TECHNICAL REPORT

IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

PHASE 3 VOLUME 1

NORTHERN AND YORKE NATURAL RESOURCES MANAGEMENT REGION

2011/03

Government of South Australia
Department for Water

IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

PHASE 3 VOLUME 1

NORTHERN AND YORKE NATURAL RESOURCES MANAGEMENT REGION

Graham Green, Matt Gibbs and Cameron Wood

Science, Monitoring and Information Division
Department for Water

June 2011

Technical Report DFW 2011/03

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

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

ISBN 978-1-921923-11-1

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

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

FOREWORD

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

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

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

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

Scott Ashby
CHIEF EXECUTIVE
DEPARTMENT FOR WATER

ACKNOWLEDGEMENTS

The authors wish to thank a number of people for their contribution to this work. We are particularly grateful to Dr John Hutson of Flinders University, who has provided invaluable support and advice on the use and application of the LEACHM modelling software. Thanks also to Martha Augoustinos and Judy Tan for their work on the maps included in this report. We are also grateful to the members of the End User Reference group of the Impacts of Climate Change on Water Resources project, including representatives from SA Water Corporation, Department of Environment and Natural Resources, and the Policy and Urban Water Division of the Department for Water, for their comments and suggestions.

Peer reviews of this report were provided by Wei Yan and Mark Alcorn of the Department for Water and Dr Russell Crosbie of the CSIRO.

CONTENTS

CONTENTS

CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

The Department for Water's 'Impacts of Climate Change on Water Resources' (ICCWR) project has undertaken detailed hydrologic modelling in order to determine the potential impact of climate change on the prescribed surface water and groundwater resources of the Northern and Yorke Natural Resources Management Region, namely the Clare Valley Prescribed Water Resource Area (PWRA) and the Baroota PWRA. This report is presented as Volume 1 of project Phase 3, with the intention that modelling reports for 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 projections and downscaling methodology.

Numerical models of groundwater recharge and surface water runoff were developed for the target water resources and calibrated against all available water level and flow data to ensure the models represented the variability of the key hydrological records in response to annual variations in key climate variables. For the Clare Valley PWRA, groundwater recharge models were constructed which simulate the flux of rainfall through the land surface and soil to the watertable, using the modelling code LEACHM. 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. The area weighted recharge rates take into account the land cover variables across the study area, including soil types, land uses, climate zones, depths to groundwater and land surface slope.

Surface water models were developed for the Hutt River (a tributary of the Broughton River) and the Wakefield River to represent the surface water resources near the Clare Valley PWRA. The models were developed using the WaterCress platform, implementing the WC1 rainfall – runoff model and calibrated to the available flow records for each case. A similar surface water model was developed for Baroota Creek, which contributes to the Baroota reservoir, to represent the surface water resources near the Baroota PWRA. Groundwater recharge models were not constructed for the Baroota PWRA, due to a paucity of groundwater monitoring data with which to calibrate a model of diffuse recharge processes. However, the dominant recharge process in Baroota has been shown to be due to losses from Baroota Creek downstream of Baroota Reservoir, occurring only at times when the reservoir reaches a critical level and seepage or overflows occur. Hence, the storage in the Baroota reservoir was included as part of the surface water model, to provide an indication of the frequency of reservoir overflows and resulting groundwater recharge events in the Baroota PWRA.

Historic climate data for a period of 50 years was applied to establish a baseline of recharge and runoff statistics under historic climate conditions. A number of 50 year time series data sets 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 data sets in place of the 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 winter rainfall totals than with any other climate variable. For the purposes of this report, "winter" has been defined as June – August, to coincide with the downscaling projections available. However, it is acknowledged that rainfall outside this period, May – November for example, will influence runoff and recharge. A relationship between reductions in winter 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 changes projected by CSIRO (2007) and summarised for South Australian regions by the Department of Environment and Natural Resources (DENR, 2010).

Potential reductions in groundwater recharge resulting from median climate scenarios projected by CSIRO (2007) range from 23% for a 2030 climate with a low emissions scenario (median 5% reduction in winter rainfall) to 58% for a 2070 climate with a high emissions scenario (median 15% reduction in winter rainfall). Similar reductions were found for surface water runoff in the major catchments of the Clare Valley. For the Wakefield and Hutt River catchments, projected reductions in median annual runoff are 24% to 32% respectively in the 2030 climate with a low emissions scenario, and 57% and 73% respectively in the 2070 climate with a high emissions scenario.

The impacts of climate change on the surface water resources of the Baroota reservoir catchment were found to be less than the Clare Valley catchments, as the streamflow was less sensitive to changes in rainfall for this catchment. For the Baroota catchment, a 5% reduction in winter rainfall, corresponding to the 2030 low emissions scenario, is projected to result in a 9% reduction in median annual runoff, and a 15% reduction in winter rainfall, corresponding to the 2070 high emission scenario, results in a 27% median annual runoff reduction.

The impacts of climate change on the groundwater resource in Baroota were estimated from a change in the number of years in which the reservoir overflows and causes significant recharge. It was found that the impact of below average rainfall on the storage in the reservoir resulted in a greater reduction in the number of years in which recharge is likely to occur(a greater reduction than that on the surface water yield). Projected reductions in the frequency of years in which significant recharge is likely to occur range from 26% for a 2030 climate with a low emissions scenario, to 62% for a 2070 climate with a high emissions scenario.

The key results of this study are discussed in Chapter 5 and presented 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 prescribed water resources of the Northern and Yorke 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. The South Australian Government's *Water For Good* plan identifies climate change as a major challenge to water resources in most of South Australia's NRM regions.

The CSIRO and Bureau of Meteorology (BoM) have previously undertaken investigations that project the likely impacts of climate change on South Australia (CSIRO, 2006, 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, 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 the Department's *Groundwater Program*. The Groundwater Program addresses Target 3.9 of *South Australia's Strategic Plan 2007* 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 climate change impact modelling of the prescribed areas of the Northern and Yorke Natural Resources Management (NYNRM) Region. This is presented as Volume 1 of Phase 3 (the climate change impact modelling phase) of the ICCWR project. The climate change impact modelling for the other seven of South Australia's eight NRM regions will be presented in further reports, presented as successive volumes of Phase 3 of the ICCWR project

1.2. PREVIOUS WORK

This report is preceded by two 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 supply. 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 and therefore should be the subject of the first detailed impact modelling studies. Through this process, the resources of the NYNRM Region and the Eyre Peninsula NRM 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’ data sets 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).

1.3. AIMS AND OBJECTIVES

The objective of the NYNRM Region study is to provide, for water planning and adaptation policy purposes, an understanding of the likely changes to surface water runoff and groundwater recharge in the Clare Valley and Baroota PWRAs under a limited 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 through the 21st century.

It is not the intention of this study to provide any guideline to the most likely climate change scenarios, nor to predict what changes in climate will occur. Rather, the intention has been to adopt an approach wherein the climate change projections of a range of existing GCMs are applied to 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 aims:

1. Develop models for the water resources of the Clare Valley and Baroota PWRAs 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 (PET).

2. Generate a baseline time series of historic runoff and recharge amounts related to the target water resources of the Clare Valley and Baroota.

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 related to the target water resources and key climate variables.

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 NORTHERN AND YORKE NATURAL RESOURCES MANAGEMENT REGION

The Northern and Yorke Natural Resources Management (NYNRM) Region encompasses a diverse landscape from the coastal regions of Yorke Peninsula, through the Clare Valley and into the Southern Flinders Ranges. Both surface water and groundwater are important sources of water in the region and support a diverse range of agricultural and industrial practices, as well as supplying townships with potable water and supporting water dependent ecosystems. Currently, the groundwater resources of only two areas in the NYNRM Region are prescribed – Clare Valley and Baroota. For this reason, both of these areas are the subject of detailed modelling in this report.

2.1. CLARE VALLEY PRESCRIBED WATER RESOURCE AREA

2.1.1. REGIONAL SETTING

The Clare Valley Prescribed Water Resources Area (PWRA) is located 100 km north of Adelaide and occupies some 700 km^2 (Figure 1). The population in the PWRA is approximately 5000, with Clare being the largest town in the region. The PWRA is characterised by numerous small catchments developed in valleys, separated by the ridges of the Northern Mount Lofty Ranges. The western boundary of the region is dominated by a fault ridge rising to 400 mAHD, while to the east a fault ridge rises to 550 mAHD.

Land use in the Clare Valley PWRA is dominated by vineyards, perennial pastures and orchards (Figure 21 later in the report shows land use areas). Native vegetation is generally confined to ridge-tops where productive agriculture is limited by thin soils.

2.1.2. CLIMATE

The climate in the Clare Valley is characterised by hot, dry summers and cool to cold, wet winters. Average annual rainfall over the BoM reference period 1975-2004 varies from 618 mm/y and 629 mm/y at Watervale and Hill River (respectively) to 535 mm/y at Calcannia. Generally, higher rainfall areas are located in the centre of the PWRA and decrease approximately radially outwards (Figure 1). Average annual potential evapotranspiration (PET) ranges from 1199 mm/y at Watervale to 1276 mm/y at Calcannia. Rainfall is generally greater than mean monthly PET from May until August, making winter rainfall an important driver for surface water runoff and groundwater recharge (Figure 2). Throughout this work, FAO56 PET has used for all modelling and reporting of results.

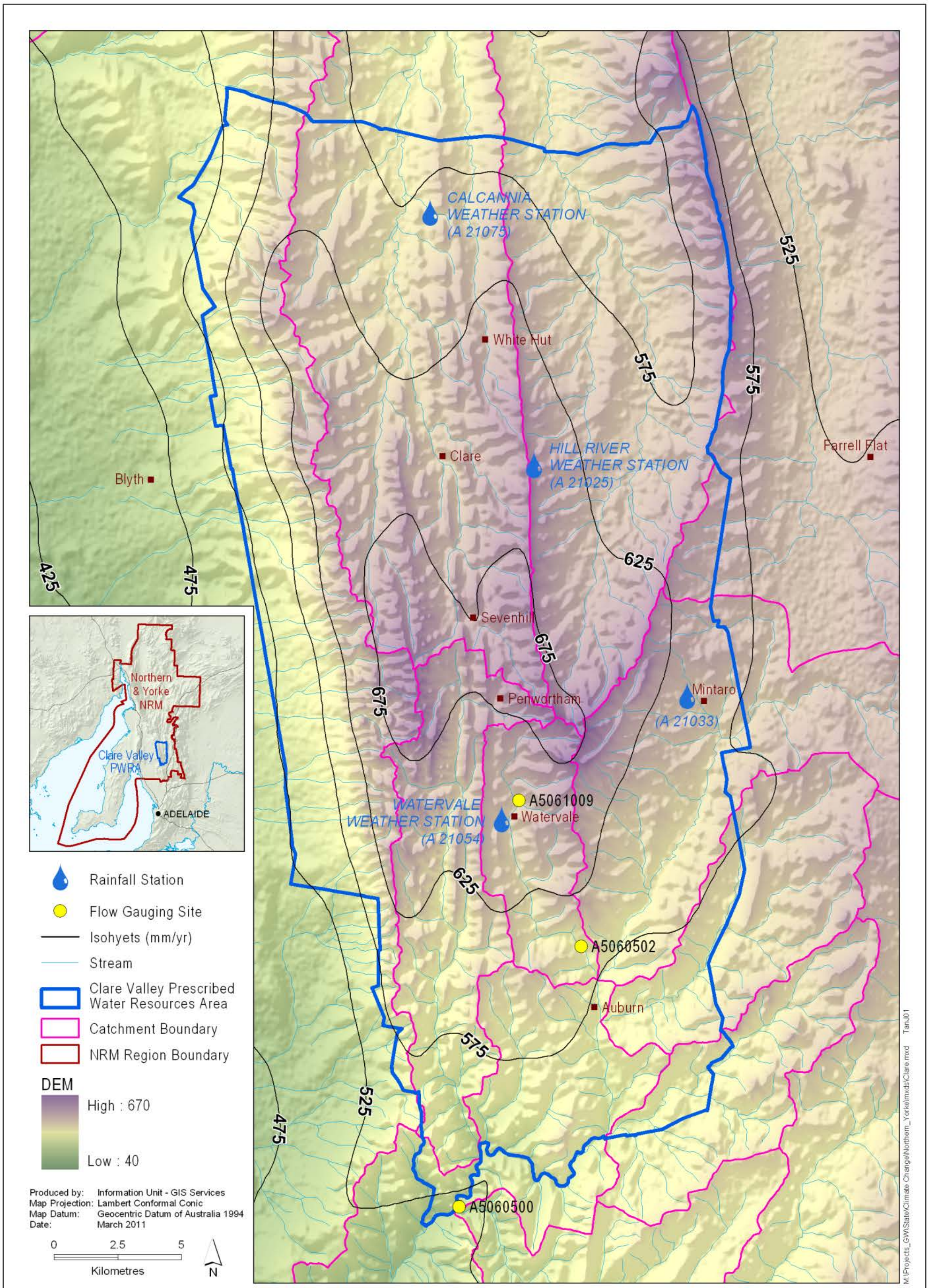


Figure 1. The Clare Valley PWRA

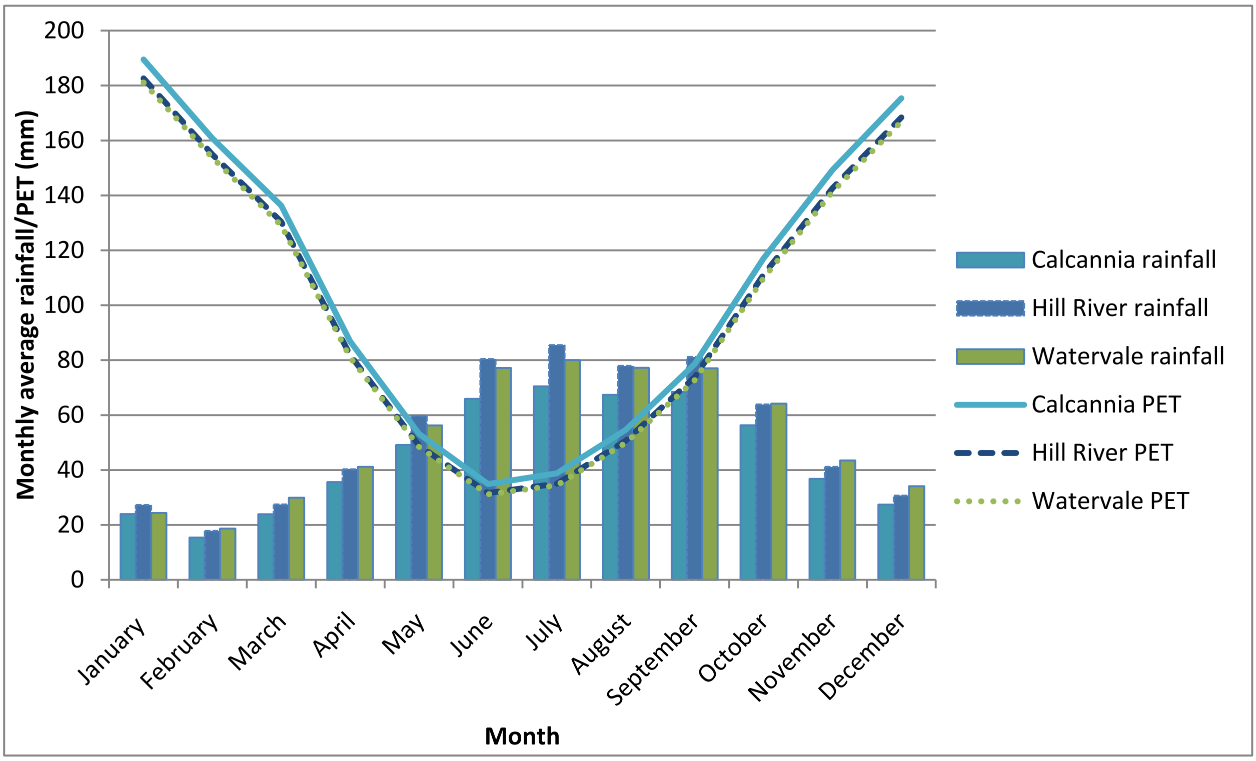


Figure 2. Mean monthly rainfall and PET in and around the Clare Valley PWRA

2.1.3. HYDROLOGY

Two hydrological catchments cover the Clare Valley PWRA, with the northern section contributing to the Hutt and Hill Rivers, tributaries of the Broughton River, and the southern section contributing to Eyre Creek and Skillogalee Creek, tributaries of the Wakefield River. The ridge of the Northern Mount Lofty Ranges dividing the two catchments is located approximately 3km north of Watervale (Figure 1).

