TECHNICAL REPORT

IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

PHASE 3 VOLUME 2

EYRE PENINSULA NATURAL RESOURCES MANAGEMENT REGION

2012/04

Government of South Australia
Department for Water

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EYRE PENINSULA NATURAL RESOURCES MANAGEMENT REGION

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March, 2012

Technical Report DFW 2012/04

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ISBN 978-1-921923-25-8

Preferred way to cite this publication
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 2012/04, Government of South Australia, through Department for Water, Adelaide

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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.

Scott Ashby
CHIEF EXECUTIVE
DEPARTMENT FOR WATER

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SUMMARY

The Department for Water's 'Impacts of Climate Change on Water Resources' (ICCWR) project has undertaken detailed hydrologic modelling to determine the potential impact of climate change on the prescribed groundwater resources of the Eyre Peninsula Natural Resources Management Region, namely the Musgrave and Southern Basins Prescribed Wells Areas (PWA), and the surface water resource of the Tod Reservoir. This report is presented as Volume 2 of Phase 3 of the ICCWR project with the intention that reports of the 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 modelling 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.

Numerical models of groundwater recharge and surface water runoff were developed for the target water resources and calibrated against historic water level and flow data to ensure the models appropriately represented the variability of key hydrological records in response to annual variations in key climate variables. For the Musgrave and Southern Basins PWAs, groundwater recharge models were constructed using the modelling code LEACHM (Leaching Estimation and Chemistry Model) to simulate the flux of rainfall through the land surface and soil to the watertable. These recharge models were calibrated to estimates of groundwater recharge made in previous studies and aggregated in a GIS-linked modelling framework to give area-weighted average recharge rates. These take into account the variability of landscape attributes across the study area, including soil types, land uses, vegetation, climatic zones, depths to groundwater and land surface slope.

A surface water model was developed to represent the catchments naturally contributing to the Tod Reservoir, as well as those that can be diverted to the reservoir via constructed channels. The models were developed using the WaterCRESS platform, implementing the AWBM rainfall–runoff model and calibrated to the available flow record upstream of the reservoir. Two farm dam scenarios have been considered, representing the current conditions in the catchment and the full potential future development allowed by the Eyre Peninsula Natural Resources Management (EPNRM) Plan (EPNRMB 2009b).

Historic climate data for a period of 50 years were applied to establish a baseline of recharge and runoff statistics under historic climate conditions. A number of 50-year time series datasets of climate variables were generated to represent climates at three future time horizons (2030, 2050 and 2070), for two greenhouse gas emissions scenarios (B1 'low' emissions and A2 'high' emissions) using four different Global Climate Models (GCMs). The calibrated hydrologic models were then run using these datasets in place of historic climate data. The resulting modelled runoff and recharge statistics under future climate scenarios were compared with those from the historic baseline.

Annual recharge and runoff totals were found to be more closely correlated with variations in annual rainfall totals than with variations in seasonal rainfall totals or potential evapotranspiration. A relationship between future reductions in annual rainfall (as a result of climate change) and reductions in both surface runoff and groundwater recharge was determined and used to summarise the potential impacts on surface water and groundwater of the median climate change projections reported by the CSIRO Climate Change in Australia report (CSIRO and BoM, 2007) and summarised for South Australian regions by the Department of Environment and Natural Resources (DENR, 2010). Whilst the numerical modelling in this study is based on 'low' (B1) and 'high' (A2) emissions scenarios, the annual rainfall projections for South Australia summarised by DENR (2010) are based on low, medium and high emissions scenarios.

In the Musgrave PWA, the projected reductions in groundwater recharge resulting from median climate scenarios projected by CSIRO and BoM (2007) range from 12% in 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). In the Southern Basins PWA, the corresponding projected reductions in groundwater recharge range from 11% in a 2030 climate to 47% in a 2070 climate.

Greater reductions were found for surface water runoff in the catchments contributing to the Tod Reservoir. Projected reductions in median annual runoff ranged from 23% in a 2030 climate to 69% in a 2070 climate with a medium or high emissions scenario. While the surface water resources on Eyre Peninsula currently have limited use for water supply and the density of farm dams is low compared to other regions in the state, these large reductions in runoff for much smaller reductions in rainfall (i.e. 3.5% to 15%) highlight the vulnerability of catchments in regions such as this, where the average annual rainfall is 500 mm or less, to changes in climate. The scale of these projected changes also highlights a need to consider potential climate change impacts in any assessments of the future viability of the Tod Reservoir, particularly as an alternative or emergency water supply.

In addition to changes in mean annual recharge and median annual runoff, the models project significant changes to the frequency of years that would in the historic record be considered to be ‘low’ or ‘high’ recharge years. Under climate scenarios resulting from the most moderate of the four GCMs applied, the frequency of years of unusually low recharge (defined by the 20th percentile recharge in the historic record) increases by 50–70% in 2030 climate scenarios and by 80–200% in 2070 climate scenarios. The frequency of ‘high’ recharge years (as defined by the 80th percentile recharge in the historic record) reduces by 10–20% in 2030 climate scenarios and by 50–70% in 2070 climate scenarios. Similar percentage changes are projected to the frequency of high and low runoff years from the surface water runoff model of the Tod Reservoir catchments.

The key results of this study are presented in Chapter 5, in a format that is intended to provide water resource planners and other stakeholders with an overview of the potential impacts of climate change on the water resources of the Eyre Peninsula NRM Region, without reference to the details of the underlying modelling process.

1. INTRODUCTION

1.1. PROJECT BACKGROUND

Climate change is acknowledged as a potential threat to the future of South Australia's water security. South Australia'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 CSIRO and the Bureau of Meteorology (BoM) have previously undertaken investigations which project the likely impacts of climate change on South Australia (Suppiah *et al.*, 2006; CSIRO and 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 evapotranspiration (PET), 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 of good quality water resources and an increased risk to the security of important water resources.

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".

This report provides details and results of the studies of the prescribed areas of the Eyre Peninsula Natural Resources Management (EPNRM) Region and the Tod River surface water catchment.

1.2. PREVIOUS WORK

This report is preceded by three related reports that have been completed by the ICCWR project.

A prioritisation report (Wood and Green, 2011) provides a preliminary guide to the relative risk posed by climate change for all of South Australia's existing water resources. The prioritisation report provides a ranking table of the State's water resources, identifying those for which the impacts of potential climate change present the greatest risks to water availability. Further to the formal prioritisation process, a number of internal and external stakeholders were consulted in order to determine which water resources are considered to be high priorities for water planning, to be the subject of the first detailed impact modelling studies. Through this process, the resources of the Northern and Yorke Natural

Resources Management (NYNRM) Region and the EPNRM Region were selected as priorities for modelling studies.

To enable detailed modelling of climate change impacts on surface and 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' datasets that are a) representative of each study area location and b) in a form that is suitable as input for daily time step hydrological models. 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).

This report is preceded by an earlier report on the impacts of climate change on the NYNRM region, titled 'Impacts of Climate Change on Water Resources, Phase 3 Volume 1: Northern and Yorke Natural Resources Management Region' (Green *et al.* 2011). The resources considered were the Clare Valley Prescribed Water Resources Area (PWRA) and the Baroota PWRA. This report follows a similar structure, with the same methods applied to the Eyre Peninsula region.

This study draws partly from earlier work by Ward *et al.* (2009), which provided a modelling framework for assessing groundwater recharge processes and climate change on the Eyre Peninsula. The ICCWR project uses a very similar groundwater recharge modelling framework to that described by Ward *et al.* (2009), however there are several important differences in the ICCWR application of the modelling framework, including the range of climate change projections applied, the climate downscaling approach, the historic climate data baseline period, the spatial data for the modelled areas, model boundary conditions and the calibration of the model.

1.3. AIMS AND OBJECTIVES

The objective of the EPNRM Region study is to provide, for water planning and adaptation policy purposes, an understanding of the likely changes to groundwater recharge in the Southern Basins and Musgrave Prescribed Wells Areas (PWAs) and surface runoff in the Tod Reservoir catchment under a range of possible future climate scenarios.

The study was focussed on surface water runoff and groundwater recharge rates as these are the principal determinants of the capacity of water resources. With some exceptions, the amount of water that is available from surface water and groundwater resources for both environmental water provisions and human water uses is dictated by the average annual volumes of surface water runoff and groundwater recharge. Hence, knowledge of the percentage changes to these amounts that may occur due to the projected impacts of climate change is essential for the planning and adaptation of water resources management 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 Global Climate Models (GCMs) are applied to hydrological models that are calibrated to represent the target water resources. The runoff and recharge derived with models using the projected future climates are then compared with those derived by running the models with historic climate and the differences are reported.

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

1. Develop models for the water resources of the EPNRM Region that appropriately represent the relationship between the hydrologic variables of surface water runoff and groundwater recharge and the climatic variables of rainfall and potential evapotranspiration.

2. Generate a baseline time series of historic runoff and recharge amounts for the target water resources.
3. Generate a time series of recharge and runoff amounts for the target water resources under a range of future climate scenarios.
4. Develop a quantitative relationship between the runoff and recharge and key climate variables for the target water resources.
5. Report on the projected percentage changes to surface runoff and groundwater recharge under a range of projected future climates for 2030, 2050 and 2070.

2. THE EYRE PENINSULA NATURAL RESOURCES MANAGEMENT REGION

The EPNRM Region has a population of around 35 000 (ABS, 2011) across an area of around 55 000 km^2. It is a semi-arid region with scarce surface water supplies and consequently the region is almost entirely reliant on groundwater for its reticulated public water supply. Significant reserves of good quality groundwater are found in a series of fresh groundwater lenses that occur in the southern part of the region between Eyre Peninsula's main urban centre of Port Lincoln (population of ~13 000) and the township of Coffin Bay and in the north-west near the township of Elliston. A large proportion of the reticulated water supply for the EPNRM region comes from these resources (DWR 2001a) and hence they were prescribed in 2000–01 under the *Water Resources Act 1997*. The prescribed groundwater resources are separated into two PWAs – the Musgrave PWA (Fig. 1) and the Southern Basins PWA (Fig. 3). To the north-east of the Southern Basins PWA is the Tod Reservoir (Fig. 5), which is the only significant surface water storage in the region. The Tod Reservoir forms part of SA Water's contingency planning as an emergency water source for the Eyre Region (SA Water, 2008; EPNRMB, 2009a).

2.1. MUSGRAVE PRESCRIBED WELLS AREA

2.1.1. REGIONAL SETTING

The Musgrave PWA is approximately 120 km north-west of Port Lincoln (300 km west of Adelaide) and occupies approximately 3595 km^2 (Fig. 1). Elliston is the largest town within the Musgrave PWA, with a population of approximately 380. It is characterised by generally flat topography with a gradual rise in elevation to the east. Surface water flows into the Musgrave PWA are very low and surface runoff is almost non-existent. Small ephemeral creeks may develop in upland areas, however they drain locally into small closed depressions or directly recharge the groundwater system through dissolution features (Love *et al.*, 1996). Water for town supply, irrigation and stock and domestic use comes primarily from groundwater.

2.1.2. GEOLOGY AND HYDROGEOLOGY

The hydrogeology and status of groundwater resources within Eyre Peninsula's PWAs are described in *Groundwater Status Reports* prepared for each PWA. In view of this, only a limited discussion of the region's hydrogeology is presented here.

The Quaternary Limestone aquifer consists of the Bridgewater Formation, a calcareous sandy limestone with fine shell fragments, and is the main aquifer from which extraction occurs. An evaporative calcrete horizon marks its upper boundary. The Quaternary aquifer is karstic, highly heterogeneous and dissolution features and secondary cementation are common in places. Water table response to precipitation suggests that recharge occurs after intense rainfall events and occurs both as diffuse infiltration through the skeletal soils overlying the limestone aquifer and point source infiltration of rainfall and localised runoff down dissolution features (sink holes). The Quaternary Limestone aquifer contains brackish groundwater and fresh groundwater lenses.

Evans *et al.* (2009) report that the location of fresh groundwater lenses is governed by spatial variation in recharge rates, i.e. where a greater proportion of total rainfall infiltrates to the water table the groundwater is typically fresh. The Quaternary Limestone lenses are consequently defined partly by geologically controlled structures and partly by the 1 000 mg/L isohaline.

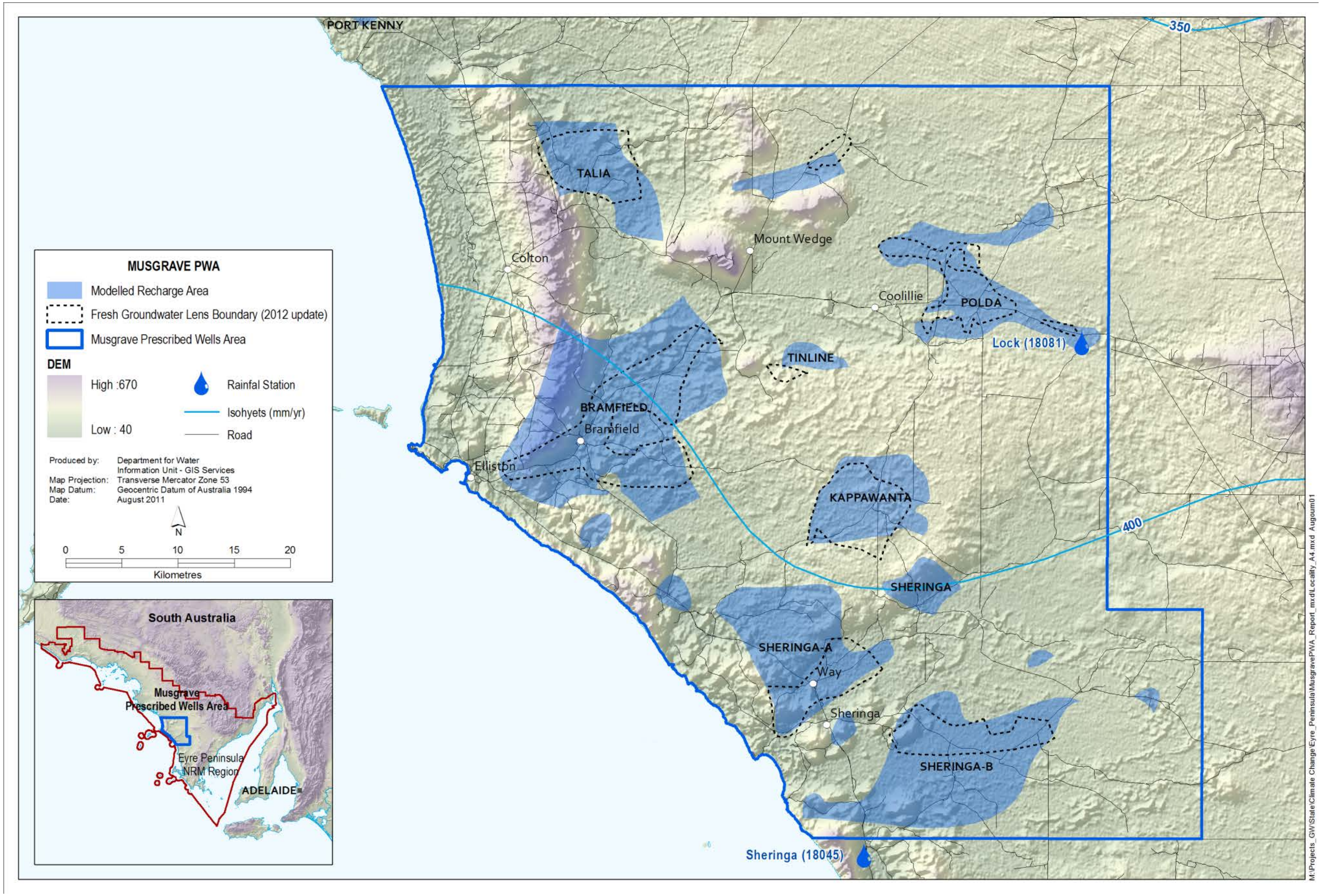


Figure 1. The Musgrave Prescribed Wells Area and location of modelled recharge areas (blue) (Evans *et al.*, 2009a) and fresh (<1000 mg/L) groundwater lens extents (Stewart *et al.*, 2012, in prep.)

The modelled recharge areas and fresh groundwater lenses are shown in Figure 1. The recharge areas defined in the current Eyre Peninsula WAPs are markedly larger than the fresh groundwater lenses which were re-defined in 2012 (Stewart *et al*., 2012, in prep.). However, they are similar in location and extent to the fresh groundwater lenses that were defined in 2008 (Evans *et al*. 2009a; Evans *et al*. 2009b). In view of this, the modelled recharge areas have been approximated according to the 2008-defined groundwater lens extents.

Estimated average annual recharge rates for the Musgrave PWA fresh groundwater lenses, based on the rainfall/recharge relationship, the rainfall and underground water chloride balance and environmental isotope analysis, range between 28–32 mm/y (ERWRPC 2000a).

A Tertiary Sand aquifer overlies the basement or Jurassic sequence. Salinities in this aquifer are up to 33 000 mg/L (DFW, 2012) and well yields are generally poor (1–10 L/s) (DFW, 2011b). The presence of unconsolidated fine quartz sands result in well production difficulties and has limited development of the Tertiary Sands aquifer to local stock and domestic purposes (Evans *et al.*, 2009a). A thin clay aquitard separates the Tertiary Sand aquifer from the overlying Quaternary Limestone aquifer. A Jurassic Sand aquifer (the Polda Formation) overlies the basement in the north west, however low well yields and high salinities (30 000–50 000 mg/L) (DFW, 2011b) mean it is unsuitable for irrigation or stock and domestic purposes. The geologic basement in the Musgrave PWA comprises crystalline gneisses and granites of the Gawler Craton.

Groundwater discharge occurs as evapotranspiration from shallow water tables, vegetation and in generally ephemeral inland wetlands and permanent saline coastal lagoonal wetlands. The majority of groundwater extraction in the Musgrave PWA is for stock and domestic purposes (Stewart *et al.* 2012, in prep.) while the majority of licensed extraction is from the Bramfield lens for Elliston's town water supply (DFW, 2011b). A more detailed discussion of the hydrogeology of the Musgrave PWA can be found in the Groundwater Status Report for the Musgrave PWA (DFW, 2011b) and Love *et al.* (1996), while a more detailed investigation of the Polda lens can be found in Evans (1993).

2.1.3. CLIMATE

The Musgrave PWA is characterised by a Mediterranean climate with hot, dry summers and mild, wet winters. Mean annual rainfall ranges from 435 mm/y at Sheringa (BoM station # 18045) to 313 mm/y further inland at Kyancutta (BoM station # 18044) (BoM, 2011a). Rainfall is winter dominant, with monthly rainfall generally exceeding monthly potential evapotranspiration only in the months of June and July (Fig. 2).

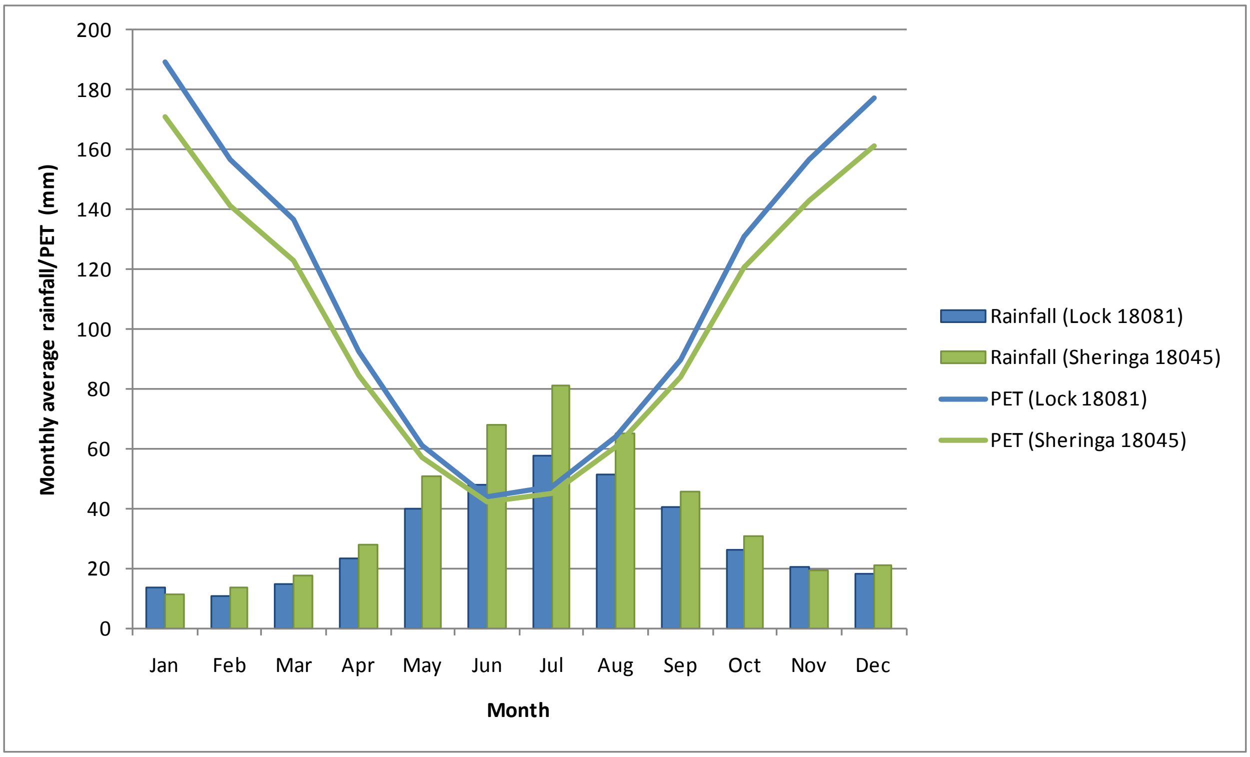


Figure 2. Mean monthly rainfall and PET in the Musgrave PWA (based on 50-year averages from 1960–2009)

2.2. SOUTHERN BASINS PRESCRIBED WELLS AREA

2.2.1. REGIONAL SETTING

The Southern Basins PWA covers an area of 870 km^2 (Fig. 3). The area is characterised by undulating topographic relief, with elevation ranging from 140 m AHD at coastal cliffs, to near sea level inland. One permanent and two ephemeral saline lakes and two brackish lakes feed ephemeral watercourses (DWR, 2001). Groundwater is the primary source of water for town water supply, irrigation and stock and domestic use.

2.2.2. GEOLOGY AND HYDROGEOLOGY

The geology of the Southern Basins is similar to that of the Musgrave PWA. The Quaternary Limestone aquifer in the Southern Basins PWA consists of the Bridgewater Formation and it displays similar characteristics to the Quaternary aquifer in the Musgrave PWA (high spatial heterogeneity, dual porosity from karstic development etc.). Recharge processes are also similar, with diffuse infiltration of rainfall being dominated by direct 'point source' infiltration of runoff through dissolution features. The extent of modelled recharge areas and fresh groundwater lenses are shown in Figure 3. The modelled recharge areas have been determined from the topography and surficial geology and their extents do not vary with time, whereas the fresh groundwater lens extents are dynamic. Long-term average recharge rates (estimated by multiple methods) have ranged between 34–155 mm/y (ERWRPC 2000b). Groundwater extraction from the Quaternary Limestone aquifer is primarily from the fresh groundwater lenses (less than 1000 mg/L). The majority of extraction is for town water supply and around 90% of the total volume extracted from the Southern Basins PWA comes from the Uley South Basin (DFW 2011c). Groundwater extractions for stock and domestic purposes are estimated to be around 133 ML/y (Stewart *et al.*, 2012, in prep.)

The Tertiary Sands aquifer is low yielding and generally shows high salinities (up to 5000 mg/L). It is primarily developed locally for stock and domestic purposes. The Quaternary Limestone aquifer and the Tertiary Sands aquifer are mostly separated by a clay confining layer. Where the clay layer is absent however, there is thought to be significant hydraulic connection between the two, with downward leakage from the Quaternary aquifer acting as a source of recharge to the Tertiary Sands aquifer (DFW, 2011c; Evans, 1997). However, Harrington *et al.* (2006) found evidence of upward leakage from the Tertiary Sands aquifer to the Uley South lens and estimated to the flux to be of the order of 14 mm/y, although this is a relatively small proportion of the water budget for this lens. The Tertiary sequences are underlain by crystalline basement rocks.

2.2.3. CLIMATE

The Southern Basins PWA has a Mediterranean climate with hot, dry summers and cool, wet winters. Mean annual rainfall is 573 mm/y (BoM station # 18137) (BoM, 2011a) and there is a gradient of decreasing rainfall to the north and east. In comparison to the Musgrave PWA, the Southern Basins has a more pronounced 'wet winter' period between May and August during which mean monthly rainfall exceeds mean monthly PET (Fig. 4).

2.3. TOD RESERVOIR

2.3.1. REGIONAL SETTING

Surface water on Eyre Peninsula is scarce. Streams flow predominately during the winter months and they generally lie in the eastern and southern ranges, where the dominant winter rainfall results in seasonal surface flows. The Tod River, located 30 km to the north of Port Lincoln, is the only permanent stream on Eyre Peninsula (EPNRMB, 2009a) and has a catchment area of approximately 388 km^2.

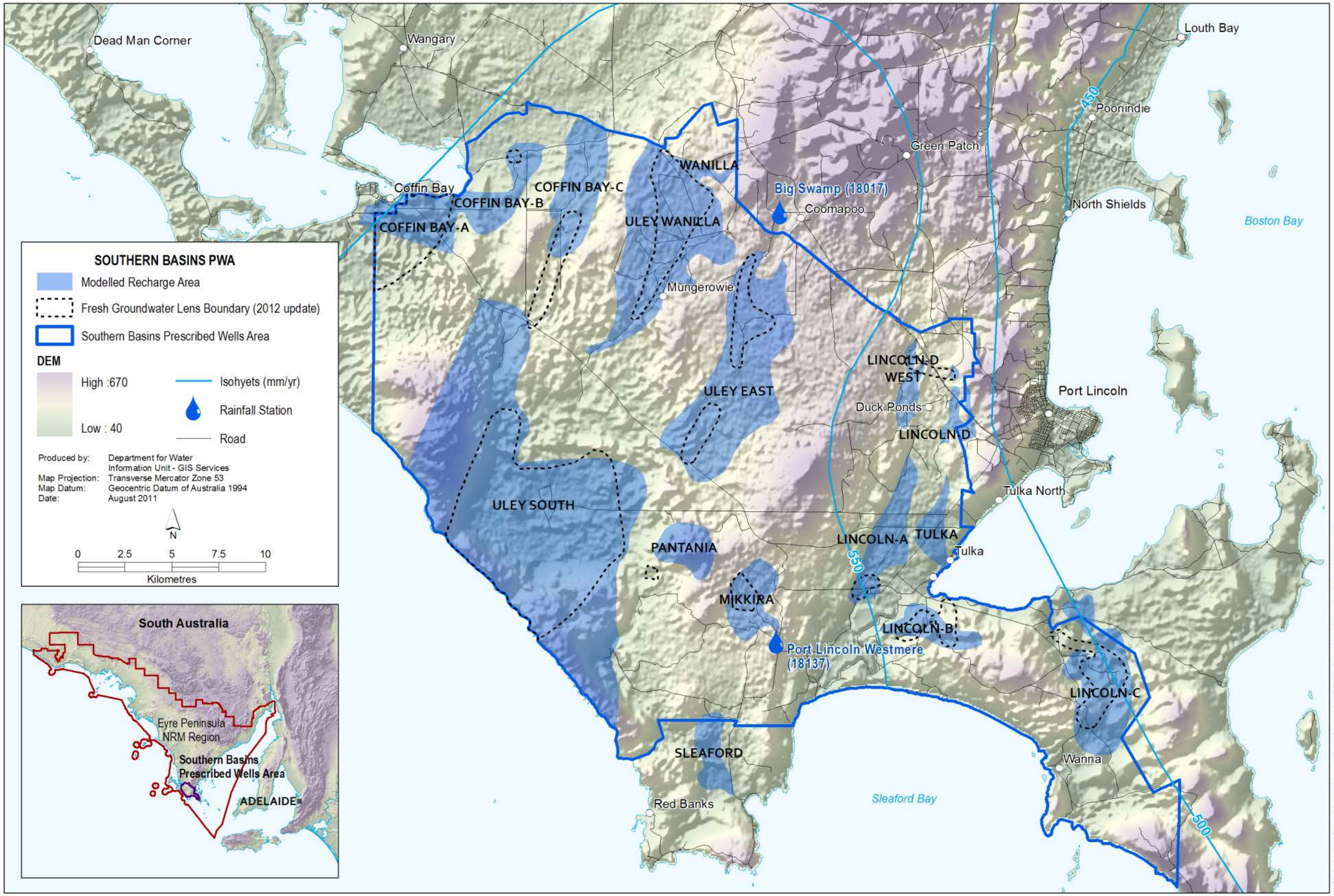


Figure 3. The Southern Basins Prescribed Wells Area and location of modelled recharge areas (blue) (Evans *et al.*, 2009b) and fresh (<1000 mg/L) groundwater lens extents (Stewart *et al.*, 2012, in prep.)

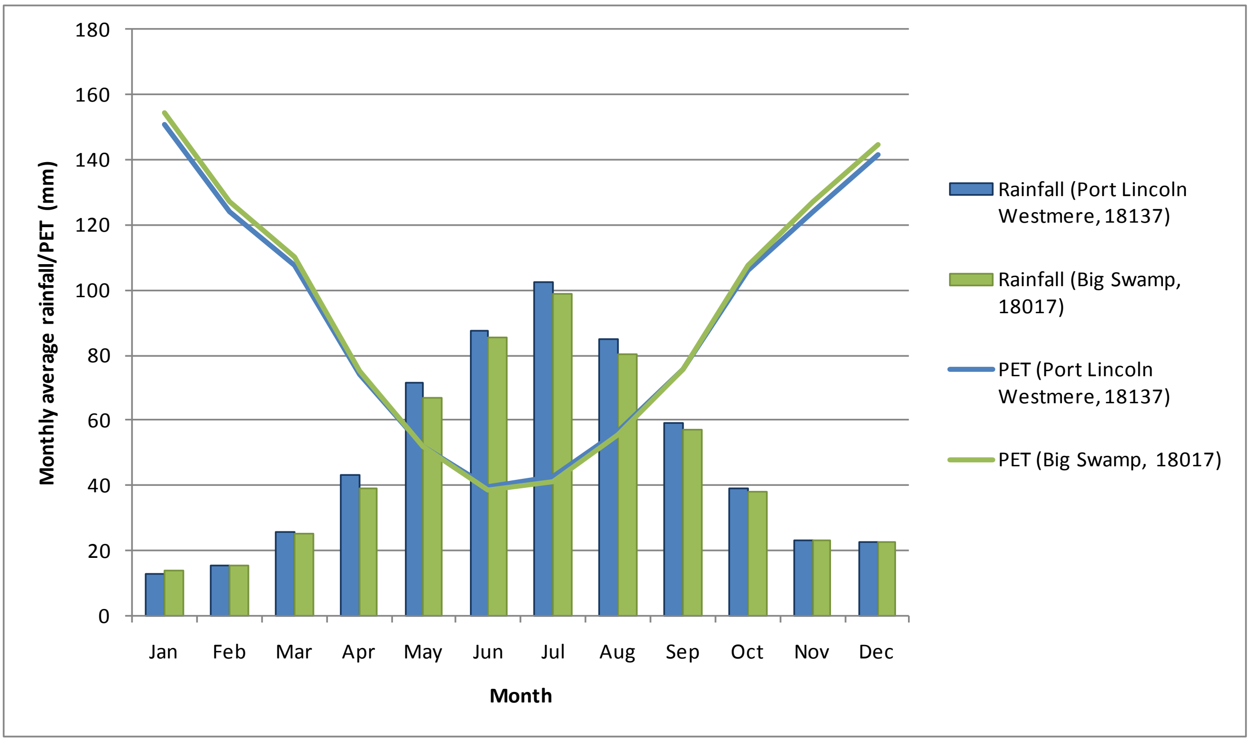


Figure 4. Mean monthly rainfall and PET in the Southern Basins PWA (based on 50-year averages from 1960-2009)

The Tod Reservoir is located in Toolillie Gully, on a tributary of the Tod River (Fig. 5), and is the only major surface water storage on Eyre Peninsula. The reservoir has a theoretical maximum capacity of 11 300 ML and was used as a water supply for lower Eyre Peninsula from 1925. Historically, up to 3000 ML/y has been extracted from the reservoir for potable use (SA Water, 2008). However, due to deteriorating water quality, this resource has not been used as a water supply since early 2002 and is held as an emergency supply of water only (DFW 2011a). The Tod Reservoir still forms part of SA Water's contingency planning for the Eyre Region and while desalination of this water was considered, the assessments undertaken indicated that it is unlikely to be a viable option (SA Water, 2008; EPNRMB, 2009a). Water from the main stream of the Tod River and the Pillaworta Creek can be diverted into the reservoir via concrete-lined channels when stream flow is of sufficiently low salinity (SA Water, 2008). Including the diversion catchments, the catchment area of the tributaries of the Tod River that can contribute flow to the Tod Reservoir is approximately 197 km^2.

2.3.2. CLIMATE

The Tod Reservoir catchments have a Mediterranean climate with hot, dry summers and cool, wet winters. Rainfall is winter dominant and mean monthly rainfall generally exceeds mean monthly PET between the months of May and August (Fig. 6). Mean annual rainfall is 505 mm/y and there is a gradient of decreasing rainfall to the north and east. Mean annual rainfall for the upper reaches of the Toolillie Gully catchment is 520 mm/y, decreasing to less than 460 mm/y in parts of the Pillaworta Creek catchment.

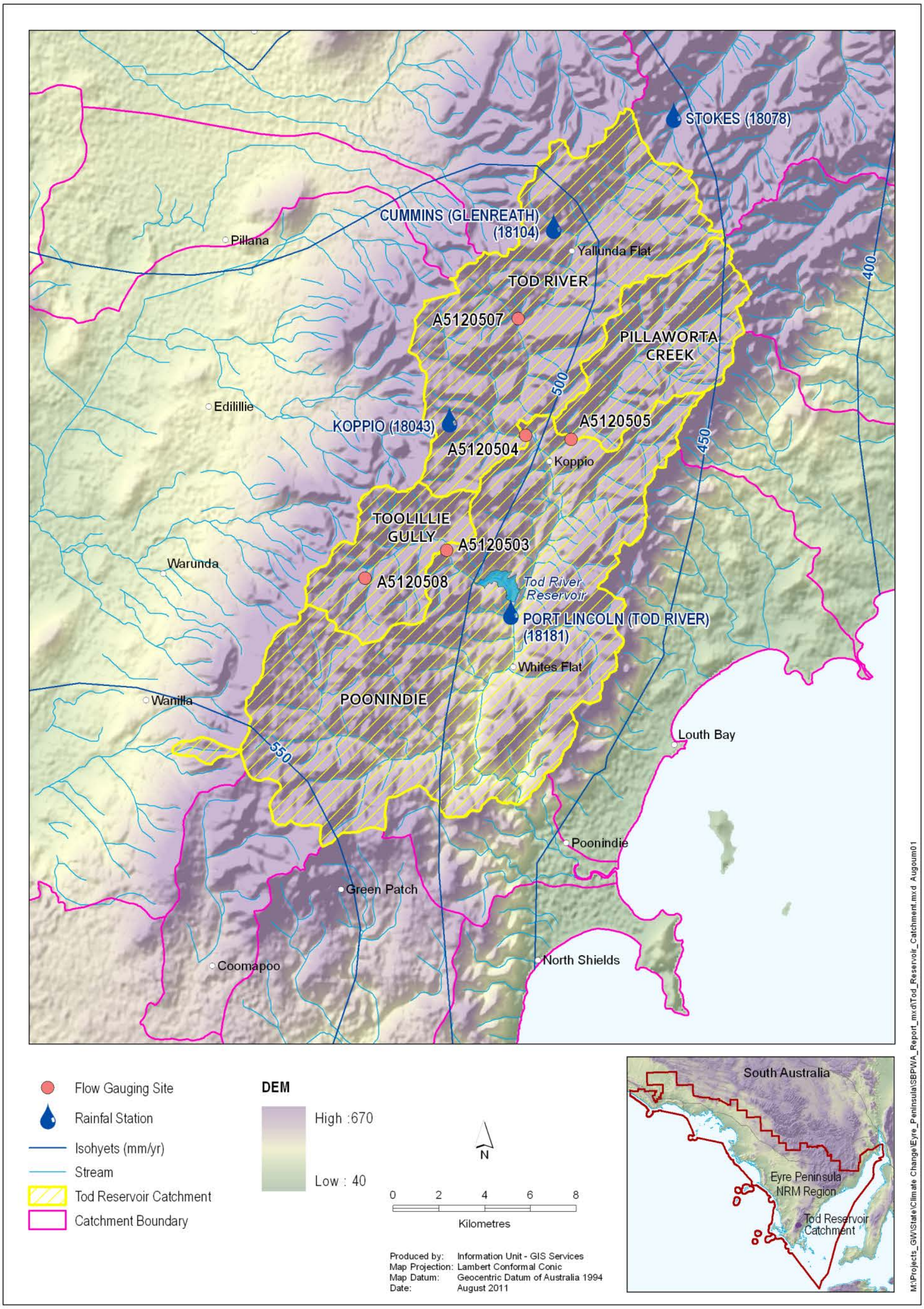


Figure 5. The Tod River catchment

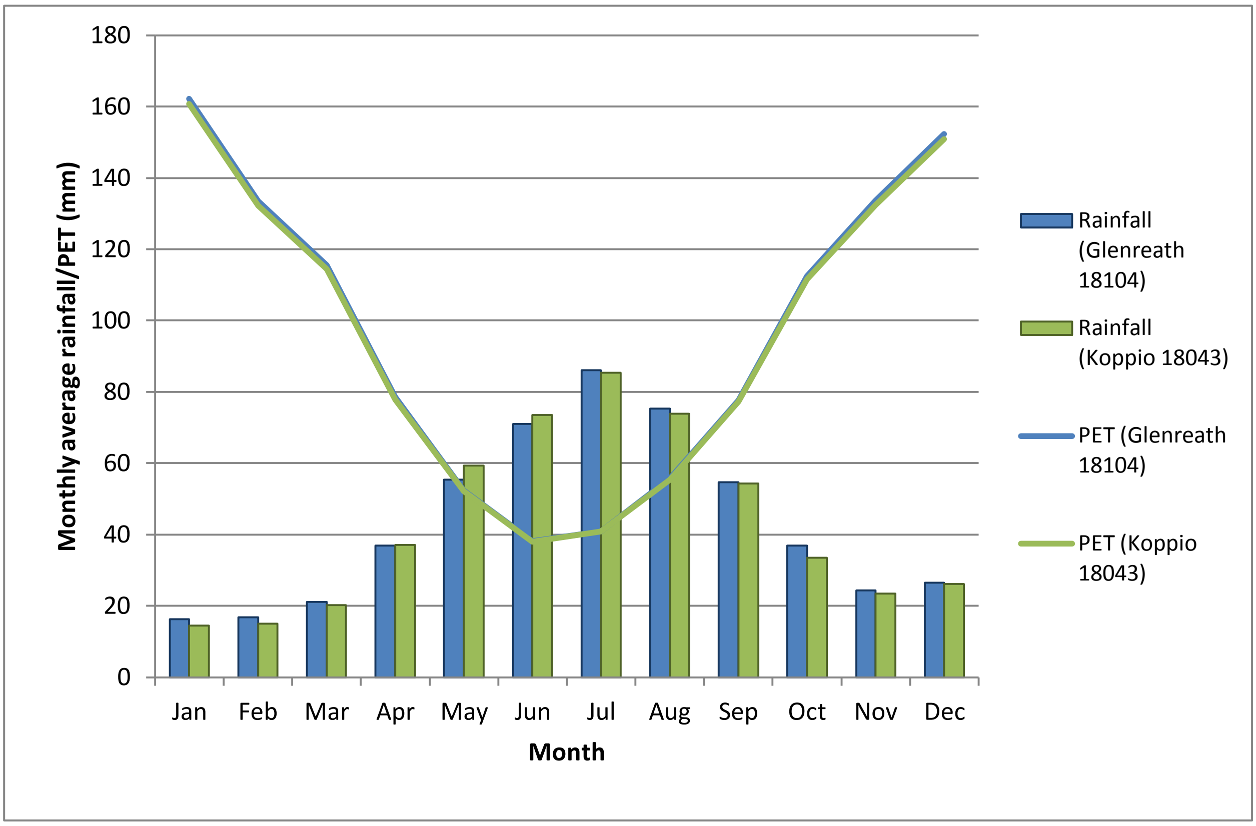


Figure 6. Mean monthly rainfall and mean monthly PET for Tod Reservoir catchments (based on 50-year averages from 1960-2009).

2.3.3. HYDROLOGY

The fraction of rainfall converted to runoff in the Tod River catchments is low, with a runoff coefficient (average annual runoff divided by average annual rainfall) of 0.047–0.066 (McMurray, 2006). This can be compared to catchments in the Mount Lofty Ranges, where runoff coefficients range from 0.11–0.28 for the western catchments and 0.06–0.09 for the eastern catchments.

The clearing of land, agricultural development (including harvesting of surface water for stock use) and use of water for potable water supply has changed considerably the approach to water resource management (McMurray, 2006). This includes widespread stock and domestic farm dams of variable size, in addition to the Tod Reservoir and the two diversion weirs. Across the Eyre Peninsula farm dam density is relatively low, with a density of 2.1 ML/km^2 for the Toolillie Gully catchment, compared to 14 ML/km^2 in the Eastern Mount Lofty Ranges (Alcorn, 2009). Along with much of the region, several areas within the Tod River catchments are affected by dryland salinity and waterlogging which threaten agricultural productivity and affect reservoir water quality (McMurray, 2006).

The Tod River Wetland System has been classified as a Nationally Significant Wetland under the Directory of Important Wetlands (Australian Nature Conservation Agency, 1996). The wetland system covers the whole catchment from the upper first order streams of the Tod River through to the Poonindie swamps and the Tod estuary (Bebbington, 2003).

3. METHODOLOGY

3.1. CLIMATE CHANGE SCENARIOS

The ICCWR project Phase 2 report (Gibbs *et al.*, 2011) describes the process by which four GCMs were selected based on the required outputs made available by each model, as well as their suitability for the South Australian climate. Based on these considerations, the GCMs selected were the NCAR-CCSM3, CSIRO Mk 3.5, LASG-IAP and MRI models. The outputs produced by the GCMs are too coarse to be used as inputs for impact models directly, as the cells in the models are hundreds of kilometres by hundreds of kilometres and even though the outputs are on a daily time step, they are generally too smooth and do not represent the observed daily variation, especially for rainfall. Hence, the GCM outputs and projections contained within the outputs were downscaled to generate daily-time-step climate data (rainfall and PET) suitable for the surface water and groundwater models used in this study.

For each region in which a surface runoff or groundwater recharge model was applied, observed historic rainfall and PET data from an appropriate Bureau of Meteorology weather station has been taken to represent the historic baseline case. A 50-year period has been used to represent the variation in the baseline case, taken as the period from 1960–2009, inclusive. This baseline weather dataset was then perturbed based on the GCM projections to produce downscaled climate variable datasets, each containing daily rainfall and PET amounts for the 24 combinations considered (three future time horizons (2030, 2050 and 2070), two emissions scenarios and four GCM projections) (Fig. 7). A daily scaling method has been used to downscale the GCM rainfall projections, which scales the historic rainfall series by different amounts, depending on the frequency of occurrence of rainfall events. This approach allows for an increase in the highest rainfall days, while still reducing the overall average rainfall if this is projected by the GCM. However, the approach does not account for changes in the sequencing and timing of rainfall events.

It is acknowledged that the sequence and timing of rainfall events of varying magnitude may be important in the recharge processes in the study areas. For example, Evans *et al.* (2009a) suggested the Polda Basin groundwater resource shows an annual water level rise when it receives greater than 60 mm of rainfall in a month between the months of May and October. However, using the downscaling technique described above, the timing of rainfall events in the downscaled climate datasets simply reflects their timing in the 1960–2009 historic baseline period. The hydrological projections resulting from the application of these climate data to hydrological models are therefore subject to the assumption that the historic sequence and timing of rainfall events of varying magnitude during the period 1960–2009 are a reasonable representation of the sequence and timing of rainfall events in future climates.

A constant, monthly scaling was used to produce the future PET time series. More details on the downscaling methods are provided in the ICCWR project Phase 2 report (Gibbs *et al.*, 2011).

In the modelling of future demand and supply for the Greater Adelaide region to the year 2050, the *Water for Good* plan considered both the Special Report on Emissions Scenarios (SRES) A2 and B2 scenarios (Nakicenovic and Stewart, 2000). The daily GCM outputs required for downscaling are generally not available for the B2 scenario, hence in this work the B1 emission scenario has been adopted to represent the low emission case, while the A2 scenario has been preserved as the high emissions scenario. CSIRO and BoM (2007) considered forecast time horizons of 2030, 2050 and 2070. These have been deemed appropriate for this study as the 2030 horizon provides a representation of the near future and is likely to be of most interest to inform current water allocation planning, 2070 and beyond is of most interest for infrastructure planning, while 2050 provides a middle-ground projection, and was also the time horizon considered in the *Water for Good* Plan.

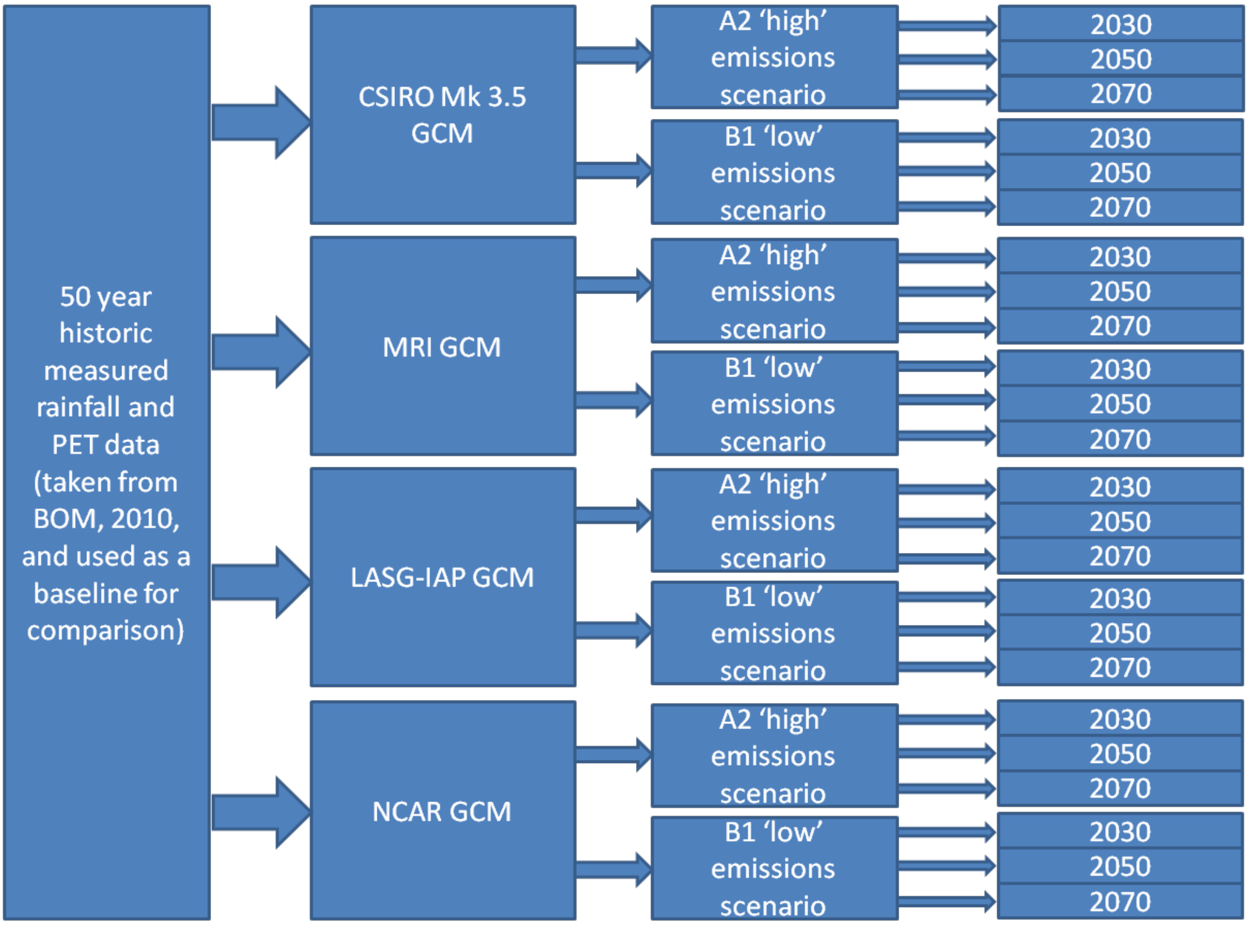


Figure 7. Flowchart describing the number of climate change scenarios that were tested in each surface water runoff and groundwater recharge model

3.2. MODELLING ASSUMPTIONS

A number of assumptions were necessary to develop models that can be used to run simulations of groundwater recharge and surface water runoff for both historic and future climates. The primary assumptions were:

- land use in future climate scenarios is the same as in the historic baseline period
- irrigated land uses maintain the same irrigation practices in future climate scenarios
- water table depths are the same under future climate scenarios as in the historic baseline period
- in the LEACHM modelling of groundwater recharge, recharge is reported as the sum of drainage to the watertable plus runoff, the assumption being that all surface runoff contributes to groundwater recharge.

These assumptions are further explained below.

The assumption of unchanged land use patterns with historic and future climate simulations is explicit in the groundwater recharge models for the EPNRM Region and is implicit in the surface runoff models for the Tod River catchments. In reality, land use patterns are likely to change with significant changes in climate. However the nature of these changes is dependent on a large number of contributing factors, including the possible introduction of new water sources. It was beyond the scope of this project to make predictions of these changes.

It is assumed that in future climate scenarios, the irrigated land use types continue with the same irrigation practices, maintaining the same soil moisture content while the crop is in place and applying more irrigation water to compensate for the lower rainfall and higher PET.

An assumption of fixed water table depth is made for the LEACHM recharge models (Sec. 3.3). The GIS-linked, spatially distributed LEACHM model for the EPNRM Region has spatially varying water table depths according to their variation across the study area. However, whilst it is recognised that water levels do change temporally, these depths are not changed in the model, either within each simulation or between historic and future climate simulations. This approach was validated with sensitivity testing and further qualification of this approach is made in Section 3.4.4.

Karst development is extensive in the Quaternary Limestone aquifer across the Eyre Peninsula. This is manifested on the surface by the undulating topography and the numerous ‘sink holes’ that occur. These sink holes often act as drainage points in the closed basins of Eyre Peninsula, with surface runoff flowing into such features and directly recharging the aquifer. This recharge via sink holes is assumed to occur in addition to diffuse recharge though variably saturated layers of soil and calcrete. In view of this conceptual model of combined diffuse and sink hole recharge and the absence of surface outflow from the groundwater resource catchments in the Eyre Peninsula, recharge to the aquifers of the Musgrave and Southern Basins PWAs has been assumed in this study to be the sum of modelled diffuse recharge to the watertable plus modelled surface water runoff. It should be noted that the LEACHM models applied here do not simulate the actual process of surface water draining into sink holes, rather runoff is calculated as part of the water balance in the model and it is all assumed to contribute to recharge via drainage into sink holes. The same approach has been applied in earlier studies (e.g. Ward *et al.* 2009).

3.3. GROUNDWATER RECHARGE MODELLING

The objective of the groundwater recharge models described here is to appropriately represent the variability of recharge to unconfined groundwater under varying climatic conditions. Whilst the assumption that all runoff contributes to groundwater recharge is likely to result in overestimates of recharge rate, it is not intended that the models provide a definitive estimate of recharge volume. As the recharge models are calibrated to produce an annual average recharge that is similar to those from previous studies, these models should not be expected to provide better estimates of average annual recharge than those from previous studies. However, the models developed here are carefully calibrated to correctly represent the inter-annual variations in recharge that result from variations in rainfall and evapotranspiration conditions from year to year.

These models should be able to correctly represent historic variations in annual recharge amounts under annual variations in recorded weather variables. The ability of the models in this regard is an important indicator of their usefulness to assess changes to recharge under alternative climates. Many studies have investigated recharge to the various groundwater lenses in the Eyre Peninsula using multiple methods (Tables 1 and 2) and a relationship to annual rainfall amounts (and rainfall intensity) is acknowledged. Also acknowledged is the influence of karst features on recharge, with surface water runoff into sink holes thought to contribute a significant amount of recharge. Ward *et al.*, (2009) modelled recharge using a similar approach to this study (unsaturated zone modelling) and considered recharge to be the sum of diffuse infiltration of rainfall to the watertable and any surface water runoff generated in the model.

Table 1. Recharge estimates from various studies for the Southern Basins Prescribed Wells Areas (PWA) (Evans, 1997)

***PWA*/Study**	**Estimation technique**	**Estimated Quaternary lens recharge (mm/y)**		
Southern Basins		***Uley South***	***Uley Wanilla***	***Uley East***
Buick (1941)	Not stated	n/a	350	350
Segnit (1942)	Not stated	n/a	145	145
Morton & Steel (1968)	Not stated	83	n/a	n/a
Sibenaler (1976)	Not stated	40	n/a	n/a
Barnett (1978)	Hydrograph method; limiting winter rainfall	105	n/a	n/a
EWS (1984)	Not stated	72	72	72
Evans (1997)	Chloride mass balance	64–71	33–51	n/a
Evans (1997)	Water balance analysis	157	85	76
Evans (1997)	Water balance with salt water interface consideration	78	n/a	n/a
Evans (1997)	Hydrograph fluctuation with specific yield calculations	46	20	11
Evans (1997)	Chlorofluorocarbon concentrations	<200	<50	<75
Water Allocation Plan (2000)	Hydrograph method; chloride mass balance; environmental isotope analysis	155	54	69
Ordens *et al.* (2011)	Chloride mass balance; water table fluctuation; chlorofluorocarbon concentrations	47–129	n/a	n/a

In order to represent variations in recharge with climate, the recharge models developed here must be calibrated against estimates of recharge for individual years. One of the most reliable methods for making annual estimates of groundwater recharge is the watertable fluctuation (WTF) method. This method relies on available groundwater level data and knowledge of aquifer properties, and assumes that a seasonal rise in groundwater level is due to rainfall recharge. Annual recharge (R) is calculated as:

$$R = \Delta GW.Sy \qquad \text{(Equation 1)}$$

Table 2. Recharge estimates from various studies for the Musgrave Prescribed Wells Areas (PWA)

***PWA*/Study**	**Estimation technique**	**Estimated Quaternary lens recharge (mm/y)**			
Musgrave		***Polda***	***Bramfield***	***Kappawanta***	***Sheringa A***
Coffey & Partners (1981)	Darcy's Law; groundwater modelling	45–49	n/a	n/a	n/a
Evans (1993)	Chloride mass balance; Darcy's Law	27–40	n/a	n/a	n/a
Love *et al.* (1994)	Chloride mass balance	n/a	15–78	20–49	30–59
Water Allocation Plan (2001)	Hydrograph method; chloride mass balance; environmental isotope analysis	28	31	32	29

Where ΔGW is the annual rise in the watertable and *Sy* is the specific yield of the aquifer (Armstrong and Narayan, 1998). Having a reliable estimate of *Sy* for a specific aquifer is often the biggest limitation in applying the WTF method. Previous studies have used the WTF method to estimate recharge from selected observation wells in the Eyre Peninsula (Evans, 1997; Ordens *et al.*, 2011) and reported values of *Sy* for the Quaternary Limestone aquifer range between 0.03–0.3 (Evans, 1993; Zulfic *et al.*, 2007). For the purposes of this study, a uniform *Sy* value of 0.15 was used to estimate annual recharge rates from multiple observation wells using the WTF method. Although it is acknowledged that the *Sy* may be lower or higher, as stated earlier our aim is not to provide contemporary estimates of recharge using either the WTF method or the LEACHM models. Rather, the broad relationship between rainfall and aquifer response (using a constant specific yield value of 0.15 to infer a recharge rate) is used as a guide to develop models to simulate groundwater recharge in Eyre Peninsula's PWAs.

In this study, LEACHM (Leaching Estimation and Chemistry Model) (Hutson, 2003) has been used to model of the relationship between rainfall and recharge. LEACHM is a modelling platform that simulates the flux of water in variably saturated conditions, such as through a soil profile above a water table. LEACHM uses a finite-difference approximation of the Richards equation (Eq. 2) to model 1-dimensional vertical movement of water between specified layers within a soil profile in response to water flux through the soil surface.

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}\left(K\frac{\partial H}{\partial z}\right) \qquad \text{(Equation 2)}$$

In the application of the Richards equation (Richards, 1931) in LEACHM, *z* is the vertical distance between nodes in the soil profile model and *t* is the time increment, which has a maximum value of 0.1 days. H is the total soil moisture head potential and is equal to $h_m(\theta) + z$, where $h_m(\theta)$ is the soil moisture matric potential at soil moisture content θ. The soil profile is represented as a number of soil layers, for which the thicknesses and hydrologic properties are specified in the model's input data file. Water retention and unsaturated hydraulic conductivity functions are encoded in the model and parameter values for these functions are user-specified in the input data file (Green, 2010).

LEACHM allows a number of options for lower boundary conditions. The option of a fixed water table depth was used in this study. Water table depths vary across the study area (Sec. 3.4.4) and this was taken into account when assigning the water table depth for each of the LEACHM calibration models and the spatially distributed Musgrave and Southern Basins models. The effect of the fixed water table lower boundary condition is to create a constant matric potential at the model's lower boundary equal to water table depth less the thickness of the modelled soil profile. For example, with a fixed water table depth of 7 m with a modelled soil thickness of 2 m (as used in this study), the model will impose constant matric potential equivalent to -5 m (approximately -50 kilopascals (kPa)) at the lower boundary of the model soil profile. The upper boundary of the model is the interface between the soil surface, crop and the atmosphere.

The input data for individual LEACHM simulations include records of rain and irrigation, PET and crop cover development. Rainfall and PET data in this study are taken from Bureau of Meteorology data (BoM, 2010), where PET is determined by methods set out in the FAO56 guidelines (Allen *et al.*, 1998). In LEACHM, the PET is split into potential evaporation and potential transpiration, such that:

Potential Transpiration, T_p = PET x crop cover fraction and

Potential Evaporation, E_p = PET (1 – crop cover fraction)

where the crop cover fraction refers to the growth and senescence of crop cover between emergence and harvest. This is simulated by a sigmoidal function that predicts crop cover fraction on each day of the simulation based on starting and end dates and maximum and final crop cover specified by the user.

