall, as this is the baseline period used to determine the OzClim seasonal percentage changes in rainfall adopted. Baseline data has been calculated for each cell. This process has been undertaken for the time horizons of 2030, 2050 and 2070 and for a high (A2) and low (B1) emission cases, as described in Nakicenovic and Swart (2000). The resulting changes in each rainfall metric, for each future scenario considered, are presented in the following section.

3.2.3. PROJECTED CHANGES IN RAINFALL METRICS

In this section, the ‘best’ case refers to the projections provided by the BCCR GCM, the ‘most-likely’ case to the NCAR CCSM3 GCM projections and ‘worst’ case to the projections provided by the CSIRO Mark 3.5 GCM. The low-emissions scenario corresponds to the B1 emissions case and the high-emissions scenario to the A2 emission case. The resulting projections for each time horizon and emissions case have been averaged across the whole AWNRM region (Table 12). In general, across the three metrics, the descriptions given to the climate scenarios are reflected by the percentage changes calculated, with the ‘best’ case GCM producing the smallest changes, while the ‘most-likely’ GCM and then the ‘worst’ case GCM producing successively larger changes. The high-emission scenario also results in greater reductions in each rainfall metric when compared to the corresponding low-emission scenario. This is especially true of average annual rainfall, which was considered along with temperature change in the process of GCM selection.

The reduction in the first percentile rainfall is less than the corresponding reduction in the average annual rainfall for 12 of the 18 combinations. This result suggests a likely increase in the more extreme events relative to the overall average, even though both metrics indicate reductions in rainfall relative to the historical case. However, in all cases, the reduction in the number of months with greater than 100 mm rainfall (as a percentage) is greater than the reduction in the annual average rainfall, for the corresponding scenario.

In the remainder of this section, the results that have been averaged over the whole AWNRM Region are investigated further by evaluating their spatial distribution.

Table 12. Change in rainfall metrics—expressed as a percentage compared to the 1990 historic baseline case—averaged across the AWNRM Region

Case	Emissions	Change in Annual Average Rainfall (%)			Change in 1st Percentile Daily Rainfall (%)			Change in Number of Months > 100mm Rainfall (%)		
		2030	2050	2070	2030	2050	2070	2030	2050	2070
Best	Low	-4	-7	-9	-4	-6	-7	-10	-14	-16
Best	High	-5	-8	-12	-7	-10	-8	-14	-19	-20
Most Likely	Low	-5	-8	-10	-6	-4	-5	-15	-14	-19
Most Likely	High	-5	-10	-14	-11	-14	-12	-26	-39	-34
Worst	Low	-13	-19	-24	-5	-5	-6	-23	-28	-30
Worst	High	-14	-24	-33	0	-8	-16	-15	-32	-42

'Best' case = BCCR GCM; 'most-likely' case = NCAR CCSM3 GCM; 'worst' case = CSIRO Mark 3.5 GCM; low-emissions scenario = SRES B1; high-emissions scenario = SRES A2

3.2.3.1. Average Annual Rainfall

In the Yalata area, projected reductions in average annual rainfall are likely to have a greater impact on the groundwater resources than changes indicated by the other two rainfall metrics. This is because rainfall is winter dominant and less episodic toward the southern, coastal fringe of the AWNRM Region (e.g. Nullarbor (Fig. 4a)). Additionally, the geology in the Yalata area is predominantly limestone-dominated, karstic terrain of the Nullabor Plain with a thin veneer of Quaternary sediments (Fig. 2), similar to climatic and geologic features in the Eyre Peninsula NRM Region.

The ICCWR project has previously undertaken detailed hydrologic modelling to determine the potential impact of climate change on the prescribed groundwater resources of the Eyre Peninsula NRM Region (Green *et al.*, 2012), much of which has similar geology and climate to the Yalata area. Results of numerical modelling in the Musgrave Prescribed Wells Area in the Eyre Peninsula indicate that reductions in groundwater recharge resulting from median climate scenarios projected by CSIRO and BoM (2007) range from 12% for a 2030 climate (median 3.5% reduction in annual rainfall with a high, medium or low-emissions scenario) to 49% in a 2070 climate (median 15% reduction in annual rainfall with a medium or high-emissions scenario). A median 7.5% reduction in annual rainfall (which is of a similar magnitude to the 6.9% reduction projected for the Yalata region) in a 2050 climate resulted in a projected 26% reduction in groundwater recharge.

Importantly, recharge to Yalata's town water supply aquifer appears to be non-local. The recharge zone for these wells may be tens to hundreds of kilometres distant (Sect. 2.5.3) and consequently, changes to recharge may take hundreds of years to impact upon Yalata's groundwater storages. However, confirmation of the location of the recharge zone would be required, in addition to a numerical groundwater flow model of the region, to estimate the timescale of this flow path.

There is a general trend for larger reductions in rainfall for the north of the region compared to the south for the majority of the projections (Figs 12–15), however this relationship is somewhat less pronounced for the 'best' case projections (Figs 10 and 11). Even when considering the 'best' case for 2030 with a low-emissions scenario (Fig. 10), reductions in average annual rainfall across the whole region are projected. The projected reductions in average annual rainfall for this scenario range from 2.8% toward the east, up to 6.9% toward the south. For the same time horizon and GCM, the pattern of projected change is similar when comparing low and high-emission scenarios, although the projected change is slightly greater for the high-emission case.

3.2.3.2. First percentile rainfall

The projected change in first percentile rainfall (Sect. 2.7.1) is generally less than the projected change in the average annual rainfall for a given future scenario (Figs 10–15) because for South Australia, many GCMs project an increase in the magnitude of extreme events while also projecting a reduction in mean annual rainfall. For all cases, there are some cells showing projected increases in the first percentile rainfall from one time horizon to the next (light-blue shading). The majority of the increases in the first percentile rainfall are projected to occur in the southern half of the region, whereas only reductions are projected to occur in the northern part of the AWNRM region, for almost all cases considered.

There is a consistent trend where, for each pixel in each scenario, the average annual rainfall is projected to reduce by a larger amount as time horizons further into the future are considered. However, this is not always true for the first percentile rainfall results. In some parts of the region, the first percentile rainfall can be seen to increase (or be projected to reduce by a smaller percentage compared to the historical case) from one time horizon to the next. In all but one scenario, there are at least some of the approximately 10 000 cells that show an increase in first percentile rainfall from one time horizon to the next. However, the number of cells that indicate an increase in first percentile rainfall are few.

The first percentile data show:

- For the ‘most-likely’ case, projections under the low-emission scenario (Fig. 12) indicate that the magnitude of first percentile rainfall will decrease by up 15% by 2070. Under a high-emissions scenario (Fig. 13), the reduction in the magnitude of first percentile rainfall is more pronounced toward the north of the study area in 2050 and 2070, reducing by up to around 30%.
- For the ‘best’ case, decreases in the magnitude of first percentile rainfall are relatively uniform over the region for both low and high-emissions scenarios. Projections under the low-emission scenario (Fig. 10) indicate that the magnitude of first percentile rainfall will decrease by around 5% by 2030 and by around 10% by 2070. Under a high-emissions scenario (Fig. 11), the magnitude of first percentile rainfall will decrease by around 5% by 2030 and by around 10% by 2050–70.
- For the ‘worst’ case, decreases in the magnitude of first percentile rainfall are most pronounced in the north of the region. Projections under the low-emission scenario (Fig. 14) indicate that the magnitude of first percentile rainfall will increase by around 0–5% central to the study area by 2050–70 and also in the south across all time horizons, but decrease in the north by around 10% by 2030 and by around 25–30% by 2070. Under a high-emissions scenario (Fig. 15), by 2030 the magnitude of first percentile rainfall will increase by around 0–5% both near the centre of the study area and to the south and decrease by around 5–10% toward the north. Some increases in the magnitude of first percentile rainfall are still projected at 2070, however decreases in the north are projected to be in the range 30–40%.

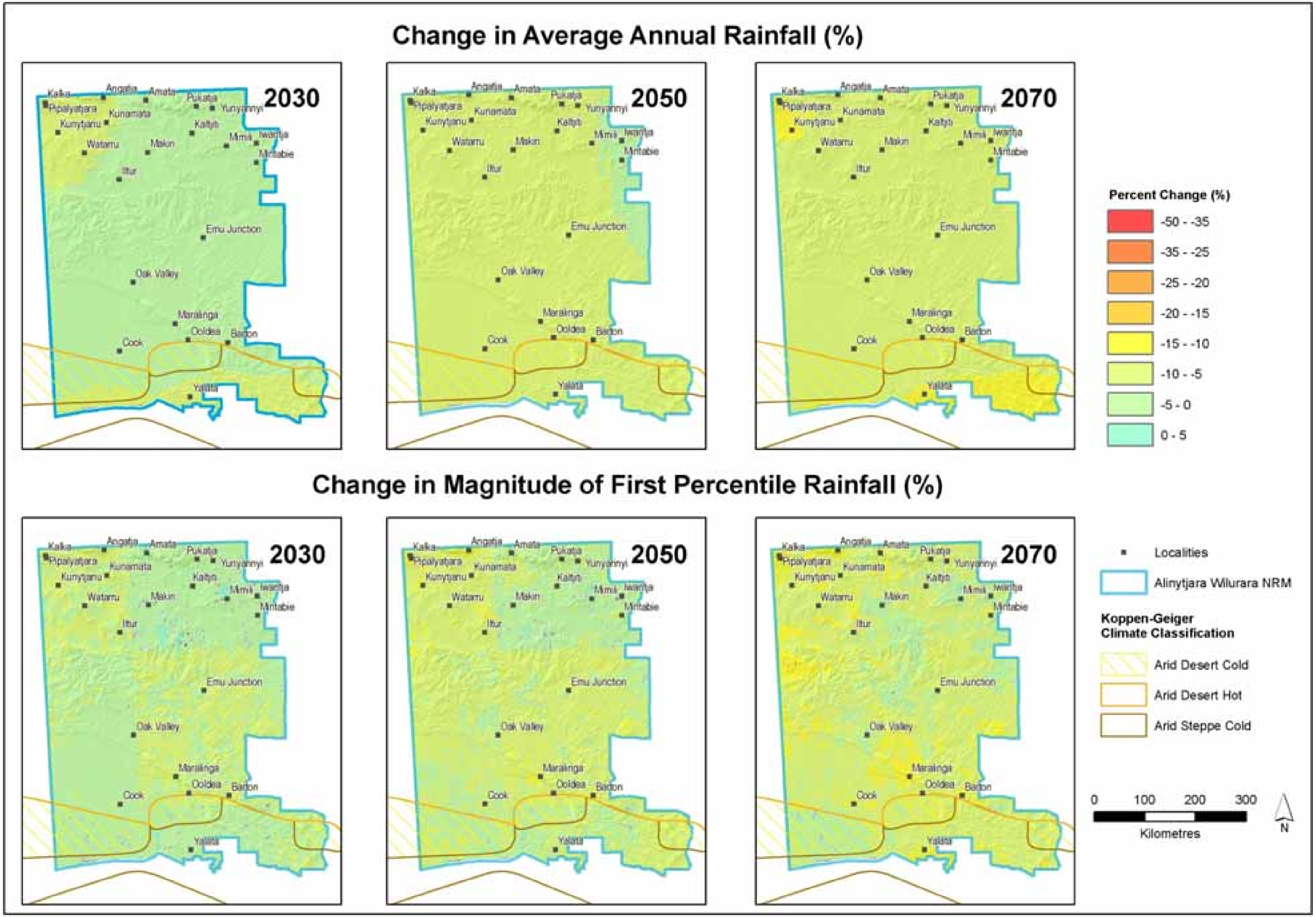


Figure 10. Change in average annual and first percentile rainfall for the 'best' case projections (BCCR GCM) and low emissions