The river systems are characterised by a defined seasonal pattern of flow with its highest monthly flows between May and October and lowest monthly flows between November and April. Flows are generally characterised by rapid rises and falls in response to rainfall, they are rarely constant over a day (Cresswell, 2000). Most of the watercourses stop flowing during the summer–autumn period and either dry out completely or contain permanent pools supported by groundwater (Favier et al., 2004).

Both climatic variation and human activity have affected the flow regime of the watercourses. A series of dry years over the past 20 years, with one or two exceptions, has resulted in decreasing flows and declining groundwater tables throughout the catchment regardless of the level of water resource development. At the same time it is clear that the flow regime in the system has been modified from its pre-European condition due to activities such as water resource developments in the form of dams and weirs, extraction, land use change and channel modifications (Favier et al., 2004). The magnitude of the climatic effect has made it difficult to distinguish the effects of farm dams and other human activities; in particular it has distorted the perception of the effects of farm dams and groundwater extraction in the area (Favier et al., 2004). It has also coincided with the implementation of improved land management practices such as contour banking, reduced stocking and improved pasture management, all of which substantially reduce the amount of runoff within the catchment (Cresswell, 2000).

For more detail on the hydrology of the Broughton River the reader is referred to Favier et al. (2004), and the Wakefield River to Favier et al. (2000).

2.1.4. GEOLOGY AND HYDROGEOLOGY

Set within the larger Adelaide Geosyncline, the geology of the Clare Valley is characterised by Neo-proterozoic rocks of the Burra and overlying Umberatana Groups, comprised of shale, siltstone, sandstone, dolomite and quartzite. Generally, the ridges that characterise the area are composed of the harder rock types that are less susceptible to weathering (quartzite and sandstone), while the valleys are dominated by softer, more easily weathered rock types (shale, siltstone and dolomite). Fracturing of these rocks took place during the Paleozoic-Ordovician period (400-500 million years ago, during a period known as the Delamerian Orogeny), along with secondary fracturing during the more recent Tertiary period.

Minor alluvial aquifer formations are present to the north of Clare, however they are not extensive and do not constitute a major groundwater resource. Regional groundwater flow occurs primarily through the fractured rock aquifers (fracturing in the different lithological units is considered to be ubiquitous, so that groundwater may flow across different units (Love et al., 2002)). Flow within the fractured rock aquifers occurs primarily through the fractures, which act as conduits, with the surrounding rock matrix acting as a storage reservoir. Fractures may vary in scale and distance from centimetres to kilometres, and may be continuous or discontinuous. Because of this high degree of heterogeneity, hydraulic conductivity of the aquifer varies by up to five orders of magnitude (<0.001 m/d to ~100m/d), however conductivity is generally higher in the shallower parts of the aquifer, and decreases with depth. Diffuse infiltration of rainfall is thought to be the dominant process of groundwater recharge, with rates determined from hydrochemical methods (Love et al., 2002) ranging from 30 – 75 mm/y. Discharge occurs as base-flow to the rivers and creeks in the PWRA, as well as extraction (pumping) for irrigated agriculture, and lateral groundwater flow out of the region. Evapotranspiration may occur from shallow watertables in the region, however this process has not been thoroughly investigated or quantified.

For a more detailed discussion on the hydrogeology of the Clare Valley, the reader is referred to Love et al. (2002) and Stewart (2010).

2.2. BAROOTA PRESCRIBED WATER RESOURCE AREA

2.2.1. REGIONAL SETTING

The Baroota PWRA is located approximately 2 km north of Port Germein and 230 km north of Adelaide, in a coastal plain bounded to the east by the Southern Flinders Ranges and to the west by Spencer Gulf (Figure 3). Land use is predominantly dryland grazing agriculture, however approximately 700 ha of land is irrigated, primarily for potatoes and vineyards.

2.2.2. CLIMATE

The climate in Baroota is semi-arid, with mean annual rainfall (taken from Port Germein weather station) of 332 mm/y and mean annual PET of 1443 mm/y. A rainfall gradient crosses the PWRA, with mean annual rainfall increasing to 450 mm/y in the Ranges to the east (Figure 3). Further east, in the catchment area for Baroota Reservoir, rainfall increases again. Mean monthly PET is only exceeded by mean monthly rainfall in these more elevated areas (Figure 4. Figure 4).

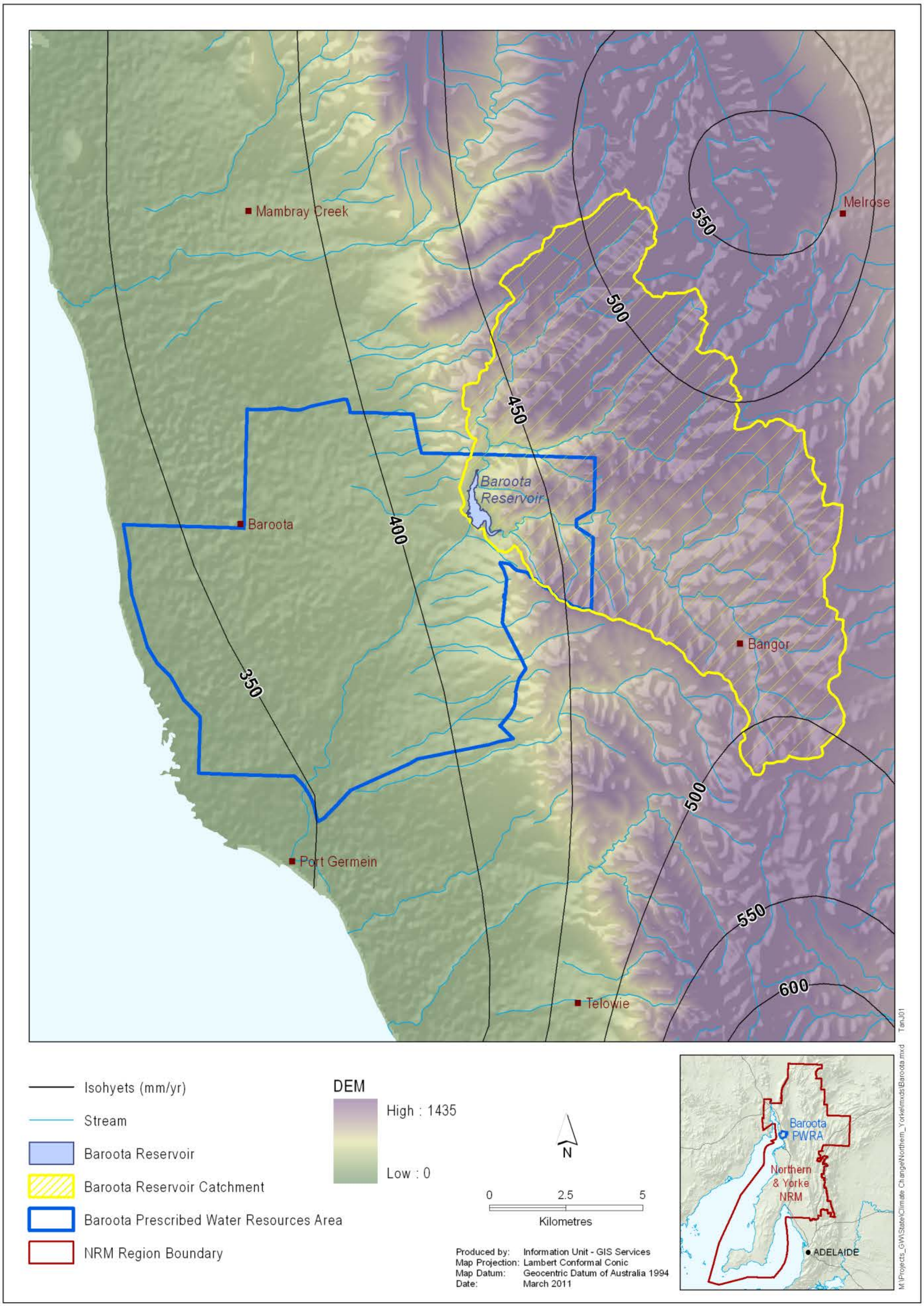


Figure 3. The Baroota PWRA

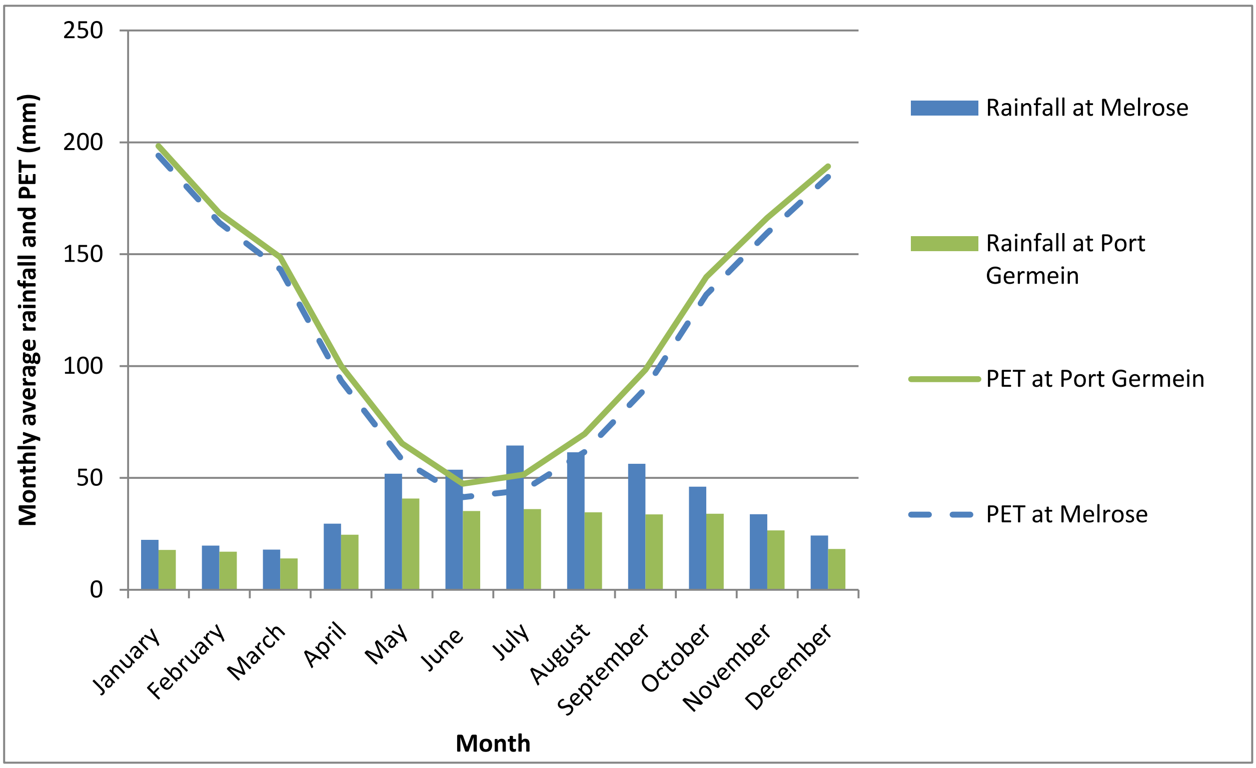


Figure 4. Mean monthly rainfall and PET in and around the Baroota PWRA

2.2.3. HYDROLOGY

The catchment contributing to the Baroota reservoir has been considered to represent the impacts of climate change on surface water availability near the Baroota PWRA. Baroota Creek is the largest of any creek in the Flinders Ranges that flows to the west across the sediments of the Pirie Basin, between Port Pirie and Port Augusta (Barnett, 2009). A catchment area of 136 km^2 contributes flows to the reservoir. The reservoir was constructed in 1921 with a capacity of 6120 ML, compared to a median runoff from the local catchment estimated to be 3300 ML/year over the period 1941 to 1994. Soon after completion it was noted the dam was leaking, with the amount of seepage in Baroota Creek below the dam proportional to the reservoir water level (Clarke, 1990).

The reservoir can be supplemented with flows from the Murray River, provided by the Morgan to Whyalla pipeline. Up until 1997, the reservoir was being used as a balancing storage for the reticulation of River Murray pipeline water, resulting in water levels being higher than those produced from the contributions from local catchment runoff. However since then, SA Water has removed the Baroota Reservoir from the major water distribution network due to water quality issues, and water levels have been consistently lower than before 1997, apart from the wet winters of 2000 and 2001 (Barnett, 2009).

2.2.4. GEOLOGY AND HYDROGEOLOGY

The Baroota PWRA is located in the Pirie Basin, which consists of Quaternary clays and gravels overlying Tertiary sands and sandstones. The Tertiary sequences are underlain by Neoproterozoic basement. Groundwater extraction for irrigation is exclusively from gravel aquifers in the Quaternary formation, which are made up of alluvial and fluvial sediments washed out from the Southern Flinders Ranges. The gravel beds in this sequence are discontinuous and regionally un-mapped and extraction wells are often screened across multiple aquifer units (Evans, 2004).

Some of the recharge to these aquifers is likely to occur via diffuse infiltration of rainfall, as groundwater levels generally follow the same trend as cumulative deviation in rainfall. However, groundwater levels do not display distinct annual fluctuations, possibly because of the time taken for recharge to reach the relatively deep watertable (generally more than 10m), but also suggesting that diffuse recharge is a only a small component of the total recharge to these aquifers. Recharge via inflows from regional groundwater flow (from the fractured rock aquifers of the Flinders Ranges) is also likely to occur, however rates have not been quantified. The most important source of recharge is surface water infiltration along Baroota Creek, especially in the vicinity of Baroota Reservoir. Groundwater levels in this area have been observed to peak in response to overflow events in Baroota Reservoir and decline when water levels in the Reservoir are lower (Barnett, 2009).

Irrigation is reliant upon groundwater extraction from the Quaternary gravels and most extraction is located in the areas which receive recharge from surface water, as the salinity is typically lower. Extraction is metered in Baroota and has averaged ~1500 ML/y in recent years (Barnett, 2009). For a more detailed discussion on the hydrogeology of the Baroota PWRA, see Evans (2004) and Barnett (2009).