The actual evaporation, E_a is limited by the potential flux (q_{max}) through the surface in the time step, which is controlled by the soil matric potential and conductivity corresponding to the water content of the uppermost soil segment and the potential of the soil surface, which is set at -3000 kPa, so

Actual Evaporation, E_a = minimum of $E_p/\Delta t$ and q_{max}

If E_a in a time step is less than the potential surface flux, then the potential transpiration is increased by the difference between Ep and Ea. However, the potential transpiration is limited by a user-specified maximum ratio of actual to potential transpiration (R_T), such that

Potential Transpiration, T_p = minimum of T_pR_t and $T_p + E_p - \Delta tE_a$

The resulting amount of water represented by T_p in a time step is then subtracted from the soil segments in proportions determined by the root distribution which is user-specified in the soil physical properties section of the model input file. For a full description on LEACHM's treatment of evaporation and transpiration partitioning and root water uptake, as well as other aspects of the model, the reader is referred to the LEACHM Model Description and User Guide (Hutson, 2003).

For the EPNRM Region, dominant soil types were identified using the Land and Soil Spatial Datasets for the State (DWLBC, 2007). Seven dominant soil types in the region were identified (Table 3).

Table 3. Dominant soil types of the EPNRM Region

Soil code	Soil type description	LEACHG raster ID
A1	Highly calcareous sandy loam	1
B1	Shallow highly calcareous sandy loam on calcrete	2
B2	Shallow calcareous loam on calcrete	3
B3	Shallow sandy loam on calcrete	4
H1	Carbonate sand	5
J2	Ironstone soil	6
N2	Saline soil (physically described as a clay overlying calcrete)	7

LEACHM models for each of these soil types were constructed based on models of similar soil types in South Australia and based on existing datasets where measurements of soil physical properties had been made (Green, 2010; Powell, 2010). Each modelled soil profile was defined as 2 m deep with 20 layers, each of 10 cm thickness. Groundwater monitoring reports for the Eyre Peninsula were then examined to identify groundwater hydrograph records in which the fluctuation in groundwater levels displayed correlation with rainfall trends. The dominant soil type in the vicinity of these observation wells was then identified from the SA Soils spatial database (Table 4). Figure 8 shows an example of data from observation well WAY054 (located in the Sheringa groundwater lens in the Musgrave PWA), in which annual fluctuations are influenced by annual recharge.

Table 4. Groundwater observation wells used in calibrating the LEACHM soil models

Soil type	Observation well	Groundwater lens
A1: Highly calcareous sandy loam	SQR031	Polda
B1: Shallow highly calcareous sandy loam on calcrete	ULE134	Uley South
B2: Shallow calcareous loam on calcrete	WAY054	Sheringa
B3: Shallow sandy loam on calcrete	ULE139	Uley South
B3: Shallow sandy loam on calcrete	SLE047	Lincoln-A
B3: Shallow sandy loam on calcrete	SQR088	Polda
N2: Saline soil	ULE101	Uley South

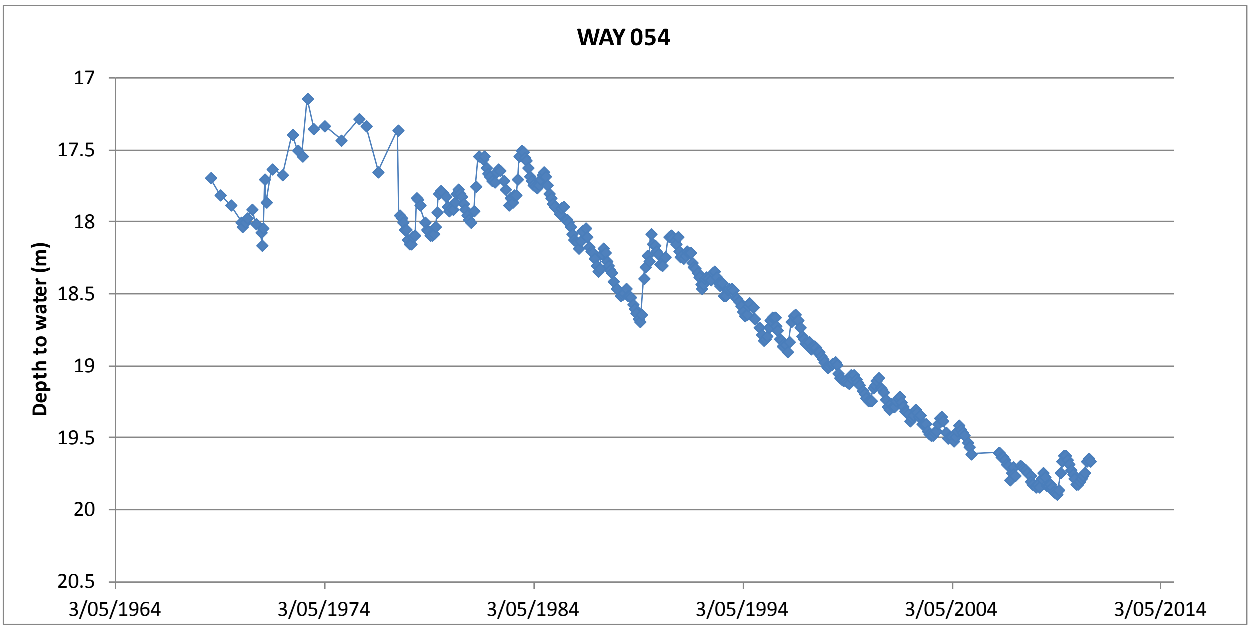


Figure 8. Groundwater levels in observation well WAY054

For each observation well, the amplitude of annual water level fluctuations was measured and multiplied by the assumed specific yield (0.15) to give an indicative recharge rate. In all cases, the average estimated recharge rates (averaged over the period of data availability) fell within the ranges of 20–39 mm/y for the Musgrave PWA and 35–66 mm/y for the Southern Basins PWA, which is generally within the ranges reported in earlier studies, although higher rates for the Southern Basins PWA have been reported (particularly the Uley South groundwater lens, see Ward *et al.* (2009) for a summary). The LEACHM models for the dominant soil types were then run for a simulation period representing the recorded climate conditions of 1960–2009. Weather data were taken from the BoM weather station closest to each observation well that had data covering this period (BoM, 2011b). Land cover data were based on the identified land use or major vegetation cover (typically either dryland pasture or native vegetation).

3.3.1. CALIBRATION OF GROUNDWATER RECHARGE MODELS

The recharge rates estimated from observation well data were compared to LEACHM modelled drainage fluxes and calibration of the models was performed by altering the soil parameters in the LEACHM models within realistic bounds until: 1) a satisfactory fit was observed between variations in modelled recharge and variations in estimated recharge for each year of the simulation period and 2) the 50-year mean annual modelled recharge flux was within the range of historic estimates of the local mean annual recharge (e.g. Ward *et al.*, 2009). A prediction of the precise recharge rate is not intended, rather it is intended that the model correctly represents the effect of annual variations in weather variables (primarily rainfall) on annual recharge fluxes.

As an example, the performance of the model for the B1 soil type (shallow highly calcareous sandy loam on calcrete) in simulating the variability in recharge in the vicinity of the ULE134 observation well is illustrated in Figure 9. The deviation from the 50-year mean annual rainfall in each year is plotted against the deviation from the 50-year mean recharge for each year of the simulation for both estimated (green) and modelled (blue) annual recharge totals (including the modelled surface runoff). As the estimated recharge rates are based on watertable fluctuations, the trend is indicative of the relationship between rainfall and recharge. A close match between the linear trend lines of variations in modelled and estimated recharge versus variations from mean annual rainfall is taken to indicate that the sensitivity of annual recharge fluxes to variations in annual rainfall is correctly predicted by the model.

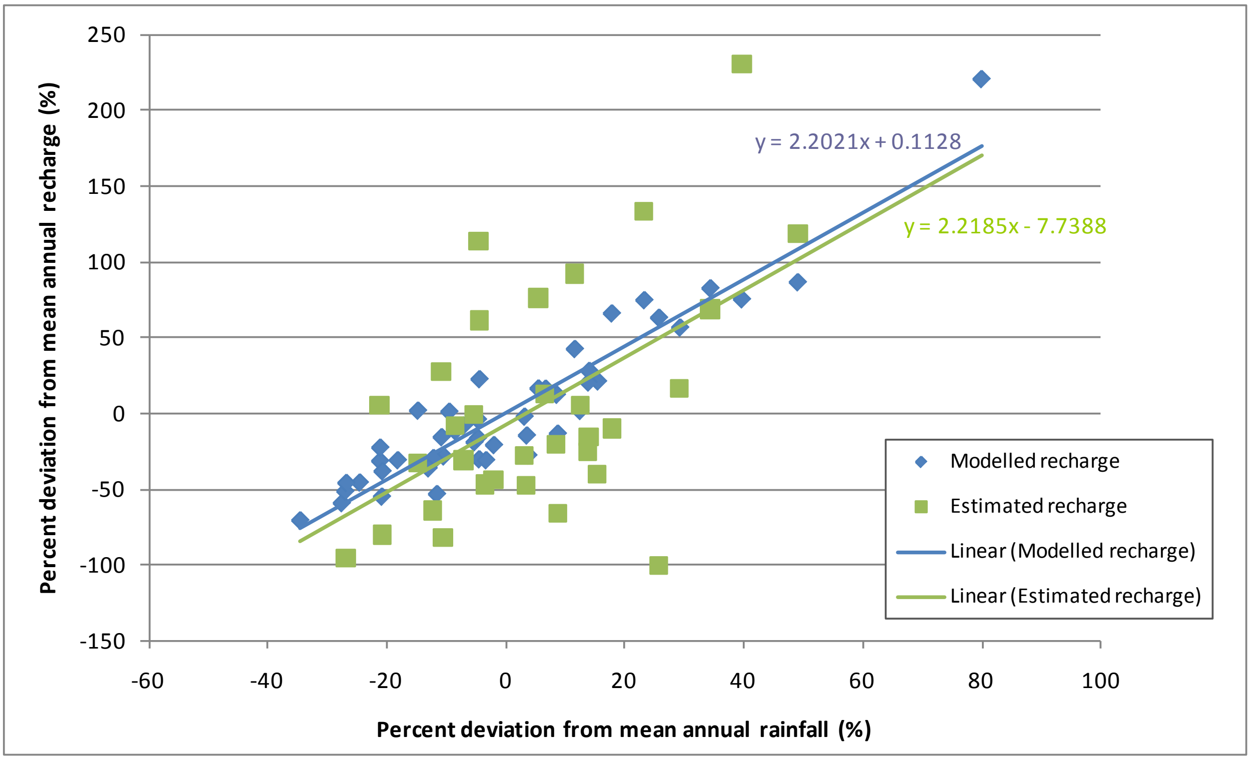


Figure 9. Percentage deviations in annual recharge versus annual rainfall for 50-year simulation (1960–2009), with estimated recharge and modelled recharge (sum of modelled diffuse recharge and runoff)

It should be noted that the comparison with average annual rainfall is made in this study, while in previous DFW ICCWR studies (e.g. Green *et al.*, 2011) the comparison is made using winter rainfall.

Annual rainfall amounts are used here as they generally show a better correlation with annual fluctuations in the watertable in the Eyre Peninsula for the observation wells used in this study.

Results of this qualitative calibration process for other soil types are shown in Appendix A. Some of the LEACHM models tended to over-estimate annual recharge compared with the recharge estimated from annual water table fluctuations. This may be partly a result of the conceptual model that suggests all runoff enters sink holes and becomes recharge and partly due to the application of a specific yield value of 0.15 to hydrograph fluctuation estimates, to estimate the annual recharge fluxes for the calibration sites. In reality, water entering sink holes may seep from them into the unsaturated zone and thereafter be taken up by plant roots and/or evaporated through the land surface (Ordens *et al.*, 2011). Also, the specific yield of the aquifer at the calibration site may in reality be higher than the assumed value of 0.15 and therefore the recharge be proportionally greater than the estimated values. Either way, the tendency of the models to over estimate the total recharge indicates that the models may not ideally represent the actual recharge processes. However, the ability of the models to represent the sensitivity of annual recharge to variability in annual rainfall totals seems very good, as illustrated by the plots comparing percent deviation from mean annual recharge (for modelled and estimated recharge) with percent deviation from mean rainfall (Appendix A, Figs. 66, 69, 72, 75, 78, 81).

As the projections of the models are only being applied in a comparative way, such that several projections from the same model using a range of climate scenarios are compared with the projections resulting from a baseline climate scenario, it is the ability of the models to represent the variation in recharge with variations in rainfall that is more important than their ability to predict absolute recharge amounts.

However, the inability of the models to accurately predict absolute recharge amounts is a potential source of uncertainty in the projections of recharge change under alternative climate scenarios. Other studies (e.g. Barron *et al.*, 2011) indicate that recharge in areas with lower recharge is more sensitive to rainfall changes than recharge in areas with higher recharge. Therefore, as the models applied here tend to over-predict recharge, they may tend to under-predict the sensitivity of recharge to rainfall changes. This is not apparent when historic climate data are applied, however it may cause the models to under-predict the change in recharge in climate states that are beyond the range of climate variability that occurred during the baseline period.

Models were also run from 1960–2009 for the remaining soil types which could not be assessed against groundwater trends. These models were considered acceptable if the average annual modelled recharge rates fell within the ranges reported in previous studies (e.g. Harrington *et al.*, 2006), and the slope of percent deviation plot of the modelled recharge was in a similar range to the slope of the percent deviation plot for similar soil types.

3.4. LEACHM - GIS MODELLING FRAMEWORK

The soil profile and land cover descriptions from the calibrated LEACHM models described above were incorporated into a spatially distributed LEACHM framework linked to a geographic information system (GIS). Termed LEACHG (Hutson *et al.*, 1997), this model framework applies the one-dimensional models described above to a large number of discrete land areas which are defined by a combination of the soil type, land use, climate zone, water table depth and land slope present at all locations in the study area. For irrigated agricultural land uses, an irrigation schedule or policy is also defined for the crop type, which is defined by the land use attribute. First, thematic maps of the distribution of spatial attributes that affect the soil water balance within the study area, such as soil profile types and land use types, are generated using a GIS. In the method used here, GIS layers for each of the variables were converted to raster images within the GIS, prior to being output as ASCII text-based raster files. The raster files each describe the spatial distribution of a single attribute over a geographical area that is common to all raster files. LEACHG reads the raster files and performs an operation to effectively overlay the raster images and encode each raster cell with the unique combination of the spatial variables identified in that cell location.

The LEACHG model requires that input data are prepared in individual data files for each spatial variable type so that data can be included for each identified class of each spatial variable existing in the study area. These data files are identical to the corresponding sections describing these variables within the standard LEACHM data file. The LEACHG model constructs and runs the LEACHP model for each unique combination of spatial variables identified by the raster file overlay process described above. The flowchart in Figure 10 describes the LEACHG distributed modelling process.

The attributes for the Musgrave and Southern Basins PWAs are identified in a number of GIS layers. These were converted into raster image files with the approximate spatial extent of the two PWAs (Figs. 11 through 14).

Attributes combined by the LEACHG process were: soil type, land cover, climate zone, depth to water and land slope. These were classified as described below. The attributes were combined into recharge models only where modelled recharge areas are identified within the two PWAs.

3.4.1. SOIL TYPE

Soil types were as defined by the SA Land and Soil Spatial Database for Southern South Australia (State Soil and Land Mapping Program (SSLMP), DWLBC, 2007). Seven major soil profile types were identified as existing in the Musgrave PWA and selected for description in the model.

The LEACHG data files constructed for each soil type were based on the soil layers defined in the single-point LEACHM models described above. Soil layer type descriptions (such as for a loam layer) were extracted from the soil profile descriptions of the calibration models and arranged to represent the soil profile description of each modelled soil type to a depth of two metres. In the majority of soils in the study area, at depths greater than two metres there is only fractured rock or calcrete. Hydraulic properties were selected to represent flow in variably saturated conditions in the calcrete layer that underlies several of the modelled soil types. The calcrete has low intrinsic permeability, however it is extensively fractured such that its hydraulic conductivity characteristics are similar to those of a fractured rock layer. The hydraulic parameters for this layer were selected to act similarly to a layer of clay, but with a high bulk density such that effective porosity is low and very little water is transmitted except when the layer is at or close to saturation. This is not intended to incorporate the hydraulic characteristics of macro flow channels, such as karst features or sink holes, that may exists in the calcrete layer. The flow of water through features such as these is assumed to be incorporated in the surface runoff component of the model, which has been added to the diffuse recharge amounts in order to determine a total recharge estimate (Sec. 3.2).

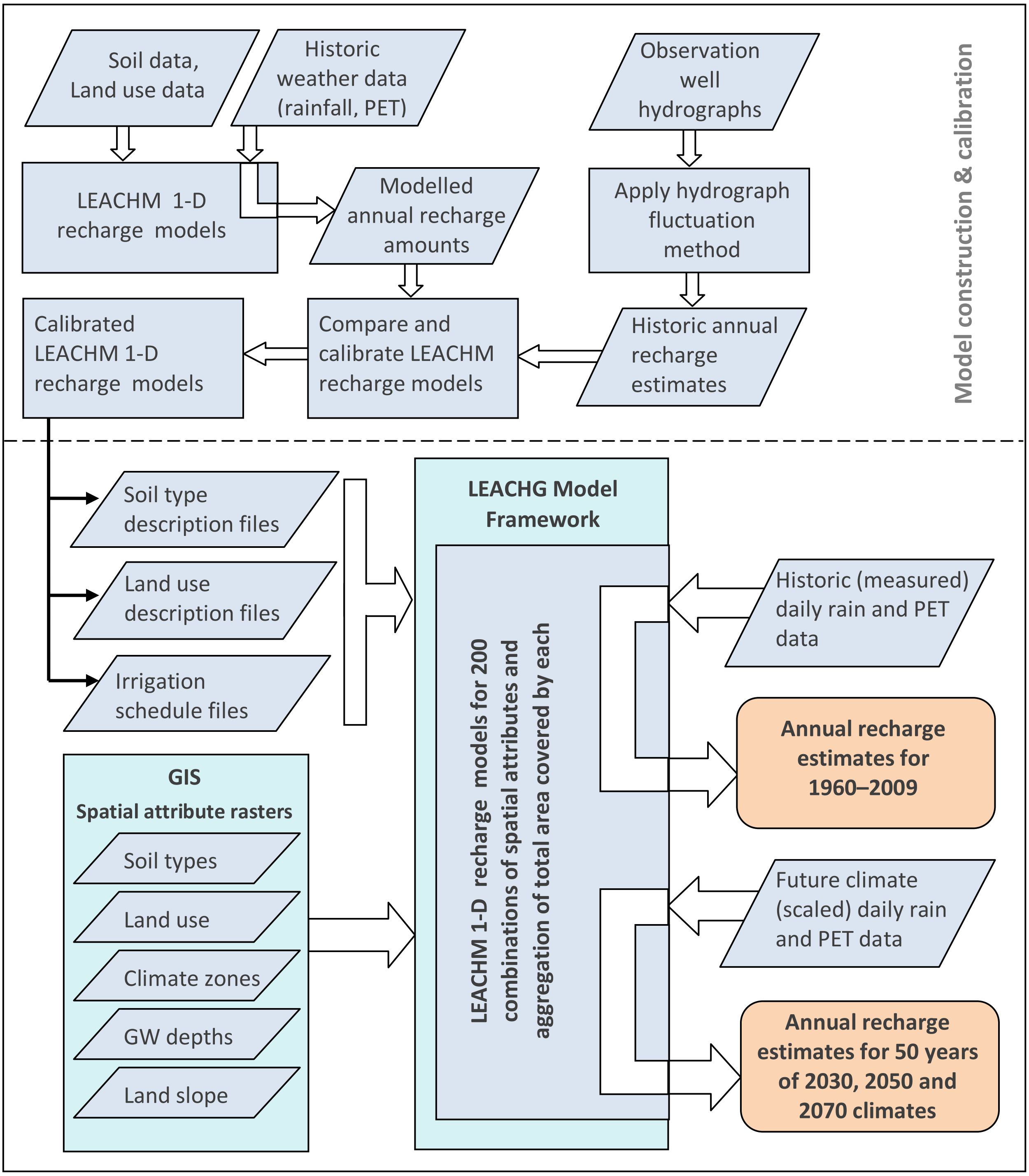


Figure 10. Flowchart of groundwater recharge modelling framework applied to the Eyre Peninsula PWAs

In the Southern Basins, the SA Land and Soil Spatial Database for Southern South Australia indicates that small areas of five other soil types exist in addition to the seven soil types identified in the Musgrave PWA. In view of the small spatial extent of these soil types (less than 1% of the PWA), in the Southern Basins PWA LEACHG model they were substituted with soil profile descriptions of the more extensive soil types. Substituted soils were given the soil profile description of whichever of the seven more extensive soil types were thought to have most similar hydraulic properties to the substituted soil (Table 5). These substitutions are expected to have a negligible impact on the recharge projections of either individual lenses or the whole prescribed area.

Table 5. Soil types encoded into the Musgrave and Southern Basins PWA LEACHG models (soil type codes and soil descriptions from DWLBC Soil and Land Information Group, 2007 (*Soils of South Australia's Agricultural Lands*))

Soil type code	Soil description	Substituted by
A1	Highly calcareous sandy loam	Not substituted
B1	Shallow highly calcareous sandy loam on calcrete	Not substituted
B2	Shallow calcareous loam on calcrete	Not substituted
B3	Shallow sandy loam on calcrete	Not substituted
H1	Carbonate sand	Not substituted
J2	Ironstone soil	Not substituted
N2	Saline soil (described as clay overlying calcrete)	Not substituted
A8	Gypseous calcareous loam	A1
F1	Loam over brown or dark clay	B3
G3	Thick sand over clay	A1
J1	Ironstone soil with alkaline lower subsoil	J2
L1	Shallow soil on rock	B3

3.4.2. LAND COVER

The land cover description files for the LEACHG model describe the crop or vegetation growth periods, vegetation cover percentages and evapotranspiration factors for each land use type included in the model. Land covers for the Musgrave and Southern Basins PWAs were defined by combining the DFW 2008 State Land Use spatial data coverage with the Department for Environment and Natural Resources (DENR) 2004–08 State Vegetation spatial data coverage. Much of the land in both of the PWAs is covered by native vegetation and grassland and as a result, a distinction between different vegetation types was deemed necessary in the model that is not provided by the State Land Use coverage alone. All areas within the two PWAs that were defined with a vegetation cover type in the SA Vegetation Coverage have been assigned that vegetation cover type in the LEACHG model. All areas that do not have a vegetation cover defined in the SA Vegetation Coverage were assigned a land cover defined in the 2008 State Land Use Coverage. A total of 25 land cover types were identified within the boundaries of the Musgrave and Southern Basins PWAs (Table 6). Only eight land cover (vegetation) description files were used to represent these land cover types, with each description file used to represent more than one land cover type (Table 5). For example, a vegetation description file developed to represent unirrigated grazing land was also used to represent land covers described as Tussock Grassland, Hummock Grassland, Coastal Shrubland and Managed Resource Protection (water resource protection areas).

Each LEACHG land cover description file defines the fraction of vegetation cover and exposed soil and the variation of this through each year according to the growth of the vegetation. For annual crop types, dates of crop emergence, maturity and harvest are defined, together with crop cover fractions at maturity and harvest. A fixed cover percentage is defined for perennial, non-deciduous vegetation. Seasonal or deciduous perennial vegetation, such as vines or fruit trees, are simulated as annual crops such that the development and decline of leaf cover can be described in the same way as the emergence, growth and harvest of an annual crop. For all vegetation types, a root depth and distribution and ET scaling factor are defined. The actual transpiration flux for each time step in the model is calculated from a function of the PET, the percentage crop cover and the ET scaling factor. The depth of soil from which the resulting amount of water is transpired is determined by the root depth distribution and is limited by the amount of water available in the soil in each depth layer, as determined by the vertical flow model. The percentage of exposed soil from which water can evaporate is defined as 100% less the crop cover percentage. The evaporation flux in each time step is a function of the PET and the percentage of exposed soil and is limited by the amount of water available to evaporate in the top soil layer.

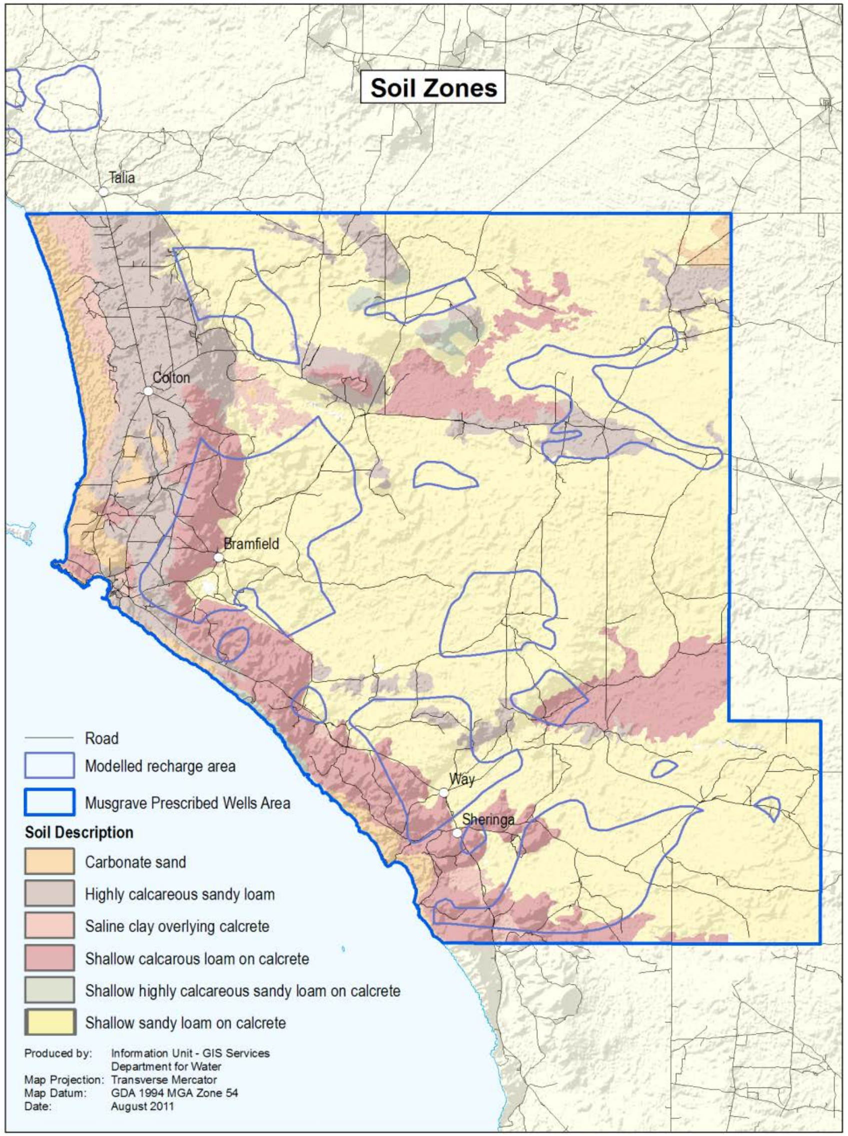
Table 6. Land cover types encoded into the Musgrave and Southern Basins PWA LEACHG models

Land cover description	Area within Musgrave Lenses (Ha)	Area within Southern Basins Lenses (Ha)	LEACHG vegetation cover description file number
Grazing modified pastures	33561.4	1351.1	1
Hummock grassland	0	256.7	1
Managed resource protection	0	60.1	1
Tussock grassland	15699.5	6073.9	1
Coastal shrubland	473.2	2902.3	1
Eucalyptus mallee forest and mallee woodland	21376	10609.9	2
Plantation forestry	0	129.9	2
Acacia shrubland	0	144.6	3
Allocasuarina forest and woodland	92.5	893.4	3
Callitris forest and woodland	204.7	372.3	3
Melaleuca shrubland >1m	1263.7	6100.4	3
Nature conservation	1027.4	871.3	3
Other minimal uses	960.6	292.2	3
Cropping	3428.7	124.1	4
Estuary/coastal waters	0	2.1	5
Lake	4.6	0.1	5
Marsh/wetland	46.9	1.9	5
Reservoir/dam	0	0	5
Mining	0	4.3	6
Residential	16.4	18.1	6
Services	5.2	43.5	6
Transport and communication (incl. roads)	431.5	25	6
Low sparse sedgeland	951.7	0	7
Rushland/sedgeland	0	194.3	7
Irrigated perennial horticulture	12	3.1	8

A factor of up to 100% is also applied to allow restriction of the amount of water that can be evaporated from land defined as "exposed soil". This allows an approximation of the evaporation conditions for non-vegetated land use types such as roads, for which a high factor may be applied to restrict the evaporation from the land surface to less than it would be for exposed soil. For the 'Roads' land use type in the model, a value for this factor was selected that assumed that some water would evaporate from the land surface while the remainder would run off and create strong infiltration conditions at the side of roads. Thus the land use description for roads tends to simulate relatively high infiltration rates. However, less than 0.5% of the land cover in the Musgrave PWA is defined as roads and less than 0.1% in the Southern Basins PWA.

For irrigated land use types, a corresponding irrigation schedule file is referred to by the model. Irrigation scheduling is automated within the model by setting the upper 200 mm of the soil profile to its saturation water content when the simulated soil moisture potential drops to a set trigger level at a depth of 300 mm whenever a crop is present. This is designed to simulate an automated irrigation system in which irrigation is triggered by soil moisture sensors. In the Eyre Peninsula PWAs only a small fraction of the area is used for irrigated horticulture. The main types of horticulture are perennial fruit trees and nut trees and so an appropriate single trigger value of -35 kPa was set within the irrigation file for the irrigated horticulture land cover type.

(a)



(b)

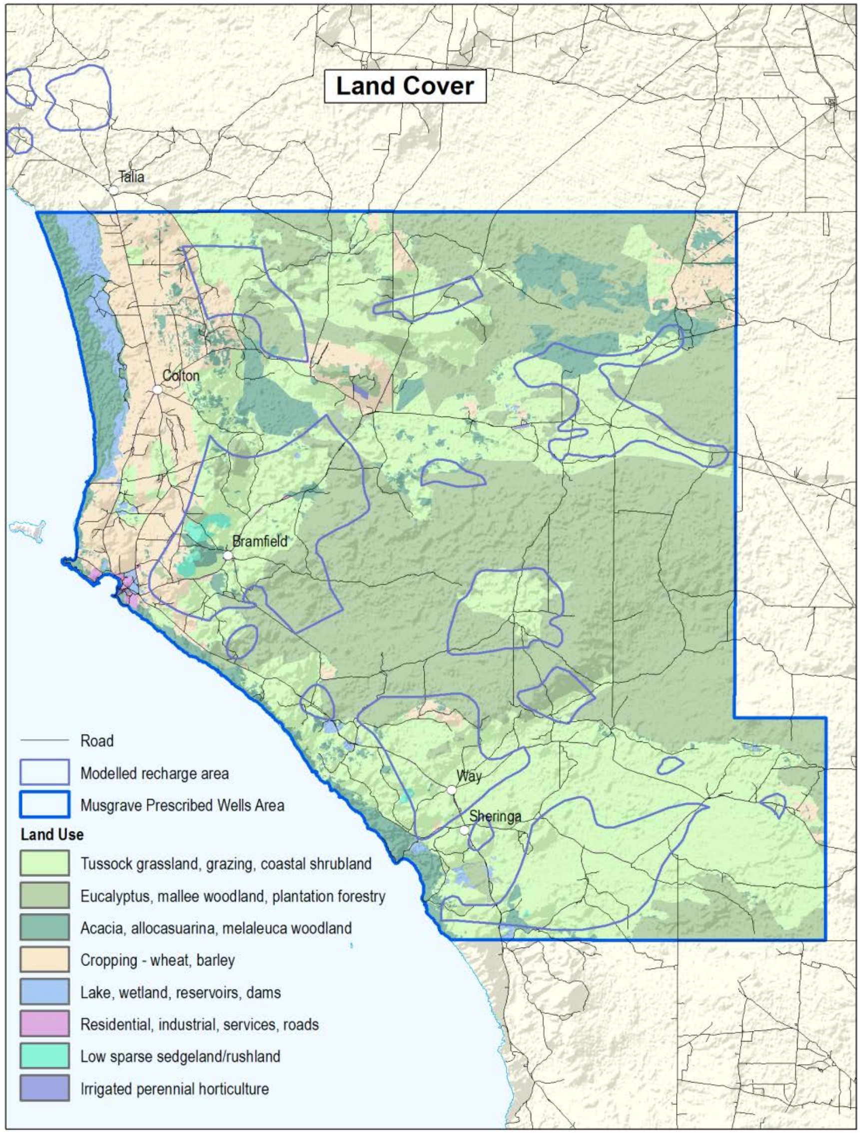


Figure 11. (a) Distribution of major soil types and (b) distribution of land cover types defined in the Musgrave PWA model. The modelled recharge areas are based on Evans *et al.* (2009a)

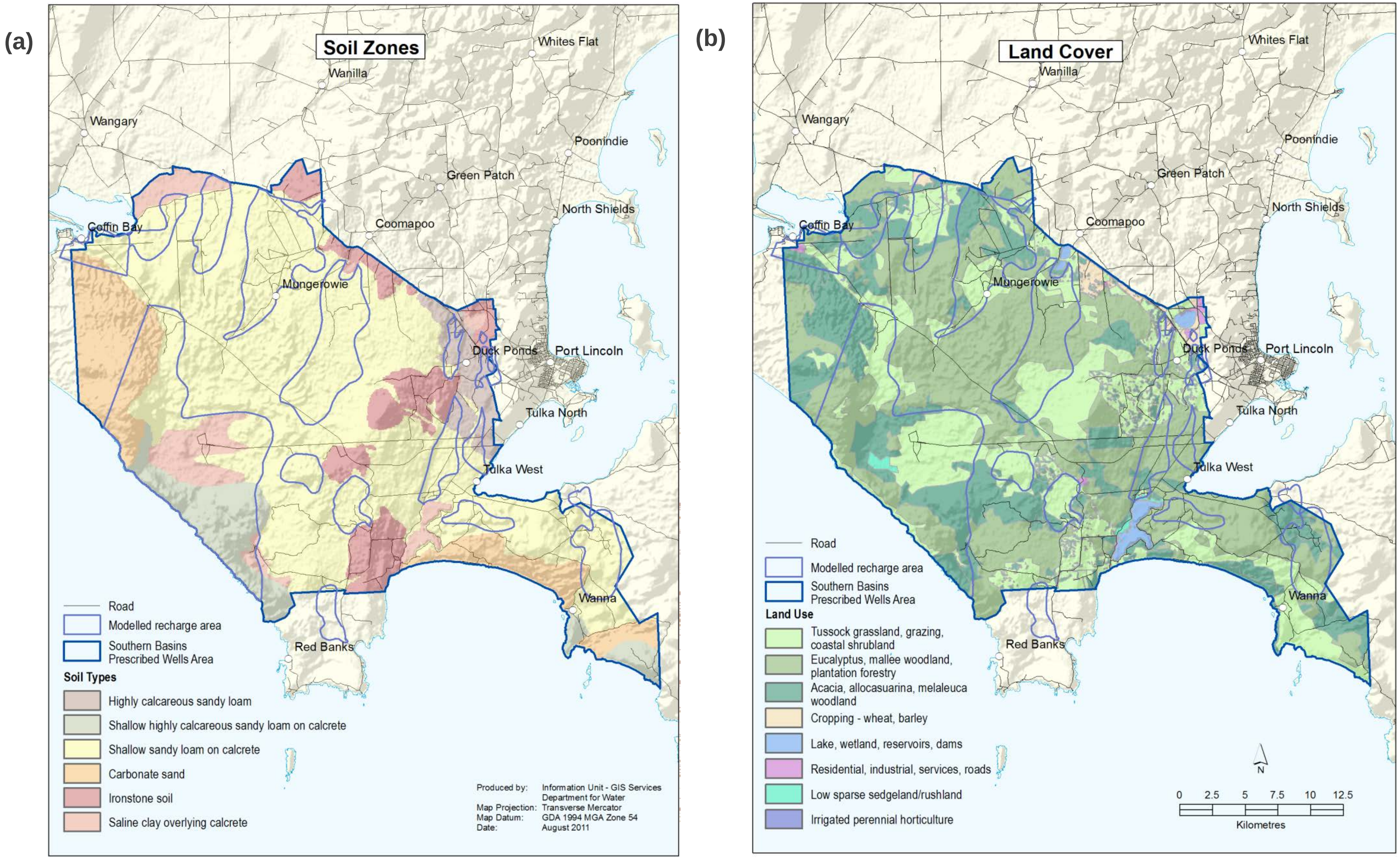


Figure 12. (a) Distribution of major soil types and (b) distribution of land cover types defined in the Southern Basins PWA model. The modelled recharge areas are based on Evans *et al.* (2009b).

3.4.3. CLIMATE ZONE

Two climate zones were defined for the Musgrave PWA and one for the Southern Basins PWA. The historic rainfall and PET data from the rainfall stations of Sheringa and Lock (Sec. 2.1.3) show that there is markedly lower winter rainfall at the more inland station of Lock compared to the Sheringa station which is closer to the coast, toward the western side of the PWA. Also, the PET at Lock is greater than at Sheringa throughout the year and is distinctly greater in spring and summer. This difference results in a greater deficit between rainfall and PET for most of the year at the more inland station compared to the more coastal location of Sheringa. In view of these distinct differences, two climate zones were defined for the Musgrave PWA, one using historic rainfall and PET data from the Sheringa weather station and one using data from the Lock weather station. The zones were divided along the 400 mm rainfall isohyet, (Fig. 13). Historic weather-variable data from the Lock and Sheringa weather stations for the 50-year period 1960–2009 were used for the historic baseline simulation with the LEACHG model.

For the Southern Basins PWA, comparison of weather stations of Port Lincoln and Big Swamp, as described in Section 2.2.3 indicate significantly higher rainfall and lower PET than the Musgrave PWA, but show a minimal gradient of rainfall and PET across the Southern Basins area. For this reason, only one climate zone was used to represent the whole PWA. The historic weather variable data for this zone were drawn from the Westmere weather station, which is fairly central to the Southern Basins PWA.

Future climate weather variable datasets, representing climates of 2030, 2050 and 2070 under high and low-emissions scenarios, were generated from the these baseline weather datasets according to the method described in the ICCWR Project Phase 2 report (Gibbs *et al.*, 2011).

3.4.4. DEPTH TO WATER

The LEACHM model has options to set a fixed water table depth, which may vary spatially in the LEACHG framework, or to allow free drainage from the lower boundary. The use of fixed water table depths that are greater than about 10 m are potentially problematic in the model as it results in a very low matric potential being maintained at the lower boundary of the model. Consequently, for areas where water table depths are commonly greater than 10 m, the use of the free drainage option is preferable. In the Southern Basins PWA, average water table depths within several of the modelled recharge areas were found to be greater than 10 m. As there is no option with the LEACHG model to have a combination of free drainage and fixed water table depth options within a single simulation, both options were tested. The resulting amounts of recharge determined with the two lower boundary condition options were found to be very similar. As the free drainage option was considered more conceptually correct for situations with water table depth greater than 10 m, this option was selected for use in the Southern Basins LEACHG model and the actual mean water table depths for the modelled recharge areas in the Southern Basins PWA were not used.

For the Musgrave and Southern Basins PWAs, the average water table depth within each of the defined modelled recharge areas was determined from the observation well network. In the Musgrave PWA the average depth for each recharge area was found to range between 4–8 m. Each recharge area in the Musgrave PWA was therefore assigned a fixed water table depth category in the LEACHG model (Fig. 13). The LEACHG model was set to use fixed water table depths in seven depth classes: 1–2 m; 2–3 m; 3–4 m; 4–6 m; 6–8 m; 8–12 m and >12 m. Only three of these classes were represented by the average water table depths in the Musgrave PWA. The resulting raster of the depth-to-water zones is depicted in Figure 13. When read into the LEACHG model, the three classes present were converted to individual water table depths of 3.5 m, 5 m and 7 m. These fixed water table depths are applied in the model for all locations where the raster image indicates their corresponding water table depth class exists.

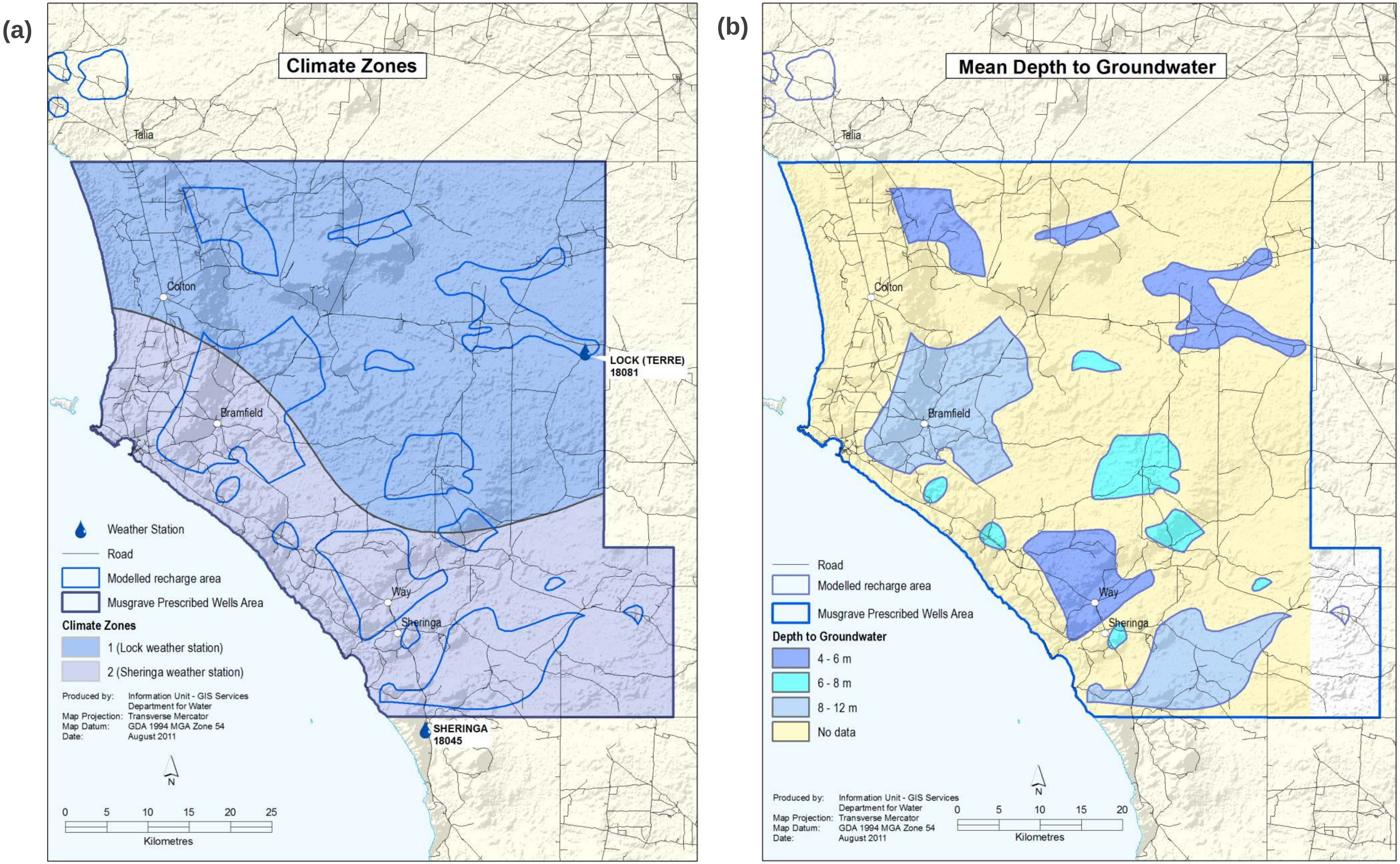


Figure 13. (a) Location of two climate zones in the Musgrave PWA and (b) Mean depths to groundwater of the Musgrave PWA modelled recharge areas (Evans *et al*., 2009a)

3.4.5. LAND SLOPE

A raster image of land slope in the Southern Basins PWA was generated from the one-second* Digital Elevation Model (DEM) for South Australia (Geoscience Australia, 2008). This was then reclassified into a raster image with eight slope classes. The resulting raster of land surface slopes is depicted in Figure 14. When read into the LEACHG model, the slope classes were converted to individual slope values (Table 7) to be applied in the model according spatial distribution of the slope values depicted by the raster image.

Table 7. Classification of land slopes in the Southern Basins PWA LEACHG model

Slope class number	Range of slope (deg.)	Individual slope value used in model (deg.)
1	0 – 2	0
2	2 – 4	3
3	4 – 6	5
4	6 – 10	8
5	10 – 16	13
6	16 – 22	19
7	22 – 30	26
8	30 – 40	35

For zero slope values, the model considers surface runoff to only occur when rainfall intensity is greater than the maximum infiltration rate of the top layer of soil. Where the land slope variable is greater than zero, the runoff rate is adjusted according to a runoff curve function that is dependent on the slope value.

The one-second DEM for South Australia, when converted to a slope category layer, shows that more than 95% of the Musgrave PWA has land slope of less than five degrees. As the runoff function in the LEACHG model is not particularly sensitive to such subtle slopes, the land slope variable was omitted from the Musgrave LEACHG model. It is expected that this will have had a negligible impact on the outcomes of the model.

* “One-second” refers to the resolution of the digital elevation model, equating to a grid resolution of approximately 30 metres on the ground.

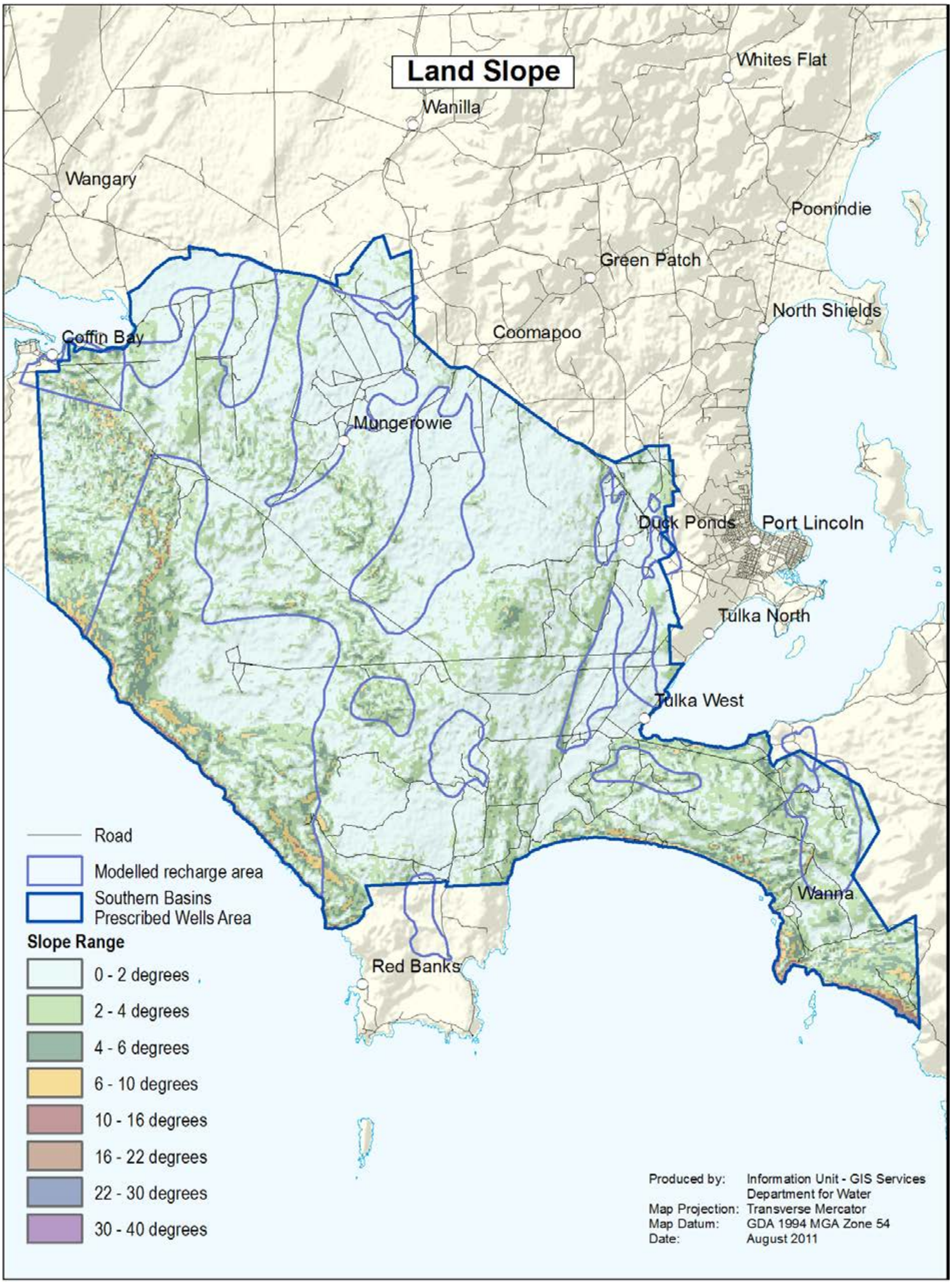


Figure 14. Distribution and categorisation of land slope in the Southern Basins PWA model. The modelled recharge areas are based on Evans *et al.* (2009b).

3.4.6. AGGREGATION OF SPATIAL VARIABLES IN THE LEACHG MODEL

The LEACHG model overlays the raster images for each of the spatial variables applied in the models (soil, land cover, climate, depth to water, land slope) and determines all combinations of values of these spatial variables that exist in the study area and the number of cells occupied by each combination. The number of cells is multiplied by the individual cell area to determine the area (ha) occupied by each combination. For all raster images in the simulations of the Musgrave and Southern Basins PWAs, a cell size of 100 m x 100 m (1 ha) was used.

The maximum number of possible combinations that can exist within the study area is a product of the number of values for each spatial variable type. In the model of the Musgrave PWA, the variables included seven soil categories, eight land cover categories, two climate zones and three depth to water classes, giving a total of 336 possible combinations. In the model of the Southern Basins PWA only one climate zone was applied and, as the free drainage lower boundary condition was applied, there were no depth to water categories incorporated in the model. The spatial variables included in the Southern Basins PWA model were therefore the seven soil categories, eight land cover categories and eight land slope categories, giving a total of 448 possible combinations.

The simulations were only executed within the modelled recharge areas of the two PWAs (Figs 1 and 3). Within the modelled recharge areas of the Musgrave PWA, only 76 different combinations of the four spatial variables exist. Within the modelled recharge areas of the Southern Basins PWA, only 32 combinations of soil types, land cover and land slope exist. This is a small subset of the total 448 possible combinations and is due to where the modelled recharge areas exist, being dominated by only a subset of the land cover categories (those grouped into land cover description files 1, 2 and 3, refer Table 6) and three of the land slope categories.

After deriving all of the combinations that exist in the study area, LEACHG creates a 1-dimensional LEACHM model for each combination and runs this model for the designated period using the weather variables provided for the climate zone(s), depending on which climate zone each of the combinations exists in. After running the models for all combinations, LEACHG outputs a summary file for each combination plus a summary file for the whole study area that contains the totals of all water balance components for the whole simulation period for all combinations. This file also includes the amount of area (ha) to which each combination simulation applies within the study area.

The LEACHG models were run firstly for the period 1960–2009 using historic rainfall and PET data from the weather stations representing each of the climate zones in Musgrave and Southern Basins. The same models were then run a further six times with the weather data scaled to represent the climates of 2030, 2050 and 2070 under high and low-emissions scenarios, as described in the ICCWR Phase 2 Report (Gibbs *et al.*, 2011). This was repeated for each of the four selected GCM projections, ultimately yielding 50-year annual recharge projections for 24 alternative climate scenarios.

This modelling framework described above is illustrated by the flowcharts in Figure 7 and Figure 10.

3.5. SURFACE WATER RUNOFF MODELLING

3.5.1. HYDROLOGICAL DATA

The only active flow gauge considered suitable for model calibration is A5120503 on the Tod River in Toolillie Gully, upstream of the Tod Reservoir (Fig. 5). There are also flow recording stations on the Tod River upstream of the diversion weir (5120504) and Pillaworta creek upstream of the Diversion Weir (5120505) and toward the end of the Tod River, 5 km NW of Poonindie, however there are large gaps in these datasets and they were deemed not suitable for modelling. There are no other active streamflow monitoring sites on Eyre Peninsula.

The contributing catchment to gauge A5120503 is 30 km^2 and the flow record began in 1991. However, the record at this station is also relatively poor, with only six of the 20 years not having any missing data. The pluviometer located in the catchment, A5120508, has been used as the rainfall data for model calibration, infilled with data from the BoM station located at the reservoir, M18181, with an adjustment factor of 1.083. SILO FAO56 PET data have been used (Jeffery *et al.*, 2001).

3.5.2. MODEL CALIBRATION

A one-node AWBM catchment model (Boughton, 2004) has been implemented in WaterCRESS to calibrate the model parameters to the flows recorded at the Toolillie Gully gauge, A5120503. The parameters have been calibrated using the Model Independent Parameter Optimization Software, PEST (Doherty, 2004). A lumped offstream storage node was used to simulate farm dams in the catchment, with a 0.3 fraction used to represent the affected catchment, where 30% of the runoff is diverted to the dam storage node, with the remaining 70% unregulated to flow downstream. An assumption of 50% of the dam capacity used for extractions, extracted over the summer months only, as adopted from McMurray (2006). A total farm dam volume upstream of the streamflow gauge was determined to be 82.3 ML, derived from the 2001 farm dam database. Both daily and monthly flows have been used simultaneously for calibration, with a weighting toward the monthly flows and no weighting given to observations that were not deemed to be of good quality (quality code = 1). The resulting calibrated model has a Nash-Sutcliffe efficiency of E=0.82 for monthly volumes and E=0.44 for daily flows. The volume bias for both cases was less than 0.1%. Annual runoff volumes are presented in this report and for this case E=0.91 and a volume bias of -0.2%. The simulated and observed monthly volumes are shown in Figure 15 and monthly flow duration curve in Figure 16. To allow a comparison against the observed data to be made, simulated flows for periods of missing data, such as 2006–08, have not been shown in Figure 15.

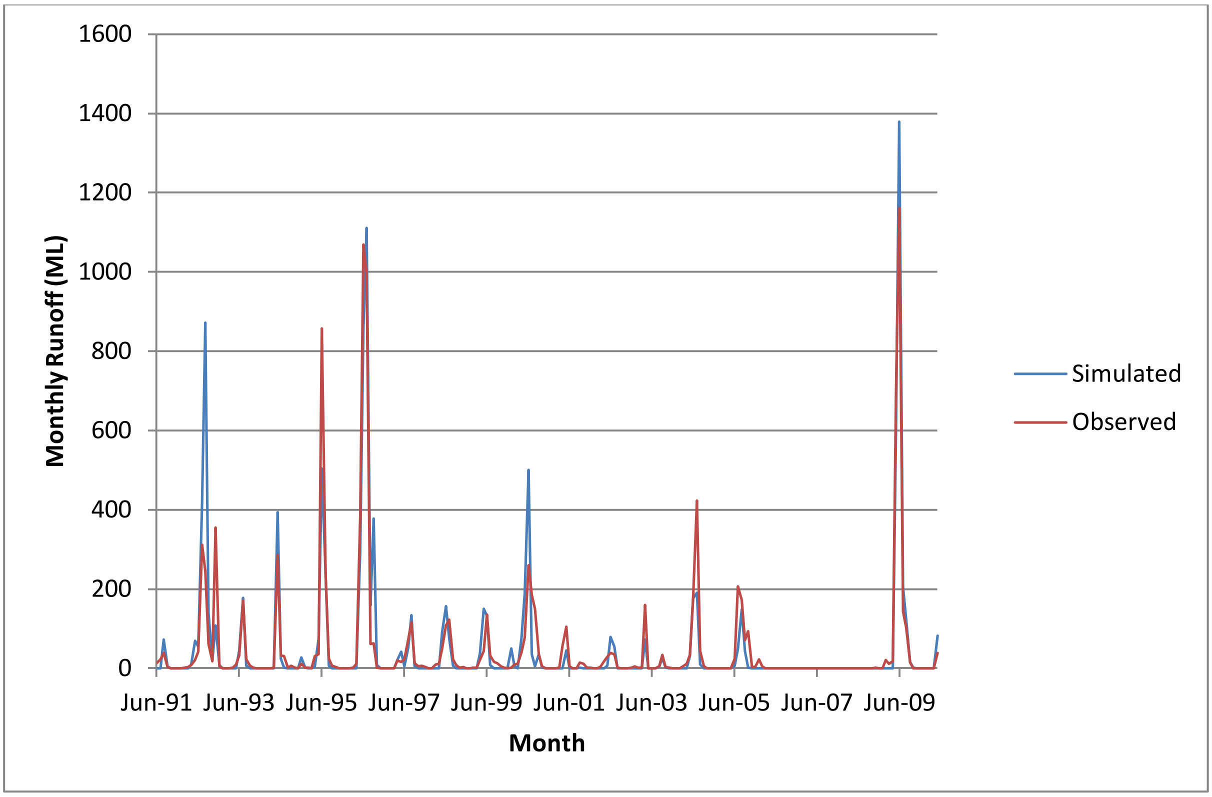


Figure 15. Simulated and observed monthly runoff for the Toolillie Gully catchment

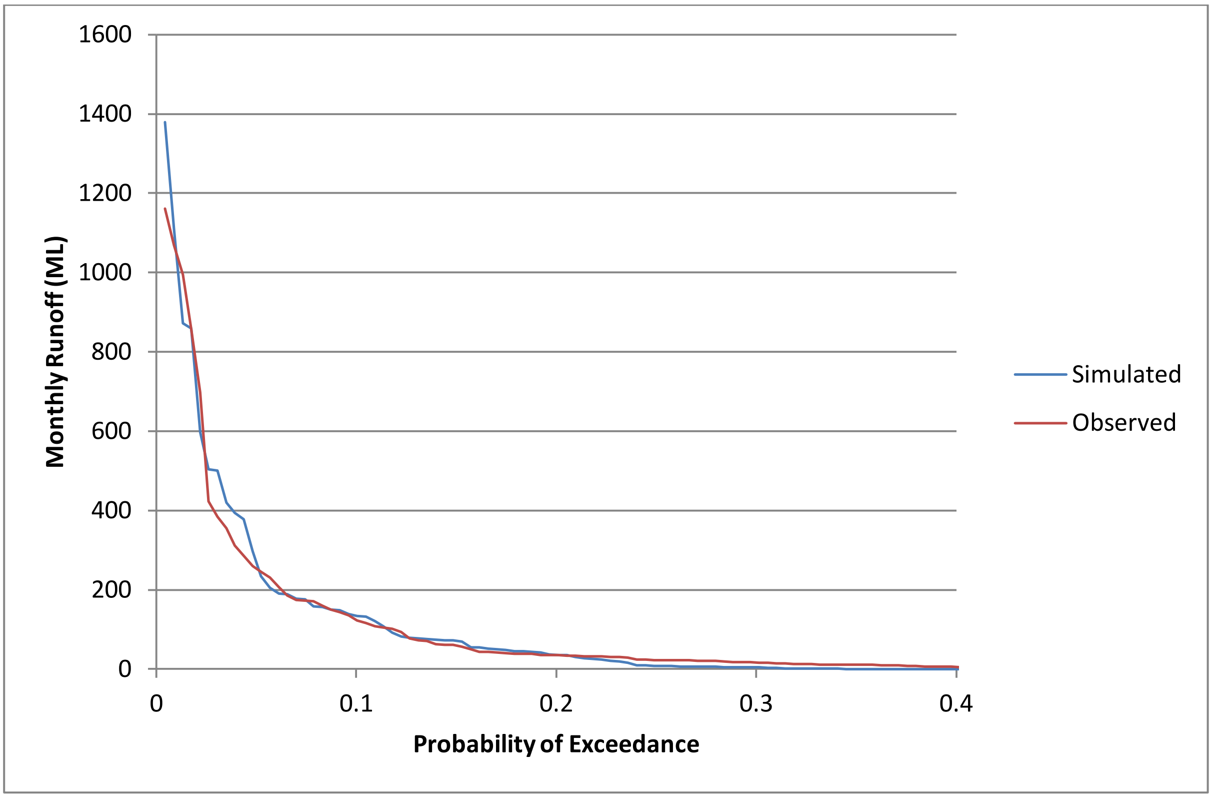


Figure 16. Simulated and observed monthly flow duration curve for the Toolillie Gully catchment

3.5.3. TOD RESERVOIR MODEL

While the Tod Reservoir is not currently used for potable water supply, it is the dominant surface water feature on Eyre Peninsula. Hence, a model to represent all Tod River catchments that contribute to the reservoir has been developed. The model parameters calibrated to the Toolillie Gully flow record have been used to parameterise a WaterCRESS model of the system (Clarke and Cresswell, 2009). As noted in Section 2, water from the main stream of the Tod River (104.7 km^2, Node 2 in Fig. 17) and the Pillaworta Creek (41.9 km^2, Node 3 in Fig. 17) can be diverted into the reservoir via concrete lined channels when stream flow is of sufficiently low salinity (SA Water, 2008). There is also a catchment that contributes to the intake channel that diverts these two catchments to the reservoir (11.9 km^2, Node 5 in Fig. 17). Including the Toolillie Gully catchments upstream (29.9 km^2, Node 1 in Fig. 17) and downstream (29.9 km^2, Node 4 in Fig. 17) of the gauge, the reservoir has a total area of contributing catchments of 197.4 km^2. The rainfall stations M018104, A5120507 and M018043 have been used along with rainfall isohyets to produce the rainfall series for the two upper catchments and the site at the reservoir (M18181) for the intake channel catchment.