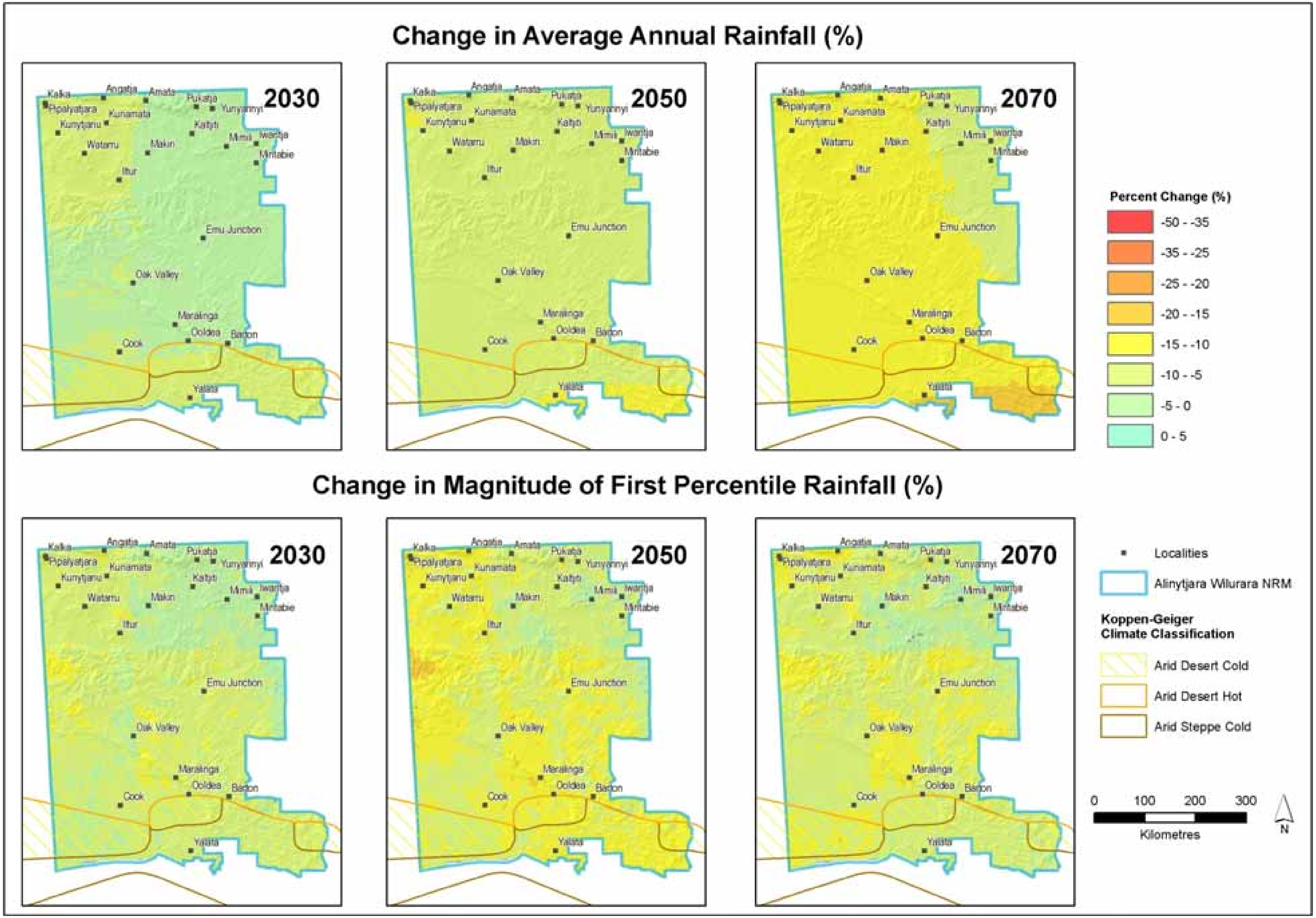


Figure 11. Change in average annual and first percentile rainfall for the 'best' case projections (BCCR GCM) and high emissions

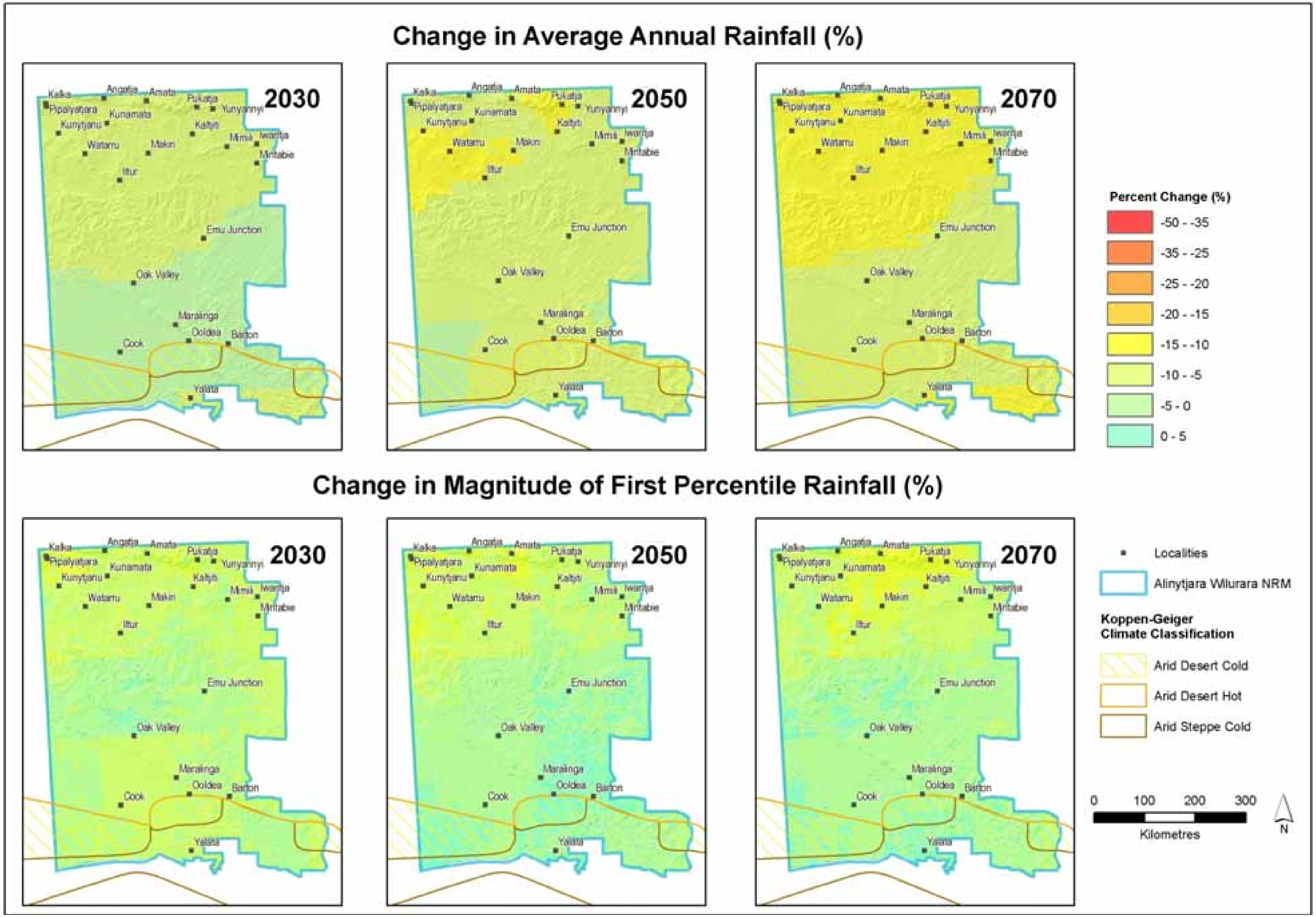


Figure 12. Change in average annual and first percentile rainfall for the 'most likely' projections (NCAR-CCSM3) and low emissions

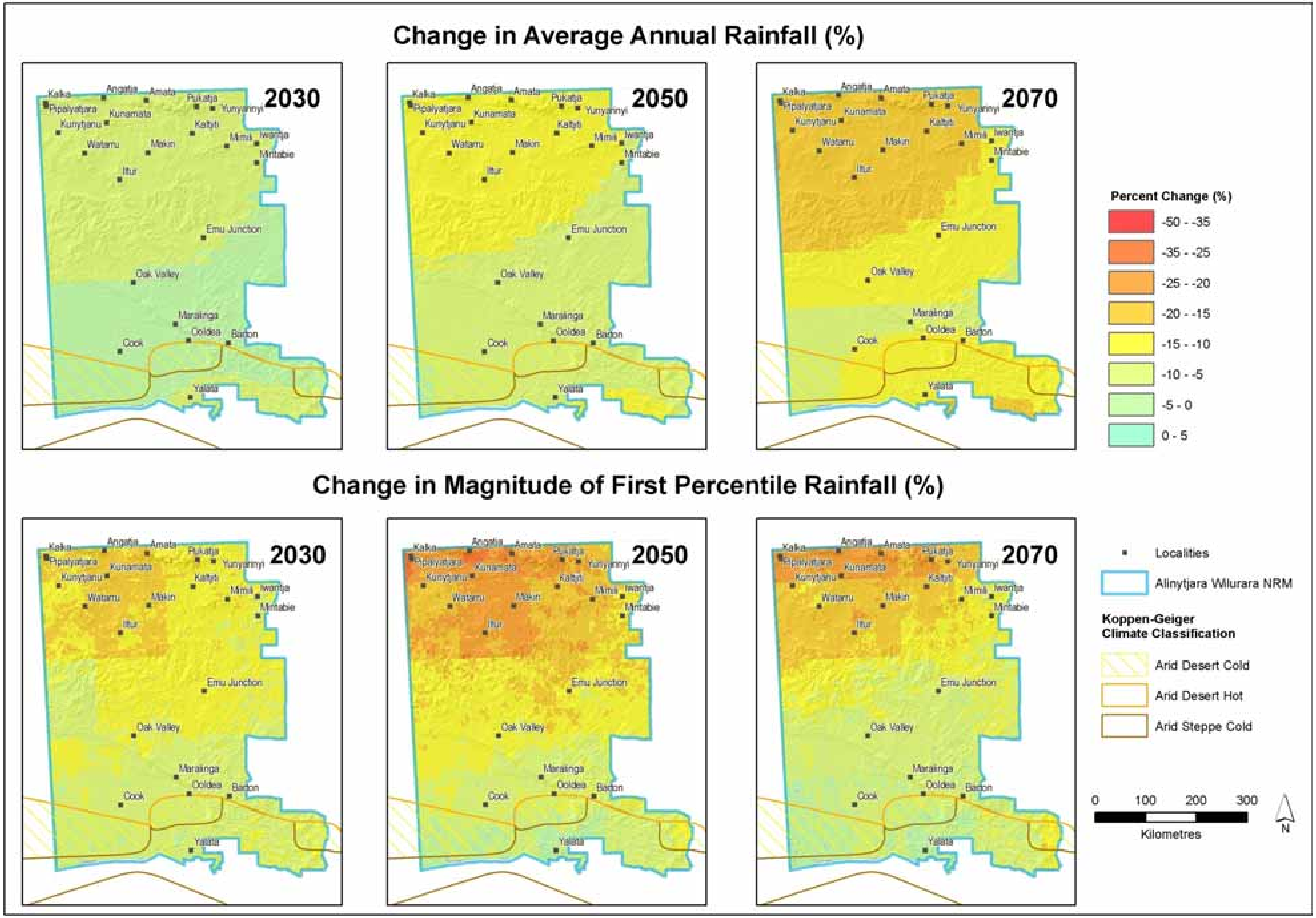


Figure 13. Change in average annual and first percentile rainfall for the 'most likely' projections (NCAR-CCSM3) and high emissions