3. METHODOLOGY

3.1. CLIMATE CHANGE SCENARIOS

The ICCWR project Phase 2 report (Gibbs et al., 2011) describes the process by which four Global Climate Models (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 course to be used directly 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 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 1961 – 2010, inclusive. This baseline weather data set was then perturbed based on the GCM projections to produce downscaled climate variable data sets, 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. This process is illustrated in Figure 5. 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. 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 Greater Adelaide up to the year 2050, the *Water for Good* plan considered both the SRES A2 and B2 scenarios (SRES, 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 – 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 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 as part of the Water for Good Plan.

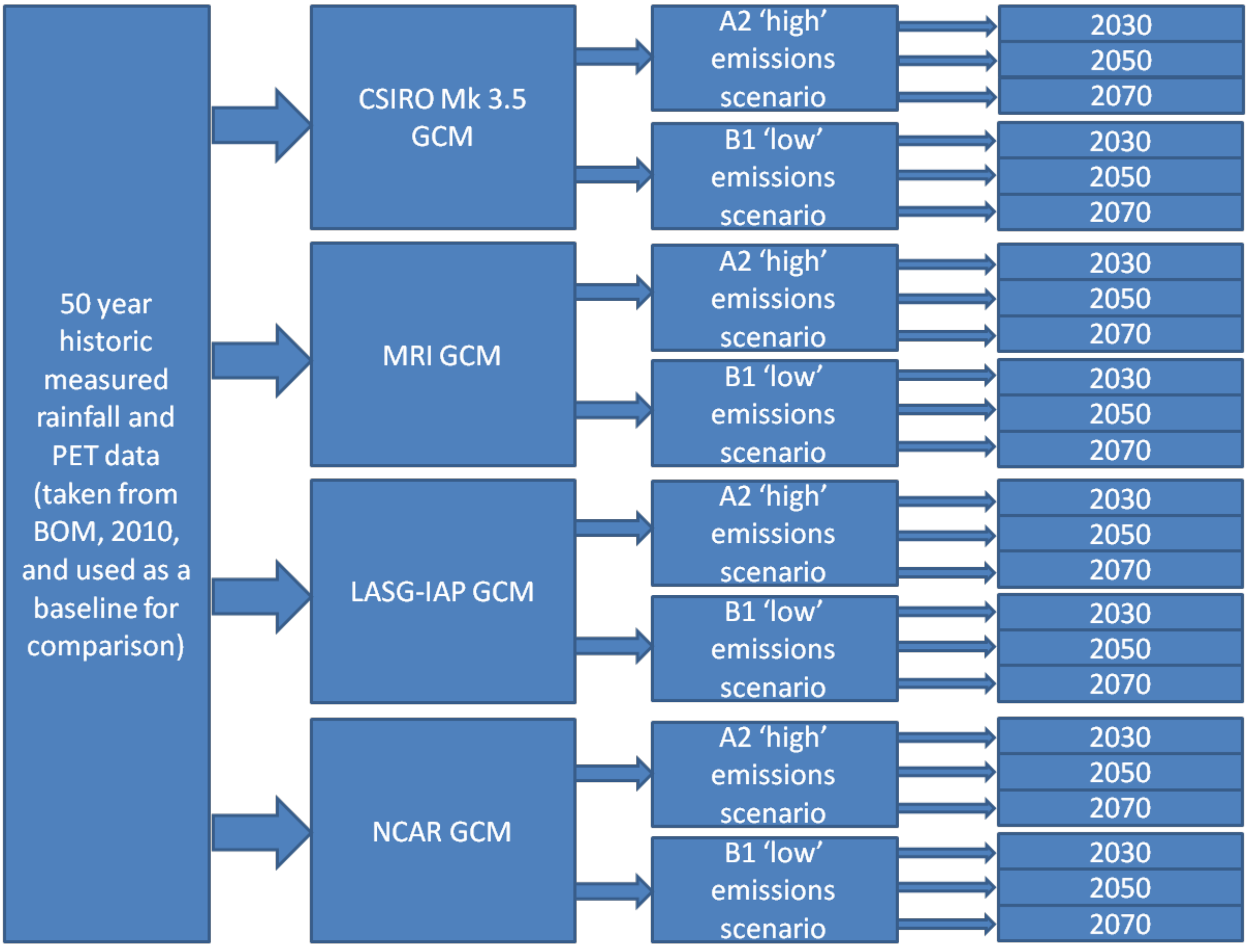


Figure 5. Flowchart describing the number of climate change scenarios that were tested in each surface water runoff and groundwater recharge model

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 policy in future climate scenarios
- Water table depths are the same under future climate scenarios as in the historic baseline period
- The majority of groundwater recharge occurs as diffuse recharge via the vadose zone (for Clare Valley only)

These assumptions are further explained below.

An assumption of unchanged land use patterns with historic and future climate simulations is explicit in the groundwater recharge models for the Clare Valley PWRA and is implicit in the surface runoff models for the Wakefield River, Hutt River and Baroota Reservoir 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 policy, 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 described in section 3.3). The GIS-linked spatially distributed LEACHM model for the Clare Valley PWRA has spatially varying water table depths according to their variation across the study area. However, it is assumed these depths do not change temporally, either within each simulation or between historic and future climate simulations. Some qualification of this assumption is made in section 3.4.2.

It is assumed in the consideration of the results of the spatially distributed LEACHM model for the Clare Valley PWRA that the majority of recharge in the study area occurs as diffuse recharge through unsaturated soil profiles.

3.3. SURFACE WATER RUNOFF MODELLING

Existing runoff models were used for climate change impact analysis where available. This included the Hutt River tributary of the Broughton River and a model to represent the Wakefield River. The impacts of climate change on water resource availability at Baroota reservoir was also identified to be of interest in the NYNRM Region. Hence a model of this catchment has been developed as part of this project.

The models have been developed in the WaterCress modelling platform using the WC1 rainfall – runoff model. The WC1 model uses three storages, as shown in Figure 6, to track the notional vertical passage of rainfall by gravity through interception, soil moisture and groundwater. The soil store is generally the main runoff producing component, requiring only changes to four of the parameters to produce reasonable model calibration (Clark and Cresswell, 2009). Surface runoff is calculated with possible contributions generated via the calculations performed for the three layers of the model (as surface, interflow and groundwater contributions).

Modelling the runoff is difficult because most of it is generated during individual, large rainfall events and there is little information about stream losses to the groundwater table. Therefore, modelled data may overestimate flows in some tributaries (Favier et al. 2004). Each model has been recalibrated to incorporate any recent data that has become available and to adjust to the potentially different rainfall and PET inputs used. Further details regarding the model structure and data availability for each catchment is provided in the remainder of this section.

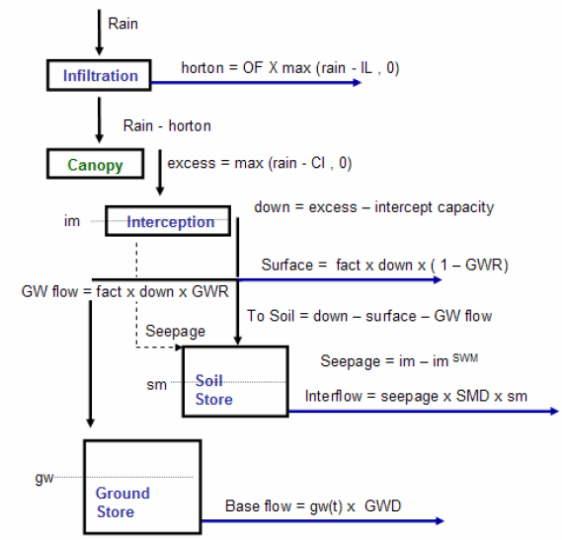


Figure 6. WC1 Model Structure (Clark and Cresswell, 2009)

3.3.1. HUTT RIVER

The Broughton River has three gauging stations only; the Mooroola gauging station on Broughton River (south of Spalding), a station on Hutt River near Spalding and another on Hill River near Hilltown. Due to data quality and existing model availability, the station on the Hutt River (A5070501) has been adopted to represent the impact of climate changes on the Broughton River.

A total area of 280 km^2 contributes flow to the gauge located on the Hutt River near Spalding. Three rainfall stations are used in the existing model, located at Clare (21014), Calcania (21075) and Hilltown (21059). To ensure there is consistency across rainfall stations, representing a storm crossing the catchment, one site has been used to generate the future time series and then adjustment factors have been used to account for the different annual rainfall and PET occurring at each site. The base site used for the Hutt River model was Hilltown, as it contributes to the largest area in the model. Scaling factors of 1.364 and 0.977 were used for rainfall and PET, respectively, for the site at Clare and factors of 1.180 and 0.995 were used for rainfall and PET for the site at Calcania, respectively. The structure for the Hutt River model can be seen in Figure 7. The four farm dam nodes included in the model (nodes 12, 13, 21 and 23) upstream of the gauge used for calibration (node 16) have been included in the simulation of future climate scenarios, to represent the changes in runoff available considering existing diversion rules. Hence the end of system flow has been reported for each scenario, as opposed to only the catchment runoff that would represent an undeveloped catchment. The diversions to the off stream dams have been simulated as a fraction of the flow passing each node, as estimated in the original model of the farm dams, with the fractions between 0.26 (node 23) and 0.56 (node 21) of the flow passing.

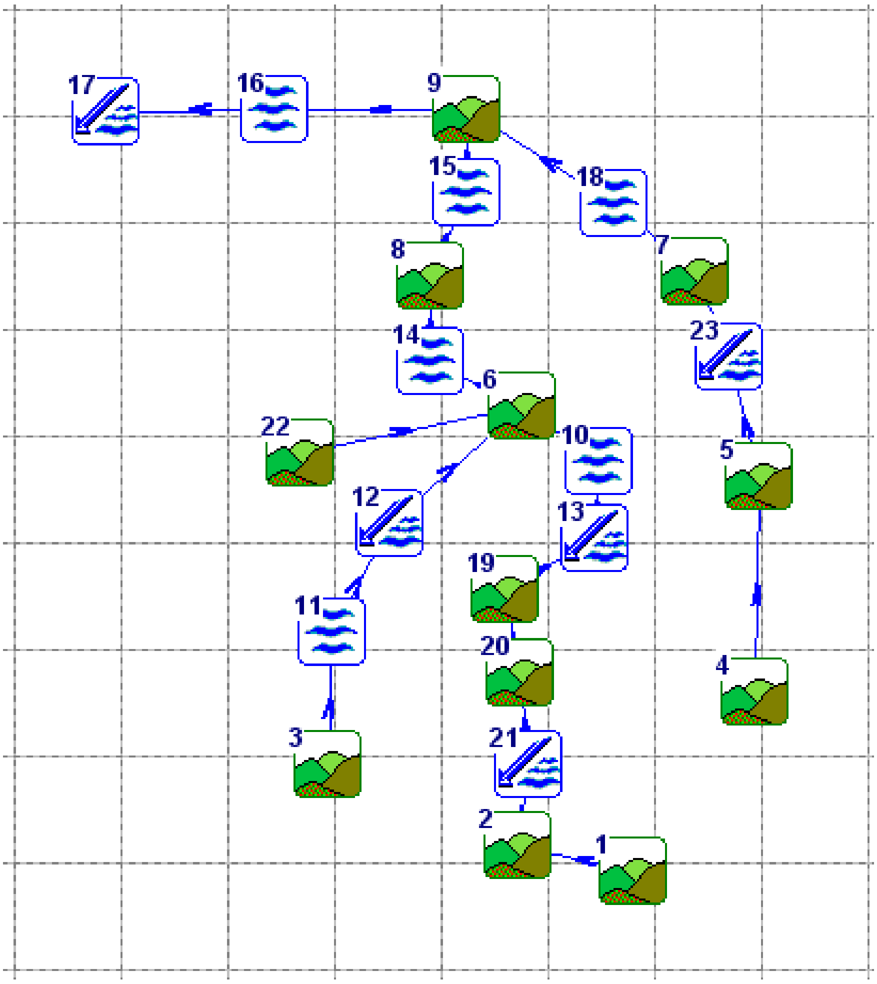


Figure 7. Hutt River Model Structure

A 20 year flow record has been used for model development, from the start of 1975 to the end of 1994. The flow record after this period has not been considered, as there has been a number of interruptions to the record, and the period since 1994 has been drier with limited flow events to assist model calibration. Rainfall data provided by the SILO Patched Point Dataset (Jeffery et al., 2001) from the three relevant rainfall sites (as outlined above) has been used for model calibration. The first 15 years of data have been used for model calibration, after permitting a one year warm up period. Both manual and automated Generalized Reduced Gradient nonlinear optimization was used for model calibration, resulting in a monthly Nash Sutcliffe error of E = 0.89. The remaining five years of data were used for validation of the model, producing a Nash Sutcliffe error of E = 0.78 for this period. A plot of the observed and simulated flows for the whole record considered can be seen in Figure 8.

The independent validation period has been used to assess the performance of the model when representing data that has not been used in the calibration process, to increase the confidence in the model at representing the general runoff response of the catchment. Given the acceptable validation error, the model has been deemed suitable for this catchment. Only monthly volumes have been considered in the calibration process, as the results presented in this work are changes in volumes, as opposed to representing peak flows, or timing of peak flows. Future application of the models calibrated as part of this work should first be assessed if the models are fit for different purposes.

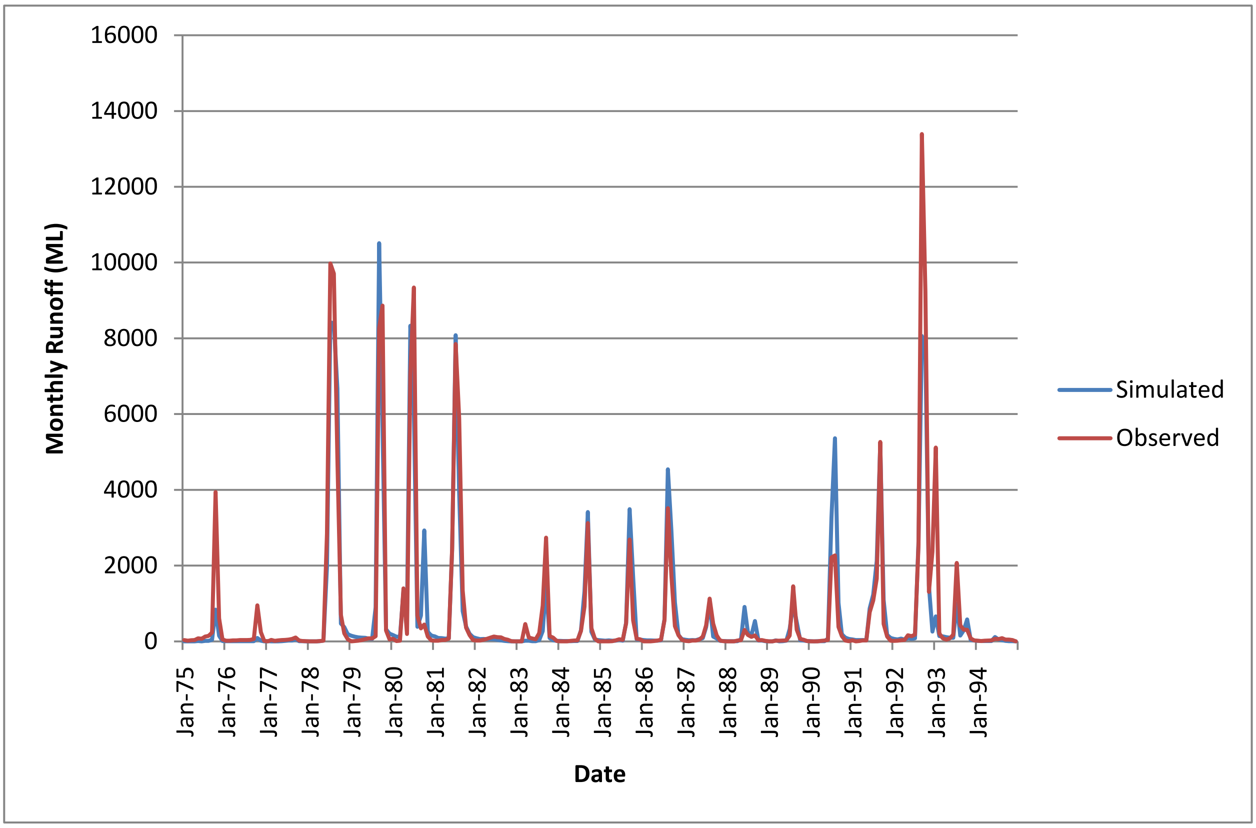


Figure 8. Simulated and Observed Monthly Runoff for the Hutt River Catchment

Changes in the median annual runoff, as well as 20th and 80th percentile annual runoff, are reported in section 4 for the different climate scenarios considered. The model performance for these events has been compared using an annual flow duration curve, as seen in Figure 9. The simulated and observed distribution of flow are relatively consistent, however the model slightly underestimates the low flows, as well as the most extreme flow years. In spite of this, the simulated climate results are in good agreement with the observed climate and the general distribution of flow is represented well, hence the model has been deemed suitable for the purposes of this report.