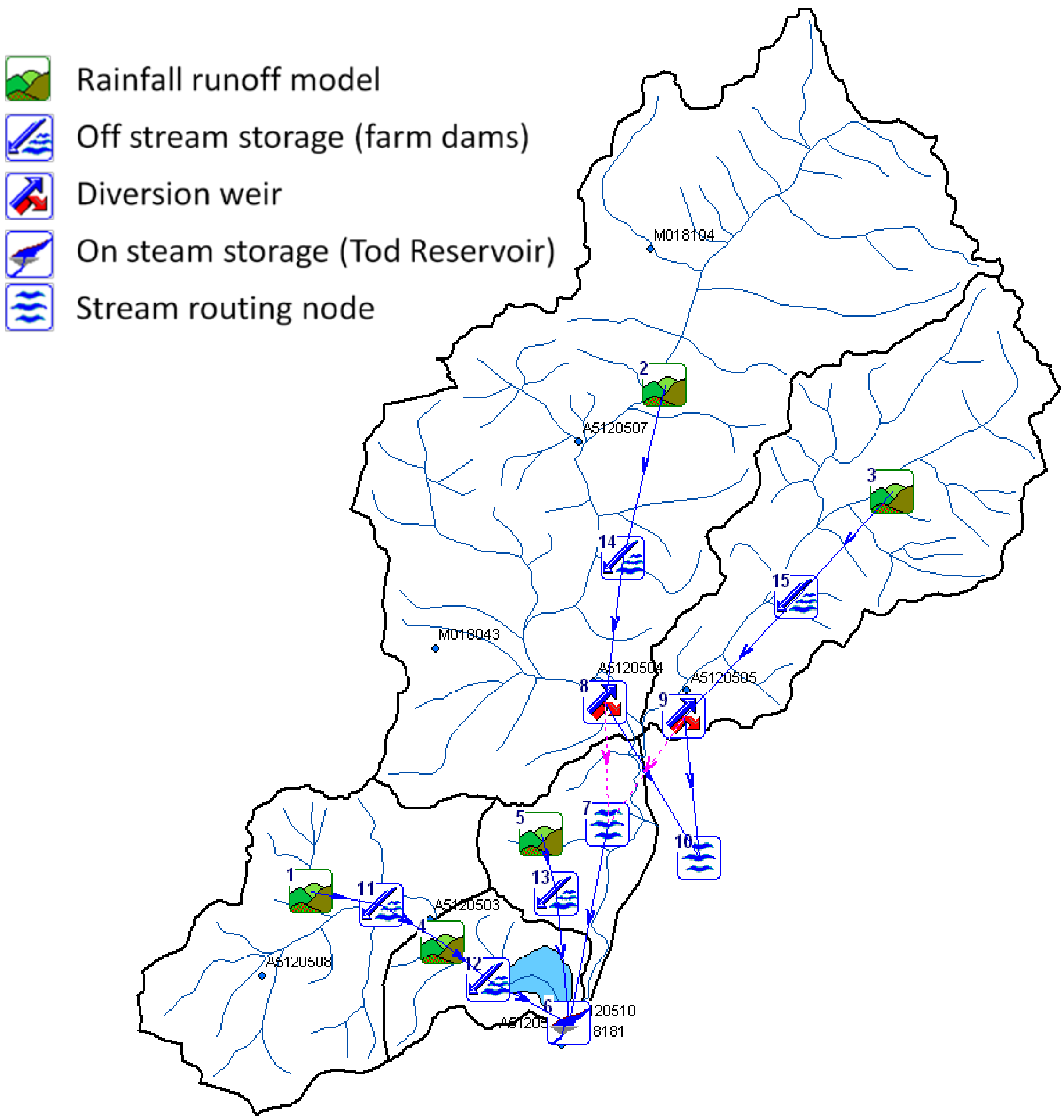


Figure 17. Tod Reservoir WaterCRESS model layout

While the farm dam density in the catchment is relatively low, farm dams have been included in the model to allow the impact of climate change projections on the storage in farm dams to be assessed. As was the case for the calibration catchment, the dam capacities for the full reservoir model have been derived from aerial photography taken in 2001 (as used by McMurray, 2006) and a diversion fraction of 0.3 has been assumed, representing the proportion of the catchment affected by farm dams. An extraction rate of 50% of the dam's capacity has been assumed, with extractions occurring over the summer months only, as derived by McMurray (2006). Two scenarios for farm dam storage volumes have been considered in this study. The first is the historic volumes, as derived from aerial photography, where the volumes can be seen in Table 8. A scenario for the maximum allowable dam volume for each catchment has also been considered, as specified as a dam density in ML/ha in the EPNRMB plan (EPNRMB, 2009b), where the equivalent dam volume for each catchment area can be seen in Table 8. This scenario considers the case where maximum development has occurred for the future scenarios. The maximum development scenario has also been run for the baseline historic case for comparative purposes, even though this is not representative of the current state of the catchment.

Table 8. Current and maximum farm dam storage volumes

Catchment	Current Volume (ML)	Area (ha)	Current Density (ML/ha)	Maximum Density* (ML/ha)	Maximum Volume (ML)
Pillawarta Creek	83.0	4190	0.020	0.042	176.0
Upper Tod River	316.0	10 470	0.030	0.054	565.4
Toolillie Gully - US Gauge	82.4	2990	0.028	0.063	188.4
Toolillie Gully - DS Gauge	14.8	902	0.016	0.063	56.8
Drainage Channel	45.4	1190	0.038	0.054	64.3

* Derived from EPNRMB (2009b)

3.5.4. MODEL VALIDATION

To assess the accuracy of the runoff simulated to the reservoir, the flows have been compared to the reservoir yields estimated in the Catchment Yield Analyses for South Australian reservoirs (referred to as DENR Yield; Tomlinson, 1996). This analysis was based on a gauge downstream on the Tod River, A5120500, which was closed in 1989 and reopened in 2000. The total area contributing to this gauge was estimated to be 355 km^2. Correlations between catchment yield and rainfall during each month, as well as one and two months previous, were used to extend the analysis to the end of 1996 by Tomlinson (1996). The monthly yield at the reservoir was then estimated as the yield determined from the correlation with rainfall, then proportioned by the contributing areas (divided by 355, then multiplied by 200). Hence, it was assumed that all runoff from the two upper catchments was diverted to the reservoir.

A similar approach has also been used as a validation in this work, with the monthly yield recorded at the Toolillie Gully site proportioned by the contributing areas to estimate the total yield to the reservoir (divided by 29.9, then multiplied by 197.4). This is expected to be an upper limit estimate as rainfall at Toolillie Gully is the highest of the whole catchment. The comparison between these two yield estimates, from the time the Toolillie Gully data commenced in 1991 up to the end 1996 when the DENR yield estimates (Tomlinson, 1996) concluded, as well as the simulated total runoff at the reservoir over this period is shown in Figure 18. There is generally good agreement between the Toolillie Gully area proportioning (based on observed data) and the WaterCRESS model. The lag between Toolillie Gully derived flows and the DENR yields is most likely due to the method used to derive the DENR catchment yield (where correlations with rainfall during the current month as well as one and two months previous was used), as well as the former gauge being located approximately 17 km further upstream and hence, flow events are recorded earlier. Generally, the magnitudes of the peak monthly flows are similar across the different yield estimates. The total volume estimated by the WaterCRESS model is less than the DENR yield estimated (represented by the area under each line). However there are expected to be large uncertainties in the DENR yield values, as they have been derived using a simple correlation with rainfall and then proportioned by area to represent the catchments contributing to the reservoir only. Hence the WaterCRESS model is assumed to be more accurate due to the closer agreement with the observed data at Toolillie Gully.

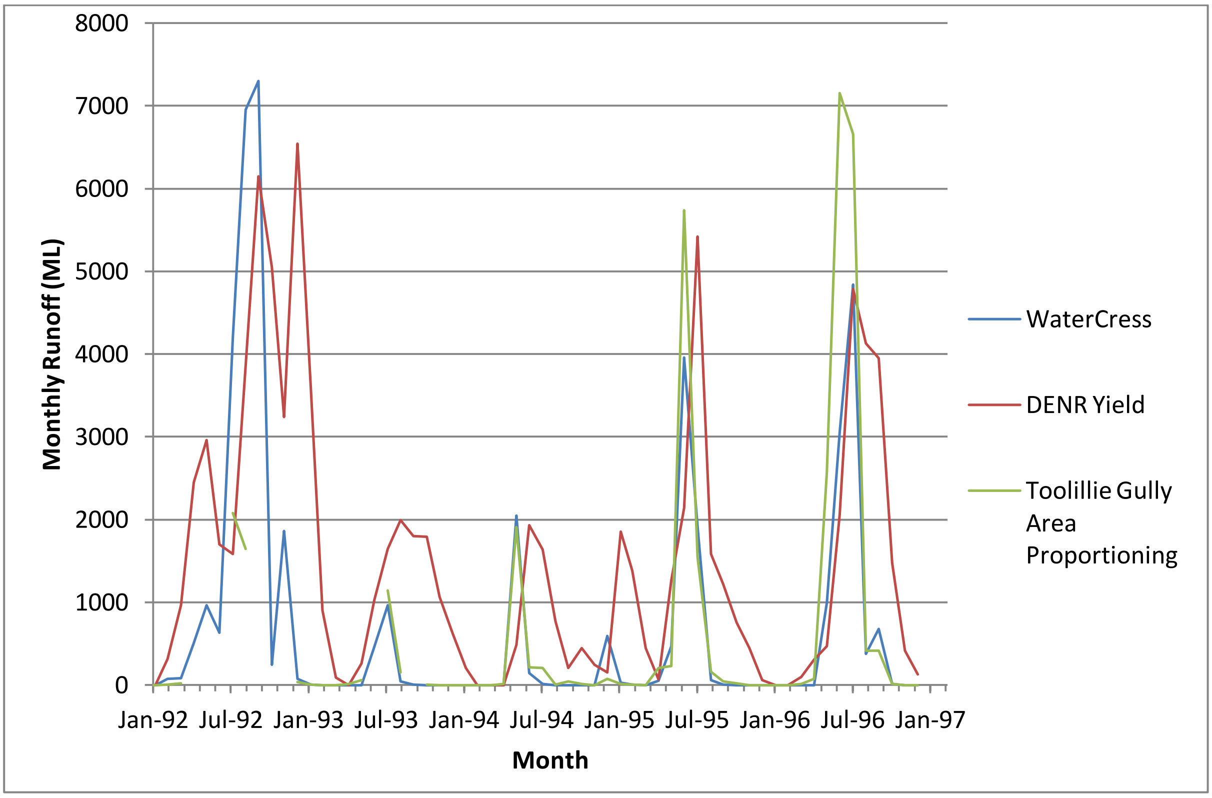


Figure 18. Estimates of monthly yield delivered to Tod Reservoir

The simulated reservoir behaviour has also been compared. A constant seepage rate of 2 ML/day has been used to represent the seepage losses from the reservoir. Records of volumes diverted from the northern catchments of upper Tod River and Pillaworta Creek are limited, making comparison of the modelled reservoir storage difficult over a long period of time. A two-year period beginning in February of 1993 has been considered to assess the accuracy of the modelled inflows and reservoir storage. Records of extractions from the reservoir for water supply are available for this period (with an average extraction of 234 ML/month and standard deviation of 98 ML/month). The simulated runoff from the two Toolillie Gully catchments and the diversion channel catchment were used as the inflows to the reservoir in the WaterCRESS model, with extractions representing the monthly water supply from the reservoir. The inflows to the reservoir have been simulated, as well as a comparison between the simulated and recorded storage in the reservoir (Fig. 19). While the inflows are slightly larger than that experienced, indicated by slightly larger simulated reservoir storage than that observed, this has been deemed an accurate representation of the runoff volumes and reservoir behaviour over this short time period. From Figure 19 it can be seen that this is a relatively dry period with low inflows, indicated by the declining reservoir storage and few inflow events. The inflows were comprised of a total of 725 ML diverted from the Pillaworta Creek catchment, 1533 ML diverted from the Upper Tod catchment, with the remaining inflows contributed by the Toolillie Gully catchment. Following this period, a number of diversions from the upper catchments appear to have occurred, indicated by an increase in the recorded reservoir level, and more recently the reservoir has not been used for supply due to elevated salinity in the reservoir.

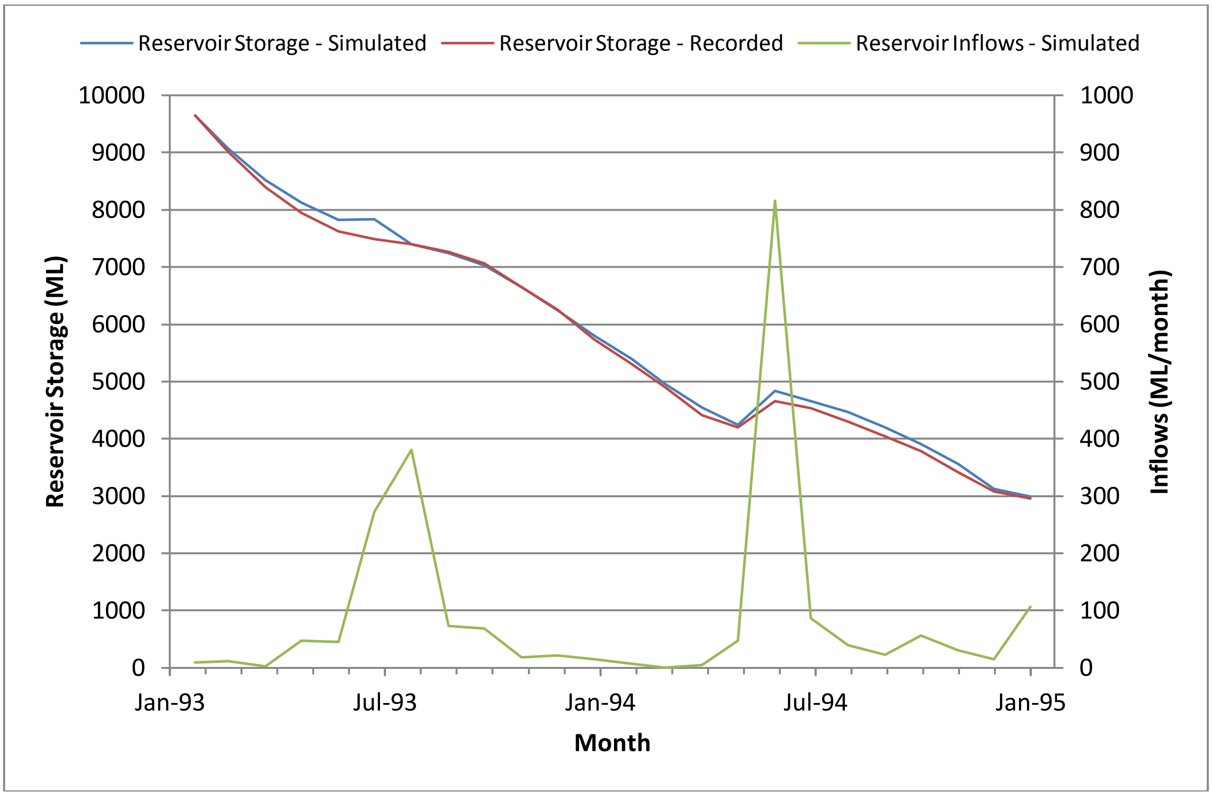


Figure 19. Simulated and observed water level, with inflows, for the Tod Reservoir

3.5.5. RULES FOR DIVERSIONS TO TOD RESERVOIR

Current diversion operating rules are that saline runoff, greater than 1500 mg/L TDS, is not diverted into the reservoir (SA Water, 2008). A significant proportion of the available water (potentially 90%) flows past the diversion weirs due to high salinity (SA Water, 2008). These high salinity levels are understood to be due to the geology and soils within the catchment mobilising salts following native vegetation clearance. Salinity tends to vary with season and rainfall event, being higher in low-flow periods and fresher at the start of high flows (SA Water, 2008).

Initial investigations were undertaken to develop a salinity model based on the simulated flows, however a relationship fitted to available salinity records (Fig. 20) would only very rarely result in fresh enough runoff being simulated to permit diversion. Hence, this approach was not pursued as it was expected to produce very similar results to a no diversion scenario. Instead, two cases have been considered for the modelling of future scenarios, (1) no diversions from the upstream catchments and (2) 10% of the flow passing the diversion weirs, allowing 90% of the flow from the upper catchments to flow past the diversion weirs, as indicated by SA Water (2008). It is acknowledged that a constant fraction is not how the diversion weirs are operated in practice, instead fresh events are diverted for short periods of time, however the resulting total volume diverted each year is expected to be similar.

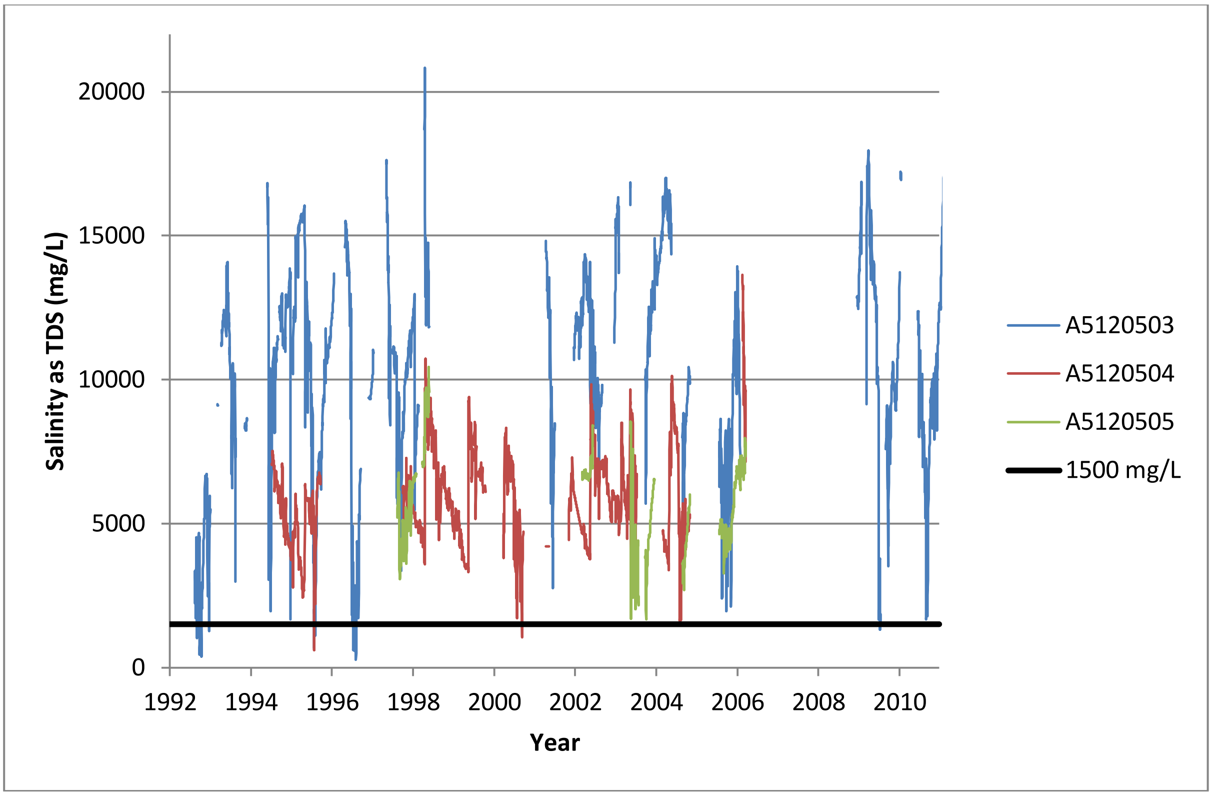


Figure 20. Recorded salinity levels in the Tod River catchment.

4. MODEL RESULTS

4.1. *MUSGRAVE PRESCRIBED WELLS AREA*

4.1.1. MUSGRAVE PWA CLIMATE CHANGE SCENARIOS

The four GCMs selected for this study produced a wide range of input data (daily rainfall and PET data) for use in the surface water and groundwater recharge models. Using the Sheringa (Lake Hamilton) rainfall station (BoM weather station # 18045) in the Musgrave PWA as an example, Figure 21 shows the changes in average annual rainfall and Figure 22 shows the changes in average winter rainfall for the four GCMs under the B1 and A2 emission scenarios. They show that the LASG-IAP GCM predicts the lowest reduction in rainfall and that the reduction in average winter rainfall is less than the reduction in average annual rainfall. All the other GCMs however predict a greater reduction in average winter rainfall than in average annual rainfall, which is significant in terms of its potential impacts on recharge and runoff. As is typical for the majority of South Australia, the CSIRO Mk 3.5 GCM projects the greatest overall reduction in rainfall.

Figure 23 shows the change in average annual PET and Figure 24 shows the change in average winter PET, with the CSIRO Mk 3.5 GCM again predicting the greatest change, followed by the NCAR CCSM3 GCM. The CSIRO Mk 3.5 GCM also predicts the greatest increase in average winter PET, but increases are matched by the NCAR-CCSM3 GCM for the 2030 A1 and 2030 B2 scenarios.

In general, both B1 and A2 emissions scenarios produce similar changes in rainfall and PET by 2030. This is to be expected, given that projected emissions under both story lines stay relatively similar up until 2030 (see CSIRO and BoM, 2007). However, a greater discrepancy is observed for 2050 and 2070. A greater reduction in rainfall and increase in PET observed for the A2 story line, which is based on greater emissions than the B1 story line after 2030.

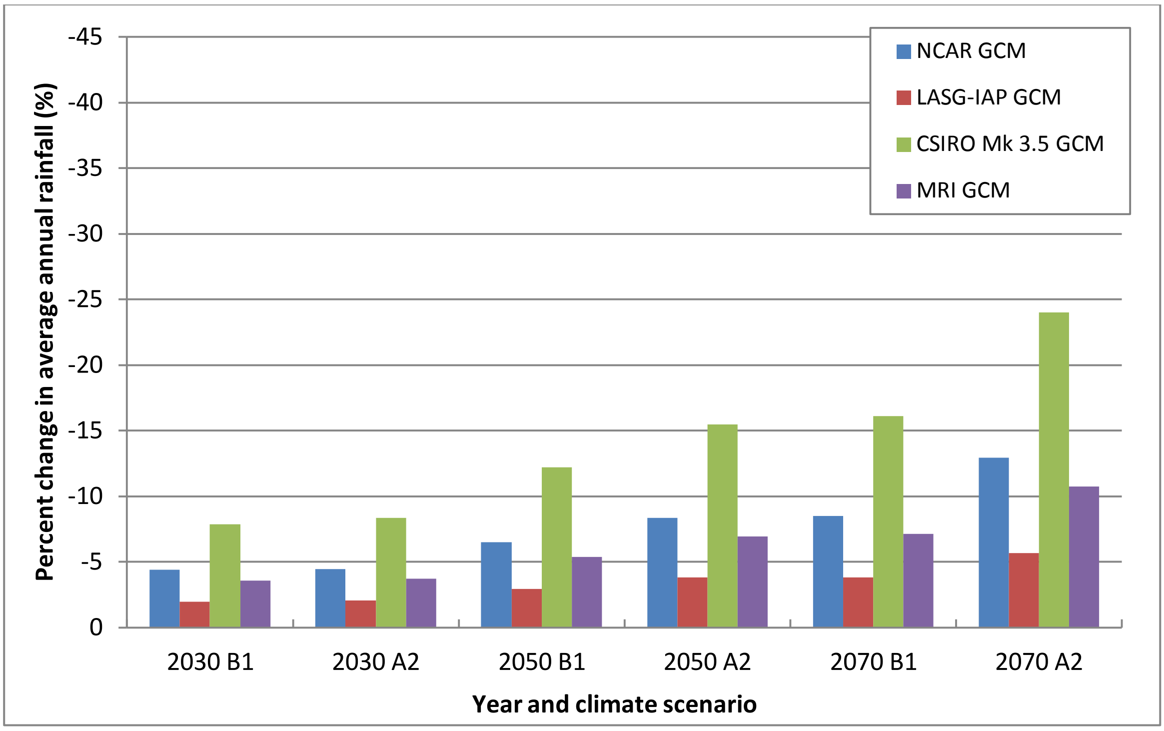


Figure 21. Reduction in average annual rainfall produced by the four different GCMs under the B1 and A2 emissions scenarios. Results are based on historic rainfall data taken from the Sheringa weather station (BoM station #18045) located within the Musgrave PWA

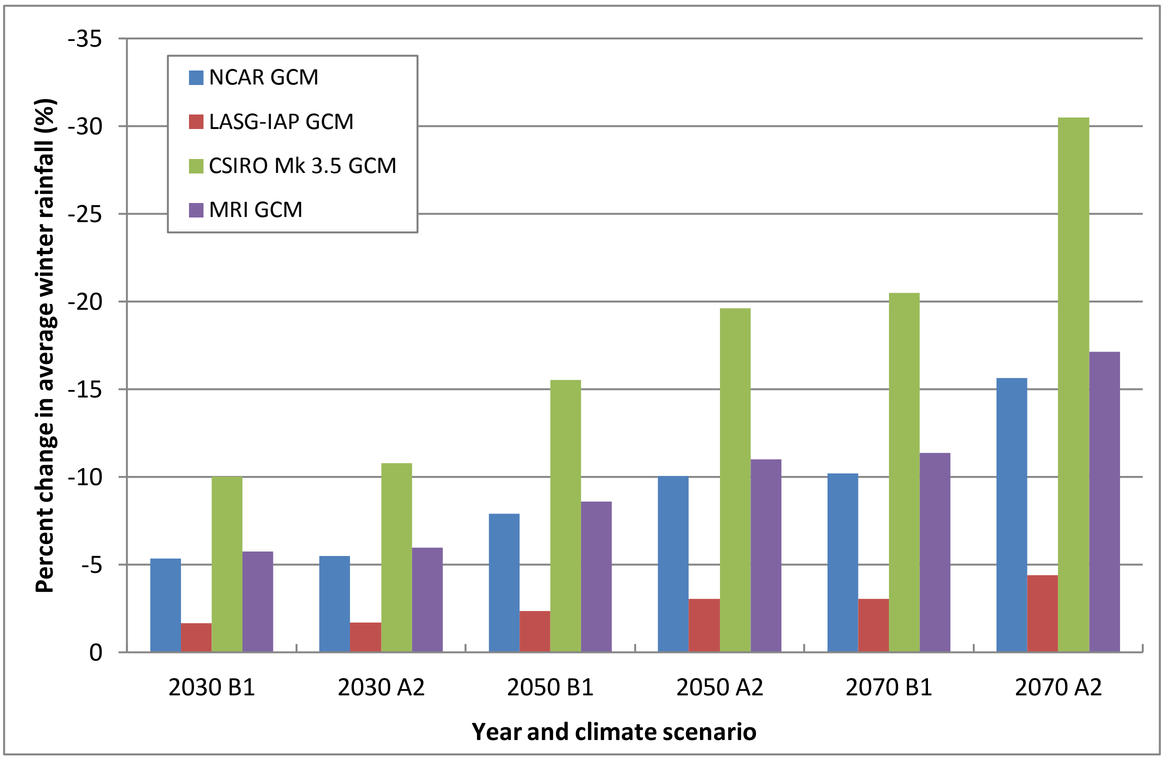


Figure 22. Reduction in average winter (May to September) rainfall produced by the four different GCMs under the B1 and A2 emissions scenarios. Results are based on historic rainfall data taken from the Sheringa weather station (BoM station #18045) located within the Musgrave PWA

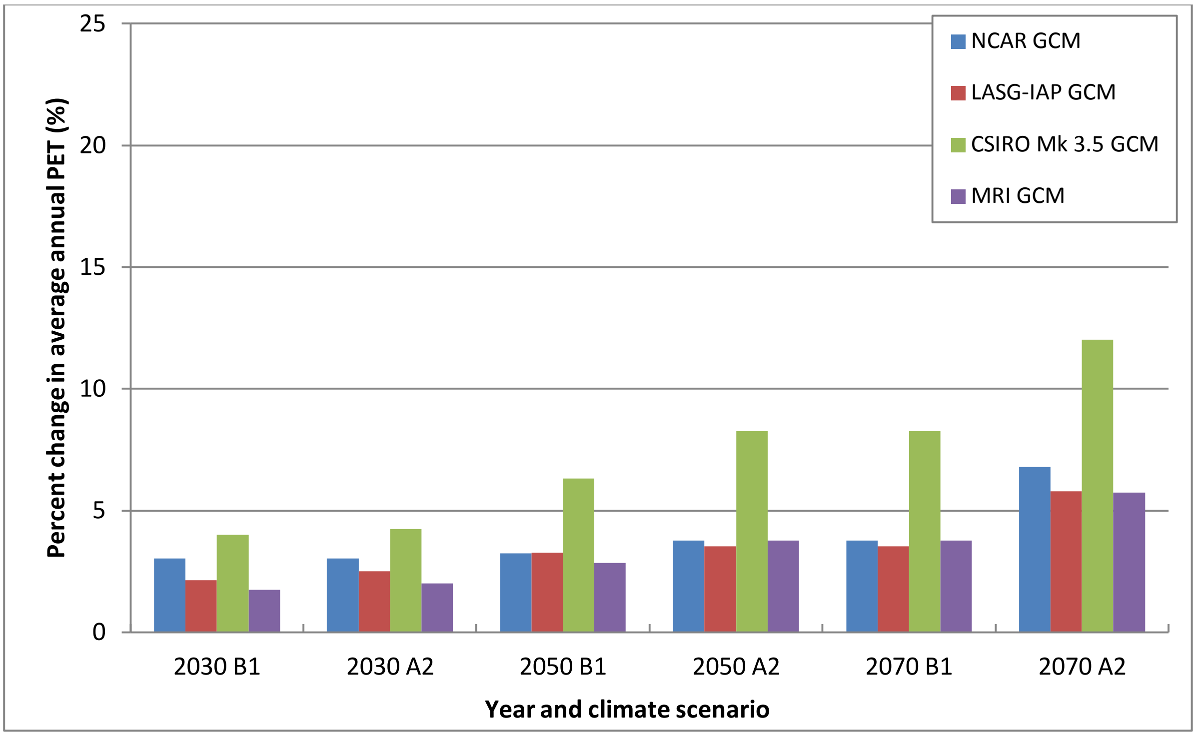


Figure 23. Reduction in average annual PET produced by the four different GCMs under the B1 and A2 emissions scenarios. Results are based on historic rainfall data taken from the Sheringa weather station (BoM station #18045) located within the Musgrave PWA

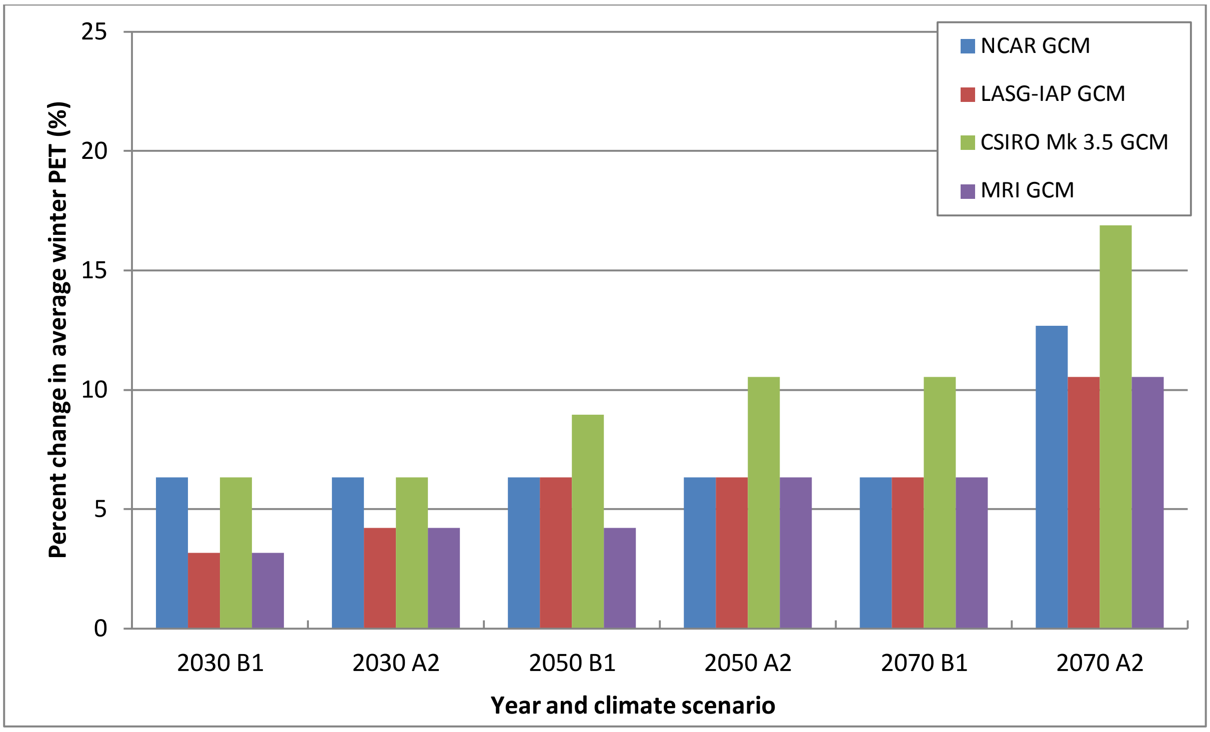


Figure 24. Reduction in average winter (May to September) PET produced by the four different GCMs under the B1 and A2 emissions scenarios. Results are based on historic rainfall data taken from the Sheringa weather station (BoM station #18045) located within the Musgrave PWA

4.1.2. MUSGRAVE PWA GROUNDWATER RECHARGE MODELS

While the recharge models have been calibrated to correctly represent the inter-annual variations in recharge that result from variations in rainfall and evapotranspiration conditions from year to year (Appendix A), the calibration was not intended to match modelled recharge rates with current or historic estimates of actual recharge. However, it is desirable that the recharge models produce an annual average recharge that is *similar* to those estimated by previous studies. For completeness, the calibrated modelled recharge rates (1990 baseline values) for selected fresh groundwater bodies are compared below with estimates of actual long-term recharge rates as reported in the current Water Allocation Plans for the Southern Basins and Musgrave PWAs (Table 9). It should be noted that although the WAPs cite a precise rate of recharge, the estimates of the current rates of recharge to Eyre Peninsula's fresh groundwater lenses are widely variable, as presented in Tables 1 and 2.

Table 9. Comparison of calibrated modelled recharge rates and estimated actual recharge rates from the current Water Allocation Plans (WAPs)

Fresh groundwater lens or basin	Calibrated modelled recharge rate – 1990 baseline (mm/y)	WAP estimated recharge rate (mm/y)
Polda lens	51	28
Bramfield lens	66	31
Lincoln Basin[#]	126	45
Uley South lens	156	155

[#] Area-weighted average of Lincoln Basin lenses; Lincoln A, B, C, D and D West

The results of the spatially distributed LEACHG modelling for the Musgrave PWA are summarised in Figure 25. The percent reductions in average annual recharge represent the area-weighted averages for the Musgrave PWA based on the results of the LEACHG model. The reductions are compared to the average annual recharge rate determined using historical climate data (1960–2009), which gave an annual, area-weighted average recharge rate (the sum of recharge and modelled runoff) of 76 mm/y. The projected reductions in average annual recharge vary markedly (Fig. 25) depending on which GCM and emission scenario is used to generate rainfall and PET data. Climate data generated using the LASG-IAP GCM projections resulted in the lowest reduction in average annual recharge, from 8% at 2030 to 22% at 2070, while data from the CSIRO Mk 3.5 GCM produced the greatest reduction in average annual recharge, from 28% at 2030 to 70% by 2070.

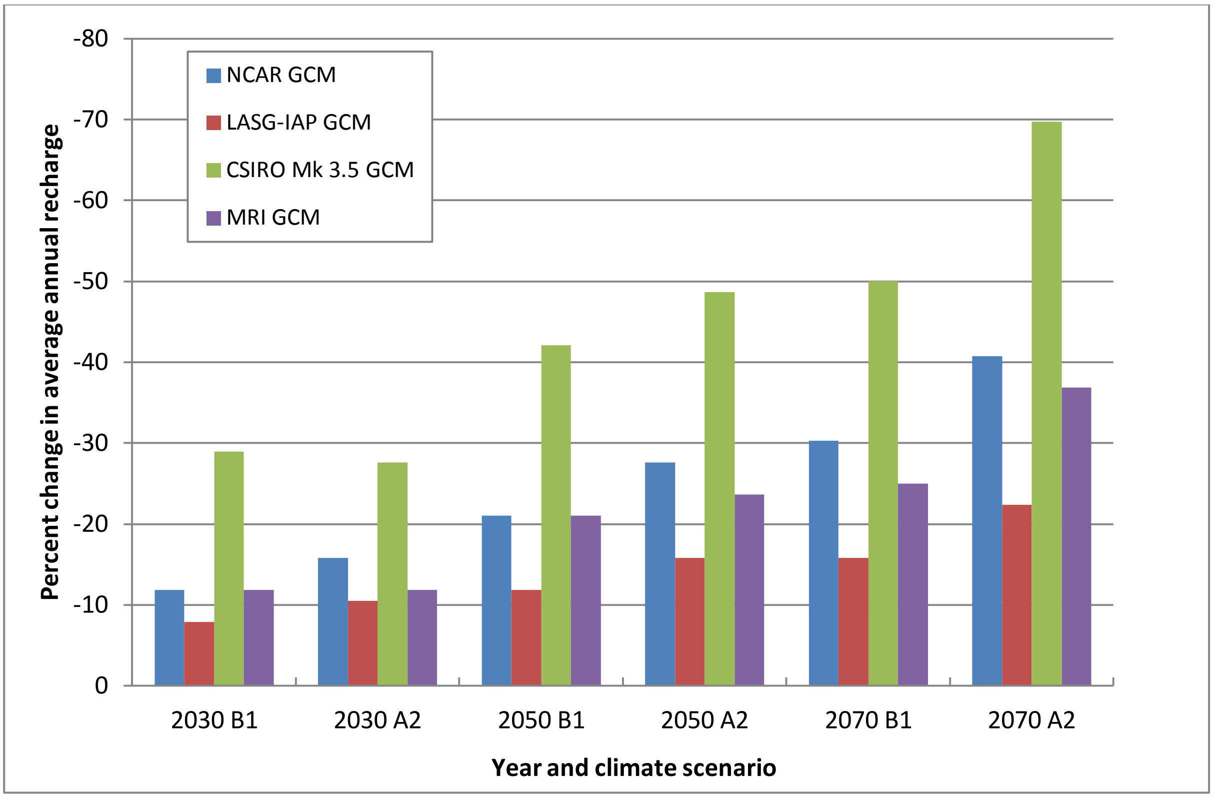


Figure 25. Modelled changes in average annual recharge for the Musgrave PWA for the different GCMs, emissions scenarios and time horizons considered, as estimated by the LEACHG models

Figure 26 shows the modelling results for the Polda and Bramfield groundwater resources for each GCM and each climate scenario. The results show only minor variations in the projected reductions in average annual recharge between these two resources. The variation in reductions in recharge are in the order of only 2–3% and, considering the Polda and Bramfield models were parameterised with rainfall and PET from different weather stations, it was concluded that the modelling approach generates similar results for all of the fresh groundwater lenses to which the model is applied. Consequently, the modelling approach has been applied to all of the individual lenses but the results have been reported more broadly at the PWA-scale.

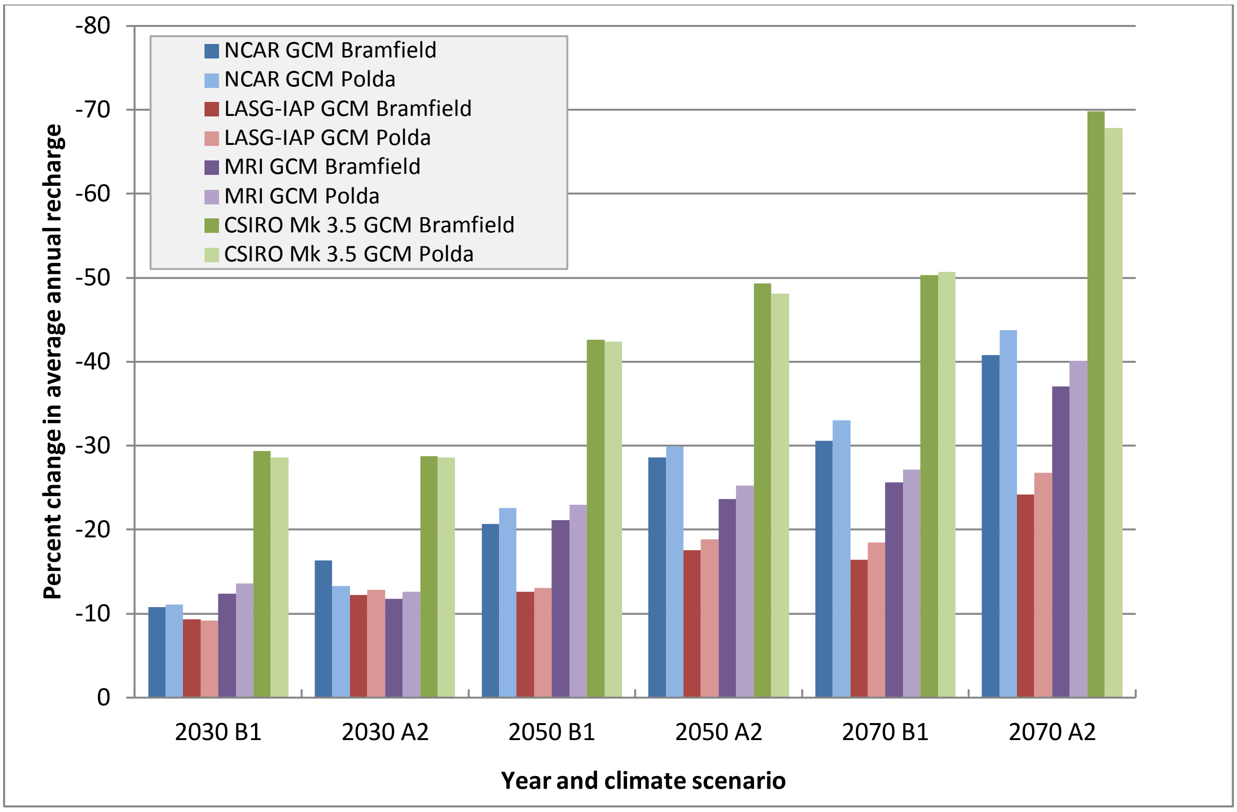


Figure 26. Modelled changes in average annual recharge for the Polda and Bramfield groundwater lenses (located within the Musgrave PWA)

Tables 10 to 13 summarise the results from the LEACHG models for future climate scenarios from all four GCMs. As well as the changes to mean recharge over the 50-year simulation period, projected changes in the frequency of high and low-recharge years, characterised by the 80th percentile and 20th percentile annual recharge respectively, are also reported. For each GCM, the historic 20th and 80th percentile annual recharge is presented in the 1990 column and by definition there are 10 years with recharge above the 80th or below 20th percentile recharge for the historic case (based on a 50-year simulation period). Then for each scenario, the projected change to the 20th and 80th percentile annual recharge amount is reported, as well as the number of years in the future climate scenario that are below the historic (1990) 20th percentile and the number of years above the 80th percentile recharge rate. For example, in Tables 10 to 13 the historic baseline (1990) low (20th percentile) and high (80th percentile) annual recharge amounts are 34 mm/y and 109 mm/y, respectively. In the results from models run with NCAR-CCSM3 GCM climate projections (Table 11) for the 2050 B1 scenario, the 20th and 80th percentile recharge fluxes are reduced to 25 mm and 92 mm, respectively. The number of years that would have historically been considered low-recharge years (less than 1990 20th percentile recharge) increases from 10 to 16 in a 50-year sequence. The number of years that would have historically been considered high-recharge years (greater than 1990 80th percentile recharge) reduces from 10 to 6 in a 50-year sequence.

When evaluating these results it is useful to consider that the LASG-IAP GCM projects the lowest amount of climate change among the four GCMs, while the CSIRO Mk3.5 projects the highest.

Table 10. Changes in climate and recharge for the Musgrave Prescribed Wells Area simulated by the LEACHM model using input data generated using the LASG-IAP GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	445	436	436	432	428	428	419
Average Winter Rainfall (mm)	210	207	207	205	204	204	201
Average Annual PET (mm)	1210	1236	1240	1249	1253	1253	1280
Average Winter PET (mm)	145	150	151	154	154	154	160
Average Annual Recharge (mm)	76	70	68	67	64	64	59
Change in Annual Rainfall (%)		-2	-2	-3	-4	-4	-6
Change in Winter Rainfall (%)		-2	-2	-2	-3	-3	-4
Change in Annual PET (%)		2	3	3	4	4	6
Change in Winter PET (%)		3	4	6	6	6	11
Change in average recharge (mm [%])		-6 [-8]	-8 [-11]	-9 [-12]	-12 [-16]	-12 [-16]	-17 [-22]
Low Events							
20th Percentile Recharge (mm)	34	31	30	28	28	28	25
Years Below 1990 20th %	10	12	12	13	15	15	16
High Events							
80th Percentile Recharge (mm)	109	100	98	95	92	91	83
Years Above 1990 80th %	10	10	9	9	8	8	6

Table 11. Changes in climate and recharge for the Musgrave PWA simulated by the LEACHM modelling using input data generated using the NCAR-CCSM3 GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	445	425	425	416	408	407	387
Average Winter Rainfall (mm)	210	199	199	194	189	189	178
Average Annual PET (mm)	1210	1246	1246	1249	1255	1255	1292
Average Winter PET (mm)	145	154	154	154	154	154	163
Average Annual Recharge (mm)	76	67	64	60	55	53	45
Change in Annual Rainfall (%)		-4	-4	-6	-8	-8	-13
Change in Winter Rainfall (%)		-5	-6	-8	-10	-10	-16
Change in Annual PET (%)		3	3	3	4	4	7
Change in Winter PET (%)		6	6	6	6	6	13
Change in average recharge (mm [%])		-9 [-12]	-12 [-16]	-16 [-21]	-21 [-28]	-23 [-30]	-31 [-41]
Low Events							
20th Percentile Recharge (mm)	34	29	26	25	23	21	18
Years Below 1990 20th %	10	15	16	16	18	18	22
High Events							
80th Percentile Recharge (mm)	109	99	95	92	85	83	70
Years Above 1990 80th %	10	9	8	6	5	5	4

Table 12. Changes in climate and recharge for the Musgrave PWA simulated by the LEACHM modelling using input data generated using the MRI GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	445	429	428	421	414	413	397
Average Winter Rainfall (mm)	210	198	198	192	187	187	174
Average Annual PET (mm)	1210	1231	1234	1244	1256	1256	1279
Average Winter PET (mm)	145	150	151	151	154	154	160
Average Annual Recharge (mm)	76	67	67	60	58	57	48
Change in Annual Rainfall (%)		-4	-4	-5	-7	-7	-11
Change in Winter Rainfall (%)		-6	-6	-9	-11	-11	-17
Change in Annual PET (%)		2	2	3	4	4	6
Change in Winter PET (%)		3	4	4	6	6	11
Change in average recharge (mm [%])		-9 [-12]	-9 [-12]	-16 [-21]	-18 [-24]	-19 [-25]	-28 [-37]
Low Events							
20th Percentile Recharge (mm)	34	29	26	25	23	21	18
Years Below 1990 20th %	10	15	16	16	18	18	22
High Events							
80th Percentile Recharge (mm)	109	99	95	92	85	83	70
Years Above 1990 80th %	10	9	8	6	5	5	4

Table 13. Changes in climate and recharge for the Musgrave PWA simulated by the LEACHM modelling using input data generated using the CSIRO Mk 3.5 GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	445	410	407	391	376	373	338
Average Winter Rainfall (mm)	210	189	188	178	169	167	146
Average Annual PET (mm)	1210	1258	1261	1286	1310	1310	1355
Average Winter PET (mm)	145	154	154	158	160	160	170
Average Annual Recharge (mm)	76	54	55	44	39	38	23
Change in Annual Rainfall (%)		-8	-8	-12	-15	-16	-24
Change in Winter Rainfall (%)		-10	-11	-16	-20	-20	-31
Change in Annual PET (%)		4	4	6	8	8	12
Change in Winter PET (%)		6	6	9	11	11	17
Change in average recharge (mm [%])		-22 [-29]	-21 [-28]	-32 [-42]	-37 [-49]	-38 [-50]	-53 [-70]
Low Events							
20th Percentile Recharge (mm)	34	22	22	16	13	13	5
Years Below 1990 20th %	10	18	17	22	26	25	40
High Events							
80th Percentile Recharge (mm)	109	79	79	63	57	57	32
Years Above 1990 80th %	10	5	5	4	3	3	0

An example of an application of the model, using the NCAR-CCSM3 GCM, is outlined in Table 14 below. The modelled change in average recharge (%) (Table 8) has been used to project the reduced recharge rates in the future relative to the long-term recharge rates reported in the current Musgrave WAP (DWR, 2001b). Results indicate that, under the B1 scenario for example, recharge to the Bramfield lens will reduce from the current estimated rate of 31 mm/y down to 27 mm/y by 2030 and down to 22 mm/y by 2070.

Table 14. An application of the model using the NCAR-CCSM3 GCM and estimated recharge rates from the current Musgrave Water Allocation Plan

Lens	WAP estimated recharge (mm/y)	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Bramfield	31	27	26	24	22	22	18
Kappawanta	32	28	27	25	23	22	19
Polda	28	25	24	22	20	20	17
Polda North	25	22	21	20	18	18	15
Polda East	11	10	9	9	8	8	6
Sheringa A	29	26	24	23	21	20	17
Sheringa B	28	25	24	22	20	20	17
Talia	28	25	24	22	20	20	17
Tinline	31	27	26	24	22	22	18
Minor Lenses	25	22	21	20	18	18	15

Figures 29 to 34 show the area-weighted recharge rates from each year of the 50-year LEACHG model simulations, using baseline historic climate data (Fig. 28) and climate data scaled according to the projections of the NCAR-CCSM3 GCM. In these results, mean annual recharge rates generally decrease with increasing time, with a greater decrease observed under A2 emissions scenarios. However, there are some exceptions. For example, under the B1 emission scenario, a slightly greater reduction in recharge is predicted by 2030. The downscaling methodology produced the same average annual rainfall and PET for both the 2030 B1 and A2 scenarios. However, differences in the daily scaling and incorporation of intensity effects resulted in slightly different results for groundwater recharge. This is a result of differences in rainfall distribution indicated by the NCAR-CCSM3 GCM under the two different emissions scenarios. These differences are displayed in the quantile-quantile plot below (Fig. 27), which shows that under the A2 emission scenario there is an overall reduction with very little change in rainfall greater than 10 mm/d and a slight reduction in rainfall events less than 10 mm/d. Under the B1 scenario, there is also an overall reduction, however there is a greater reduction in rainfall less than 10 mm/d and an increase in the larger rainfall events (greater than 10 mm/d) compared to the historic (i.e. baseline 1960–2009) average.

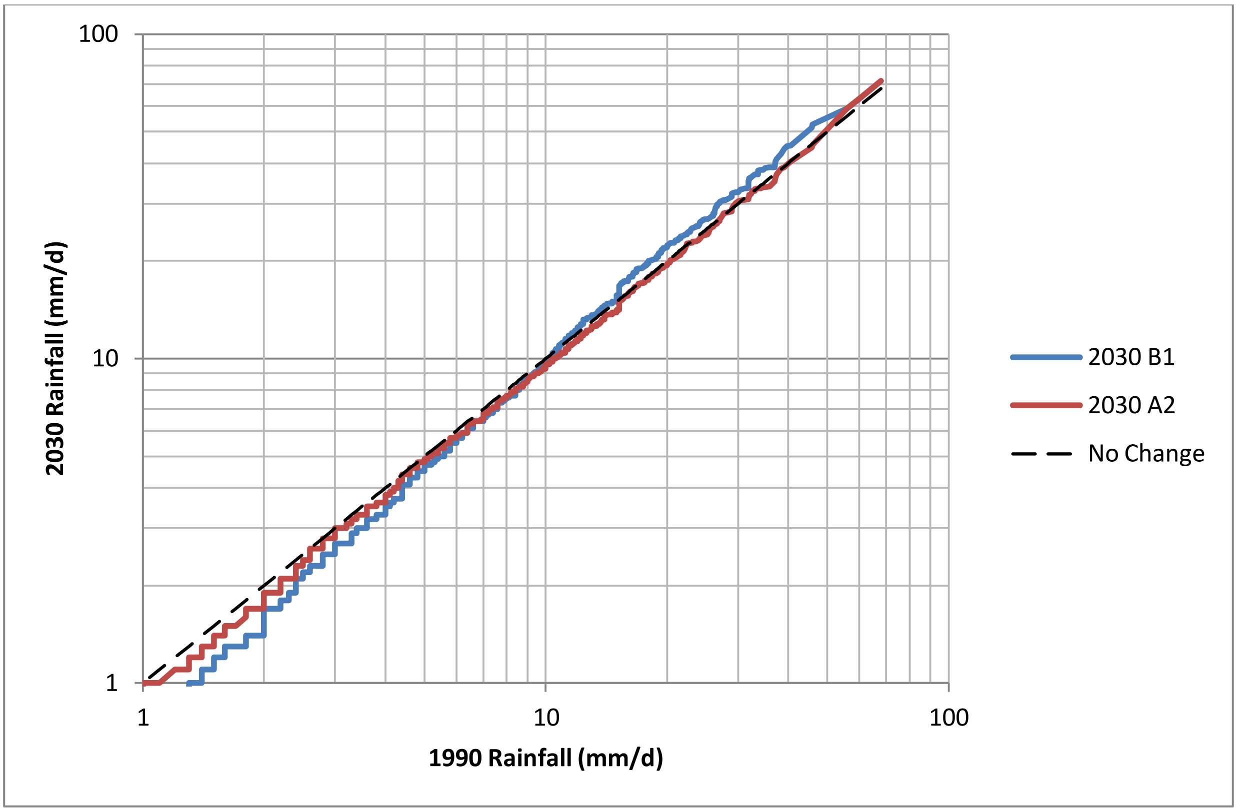


Figure 27. Quantile-quantile plot showing the differences in rainfall distributions for the 2030 B1 and A2 emission scenarios using the NCAR-CCSM3 GCM (compared to the historic baseline)

Of particular note in Figures 29 to 34 and Tables 10 to 13 is the increase in low-recharge years (years where recharge is below the 1990 20th percentile recharge rate) and a decrease in the number of high-recharge years (years where recharge is above the 1990 20th percentile recharge rate) under the future climate scenarios. These changes are in many cases greater in percentage terms than the changes in mean annual recharge. For example, under the NCAR-CCSM3 GCM A2 emissions scenario climate for 2050, there is a projected reduction in average annual recharge of 28%, however, the number of low-recharge years (as indicated by the 1990 20th percentile recharge) increases by 80% from 10 to 18 out of 50 years and the number of high-recharge years reduces by 50% to five out of 50 years.