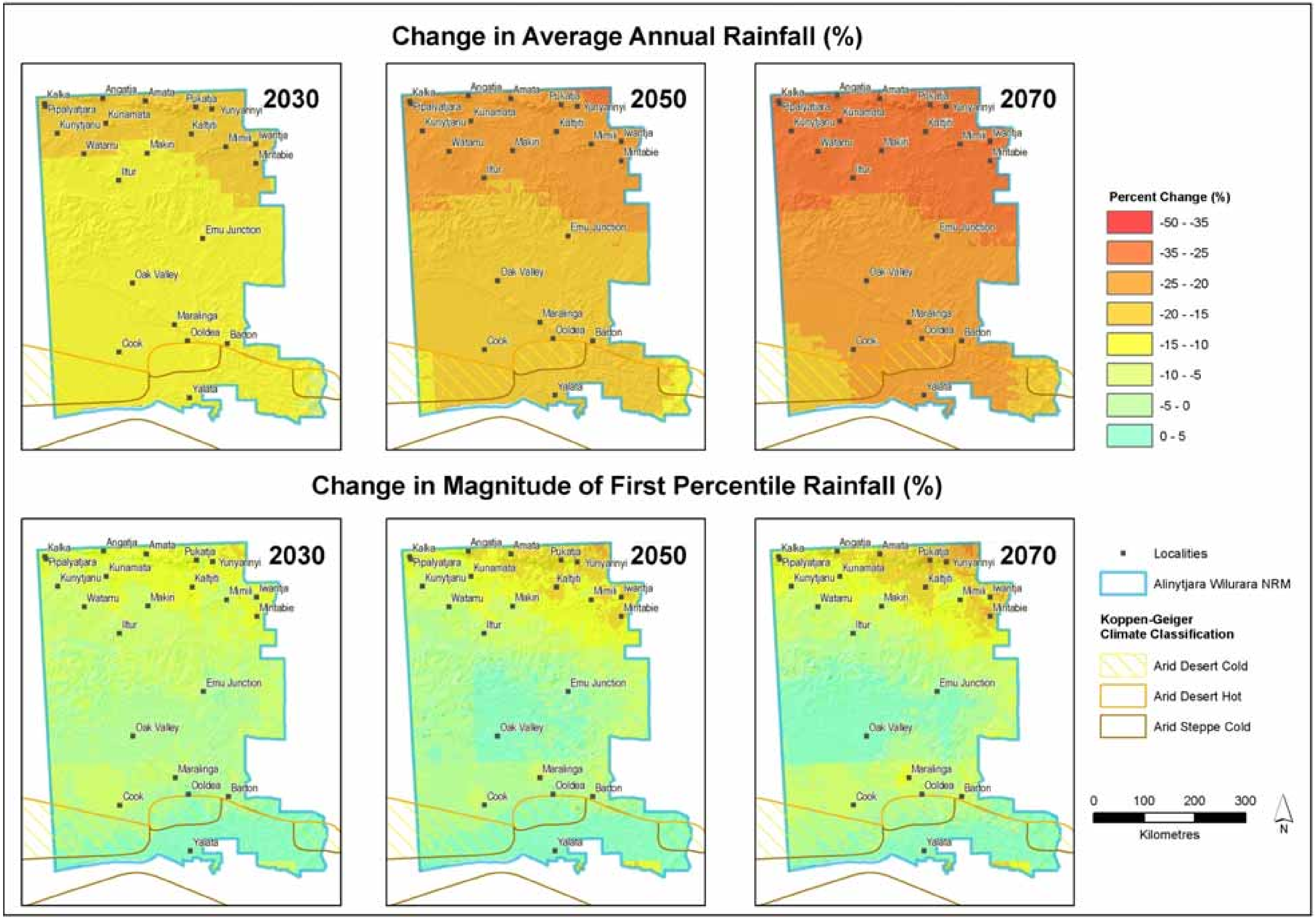


Figure 14. Change in average annual and first percentile rainfall for the ‘worst’ case projections (CSIRO Mark 3.5) and low emissions

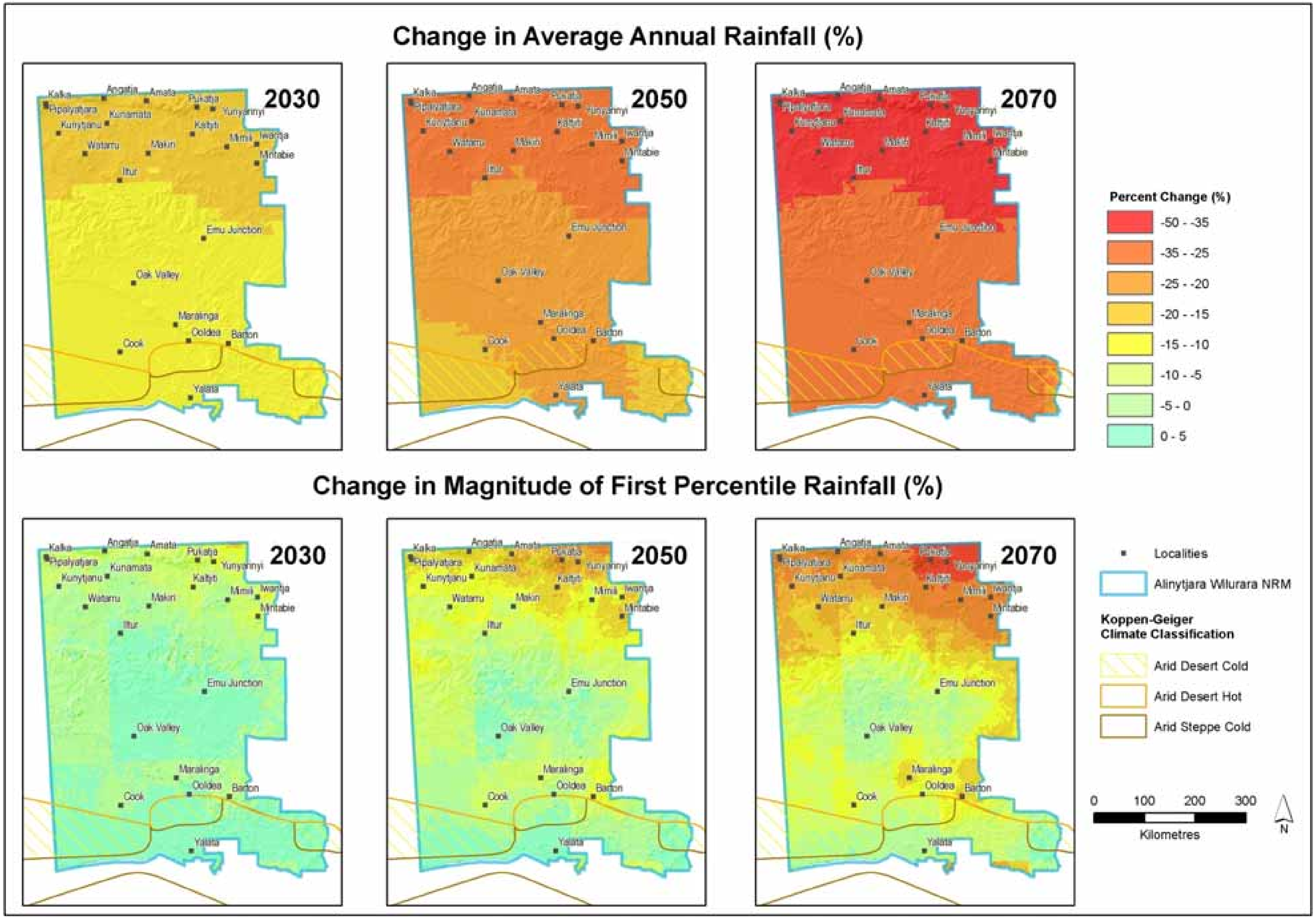


Figure 15. Change in average annual and first percentile rainfall for the 'worst' case projections (CSIRO Mark 3.5) and high emissions

3.2.3.3. Number of Months with Rainfall Greater Than 100 mm

Recharge in the 'hot desert' climate sub-zone is likely to be governed by localised and indirect recharge resulting from extreme rainfall events rather than diffuse recharge (de Vries & Simmers, 2002). Figures 16 through 21 show the projected frequency of extreme rainfall events (greater than 100 mm/month) and the percentage changes in this frequency under a range of future climate scenarios compared to the 1990 historic baseline period. Historically, the occurrences of summer-dominant recharge events in the 'hot desert' climate sub-zone are most frequent in the north, while the southern-half of the climate sub-zone experiences not more than one recharge event every 10 years, on average. The number of months that had a total rainfall greater than 100 mm over the period 1970–99 has been calculated and presented as the average number of years between recharge events (where recharge events are defined as any month with rainfall greater than 100 mm) in the top left map. Most of the southern region recorded less than one event every 9 or more years (Fig. 16) and as such, the projected changes in the frequency of extreme rainfall events are expected to have a minor impact on the sustainability of local groundwater resources for this area.

The greatest change in the frequency of extreme rainfall events are projected to occur in the north of the 'hot desert' climate sub-zone. This corresponds to the part of the region that is most susceptible to changes in climate. The cause of the small patch of more frequent recharge events toward the south-east is unclear, but may be a function of the limited field data or the interpolation method used by the Department of Environment and Resources Management (Queensland) (Jeffrey, 2001) to produce the gridded rainfall datasets.

For most of the region, it is difficult to present the change in number of months with rainfall greater than 100 mm/month in percentage terms, as the change in a small number of events can lead to a misleadingly high percentage change. For example, a reduction in the number of events from two in the 1990 historic baseline period to one event for a future projection scenario represents a 50% reduction. But these occurrences are highly uncertain, given that there was only one or two events over a 30-year period, whereas a different 30-year period (or a longer period) may produce a different result. In order to provide a better representation of the percentage changes to the frequency of recharge events, adjacent cells have been aggregated from 0.05° grid cells to 0.25° grid cells in order to 'smooth' the changes across the landscape. Also, the maximum percentage change (Figs 16–21) has been limited to ±50%. Whilst it is acknowledged that there are cells with projected changes in the number of recharge events greater than ±50%, these cells represent a small proportion of the region and generally occur for cases where the number of recharge events is very low. Hence, the scale has been limited to ±50% to allow clearer detail in the smaller percentage changes that occur in the north of the region. This northern region is where the impacts of changes in the high-rainfall months is likely to be of the greatest consequence, due to the nature of recharge processes in arid areas (Sect. 2.4). Consequently, the northern region has been further investigated as a subset of the whole study area.

For the purposes of this analysis, the northern region is considered to be the northern-most third of the AWNRM Region lying north of 28°S latitude parallel (Fig. 4). The change in the number of months with rainfall greater than 100 mm, compared to the 1990 historic baseline period, has been projected for each Climate Futures case and emissions scenario (Table 13). Also, the projected change in the number of months with rainfall greater than 100 mm for the whole region has been reproduced in Table 13 for comparison with the northern region. The reductions projected for the northern region are larger than for the whole region in all but two cases; (1) at 2050 with the 'most-likely' case and high-emission scenario, the reductions are projected to be 38% and 39% for the northern region and whole region, respectively; and (2) at 2070 with the 'worst' case and low-emissions scenario, the reductions are projected to be 39% and 42% for the northern region and whole region, respectively.

Table 13. Change in the frequency of months with rainfall greater than 100 mm, expressed as a percentage compared to 1990 historic baseline conditions

Case	Emissions	Change in frequency of months with rainfall >100 mm (%)					
		Above 28°S Latitude			Whole AWNRM Region		
		2030	2050	2070	2030	2050	2070
Best	Low	-14	-17	-19	-10	-14	-16
Best	High	-16	-20	-21	-14	-19	-20
Most Likely	Low	-22	-23	-27	-15	-14	-19
Most Likely	High	-28	-38	-38	-26	-39	-34
Worst	Low	-28	-33	-35	-23	-28	-30
Worst	High	-24	-34	-39	-15	-32	-42

While an increase in the number of months with rainfall greater than 100 mm is projected for some cells, the majority of these cells occur in the southern half of the region where a very low frequency of these events occur. As such, these increases are unlikely to result in a marked increased capacity of water resources in this region. In contrast, there is largely a reduction in the number of recharge events projected for the northern region, where high-rainfall events historically occur every few years. Further, the percentage reduction in the frequency of events is greater than the corresponding percentage reduction in the average annual rainfall at the same location.

This result is consistent with the findings for other regions studied by the ICCWR project to date, where the projected reductions in runoff and recharge are greater than the corresponding changes in rainfall. For example, in the Northern and Yorke and Eyre Peninsula NRM Regions, runoff and recharge modelling suggests that a 1% reduction in rainfall generally results in a 2% to 4% reduction in runoff or recharge (Green *et al.*, 2011, *Green et al*. 2012). In the current study, the reduction in the number of months with rainfall greater than 100 mm (i.e. frequency of episodic recharge events) is approximately 2.2 times greater than the reduction in average annual rainfall, on average across all time horizons, GCMs and emissions scenarios.