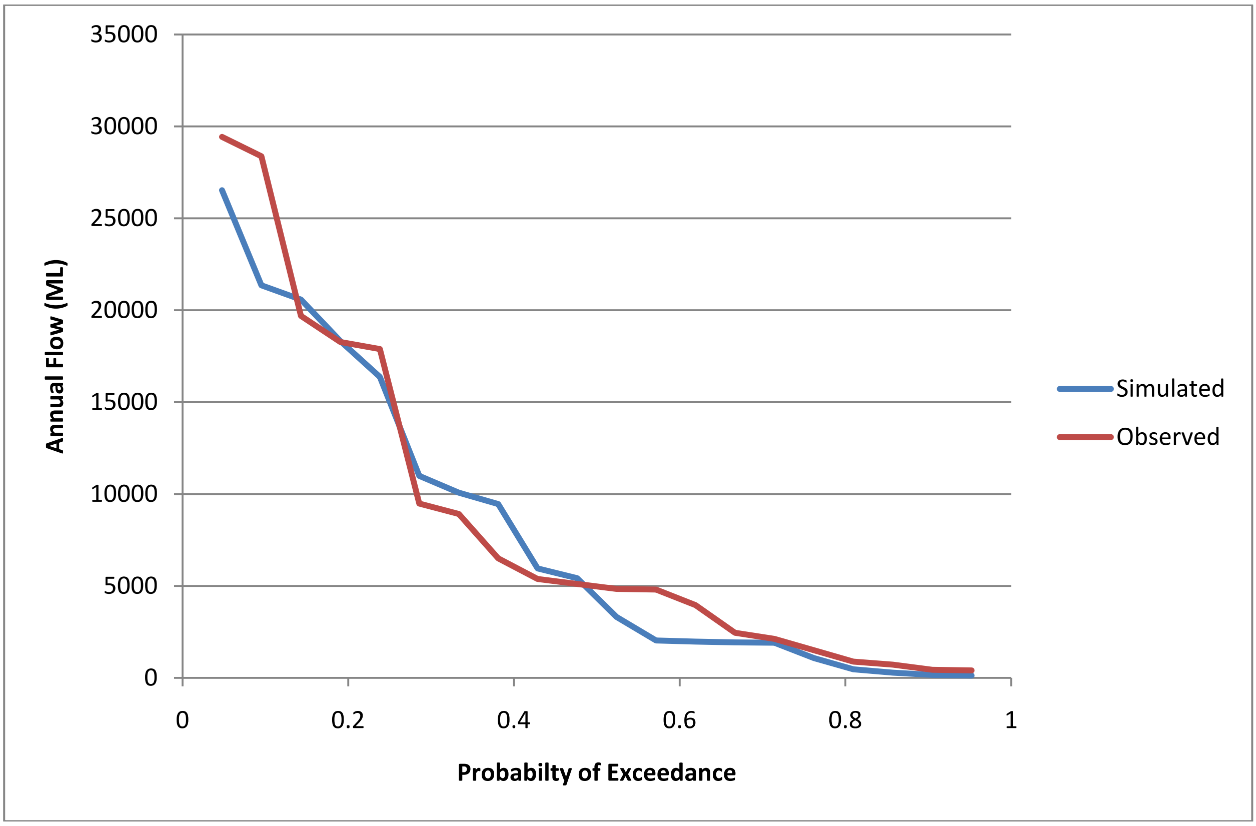


Figure 9. Simulated and observed annual flow duration curve for the Hutt River catchment

3.3.2. WAKEFIELD RIVER

The flow recording site at A5060500 was used to develop the Wakefield River model. A total area of 416 km^2 contributes to this site, with the model structure seen in Figure 10. As with the Hutt River model, the off stream farm dams in the model have been included in the simulations of future scenarios, with diversion fractions between 0.2 (node 12) and 0.5 (nodes 15, 18, 20, 22, 24 and 25). The flow gauging sites located at Watervale (A5061009) and Auburn (A5060502) were also used to assist model development. As with the Hutt River model, scaling factors have been used to adjust the rainfall and PET amounts for each of the rainfall sites used in the original model development. The base site for the Wakefield River model was at Auburn (21001), as again it was used as the input for the greatest area of sub-catchments in the model. The other stations in the model, along with the adjustment factors used, are presented in Table 1.

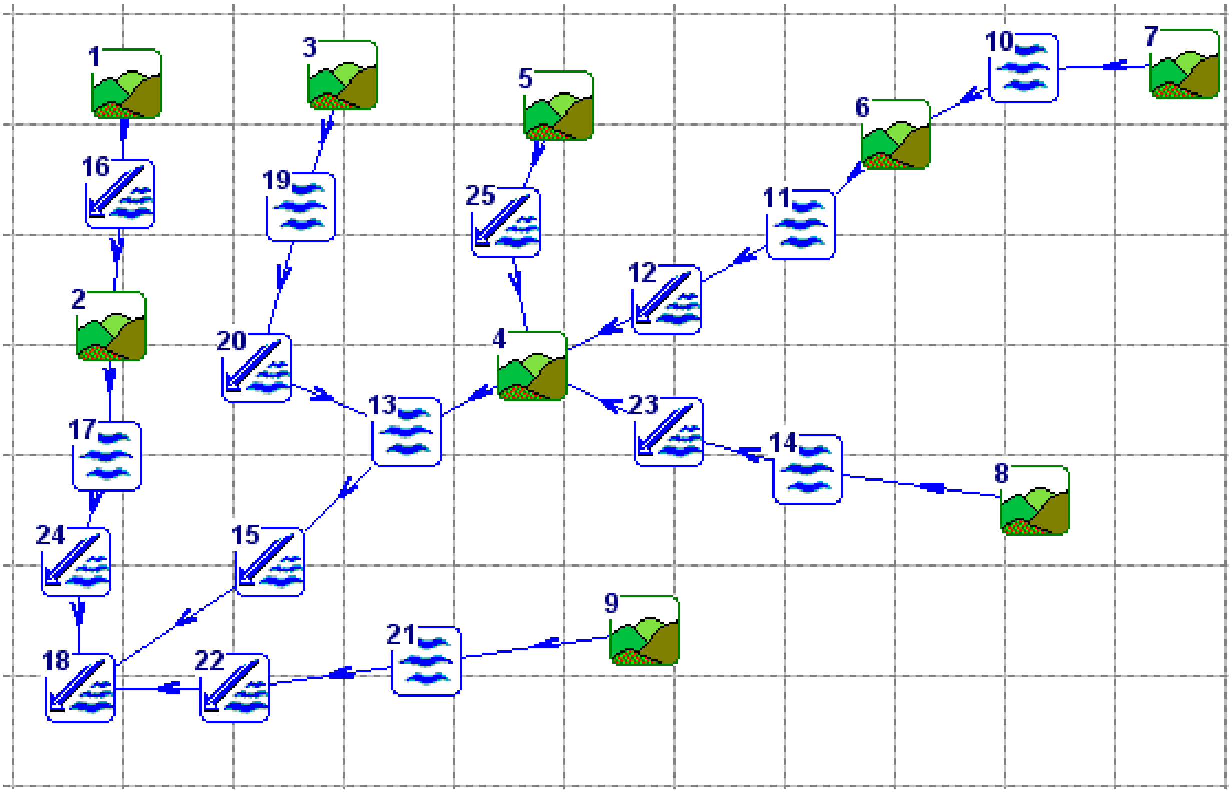


Figure 10. Wakefield River Model Structure

Table 1. Rainfall and PET adjustment Factors for Wakefield River Model

Location	Station ID	Adjustment Factors	
		Rainfall	PET
Watervale	21054	1.129	0.950
Mintaro	21033	1.030	0.987
Manoora	23310	0.884	1.010
Saddleworth	23315	0.889	1.051

A 25 year period has been used for model calibration, 1975-1999, with the following five years, up to the end of 2004, used for model validation. Again, the most recent flow record (since 2005) has not been considered due to the limited flow events to assist model calibration. Using the same calibration method as that for the Hutt River model, a Nash Sutcliffe efficiency for the calibration period of E = 0.63 was obtained, with an accuracy of E = 0.5 for the independent validation period. This model is less accurate than the Hutt River model, most likely due to unaccounted for extractions and groundwater interactions (Favier et al., 2000). A plot of the observed and simulated flows for the complete flow record considered (both calibration and validation) can be seen in Figure 11. The simulated and observed annual flow duration curves for the Wakefield River catchment are presented in Figure 12, where the model can be seen to adequately represent the distribution of annual flows recorded from the Wakefield catchment, especially the 20th, 50th (median) and 80th percentile flows, which are reported in Section 4. There is some underestimation of both the highest and lowest flow events, however this is not expected to influence the results presented as part of this work.

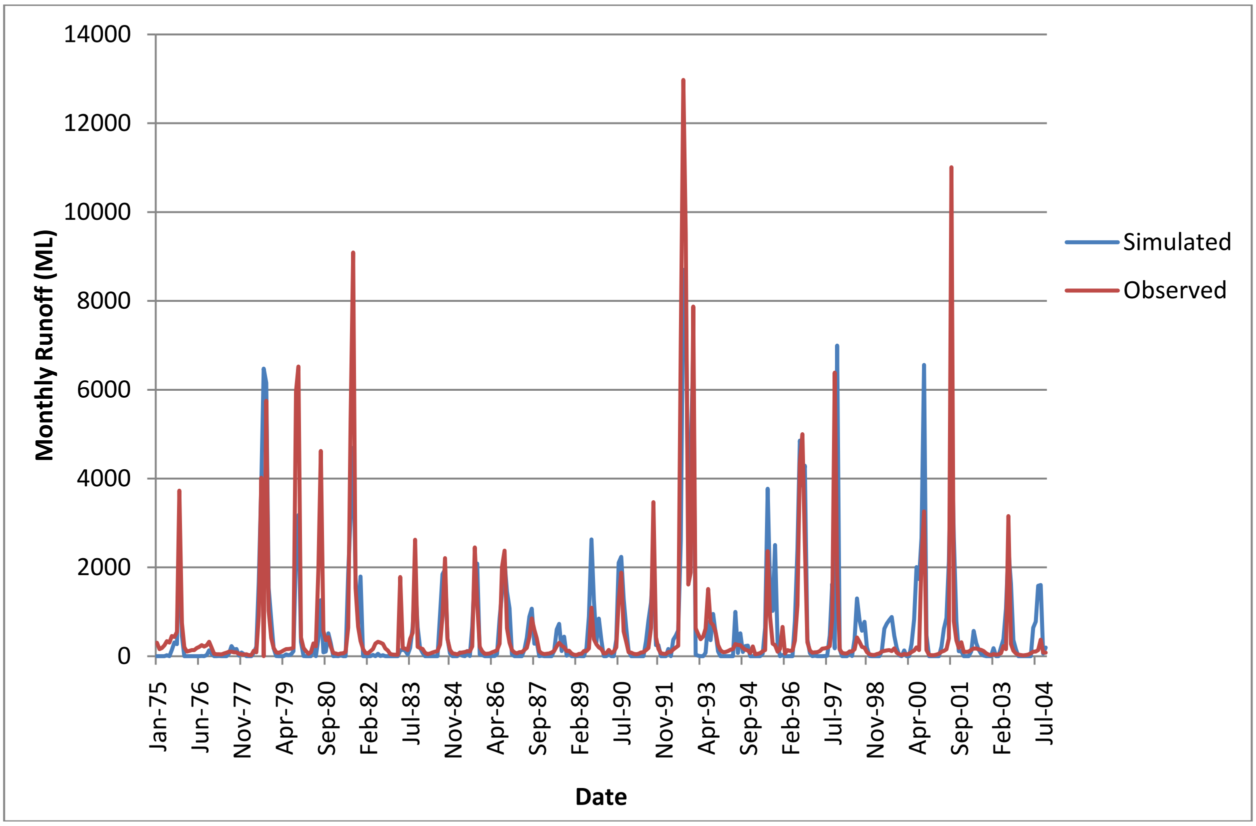


Figure 11. Simulated and Observed Monthly Runoff for the Wakefield River Catchment

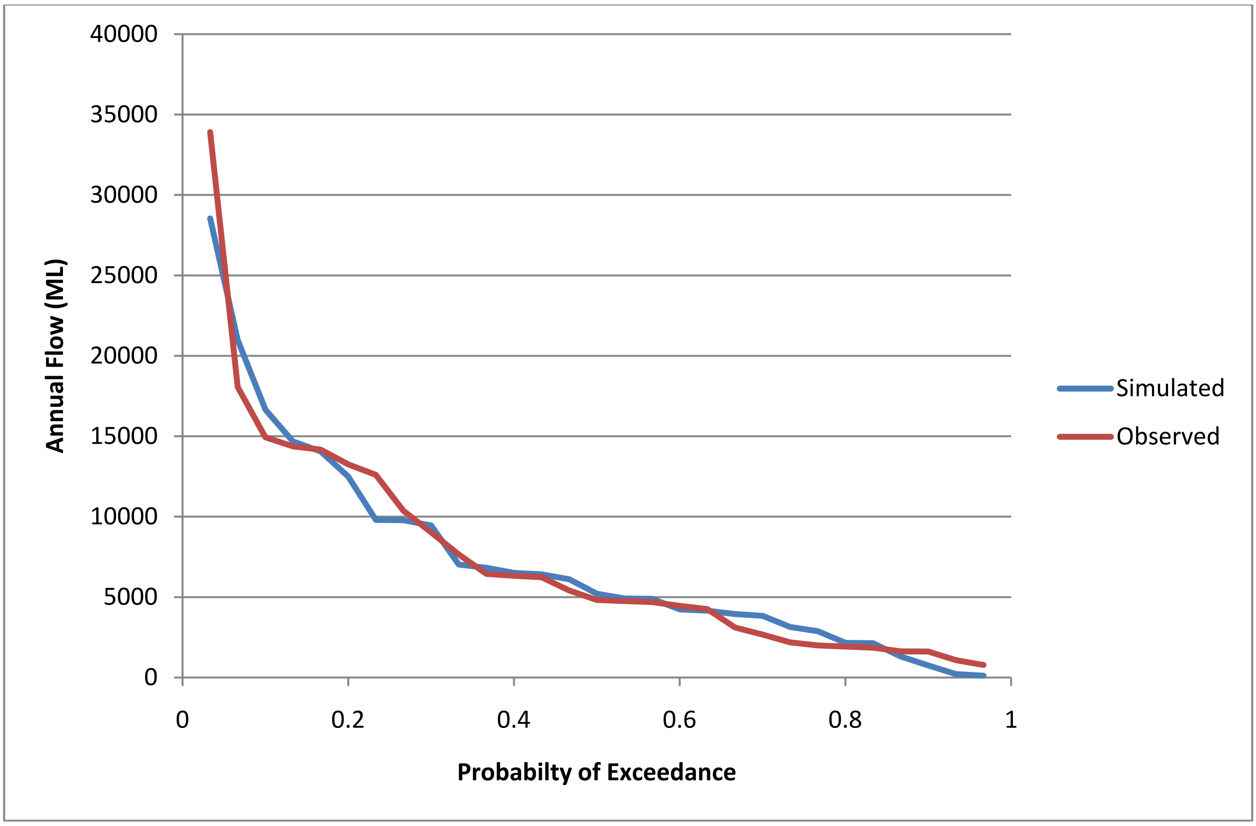


Figure 12. Simulated and observed annual flow duration curve for the Wakefield River catchment

3.3.3. BAROOTA RESERVOIR

An area of 136 km^2 contributes local runoff to the Baroota reservoir (Figure 3). The available data for model calibration is less reliable than the other catchments considered, as the gauging station at the reservoir records only water level and spill from the reservoir, not inflows. Also, the volumes of extraction from the reservoir and transfers from the River Murray via the Morgan – Whyalla pipeline influence the water level at the Baroota Reservoir.