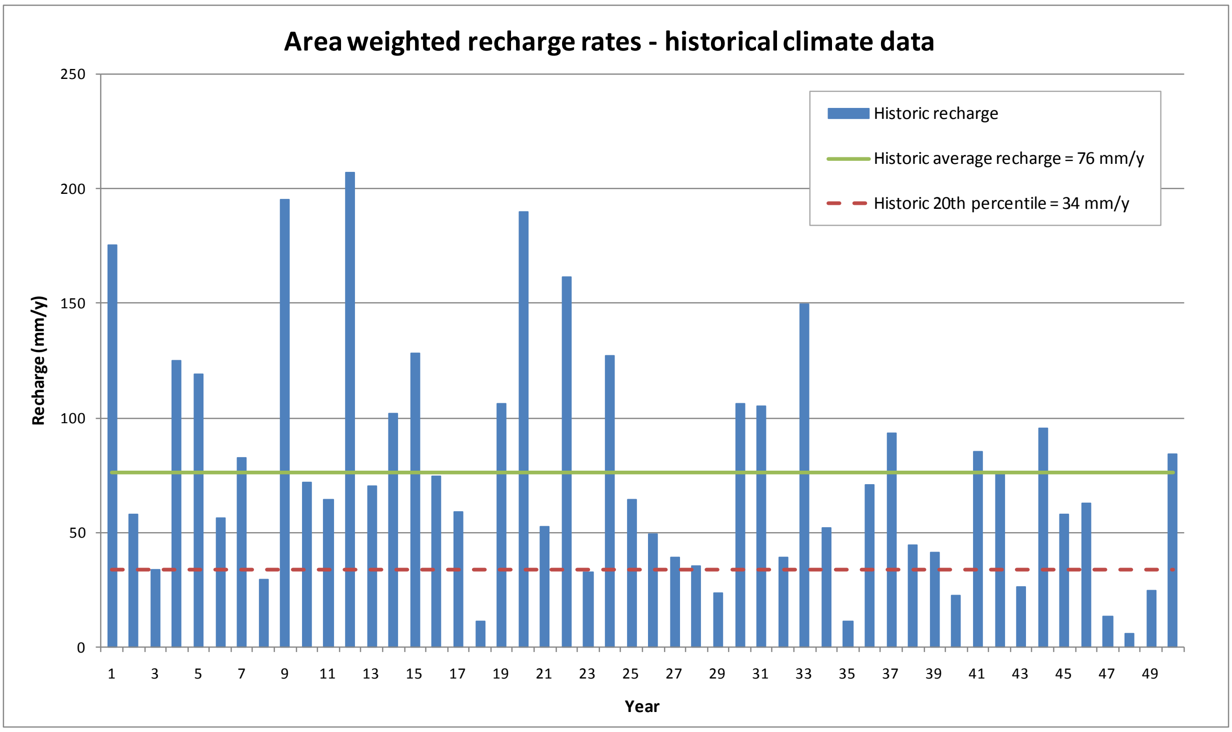


Figure 28. Annual area-weighted recharge rates over 50 years produced by the LEACHG model for the Musgrave PWA, using historical measured rainfall and PET data. Year 1 on the x axis represents 1960.

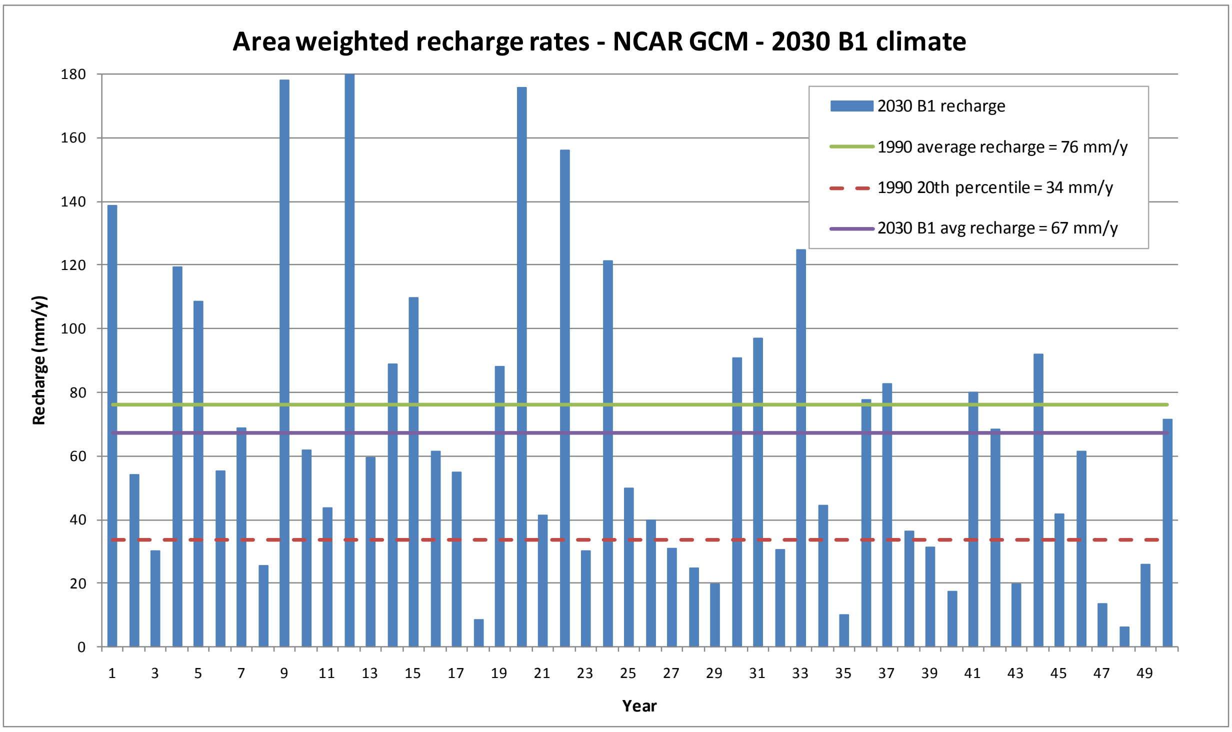


Figure 29. Annual area-weighted recharge rates produced by the LEACHG model for the Musgrave PWA, using rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2030 climate and B1 emissions

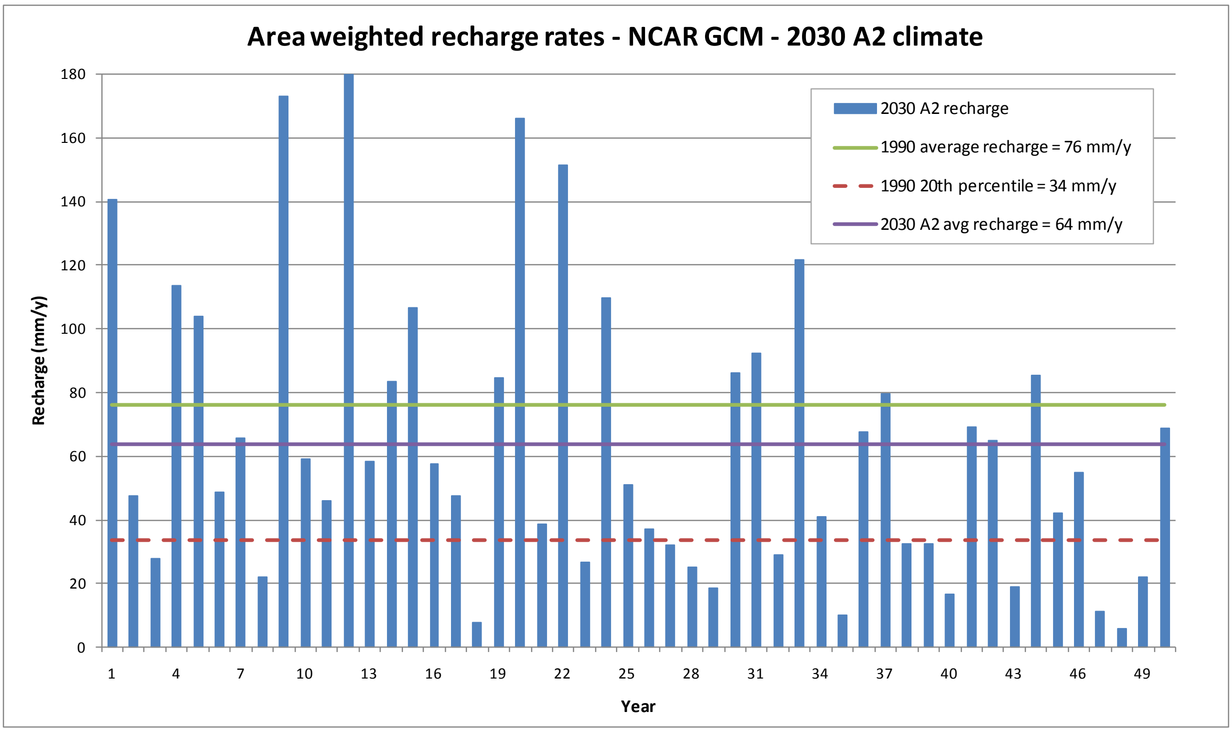


Figure 30. Annual area-weighted recharge rates produced by the LEACHG model for the Musgrave PWA, using rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2030 climate and A2 emissions

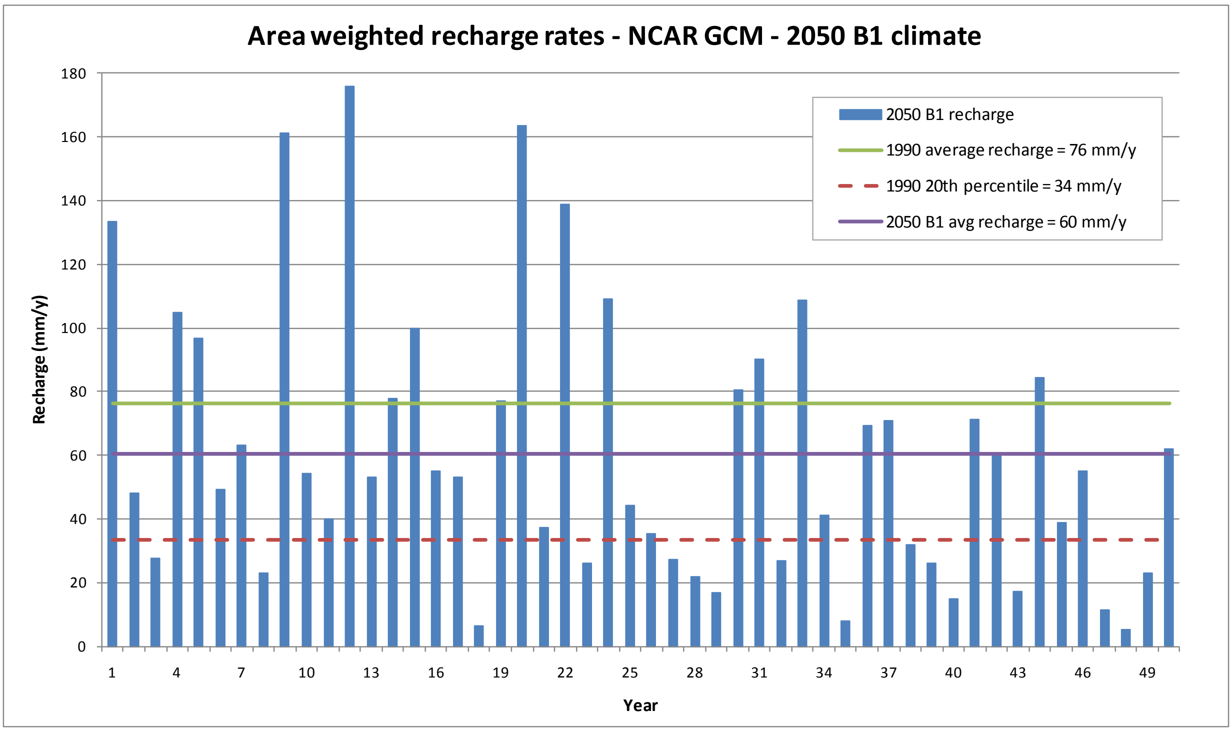


Figure 31. Annual area-weighted recharge rates produced by the LEACHG model for the Musgrave PWA, using rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2050 climate and B1 emissions

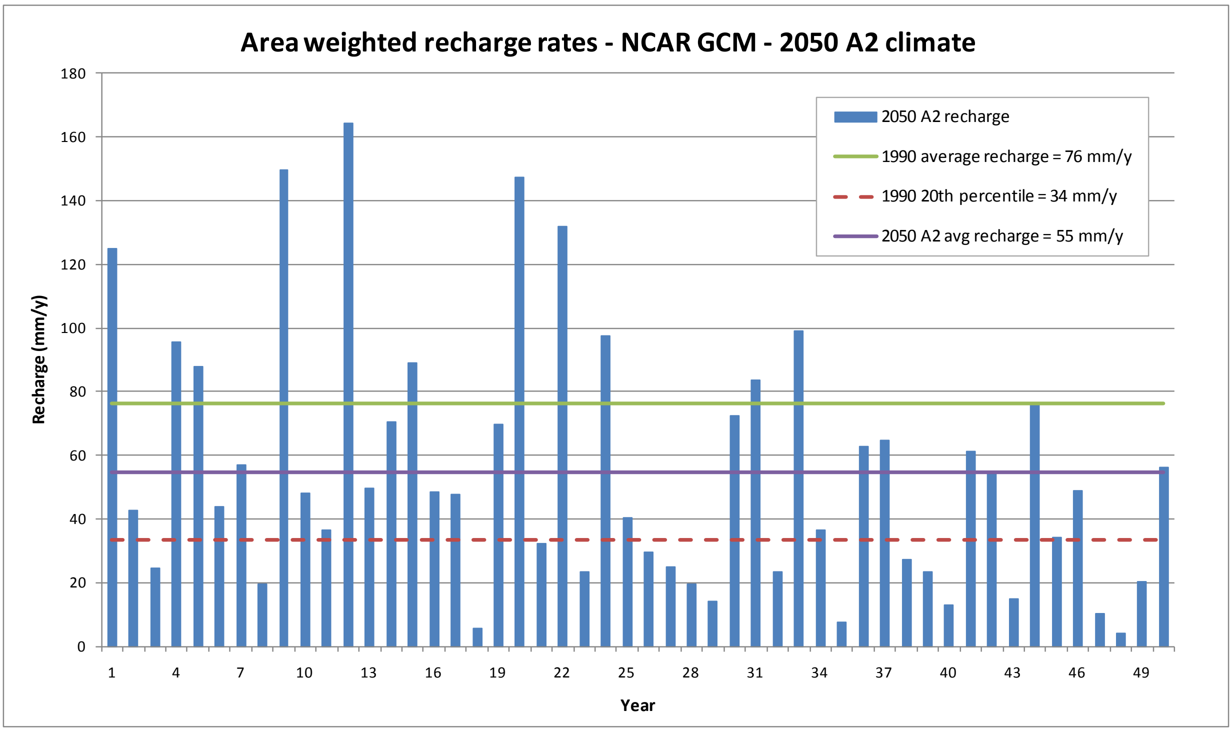


Figure 32. Annual area-weighted recharge rates produced by the LEACHG model for the Musgrave PWA, using rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2050 climate and A2 emissions

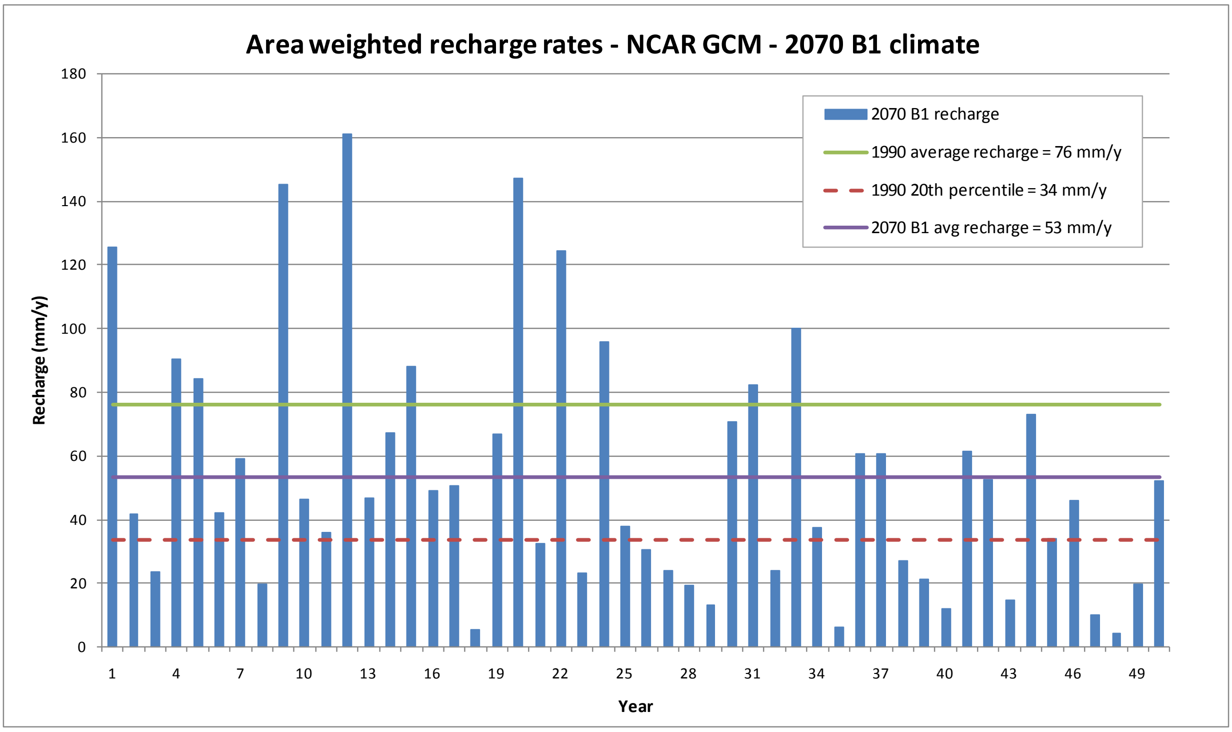


Figure 33. Annual area-weighted recharge rates produced by the LEACHG model for the Musgrave PWA, using rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2070 climate and B1 emissions

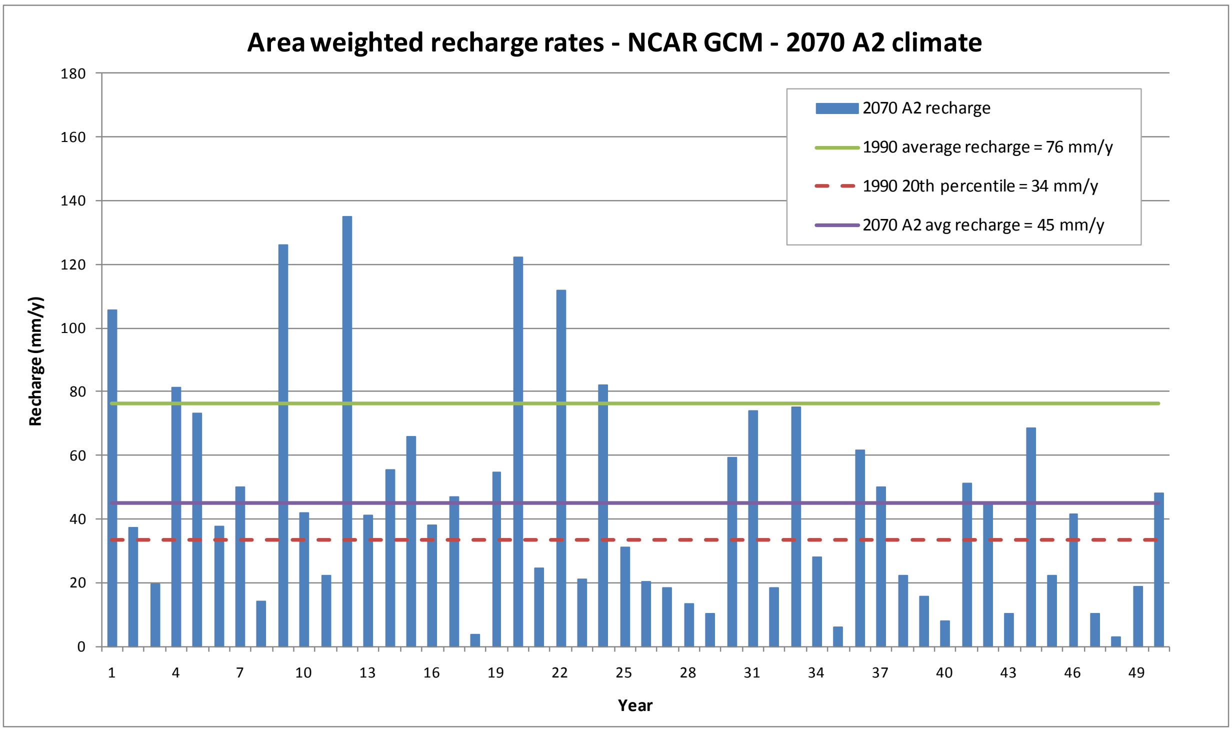


Figure 34. Annual area-weighted recharge rates produced by the LEACHG model for the Musgrave PWA, using rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2070 climate and A2 emissions

In all scenarios, the annual recharge changes are most closely correlated with annual rainfall changes. This is a different result to previous modelling in the ICCWR project (Green *et al.*, 2011), in which a closer correlation between recharge and winter (June–August) rainfall was observed. However, it is not an unexpected result for Eyre Peninsula, as a better correlation was also found between observed watertable depth fluctuations in Musgrave and Southern Basins observation wells and annual rainfall than winter rainfall. For this reason, the calibration of the soil models was focused on sensitivity to changes in annual rainfall (see Sec. 3.3).

To generalise the impacts on recharge resulting from the various climate change projections from the four GCMs, the change in recharge corresponding to each projected change in annual rainfall is presented in Figure 35. These results are based on area-weighted averages of all the modelled recharge areas in the Musgrave PWA. However, the changes in recharge for the historically most utilised lenses in the PWA (the Polda and Bramfield lenses) were within 2–3% of absolute agreement. (Fig. 26). Based on these results, it was concluded that the modelling approach is applicable across the broader Musgrave PWA.

The solid trend line in Figure 35 represents a hyperbolic tangent (tanh) function fitted to the results obtained from all GCM projections. This function is commonly used to represent the relationship between rainfall and surface water runoff, but can be seen to also provide a suitable representation of the trend of climate change impacts on groundwater recharge according to these model results.

The relationship derived allows the expected change in recharge to be estimated for any given change in annual rainfall. Thus, rainfall changes reported by other climate change projection summaries (such as the Regional Climate Change Projections, Eyre Peninsula (DENR, 2010)) can be used to give recharge change projections, based on the results of the hydrologic models presented here.

The dashed lines in Figure 35 represent 95% confidence limits, assuming normally distributed variation of the simulated results around the trend line. The 95% confidence intervals are defined according to Equation 3 (Sec. 4.3). They provide an indication of the impact of the inherent uncertainty around projections and simulation of a future climate. It must be stressed that the confidence bounds indicated here do not represent the entire uncertainty in the projected changes in recharge. These bounds only represent the variation resulting from the application to the recharge model of the 24 different climate datasets that result from the differing climate projections of the four GCMs, for the three time horizons, with two alternative emissions scenarios.

The variation in the mean annual recharge simulated for a given change in annual rainfall is due to a number of factors, including the change in rainfall projected for different seasons of the year, the change in intensity of rain events and the corresponding change in PET. The assumption applied in the recharge model, that recharge is the sum of diffuse recharge and surface runoff, has a large influence on the narrow uncertainty bounds indicated in Figure 35. The result of this approach is that changes in rainfall intensity under the various climate scenarios have little impact on the modelled recharge rate because as greater rainfall intensity may cause a shift from diffuse recharge to more runoff, both of these water balance components are incorporated in the modelled recharge. Thus the change in recharge under alternative climates results only from an increase in the proportion of the water balance that is taken by actual evapotranspiration. This is affected primarily by changes in PET and changes in the seasonality of rainfall. The various changes in rainfall and PET projected by the four GCMs are shown Figures 21 to 24 in Section 4.1.1. The variation between the changes projected by the four GCMs is very similar for average winter and average annual rainfall, indicating that any projected change in seasonality of rainfall is similar in all four GCMs. The projected changes in PET are similar across three of the four GCM, with only the CSIRO projecting a significantly greater change in PET. It is these similarities in the projections of rainfall seasonality and PET change from the four GCMs that leads to the narrow confidence bounds shown in Figure 35.

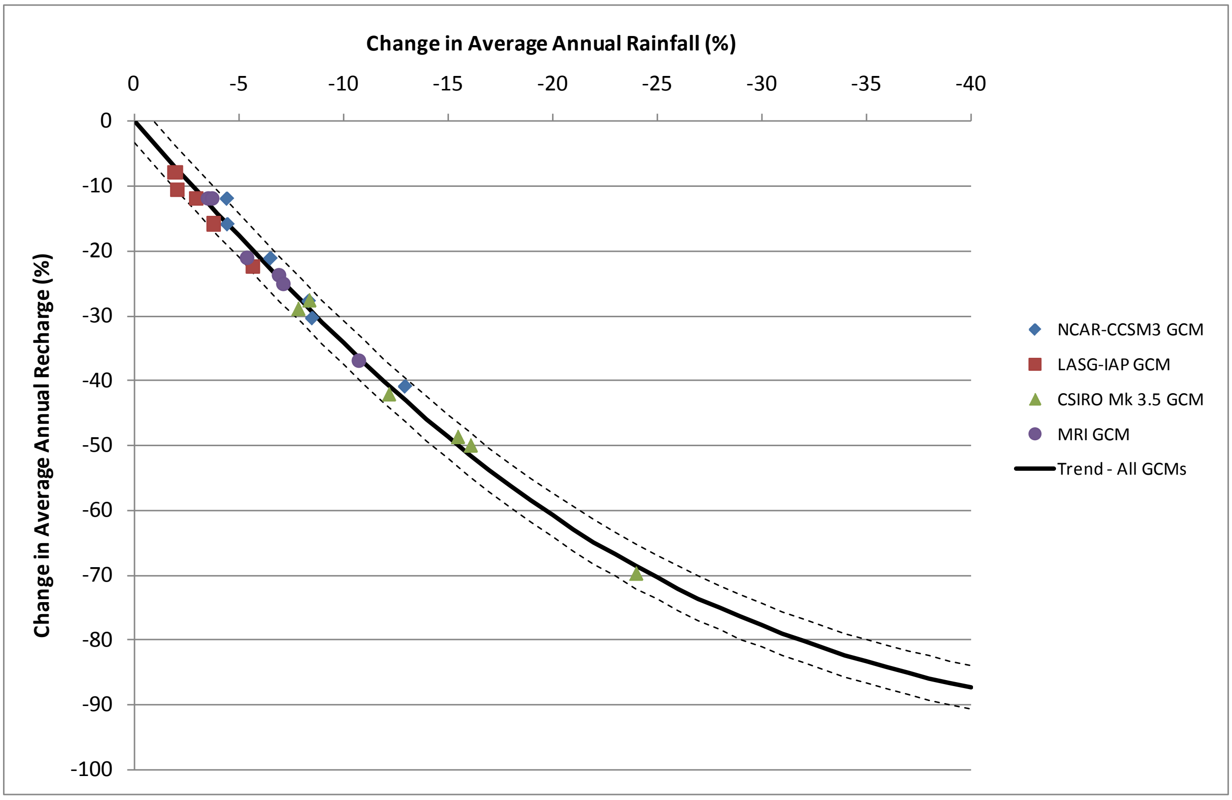


Figure 35. Changes in average annual rainfall versus changes in average annual recharge for the Musgrave PWA. The trend line is a tanh relationship, dashed lines show the upper and lower 95% bounds.

4.2. SOUTHERN BASINS PRESCRIBED WELLS AREA

4.2.1. SOUTHERN BASINS PWA CLIMATE CHANGE SCENARIOS

Figure 36 shows the reductions in average annual rainfall and Figure 37 shows the reductions in average winter rainfall projected for Southern Basins PWA based on the four different GCMs (using historical rainfall and PET data from Port Lincoln (Westmere) rainfall station, BoM reference #18137). Similarly, Figure 38 shows the increases in average annual PET and Figure 39 shows the increase in average winter PET based on the four different GCMs. The results are comparable with those for the Musgrave PWA (Sec. 4.1.1). For all future time horizons and emissions scenarios, the CSIRO Mk 3.5 GCM predicts both the greatest decrease in rainfall and the greatest increase in PET.

The main difference between the results for the Musgrave PWA and these results for the Southern Basins PWA is the differences in projected changes in winter PET. The results from the Musgrave PWA show higher increases in winter PET for the LASG-IAP and MRI GCMs and a lower increase in winter PET compared to the projections for the Southern Basins PWA.

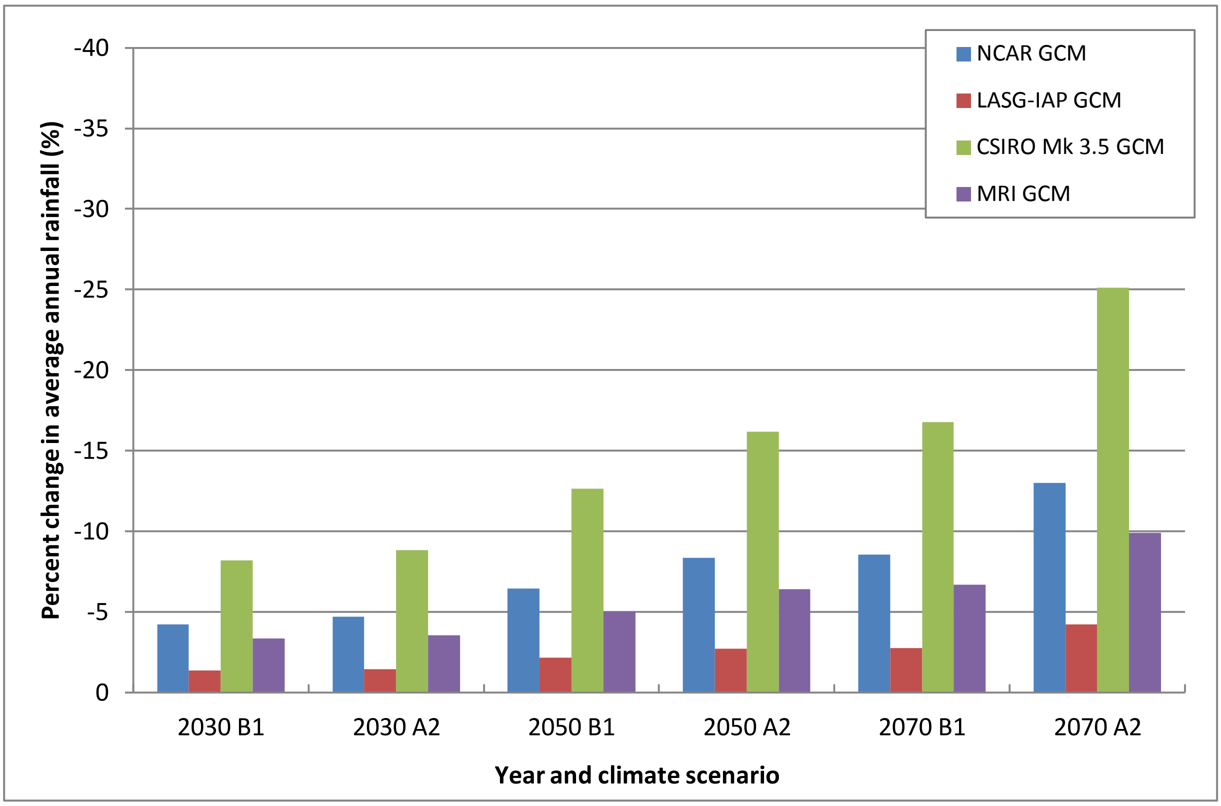


Figure 36. Reduction in average annual rainfall produced by the four different GCMs under the B1 and A2 emissions scenarios based on historic rainfall data taken from the Port Lincoln (Westmere) weather station (BoM station #18137)

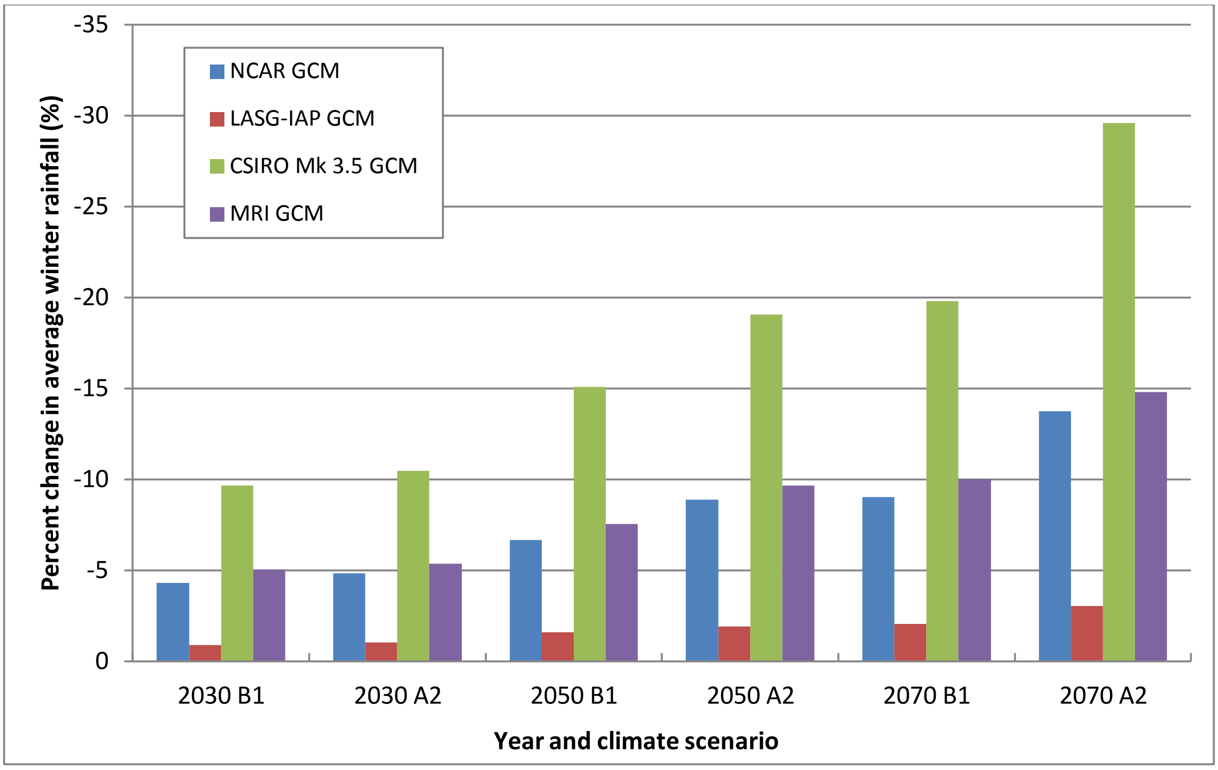


Figure 37. Reduction in average winter (May to September) rainfall produced by the four different GCMs under the B1 and A2 emissions scenarios based on historic rainfall data taken from the Port Lincoln (Westmere) weather station (BoM station #18137)

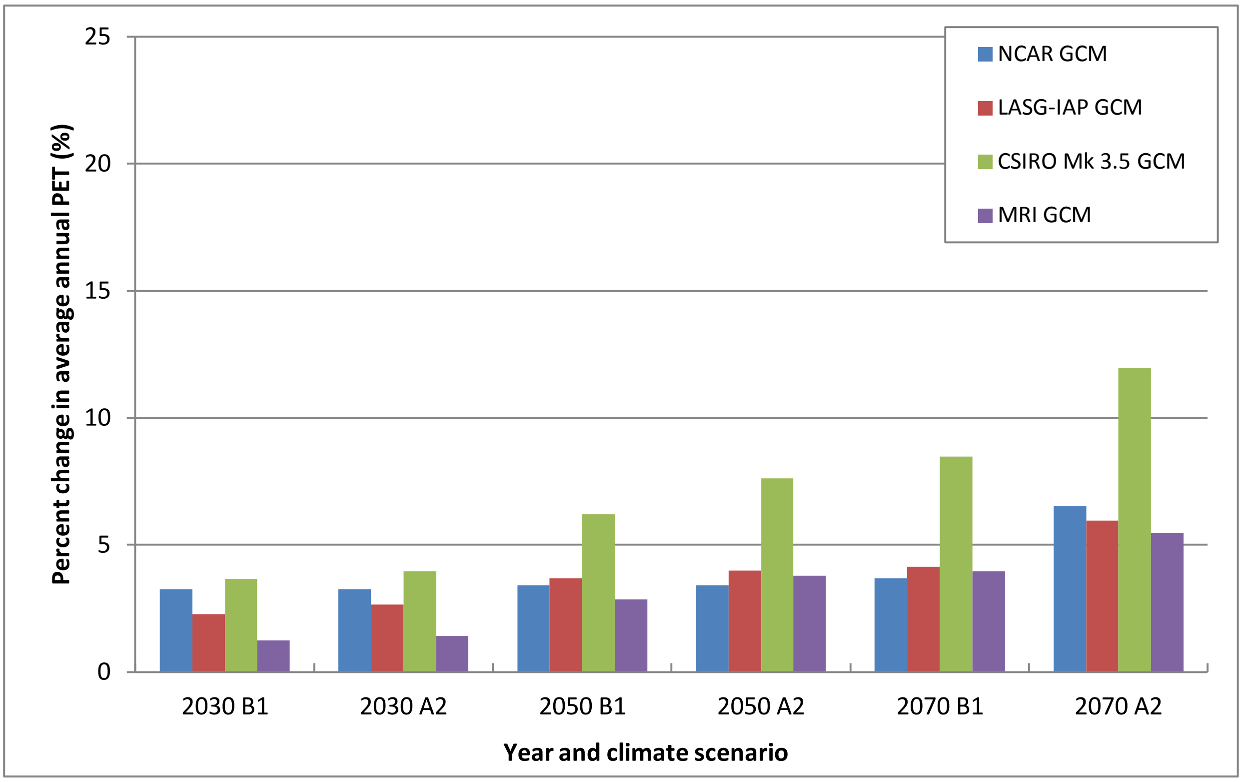


Figure 38. Reduction in average annual PET produced by the four different GCMs under the B1 and A2 emissions scenarios based on historic rainfall data taken from the Port Lincoln (Westmere) weather station (BoM station #18137)

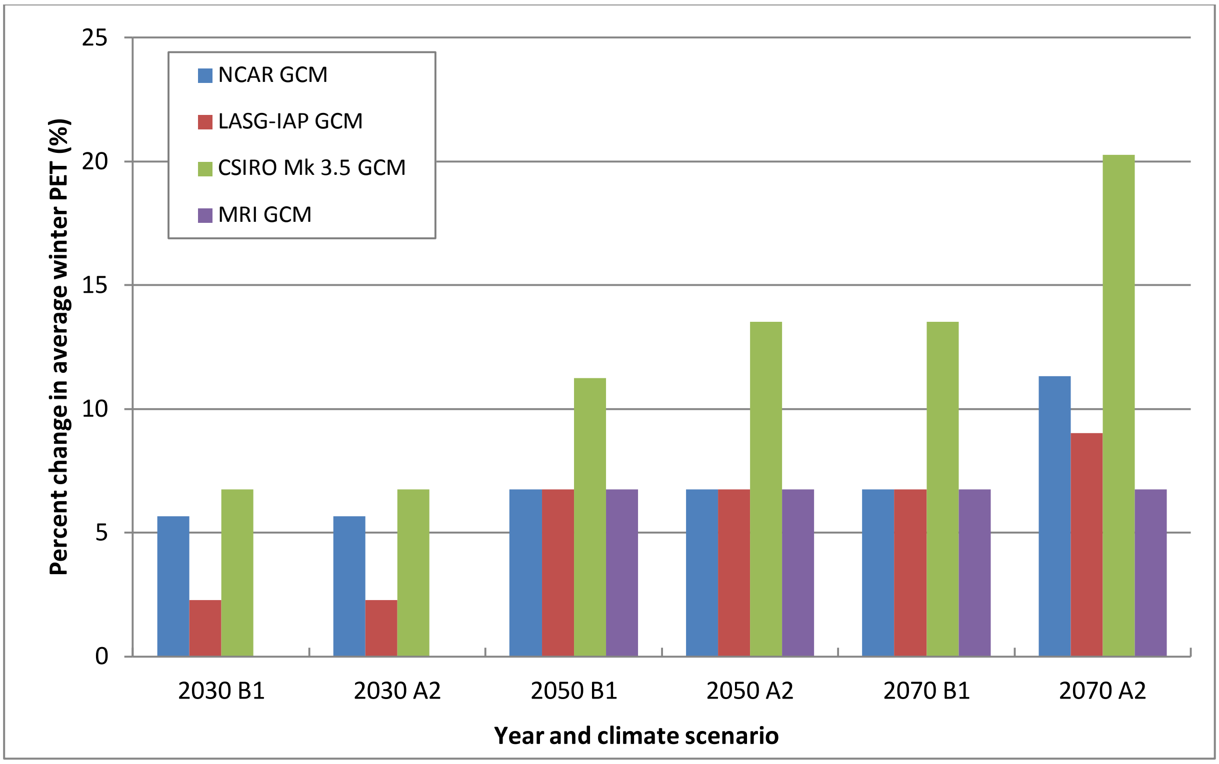


Figure 39. Reduction in average winter (May to September) PET produced by the four different GCMs under the B1 and A2 emissions scenarios based on historic rainfall data taken from the Port Lincoln (Westmere) weather station (BoM station #18137)

4.2.2. SOUTHERN BASINS PWA GROUNDWATER RECHARGE MODELS

The results of the spatially distributed LEACHG modelling for the Southern Basins PWA are summarised in Figure 40. The reductions in average annual recharge represent the area-weighted averages for the PWA, based on the results of the LEACHG model. The reductions are compared to the average annual recharge rate determined using historical climate data (1960–2009), which gave an annual, area-weighted average recharge rate of 151 mm/y (the sum of recharge and modelled runoff). The results are very similar to those from the Musgrave PWA, with the projected reductions in recharge varying significantly depending on which GCM and emission scenario is used to generate rainfall and PET data. Generally, climate data generated using the LASG-IAP GCM projections result in the least reduction in recharge, from 4% at 2030 to 15% at 2070, while data from the CSIRO Mk 3.5 GCM produces the greatest reduction in recharge, from 27% at 2030 to 72% by 2070.

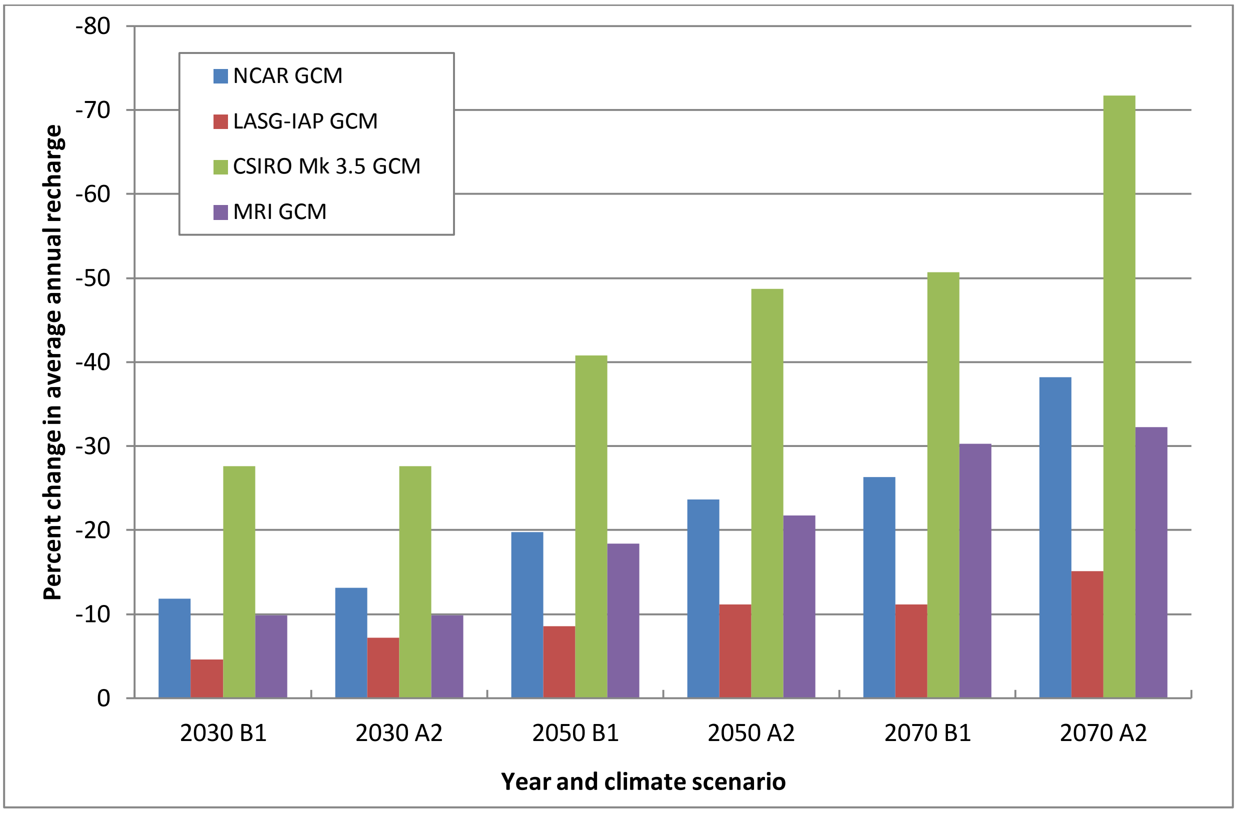


Figure 40. Modelled changes in average annual recharge for the Southern Basins PWA for the different GCMs, emissions scenarios and time horizons considered, as estimated by the LEACHG model

Figure 41 shows the corresponding results for the Uley South groundwater lens and Lincoln groundwater lens (considered the sum of the Lincoln A, B, C, D lenses). As with the results from the Musgrave PWA, slight differences arise due to variations in the models for each area (eg. different combinations of soil and land use). Also, there are considerable differences in topography and vegetation cover between the Uley and Lincoln Basins. Irrespective of these physiographic differences, the percentage changes in annual average recharge for these two areas were within 2–3% of absolute agreement (Fig. 41). Based on these results, it was concluded that the modelling approach generates similar results for all of the fresh groundwater lenses to which the model is applied. Consequently, the modelling approach has been applied to all lenses individually but the results have been reported more broadly at the PWA-scale.

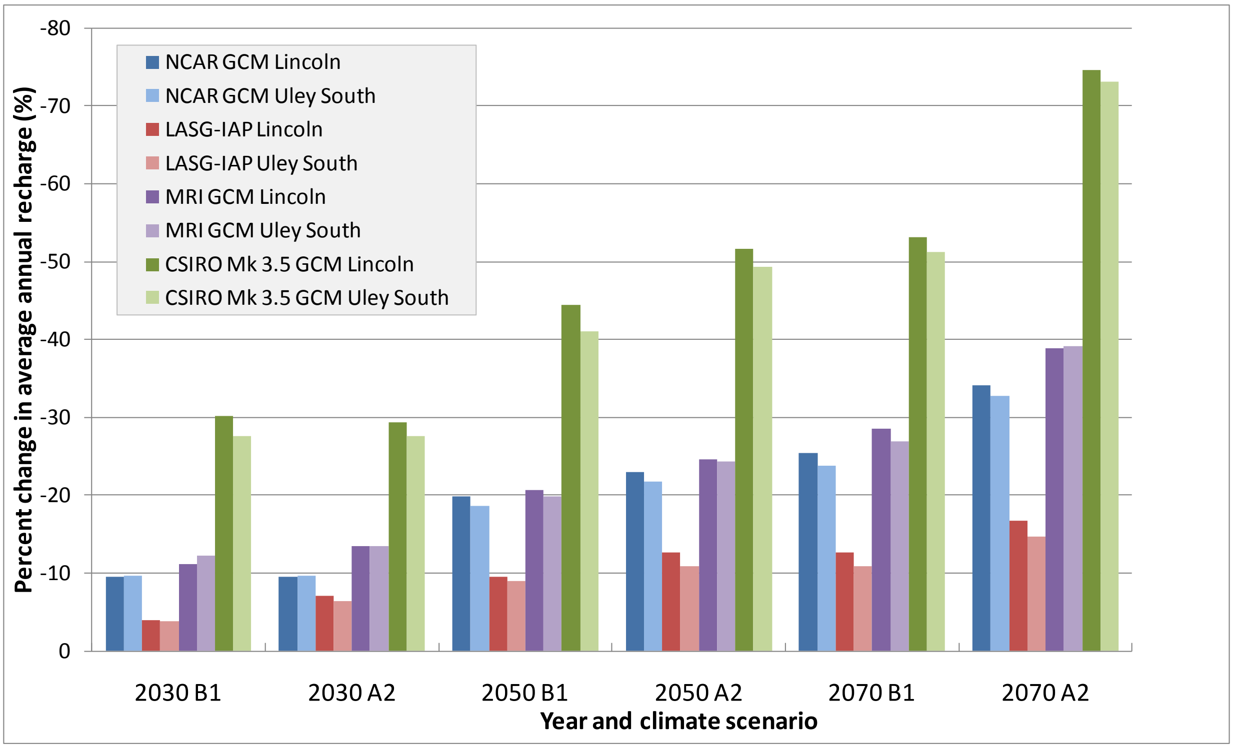


Figure 41. Modelled changes in average annual recharge for the Uley South groundwater lens and the Lincoln Basin (Lincoln A, B, C, D and D West groundwater lenses) located within the Southern Basins PWA

Tables 15 to 18 summarise the results from the LEACHG models for future climate scenarios from all four GCMs. As well as the changes to mean recharge over the 50-year simulation period, information about the projected change in frequency of high and low-recharge years, characterised by the 80th percentile and 20th percentile annual recharge respectively, are also provided. For each GCM, the historic 20th and 80th percentile annual recharge is presented in the 1990 column and by definition there are 10 years with recharge above the 80th or below the 20th percentile recharge for the historic case (based on a 50-year simulation period). Then for each scenario, the projected change to the 20th and 80th percentile annual recharge amount is reported, as well as the number of years in the future climate scenario that are below the historic (1990) 20th percentile and the number of years still above the 80th percentile recharge rate. For example, in Tables 15 to 18 the historic baseline (1990) low (20th percentile) and high (80th percentile) annual recharge amounts are 87 mm/y and 203 mm/y respectively. In the results from models run with NCAR-CCSM3 GCM climate projections (Table 16) for the 2050 B1 scenario, the 20th and 80th percentile recharge fluxes are reduced to 64 mm and 163 mm respectively. The number of years that would have historically been considered low-recharge years (less than 1990 20th percentile recharge) increases from 10 to 21 in a 50-year sequence. The number of years that would have historically been considered high-recharge years (greater than 1990 80th percentile recharge) reduces from 10 to 7 in a 50-year sequence.

The recharge results in Tables 15 to 18 are all area-weighted averages for the groundwater recharge areas of the whole Southern Basins PWA.

When viewing these results it is useful to consider that the LASG-IAP GCM projects the lowest amount of climate change among the four GCMs, while the CSIRO Mk3.5 projects the highest.

Table 15. Changes in climate and recharge for the Southern Basins PWA simulated by the LEACHM modelling using input data generated using the LASG-IAP GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	577	569	569	564	561	561	552
Average Winter Rainfall (mm)	270	268	267	266	265	265	262
Average Annual PET (mm)	1074	1098	1102	1113	1116	1118	1138
Average Winter PET (mm)	136	139	139	145	145	145	148
Average Annual Recharge (mm)	152	145	141	139	135	135	129
Change in Annual Rainfall (%)		-1	-1	-2	-3	-3	-4
Change in Winter Rainfall (%)		-1	-1	-2	-2	-2	-3
Change in Annual PET (%)		2	3	4	4	4	6
Change in Winter PET (%)		2	2	7	7	7	9
Change in average recharge (mm [%)]		-7 [-5]	-11 [-7]	-13 [-9]	-17 [-11]	-17 [-11]	-23 [-15]
Low Events							
20th Percentile Recharge (mm)	87	83	81	78	75	75	69
Years Below 1990 20th %	10	14	15	16	18	16	20
High Events							
80th Percentile Recharge (mm)	203	198	192	186	184	182	179
Years Above 1990 80th %	10	10	10	10	10	8	8

Table 16. Changes in climate and recharge for the Southern Basins PWA simulated by the LEACHM modelling using input data generated using the NCAR-CCSM3 GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	577	552	550	540	529	528	502
Average Winter Rainfall (mm)	270	258	257	252	246	246	233
Average Annual PET (mm)	1074	1109	1109	1110	1110	1113	1144
Average Winter PET (mm)	136	144	144	145	145	145	152
Average Annual Recharge (mm)	152	134	132	122	116	112	94
Change in Annual Rainfall (%)		-4	-5	-6	-8	-9	-13
Change in Winter Rainfall (%)		-4	-5	-7	-9	-9	-14
Change in Annual PET (%)		3	3	3	3	4	7
Change in Winter PET (%)		6	6	7	7	7	11
Change in average recharge (mm [%)]		-18 [-12]	-20 [-13]	-30 [-20]	-36 [-24]	-40 [-26]	-58 [-38]
Low Events							
20th Percentile Recharge (mm)	87	73	68	64	57	58	46
Years Below 1990 20th %	10	16	19	21	25	25	30
High Events							
80th Percentile Recharge (mm)	203	175	174	163	154	151	133
Years Above 1990 80th %	10	9	9	7	7	7	3

Table 17. Changes in climate and recharge for the Southern Basins PWA simulated by the LEACHM modelling using input data generated using the MRI GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	577	558	556	548	540	538	520
Average Winter Rainfall (mm)	270	256	256	250	244	243	230
Average Annual PET (mm)	1074	1087	1089	1104	1114	1116	1133
Average Winter PET (mm)	136	136	136	145	145	145	145
Average Annual Recharge (mm)	152	137	137	124	119	106	103
Change in Annual Rainfall (%)		-3	-4	-5	-6	-7	-10
Change in Winter Rainfall (%)		-5	-5	-8	-10	-10	-15
Change in Annual PET (%)		1	1	3	4	4	5
Change in Winter PET (%)		0	0	7	7	7	7
Change in average recharge (mm [%])		-15 [-10]	-15 [-10]	-28 [-18]	-33 [-22]	-46 [-30]	-49 [-32]
Low Events							
20th Percentile Recharge (mm)	87	80	78	70	64	63	51
Years Below 1990 20th %	10	17	16	22	23	26	27
High Events							
80th Percentile Recharge (mm)	203	180	181	161	156	153	133
Years Above 1990 80th %	10	9	9	8	8	7	5

Table 18. Changes in climate and recharge for the Southern Basins PWA simulated by the LEACHM modelling using input data generated using the CSIRO Mk 3.5 GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	577	530	526	504	484	480	432
Average Winter Rainfall (mm)	270	244	242	229	219	217	190
Average Annual PET (mm)	1074	1113	1116	1140	1156	1165	1202
Average Winter PET (mm)	136	145	145	151	155	155	164
Average Annual Recharge (mm)	152	110	110	90	78	75	43
Change in Annual Rainfall (%)		-8	-9	-13	-16	-17	-25
Change in Winter Rainfall (%)		-10	-10	-15	-19	-20	-30
Change in Annual PET (%)		4	4	6	8	8	12
Change in Winter PET (%)		7	7	11	14	14	20
Change in average recharge (mm [%])		-42 [-28]	-42 [-28]	-62 [-41]	-74 [-49]	-77 [-51]	-109 [-72]
Low Events							
20th Percentile Recharge (mm)	87	58	55	40	30	29	10
Years Below 1990 20th %	10	25	27	32	34	36	42
High Events							
80th Percentile Recharge (mm)	203	146	149	122	108	106	66
Years Above 1990 80th %	10	7	7	4	1	1	1

An example of an application of the model, using the NCAR-CCSM3 GCM, is outlined in Table 19, below. The modelled change in average recharge (%) (Table 16) has been used to project the reduced recharge rates in the future relative to the long-term recharge rates reported in the current Southern Basins Water Allocation Plan (DWR, 2000). Results indicate that, under the B1 scenario for example, recharge to the Uley South lens will reduce from the current estimate of long-term average recharge of 155 mm/y down to 136 mm/y by 2030 and down to 96 mm/y by 2070.

Table 19. An application of the model using the NCAR-CCSM3 GCM and estimated recharge rates from the current Southern Basins Water Allocation Plan

Lens	WAP estimated recharge (mm/y)	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Coffin Bay A	34	30	30	27	26	25	21
Coffin Bay B	16	14	14	13	12	12	10
Coffin Bay C	18	16	16	14	14	13	11
Uley Wanilla	54	48	47	43	41	40	33
Wanilla	20	18	17	16	15	15	12
Uley East	69	61	60	55	52	51	43
Uley South	155	136	135	124	118	115	96
Lincoln A	56	49	49	45	43	41	35
Lincoln B	56	49	49	45	43	41	35
Lincoln C	56	49	49	45	43	41	35
Lincoln D	32	28	28	26	24	24	20
Lincoln D West	32	28	28	26	24	24	20
Minor Lenses	40	35	35	32	30	30	25

Figures 42 to 48 show the area-weighted recharge rates from each year of the 50-year LEACHG model simulations, using baseline historic climate data (Fig. 42) and climate data scaled according to the projections of the NCAR-CCSM3 GCM. In these results, mean annual recharge rates decrease with increasing time, with a greater decrease generally observed under A2 emissions scenarios.

As observed in the corresponding results for the Musgrave PWA, the increase in low-recharge years (years where recharge is below the 1990 20^{th} percentile recharge rate) and decrease in the number of high-recharge years (years where recharge is above the 1990 20^{th} percentile recharge rate) is particularly notable in the results shown in Tables 15 to 18 and Figures 42 to 48. For example, under the NCAR-CCSM3 GCM A2 emissions scenario climate for 2050, there is a projected reduction in average annual recharge of 24%, however, the number of low-recharge years (as indicated by the 1990 20^{th} percentile recharge) increases by 150% from 10 to 25 out of 50 years, while the number of high-recharge years reduces by 30% to 7 out of 50 years. In the worst case scenario, projected by the CSIRO Mk 3.5 GCM with A2 emissions scenario for a 2070 climate, the frequency of low-recharge years in the

Musgrave PWA increases to 30 out of 50 years and the number of high-recharge years reduces to three out of 50 years (Table 13).