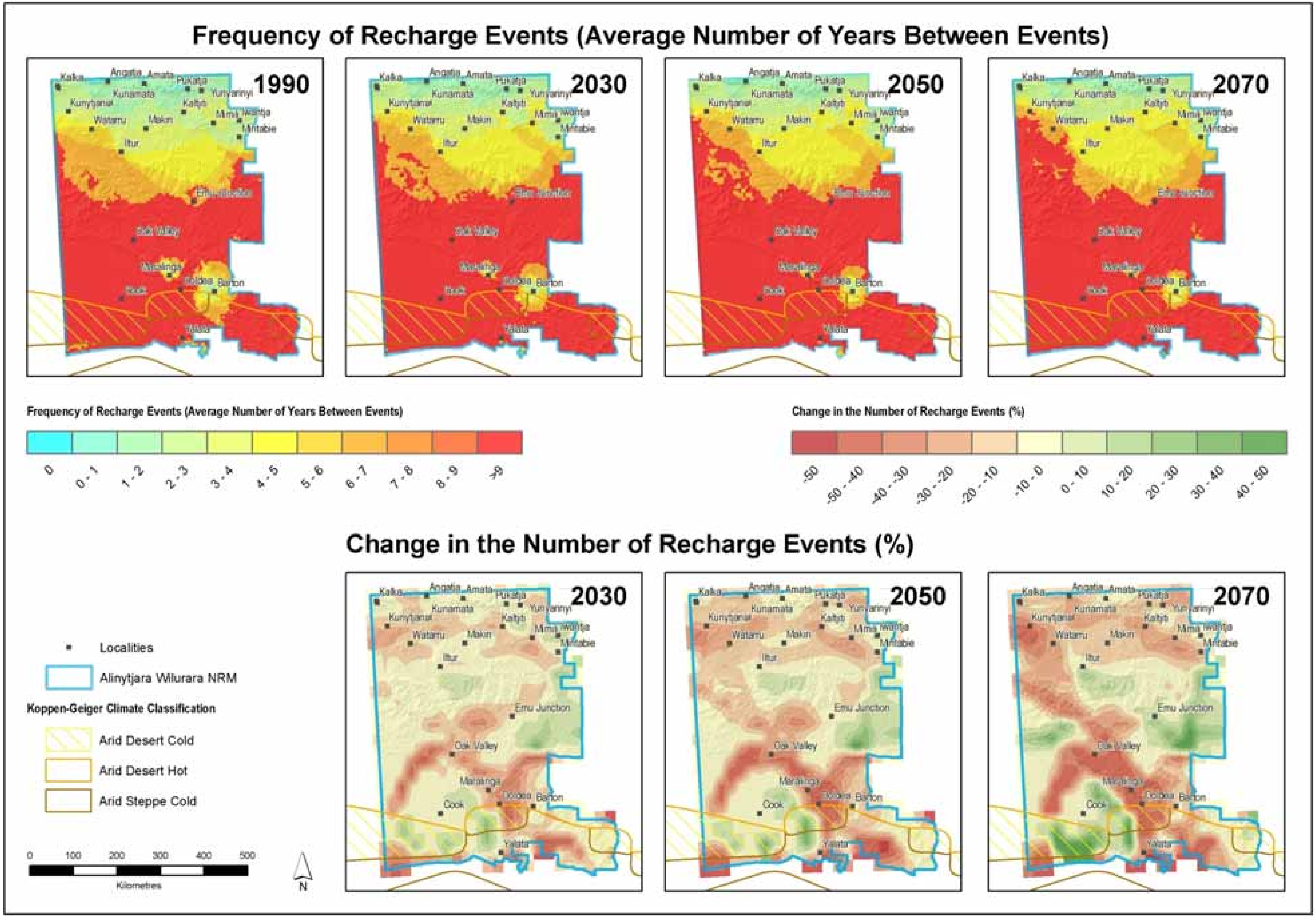


Figure 16. Change in the frequency of recharge events, and the number of events as a percentage, for the 'best' case projections with low emissions.

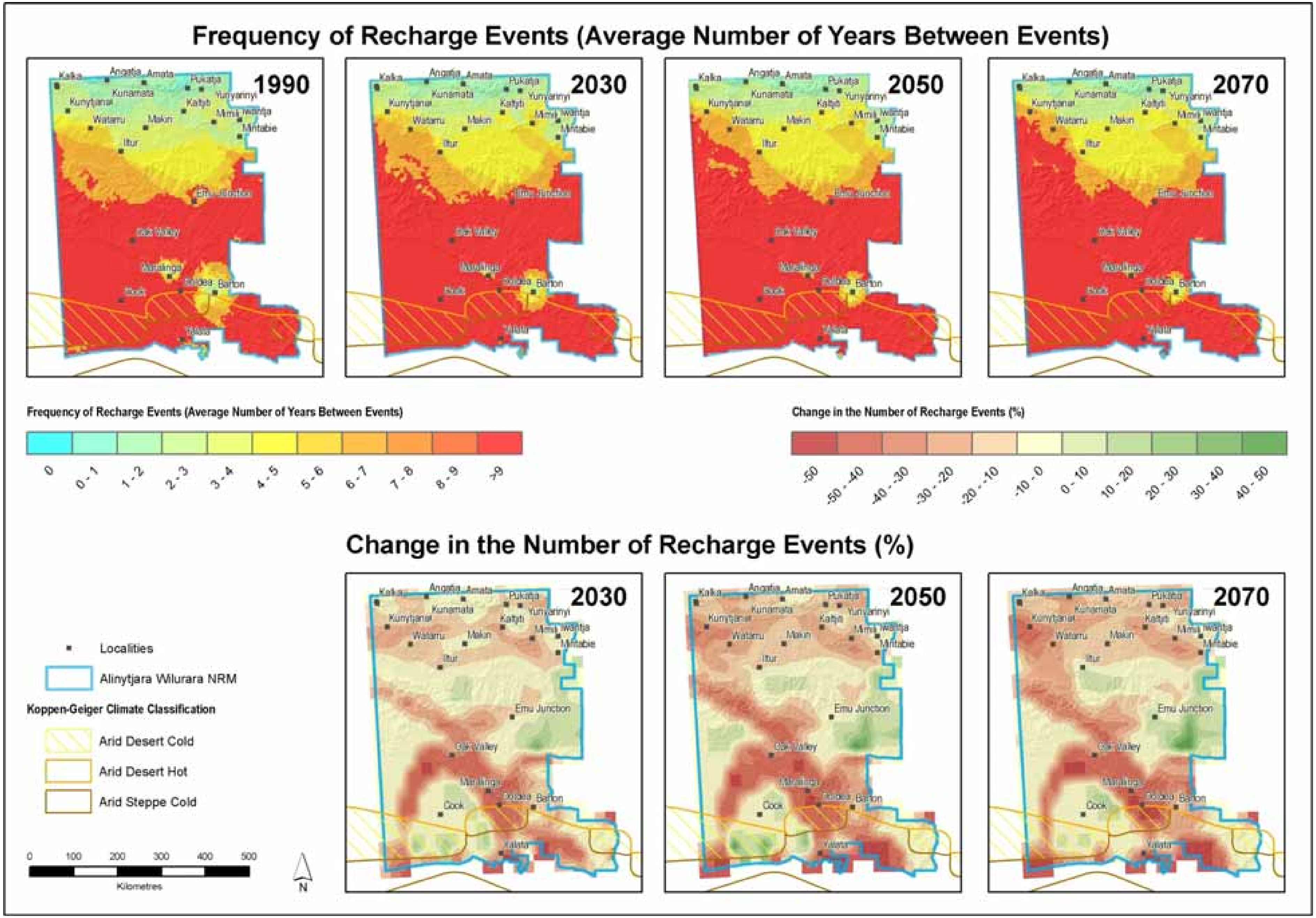


Figure 17. Change in the frequency of recharge events, and the number of events as a percentage, for the 'best' case projections with high emissions

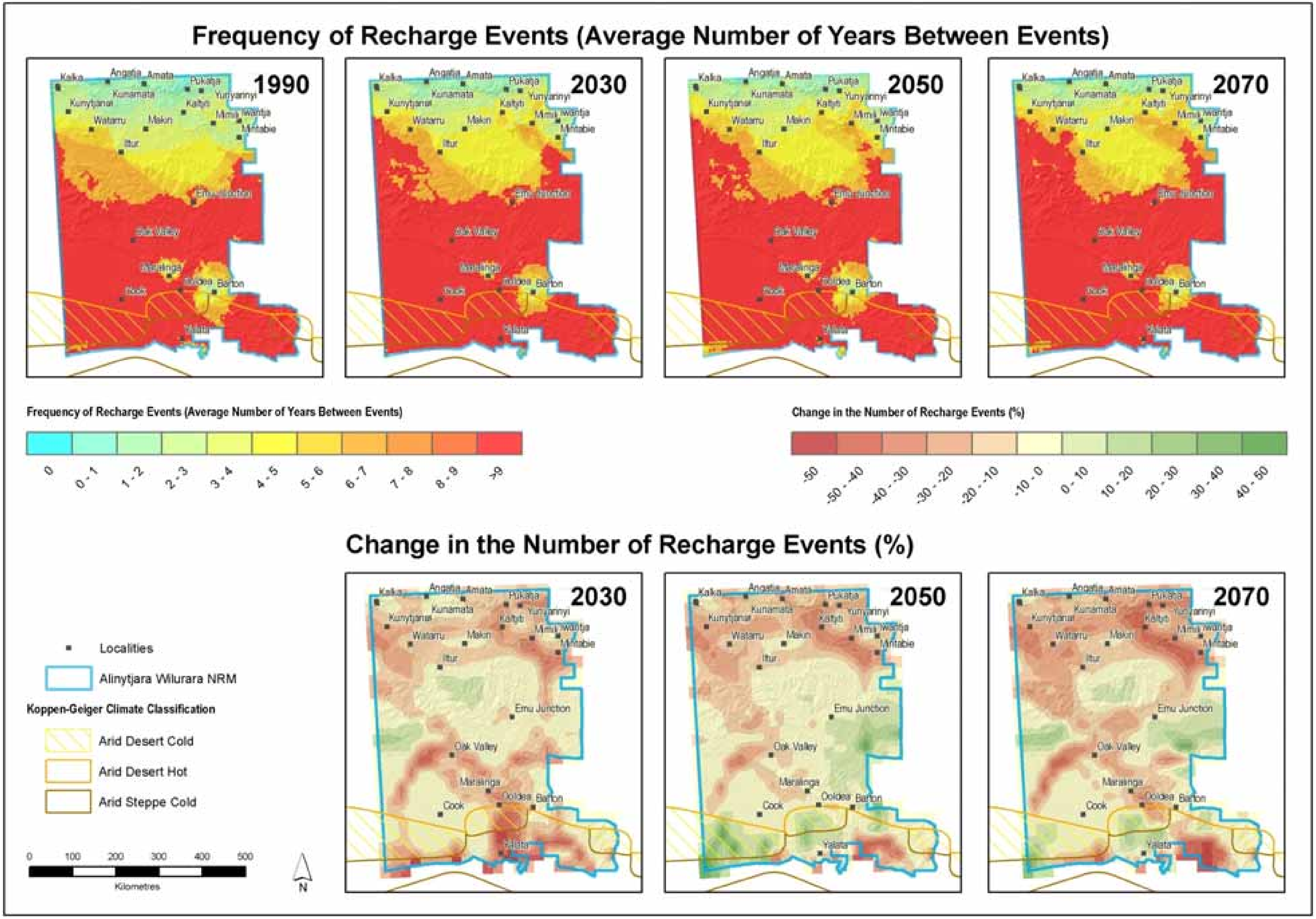


Figure 18. Change in the frequency of recharge events, and the number of events as a percentage, for the 'most likely' case projections with low emissions

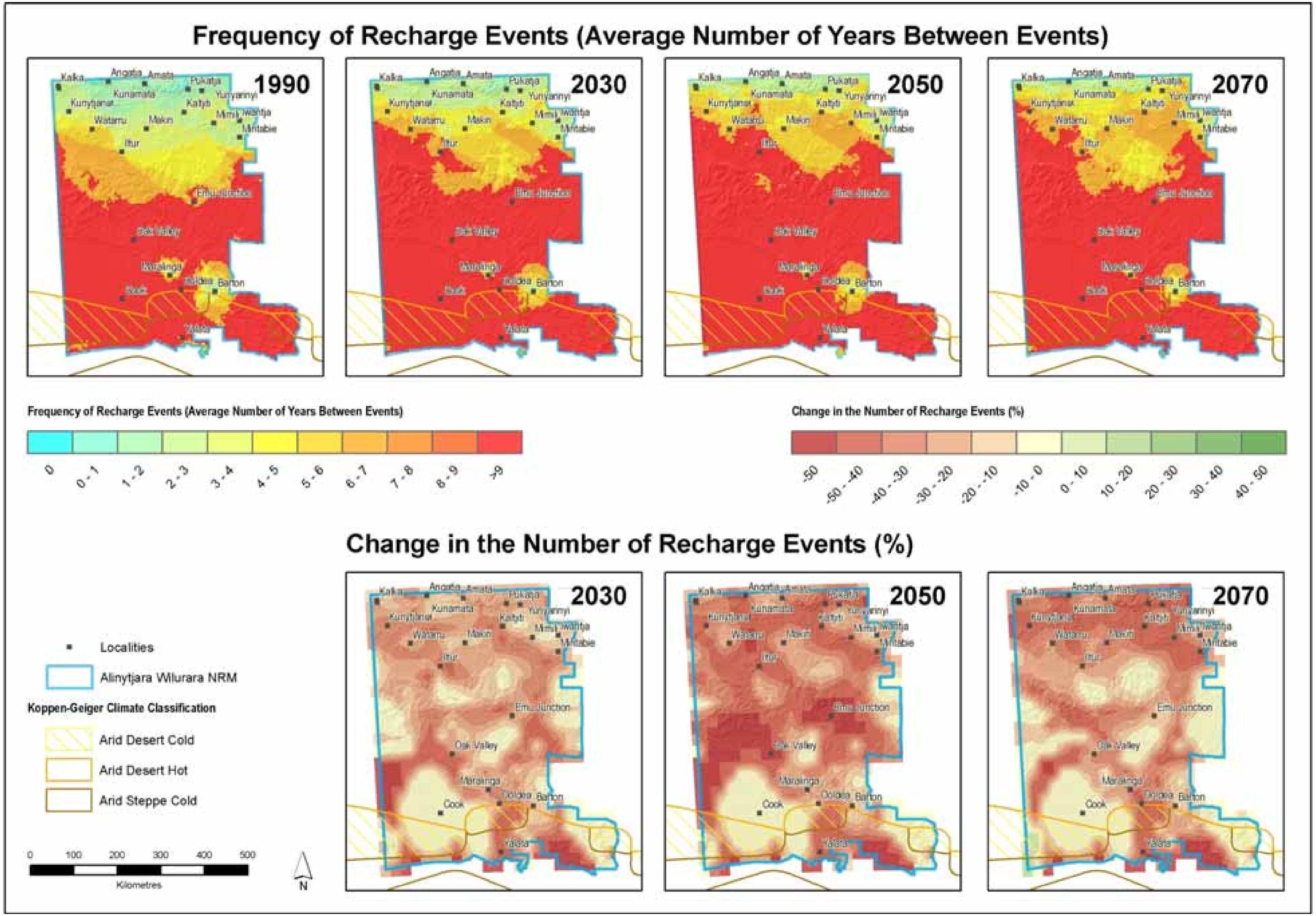


Figure 19. Change in the frequency of recharge events, and the number of events as a percentage, for the 'most likely' case projections with high emissions