A monthly water balance to estimate the catchment yield at the reservoir has been undertaken for the period 1941 to 1994 (DENR, 1996). A one node WC1 model has been calibrated to these monthly yields. Given the monthly time step of this data and the uncertainties around the yield estimates, a more detailed model is not justified. The BoM station located at the reservoir (19102) was used for the rainfall and PET inputs to the model. The most recent data has been used for model calibration, with the start of the record used for model validation. The calibration period used commenced in 1950, with a Nash Sutcliffe Efficiency of E = 0.58 obtained. The first 10 years of the data record, from the start of 1941 to the end of 1950, was used for model validation and produced an error measure of E = 0.59. Given the uncertainties inherent in the estimated catchment yield values, this model accuracy has been deemed acceptable. A plot of the observed and simulated flows for the complete flow record considered (both calibration and validation) can be seen in Figure 13. The simulated and observed annual flow duration curves for this catchment can be seen in Figure 14, where the distribution of annual flows are generally accurately represented across the whole range of flows observed over the period of observed data from 1941 to 1994.

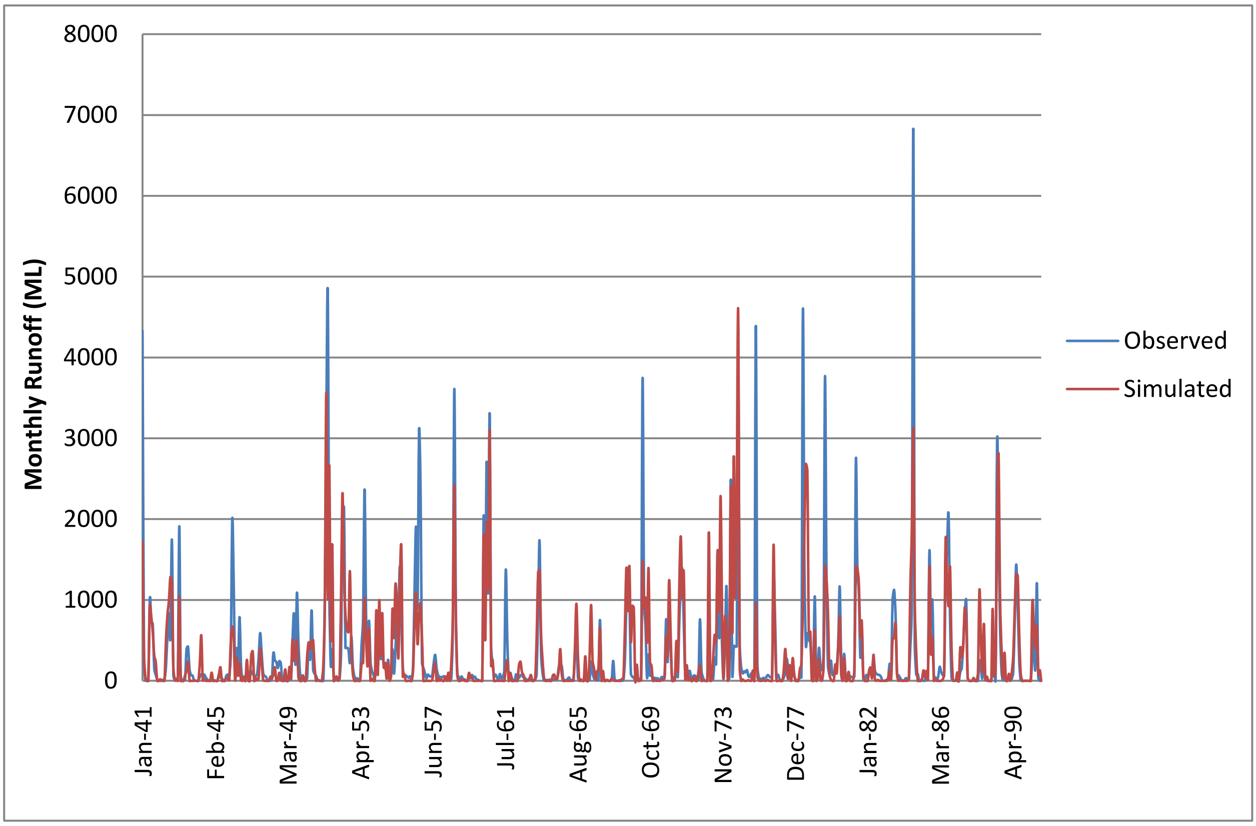


Figure 13. Simulated and Observed Monthly Runoff for the Baroota Reservoir Catchment

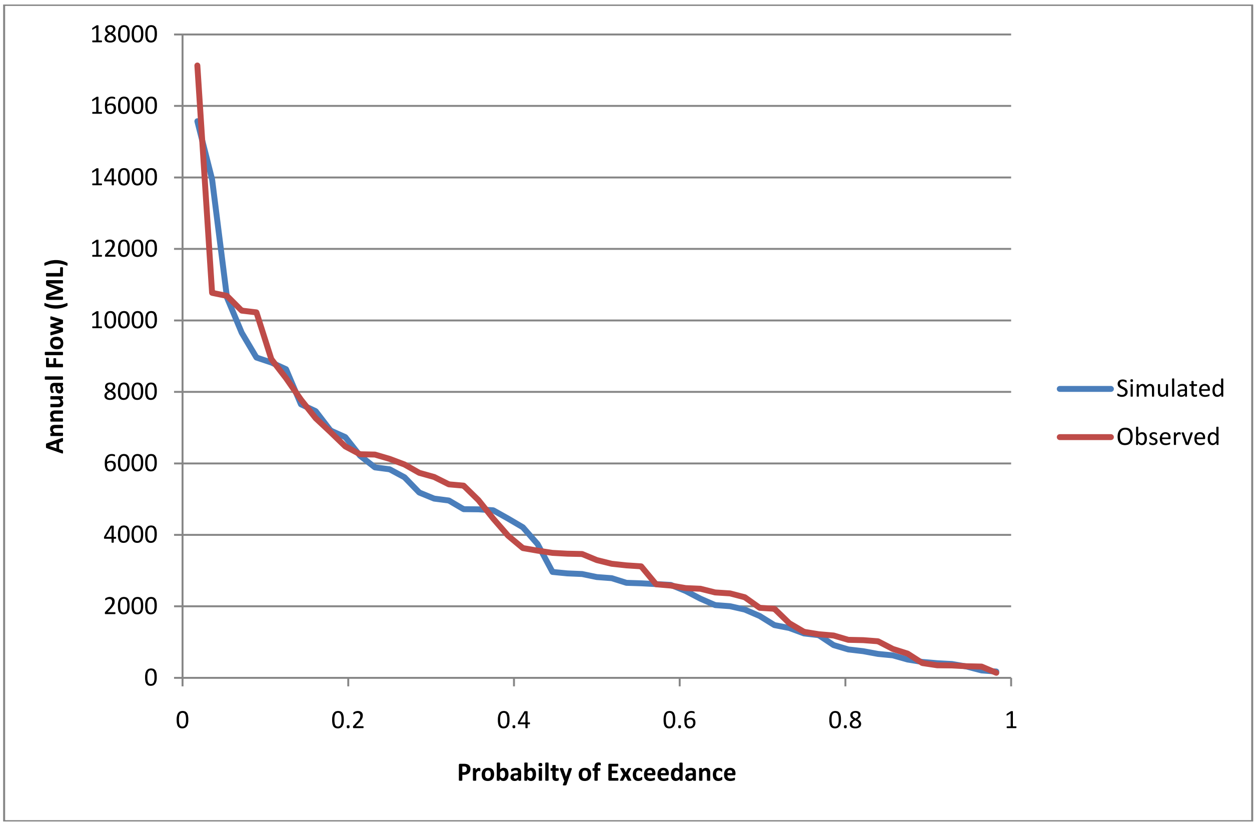


Figure 14. Simulated and observed annual flow duration curve for the Baroota reservoir catchment

The water level in the Baroota reservoir is also of interest for this work, as recharge in the area is significantly enhanced when the water level in the reservoir reaches a critical level exceeding 20 m (Barnett, 2009). The depth to volume relationship for the reservoir has been extracted from the Hydstra database, with the corresponding surface area estimated from the change in volume expected for a change in depth, using increments of 0.1m. These data have been input to a Flow – Elevation – Volume – Area relationship for a WaterCress storage node. Data collated to estimate the catchment yield (DENR, 1996) have been used to calibrate the loss rate from the reservoir, with inputs representing the catchment yield and Murray River transfers and outputs representing extractions from the reservoir. Evaporation from the reservoir is simulated explicitly as part of the model. A constant seepage rate of 15 ML/day from the reservoir, irrespective of the depth, was used to provide the best fit of the simulated water level to the observed reservoir levels, as seen in Figure 15.

It is likely that the errors in the modelled reservoir levels are largely due to the uncertainties around the volumes of water historically transferred to and extracted from the reservoir. Also, it is likely that the seepage rate is greater near the full supply level of the reservoir compared to when the water level has drawn down a number of meters (Clarke, 1990), which may explain the low water levels simulated in 1989 and 1992. The simulated reservoir behaviour has been deemed reasonable for the purposes of this work, as generally the fill and drawdown rates are similar, and most importantly the reservoir levels greater than 20 m are simulated accurately, which is of interest because it determines when recharge events will most likely occur.

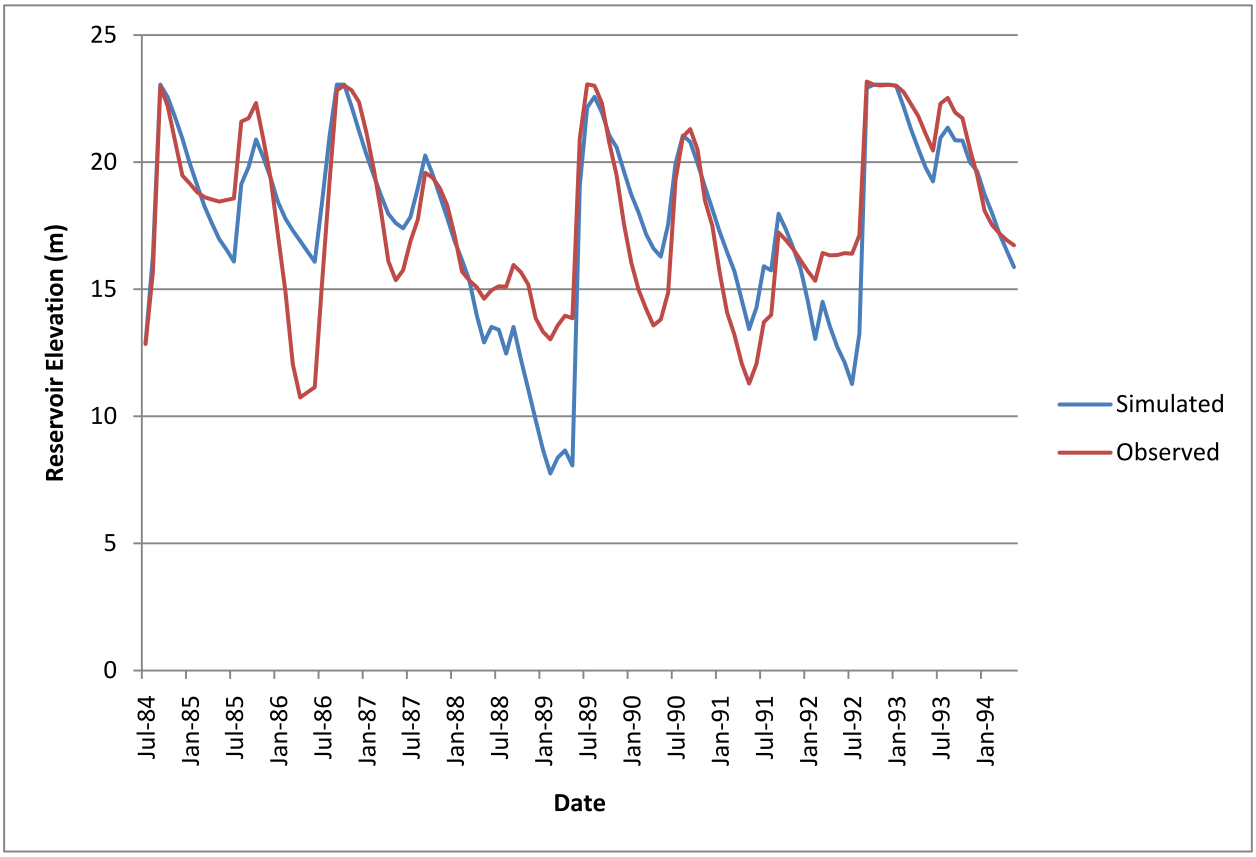


Figure 15. Simulated and Observed Water Level for the Baroota Reservoir

3.4. GROUNDWATER RECHARGE MODELLING

3.4.1. CLARE VALLEY PWRA

The objective of the groundwater recharge models described here is to appropriately represent the variability of recharge to unconfined groundwater under varying climate conditions. It is not intended that the models provide a definitive estimate of recharge. 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.

The most important indicator of the usefulness of these models to assess changes to recharge under alternative climates is their ability to correctly represent historic variations in annual recharge amounts under annual variations in recorded weather variables. While previous studies (Love et al., 2002) have made estimates of long term average recharge fluxes, 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 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:

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

Where ΔGW is the annual rise in the watertable, and Sy is the specific yield of the aquifer (Armstrong and Narayan, 1998).