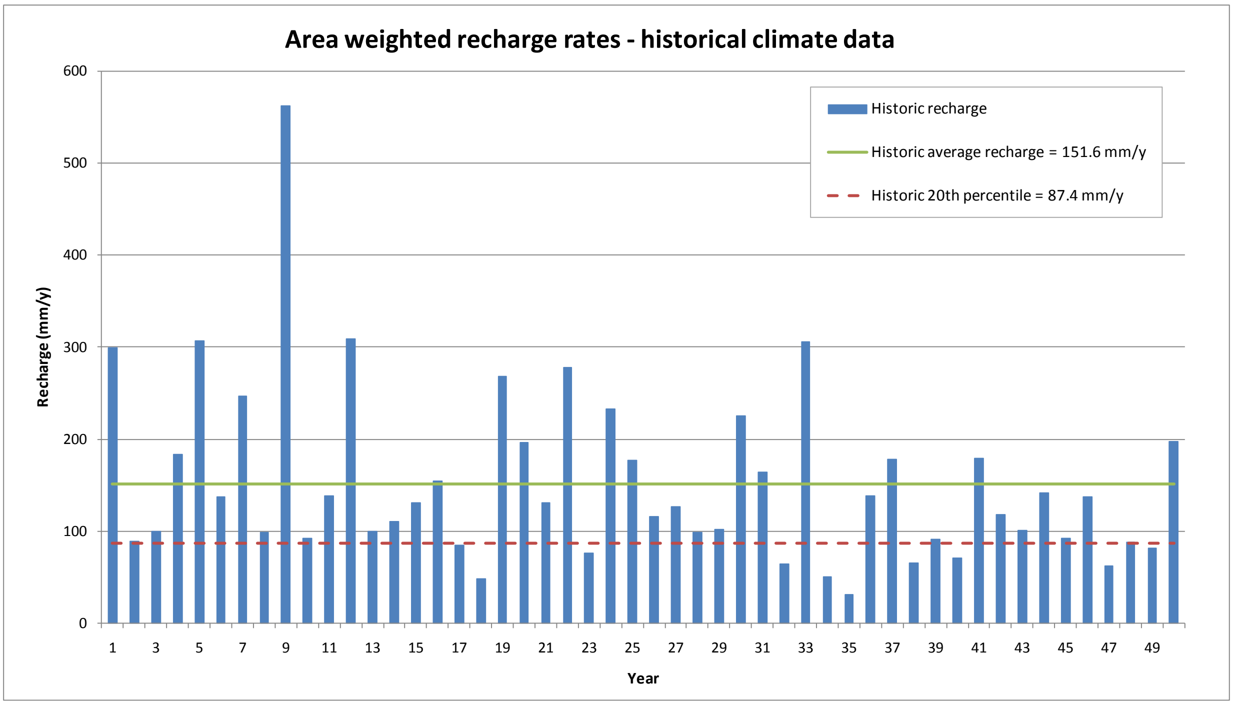


Figure 42. Annual area-weighted recharge rates over 50 years produced by the LEACHG model for the Southern Basins PWA, using historical measured rainfall and PET data. Year 1 on the x axis represents 1960.

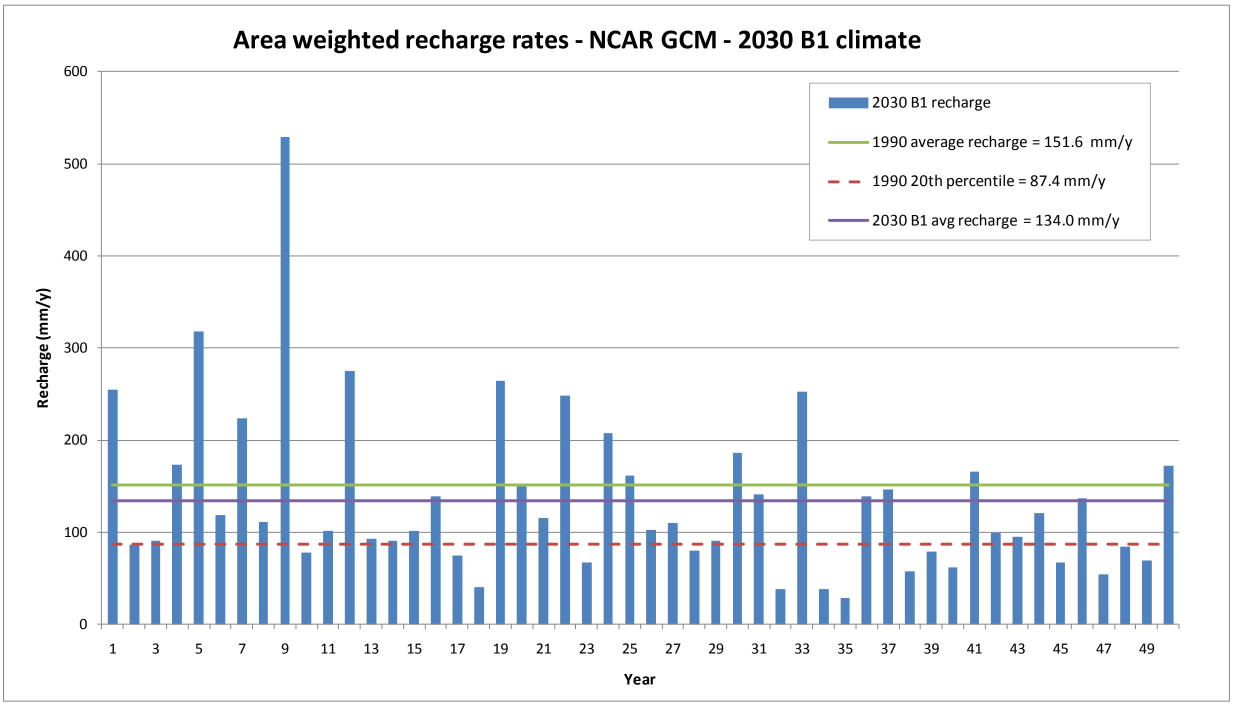


Figure 43. Annual area-weighted recharge rates produced by the LEACHG model for the Southern Basins PWA, using rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2030 climate and B1 emissions

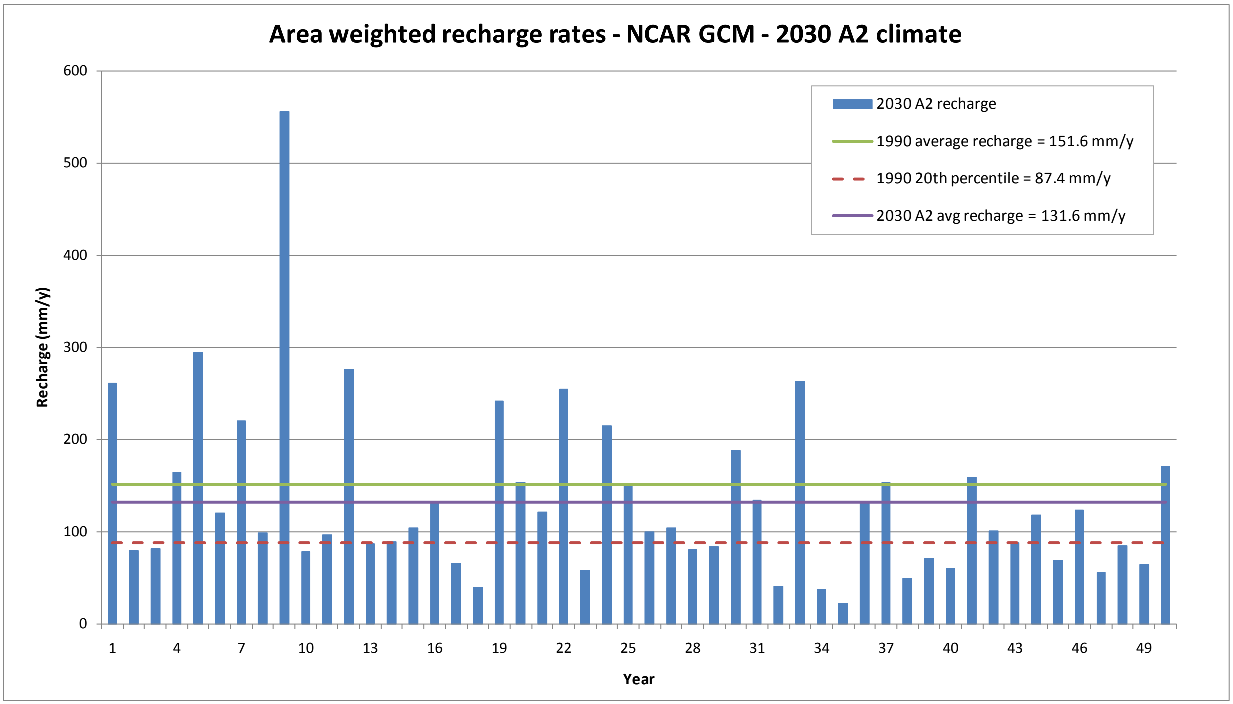


Figure 44. Annual area-weighted recharge rates produced by the LEACHG model for the Southern Basins PWA, using rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2030 climate and A2 emissions

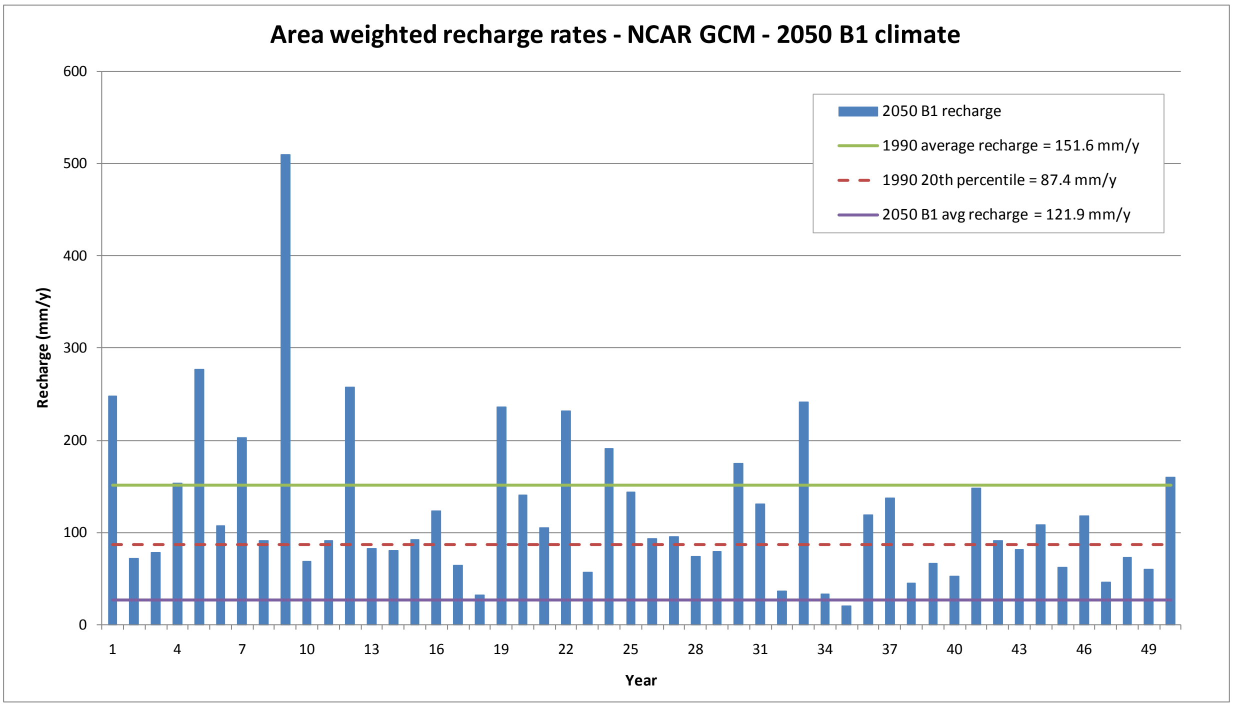


Figure 45. Annual area-weighted recharge rates produced by the LEACHG model for the Southern Basins PWA, using rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2050 climate and B1 emissions

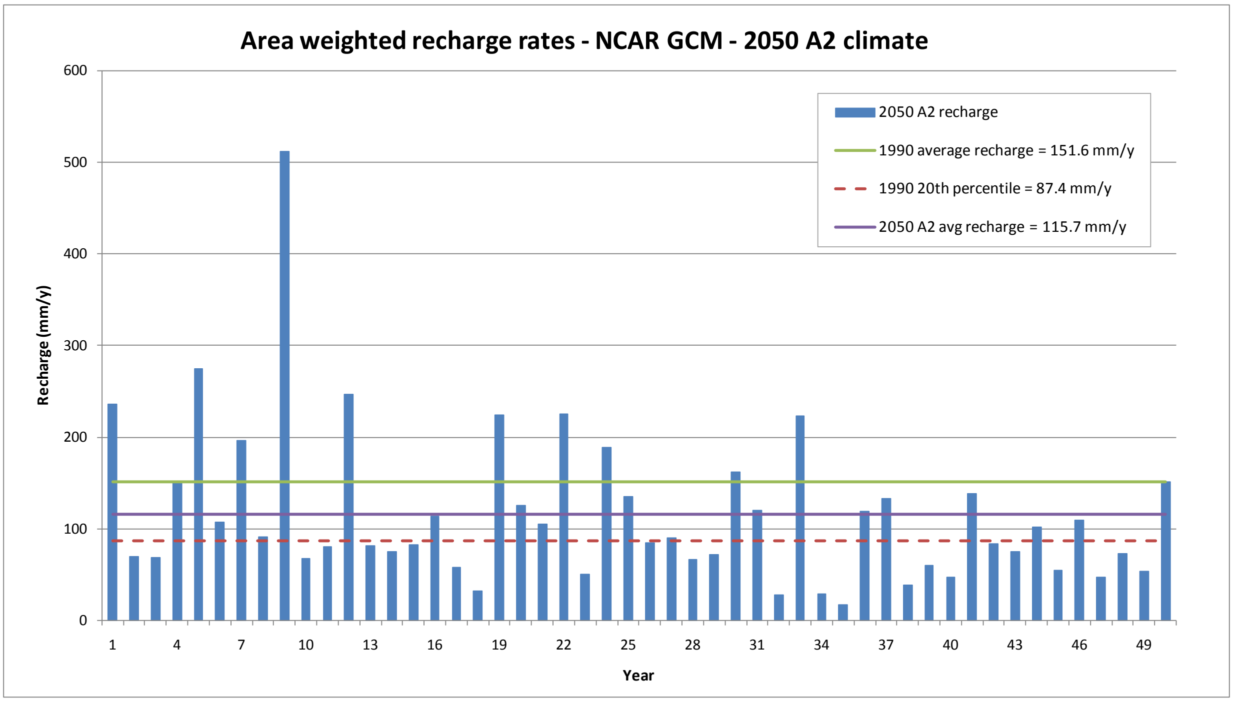


Figure 46. Annual area-weighted recharge rates produced by the LEACHG model for the Southern Basins PWA, using rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2050 climate and A2 emissions

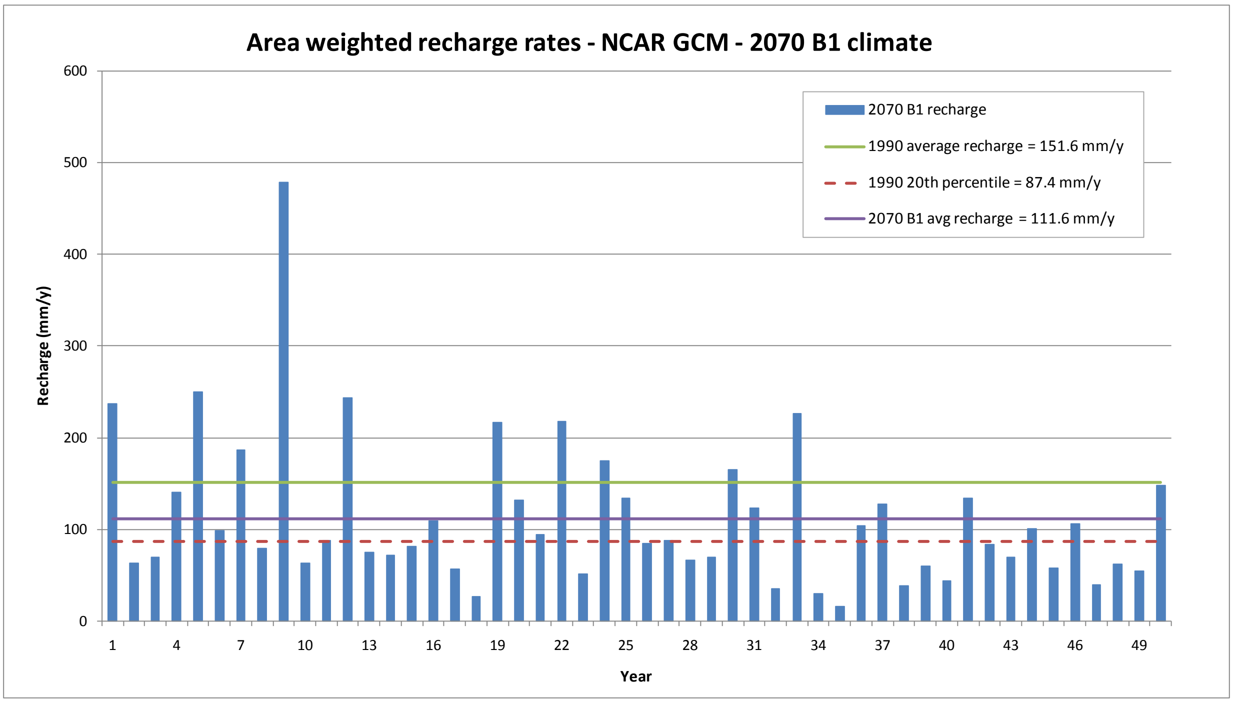


Figure 47. Annual area-weighted recharge rates produced by the LEACHG model for the Southern Basins PWA, using rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2070 climate and B1 emissions

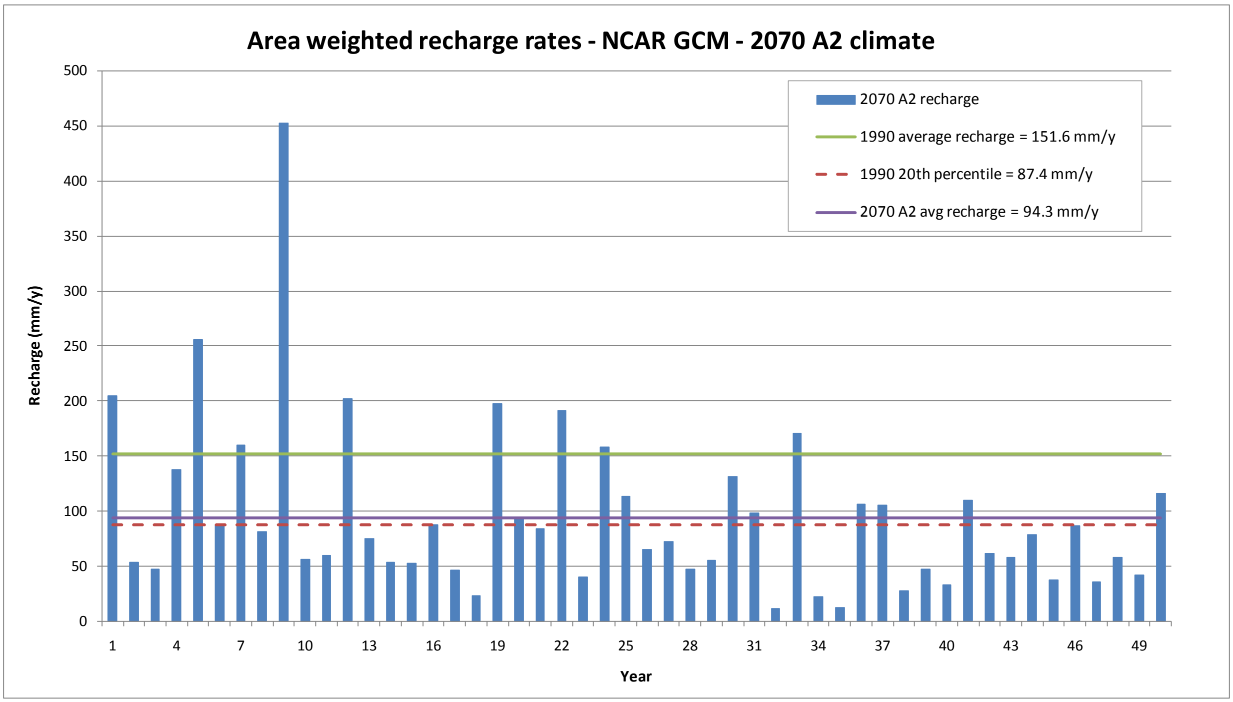


Figure 48. Annual area-weighted recharge rates produced by the LEACHG model for the Southern Basins PWA, using rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2070 climate and A2 emissions

To generalise the impacts on recharge resulting from the various climate change projections from the four GCMs, the change in recharge corresponding to each projected change in annual rainfall is presented in Figure 49. These are 'lumped' results for all the groundwater lenses in the Southern Basins PWA. However, the difference in changes in recharge for the most utilised basins in the PWA (the Uley South and Lincoln basins) were within 2–3% of absolute agreement (Fig. 41). Based on these results, it was concluded that the modelling approach is applicable across the broader Southern Basins PWA.

The solid trend line represents a hyperbolic tangent (tanh) function fitted to the results obtained from all GCM projections. This function is commonly used to represent the relationship between rainfall and surface water runoff, but can be seen to also provide a suitable representation of the trend of climate change impacts on groundwater recharge according to these model results.

The dashed lines in Figure 49 represent 95% confidence limits, assuming normally distributed variation of the simulated results around the trend line. The 95% confidence intervals are defined according to Equation 3 (Sec. 4.3).

The relationship derived allows the expected change in recharge to be estimated for any given change in annual rainfall. Thus, rainfall changes reported by other climate change projection summaries (such as the Regional Climate Change Projections, Eyre Peninsula (DENR, 2010)) can be used to give recharge change projections, based on the results of the hydrologic models presented here. The confidence intervals provide an indication of the impact of the inherent uncertainty around projections and simulation of a future climate. The variation in the mean annual recharge simulated for a given change in annual rainfall is due to a number of factors, including the changes in seasonality of rainfall, changes in rainfall intensity and the change in PET projected by the GCM.

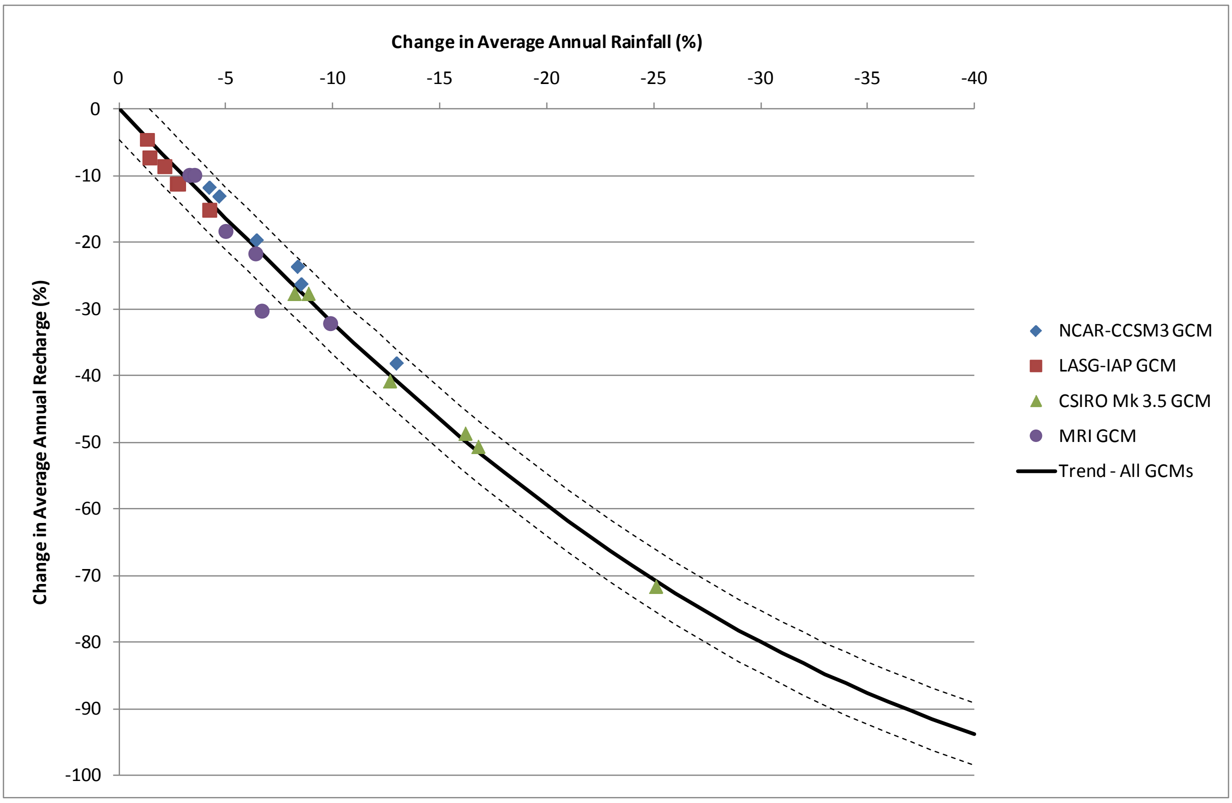


Figure 49. Changes in average annual rainfall versus changes in average annual recharge for the Southern Basins PWA. The trend line is a tanh relationship, dashed lines show the upper and lower 95% bounds.

4.3. TOD RESERVOIR

The runoff model developed to represent inflows to the Tod Reservoir has been used to assess the impacts of the projected changes in future climate on the surface water resources of the Eyre Peninsula. Rainfall and FAO56 PET time series provided by the SILO Patched Point Datasets (Jeffrey, 2001) have been used, as they provide the long, consistent datasets required for the downscaling technique adopted (Gibbs *et al.*, 2011). For this case, data for the Upper Tod and Pillaworta have been based on BoM rainfall station #18104 using rainfall adjustment factors of 0.998 and 0.944, respectively. The Toolillie catchment data are based on BoM rainfall station #18043 with a rainfall adjustment factor 1.041. The reservoir and intake catchments are based on BoM rainfall station #18181 (located at Tod Reservoir) with rainfall adjustment factors of 1.074 and 1.066, respectively. In this section, the term runoff has been used to refer to catchment yields to the reservoir, after accounting for the storages representing farm dams and any diversions to the reservoir from upstream catchments. Changes in runoff or streamflow for the complete Tod River (for example to Poonindie) have not been considered, nor have changes in the storage of the Tod Reservoir. However, the change in catchment inflows to the reservoir that are reported can be used an indication of the sustainable yield expected from the contributing catchments.

The results from the runoff modelling with no diversions from the Upper Tod and Pillaworta catchments are summarised in Figure 50 and an alternative scenario with 10% of the flow passing the diversion weirs at these two catchments is presented in Appendix B. The scenario with 10% diversions results in greater volumes diverted to the reservoir, however the reductions in runoff for the future time horizons compared to the historic case are very similar to the no diversions scenario and therefore, are not repeated in the body of this report. The expected reductions in runoff can be seen to increase as the emission case increases for 2050 and 2070 (A2 compared to B1) as well as the simulated time horizon increases. There is a vast range in the simulated changes in runoff based on the projections provided by the different GCMs. The simulated reductions in runoff based on the most extreme projections (CSIRO Mk. 3.5 GCM) are three to six times greater than that based on the smallest change projections (LASG-IAP GCM). The runoff results based on the MRI and NCAR-CCSM3 GCM projections are generally in agreement and fall between the lowest and the highest simulated reductions in runoff (LASG-IAP and CSIRO Mk. 3.5 GCMs, respectively).

Values for the change in median runoff for the Tod Reservoir catchments for each GCM with the no diversion case, as well as the changes to rainfall and PET that produced those changes, can be seen in Table 16 to Table 19 and in Appendix B for the 10% diversion case. The mild projections simulated by the LASG-IAP GCM are evident, suggesting only a 5% reduction in annual rainfall and 6% increase in annual PET for the most extreme 2070 A2 emission case. This results in the smallest reductions in annual runoff (Fig. 50). In contrast, the most extreme GCM (CSIRO Mk 3.5) projects a 29% reduction in annual rainfall and 10% increase in annual PET for the same (2070 A2) scenario. Median rather than average runoff has been reported as the distribution of flow is positively skewed, resulting in larger average values biased by high-flow years. Annual Rainfall and PET data are more normally distributed and so the median and average values are typically very similar.

The impact of farm dams on the runoff can also be seen in Tables 16 to 19, where the changes in runoff for each climate scenario are presented for both the current and maximum farm dam development scenarios. Modelling results show that increasing farm dam density results in small decreases in projected runoff. However, these increased reductions are generally less than 5% above reductions based on current farm dam density. These small increases in projected runoff are most likely due to the relatively low dam density in the catchments, with the current dam storage intercepting approximately 6% of the annual runoff. The impact of climate change projections on farm dam storage is also less than the impact on the watercourse flows. On average, the percentage reduction in dam storage is 4.7 times less than the percentage reduction in total runoff for the current storage scenario and 3.5 times less for the maximum storage scenario. This reduction is expected to be a function of both the dam density and of the ratio of dam storage to the captured runoff. More specifically, the greater the volume of dams relative to the total runoff, the less they will be able to fill and spill downstream and the closer the reduction in dam storage will tend toward the reduction in total runoff.

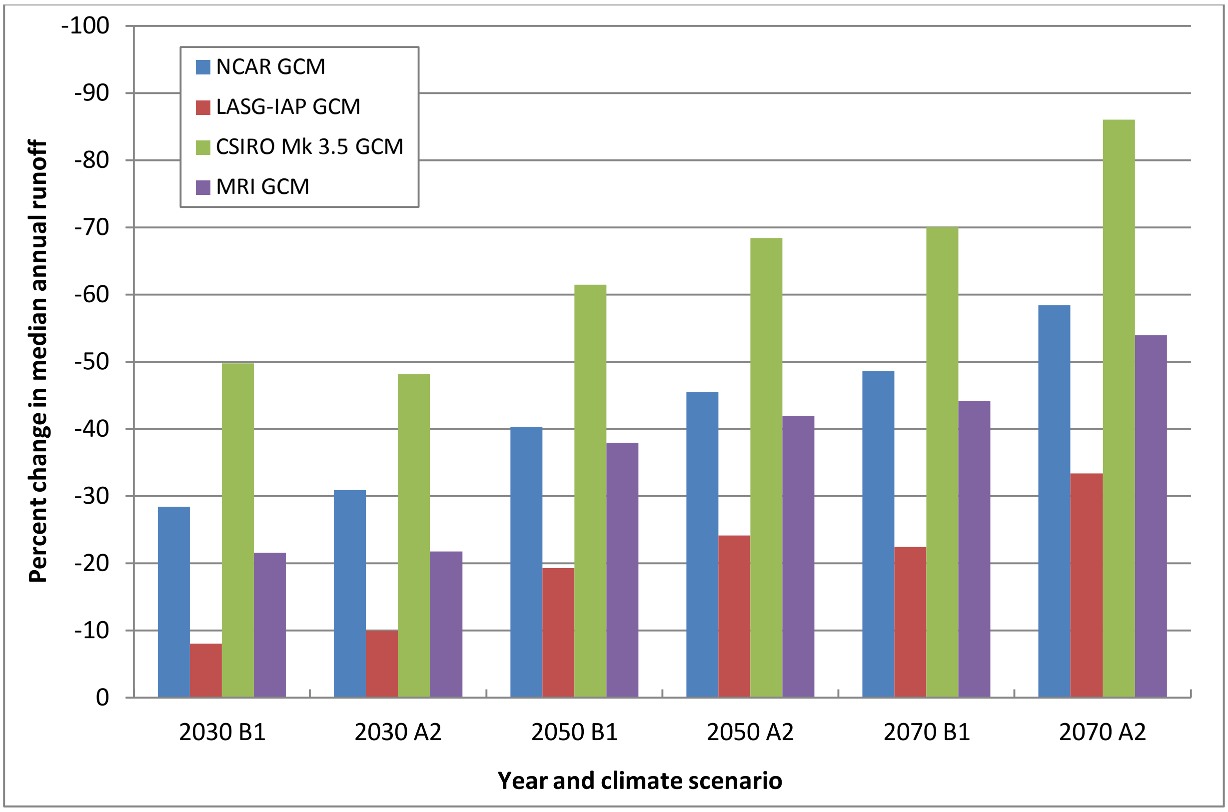


Figure 50. Projected changes in average annual runoff for runoff to the Tod Reservoir (no diversions, current farm dam storage)

As well as the changes to median runoff over the 50-year simulation period, information about the projected change in the high- and low-flow events, characterised by the 80th percentile and 20th percentile flows, respectively, are also provided in Tables 20 to 23. For each GCM, the historic 20th and 80th percentile annual flows are presented in the 1990 column. By definition, there are 10 years with flow above or below each runoff volume for the historic case (based on a 50-year simulation period). Then for each scenario, the projected change to the 20th and 80th percentile flows are reported, as well as the number of years that are below the historic (1990) 20th percentile flow for the climate change scenario and the number of years still above the 80th percentile flow.

Tables 20 to 23 show that for all cases it is not only the median flow that is decreasing, but the whole flow distribution is changing. With each increasing time horizon the number of flow events below the historic low-flow level is increasing and the number of years above the high-flow level is decreasing. The exceptions are the results based on the LASG-IAP GCM, where there is an increase in the number of dry years below the 20th percentile historic flow and a decrease in the high 80th percentile flow for the future scenarios. However, for this case the number of years where historic high flows are exceeded is similar (only decreasing from 10 in 50 years to 9 in 50 years). Again, the CSIRO Mk 3.5 GCM is more extreme than the other GCMs. Based on this GCM for the 2070 A2 scenario, 46 of the 50 years simulated are below the historic 20th percentile flow and the high 80th percentile flow for the future case is only equal to approximately 30% of the historic median flow.

Table 20. Changes in climate and runoff simulated for Tod Reservoir using input data generated using the LASG-IAP GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	506	498	497	494	490	490	482
Average Winter Rainfall (mm)	228	225	225	224	223	223	220
Average Annual PET (mm)	1121	1146	1150	1158	1164	1164	1185
Average Winter PET (mm)	132	135	135	141	141	141	144
Change in Annual Rainfall (%)		-2	-2	-2	-3	-3	-5
Change in Winter Rainfall (%)		-1	-1	-2	-2	-2	-3
Change in Annual PET (%)		2	3	3	4	4	6
Change in Winter PET (%)		2	2	7	7	7	9
Current Farm Dam Storage Scenario							
Median Annual Runoff (ML)	1897	1744	1708	1531	1439	1472	1263
Change in Median Runoff (%)		-8	-10	-19	-24	-22	-33
Average Annual Storage (ML)	170	166	165	163	161	161	158
Change in Annual Storage (%)		-2	-3	-4	-5	-5	-7
Low Events							
20th Percentile Runoff (ML)	915	860	842	779	769	769	724
Years Below 1990 20th %	10	13	14	16	16	16	17
High Events							
80th Percentile Runoff (ML)	3721	3432	3329	3251	3102	3122	2892
Years Above 1990 80th %	10	9	9	9	9	9	9
Maximum Farm Dam Storage Scenario							
Median Annual Runoff (ML)	1779	1622	1582	1340	1241	1285	1104
Change in Median Runoff (%)		-9	-11	-25	-30	-28	-38
Average Annual Storage (ML)	320	312	308	302	297	298	288
Change in Annual Storage (%)		-2	-4	-6	-7	-7	-10
Low Events							
20th Percentile Runoff (ML)	763	705	699	676	654	667	609
Years Below 1990 20th %	10	14	14	16	17	16	17
High Events							
80th Percentile Runoff (ML)	3703	3435	3346	3262	3120	3137	2908
Years Above 1990 80th %	10	9	9	9	9	9	9

Table 21. Changes in climate and runoff simulated for Tod Reservoir using input data generated using the NCAR-CCSM3 GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	506	484	483	474	465	464	443
Average Winter Rainfall (mm)	228	217	216	212	207	207	196
Average Annual PET (mm)	1121	1156	1158	1158	1164	1164	1194
Average Winter PET (mm)	132	139	141	141	141	141	150
Change in Annual Rainfall (%)		-4	-5	-6	-8	-8	-13
Change in Winter Rainfall (%)		-5	-5	-7	-9	-9	-14
Change in Annual PET (%)		3	3	3	4	4	7
Change in Winter PET (%)		6	7	7	7	7	14
Current Farm Dam Storage Scenario							
Median Annual Runoff (ML)	1897	1358	1310	1132	1034	975	789
Change in Median Runoff (%)		-28	-31	-40	-45	-49	-58
Average Annual Storage (ML)	170	162	160	157	154	153	138
Change in Annual Storage (%)		-4	-6	-7	-9	-10	-19
Low Events							
20th Percentile Runoff (ML)	836	674	662	624	573	571	441
Years Below 1990 20th %	10	17	17	17	18	19	28
High Events							
80th Percentile Runoff (ML)	3821	3502	3265	3011	2962	2711	2176
Years Above 1990 80th %	10	9	8	6	4	4	3
Maximum Farm Dam Storage Scenario							
Median Annual Runoff (ML)	1779	1232	1167	1021	942	855	718
Change in Median Runoff (%)		-31	-34	-43	-47	-52	-60
Average Annual Storage (ML)	320	295	292	284	275	272	235
Change in Annual Storage (%)		-8	-9	-11	-14	-15	-26
Low Events							
20th Percentile Runoff (ML)	763	632	624	575	515	516	400
Years Below 1990 20th %	10	17	17	17	17	20	29
High Events							
80th Percentile Runoff (ML)	3703	3380	3151	2894	2851	2596	2024
Years Above 1990 80th %	10	9	8	6	4	4	2

Table 22. Changes in climate and runoff simulated for Tod Reservoir using input data generated using the MRI GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	506	489	489	481	474	474	457
Average Winter Rainfall (mm)	228	216	215	210	205	205	192
Average Annual PET (mm)	1121	1134	1135	1152	1161	1161	1179
Average Winter PET (mm)	132	132	132	141	141	141	141
Change in Annual Rainfall (%)		-3	-3	-5	-6	-6	-10
Change in Winter Rainfall (%)		-5	-6	-8	-10	-10	-16
Change in Annual PET (%)		1	1	3	4	4	5
Change in Winter PET (%)		0	0	7	7	7	7
Current Farm Dam Storage Scenario							
Median Annual Runoff (ML)	1897	1488	1485	1177	1101	1060	873
Change in Median Runoff (%)		-22	-22	-38	-42	-44	-54
Average Annual Storage (ML)	170	165	165	159	156	155	147
Change in Annual Storage (%)		-3	-3	-6	-8	-8	-13
Low Events							
20th Percentile Runoff (ML)	836	733	728	640	608	596	505
Years Below 1990 20th %	10	16	15	17	17	17	24
High Events							
80th Percentile Runoff (ML)	3821	3507	3536	2970	2864	2891	2417
Years Above 1990 80th %	10	9	9	8	5	5	4
Maximum Farm Dam Storage Scenario							
Median Annual Runoff (ML)	1779	1371	1369	1069	994	963	792
Change in Median Runoff (%)		-23	-23	-40	-44	-46	-55
Average Annual Storage (ML)	320	306	305	288	280	278	255
Change in Annual Storage (%)		-4	-5	-10	-12	-13	-20
Low Events							
20th Percentile Runoff (ML)	763	689	687	601	568	559	465
Years Below 1990 20th %	10	16	16	17	17	17	23
High Events							
80th Percentile Runoff (ML)	3703	3388	3417	2850	2740	2769	2282
Years Above 1990 80th %	10	9	9	8	5	5	4

Table 23. Changes in climate and runoff simulated for Tod Reservoir using input data generated using the CSIRO Mk 3.5 GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	506	464	461	441	423	420	378
Average Winter Rainfall (mm)	228	206	204	194	184	183	161
Average Annual PET (mm)	1121	1164	1164	1188	1209	1212	1258
Average Winter PET (mm)	132	141	141	147	150	150	159
Change in Annual Rainfall (%)		-8	-9	-13	-16	-17	-25
Change in Winter Rainfall (%)		-10	-11	-15	-19	-20	-30
Change in Annual PET (%)		4	4	6	8	8	12
Change in Winter PET (%)		7	7	12	14	14	21
Current Farm Dam Storage Scenario							
Median Annual Runoff (ML)	1897	953	984	732	599	568	266
Change in Median Runoff (%)		-50	-48	-61	-68	-70	-86
Average Annual Storage (ML)	170	152	152	137	126	123	87
Change in Annual Storage (%)		-10	-10	-19	-26	-27	-48
Low Events							
20th Percentile Runoff (ML)	836	574	555	416	310	295	114
Years Below 1990 20th %	10	18	18	30	35	35	45
High Events							
80th Percentile Runoff (ML)	3821	2536	2550	1888	1470	1527	574
Years Above 1990 80th %	10	4	4	2	0	0	0
Maximum Farm Dam Storage Scenario							
Median Annual Runoff (ML)	1779	835	841	659	523	498	232
Change in Median Runoff (%)		-53	-53	-63	-71	-72	-87
Average Annual Storage (ML)	320	271	271	231	204	198	125
Change in Annual Storage (%)		-15	-15	-28	-36	-38	-61
Low Events							
20th Percentile Runoff (ML)	763	520	501	388	284	272	101
Years Below 1990 20th %	10	19	19	31	35	36	46
High Events							
80th Percentile Runoff (ML)	3703	2416	2430	1749	1326	1350	491
Years Above 1990 80th %	10	4	4	2	0	0	0

To investigate the impact of this change in flow distribution further, the simulated annual runoff for each case, based on the NCAR-CCSM3 GCM projections, has been plotted. This GCM was selected as it provides a mid-range projection for the change in winter rainfall. The annual runoff for the historic scenario with no diversions from the upper catchments is presented in Figure 51, followed by the same plot for each time horizon and emission scenario considered in Figures 52 to 57. Similar results are presented for the 10% diversion scenario in Appendix B, where similar rates of reduction in runoff were found for each scenario.

Figures 52 to 57 display the simulated annual runoff to the Tod Reservoir (blue bars) according to the NCAR-CCSM3 GCM applied to each of the three time horizons and two emission scenarios. Also shown in these graphs are the 1990 median runoff (green line), the 1990 20th percentile flows (red dashed line) and the projected median runoff (purple line). Figure 51 shows simulated annual runoff based on historic (1990) climate data. The 2070 A2 scenario model results (Fig. 57) show that the median runoff is slightly below the 1990 20th percentile runoff, highlighting the marked reduction in surface water resources that are projected under this scenario. Notably, annual flows which are considered 'low-flow years' in the historic record are higher than the projected median annual runoff under the 2070 A2 scenario.

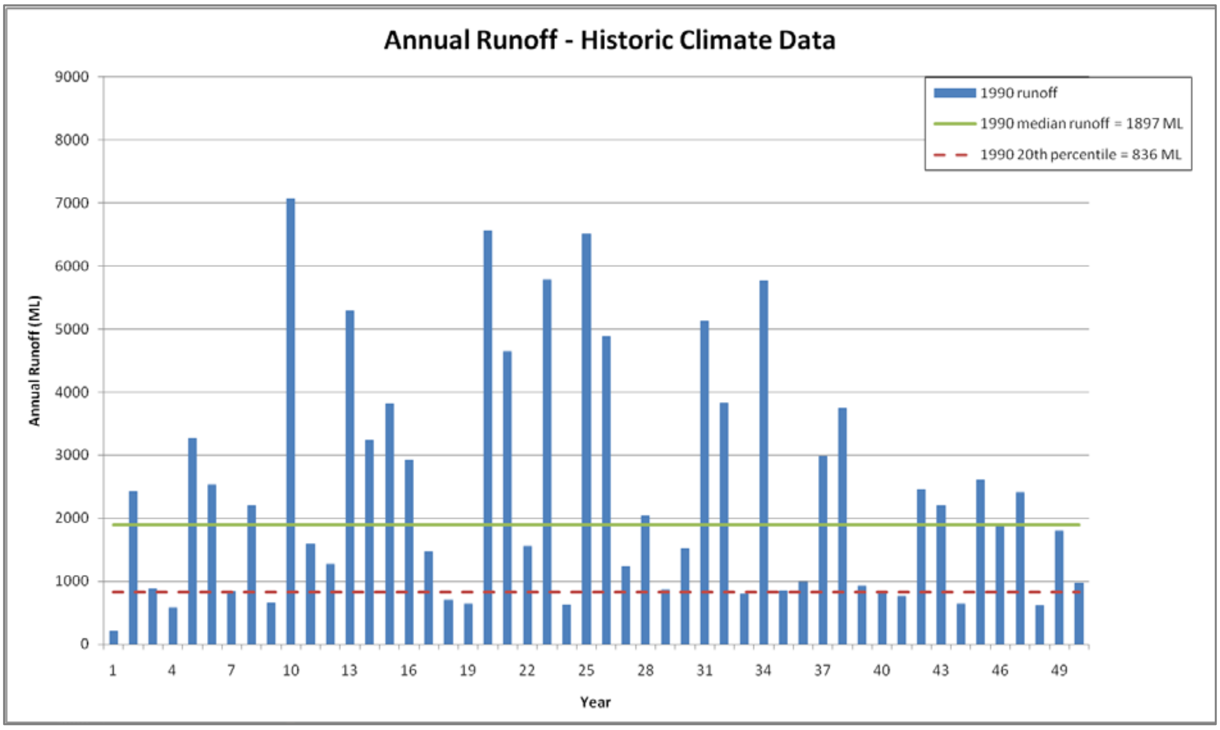


Figure 51. Annual runoff simulated over 50 years for the Tod Reservoir, based on historically measured rainfall and PET data. Year 1 on the x axis represents 1960

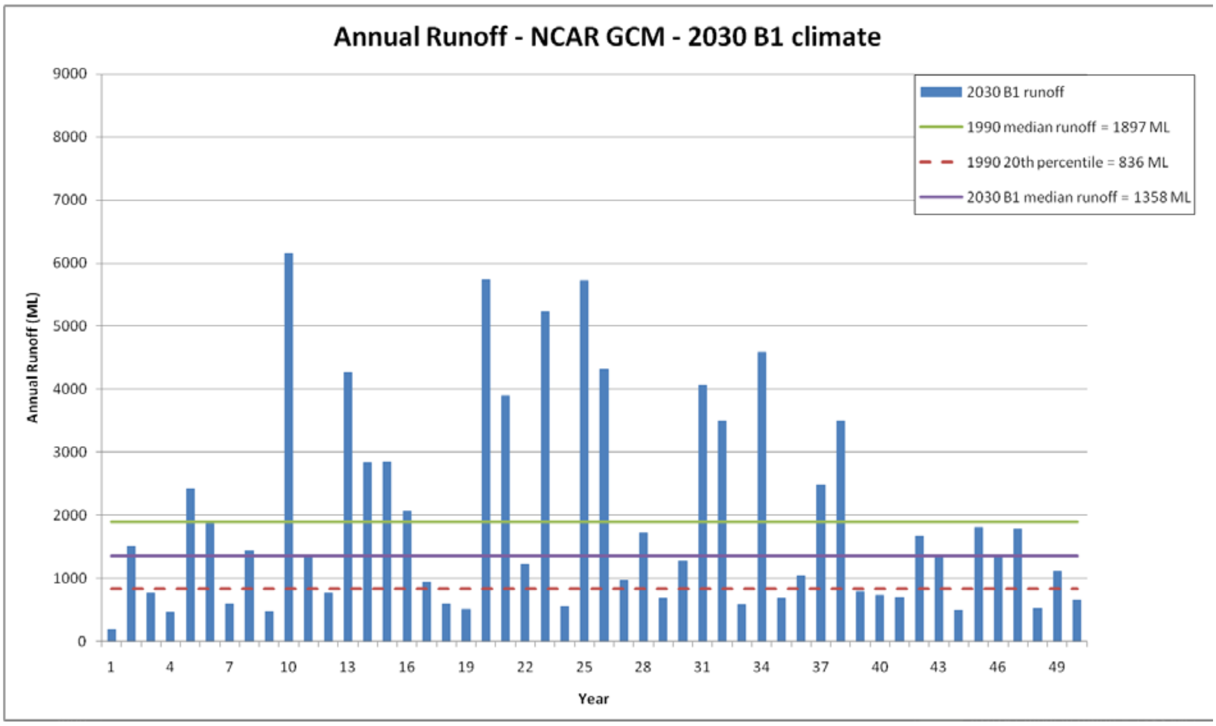


Figure 52. Annual runoff simulated for the Tod Reservoir, based on rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2030 climate and B1 emissions

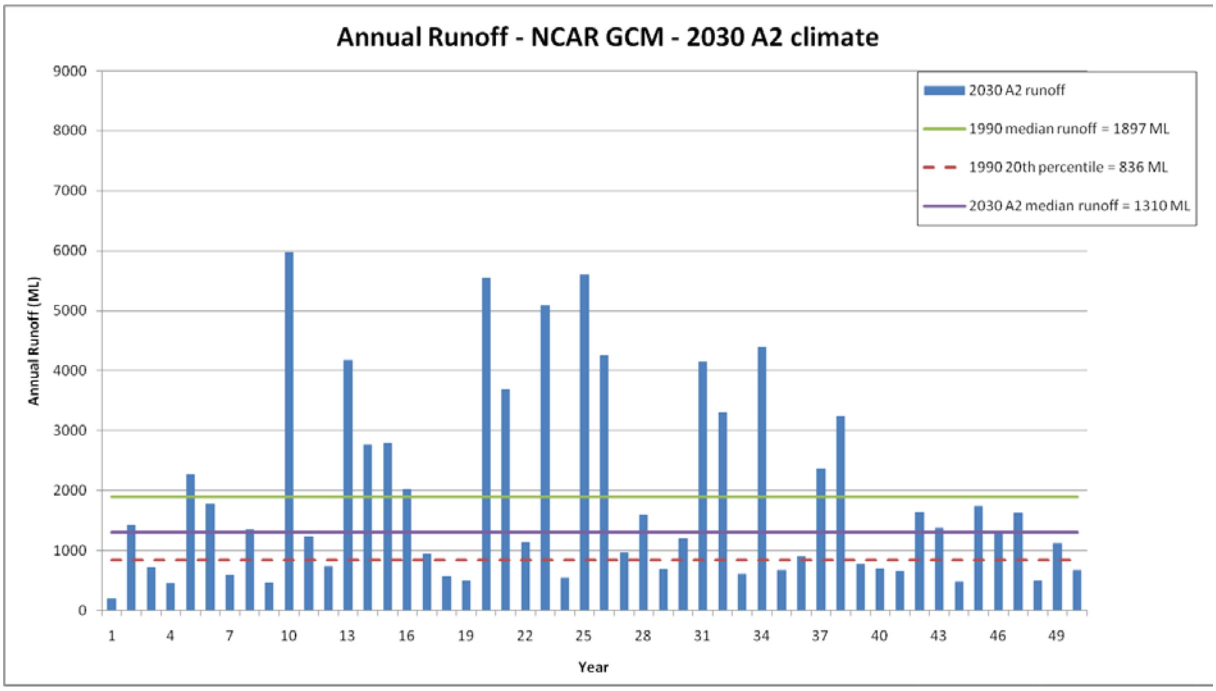


Figure 53. Annual runoff simulated for the Tod Reservoir, based on rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2030 climate and A2 emissions

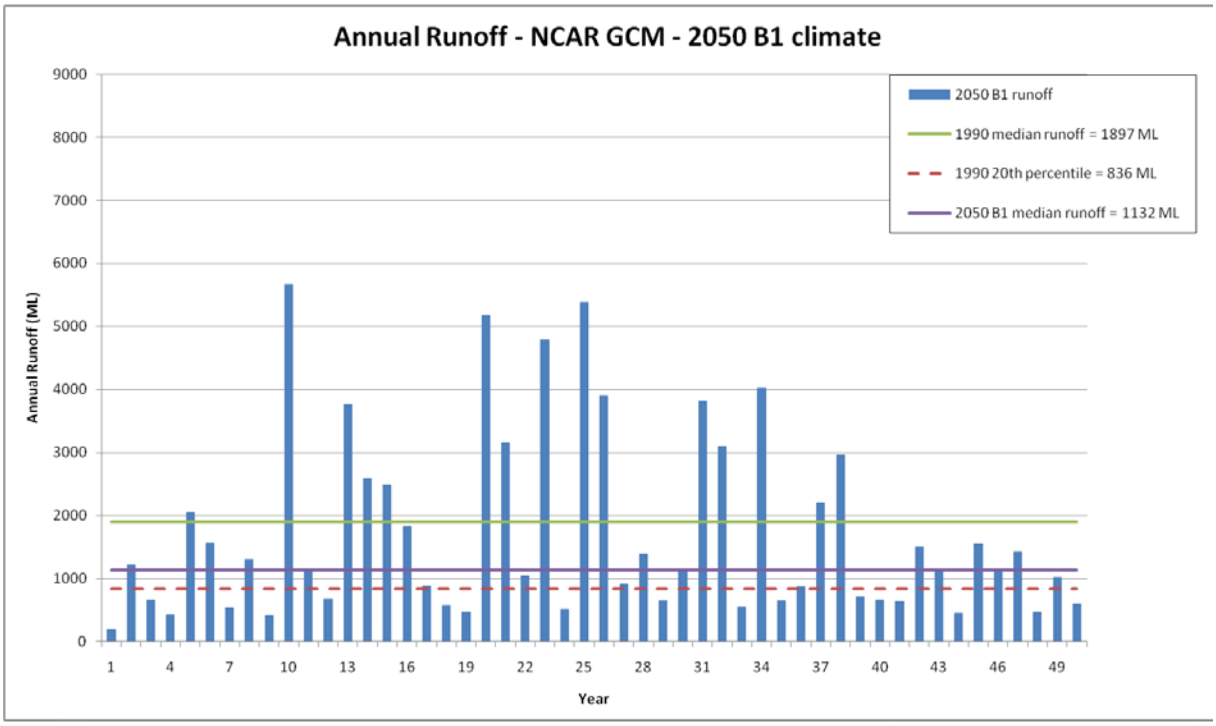


Figure 54. Annual runoff simulated for the Tod Reservoir, based on rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2050 climate and B1 emissions

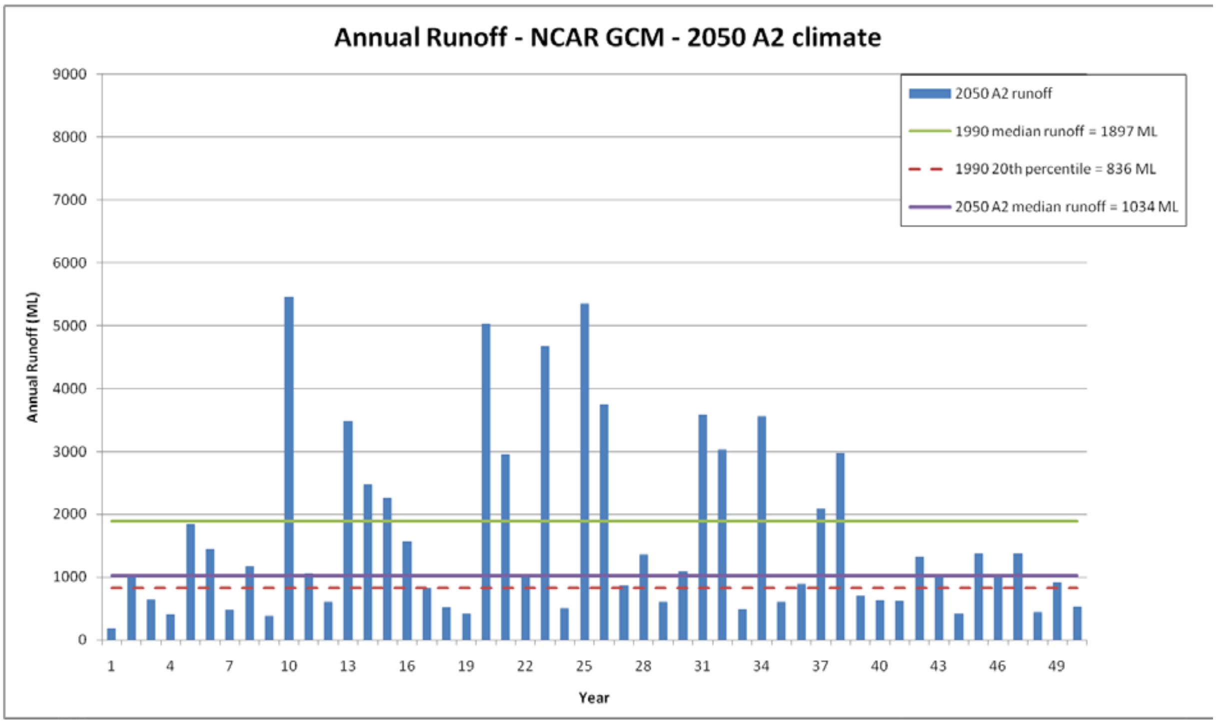


Figure 55. Annual runoff simulated for the Tod Reservoir, based on rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2050 climate and A2 emissions

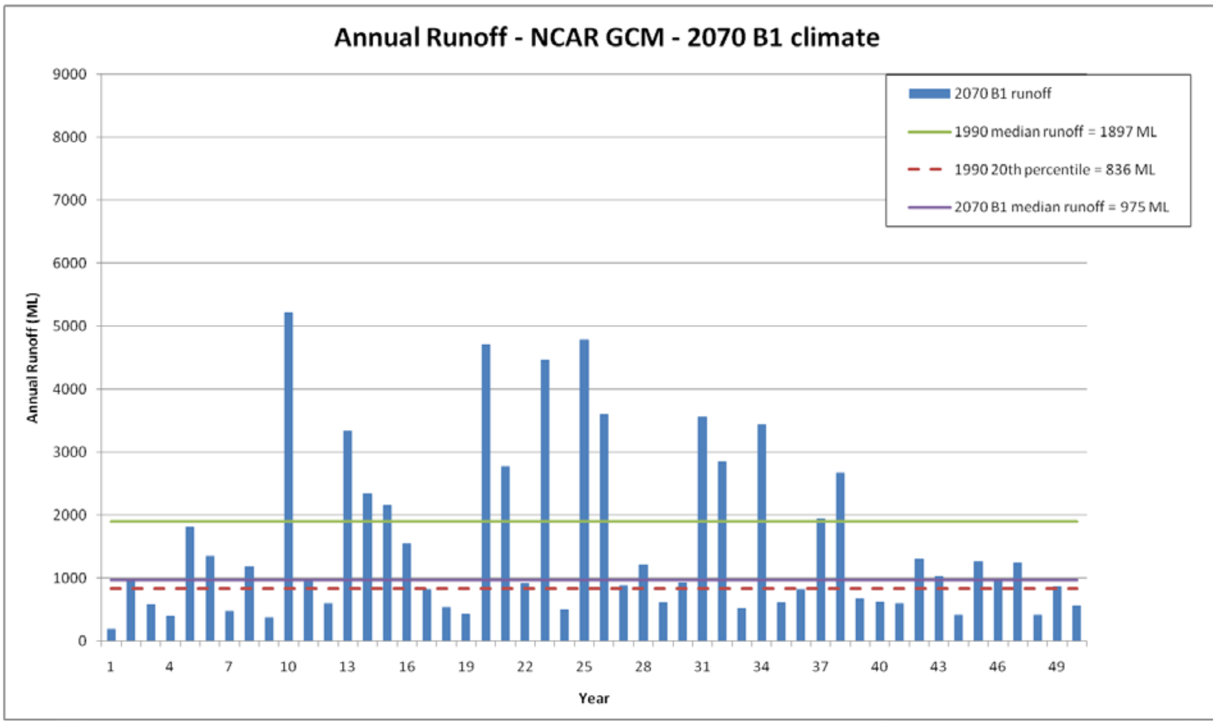


Figure 56. Annual runoff simulated for the Tod Reservoir, based on rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2070 climate and B1 emissions

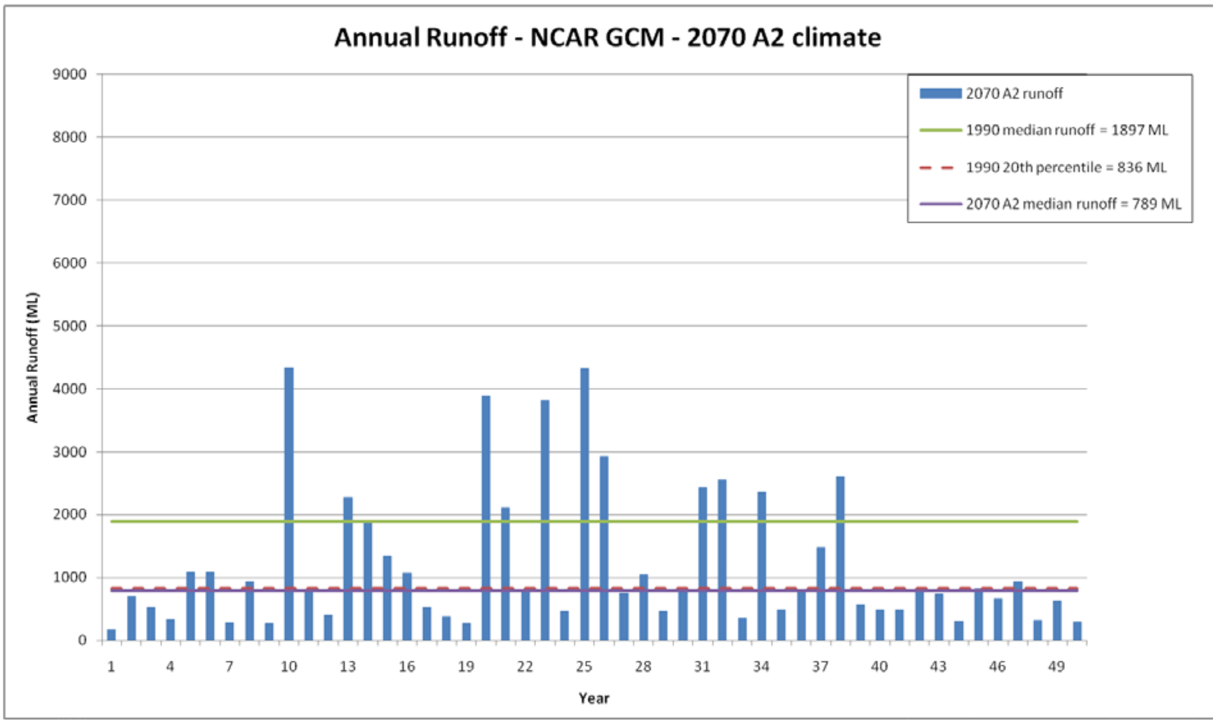


Figure 57. Annual runoff simulated for the Tod Reservoir, based on rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2070 climate and A2 emissions

The modelling results presented thus far are specific to each GCM, emission scenario and time horizon. To generalise the impacts of climate change on simulated runoff, the change in runoff for the Tod Reservoir corresponding to each projected change in winter rainfall has been plotted on a single chart (Fig. 58). The model assumes no diversions from the upper Tod Reservoir catchments. A second model that assumes 10% of the runoff generated from the upper catchments is diverted to the reservoir (Appendix B). For both cases, only the current farm dam density has been considered.