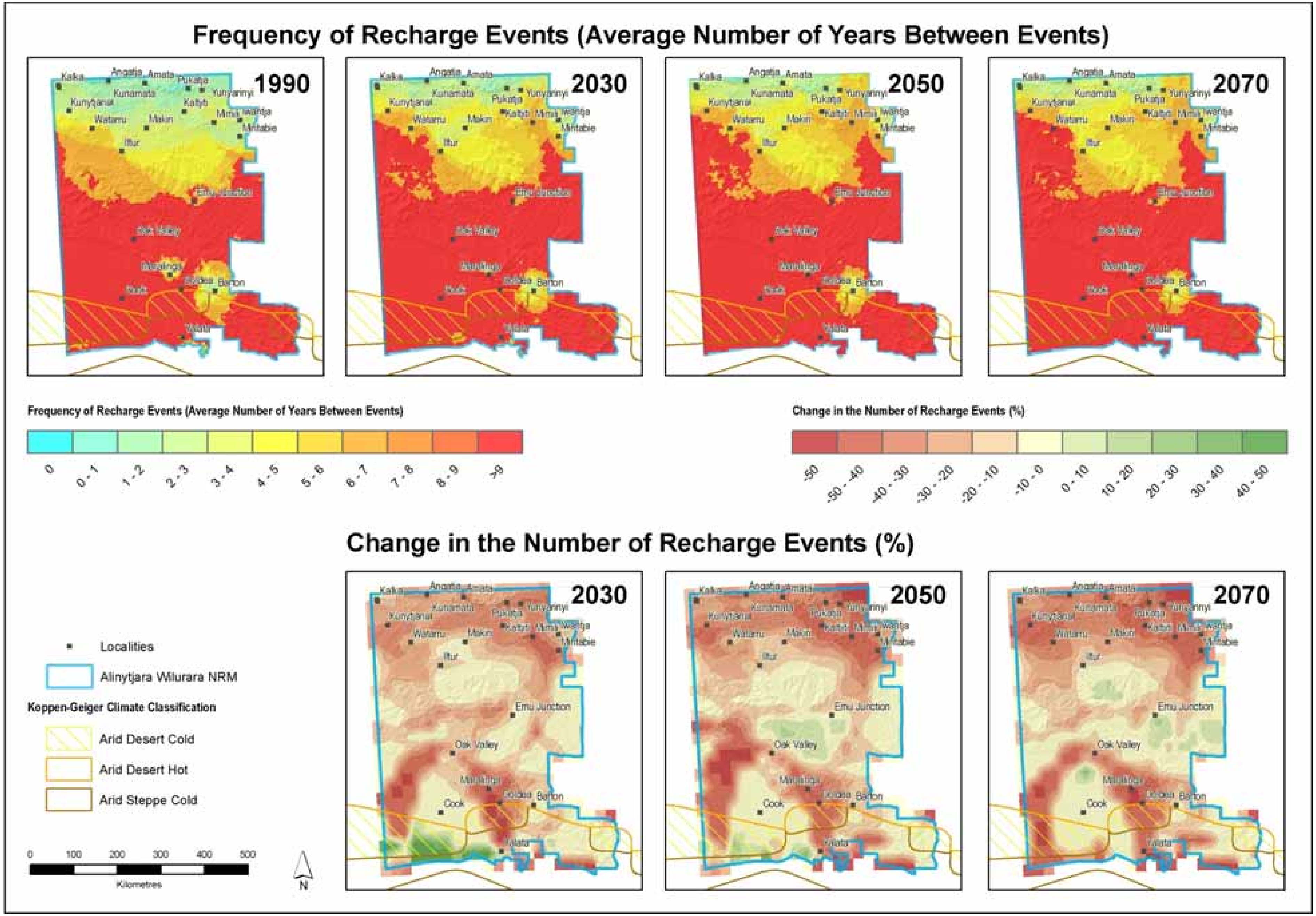


Figure 20. Change in the frequency of recharge events, and the number of events as a percentage, for the 'worst' case projections with low emissions

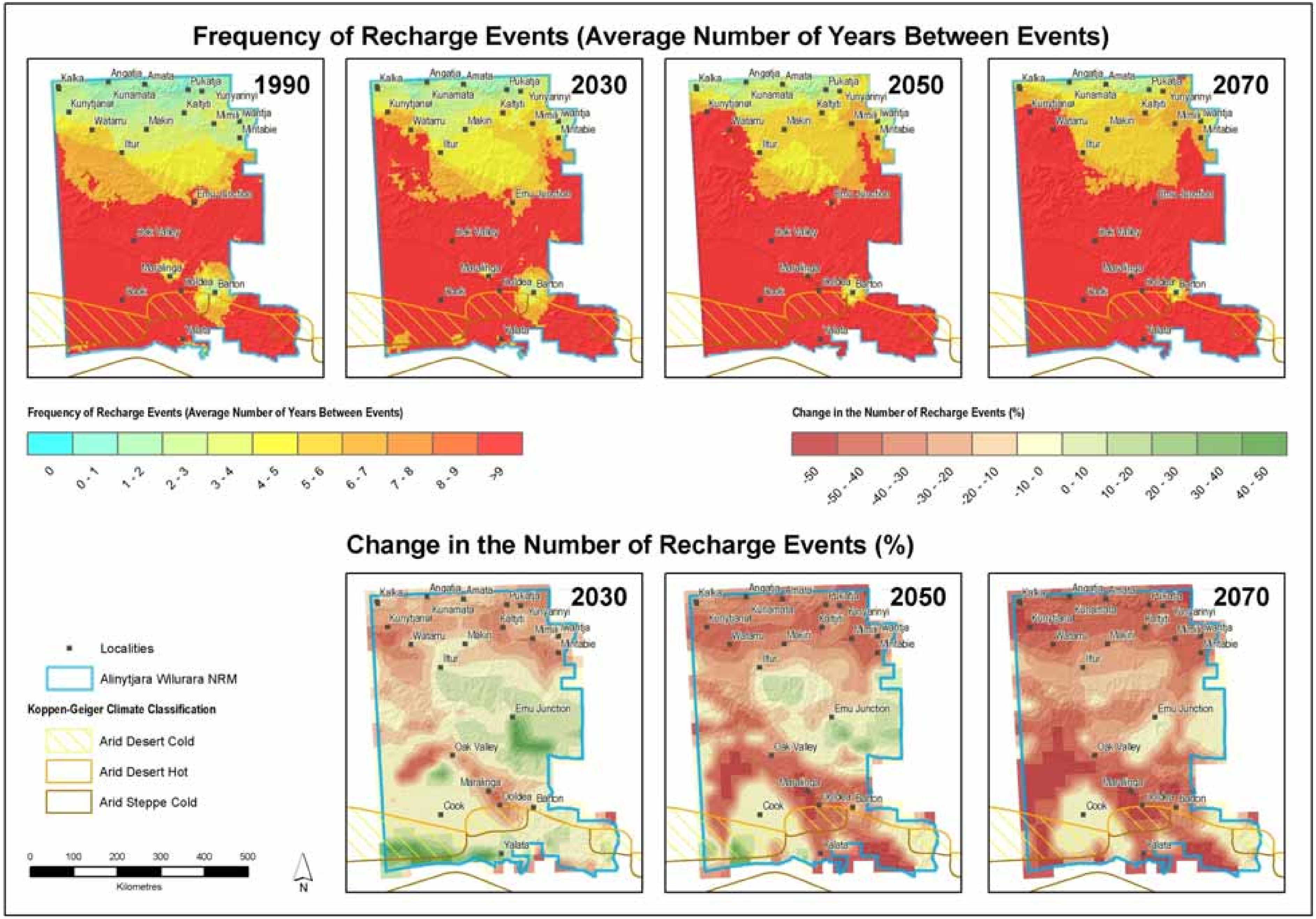


Figure 21. Change in the frequency of recharge events, and the number of events as a percentage, for the 'worst' case projections with high emissions

4. DISCUSSION

Changes in the important rainfall metrics that are likely to indicate the occurrence of recharge events (Sect. 3) are based on GCMs selected to represent the 'best', 'worst' and 'most-likely' ranges of projections. The three climate metrics vary in their application to different areas within the AWNRM Region. For example, toward the south of the region where the rainfall is winter dominant, changes in annual average rainfall may be the most reliable indicator of changes in the capacity of groundwater resources. In contrast, toward the north where large, episodic events typically drive recharge processes, the change in the frequency of high-rainfall months (defined in this study as greater than 100 mm/month) is likely to be the most reliable indicator of impacts to the capacity of groundwater resources. In this area, the change in average annual rainfall is likely to be less reliable as an indicator.

The ICCWR project has previously undertaken detailed hydrologic modelling to determine the potential impact of climate change on the prescribed groundwater resources of the Eyre Peninsula NRM Region (Green *et al.*, 2012), which has similar geology and climate to the Yalata area in the south of the AWNRM Region. The modelling undertaken by Green *et al.* (2012) found that the change in recharge in the Musgrave PWA was approximately 3.4 times greater than the corresponding change in annual rainfall. As the climate and geology of the Musgrave PWA are similar to that of the Yalata area, a multiplier of the same magnitude could be applied to estimate the change in recharge at Yalata, based on the projected changes in average annual rainfall (Figs 10–15). However, the distance between the Yalata town water supply wells and the recharge zone of the aquifer in which these wells are completed will, in part, influence the time taken between changes in rainfall patterns and any corresponding changes in water levels.

In the north of the AWNRM Region, recharge is typically driven by the occurrence of extreme rainfall events. As some climate change projections indicate an increase in intensity of rainfall events for South Australia (e.g. Suppiah *et al*., 2006; CSIRO & BoM, 2007), it might be expected that any projected increases in rainfall intensity may have a positive impact on the water resources. However, where increases in intensity are projected, these are in combination in an overall reduction in the amount of annual rainfall. The results presented in Section 3 indicate that an increase in extreme rainfall events is unlikely. The change in the first percentile rainfall, used to provide an indication of the change in the magnitude of larger rainfall events, generally decreased, albeit by less than the corresponding average annual rainfall for a given scenario. For some cases, the first percentile rainfall can be seen to increase in one future scenario relative to another, however the changes were still a decrease relative to the historic climate, suggesting that it is unlikely that recharge events will increase in magnitude. A more sophisticated downscaling approach is required to investigate the impacts of the frequency of extreme rainfall events, as opposed to the magnitude of rainfall events as considered in this study.

Similarly, most of the GCMs project a reduction in the frequency of the large events and a reduction in the magnitude of the largest events. This was especially the case for the north of the AWNRM Region, where extreme events are likely to govern groundwater recharge. The reduction in the number of months with rainfall greater than 100 mm is projected to be 2.2 times greater than the reduction in average annual rainfall, when projections are averaged over the whole AWNRM Region.

A number of the uncertainties inherent in the results presented in the previous section are addressed in the following discussion. The changes in the important rainfall metrics for the different climate and geological areas in the AWNRM Region are then considered in a risk-management framework to provide an indication of the potential impacts of these changes on the capacity of the water resources in each area.