The complications associated with the high degree of aquifer heterogeneity in fractured rock aquifers limit the usefulness of the watertable fluctuation method in the Clare Valley, as the estimation of aquifer specific yield is problematic (Cook, 2003). Nevertheless, groundwater hydrographs in the Clare Valley do fluctuate annually in response to rainfall (Figure 16) and hydrograph trends approximately follow rainfall trends (Stewart, 2010). These trends can be used as a guide to assess the relationship between rainfall and groundwater recharge processes. For example, Cook (2003) reported that annual fluctuations in the watertable of 1.2m-1.5m at an investigation site in the Clare Valley yielded recharge estimates of 60 mm/y, using a specific yield value close to the total effective porosity of the aquifer (ie, fracture and matrix porosity). This estimate of recharge agreed with estimates made using hydrochemical methods at this site.

Note in Figure 16, the annual watertable fluctuation is plotted against winter rainfall. While the relationship between rainfall and recharge is complex, there is generally a better correlation between winter rainfall (ie. months in which total rainfall exceeds total PET, referring back to Figure 2) and watertable flux than there is between annual rainfall and watertable flux. The different data series shown in Figure 16 (taken from different observation well records) display coefficients of determination ranging from 0.4 to 0.8 (ie. R^2 = 0.4 – 0.8). Not shown is the relationship between annual rainfall and watertable flux, which gives a lower R^2 value of 0.33. Similarly, the strongest indicator for runoff was also the winter rainfall, with R^2 = 0.81 for the Wakefield River catchment, decreasing to R^2 = 0.72 for annual rainfall. The correlation with winter rainfall was also found to be stronger than with the other climate variable input, PET, or the driving factor in the GCM projections, temperature. For this reason, comparisons between rainfall and recharge throughout this report are made using winter rainfall.

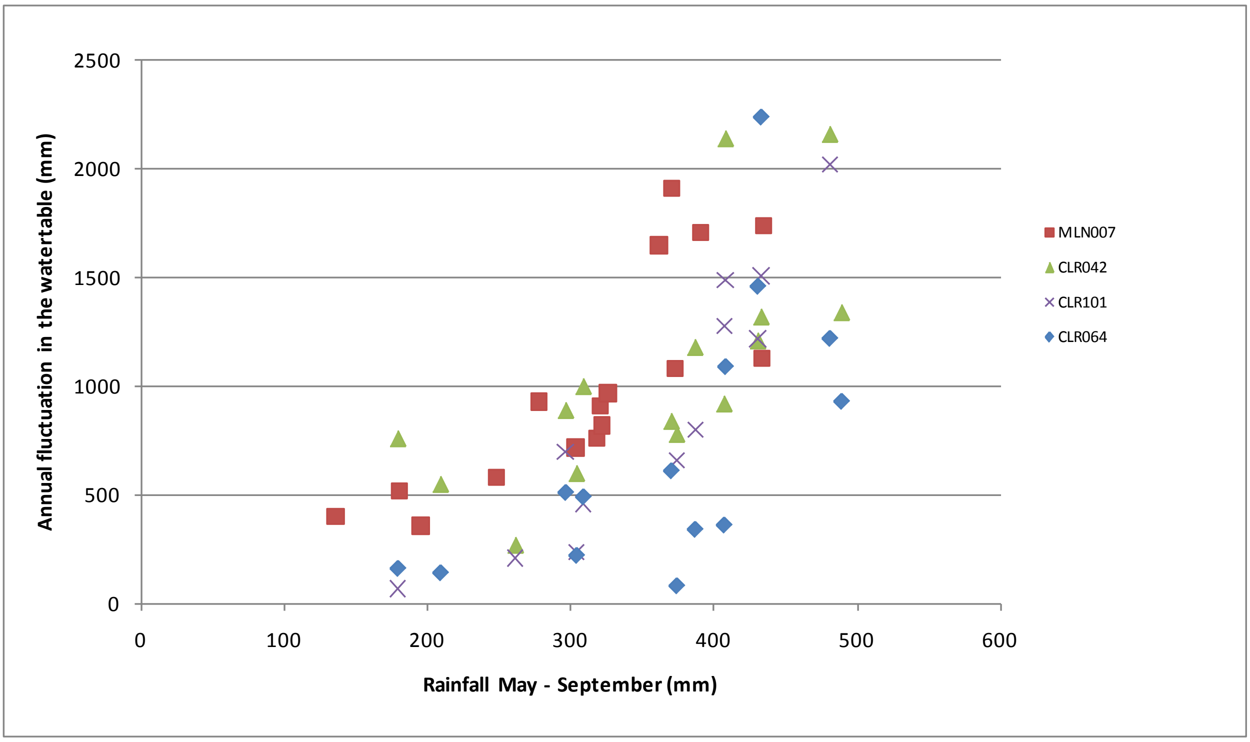


Figure 16. Relationship between annual groundwater level fluctuation in the Clare Valley (from selected Obswells) and winter rainfall, with r^2 = 0.4 – 0.8 for the separate data series

As stated, our aim is not to provide contemporary estimates of recharge from the water table fluctuation method, as we acknowledge the uncertainty involved in using this method in a fractured rock setting. Rather, the broad relationship between rainfall and aquifer response (using aquifer porosity to infer a recharge rate) is used as a guide to develop models to simulate groundwater recharge in the Clare Valley.

In this study, the Leaching Estimation and Chemistry Model (LEACHM, Hutson, 2003) has been used to model of the relationship between rainfall and recharge in the Clare Valley. 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 (Equation 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 each of which the thickness 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 (as discussed in section 3.3.2) and this was taken into account when assigning the water table depth for each of the LEACHM calibration models and the spatially distributed Clare Valley PWRA model. The effect of the fixed water table lower boundary condition is to create a constant matric potential at the models lower boundary equal to water table depth minus the thickness of the modelled soil profile. For example, with a fixed water table depth of 7 metres with a modelled soil thickness of 2 metres (as used in this study), the model will impose constant matric potential equivalent to -5 metres (approximately -50 kilopascals) 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 is 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, and 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. Thus,

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,

$$\text{Potential Transpiration, } T_p = \text{minimum of } T_pR_t \text{ and } T_p + E_p - \Delta t E_a$$

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 Clare Valley PWRA, dominant soil types were identified using the Land and Soil Spatial Data sets for the State (DWLBC, 2007). Seven dominant soil types in the region were identified, and these are summarised in Table 2.

Table 2. Dominant soil types of the Clare Valley PWRA

Soil code	Soil type description	LEACHGIS raster ID
C2	Gradational loam on rock	1
A6	Gradational calcareous clay loam	3
B4	Shallow red loam on limestone	4
D1	Loam over clay on rock	5
D2	Loam over red clay	6
D3	Loam over poorly structured red clay	7
L1	Shallow soil on rock	9

LEACHM models for each of these soil types were constructed based on models of like soil types in South Australia and based on existing data sets where measurements of soil physical properties had been made (Green, 2010). Each modelled soil profile in this study was defined as 2m deep with 20 layers, each of 0.1 m thickness. The groundwater monitoring network in the Clare Valley was then queried to identify groundwater hydrograph records that displayed some correlation with rainfall trends, or at least a seasonal flux in groundwater levels (ie. annual watertable fluctuations). Unfortunately, suitable groundwater data was only available for three of the seven dominant soil types, as summarised in Table 3. Figure 17 shows an example of data from observation well MLN007, each annual fluctuation being representative of annual recharge. As can be seen, groundwater level trends resemble rainfall trends, with declines in groundwater since 2002 being the result of below average rainfall and hence reduced recharge.

Table 3. Groundwater observation wells used in calibrating the LEACHM soil models

Soil type	Observation well
D1: Loam over clay on rock	CLR101
D2: Loam over red clay	MLN007
A6: Gradational calcareous clay loam	CLR042

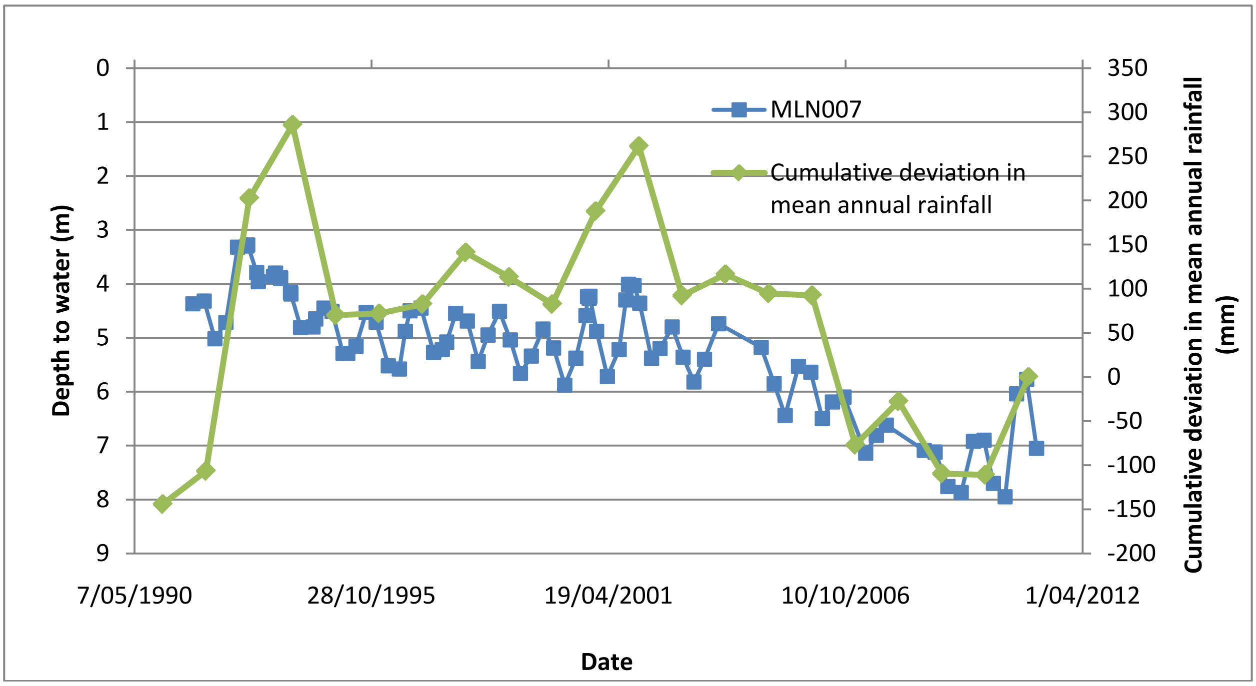


Figure 17. Groundwater levels in observation well MLN007, and cumulative deviation in mean annual rainfall recorded at Calcannia weather station (21075) located in the Clare Valley

For each observation well, the annual flux was measured and multiplied by the average porosity of the fractured rock aquifers in the area (6×10^{-2}, estimated based on values reported in Love et al., 2002), 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 30 – 75 mm/y, in agreement with the estimates based on hydrochemical methods. The LEACHM models for the dominant soil types were then run from 1990-2010 (as there is scant monitoring data in the Clare Valley PWRA prior to 1990). Weather data was taken from the nearest BoM weather station (BoM, 2010) and crop data was based on the identified land use (typically either irrigated vines or grazing modified pasture).

Estimated recharge rates from the observation wells were compared to LEACHM modelled drainage fluxes and calibration performed by altering the soil parameters in the LEACHM models, within realistic bounds, until a reasonable fit was observed. Figure 18 gives an example result, where LEACHM modelled recharge rates compare well with recharge rates estimated from an observation well. As emphasized above, a prediction of the precise recharge rate is not intended. It is intended that the model correctly represents the effect of annual variations in weather variables (primarily rainfall) on annual recharge fluxes. The skill of the model in this respect is illustrated in Figure 19, which plots the percent deviation in winter rainfall versus the percent deviation in estimated and modelled recharge. As the estimated recharge rates are based on watertable fluctuations, the trend is indicative of the relationship between rainfall and recharge and as can be seen, the LEACHM model reproduces this trend well. A close match between the slopes of the linear trend lines of variations in modelled and estimated recharge versus annual variations from mean measured annual rainfall is taken to indicate that the sensitivity of annual recharge fluxes to variations in annual rainfall is correctly predicted by the model.

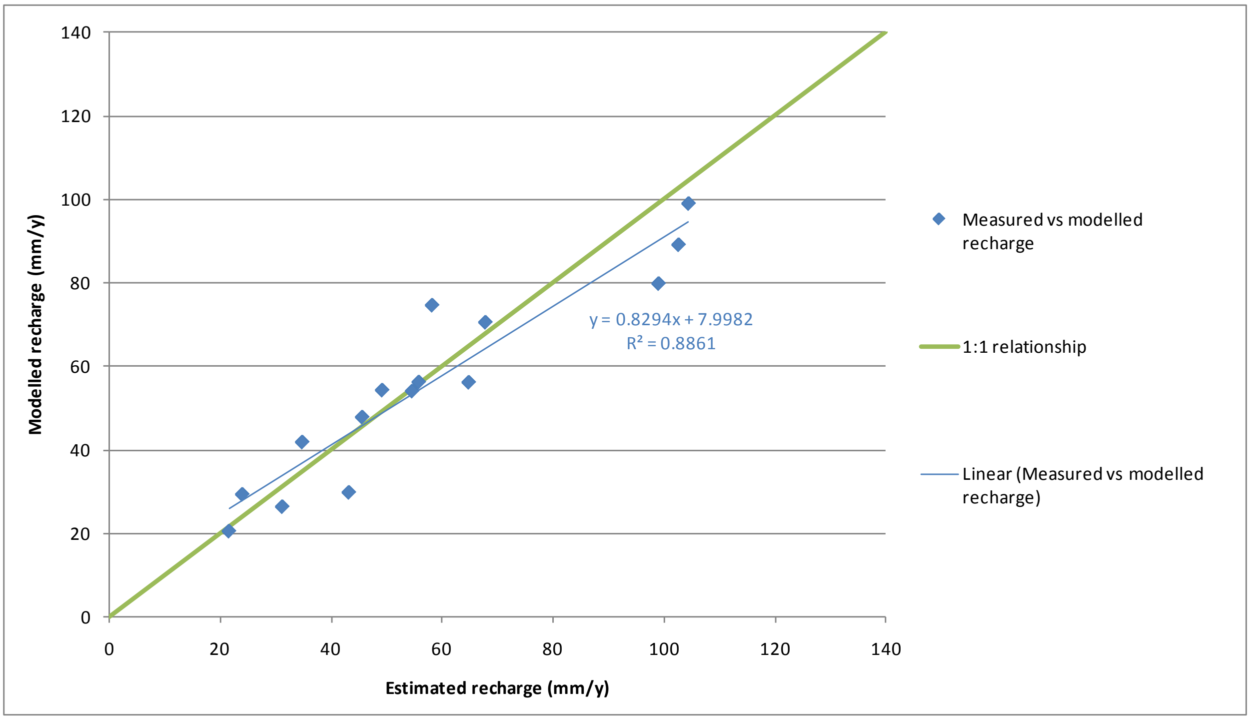


Figure 18. Modelled recharge rates (taken from LEACHM model of a loam over red clay soil) versus estimated recharge rates (based on observation well MLN007)