The solid trend line represents a hyperbolic tangent (tanh) function fitted to the results obtained from all GCM projections. This function is commonly used to represent the relationship between rainfall and runoff and can be seen to also provide a suitable representation of the results of projected climate change impacts. The resulting equation for the tanh function is:

$$PR = 0.81 \tanh(6.69\, PW) \qquad \text{(Equation 3)}$$

Where PR is the percentage change in median annual runoff and PW is the percentage change in average winter rainfall.

The thin lines on Figure 58 represent 95% confidence limits, assuming normally distributed variation of the simulated results around the trend line. The 95% confidence intervals have been computed by:

$$CI_{95} = Q_T \pm 1.96\sqrt{\frac{s_{Y|X}}{n}} \qquad \text{(Equation 4)}$$

where CI_{95} is the 95% confidence intervals; Q_T is the change in median annual runoff calculated using the tanh relationship; $s_{Y|X}$ is the sum of squared errors between each change in median runoff resulting from the model simulations and that estimated by the tanh relationship; and n is the number of samples (in this case n = 6 scenarios x 4 GCMs, so n = 24). The computed error bounds correspond to ±12.4% around that provided by the tanh relationship.

The relationships derived allow the expected change in runoff to be estimated for any given change in winter rainfall, based on rainfall projections or climate scenarios that have not been considered as part of this study. The variation in the change in median runoff simulated for a given change in winter rainfall is due to a number of factors including the change in rainfall projected for the other seasons of the year, the corresponding change in PET projected by the GCM and the change in the rainfall intensity introduced by the downscaling method according to the daily GCM rainfall projections. Hence, the confidence intervals provide an indication of the impact of these variations on the total annual runoff for the same winter rainfall.

Traditionally, winter rainfall would be expected to drive the runoff experienced in a catchment for the South Australian climate, as this is when most rainfall occurs and is the period when rainfall exceeds PET. Runoff was modelled using a number of different 'winter month' durations and these outputs were compared to modelled runoff using average annual rainfall. The winter month subsets were based on mean monthly rainfall and mean monthly evapotranspiration statistics (Figs 2 and 4).

For the Tod Reservoir model, using the 1990 historical scenario, the winter months of June, July and August account for only 45% of the average annual rainfall and 67% of the average annual runoff. Extending this period to between May and September increases the percentages to 67% for rainfall and 87% for runoff. This implies that for the rainfall sites located in the Tod River catchment, 33% of the average annual rainfall falls outside these extended winter months, however due to increased evapotranspiration this rainfall leads to a smaller percentage of runoff (13%).

For this case, the change in the annual rainfall, as opposed to winter rainfall, may produce a better explanation of the changes in median annual runoff, due to the amount of runoff occurring outside the winter months, as well as having an impact on the modelled soil storages that will wet up as more frequent rainfall events start occurring before the winter period. The same process of fitting a tanh relationship between average winter rainfall and median annual runoff was undertaken, with the winter months defined as May to September inclusive. This resulted in a slight reduction in the scatter produced by the different GCM and emissions scenarios and the confidence bounds were reduced to 10.7%. The process was repeated using average annual rainfall as the independent variable and in this case the confidence bounds reduced to 6%. A tanh function was generated assuming no diversions from the upper Tod Reservoir catchments into the reservoir (Fig. 59) while a second model assumes 10% of the runoff generated from the upper catchments is diverted to the Tod Reservoir (Appendix B). Due to the increased accuracy in projecting the change in median annual runoff, it is recommended to parameterise the model with average *annual* rainfall for the Tod River catchment. For the annual rainfall case, the tanh function can be seen in Equation 5, where PA is the percentage change in average annual rainfall.

$$PR = 0.81 \tanh(8.5\, PA) \qquad \text{(Equation 5)}$$

Farm dam storage can also be related to the average annual rainfall using a tanh relationship with 95% confidence intervals. The tanh function for the current dam density scenario (Fig. 60) results in a R^2 value of 0.96. A linear trend line fitted through the origin provides only a slightly poorer fit (R^2=0.94), but provides a relationship which is more easily interpreted: a slope of 1.55 indicates that a 1% reduction in annual rainfall is likely to result in a 1.55% reduction in farm dam storage. For the maximum dam storage scenario, similar correlation coefficients for the trend line fits are observed (R^2=0.98 for the tanh relationship, compared to R^2=0.97 for the linear relationship). The slope of the linear trend line increases to 2.16.

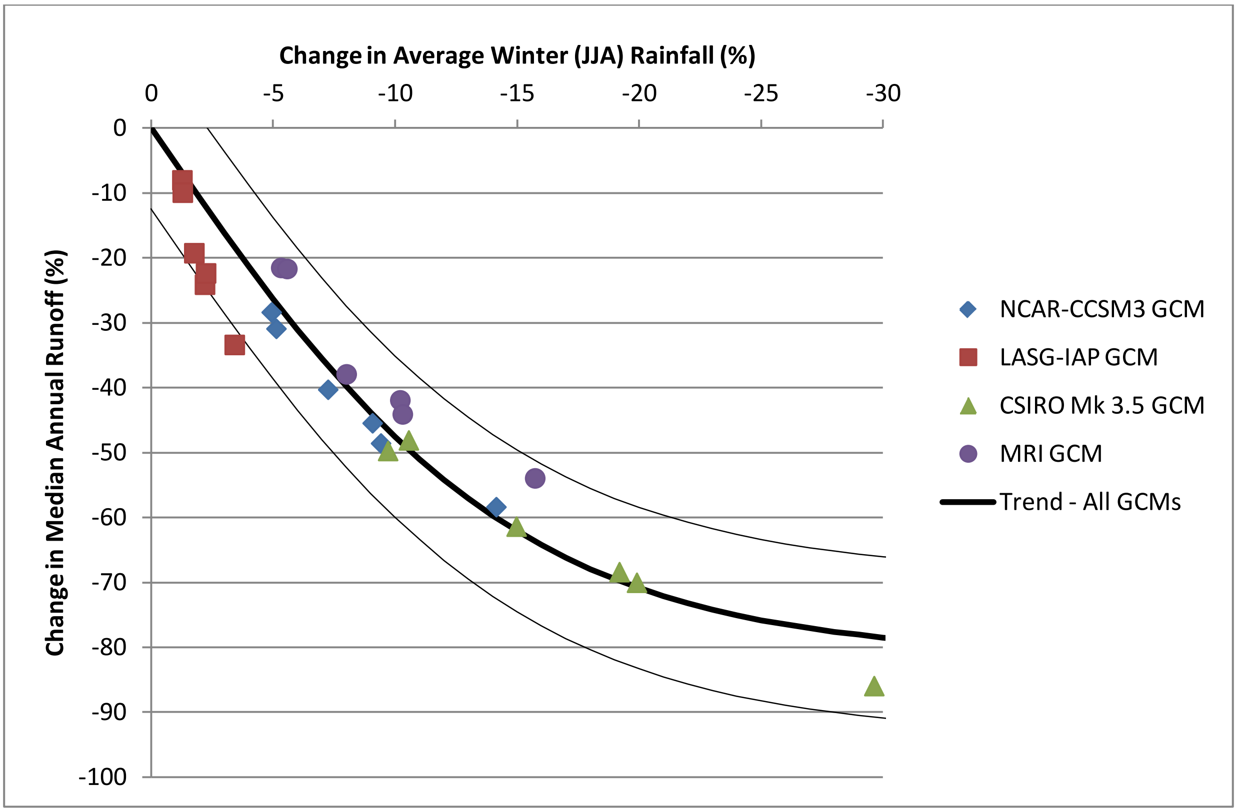


Figure 58. Changes in average winter rainfall versus changes in median annual runoff for the Tod Reservoir. Trend line is a tanh relationship, thin lines show the upper and lower 95% bounds.

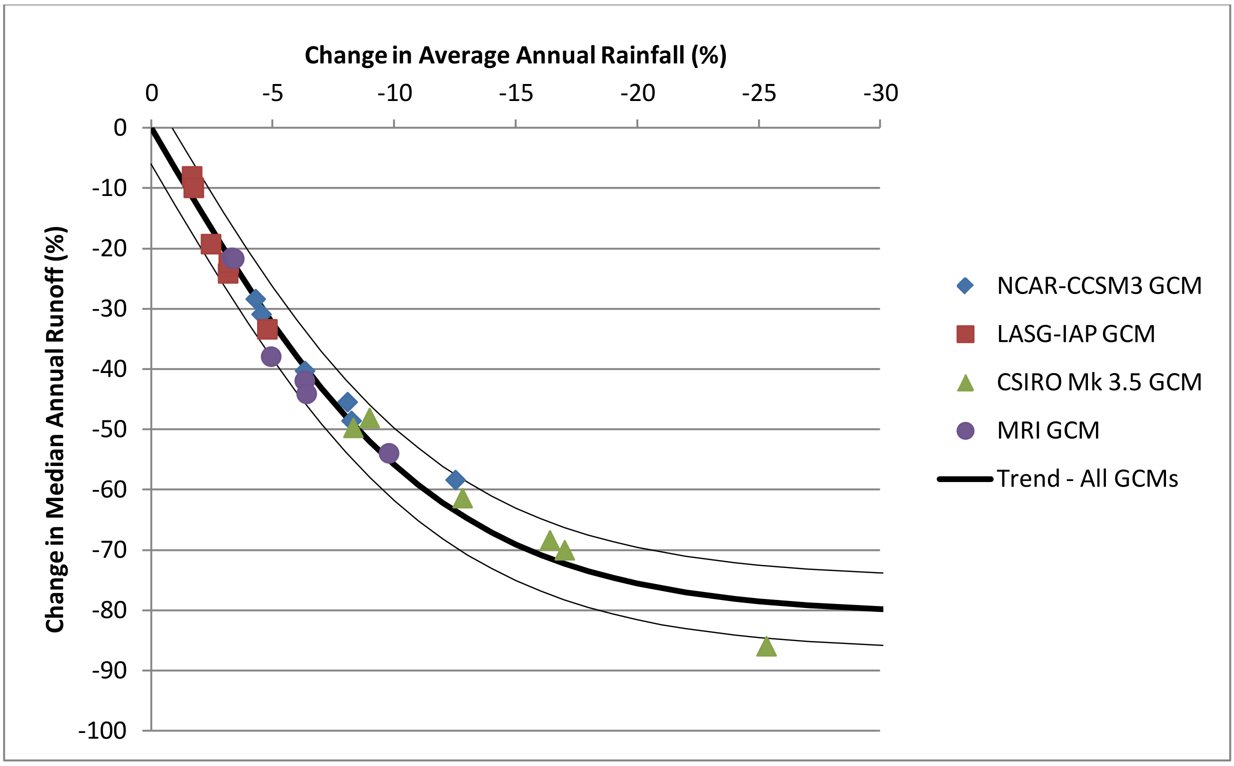


Figure 59. Changes in average annual rainfall versus changes in median annual runoff for the Tod Reservoir. Trend line is a tanh relationship, thin lines show the upper and lower 95% bounds.

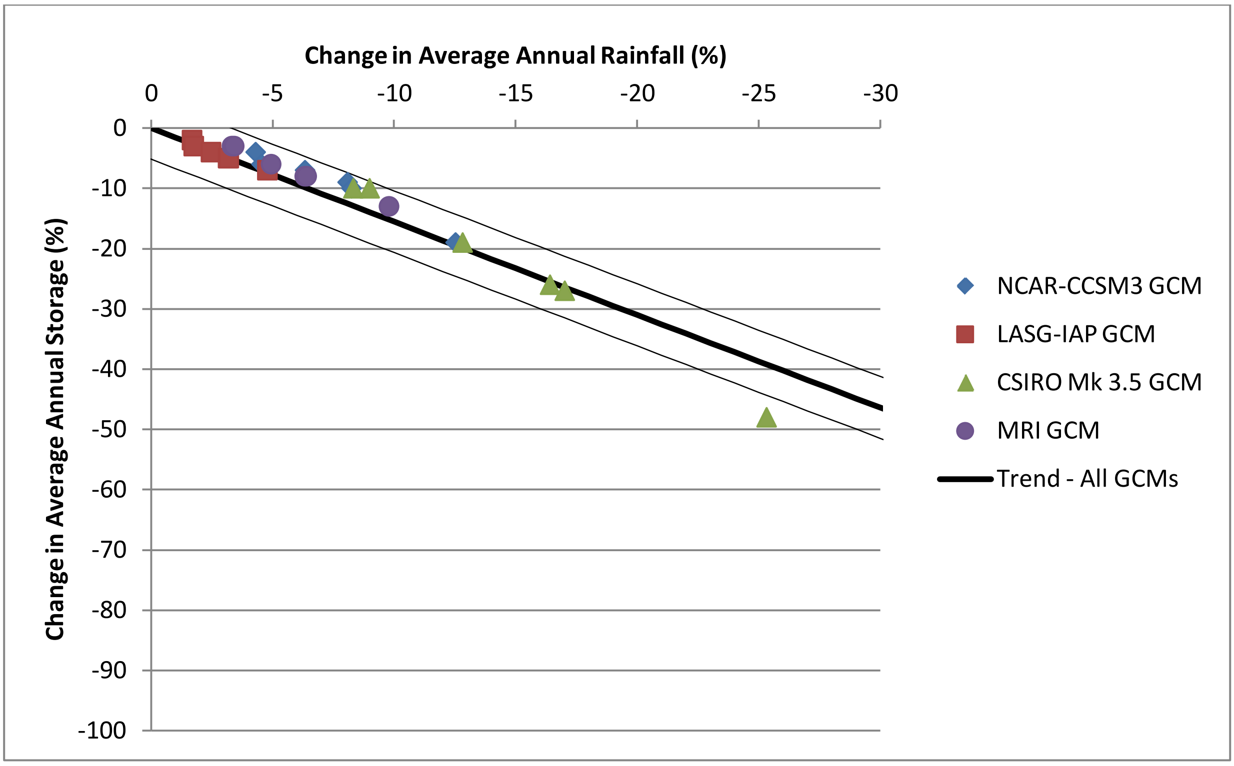


Figure 60. Changes in average annual rainfall versus changes in average annual farm dam storage for the Tod Reservoir. Trend line is a linear relationship, thin lines show the upper and lower 95% bounds.

4.4. UNCERTAINTIES AND LIMITATIONS

There are two primary sources of uncertainty in projections of climate change: inter-model variations and variations in greenhouse gas emissions scenarios. While the GCMs are complex three dimensional models of coupled atmospheric and oceanic processes, they still make many assumptions and simplifications of 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.

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 and Stewart, 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 widely accepted emissions scenarios.

When projected changes in climate are applied to hydrological models the uncertainty in the climate projections is compounded by the uncertainty in the hydrological models. Sensitivity analysis and calibration of the hydrological models developed in this study has ensured they closely replicate the sensitivity of the real hydrologic systems to inter-annual variations in climate variables. However, a degree of uncertainty remains in the outputs of the models and in the structure of the models selected and this is difficult to quantify. For the most extreme cases of a drier climate considered, there is also uncertainty in how well models that are calibrated to historic conditions perform when applied to a climate with much lower rainfall and higher PET.

The South Eastern Australian Climate Initiative (SEACI) has undertaken modelling studies to investigate the relative uncertainties in the three main modelling components in the majority of studies on climate change impacts on runoff. These components, as used in this study, are the projections of the future climate provided by GCMs, the downscaling approach used to convert the regional scale projections to the local scale suitable for impact assessment and the hydrological model used to convert the projected climate into the available runoff or recharge. The SEACI modelling studies (CSIRO, 2010) showed that:

- the largest uncertainties come from the GCM projections
- the difference in simulations using different downscaling methods is about half the rainfall of future projections from the different GCMs
- the difference in runoff simulations using different lumped conceptual rainfall-runoff models is small compared to the differences amongst GCM projections and downscaling methods.

While the SEACI project considered runoff only and not recharge, the uncertainty contributions are expected to translate similarly. Hence, while there are errors and uncertainties involved in the hydrological modelling used to produce the runoff and recharge results presented, by far the largest uncertainties are produced by the GCM projections of the future climate.

For south-eastern Australia, rainfall–runoff models calibrated with more than 20 years of historical data have been found to be suitable for use in climate impact studies when the projected change in mean annual rainfall is less than around 15% (Vase *et al.*, 2010). For larger changes in the future rainfall, hydrological models need to account for potential changes in the rainfall-temperature-runoff relationship and dominant hydrological processes in a warmer, drier and higher CO_2 environment (CSIRO, 2010). For the GCMs and scenarios considered in this report, only the CSIRO Mk 3.5 GCM projects a change in mean annual rainfall greater than 15% for the both 2070 emission scenarios, as well as the 2050 A2 case (with 16% reduction in mean annual rainfall). For these scenarios, the changes in water resources presented in this work should be treated with caution as it is possible that models calibrated to historic conditions may not be able to replicate the dominant processes occurring under a substantially different climate.

The projected variables of interest in the modelling presented in this report are the percentage changes in groundwater recharge and surface runoff at each time horizon. For users of this information, it is recommended that the projected percentage changes in runoff and recharge are considered to be a best estimate of the change that will occur in these variables in the event that a particular climate change scenario eventuates.

The hydrological models have been run using the climate change projections of four of the GCMs that are deemed most appropriate for South Australia (Gibbs *et al.*, 2011), combined with high and low-emissions scenarios, to present a range of possible recharge and runoff changes. The component of uncertainty that results only from the range of climate projections applied is indicated by the 95% confidence intervals.

5. DISCUSSION

This report has presented the results of the surface water runoff and groundwater recharge modelling in several different ways. These results illustrate some of the complexities involved in modelling the potential impacts of climate change on water resources and highlight the need to consider a number of factors in assessing potential impacts, such as the variation in results of multiple GCMs and the differences resulting from changes to seasonality of rainfall and PET. However, it is important that these results are summarised so that they may be interpreted more broadly in a water planning context. The aim of this section of the report is to provide a concise and user-friendly summary of results for potential use in water planning.

There are large uncertainties involved in projections of future climate conditions and the corresponding impact that climate change and climate variability will have on water resources availability. In the context of planning water resources, Chiew *et al.* (2009) recommended using:

> *"…a range of possible scenarios to assess system robustness and resilience (at least a median scenario and a conservative dry scenario). Planning decisions will need to consider the planning horizon and the balance between risks and rewards and whether the system can adapt to climate change and other development drivers on water. For example, planning decisions need not be based on the worse-case scenario, but a management plan is needed to deal with it if it does eventuate."*

This has been the process undertaken in this study; to assess a number of possible scenarios, selected according to their suitability for representing the South Australian climate. The climate projections used in this study (Secs 4.1.1 and 4.2.1) vary markedly depending on the timeframe, GCM and emission scenario considered. The resulting changes in runoff and recharge have been generalised to some extent by considering the change in the water resource based on a given reduction in rainfall, which could occur at various times into the future depending on the emission scenario or GCM projections considered.

When projected changes in climate are applied to hydrological models, the uncertainty in the climate projections is compounded with the uncertainty inherent in the hydrological models. The projected variables of interest in the modelling presented in this report are the percentage changes in groundwater recharge and surface runoff at each time horizon. For users of this information, it is recommended that the projected percentage changes in runoff and recharge are considered to be a best estimate of the change that will occur in these variables in the event that a particular climate change scenario eventuates. As the hydrological models have been run using the climate change projections of a range of climate models that are deemed appropriate for South Australia (Gibbs *et al.*, 2011), combined with high and low-emissions scenarios, a range of possible recharge and runoff changes is presented. The component of uncertainty that results only from the range of climate projections applied is indicated by 95% confidence interval lines in the graphs shown in Figures 61 to 63.

5.1. CLIMATE CHANGE PROJECTIONS FOR THE EYRE PENINSULA

In general, projected reductions in groundwater recharge will ultimately result in lower groundwater levels which will likely impact on the capacity of groundwater systems to support sustainable levels of groundwater abstractions into the future. Furthermore, as rates of evapotranspiration increase and rainfall decrease, the salinities of recharging waters can also be expected to increase to levels higher than those observed historically. It is beyond the scope of the current study to attempt to quantify the rates of falling groundwater levels or increasing salinities. Specific impacts on groundwater resource condition would need to be determined through numerical modelling studies. The ICCWR project is well placed to facilitate further research in these areas. In this study, quantifiable impacts on water resources due to climate change have been limited to the parameters of rainfall, PET, runoff and groundwater recharge.

The national climate projections presented in the 2007 CSIRO Climate Change in Australia report (CSIRO and BoM, 2007) are summarised for each of South Australia's NRM regions in a series of regional climate change projections reports published by the Department of Environment and Natural Resources (DENR). The Regional Climate Change Projections report for the EPNRM Region (DENR, 2010) provides a reference set of climate change projections for that region, which can be used for all climate change impact and adaptation studies that focus on the EPNRM Region. The median projected changes in annual rainfall in the EPNRM Region under high, low and medium emissions scenarios for 2030, 2050 and 2070 are shown in Table 24.

In the recharge and runoff modelling results described in Section 4 of this report, projected changes in annual rainfall were found to provide the strongest indication of the change in runoff and recharge expected from the different future climate scenarios considered. The amounts of projected annual rainfall change have therefore been used within this section as climate change reference points against which the annual rainfall/water resource impact relationships are compared in Figures 61 to 63 and in the corresponding Tables 25 to 27. Using these tables and graphs, the reader can select future time horizon and emissions scenarios and read the corresponding water resource impacts directly from the table or figure that relates to the water resource in question. To further understand how these annual rainfall/water resource impact relationships were developed, the reader should refer to Sections 3 and 4 of this report.

Table 24. Median projections of percentage change in average annual rainfall for the EPNRM Region, based on an ensemble of 13 GCMs suitable for the South Australian Climate, as reported by DENR (2010) and CSIRO (2007)

Time horizon	**2030**			**2050**			**2070**		
Emissions scenario	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Change in average annual rainfall (%)	-3.5	-3.5	-3.5	-7.5	-7.5	-7.5	-7.5	-15	-15

5.2. IMPACTS OF CLIMATE CHANGE ON GROUNDWATER RESOURCES IN THE EYRE PENINSULA NRM REGION

The LEACHM modelling code was used to construct models to determine the potential impacts of climate change on groundwater recharge in the Musgrave and Southern Basins PWAs. A number of models were constructed to represent the different soil types and land uses and these were aggregated in a GIS framework to give area-weighted average recharge rates for all of the defined fresh groundwater lenses in the two PWAs. The models were calibrated to observed water level data where possible. Recharge under current climate conditions was simulated using measured rainfall and PET data from 1960–2009 as input into the model. The potential impacts of climate change were then simulated for three future climate time horizons (2030, 2050 and 2070) under two different emissions scenarios (B1 being relatively low emissions and A2 being relatively high emissions). Four different GCMs were used to generate future rainfall and PET data for these future scenarios, resulting in 24 different projections of future climate. This gave a wide variety of results for the potential impact of climate change on groundwater recharge in the Musgrave and Southern Basins PWAs.

5.2.1. MUSGRAVE PWA

Model results gave a wide variety of projections for potential impacts of climate change on groundwater recharge in the Musgrave PWA. Figure 61 shows the relationship between modelled changes in recharge and related changes in annual rainfall. The trend of this relationship is represented by a tanh curve. This trend provides an indication of the potential reduction in groundwater recharge resulting from projected changes in annual rainfall.

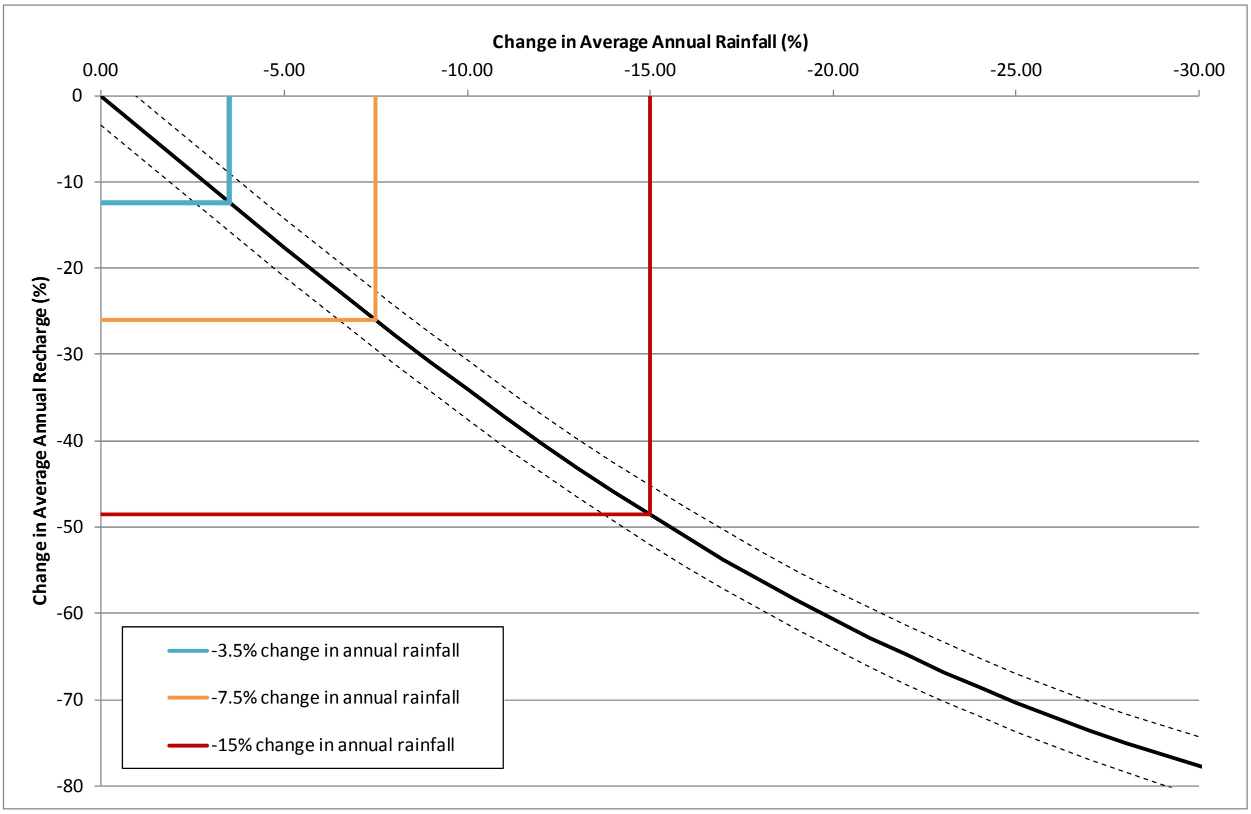


Figure 61. Change in average annual recharge for a given change in average annual rainfall in the Musgrave PWA. Dashed lines indicate 95% confidence bounds. Coloured lines show the annual rainfall projections reported by DENR (2010) and CSIRO and BoM (2007) for the EPNRM Region.

The coloured lines in Figure 61 represent the median projected changes in annual rainfall, as reported by DENR (2010) and CSIRO and BoM (2007). The changes to average annual recharge, corresponding to the median climate change projections are also presented in Table 25.

Table 25. Summary of changes in average annual recharge to the Musgrave groundwater resources for the projected changes in annual rainfall in the EPNRM Region. The colours of each box in the table correspond to the colours shown on Figure 61 (annual rainfall projections from DENR (2010) and CSIRO and BoM (2007)).

Time horizon	**2030**			**2050**			**2070**		
Emissions scenario	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Change in average annual rainfall (%)	-3.5	-3.5	-3.5	-7.5	-7.5	-7.5	-7.5	-15	-15
Change in average annual recharge (%)	-12	-12	-12	-26	-26	-26	-26	-49	-49

5.2.2. SOUTHERN BASINS PWA

The models also resulted in a wide variety of results for the potential impact of climate change on groundwater recharge in the Southern Basins PWA. Figure 62 shows the trend line of modelled changes in recharge and related changes in average annual rainfall. The trend is again represented by a tanh curve and provides an indication of the potential reduction in groundwater recharge as a result of climate change for the fresh groundwater lenses in the Southern Basins PWA.

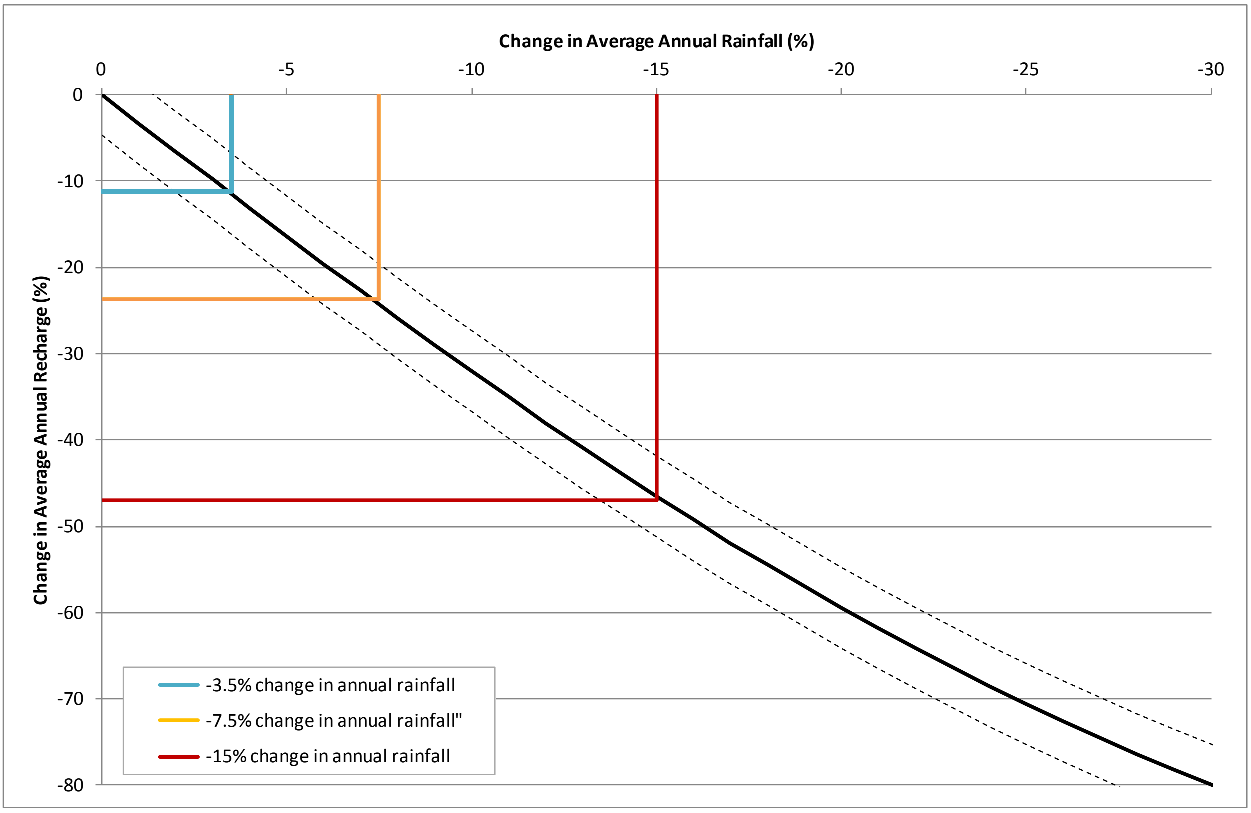


Figure 62. Change in average annual recharge for a given change in average annual rainfall in the Southern Basins PWA. Dashed lines indicate 95% confidence bounds. Coloured lines show the annual rainfall projections reported by DENR (2010) and CSIRO and BoM (2007) for the EPNRM Region.

The coloured lines in Figure 62 represent the median projected changes in annual rainfall, as reported by DENR (2010) and CSIRO and BoM (2007). The changes to average annual recharge, corresponding to the median climate change projections are also presented in Table 26. The results from the Southern Basins models are very similar to those from the Musgrave models, only the reductions in recharge are slightly less. This is most likely due to the fact that rainfall is higher and generally more reliable in the Southern Basins PWA.

Table 26. Summary of changes in average annual recharge to the Southern Basins groundwater resources for the projected changes in annual rainfall in the EPNRM Region. The colours in the table correspond to the colours shown on Figure 62 (annual rainfall projections from DENR (2010) and CSIRO and BoM (2007)).

Time horizon	**2030**			**2050**			**2070**		
Emissions scenario	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Change in average annual rainfall (%)	-3.5	-3.5	-3.5	-7.5	-7.5	-7.5	-7.5	-15	-15
Change in average annual recharge (%)	-11	-11	-11	-24	-24	-24	-24	-47	-47

5.3. IMPACTS OF CLIMATE CHANGE ON SURFACE WATER RESOURCES IN THE EYRE PENINSULA NRM REGION

To assess the impact of projected changes in climate on the surface water resources on Eyre Peninsula, a rainfall-runoff model was developed to represent the catchments that contribute flow to the Tod Reservoir. The model was calibrated to represent runoff under the historic climate, based on the observed flow record upstream of the reservoir. Six future climate scenarios were then considered, for time horizons of 2030, 2050 and 2070, with high and low-emission scenarios. Four GCMs were used to derive different projections for each of the six cases, resulting in 24 different projections of the future climate.

The change in runoff resulting from the different climate projections considered was found to have the strongest relationship with the projected annual rainfall, as opposed to only winter rainfall (Sec. 4.3). Hence, a relationship was developed between the change in runoff simulated compared to projected changes in annual rainfall, with the result shown in Figure 63. The dashed lines represent the 95% confidence intervals for the relationship between rainfall and runoff, where the variation leading to the confidence bounds is due to a number of factors including the change in rainfall projected for the other seasons of the year, the corresponding change in PET projected by the GCM, as well as the change in the rainfall intensity introduced by the downscaling method according to the daily GCM rainfall projections.

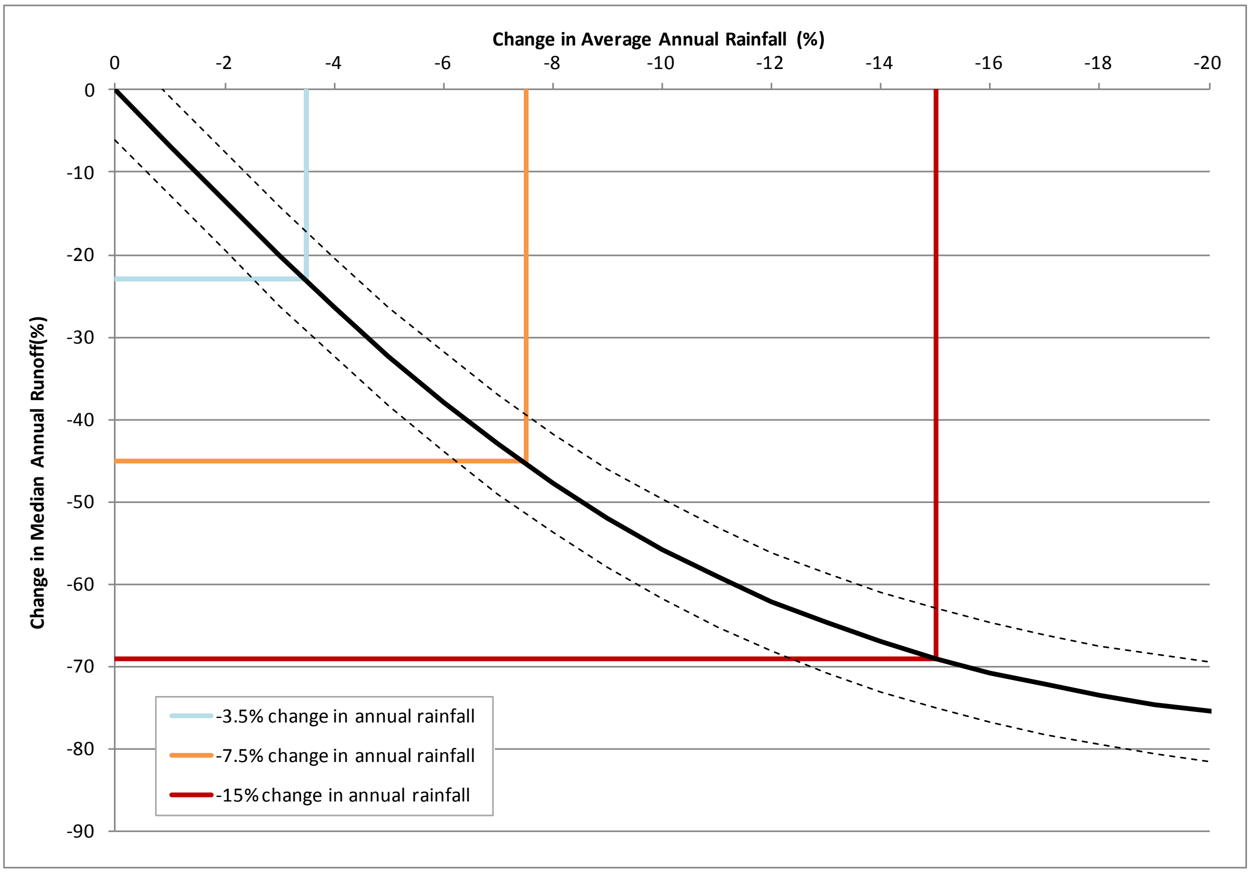


Figure 63. Change in median annual runoff for a given change in average annual rainfall for the Tod Reservoir catchment. Dashed lines represent 95% confidence bounds. Coloured lines indicate the annual rainfall projections reported by DENR (2010) and CSIRO and BoM (2007) for the EPNRM Region.

The coloured lines in Figure 63 represent the median projected changes in annual rainfall, as reported by DENR (2010) and CSIRO and BoM (2007). The corresponding changes to the simulated median annual runoff are also presented in Table 27.

Table 27. Summary of changes in median annual runoff for the Tod Reservoir for the projected changes in annual rainfall for the EPNRM Region. The colours of each box in the table correspond to the colours shown on Figure 63 (annual rainfall projections from DENR (2010) and CSIRO and BoM (2007)).

Time horizon	**2030**			**2050**			**2070**		
Emissions scenario	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Change in average annual rainfall (%)	-3.5	-3.5	-3.5	-7.5	-7.5	-7.5	-7.5	-15	-15
Change in median annual runoff (%)	-23	-23	-23	-45	-45	-45	-45	-69	-69

The results indicate that runoff in the Tod Reservoir catchments is highly susceptible to changes in climate. For Australian conditions, typically the change in runoff is in the order of three times greater than the corresponding change in rainfall, for example a 10% reduction in rainfall often leads to a 30% reduction in runoff (Chiew, 2006, Heneker and Cresswell, 2011). However, the modelling undertaken in this project indicates that the change in runoff is approximately six times more than the change in rainfall for small reductions (less than 10%). For changes in rainfall greater than this, it can be seen from Figure 63 that the reduction in runoff for a given reduction in rainfall begins to decrease, however significant reductions in the median annual runoff (69%) are simulated for a relatively small changes in average annual rainfall (15% reduction) and PET (6% increase; DENR, 2010).

6. CONCLUSIONS AND RECOMMENDATIONS

The focus of this study was the impacts of climate change on groundwater recharge in the Southern Basins and Musgrave PWAs and surface water runoff in the Tod Reservoir catchment in the EPNRM Region. Hydrologic models were constructed and calibrated for the key water resources in these areas and run with historic and future climate datasets to estimate potential changes to surface water runoff and groundwater recharge under a range of future climate scenarios.

For the Southern Basins PWA, modelled percentage changes in average annual recharge for the lumped Lincoln (A, B, C and D) lenses were compared to modelled changes for the Uley South lens. The percentage changes for these two areas were within 2–3% of absolute agreement. Similar agreement was observed for modelled percentage changes in average annual recharge for the Bramfield and Polda lenses of the Musgrave PWA. Based on these results, it was concluded that for a given PWA, the modelling approach generates similar results for all of the fresh groundwater lens to which the model is applied. Consequently, the modelling approach has been applied to all lenses individually but the results have been reported more broadly at the PWA-scale.

Similarly, the model developed to represent the runoff for the Tod Reservoir was deemed suitable for assessing the impacts of projected changes in climate on runoff, with accurate simulation of monthly and annual volumes (Nash-Sutcliffe Efficiencies greater than 0.8) and very low bias (less than 0.1%).

An array of results was produced, with significant diversity in the runoff and recharge reductions derived from using climate projections from a variety of climate models and emissions scenarios. This highlights the importance of considering projections from multiple GCMs to capture the degree of uncertainty inherent in climate change projections. However, general quantitative relationships have been identified between projected changes in annual rainfall and resulting changes in runoff and groundwater recharge projected by the hydrological models. This enables a simple conversion between climate change projections and changes in water resource runoff or recharge for resource planning purposes. Whilst the numerical modelling in this study is based on ‘low’ (B1) and ‘high’ (A2) emissions scenarios, the annual rainfall projections for South Australia summarised by DENR (2010) are based on low, medium and high emissions scenarios.

The changes in surface water runoff and groundwater recharge projected in this study represent large percentages of the renewable capacity of the water resources in these key water resource areas. For a 2070 climate scenario, reductions of up to 12–49% and 11–47% compared to historic annual groundwater recharge in the Musgrave and Southern Basins PWAs respectively and from 23% to 69% of annual runoff in the Tod Reservoir catchment are projected for the median rainfall change under the medium range emissions scenario projection reported by CSIRO and BoM (2007). Historic annual recharge and runoff is based on estimates for the period 1960–2009.

Also notable are the projected changes to the frequency of years with unusually low and high runoff or recharge, characterised by annual amounts below the 20th percentile and above the 80th percentile of annual runoff and recharge in the historic baseline period. In most scenarios there are marked increases in the occurrence of years of low recharge and runoff. Among the range of climate scenarios applied, increases in the frequency of years with low recharge or runoff range between 20% and 320% compared to the 1960–2009 baseline period. The frequency of occurrence of years with high recharge and runoff is reduced by between 10% and 100% compared to the 1960–2009 baseline. In many of the scenarios the percentage changes in these frequencies are greater than the percentage changes in mean recharge and median runoff amounts.

If these changes eventuate they will have major implications for the continued development of the EPNRM Region and for the viability of current agricultural practices, unless mitigated by alternative water sources and/or water demand reduction strategies. It is recommended that natural resource and water resources management agencies (as well as other relevant stakeholders) with interests in this region should consider the range of projected changes to these resources when assessing risks in medium and long-term plans for the region.

The projected reductions in surface water runoff and groundwater recharge are not directly convertible into changes in water available for allocation from these specific resources. At the time of writing there is no existing policy for re-apportioning the reduced capacity of these resources between human and environmental requirements under future climate scenarios. However, on Eyre Peninsula it is broadly accepted at the State and national levels that critical human water needs are the highest priority. Any future changes required to diversion and extraction limits for these resources under future climate scenarios will be the subject of extensive public consultation through the water allocation planning process.

Ongoing science will continue to provide new data and knowledge of the components of climate change and hydrological science used to derive these estimates of climate change impacts. It is recommended that the projections of impacts on water resources in these prescribed areas are revisited when new downscaled climate 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 affect the hydrological model outputs should also be incorporated, including any improvements in the conceptual understanding of recharge processes and projections of possible land use changes in the EPNRM Region.

The study presented in this report is the most comprehensive effort to date to estimate the impacts of climate change on water resources in the EPNRM Region, based on current knowledge of the water resources and current projections of climate change through the 21st century. It must be emphasised that the results of this study derive from a multi-layered process in which there is a high degree of uncertainty in each layer. Nonetheless, this study currently represents the best available science with which to plan future water supply scenarios for this region.

APPENDICES

A. CALIBRATION OF RECHARGE MODELS

Soil type A1 – Highly calcareous sandy loam

Polda – SQR031

Soil type A1 is most prevalent in the north-west of the Musgrave PWA (DWLBC, 2007), however a significant area is also present in the south-western portion of the Polda modelled recharge area. Observation well SQR031 within the Polda lens was identified as providing an appropriate record of annual watertable fluctuations to calibrate the LEACHM model for this soil type. Weather data were taken from the Polda weather station (BoM station #18139). Figure 64 shows the groundwater level record in SQR031.

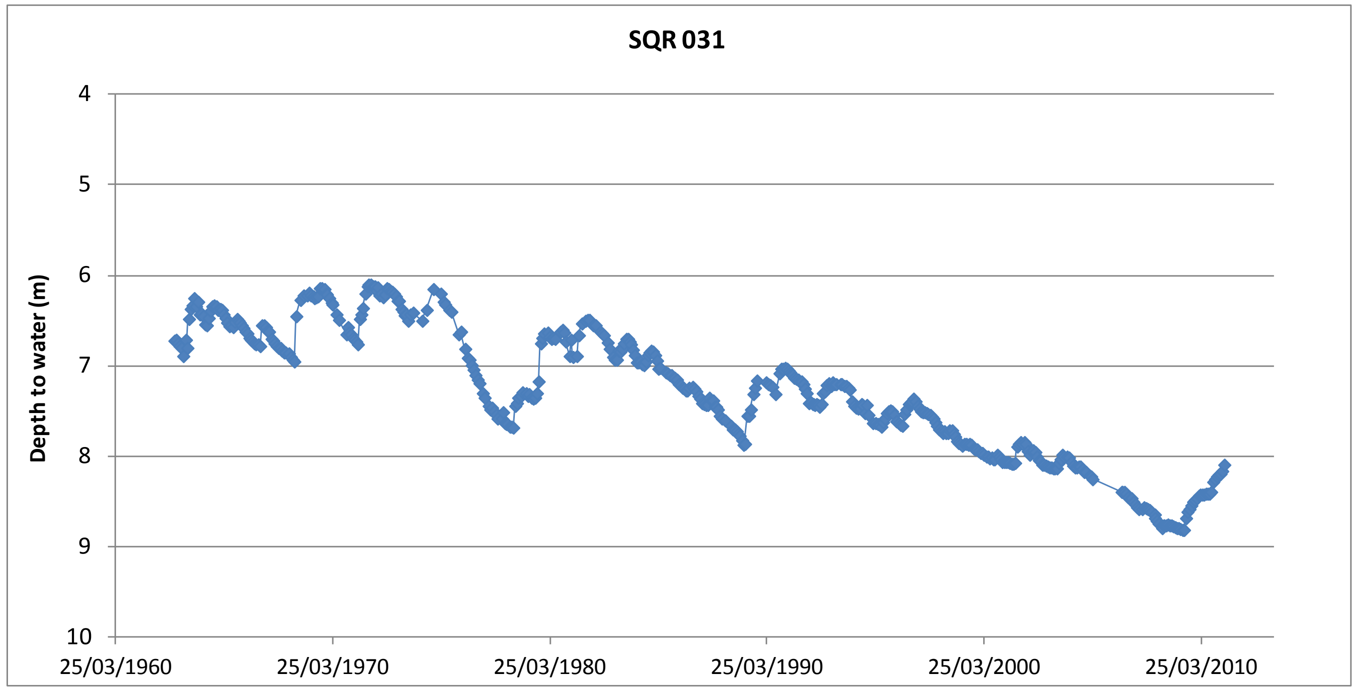


Figure 64. Observed groundwater levels in Obswell SQR031

Figure 65 shows the relationship between estimated recharge (according to the water table fluctuation method applied to Obswell SQR031) and LEACHM modelled recharge (including diffuse and sink hole recharge). While a relationship is observed between the modelled and estimated recharge, there is a significant amount of scatter around the 1:1 relationship. However, the average annual modelled recharge of 29 mm/y is in good agreement with previous estimates of recharge to the Polda groundwater lens of 17–49 mm/y (adopted rate is 28 mm/y). These estimates were determined by multiple studies using different methods (Evans, 1993; Ward *et al.*, 2009).

It is more important that the variations in modelled annual recharge compared to variations in annual rainfall represent the sensitivity of the estimated recharge to rainfall variations. Figure 66 plots percentage deviations from average values of modelled recharge and estimated recharge against deviations from annual rainfall for each year of a 50-year simulation. The similarity of the slopes of the trend lines of the modelled and estimated annual recharge values here indicates that the annual recharge totals predicted by the model have a sensitivity to changes in rainfall that is similar to that indicated by the variation of the estimated recharge rates against rainfall variations. The model can be considered to simulate the changes in recharge in response to changes in rainfall reasonably well and is therefore a useful tool to assess the potential impacts of climate change on recharge in areas with this soil type.

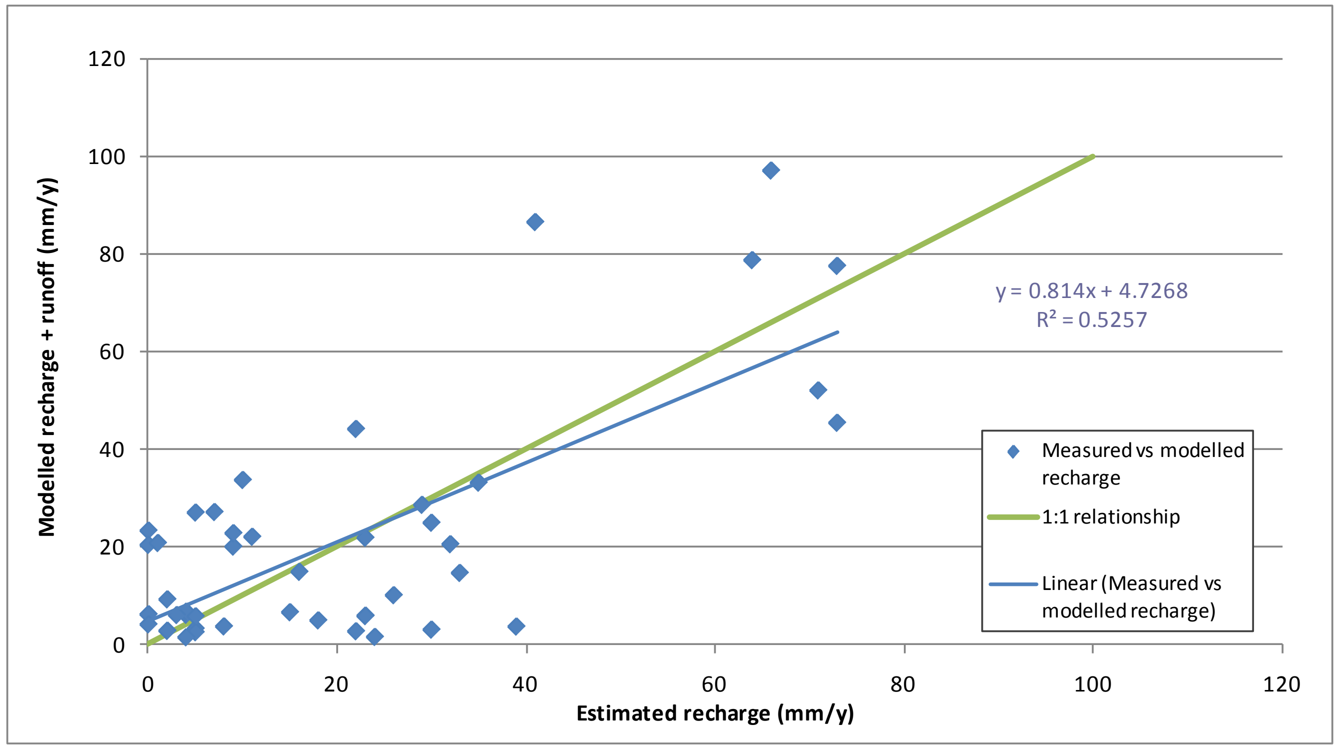


Figure 65. LEACHM modelled recharge for soil A1 versus estimated recharge for Obswell SQR031

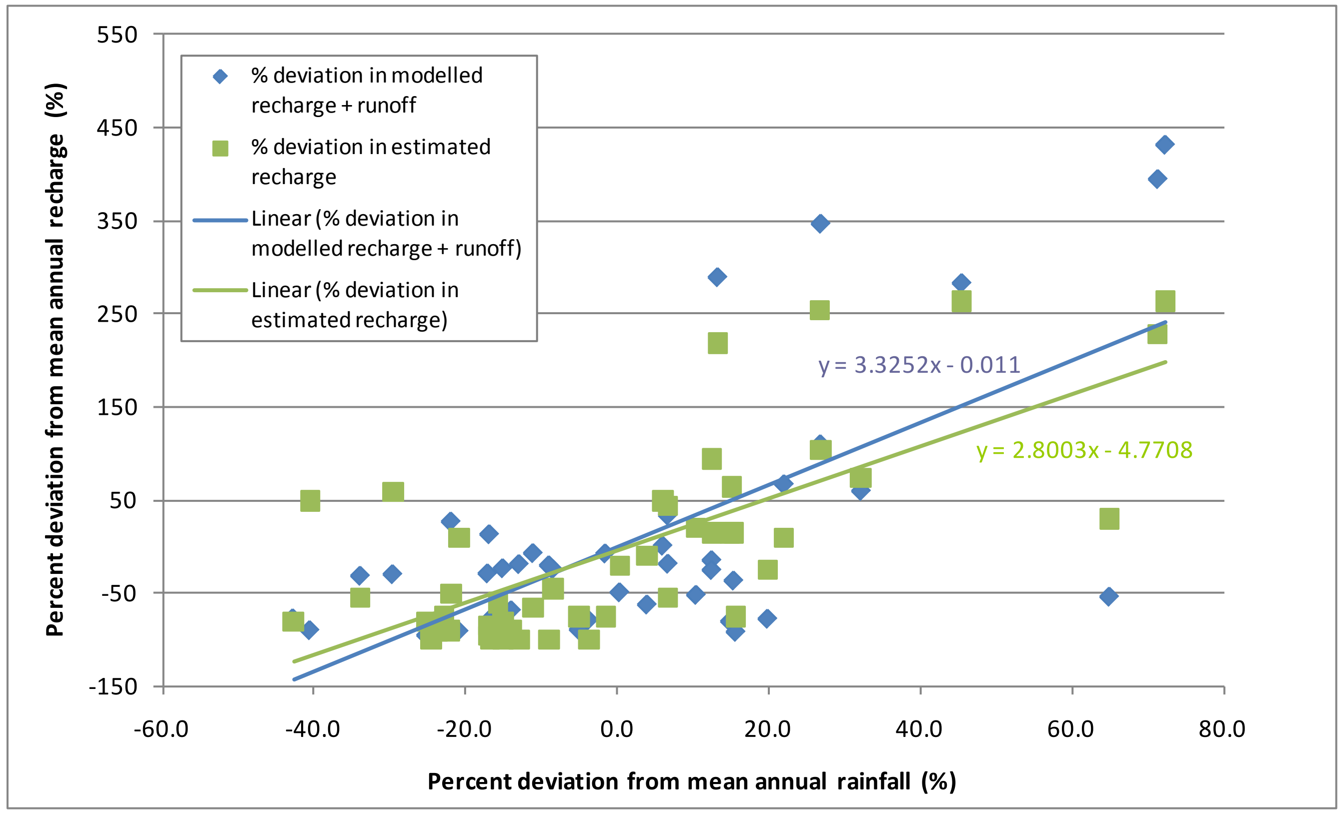


Figure 66. Modelled percent deviation in mean annual recharge and estimated percent deviation in mean annual recharge versus percent deviation in mean annual rainfall

Soil type B1 – Shallow highly calcareous sandy loam on calcrete
Uley South – ULE134

Soil type B1 is most prevalent along the coastal margin of the Uley South groundwater lens in the Southern Basins PWA. Observation well ULE134 was identified as providing an adequate record of annual watertable fluctuations to calibrate the LEACHM model. Weather data for the model were taken from the Port Lincoln (Westmere) (BoM station # 18137) weather station. Figure 67 shows the groundwater level record in ULE134.