4.1. UNCERTAINTY

There are two primary sources of uncertainty in projections of climate change; (1) inter-model variations; and (2) variations in greenhouse gas emissions scenarios. While the GCMs are complex, there are many assumptions and simplifications underpinning these three-dimensional models of the coupled atmospheric and oceanic processes that drive the Earth's climatic system. The variations in the mathematical representation of global energy and mass fluxes used by each of the models leads to variations in the projections of climate change. The differences are more marked in variables that are influenced by a large number of climate processes, such as rainfall, compared to the more primary variables such as temperature. There are many downscaling methods that can be used to convert the large-scale GCM outputs to the local scale, each with different advantages and disadvantages and with different outputs representing possible future climates. Hence, a degree of uncertainty is also introduced by the downscaling technique adopted.

It is unclear how suitable the daily downscaling method (Sect. 3.2.2) is in its application to the metrics of recharge occurrence in the AWNRM Region. As the method is based on scaling the historic rainfall record, the frequency of rain days does not change, only the magnitude of the rainfall on these days. In order to incorporate changes in the temporal distribution of rainfall in the downscaling approach, more sophisticated methods are required, such as the NHMMs that are being developed by the Goyder Institute for Water Resource's Climate Change project. While an approach such as this will provide the ability to consider the change in frequency of extreme events, Crosbie *et al*. (2011) found that future datasets downscaled using the NHMM approach were more pessimistic than the daily scaling approach adopted in this work. It is unclear which of these downscaling methods, or other available methods, is likely to provide the most realistic daily rainfall dataset at the local scale, based on coarse GCM projections.

The Climate Futures analysis has produced a small number of categories of possible climate change scenarios, each with a relative likelihood based on the number of models that project that category. The uncertainty arising from the variation between different climate models is compounded by the uncertainty in future greenhouse gas emission rates through the 21st century. The IPCC provides a range of possible emissions scenarios (Nakicenovic & Swart, 2000) that are widely adopted in climate change studies. From these, high and low-emissions scenarios have been selected for use in this study, resulting in a range of climate projections that span the range of emissions scenarios. Typically, climate projections for 2030 show variations in regional-scale changes between different climate models, but less variation due to different emissions scenarios. This is because in the near term (< 20 years), changes in climate are governed by greenhouse gases that have already been released into the atmosphere (CSIRO & BoM, 2007). Climate change projections that are based on different emissions scenarios out to 2050 and beyond show greater variation between projections because the divergence of the emissions scenarios is much greater in the second half of the century.

There is scope for reduction in the range of uncertainty in the climate projections by eliminating some of the emissions scenarios that may be considered to be unlikely in view of knowledge gained since the IPCC emissions scenarios were published in 2000. For example, Steffen *et al.* (2009) report that anthropogenic emissions of carbon dioxide have been rising at, or near, the upper limit of the envelope of the IPCC emissions projections since they were first published in 2000, while CSIRO-BoM (2012) indicates that this trend has continued to 2011. As the emissions scenario outcomes (atmospheric concentrations of greenhouse gases) are dependent on the progress of emissions over a period of time, there is now a very low probability that low-emissions scenarios will be realised in 2030 (Anderson & Bows 2008). A study by Ward *et al.* (2011) proposes that a reduction in uncertainty can be achieved by reducing the range of longer-term emissions scenarios to only those that align with known abundance of fossil fuels. Although there is uncertainty in the global capacity of fossil fuels, Ward *et al*. (2011)

highlight the growing body of literature that challenges the assumptions underpinning the high-growth emissions scenarios. They project that fossil fuel production occurring in the 21st century will limit longer-term atmospheric carbon dioxide emissions to a either a low-medium or low-emissions scenario and showed that the median change and spread of hydrologic model results (and resulting uncertainty) can be reduced if projections of climate in 2070 are limited to those resulting from the lower-emissions scenarios. Thus, by combining these findings it can be conjectured that low-emissions scenarios could be ruled out for the shorter-term time horizon 2030, while the higher emissions scenarios could be ruled out for the longer term 2070 time horizon. If this is accepted, the uncertainty in the projections for the short and long-term scenarios are somewhat reduced.

4.2. RISK MANAGEMENT

Whilst it is not possible to eliminate risk to natural resources entirely, identifying the likely level of risk to water resources in the AWNRM Region in a systematic and structured way (Table 14) will assist in planning and adaptation of water resources management into the future.

Table 14. Risk analysis matrix showing the projected risk to the capacity of water resources based on (1) the groundwater level response to contemporary rainfall and (2) the projected percentage change in the frequency of large episodic rainfall (i.e. recharge) events between using the NCAR-A1 (high-emissions scenario) GCM. Recharge is assumed to occur following rainfall greater than 100 mm/month.

		Groundwater level response to contemporary rainfall			
		None apparent	**Weak**	**Moderate**	**Strong**
Projected change in frequency of recharge events (%)	**0 – -10**	Low	Low	Low	Moderate
	-11 – -20	Low	Low	Moderate	Moderate
	-21 – -30	Low	Moderate	High	High
	-31 – -40	Low	Moderate	High	Very high
	-41 – -50	Low	High	Very high	Very high

The risks to the capacity of the AWNRM Region's groundwater resources that are likely to be recharged by large episodic rainfall events have been projected based on two criteria:

1. Whether the groundwater resources are responsive to contemporary, extreme rainfall events (Table 5). A relationship of contemporary rainfall with recharge would suggest that changes in the frequency and/or magnitude of extreme rainfall events will impact on the rate of rainfall recharge to the region's aquifers.
2. The projected change in the frequency of extreme rainfall events that lead to recharge. The change in rainfall events was analysed using the 'most likely' NCAR GCM and A1 scenario (i.e. high-emissions scenario). It has been assumed that recharge occurs following rainfall greater than 100 mm/month.

The risk analysis matrix has been applied to each locality within the 'arid-desert-hot' and 'arid-desert-cold' climate sub-zones (Table 15), because the groundwater resources occurring in these locations are potentially recharged by large, episodic, contemporary rainfall events.

The capacity of groundwater resources around the communities of Yunyarinyi (Kenmore Park), Pukatja (Ernabella) and Kaltjiti (Fregon) have been identified as being at the greatest risk from impacts due to climate change. Importantly, in addition to the high-risk rating for the capacity of Pukatja's groundwater resources due to projections of future climate change, these groundwater resources are also currently experiencing increasing demand and declining water levels (Sect. 2.3 and Table 3).

Yalata has been omitted from the risk analysis because recharge in this 'arid-steppe-cold' climate sub-zone is not likely to be governed by extreme, summer-dominant rainfall events. Furthermore, the data suggest that there is only a weak relationship between rainfall and water level and consequently, it is possible that the aquifer upon which the residents of Yalata rely for potable supply is recharged tens or hundreds of kilometres away (Section 2.5.3). As a result, it is very unlikely that climate change will have any short to medium-term impact on water levels and as such, the resource has been assigned to the low-risk category of impacts from climate change. However, it is acknowledged that this groundwater resource is vulnerable to continued reductions in storage, as shown by the trend of falling water levels since records began in 2000 (Sect. 2.5.3).

Table 15. The projected risk to the capacity of water resources in the AWNRM Region as a result of climate change, based on the risk analysis matrix (Table 14)

Area/well	Years between recharge events (1990 historical)	Change in frequency of recharge events (%)			Groundwater response to contemporary rainfall (from Table 5)	Projected risk to capacity of water resources		
		1990–2030	1990–2050	1990–2070		2030	2050	2070
Amata	2	-26	-32	-38	Moderate	**High**	**High**	**High**
Iwantja (Indulkana)	3	-7	-10	-23	Weak	**Low**	**Low**	**Moderate**
IMB-19	3	-7	-10	-23	None apparent	**Low**	**Low**	**Low**
IMB-19A	3	-7	-10	-23	Weak	**Low**	**Low**	**Moderate**
IMB-25	3	-7	-10	-23	Weak	**Low**	**Low**	**Moderate**
IMB-27	3	-7	-10	-23	Moderate	**Low**	**Low**	**High**
IR-1&IR-2	3	-7	-10	-23	None apparent	**Low**	**Low**	**Low**
Kalka	3	-12	-21	-25	Weak	**Low**	**Moderate**	**Moderate**
Kaltjiti (Fregon)	3	-30	-45	-50	Moderate	**High**	**Very high**	**Very high**
Mimili	4	-11	-36	-45	Weak	**Low**	**Moderate**	**High**
Oak Valley	10	-20	-50	-20	Weak	**Low**	**High**	**Low**
Pipalyatjara	3	-20	-36	-35	Moderate	**Moderate**	**High**	**High**
Pukatja (Ernabella)	1	-28	-43	-49	Strong	**High**	**Very high**	**Very high**
Yunyarinyi (Kenmore Park)	2	-30	-42	-50	Strong	**High**	**Very high**	**Very high**

5. CONCLUSIONS

The focus of this study was the impacts of climate change on the capacity of water resources in the AWNRM Region.

The region can be broadly described as having two distinct climate zones: (1) along the southern-coastal fringe, where rainfall is winter dominant and the climate is semi-arid; and (2) north of the southern-coastal fringe, where rainfall is summer dominant and the climate is more arid. Rainfall in the arid zone becomes increasingly episodic and unpredictable with decreasing latitude. Due to the low rainfall and high potential evapotranspiration in the arid zone, recharge is likely to occur only following extreme rainfall events. Previous studies have shown that in arid environments similar to the northern AWNRM Region, recharge occurs episodically, typically resulting from rainfall events greater than around 100 mm/month (Harrington, Cook & Herczeg, 2002; Tweed *et al.,* 2011).

There are only limited data available to estimate the capacity of the groundwater resources in the AWNRM Region. Whilst groundwater and rainfall data are sparse at the regional scale, water level and rainfall data are available for most communities that rely on groundwater for potable water. These data indicate that some groundwater levels respond to high-rainfall events, suggesting that contemporary rainfall is recharging local aquifers in some areas.

The limited nature of the data on the groundwater resources in the AWNRM Region makes it impractical to develop and calibrate numerical models of recharge and runoff, which has been the approach taken in projecting impacts to water resources as a result of climate change in previous ICCWR studies. Instead, rainfall metrics have been used to provide projections of the impact of climate change on the water resources of the region in lieu of numerical modelling approaches. The metrics selected are the change in:

- annual average rainfall, as an indicator of the overall projected change
- the first percentile daily rainfall amount, as an indicator of the change in the intensity of the largest rainfall events
- the frequency of rainfall events of greater than 100mm/month, as an indicator of episodic large rainfall events that generate groundwater recharge in the arid north of the region.

Projected changes in the magnitude and frequency of the largest rainfall events, compared to the 1990 historic baseline period, are considered to be indicative of the resulting changes in frequency of groundwater recharge events in the arid part of the region with summer-dominant rainfall.

A Climate Futures approach was used to select the GCMs applied in this study. The Climate Futures Framework (Clarke *et al.*, 2011) provides a simplified representation of GCM projections, while still addressing uncertainty and maintaining internally consistent combinations of climate variables from the different models. Three GCMs were selected that represent, the 'best', 'most-likely' and 'worst' case projections for the AWNRM Region. High and low greenhouse gas emissions scenarios were considered for time horizons of 2030, 2050 and 2070.

The GCM selected to represent the 'most-likely' future climate case projected that the average annual rainfall is likely to decrease from between 5% by 2030 (irrespective of the emission scenario), to 14% by 2070 with a high-emission scenario. Both the Climate Futures and downscaling results suggest that the reductions in average rainfall are likely to be slightly greater in the north compared with the south.

Reductions in the magnitude of extreme rainfall events (i.e. the first percentile daily rainfall), compared to the 1990 historic baseline period, are projected for all combinations of Climate Futures cases and emissions scenarios across the whole AWNRM Region. The projected change in first percentile rainfall is generally less than the projected change in the average annual rainfall for a given future scenario. This is because for South Australia, many GCMs project an increase in the magnitude of extreme events while also projecting a reduction in mean annual rainfall.

For some locations, the first percentile daily rainfall is projected to increase from one future time horizon to the next (e.g. 2030 compared to 2050), but still not when compared to the historic case.

A reduction in the frequency of the large events expected to lead to recharge (i.e. months of rainfall greater than 100 mm) is projected when results are averaged across the whole AWNRM Region. However, these reductions are highly variable, due to the very low frequency of months with rainfall greater than 100 mm for most of the region; in some cases the frequency is less than once every 10 years, on average.

To the north of the region, where the recharge events are the most frequent (one every two to three years, on average), the frequency of large, recharge-generating rainfall events is projected (using the 'most-likely' GCM climate projection) to decrease by between 22% under a low-emissions scenario for 2030, and 38% under a high-emissions scenario for 2070. Averaged across the region and across the scenarios considered, the reduction in the frequency of extreme rainfall events that are expected to lead to recharge is 2.2 times greater that the corresponding change in annual rainfall. These results are in general agreement with the results from previous ICCWR studies of other regions of South Australlia, where the reduction in recharge and runoff is generally between 2–4 times greater than the corresponding change in rainfall.