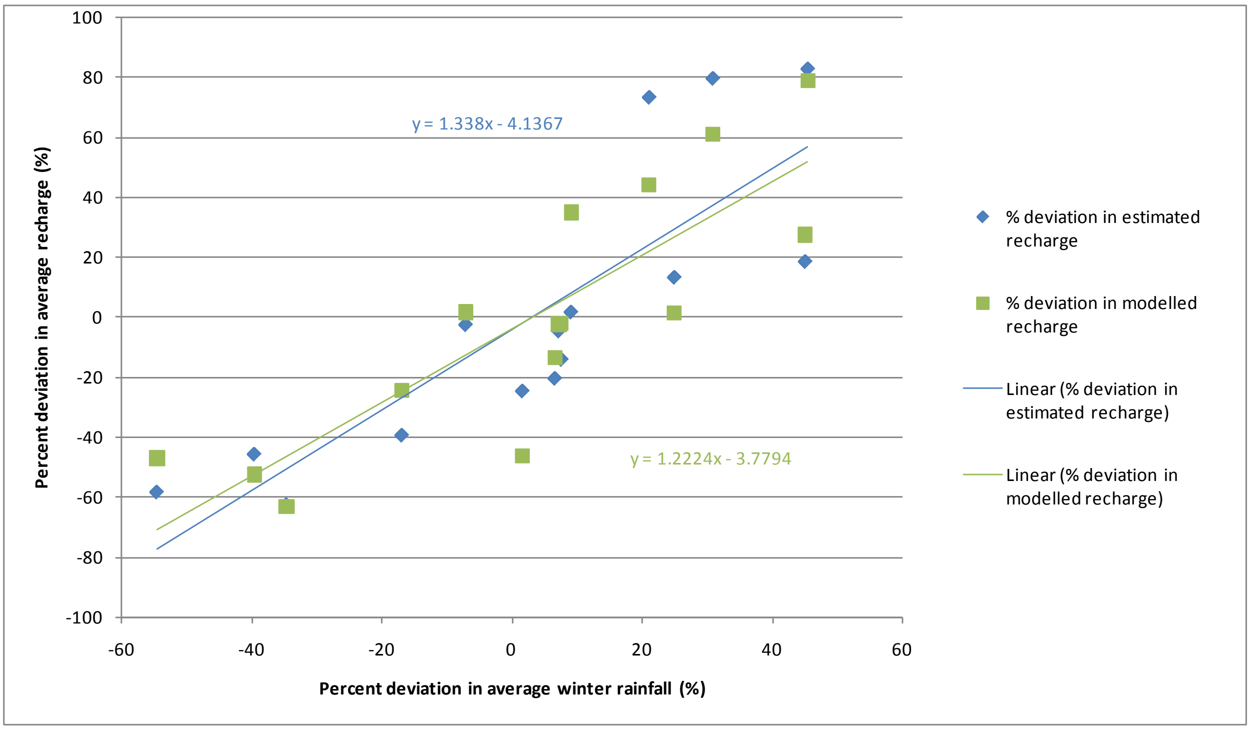


Figure 19. Modelled versus estimated percentage deviations in rainfall and recharge

Appendix A presents further results of this qualitative calibration process for other soil types. Models were also run from 1990-2010 for the remaining seven 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 by Love et al. (2002) and the slope of percent deviation plots seemed realistic (these results are also in Appendix A).

3.4.2. LEACHM-GIS MODELLING FRAMEWORK

The soil profile and land use descriptions from the calibrated LEACHM models described above were incorporated into a spatially distributed LEACHM framework linked to a geographical 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. Firstly, 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 is prepared in individual data files for each data 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 LEACHP 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 21 describes the whole LEACHG distributed modelling process.

The attributes for the Clare Valley PWRA are identified in a number of GIS layers. These were converted into raster image files with a spatial extent of the PWRA (Figure 20 to Figure 22).

Attributes combined by the LEACHG process were: soil type, land use, climate, water table depth and land slope. These were classified as described below.

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 for description in the model, out of a total of 17 soil types existing within the boundary of the PWRA. The remaining soil types were substituted with the most analogous major soil types. For example, in locations where the Land and Soil Spatial Database indicates soil type C3, ‘friable gradational clay loam’, this was substituted with major soil type A6, ‘Gradational calcareous clay loam’.

The LEACHG data files constructed for each soil type were based on the soil layers 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 addition, hydraulic properties were selected to represent flow in variably saturated conditions in the fractured rock layer that underlies several of the modelled soil types. 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.

Table 4. Soil types encoded into the Clare Valley PWRA LEACHG model (Soil type codes from DWLBC Soil and Land Information Group, 2002 (*Soils of South Australia's Agricultural Lands*)

Soil type code	**Area (Ha)**	**Soil description**	**Substited by**
D1	13793.6	Loam over clay on rock	Not substituted
L1	10156.8	Shallow soil on rock	Not substituted
D3	8505.5	Loam over poorly structured red clay	Not substituted
C2	8494.4	Gradational loam on rock	Not substituted
K2	7852.6	Acidic loam over clay on rock	D1
K3	4966.2	Acidic sandy loam over red clay on rock	D1
A6	3540.0	Gradational calcareous clay loam	Not substituted
D7	3287.4	Loam over poorly structured clay on rock	D1
D2	2059.6	Loam over red clay	Not substituted
A2	1411.7	Calcareous loam on rock	C2
M2	1370.1	Deep friable gradational clay loam	A6
B4	1189.3	Shallow red loam on limestone	Not substituted
B3	907.5	Shallow sandy loam on calcrete	B4
F2	812.6	Sandy loam over poorly structured brown or dark clay	D3
F1	673.4	Loam over brown or dark clay	D2
E1	555.4	Black cracking clay	D2
C3	523.0	Friable gradational clay loam	A6

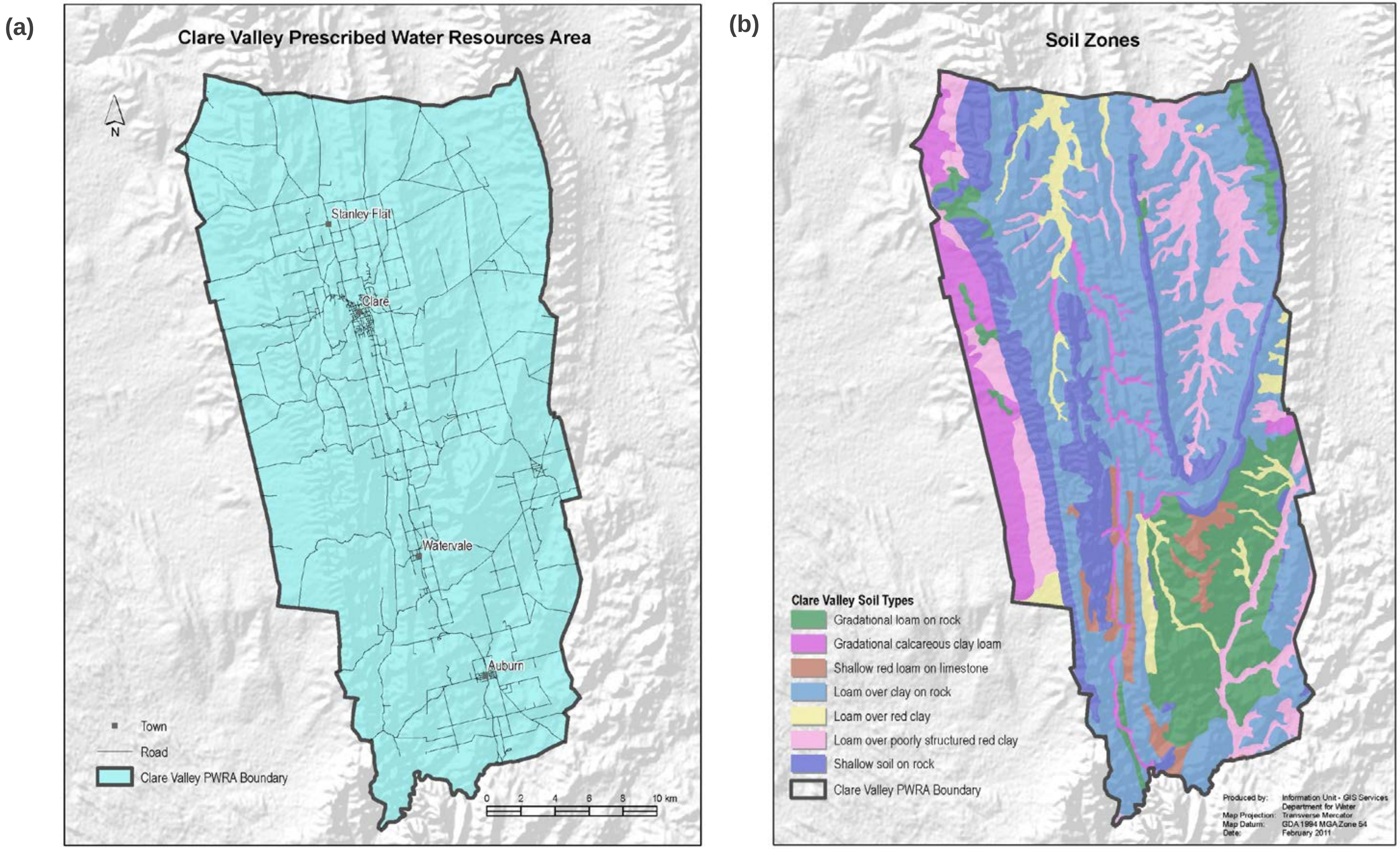


Figure 20. (a) Study area and model domain for the spatially distributed recharge model and (b) Distribution of major soil types defined in the model

Land Use

Land uses were defined by the 2008 State Land Use coverage (DWLBC, 2008). Twelve major land use types were identified within the boundary of the Clare PWRA (Table 5). A further ten land use types with minor coverage in the area were also identified and these were each substituted with one of the major land use types. Only the major land use types were encoded into input files for the LEACHG model. The minor land use types that were substituted only comprise approximately 0.4% of the total study area and hence the substitution of these is considered to have insignificant effect on the model results. The land use description files for LEACHG describe the crop or vegetation growth periods, soil or vegetation cover percentages and evapotranspiration factors for each land use type included in the model.

Table 5. Land use types encoded into the Clare PWRA LEACHG model

Land use type	Total area (Ha)	Substituted by
Grazing modified pastures	31032.2	Not substituted
Cereals	17123.8	Not substituted
Grazing natural vegetation	4928.4	Not substituted
Irrigated vine fruits	4857.9	Not substituted
Legumes	3871.7	Not substituted
Oil seeds	3793.1	Not substituted
Roads	1968.0	Not substituted
Rural residential	693.5	Not substituted
Irrigated sown grasses	664.9	Not substituted
Natural feature protection	396.5	Not substituted
Urban residential	348.6	Not substituted
Irrigated perennial horticulture	132.3	Not substituted
Other conserved area	72.2	Grazing natural vegetation
Recreation and culture	69.2	Rural residential
Reservoir/dam	49.2	Natural grass growth/senescence
Manufacturing and industrial	43.9	Roads
Intensive animal production	12.7	Rural residential
Services	10.5	Roads
Softwood production	10.2	Grazing natural vegetation
Public services	8.4	Roads
Wastewater treatment	6.6	Natural grass growth/senescence
Quarries	5.4	Roads

The LEACHG input file for each land use describes the mix of vegetation coverage 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 stated, together with crop cover fractions at maturity and harvest. For perennial non-deciduous vegetation, a fixed cover percentage is stated. 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 stated. 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 that the resulting amount of water is transpired from 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 difference between the crop cover percentage and 100% is assumed to be the percentage of exposed soil from which water can evaporate. 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.

A 'mulch' factor is also applicable which limits the amount of water that can be evaporated from the exposed soil percentage. Up to 100% of the modelled evaporation from the exposed soil can be restricted by this factor. This allows an approximation of the evaporation conditions for non-vegetated land use types such as roads, for which a high mulch 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 mulch 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. Roads and the land use types substituted by the Roads land use description represent 2.9% of the total area simulated (model domain).

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. The trigger values set within the irrigation files for the irrigated land use types were:

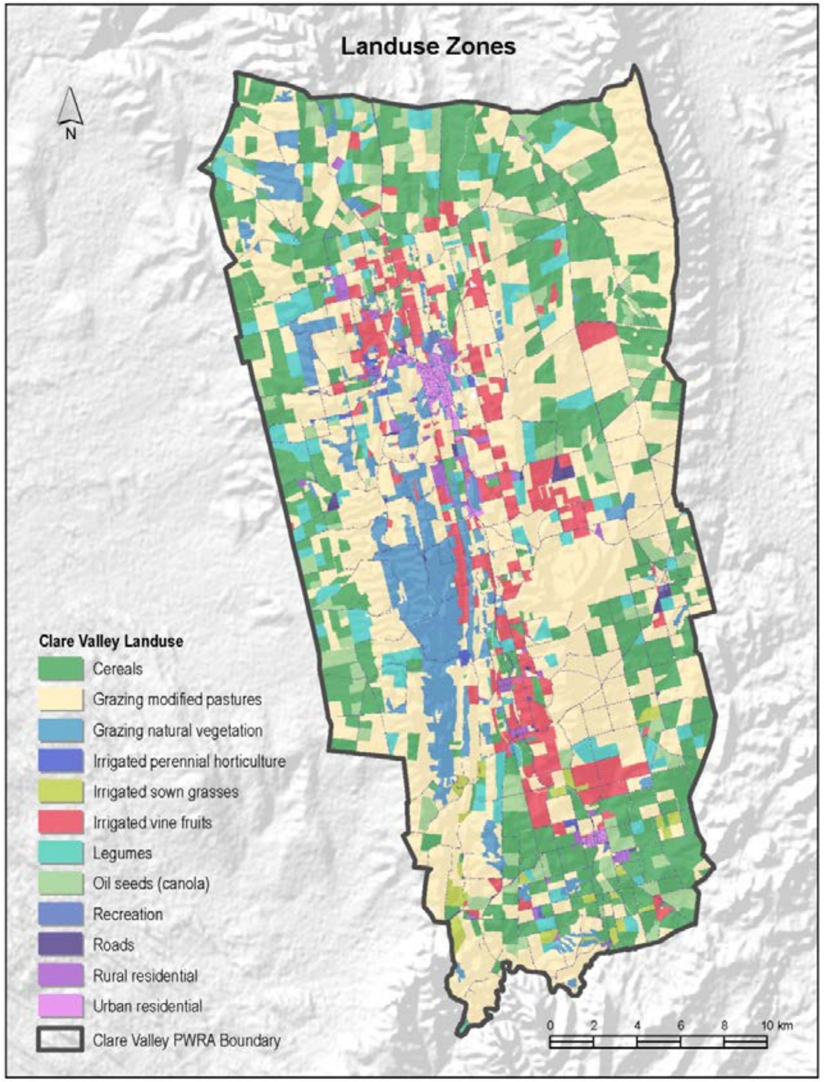
- Lucerne: -35 KPa
- Grape vines: -35 KPa
- Irrigated sown grasses: -30 KPa
- Irrigated perennials (fruit trees): -25 KPa

Climate Zone

Two climate zones were defined for the study area. The analysis of historic rainfall and PET data from the three rainfall stations of Calcannia, Hill River and Watervale as discussed in section 2.1.2 indicate that the conditions at the Watervale and Hill River stations are very similar, while weather conditions at the Calcannia station are closely correlated with the other two but with consistently lower rainfall and higher PET. The Hill River and Watervale stations both lie within the 625 mm rainfall isohyet, while the Calcannia station lies outside. This isohyet, which forms a closed boundary within the study area, was therefore used to define a boundary between two climate zones: the area inside the 625 mm isohyet was taken to be represented by the Hill River weather station and the area within the PWRA outside of the 625 mm isohyet was taken to be represented by the Calcannia weather station. These zones are depicted in Figure 21.