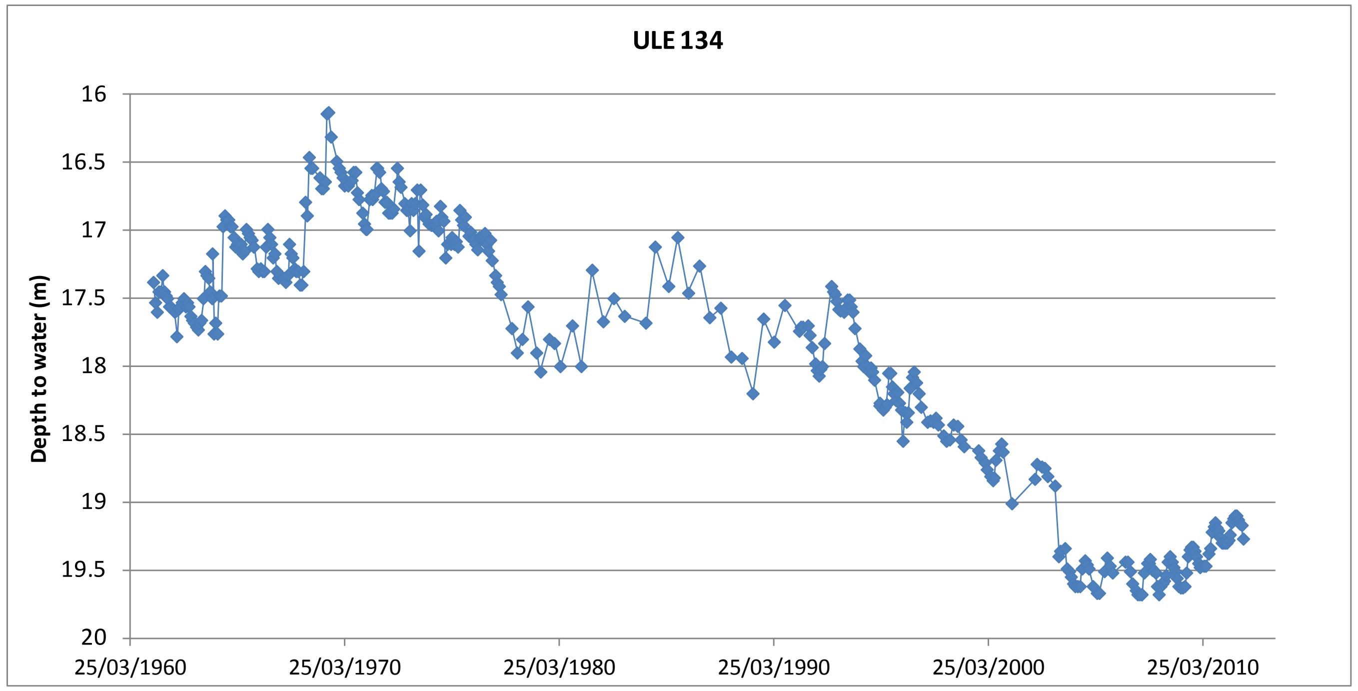


Figure 67. Observed groundwater levels in Obswell ULE134

Figure 68 shows the relationship between estimated recharge (from Obswell ULE134) and modelled recharge for each year of a 50-year simulation using the modelled B1 soil type. There is a reasonable correlation between the two (r^2 = 0.63), however the modelled rates of recharge and runoff are consistently higher than the estimated recharge rates, as discussed in Section 3.3.1. The average annual modelled recharge (plus runoff) of 133 mm/y is in good agreement with previous estimates of recharge to the Uley South groundwater lens of ~155 mm/y, which is the rate currently used to inform water allocation planning (Harrington *et al.*, 2009), although there are some much lower estimates, such as the 47 mm to 129 mm suggested by Ordens *et al.* (2011).

Figure 69 plots percentage deviations from average values of modelled recharge and estimated recharge against deviations from annual rainfall for each year of a 50-year simulation. The close similarity of the slopes of the trend lines of the modelled and estimated annual recharge values here indicates that the annual recharge totals predicted by the model have a sensitivity to variations in annual rainfall that is similar to that indicated by the variation of the estimated recharge rates against rainfall variations. The model can be considered to simulate the changes in recharge in response to changes in rainfall reasonably well and is therefore a useful tool to assess the potential impacts of climate change on recharge in areas with this soil type.

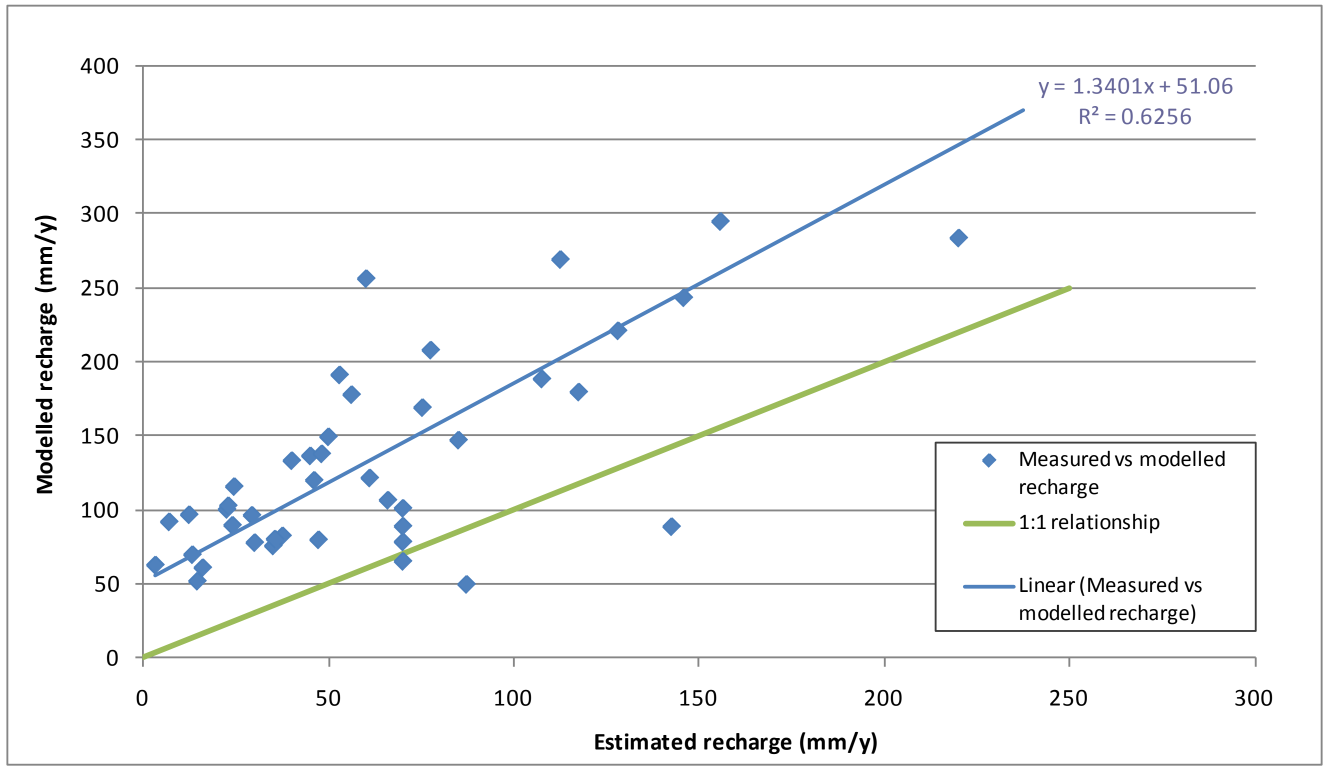


Figure 68. LEACHM modelled recharge for soil B1 versus estimated recharge for Obswell ULE134

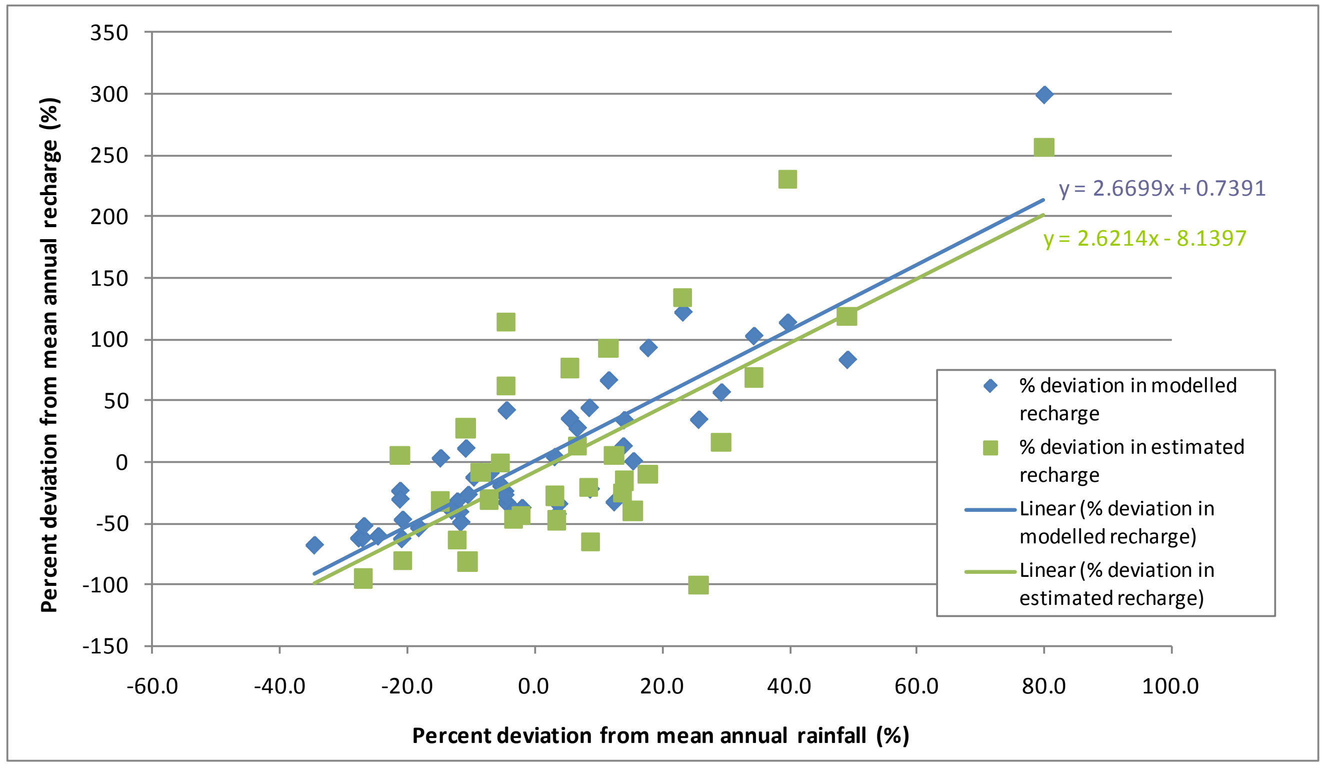


Figure 69. Modelled percent deviation in mean annual recharge and estimated percent deviation in mean annual recharge versus percent deviation in mean annual rainfall

Soil B2 – Shallow calcareous loam on calcrete
Bramfield – WAY054

Soil type B2 occurs predominantly along the southern coastal margin of the Musgrave PWA and stretches north into the Bramfield modelled recharge area. It also dominates the eastern extent of the Sheringa modelled recharge area. Observation well WAY054 (in the Sheringa lens) was identified as providing an adequate record of annual watertable fluctuations to calibrate the LEACHM model against. Input weather data for the model were taken from the Sheringa weather station (Lake Hamilton, BoM station # 18045). Figure 70 shows the groundwater level record for WAY054.

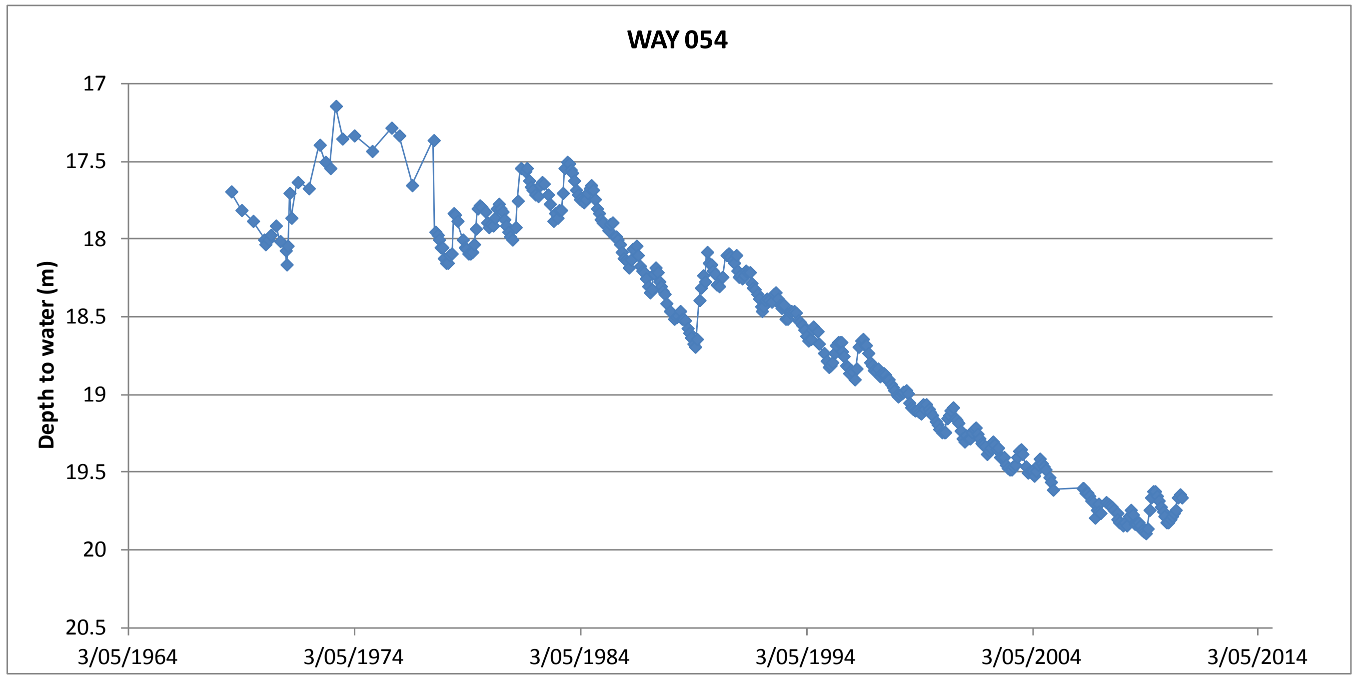


Figure 70. Observed groundwater levels in Obswell WAY054

Figure 71 shows the relationship between annual estimated recharge (from Obswell WAY054) and annual modelled recharge for each year of the 50-year simulation with the modelled B2 soil type. There is a good correlation between the two (r^2 = 0.59), although the modelled recharge is consistently greater than the estimated recharge, as discussed in Section 3.3.1.

It is more important that the variations in modelled annual recharge compared to variations in annual rainfall represent the sensitivity of the estimated recharge to rainfall variations. Figure 72 plots percentage deviations from average values of modelled recharge and estimated recharge against deviations from annual rainfall for each year of a 50-year simulation. The close similarity of the slopes of the trend lines of the modelled and estimated annual recharge values here indicates that the annual recharge totals predicted by the model have a sensitivity to changes in rainfall that is very similar to that indicated by the variation of the estimated recharge rates against rainfall variations. The model can be considered to simulate the changes in recharge in response to changes in rainfall reasonably well and is therefore a useful tool to assess the potential impacts of climate change on recharge in areas with the B2 soil type.

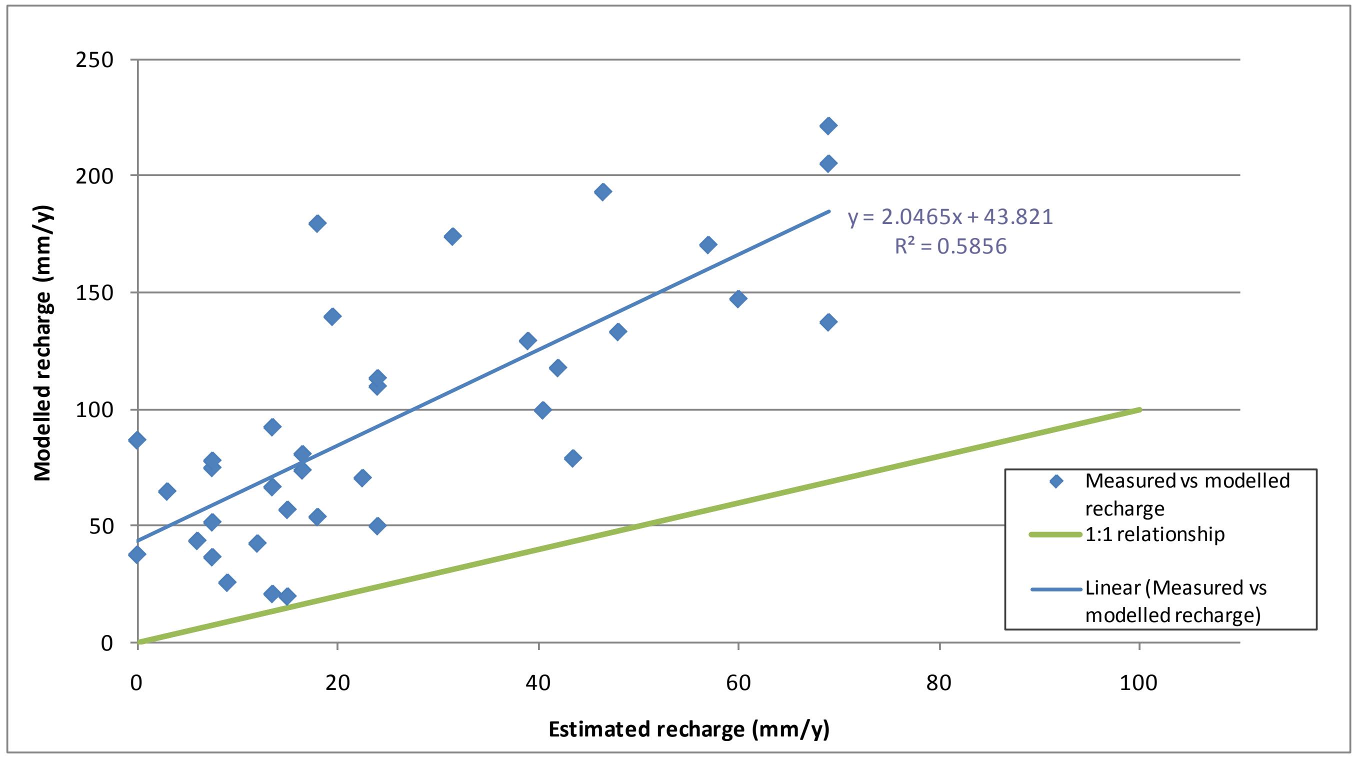


Figure 71. LEACHM modelled recharge for soil B2 versus estimated recharge for Obswell WAY054

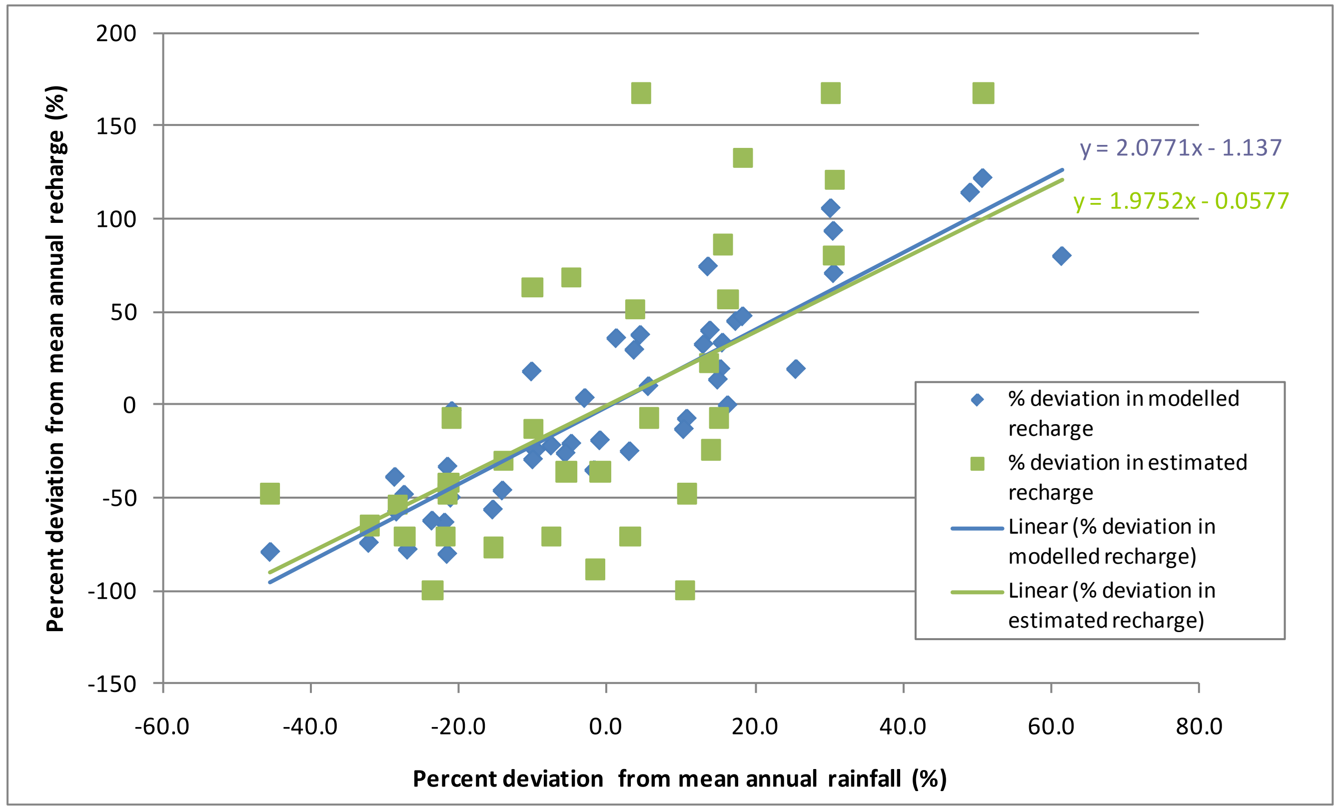


Figure 72. Modelled percent deviation in mean annual recharge and estimated percent deviation in mean annual recharge versus percent deviation in mean annual rainfall

B3 soil – Shallow sandy loam on calcrete

Soil type B3 is the most prevalent soil type in both prescribed wells areas. In the Musgrave PWA it occurs significantly in nearly all the modelled recharge areas, including the Polda, Bramfield and Sheringa recharge areas. In the Southern Basins PWA, it covers a large proportion of most recharge areas including Uley South, Uley East, Uley Wanilla and Lincoln A, B and C. For this reason, the performance of the model developed for soil type B3 was tested against recharge estimates from observation wells in more than one of these areas. In all, three examples were used to asses and calibrate the model for soil type B3 and details of all are given in Table 28.

Table 28. Calibration targets for soil type B3

Prescribed Wells Area	Groundwater lens	Obswell used to estimate recharge	Weather data used in the model
Southern Basins	Uley South	ULE139	Port Lincoln (Westmere), station # 18137
Southern Basins	Lincoln-A	SLE047	Port Lincoln (Westmere), station # 18137
Musgrave	Polda	SQR088	Polda, station # 18139

Uley South – ULE139

Figure 73 shows the observation well record for ULE139, located within the Uley South modelled recharge area.

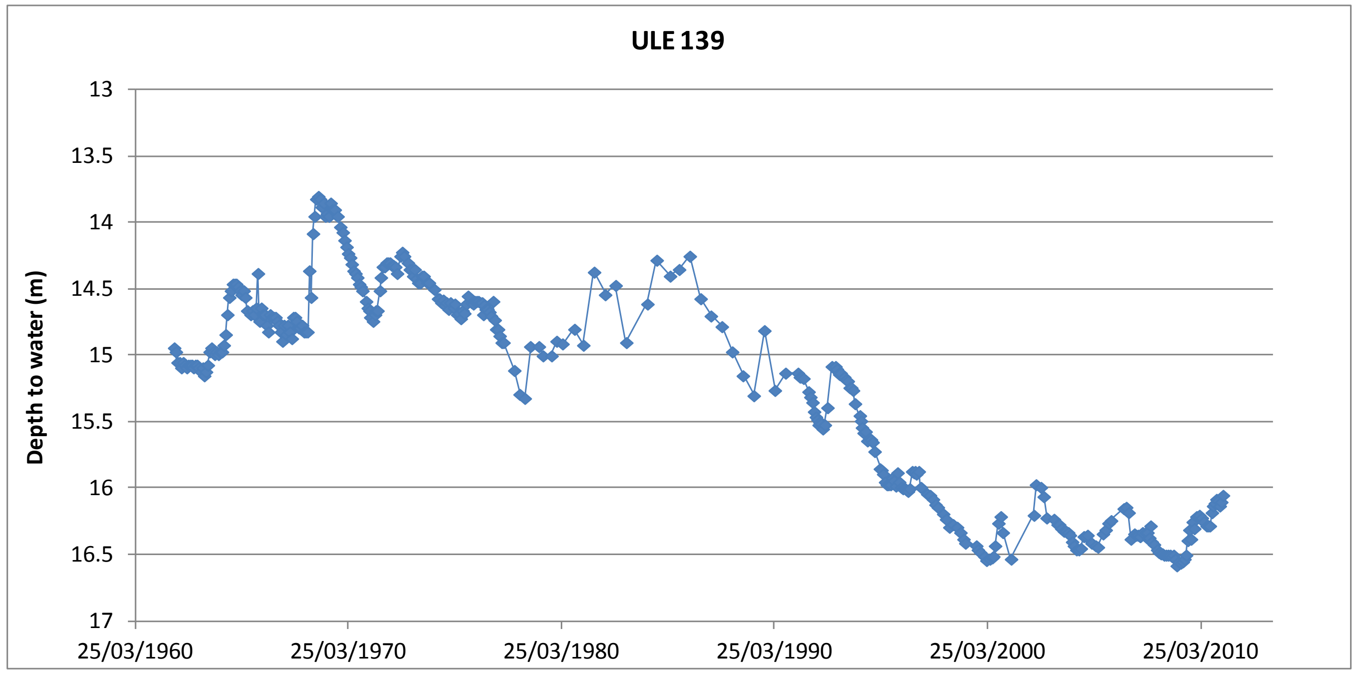


Figure 73. Observed groundwater levels in Obswell ULE139

Figure 74 shows the relationship between estimated recharge (from Obswell ULE139) and modelled recharge. The modelled annual recharge is consistently greater than the estimated recharge rates, as discussed in Section 3.3.1, however a good correlation is still observed (r^2 = 0.61). The average annual modelled recharge rate is 153 mm/y, which is in good agreement with the currently adopted annual recharge value for Uley South of 155 mm/y. Input weather data for the model were taken from Port Lincoln (Westmere, BoM station # 18137)

The percent deviation plot (Fig. 75) shows a good agreement between the sensitivity of modelled and estimated annual recharge to variations in annual rainfall, suggesting that the model can be considered to provide a good representation of the changes in recharge in response to changes in rainfall and is useful to assess the potential impacts of climate change on recharge in areas with this location's combination of climate and B3 soil type.

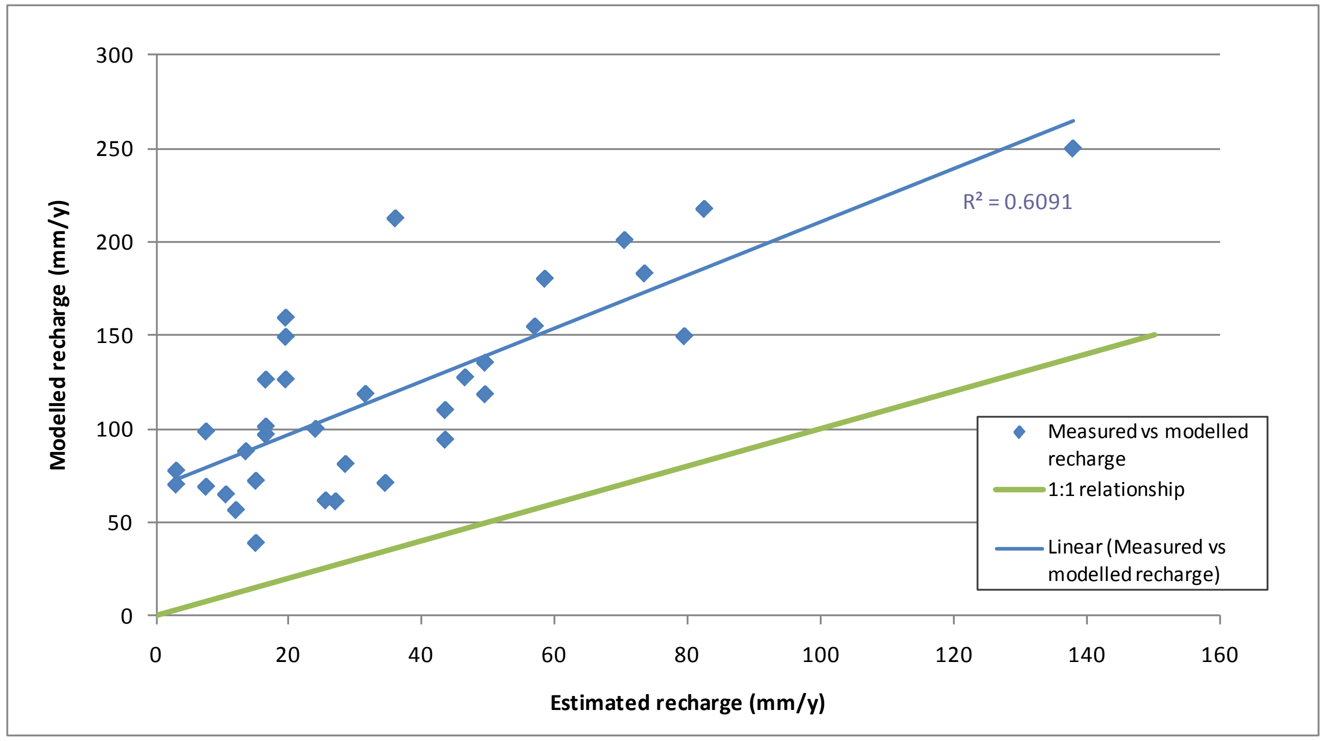


Figure 74. LEACHM modelled recharge for soil B3 versus estimated recharge for Obswell ULE139

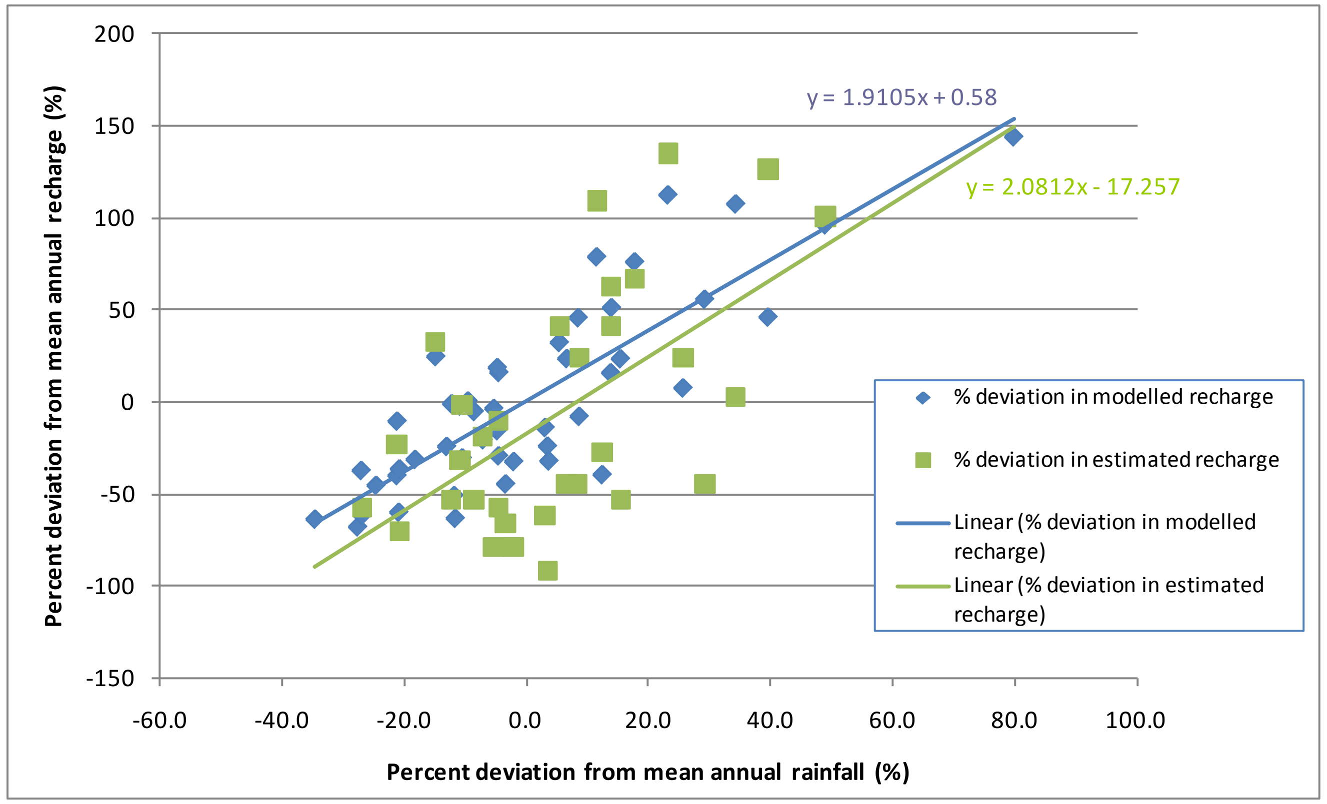


Figure 75. Modelled percent deviation in mean annual recharge and estimated percent deviation in mean annual recharge versus percent deviation in mean annual rainfall

Soil B3 – Shallow sandy loam on calcrete (continued)
Lincoln-A – SLE047

Observation well SLE047 was used as the second example which the model for soil type B3 was compared to SLE047 is located in the Lincoln-A groundwater lens and input weather data for the model were taken from Port Lincoln (Westmere) (BoM station # 18137). Figure 76 shows the groundwater level record from SLE047.

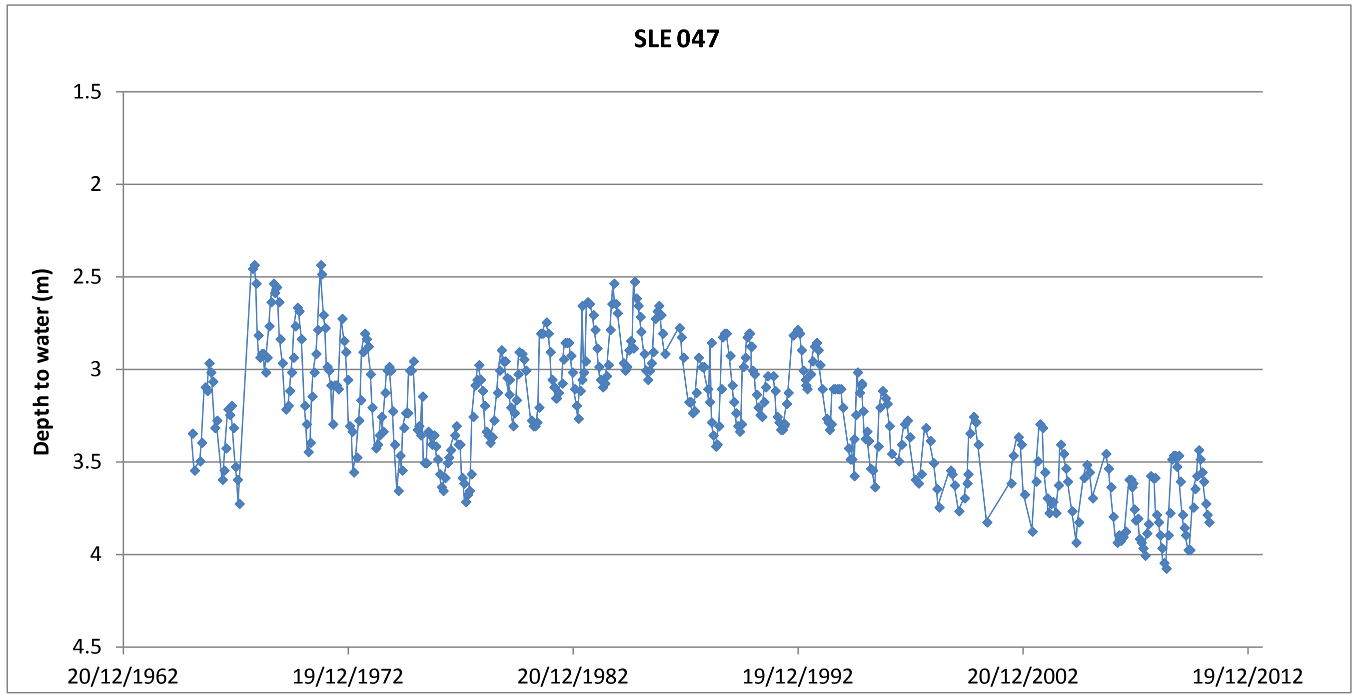


Figure 76. Observed groundwater levels in Obswell SLE047

Figure 77 shows the relationship between estimated recharge (from Obswell SLE047) and modelled recharge. The modelled recharge is generally greater than the estimated recharge, as discussed in Section 3.3.1.

Figure 78 plots percentage deviations from average values of modelled recharge and estimated recharge against deviations from mean annual rainfall for each year of a 50-year simulation. The close similarity between the slopes of the trend lines of the modelled and estimated annual recharge values here indicates that the annual recharge totals predicted by the model have a sensitivity to changes in rainfall that is very similar to that indicated by the variation of the estimated recharge rates against rainfall variations. This confirms the model can is a useful tool to assess the potential impacts of climate change on recharge with this location's combination of climate and B3 soil type.

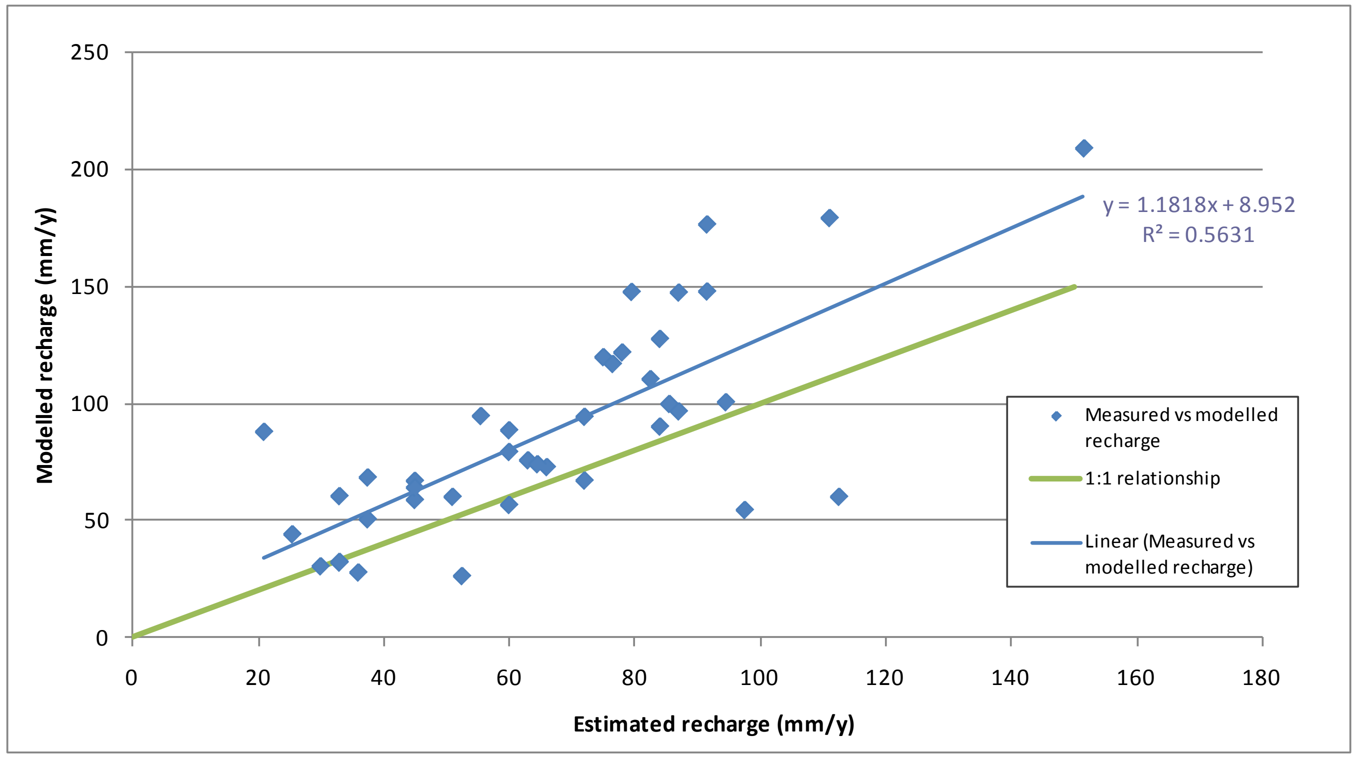


Figure 77. LEACHM modelled recharge for soil B3 versus estimated recharge for Obswell SLE047

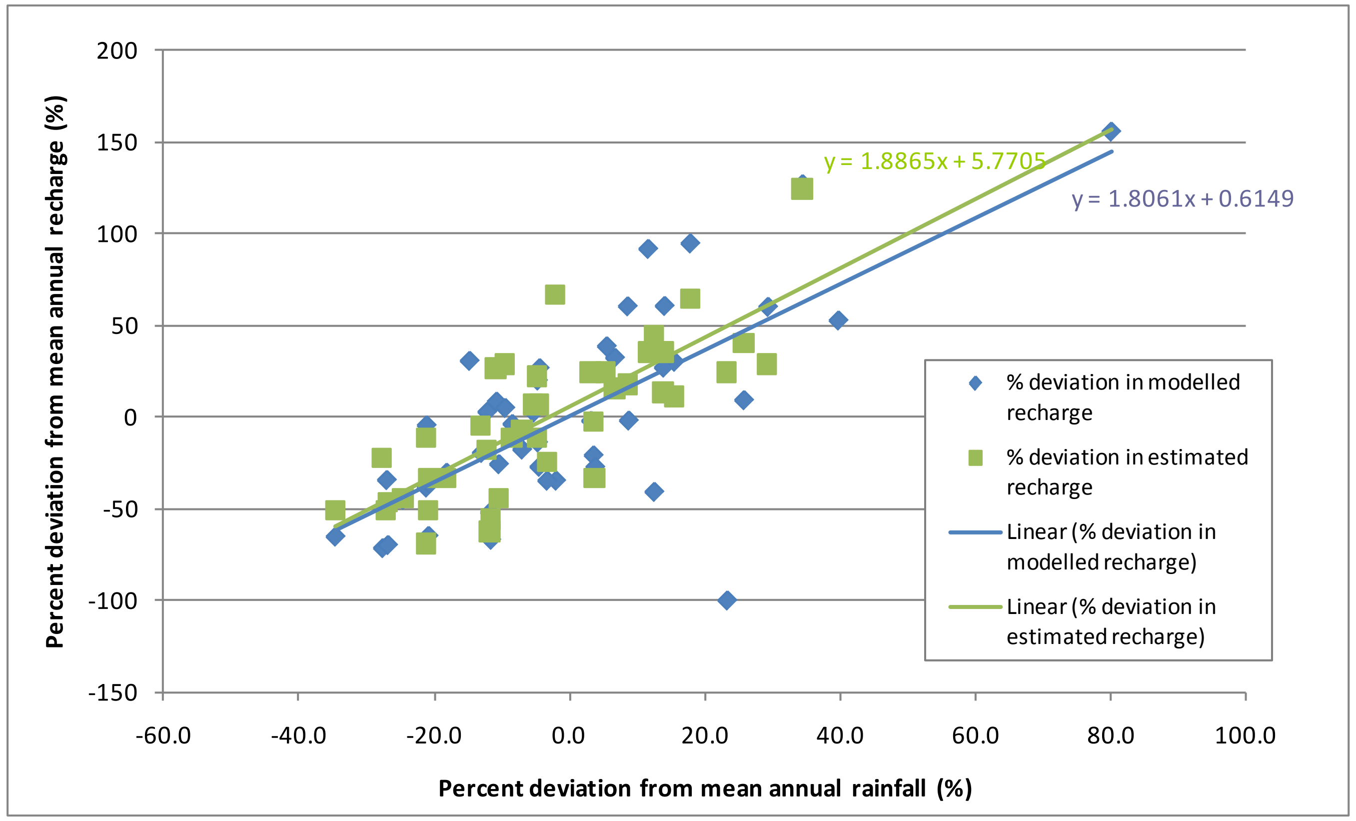


Figure 78. Modelled percent deviation in mean annual recharge and estimated percent deviation in mean annual recharge versus percent deviation in mean annual rainfall

Soil B3 – Shallow sandy loam on calcrete (continued)
Polda – SQR088

The model for soil type B3 was lastly tested for the Polda groundwater lens. Figure 79 shows the record of water table fluctuations for Obswell SQR088, located within the Polda modelled recharge area. There is a gap in the data between 1982 and 1993, however sufficient data exists to test the performance of the model in a relatively 'wet' climatic period (1963–1982) and a relatively 'dry' climatic period (1993–2010). Input weather data were taken from the Polda weather station (BoM station #18139).

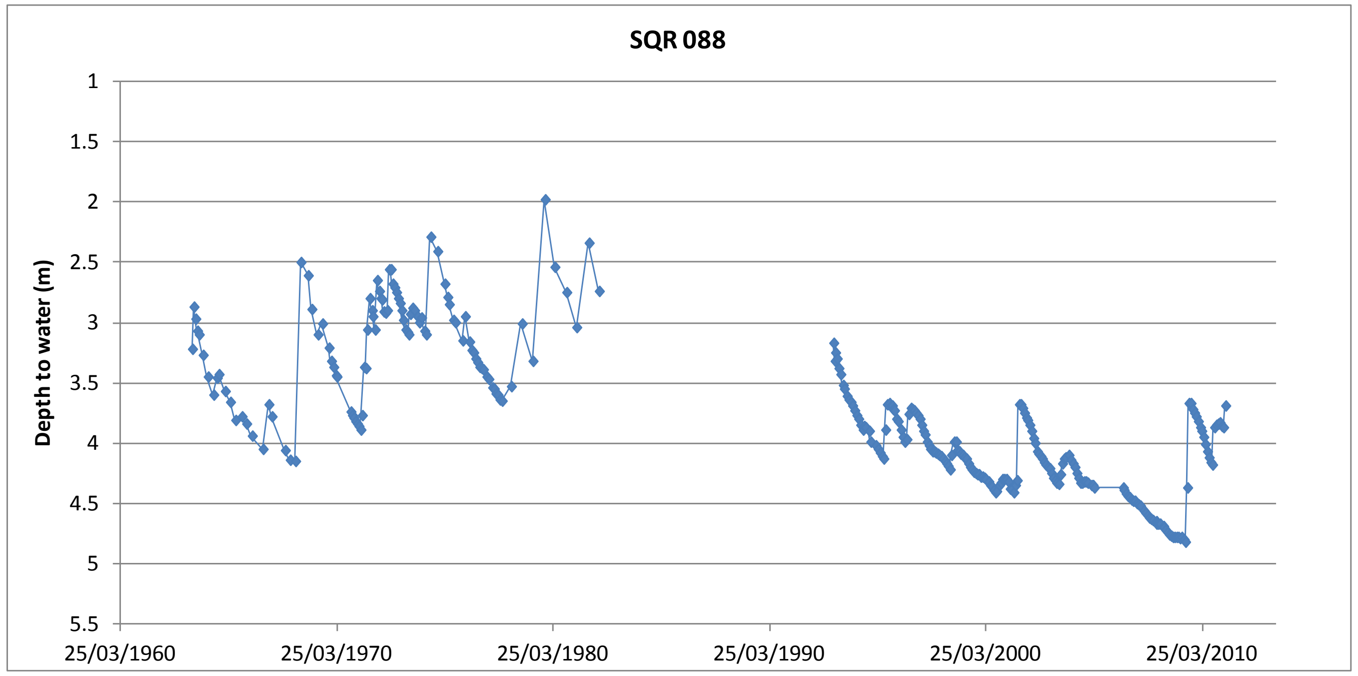


Figure 79. Observed groundwater levels in Obswell SQR088

Figure 80 shows the relationship between estimated recharge (from Obswell SQR088) and modelled recharge for the model B3 soil type and the Polda weather data for a total of 38 simulated years. There is a good correlation between the two (r^2 = 0.75), however the modelled rates of recharge are generally higher than the estimated recharge rates. The average annual modelled recharge is 50 mm/y, which is higher than the adopted rate of 28 mm/y for the Polda groundwater lens (and the rate of 39 mm/y determined for SQR088 using the watertable fluctuation method). However, in view of the performance of the modelled B3 soil type in other parts of the Eyre Peninsula and the trend plot in Figure 81, this difference is considered acceptable.

Figure 81 plots deviations from average values of annual rainfall and average modelled recharge and estimated recharge. The plot shows that the LEACHM model replicates the change in recharge with changes in rainfall very accurately. Again, given the assumptions made and the performance of the model in other areas of the Eyre Peninsula, it can be considered to simulate the changes in recharge in response to changes in rainfall reasonably well and is therefore a useful tool to assess the potential impacts of climate change on recharge in the region.

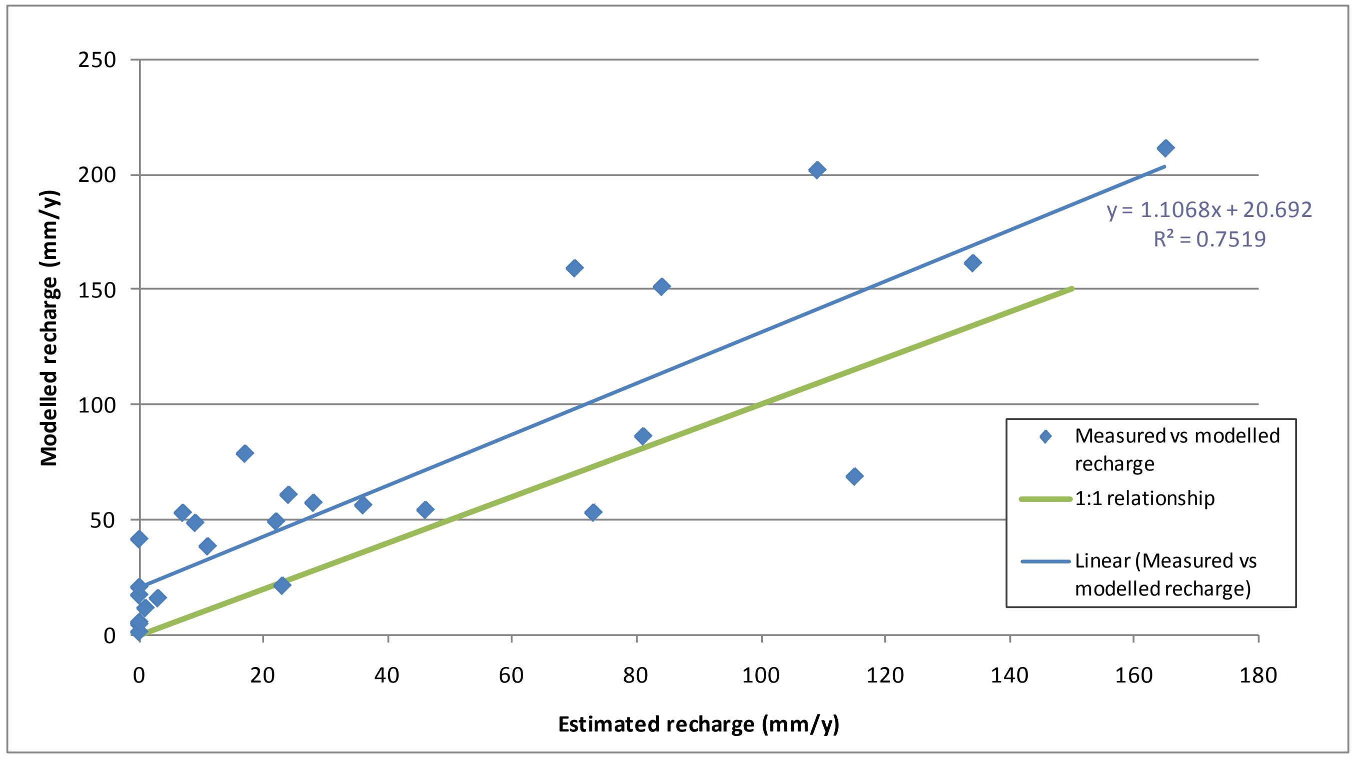


Figure 80. LEACHM modelled recharge for soil B3 versus estimated recharge for Obswell SQR088

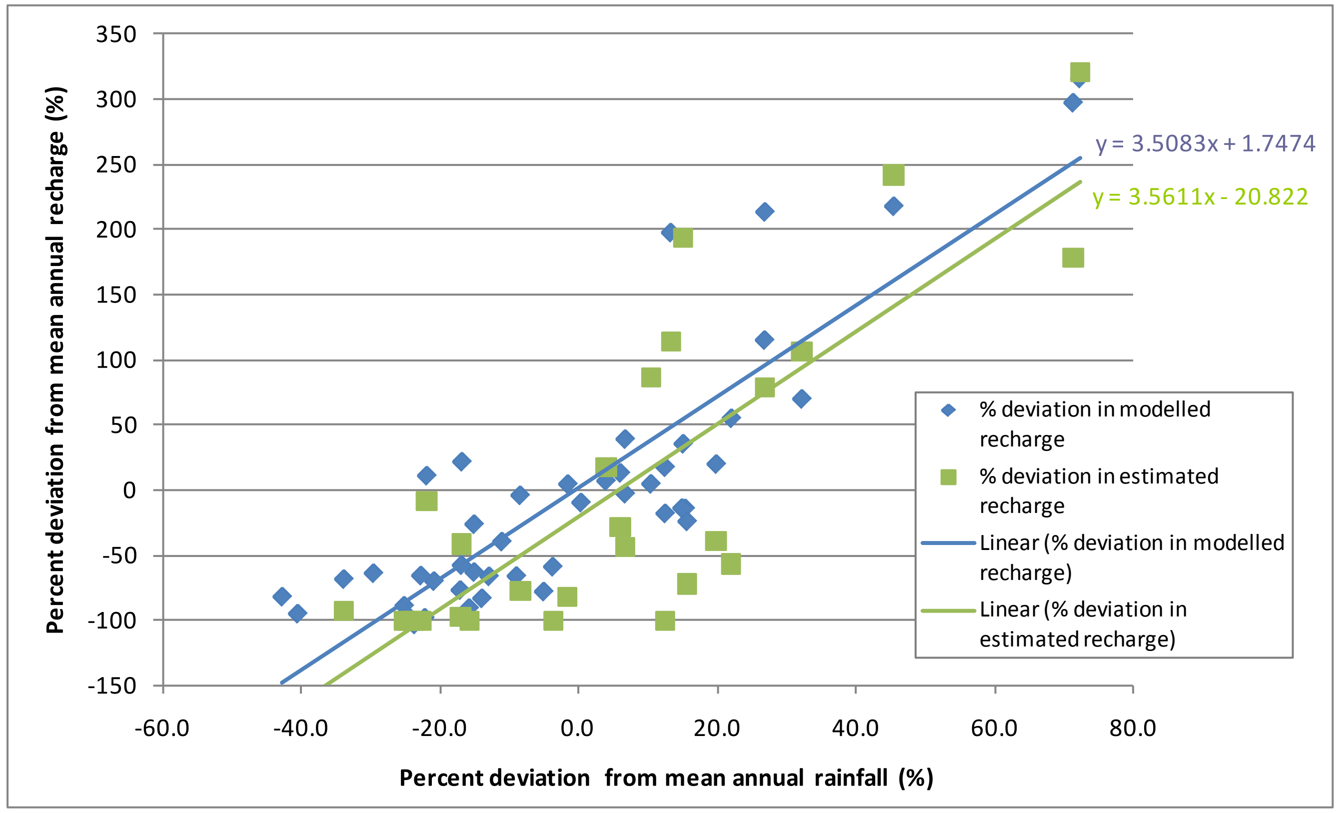


Figure 81. Modelled percent deviation in mean annual recharge and estimated percent deviation in mean annual recharge versus percent deviation in mean annual rainfall

Soil H1 – Carbonate sand

Soil type H1 is typical of coastal sand dune areas and is prevalent along the western edge of the Southern Basins PWA (including the western boundary of the Uley South modelled recharge area) and the coastal margin of the Musgrave PWA. This soil type is described as having low clay and allowing very high drainage, resulting in low fertility (DWLBC, 2007). Unfortunately, no observation wells with sufficient monitoring data could be identified in an area dominated by this soil type. A model was nevertheless constructed, using typical soil hydrologic parameters for a fine sandy soil. This was run with two alternative land cover descriptions—one with crop coverage and one with no crop coverage, to represent the significant area of bare sand dune observed in the Southern Basins PWA. Input weather data for the model were taken from Port Lincoln (Westmere) (BoM station # 18137).

Figure 82 plots the relationship between percent deviation from mean modelled recharge and percent deviation from mean annual rainfall, for the model with simulated crop cover, for each year of a 50-year simulation. The trend line slope value of 2.3 is within with the range of the models of other soil types in the region (slopes varying from 1–3.5). Also, the modelled average annual recharge rate of 152 mm/y is in good agreement with the adopted value for Uley South of 155 mm/y. The model does differ from other soil types in that no runoff is simulated—the modelled soil parameters are sufficiently permeable to allow enough infiltration to stop runoff occurring.