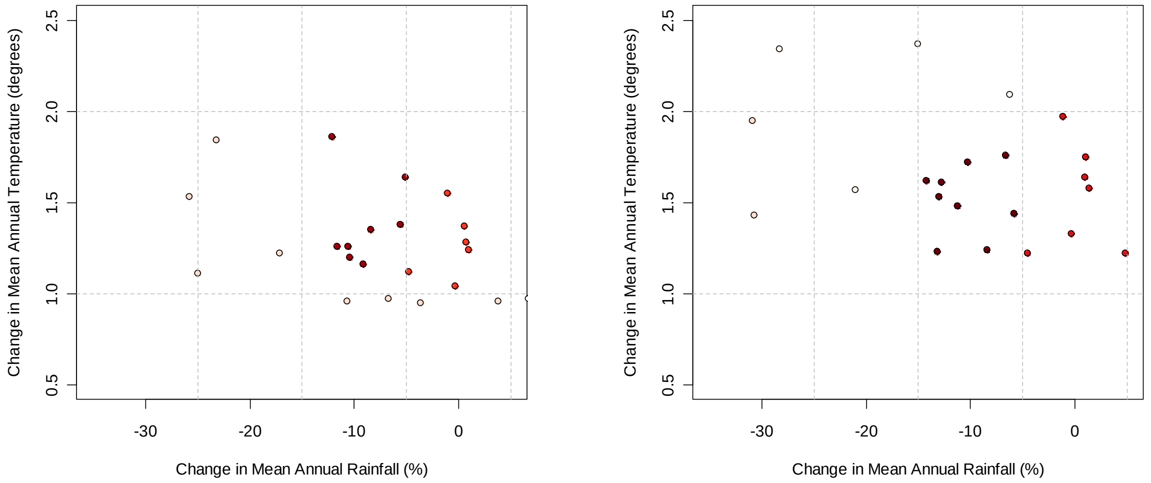
A risk analysis has been conducted that aims to assist, in a systematic and structured way, in planning and adaptation of water resources management in the AWNRM Region into the future. The risk analysis is based on two criteria; (1) whether the groundwater resources appear to be responsive to contemporary, extreme rainfall events; and (2) the projected change in the frequency of extreme rainfall events that lead to recharge. The groundwater resources that were identified as at the highest risk from impacts from climate change are those used by the communities of Yunyarinyi (Kenmore Park), Pukatja (Ernabella) and Kaltjiti (Fregon).

Ongoing monitoring and science will continue to provide new data and knowledge of the components of climate change and hydrological science used to derive estimates of climate change impacts on water resources across the region. It is recommended that the projections of impacts on water resources in these areas are revisited when new downscaled climate change projections are made available by the Goyder Institute for Water Research project *Development of an agreed set of climate projections for South Australia* in the 2013–14 business year. At that time, any additional new data that may enable hydrogeological modelling should also be considered, including any improvements in the conceptual understanding of recharge processes and projections of possible land use changes in the AWNRM Region.

APPENDIX

CLIMATE FUTURES DERIVED USING ALL GCMS

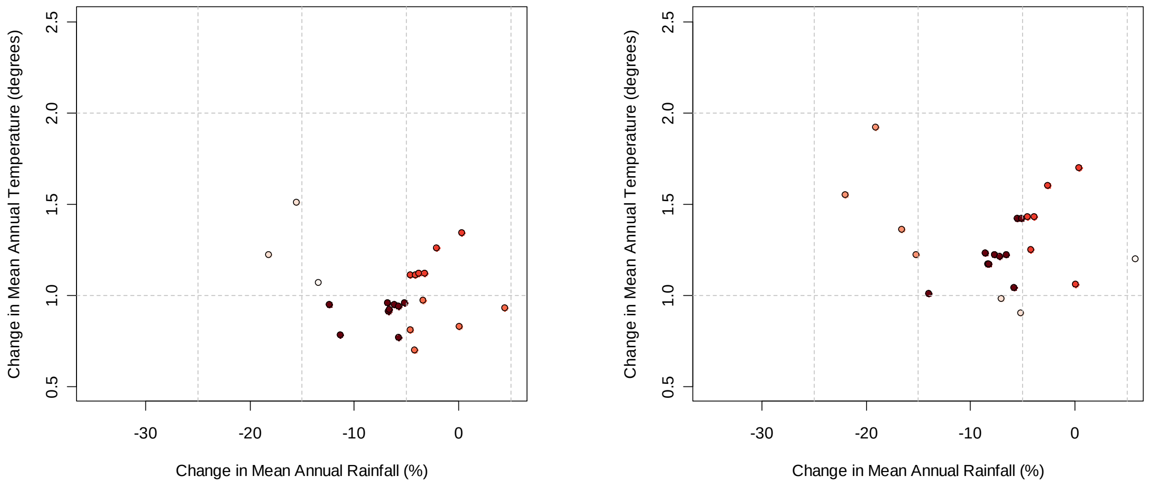
All GCMs is defined as the 23 IPCC Fourth Assessment Report GCMs (IPCC, 2007) and the CSIRO Mark 3.5 GCM.



B1 Emissions

A2 Emissions

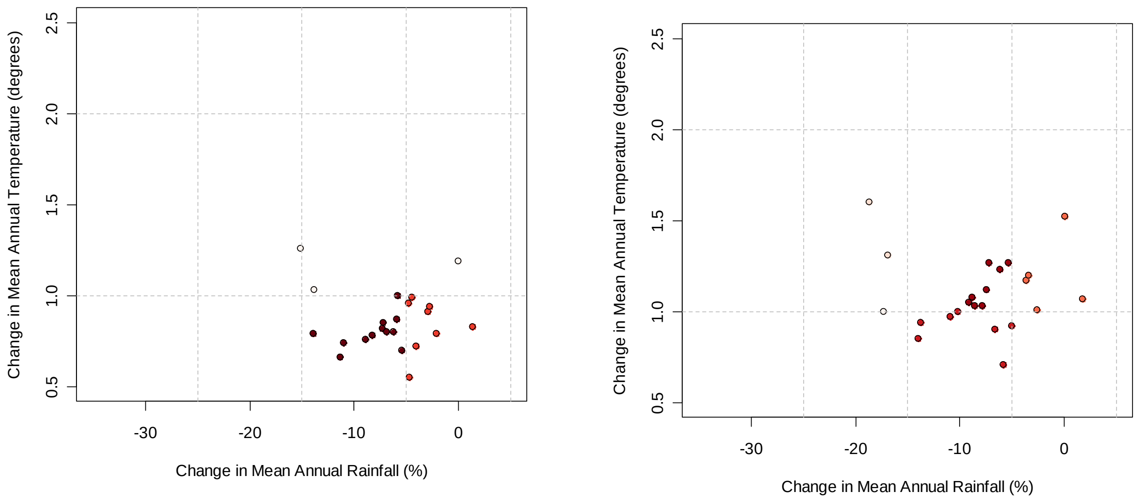
Figure 22. GCM Projections for Pukatja for 2050 using all available GCMs



B1 Emissions

A2 Emissions

Figure 23. GCM Projections for Maralinga for 2050 using all available GCMs



B1 Emissions A2 Emissions

Figure 24. GCM Projections for Nullarbor for 2050 using all available GCMs

UNITS OF MEASUREMENT

Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	volume
gram	g	10^{-3} kg	mass
hectare	ha	10^4 m^2	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	10^3 m	length
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
metre	m	base unit	length
microgram	µg	10^{-6} g	mass
microlitre	µL	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	365 or 366 days	time interval

Shortened forms

~	approximately equal to
bgs	below ground surface
EC	electrical conductivity (µS/cm)
K	hydraulic conductivity (m/d)
pH	acidity
pMC	percent of modern carbon
ppb	parts per billion
ppm	parts per million
ppt	parts per trillion
w/v	weight in volume
w/w	weight in weight

GLOSSARY

ABS — Australian Bureau of Statistics

APY — Anangu Pitjantjatjara Yankunytjatjara

Aquatic ecosystem — The stream channel, lake or estuary bed, water, and/or biotic communities, and the habitat features that occur therein

Aquifer — An underground layer of rock or sediment that holds water and allows water to percolate through

Aquifer, confined — Aquifer in which the upper surface is impervious (see 'confining layer') and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer

Aquifer, unconfined — Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure

Aquitard — A layer in the geological profile that separates two aquifers and restricts the flow between them

AWBM — Australian Water Balance Model

AWNRM(B) — see Alinytjara Wilurara Natural Resources Management (Board**)**

BCCR — Bjerknes Centre for Climate Research

Baseflow — The water in a stream that results from groundwater discharge to the stream; often maintains flows during seasonal dry periods and has important ecological functions

Biodiversity — (1) The number and variety of organisms found within a specified geographic region. (2) The variability among living organisms on the earth, including the variability within and between species and within and between ecosystems

BoM — Bureau of Meteorology, Australia

Bore — See 'well'

Catchment — That area of land determined by topographic features within which rainfall will contribute to run-off at a particular point

Confining layer — A rock unit impervious to water, which forms the upper bound of a confined aquifer; a body of impermeable material adjacent to an aquifer; see also 'aquifer, confined'

CSIRO – Commonwealth Scientific and Industrial Research Organisation

DENR – Department of Environment and Natural Resources

DFW — Department for Water (Government of South Australia)

DTEI — Department for Transport, Energy and Infrastructure

DWLBC — Department of Water, Land and Biodiversity Conservation (Government of South Australia)

DWR – Department for Water Resources

Environmental water requirements — The water regimes needed to sustain the ecological values of aquatic ecosystems, including their processes and biological diversity, at a low level of risk

Evapotranspiration — The total loss of water as a result of transpiration from plants and evaporation from land, and surface water bodies

GCM — Global Climate Model

GFDL — Geophysical Fluid Dynamics Laboratory

GIS — Geographic Information System; computer software linking geographic data (for example land parcels) to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis

Groundwater — Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground; see also 'underground water'

Hydraulic conductivity (K) — A measure of the ease of flow through aquifer material: high K indicates low resistance, or high flow conditions; measured in metres per day

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes, and the properties of aquifers; see also 'hydrology'

Hydrology — The study of the characteristics, occurrence, movement and utilisation of water on and below the Earth's surface and within its atmosphere; see also 'hydrogeology'

IAP —- Institute of Atmospheric Physics

ICCWR — Impacts of Climate Change on Water Resources

IPCC — International Panel on Climate Change

Irrigation season — The period in which major irrigation diversions occur, usually starting in August–September and ending in April–May

Leaching — Removal of material in solution such as minerals, nutrients and salts through soil

Model — A conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions. Examples include estimating storm run-off, assessing the impacts of dams or predicting ecological response to environmental change

Monitoring — (1) The repeated measurement of parameters to assess the current status and changes over time of the parameters measured (2) Periodic or continuous surveillance or testing to determine the level of compliance with statutory requirements and/or pollutant levels in various media or in humans, animals, and other living things.

MT — Maralinga Tjar̲utja

Natural recharge — The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc). See also recharge area, artificial recharge

Natural resources — Soil, water resources, geological features and landscapes, native vegetation, native animals and other native organisms, ecosystems

NCAR — National Center for Atmospheric research

NHMM — Non-homogenous Hidden Markov Model

NRM — Natural Resources Management; all activities that involve the use or development of natural resources and/or that impact on the state and condition of natural resources, whether positively or negatively

EPNRM — Eyre Peninsula Natural Resources Management (region)

Observation well — A narrow well or piezometer whose sole function is to permit water level measurements

Obswell — Observation Well Network

PET — Potential evapotranspiration

Prescribed area, surface water — Part of the state declared to be a surface water prescribed area under the Act

Prescribed watercourse — A watercourse declared to be a prescribed watercourse under the Act

Prescribed water resource — A water resource declared by the Governor to be prescribed under the Act, and includes underground water to which access is obtained by prescribed wells. Prescription of a water resource requires that future management of the resource be regulated via a licensing system.

Prescribed well — A well declared to be a prescribed well under the Act

PWA — Prescribed Wells Area

PWRA — Prescribed Water Resources Area

Raster – a data structure representing a grid of pixels, or points of color, in which each pixel holds a single value representative of a spatial variable depicted by the raster

Recharge area — The area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer. See also artificial recharge, natural recharge

SA Water — South Australian Water Corporation (Government of South Australia)

Specific yield (S_y) — The volume ratio of water that drains by gravity, to that of total volume of the porous medium. It is dimensionless

SRES — Special Report on Emissions Scenarios

Surface water — (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir

Surface Water Archive — An internet-based database linked to Hydstra and operated by DWLBC. It contains rainfall, water level, streamflow and salinity data collected from a network of surface water monitoring sites located throughout South Australia

Tertiary aquifer — A term used to describe a water-bearing rock formation deposited in the Tertiary geological period (1–70 million years ago)

Underground water (groundwater) — Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground

Vadose zone — The zone between the land surface and the water table. This includes the zone of soil water and the capillary fringe. Also called the unsaturated zone.

Water allocation — (1) In respect of a water licence means the quantity of water that the licensee is entitled to take and use pursuant to the licence. (2) In respect of water taken pursuant to an authorisation under s.11 means the maximum quantity of water that can be taken and used pursuant to the authorisation

Water allocation, area based — An allocation of water that entitles the licensee to irrigate a specified area of land for a specified period of time usually per water–use year

WAP — Water Allocation Plan; a plan prepared by a CWMB or water resources planning committee and adopted by the Minister in accordance with the Act

Watercourse — A river, creek or other natural watercourse (whether modified or not) and includes: a dam or reservoir that collects water flowing in a watercourse; a lake through which water flows; a channel (but not a channel declared by regulation to be excluded from the this definition) into which the water of a watercourse has been diverted; and part of a watercourse

Well — (1) An opening in the ground excavated for the purpose of obtaining access to underground water. (2) An opening in the ground excavated for some other purpose but that gives access to underground water. (3) A natural opening in the ground that gives access to underground water

Wetlands — Defined by the Act as a swamp or marsh and includes any land that is seasonally inundated with water. This definition encompasses a number of concepts that are more specifically described in the definition used in the Ramsar Convention on Wetlands of International Importance. This describes wetlands as areas of permanent or periodic to intermittent inundation, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tides does not exceed six metres.

REFERENCES

Alinytjara Wilurara Natural Resources Management Board, (2009), Draft Regional NRM Plan, Government of South Australia, through Alinytjara Wilurara Natural Resources Management Board, Ceduna

Anderson, K and Bows, A, (2008), 'Reframing the climate change challenge in light of post-2000 emission trends', in *Philosophical Transactions of the Royal Society A*, 366, pp. 3863–3882

Australian Groundwater Technologies, (2008), Sustainability of water resources in Anangu Pitjantjatjara Yankunytjatjara Lands, Maralinga Tjarutja Lands & Aboriginal Lands Trust Lands, South Australia, Report prepared for Department of Water, Land and Biodiversity Conservation, Adelaide

Australian Groundwater Technologies, (2010), Alinytjara Wilurara Natural Resources Management Region Groundwater Review, report prepared for Department of Water, Land and Biodiversity Conservation, Adelaide

Bureau of Meteorology, 2011, Climate Data Online, viewed December 2011, http://www.bom.gov.au/climate/data/

Buxton, P, (2005), Alinytjara Wilurara Natural Resources Management Region — Water Monitoring Review, Report DWLBC 2005/037, Government of South Australia, through Department of Water, Land and Biodiversity Conservation, Adelaide

Clark, ID, Fritz, P, Quinn, OP, Rippon, PW and Nash, H, (1987), 'Modern and fossil groundwater in an arid environment: A look at the hydrogeology of Southern Oman', in *Isotope Techniques in Water Resources Development*, Proceedings of an International Symposium, International Atomic Energy Agency, Vienna, pp. 167–187

Clarke, JM, Whetton, PH, Hennessy, KJ, (2011), 'Providing application-specific climate projections datasets: CSIRO's Climate Futures Framework', 19th International Congress on Modelling and Simulation, December 2011, Perth, Australia, pp. 12–16

Costar, A and Sampson, L, (2004), Interim report on the monitoring of groundwater bores in Aboriginal Trust Lands, South Australia, Monitoring period October 2003 to April 2004, Report DWLBC 2004/46, Government of South Australia, through Department of Water, Land and Biodiversity Conservation, Adelaide

Crosbie, RS, Dawes, WR, Charles, SP, Mpelasoka, FS, Aryal, S, Barron, O, and Summerell, GK, (2011), 'Differences in future recharge estimates due to GCMs, downscaling methods and hydrological models', in *Geophysical Research Letters*, 38, L11406

Crosbie, RS, McCallum, JL, Walker, GR, and Chiew, FHS, (2012), 'Episodic recharge and climate change in the Murray-Darling Basin, Australia', in *Hydrogeology Journal*, 20, pp. 245–261

Commonwealth Scientific and Industrial Research Organisation, (2012), OzClim, Website Build Number: 4.2.01, viewed January 2012,
http://csiro.au/ozclim/

Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology (CSIRO-BoM), (2007), Climate Change in Australia, Pearce, K, Holper, P, Hopkins, M, Bouma, W, Whetton, P, Hennessy, K and Power, S, (Eds.), CSIRO Technical Report 2007, Commonwealth of Australia, through Commonwealth Scientific and Industrial Research Organisation, Melbourne

Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology (CSIRO-BoM), (2012), State of the Climate – 2012, viewed April 2012,
http://www.csiro.au/Outcomes/Climate/Understanding/State-of-the-Climate-2012.aspx

de Vries, JJ and Simmers, I, (2002), 'Groundwater recharge: an overview of processes and challenges', in *Hydrogeology Journal*, 10, pp. 5–17

Department for Transport, Energy and Infrastructure, (2005), Strategic Infrastructure Plan for South Australia 2005/6–2014/15, Government of South Australia, through Department of Transport, Energy and Infrastructure, Adelaide

Dodds, AR, (1997), An assessment of the groundwater resources of the Lake Maurice area, northwest South Australia, for the Oak Valley community, Maralinga Tjarutja Aboriginal Lands, Report book 97/56, Government of South Australia, through Department of Mines and Energy Resources South Australia, Adelaide

Dodds, AR and Sampson, L,(2001), Hydrogeological report on water well monitoring in Aboriginal lands — October 2000 to April 2001, Report DWR 2001/012, Government of South Australia, through Department for Water Resources, Adelaide

Dodds, AR and Sampson, L, (2002a), Hydrogeological report on water well monitoring in Aboriginal lands – October 2000 to April 2001, Report DWLBC 2001/012, Government of South Australia, through Department of Water, Land and Biodiversity Conservation, Adelaide

Dodds, AR and Sampson, L, (2002b), Hydrogeological report on water well monitoring in Aboriginal lands to May 2002, Report DWLBC 2002/026, Government of South Australia, through Department of Water, Land and Biodiversity Conservation, Adelaide

Dodds, AR, Tewksbury, P, Jacobson, G and Lau, JE, (1995), Groundwater salinity (1:1,000,000), in Lindsay, JF (ed.), *Geological Atlas of the Officer Basin, South Australia*, Australian Geological Survey Organisation, Canberra

GHD, (2009a), Report for Future Management of Water Resources, Consolidated Report for Stages 1 and 2, Report prepared for Alinytjara Wilurara NRM Board, GHD, Adelaide

GHD, (2009b), Report for Future Management of Water Resources, Consolidated Report for Stages 3,4 and 5, Report prepared for Alinytjara Wilurara NRM Board, GHD, Adelaide

GHD, (2010), Report for Future Management of Water Resources, Year 2 Summary Report, Report prepared for Alinytjara Wilurara NRM Board, GHD, Adelaide

Gibbs, M, Green, G, and Wood, C, (2011), Impacts of Climate Change on Water Resources Phase 2: Selection of Future Climate Projections and Downscaling Methodology, DFW Technical Report 2011/02, Government of South Australia, through Department for Water, Adelaide

Green, G, Gibbs, M, Alcoe, D, and Wood, C, (2012), Impacts of Climate Change on Water Resources, Phase 3 Volume 2: Eyre Peninsula Natural Resources Management Region, DFW Technical Report 2011/04, Government of South Australia, through Department for Water, Adelaide

Green, G, Gibbs, M, and Wood, C, (2011), Impacts of Climate Change on Water Resources, Phase 3 Volume 1: Northern and Yorke Natural Resources Management Region, DFW Technical Report 2011/03, Government of South Australia, through Department for Water, Adelaide

Harrington, GA, Cook, PG and Herczeg, AL, (2002), 'Spatial and temporal variability of ground water recharge in central Australia: a tracer approach', in *Ground Water*, 40, pp.518–528

Healy, RW and Cook, PG, (2002), 'Using groundwater levels to estimate recharge', in *Hydrogeology Journal*, 10, pp. 91–109

Herczeg, AL and Love, AJ, (2007), 'Review of recharge mechanisms for the Great Artesian Basin', Commonwealth of Australia, through the Commonwealth Scientific and Industrial Research Organisation, Canberra

International Panel on Climate Change, (2007), Climate change 2007 synthesis report, Pachauri, RK and Reisinger, A (Eds.), IPCC, Geneva, Switzerland

REFERENCES

Jeffrey, SJ, Carter, JO, Moodie, KB, and Beswick, AR, (2001), 'Using spatial interpolation to construct a comprehensive archive of Australian climate data', in *Environmental Modelling Software*, 16, pp. 309–330

Kottek, M, Grieser, J, Beck, C, Rudolf, B and Rubel, F, (2006), 'World map of the Köppen-Geiger climate classification updated, in *Meteorologische Zeitschrift*, 15, pp. 259–263

Littleboy, M, Silburn, DM, Freebairn, DM, Woodruff, DR and Hammer, GL, (1989), PERFECT, A computer simulation of productivity, erosion and runoff functions to evaluate conservation techniques, Bulletin QB89005, Government of Queensland, through Queensland Department of Primary Industries, Brisbane

Magee, JW, (2009), Palaeovalley groundwater resources in arid and semi-arid Australia – A Literature Review, Record 2009/03, Commonwealth of Australia, through Geoscience Australia, Canberra

Martin, R, Sereda, A and Clarke, D, (1998), Spencer Regions strategic water management study, Report Book 98/19, Government of South Australia, through Primary Industries and Resources South Australia, Adelaide

Miller, PG, (1967), Report on groundwater prospects, northwest reserve, Report Book 64/39, Government of South Australia, through Department of Mines, Adelaide

Nakicenovic, N, and Swart, R, (2000), IPCC Special Report on Emissions Scenarios, Cambridge University Press, Cambridge

Parsons Brinkerhoff, (2008), Jacinth-Ambrosia mineral sands mining project – mining and rehabilitation project, Report prepared for Iluka Resources, Parsons Brinkerhoff, Adelaide

Read, RE, (1989), Ernabella drilling, 1989, Report Book 89/80, Government of South Australia, through South Australia Department of Mines and Energy, Adelaide

Rowe, K, Woods, J, Denny, M and Mackenzie, E, (2006), Alinytjara Wiluṟara Natural Resources Management Region Draft Catchment Water Management Plan, Report prepared for Alinytjara Wiluṟara Natural Resources Management Board, South Australian Arid Lands Natural Resources Management Board, Port Augusta

Scanlon, BR, Healy, RW and Cook, PG, (2002), 'Choosing appropriate techniques for quantifying groundwater recharge', in *Hydrogeology Journal*, 10, pp. 18–39

Smith, I, and Chandler, E, (2010), 'Refining rainfall projections for the Murray-Darling Basin of south-east Australia - the effect of sampling model results based on performance, in *Climate Change*, 102, pp.377–393

Steffen, W, (2009), Climate change 2009: Faster change and more serious risk, Commonwealth of Australia, through Department of Climate Change, Canberra

Suppiah, R, Preston, B, Whetton, PH, McInnes, KL, Jones, RN, Macadam, I, Bathols, J and Kirono, D, (2006), Climate change under enhanced greenhouse conditions in South Australia, Commonwealth of Australia, through Commonwealth Scientific and Industrial Research Organisation Marine and Atmospheric Research, Melbourne

Tewksbury, P and Dodds, AR, (1997), An appraisal of the water resources of the Musgrave Block, South Australia, Report Book 96/009, Government of South Australia, through Department of Mines and Energy Resources South Australia, Adelaide

Tweed, S, Leblanc, M, Cartwright, I, Favreau, G, Leduc, C, (2011), 'Arid zone groundwater recharge and salinisation processes; an example from the Lake Eyre Basin, Australia', in *Journal of Hydrology*, 408, pp. 257–275

Ward, JD, Werner, AD, Nel, WP and Beecham, S,(2011), 'The influence of constrained fossil fuel emissions scenarios on climate and water resource projections', in *Hydrology and Earth Systems Sciences Discussions*, 8, pp. 2627–2665

Watt EL and Berens V, (2011), Non-prescribed groundwater resources assessment – Alinytjara Wiluṟara Natural Resources Management Region. Phase 1 – Literature and Data Review, DFW Technical Report 2011/18, Government of South Australia, through Department for Water, Adelaide

REFERENCES

Wood, C, and Green, G, (2011), Impacts of climate change on water resources phase 1: First order assessment and prioritisation, DFW Technical Report 2011/01, Government of South Australia, through Department for Water, Adelaide