Figure 83 plots the results of the same soil type model, but with no plant cover (i.e. bare sand). Again, the slope of the percent deviation line is within the range of the other soil type models. Also, the average annual recharge rate is 196 mm/y, which seems realistic for this soil type and environment. In the absence of data to perform a more rigorous calibration, the model has been be considered to sufficiently represent the annual variation of recharge with annual variations in rainfall to assess the potential impacts of climate change on recharge in the region.

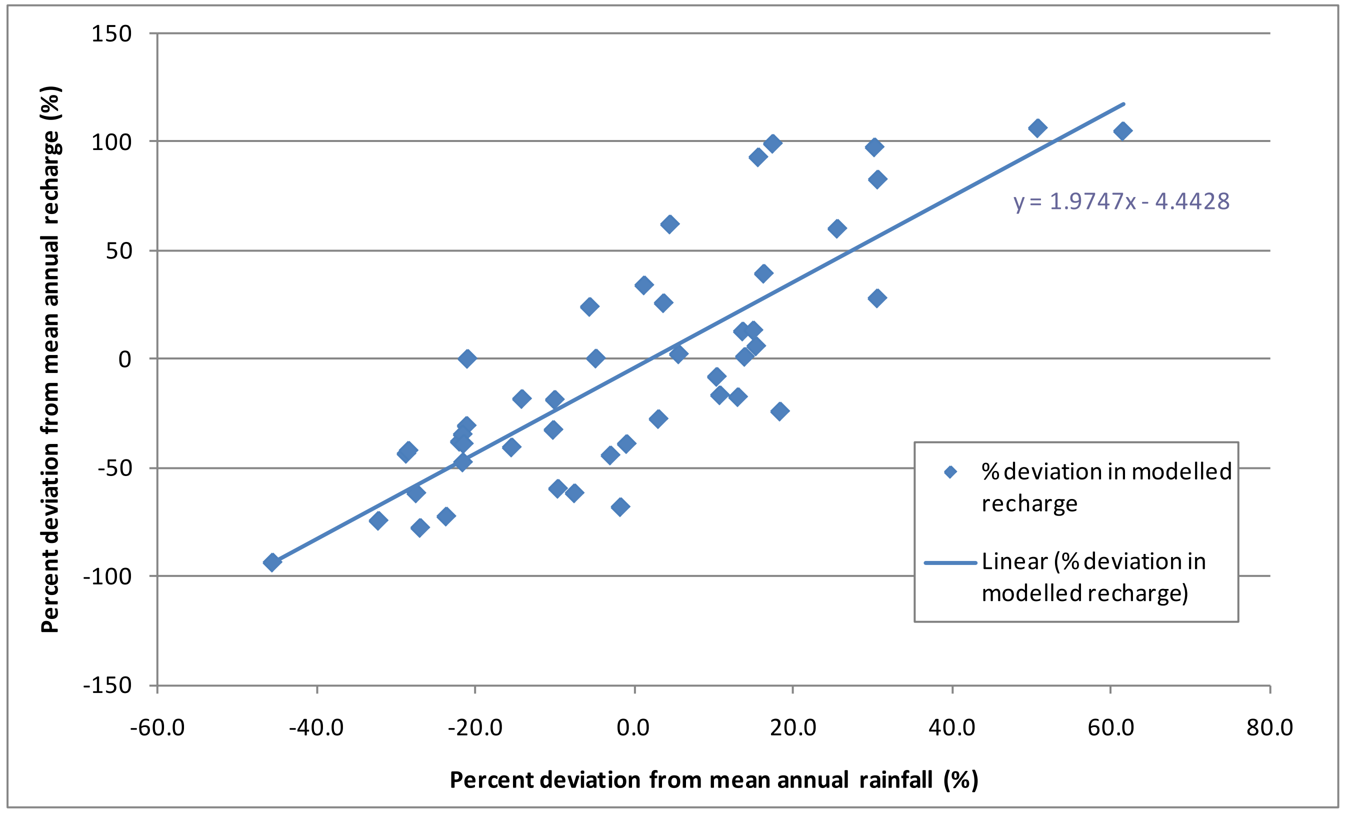


Figure 82. Modelled percent deviation in mean annual recharge versus percent deviation in mean annual rainfall for the H1 model with crop coverage

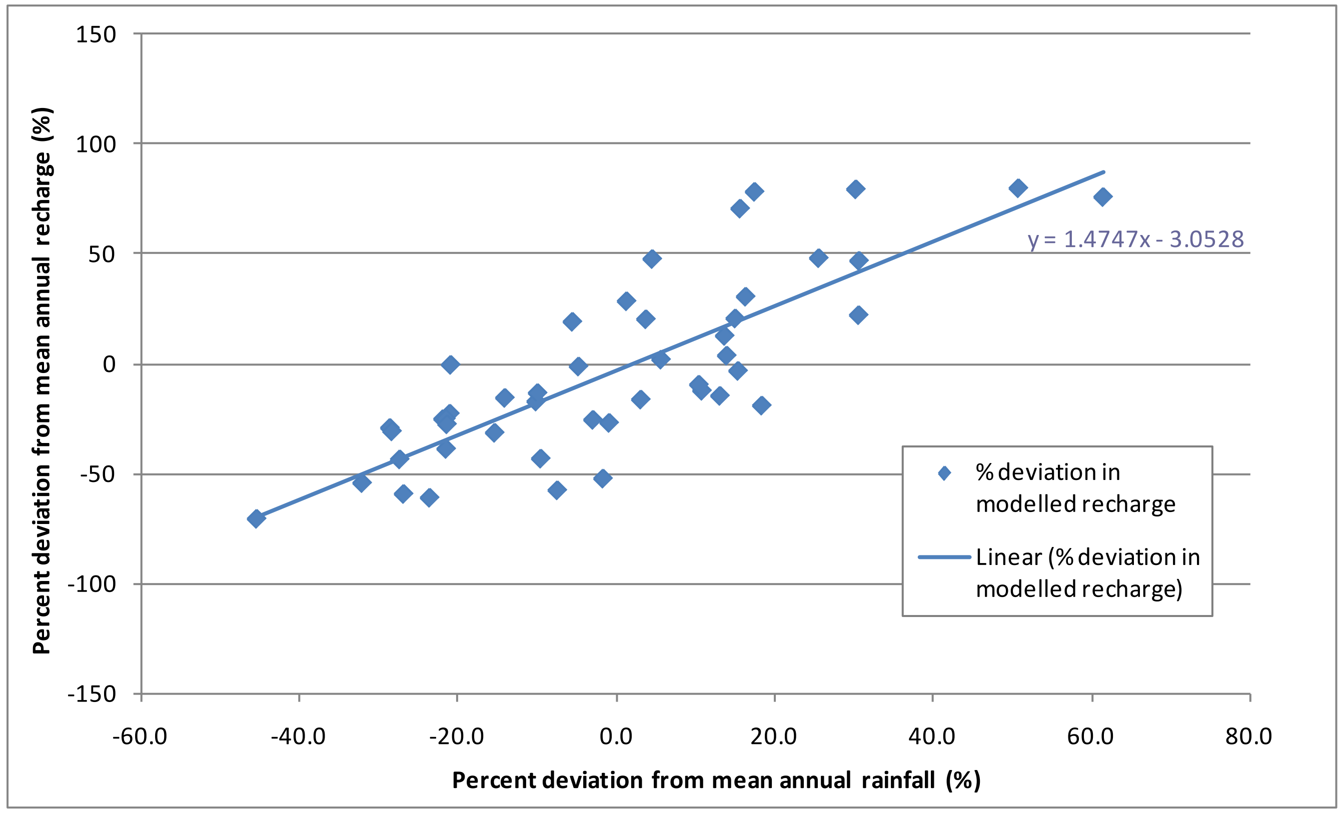


Figure 83. Modelled percent deviation in mean annual recharge versus percent deviation in mean annual rainfall for the H1 model with no crop cover (i.e. bare carbonate sand surface)

Soil N2 – Saline soil

Uley South – ULE101

Soil type N2 occurs primarily within the Uley South modelled recharge area. It is described as a clayey saline soil overlying sheet calcrete and is therefore similar to the B1–B3 soil types, but with poorer drainage properties (DWLBC, 2007). Observation well ULE101 within the Uley South modelled recharge area was identified as having a suitable record with which to calibrate the model of this soil type. Weather data for the model were taken from the Port Lincoln (Westmere) weather station (BoM 18137). Figure 84 shows the record of water table fluctuations for Obswell ULE101.

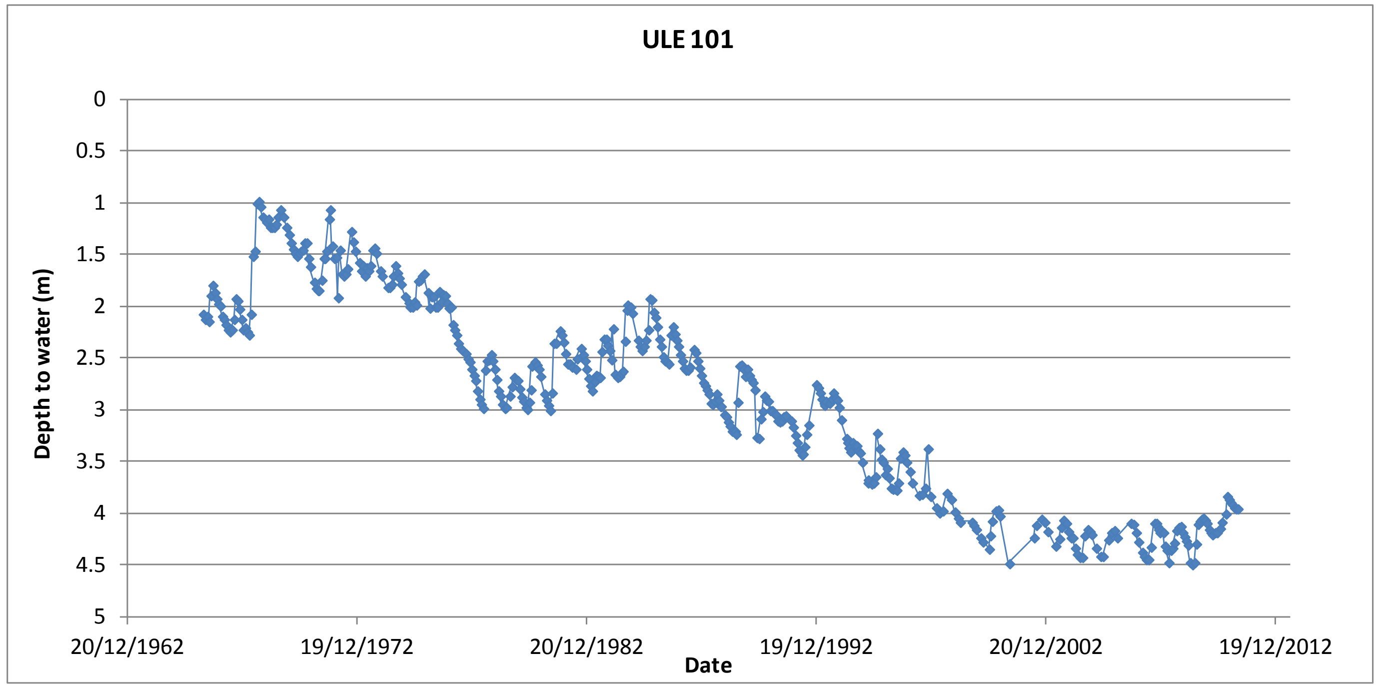


Figure 84. Observed groundwater levels in Obswell ULE101

Figure 85 shows the relationship between estimated recharge (from Obswell ULE101) and modelled recharge. There is some correlation between the two (r^2 = 0.57), however the modelled rates of recharge are generally slightly higher than the estimated recharge rates. The average annual modelled recharge rate is 57 mm/y, which is in good agreement with the average annual rate estimated from ULE101 of 52 mm/y.

Figure 86 plots percentage deviations from average values of modelled recharge and estimated recharge against deviations from mean annual rainfall for each year of a 50-year simulation. The close similarity between the slopes of the trend lines of the modelled and estimated annual recharge values here indicates that the annual recharge totals predicted by the model have a sensitivity to changes in rainfall that is very similar to that indicated by the variation of the estimated recharge rates against rainfall variations. This confirms the model can be a useful tool to assess the potential impacts of climate change on recharge with this location's combination of climate and N2 soil type.

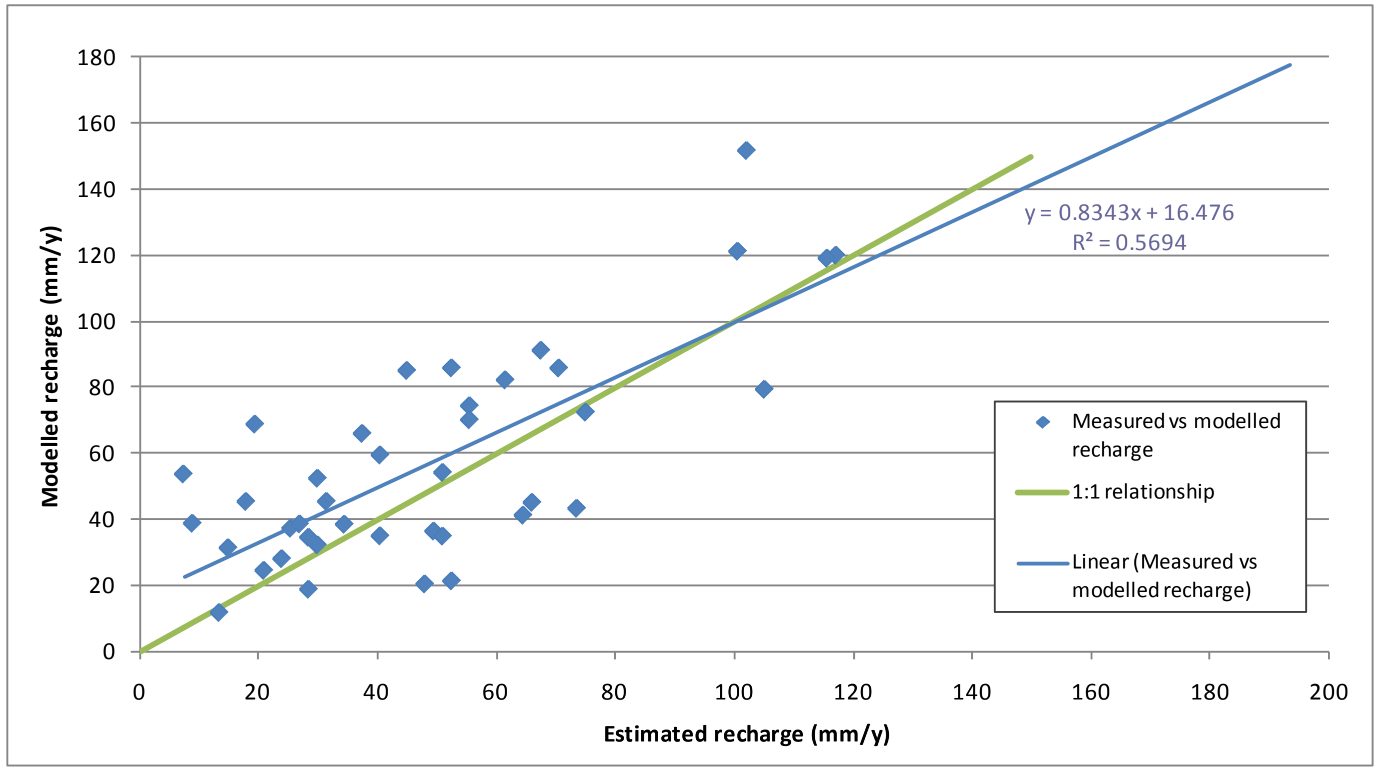


Figure 85. LEACHM modelled recharge for soil B3 versus estimated recharge for Obswell ULE101

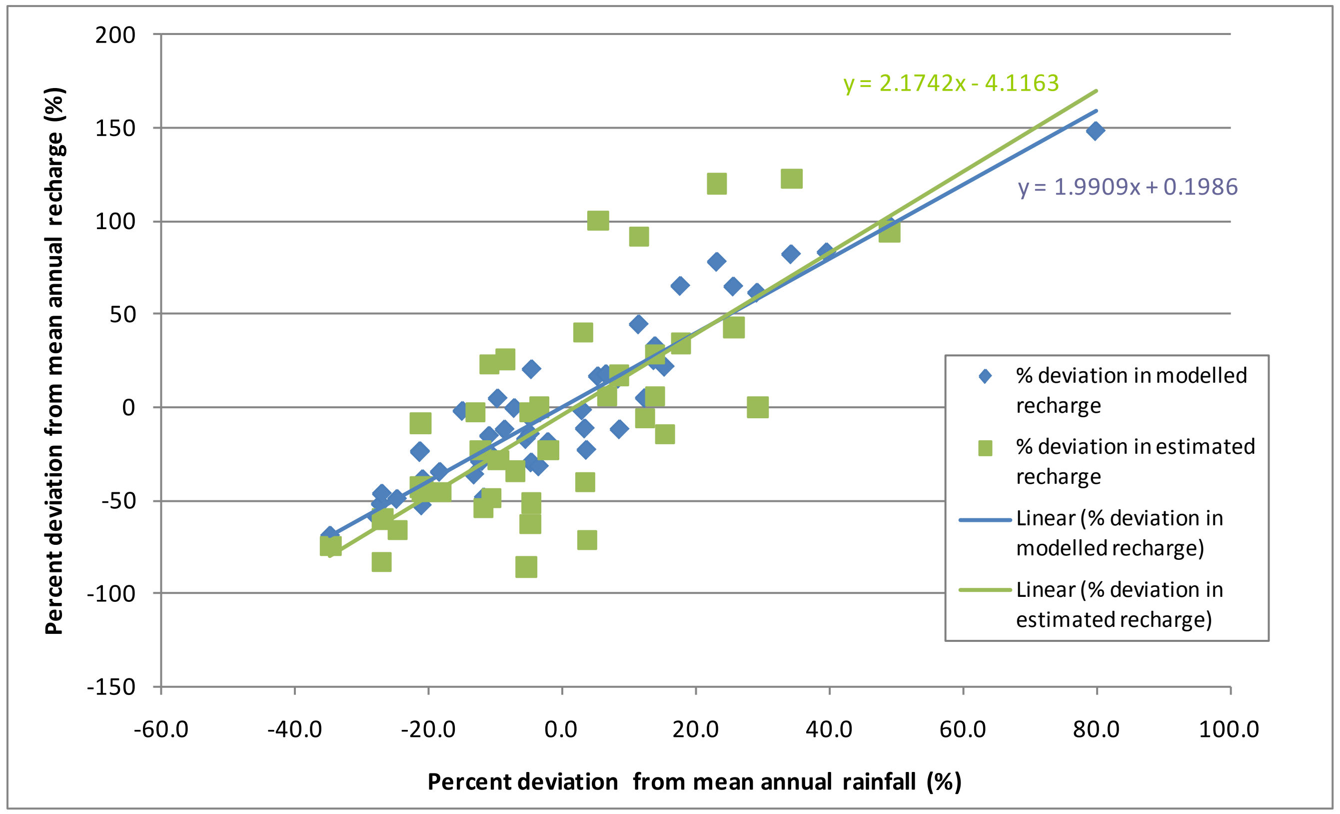


Figure 86. Modelled percent deviation in mean annual recharge and estimated percent deviation in mean annual recharge versus percent deviation in mean annual rainfall

B. TOD RESERVOIR RESULTS – WITH 10% DIVERSION

The results presented in this section represent the scenario where 10% of the flow passing the diversion points on the Upper Tod River and Pillaworta Creek is diverted to the Tod Reservoir. In comparison, the results presented in Section 4.3 include only the natural catchment for the reservoir. The figures align with those presented in Section 4.3, where the annual change in median annual runoff for each climate projection considered is presented Figure 87, followed by tables summarising the changes in climate, runoff and storage for each climate projection, the annual variability in the runoff for projections produced by the NCAR-CCSM3 GCM and finally the relationship between the percentage change in runoff for a given percentage change in both winter and annual rainfall. As larger volumes are diverted to the reservoir, the runoff volumes presented in this Appendix are higher than in Section 4.3, however similar reductions in runoff were found for this scenario compared to the no diversion case presented in Section 4.3 for each climate projection considered.

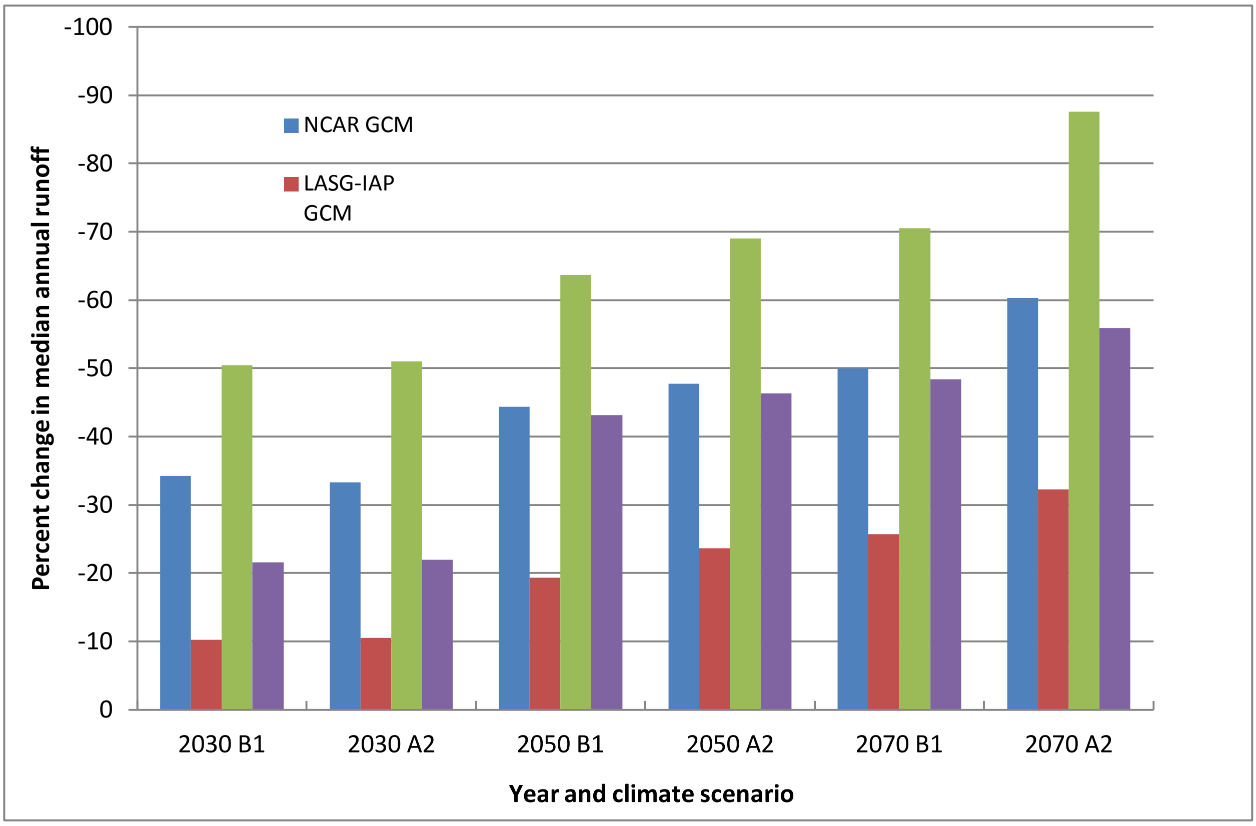


Figure 87. Estimated changes in median annual runoff for runoff to the Tod Reservoir (0.1 diversion)

Table 29. Changes in climate and runoff simulated for Tod Reservoir using input data generated using the LASG-IAP GCM

	1990	2030		2050		2070	
		B1	**A2**	**B1**	**A2**	**B1**	**A2**
Average Annual Rainfall (mm)	506	498	497	494	490	490	482
Average Winter Rainfall (mm)	228	225	225	224	223	223	220
Average Annual PET (mm)	1121	1146	1150	1158	1164	1164	1185
Average Winter PET (mm)	132	135	135	141	141	141	144
Change in Annual Rainfall (%)		-2	-2	-2	-3	-3	-5
Change in Winter Rainfall (%)		-1	-1	-2	-2	-2	-3
Change in Annual PET (%)		2	3	3	4	4	6
Change in Winter PET (%)		2	2	7	7	7	9
Current Farm Dam Storage							
Median Annual Runoff (ML)	2303	2067	2061	1857	1758	1711	1559
Change in Median Runoff (%)		-10	-11	-19	-24	-26	-32
Average Annual Storage (ML)	170	166	165	163	161	161	158
Change in Annual Storage (%)		-2	-3	-4	-5	-5	-7
Low Events							
20th Percentile Runoff (ML)	958	903	876	815	792	790	755
Years Below 1990 20th %	10	12	14	16	16	16	18
High Events							
80th Percentile Runoff (ML)	4638	4286	4171	3943	3813	3825	3493
Years Above 1990 80th %	10	9	9	9	9	9	9
Maximum Farm Dam Storage							
Median Annual Runoff (ML)	2184	1944	1937	1709	1555	1577	1395
Change in Median Runoff (%)		-11	-11	-22	-29	-28	-36
Average Annual Storage (ML)	320	312	308	302	297	298	288
Change in Annual Storage (%)		-2	-4	-6	-7	-7	-10
Low Events							
20th Percentile Runoff (ML)	890	832	819	774	758	757	715
Years Below 1990 20th %	10	12	15	16	16	16	18
High Events							
80th Percentile Runoff (ML)	4514	4166	4053	3826	3696	3707	3373
Years Above 1990 80th %	10	9	9	9	9	9	9

Table 30. Changes in climate and runoff simulated for Tod Reservoir using input data generated using the NCAR-CCSM3 GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	506	484	483	474	465	464	443
Average Winter Rainfall (mm)	228	217	216	212	207	207	196
Average Annual PET (mm)	1121	1156	1158	1158	1164	1164	1194
Average Winter PET (mm)	132	139	141	141	141	141	150
Change in Annual Rainfall (%)		-4	-5	-6	-8	-8	-13
Change in Winter Rainfall (%)		-5	-5	-7	-9	-9	-14
Change in Annual PET (%)		3	3	3	4	4	7
Change in Winter PET (%)		6	7	7	7	7	14
Current Farm Dam Storage							
Median Annual Runoff (ML)	2303	1515	1536	1281	1204	1152	915
Change in Median Runoff (%)		-34	-33	-44	-48	-50	-60
Average Annual Storage (ML)	170	162	160	157	154	153	138
Change in Annual Storage (%)		-4	-6	-7	-9	-10	-19
Low Events							
20th Percentile Runoff (ML)	958	768	744	708	647	659	515
Years Below 1990 20th %	10	16	17	18	19	19	27
High Events							
80th Percentile Runoff (ML)	4638	3999	3743	3450	3407	3102	2570
Years Above 1990 80th %	10	9	8	6	4	4	4
Maximum Farm Dam Storage							
Median Annual Runoff (ML)	2184	1393	1417	1170	1092	1035	812
Change in Median Runoff (%)		-36	-35	-46	-50	-53	-63
Average Annual Storage (ML)	320	295	292	284	275	272	235
Change in Annual Storage (%)		-8	-9	-11	-14	-15	-26
Low Events							
20th Percentile Runoff (ML)	890	726	711	672	617	624	480
Years Below 1990 20th %	10	17	17	18	18	19	29
High Events							
80th Percentile Runoff (ML)	4514	3876	3623	3326	3288	2982	2415
Years Above 1990 80th %	10	9	8	5	4	4	4

Table 31. Changes in climate and runoff simulated for Tod Reservoir using input data generated using the MRI GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	506	489	489	481	474	474	457
Average Winter Rainfall (mm)	228	216	215	210	205	205	192
Average Annual PET (mm)	1121	1134	1135	1152	1161	1161	1179
Average Winter PET (mm)	132	132	132	141	141	141	141
Change in Annual Rainfall (%)		-3	-3	-5	-6	-6	-10
Change in Winter Rainfall (%)		-5	-6	-8	-10	-10	-16
Change in Annual PET (%)		1	1	3	4	4	5
Change in Winter PET (%)		0	0	7	7	7	7
Current Farm Dam Storage							
Median Annual Runoff (ML)	2303	1807	1798	1309	1235	1189	1016
Change in Median Runoff (%)		-22	-22	-43	-46	-48	-56
Average Annual Storage (ML)	170	165	165	159	156	155	147
Change in Annual Storage (%)		-3	-3	-6	-8	-8	-13
Low Events							
20th Percentile Runoff (ML)	958	842	826	718	663	664	589
Years Below 1990 20th %	10	15	15	17	19	19	23
High Events							
80th Percentile Runoff (ML)	4638	4117	4108	3428	3248	3249	2691
Years Above 1990 80th %	10	9	9	6	6	5	4
Maximum Farm Dam Storage							
Median Annual Runoff (ML)	2184	1682	1674	1204	1127	1091	934
Change in Median Runoff (%)		-23	-23	-45	-48	-50	-57
Average Annual Storage (ML)	320	306	305	288	280	278	255
Change in Annual Storage (%)		-4	-5	-10	-12	-13	-20
Low Events							
20th Percentile Runoff (ML)	890	786	777	688	627	627	550
Years Below 1990 20th %	10	14	14	17	18	18	24
High Events							
80th Percentile Runoff (ML)	4514	3991	3982	3302	3118	3121	2556
Years Above 1990 80th %	10	9	9	6	5	5	4

Table 32. Changes in climate and runoff simulated for Tod Reservoir using input data generated using the CSIRO Mk 3.5 GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	506	464	461	441	423	420	378
Average Winter Rainfall (mm)	228	206	204	194	184	183	161
Average Annual PET (mm)	1121	1164	1164	1188	1209	1212	1258
Average Winter PET (mm)	132	141	141	147	150	150	159
Change in Annual Rainfall (%)		-8	-9	-13	-16	-17	-25
Change in Winter Rainfall (%)		-10	-11	-15	-19	-20	-30
Change in Annual PET (%)		4	4	6	8	8	12
Change in Winter PET (%)		7	7	12	14	14	21
Current Farm Dam Storage							
Median Annual Runoff (ML)	2303	1141	1127	837	713	680	286
Change in Median Runoff (%)		-50	-51	-64	-69	-70	-88
Average Annual Storage (ML)	170	152	152	137	126	123	87
Change in Annual Storage (%)		-10	-10	-19	-26	-27	-48
Low Events							
20th Percentile Runoff (ML)	958	659	638	480	362	358	128
Years Below 1990 20th %	10	20	20	30	33	34	45
High Events							
80th Percentile Runoff (ML)	4638	2883	2877	2125	1684	1783	728
Years Above 1990 80th %	10	4	4	2	0	0	0
Maximum Farm Dam Storage							
Median Annual Runoff (ML)	2184	1006	995	780	641	608	254
Change in Median Runoff (%)		-54	-54	-64	-71	-72	-88
Average Annual Storage (ML)	320	271	271	231	204	198	125
Change in Annual Storage (%)		-15	-15	-28	-36	-38	-61
Low Events							
20th Percentile Runoff (ML)	890	619	609	457	342	331	121
Years Below 1990 20th %	10	19	20	30	33	34	45
High Events							
80th Percentile Runoff (ML)	4514	2772	2754	1992	1547	1616	643
Years Above 1990 80th %	10	4	4	2	0	0	0

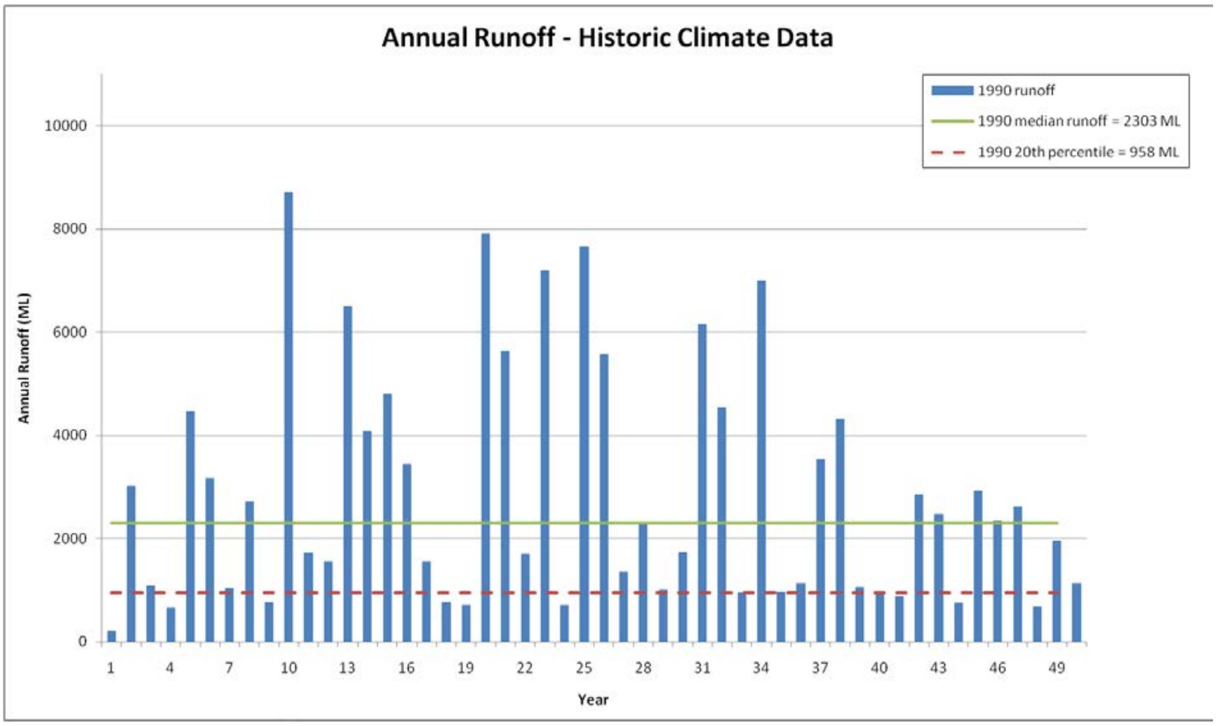


Figure 88. Annual runoff simulated over 50 years for the Tod Reservoir, based on historically measured rainfall and PET data. Year 1 on the x axis represents 1960

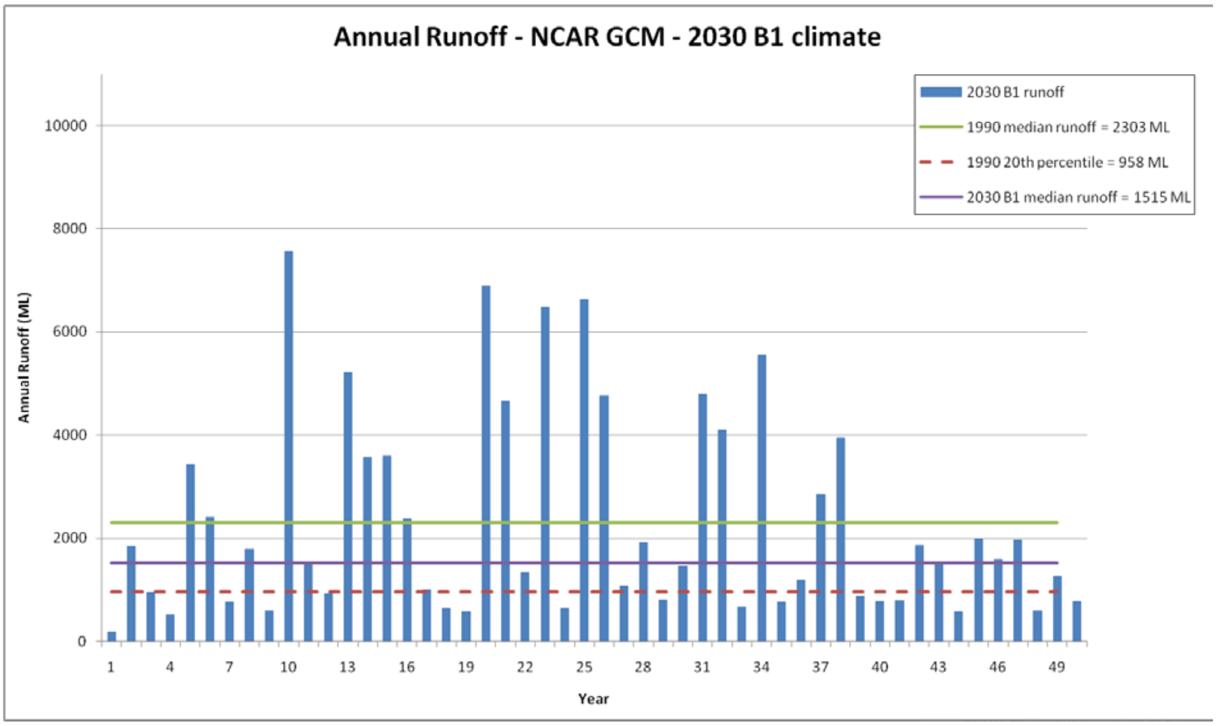


Figure 89. Annual runoff simulated for the Tod Reservoir, based on rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2030 climate and B1 emissions

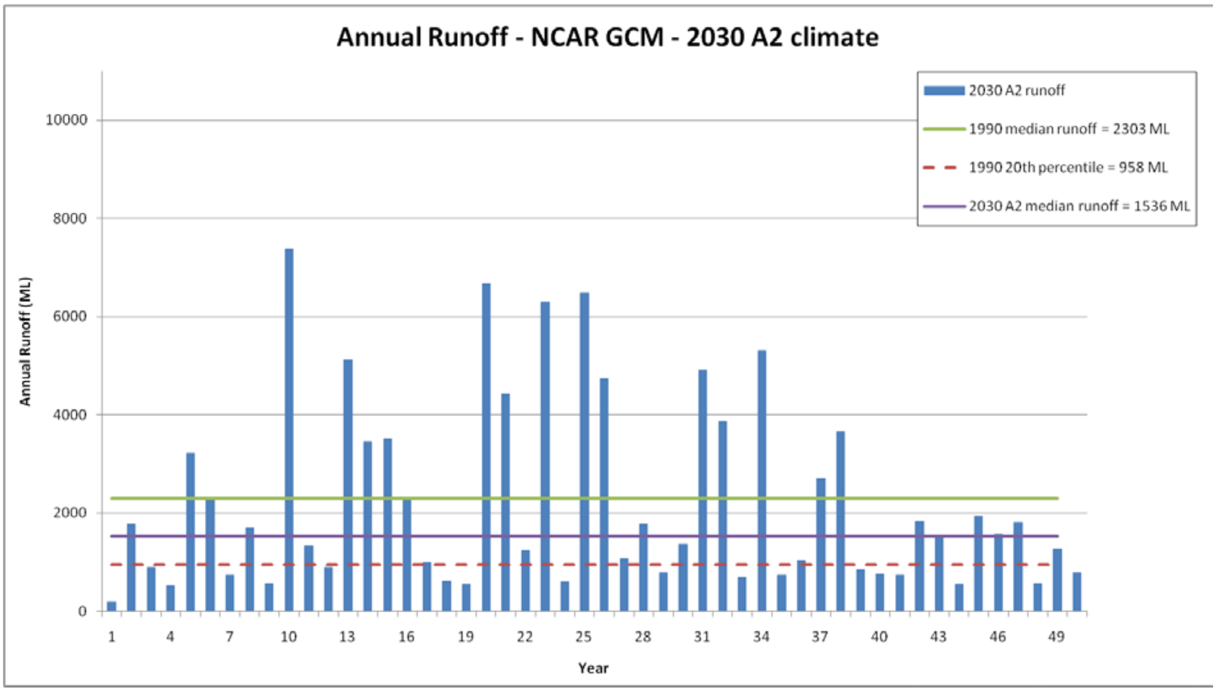


Figure 90. Annual runoff simulated for the Tod Reservoir, based on rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2030 climate and A2 emissions

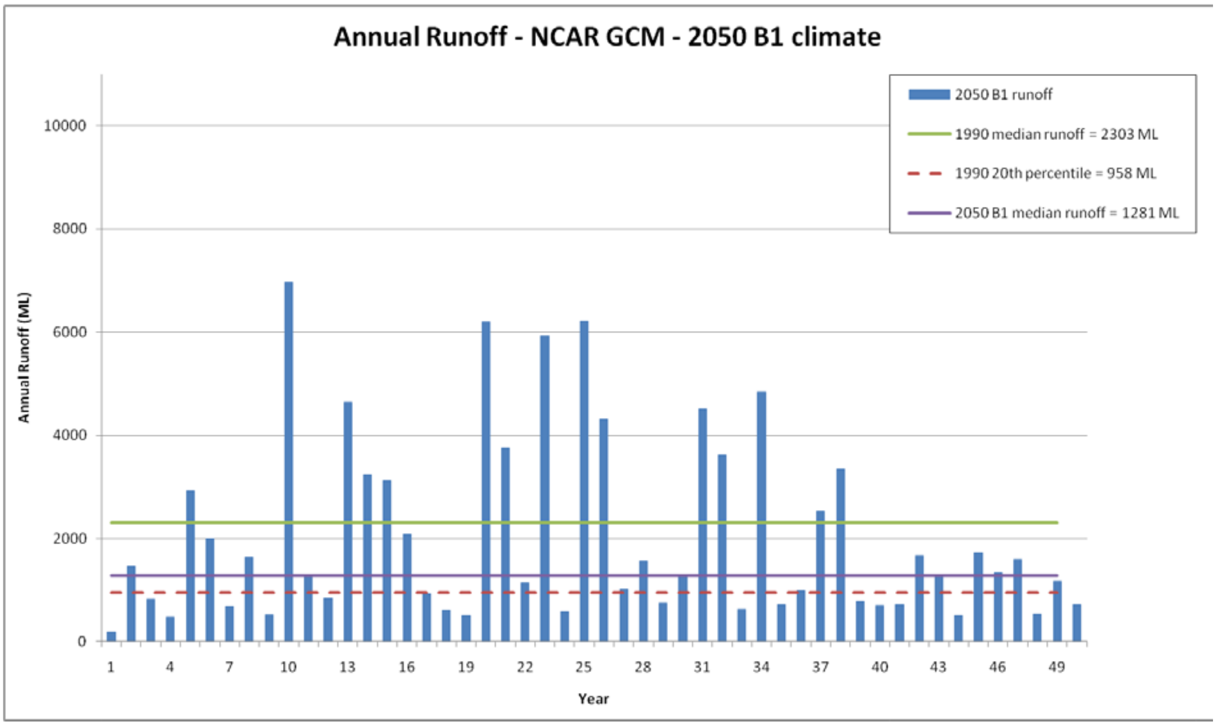


Figure 91. Annual runoff simulated for the Tod Reservoir, based on rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2050 climate and B1 emissions

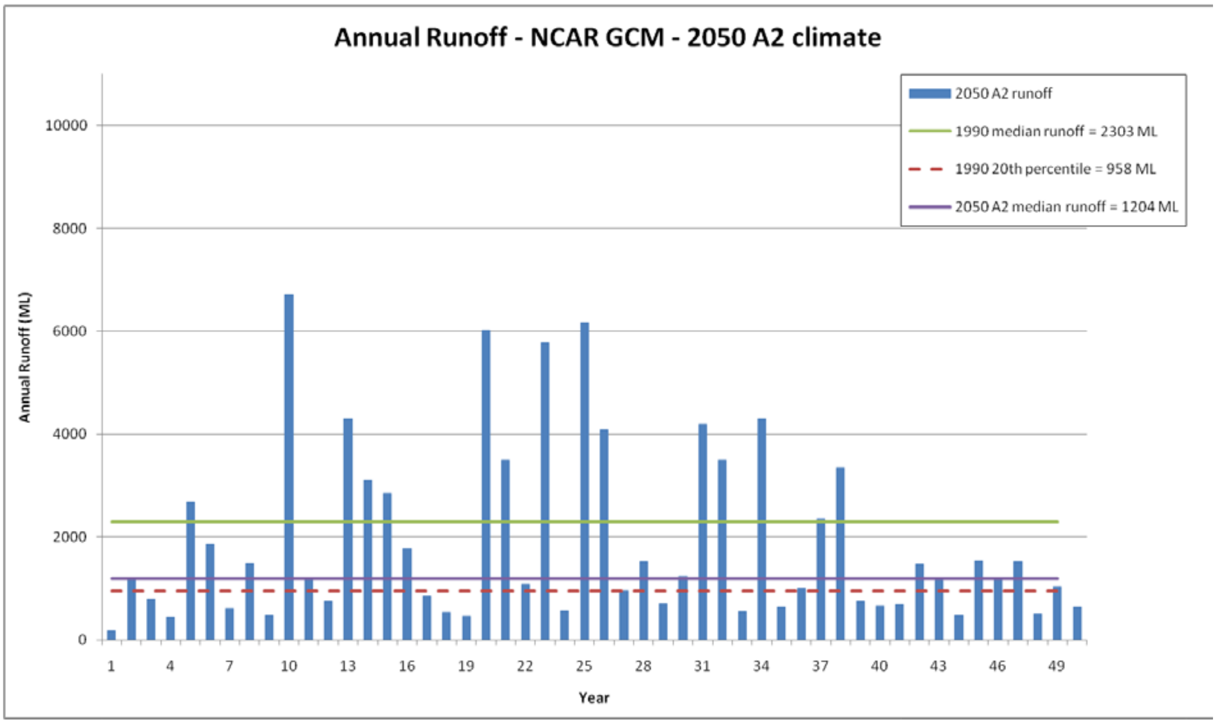


Figure 92. Annual runoff simulated for the Tod Reservoir, based on rainfall and PET input data generated by the NCAR GCM for a 2050 climate and A2 emissions

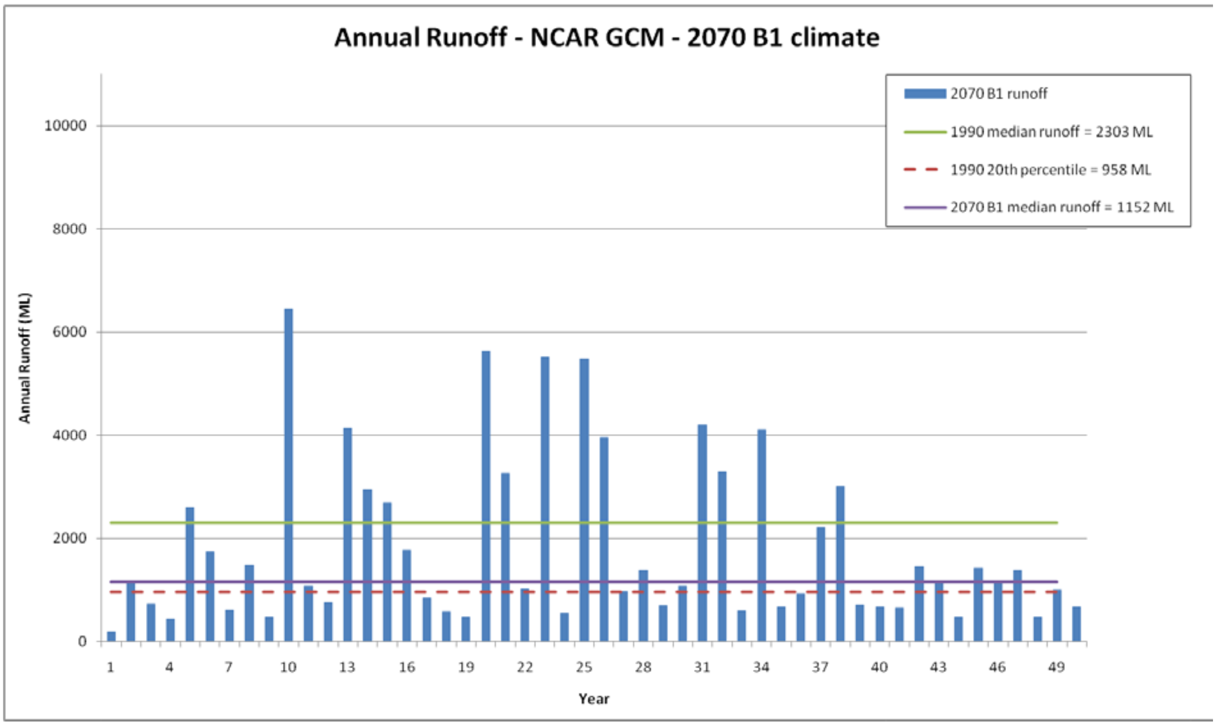


Figure 93. Annual runoff simulated for the Tod Reservoir, based on rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2070 climate and B1 emissions

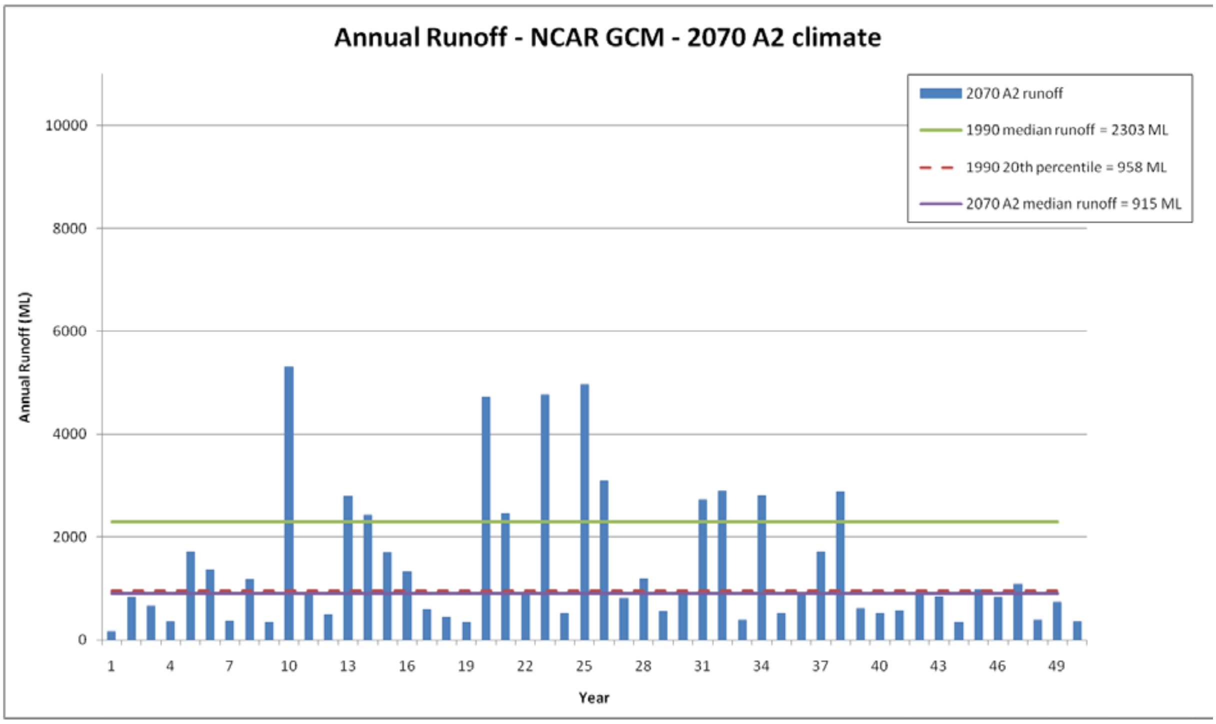


Figure 94. Annual runoff simulated for the Tod Reservoir, based on rainfall and PET input data generated by the NCAR-CCSM3 GCM for a 2070 climate and A2 emissions

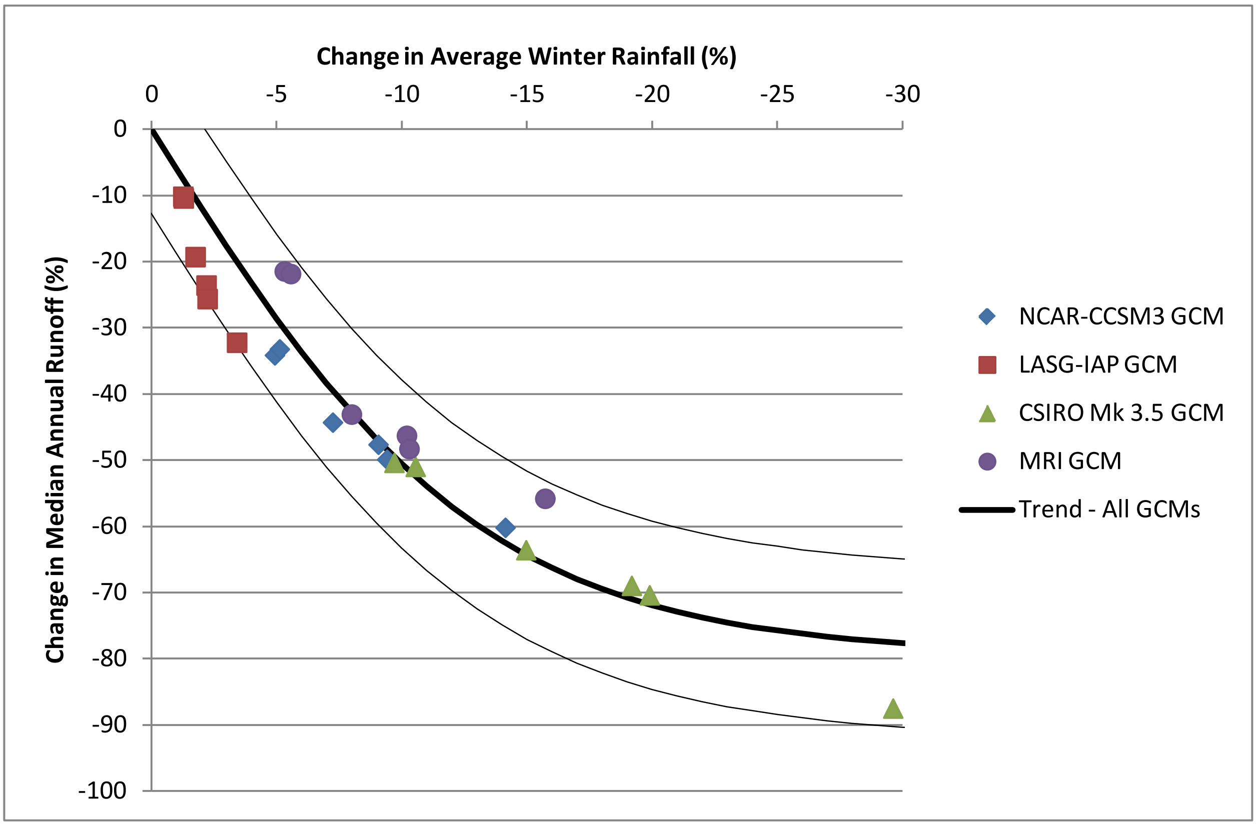


Figure 95. Changes in average winter rainfall versus changes in median annual runoff for the Tod Reservoir. Trend line is a tanh relationship, thin lines show the upper and lower 95% bounds.

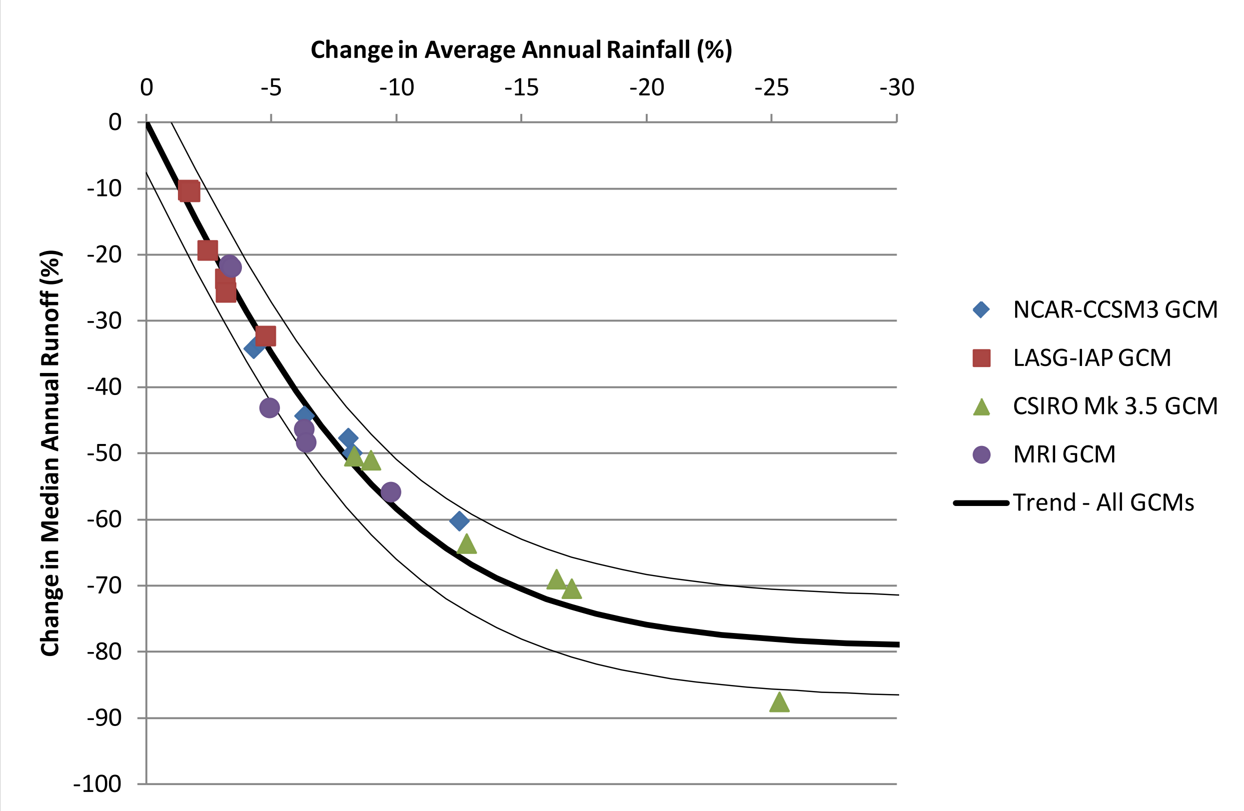


Figure 96. Changes in average annual rainfall versus changes in median annual runoff for the Tod Reservoir. Trend line is a tanh relationship, thin lines show the upper and lower 95% bounds.

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
deg	degrees
EC	electrical conductivity (µS/cm)
K	hydraulic conductivity (m/d)
pH	acidity
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

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

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)

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

EPNRMB –Eyre Peninsula Natural Resources Management Board

ERWRPC – Eyre Region Water Resources Planning Committee

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

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'

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.

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

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

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

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.

WMO — World Meteorological Organisation

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