Historic weather variable data from the Hill River weather stations for the 50-year period 1961 – 2010 was used for the higher rainfall zone (climate zone 2) in the historic baseline simulation with the LEACHG model. The historic baseline weather data for climate zone 1 was generated by scaling the Hill River rainfall data down by 12.5% and the Hill River PET data up by 5%. This was necessary to ensure that the scaled weather data sets representing future climate conditions would correlate between climate zones 1 and 2. Future climate weather variable data sets, representing climates of 2030, 2050 and 2070 under high and low emissions scenarios, were generated from the these baseline weather data sets according to the method described in the ICCWR Project Phase 2 report (Gibbs et al., 2011).

(a)



(b)

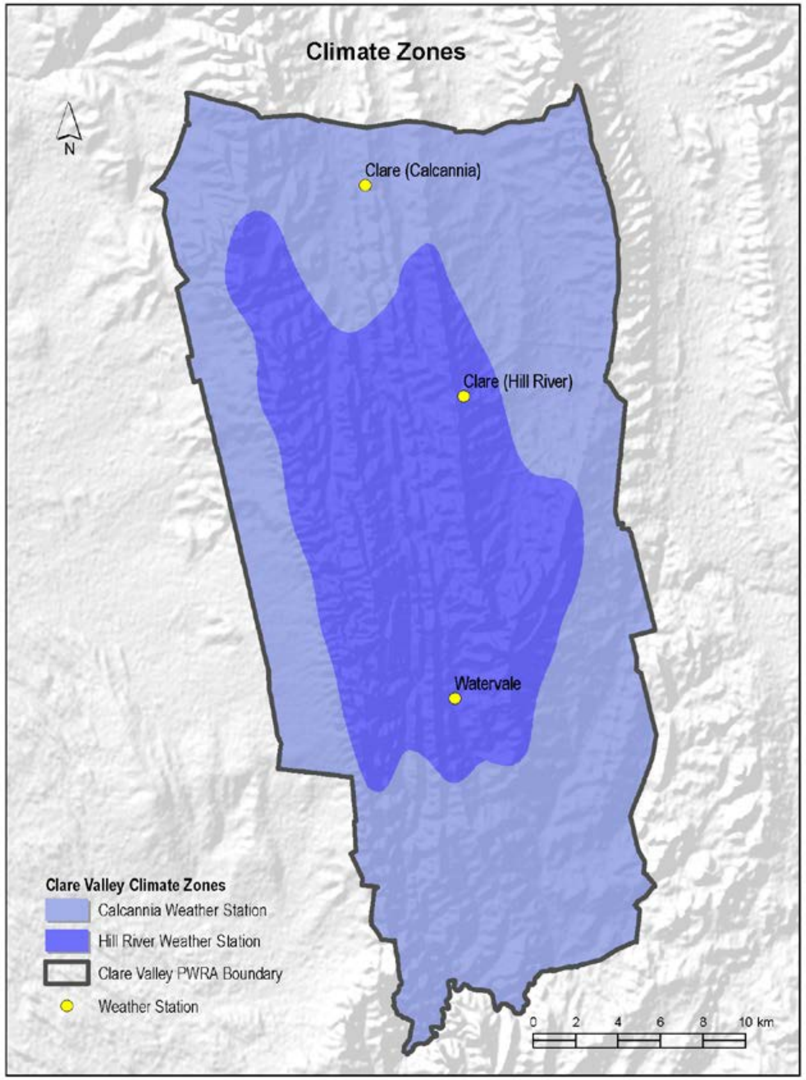


Figure 21. (a) Distribution of major land use types and (b) Distribution of two climate zones defined for the recharge model

Depth to Water

Water table depth was interpolated from standing water level (SWL) measurements from 1670 wells in and around the Clare Valley PWRA study area. The interpolation included water levels from wells that are beyond the boundary of the study area to ensure a smooth interpolation at the edges of the study area. The resulting interpolated surface represents the variations in depth to water across the study area. The surface was clipped to the boundary of the PWRA and then reclassified into seven depth classes: 1 – 2 m, 2 – 3 m, 3 – 4 m, 4 – 6 m, 6 – 8 m, 8 – 12 m and >12 m. The resulting raster of the depth-to-water zones is depicted in Figure 22. When read into the LEACHG model, the seven classes were converted to individual water table depths of 1.5 m, 2.5 m, 3.5 m, 5 m, 7 m, 10 m and 14 m respectively. These fixed water table depths are applied in the model for all locations where the raster image indicates their corresponding water tables depth class exists.

Land Slope

A raster image of land slope was generated from the Clare Valley part of the SA 1-second digital elevation model. This was then reclassified into a raster image with eight slope classes. The resulting raster of land surface slopes is depicted in Figure 22. When read into the LEACHG model, the eight slope classes were converted to individual slope values (Table 6) to be applied in the model according spatial distribution of the slope values depicted by the raster image.

Table 6. Classification of land slopes in the Clare Valley PWRA LEACHG model

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

Surface runoff is adjusted in the LEACHG model according to a runoff curve function that is adjusted according to the slope value. 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.

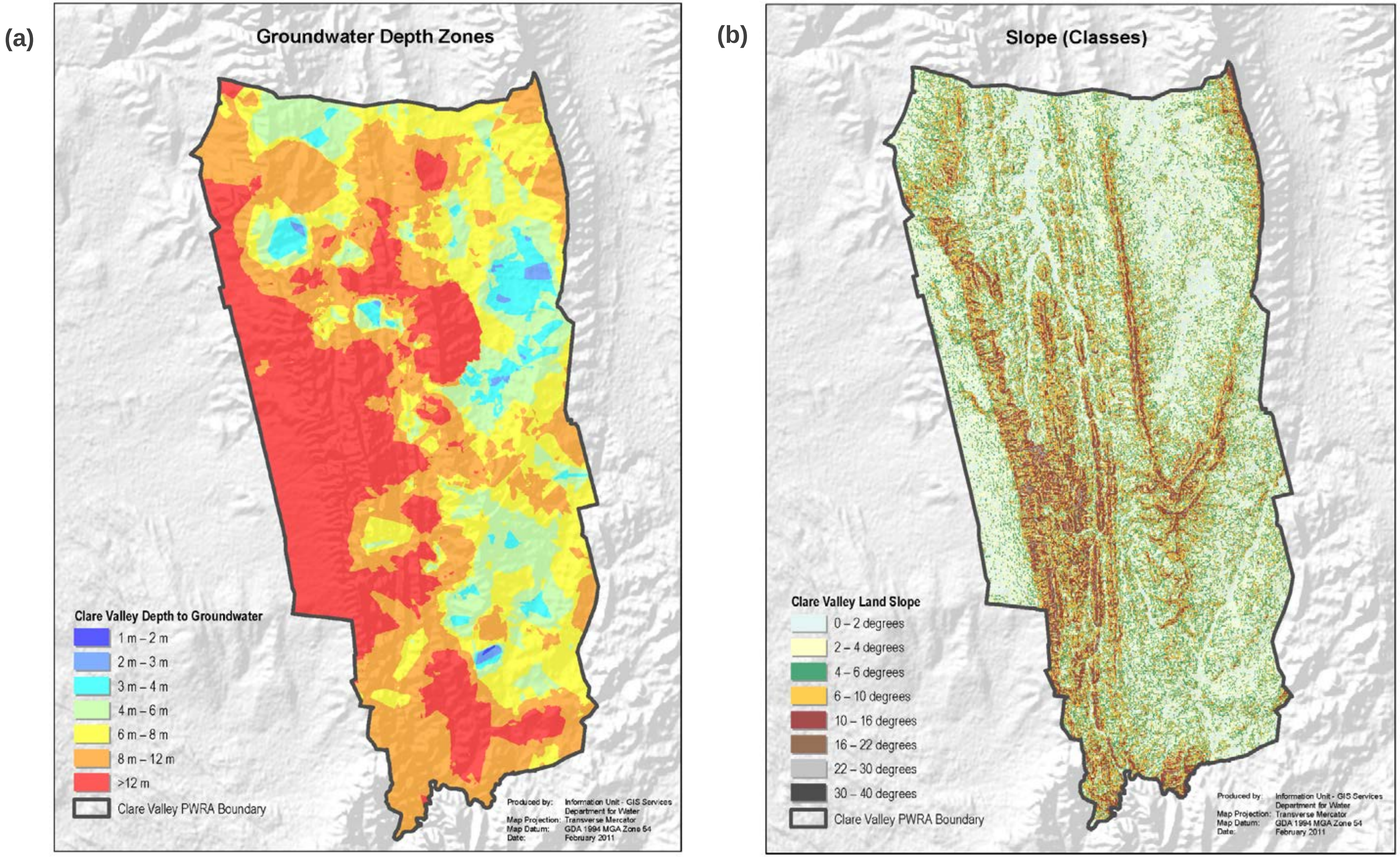


Figure 22. (a) Distribution of groundwater depth classes and (b) Distribution of land slope classes defined for the recharge model

Aggregation of Spatial Variables in LEACHG Model

The LEACHG model overlays all five raster images (soil, land use, climate, depth to water, slope) and determines all combinations of values of these 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 this simulation, a cell size of 30 m x 30 m was used, equivalent to 0.09 hectares.

The maximum number of possible combinations that can exist within the study area is a product of the number of values for each variable type:

7 soil types
x 12 land use types
x 2 climates
x 7 depth to water classes
x 8 slope classes
= 9408 possible combinations.

The overlay of the five attribute rasters for the Clare Valley study area resulted in 2753 combinations. After calculating 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 two climate zones depending on which 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 files also includes the amount of area (Ha) to which each combination simulation applies within the study area.

Analysis of the distribution of area covered by these combinations showed that a large number of combinations each only covered one cell (0.09 Ha) of the study area and that approximately 62% of the study area was represented by the top 200 combinations in terms of area covered by each. It was determined that these top 200 combinations provided a suitably distributed range of the combined variables, and a sufficient percentage of the study area, to represent the recharge characteristics of the whole study area. To aid the practicality of model processing time and data output handling, the recharge models used for the baseline and future climate scenarios were run using only these top 200 combinations.

The LEACHG model was run firstly for the period 1961 – 2010 using historic rainfall and PET data from the Hill River weather station, with an adjustment of these data to represent the Calcannia weather station. The same model was then run six further times with the same weather data scaled as described in the ICCWR Phase 2 Report (Gibbs et al., 2011) to represent the climates of 2030, 2050 and 2070 under high and low emissions scenarios. 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 flowchart in Figure 23.

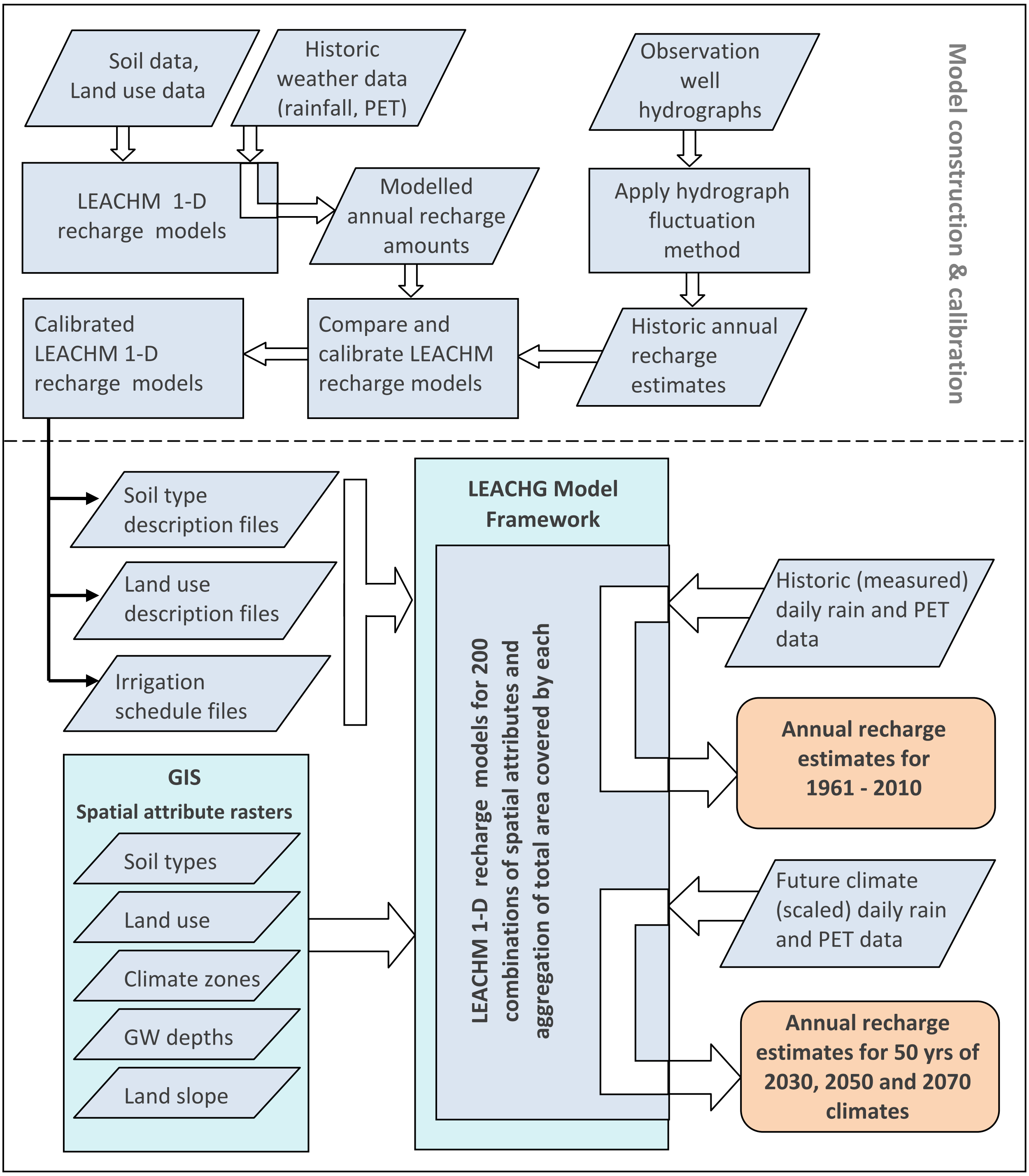


Figure 23. Flowchart of groundwater recharge modelling framework applied to the Clare Valley PWRA

3.4.3. BAROOTA PWRA

Groundwater levels in the Baroota PWRA generally follow the pattern of cumulative deviation in mean monthly rainfall, which suggests that diffuse (rainfall) infiltration contributes to recharge (Barnett, 2009). However, given the deep watertable (generally >10 m below ground level, and up to 40m in some areas), the lack of seasonal fluctuations observed in the watertable and lack of any recharge estimates from previous studies, it is difficult to quantify diffuse recharge and then create LEACHM models to simulate it. Furthermore, the most significant recharge process in Baroota appears to relate to conditions in Baroota Reservoir. Significant recharge events, marked by significant rises in groundwater level, correspond with times at which the Reservoir reaches a critical level of 20m and overflows into Baroota Creek. The resulting flows in Baroota Creek below the reservoir allow significant volumes of surface water to infiltrate through the creek bed and become groundwater recharge. This is illustrated in Figure 24, from Barnett (2009).

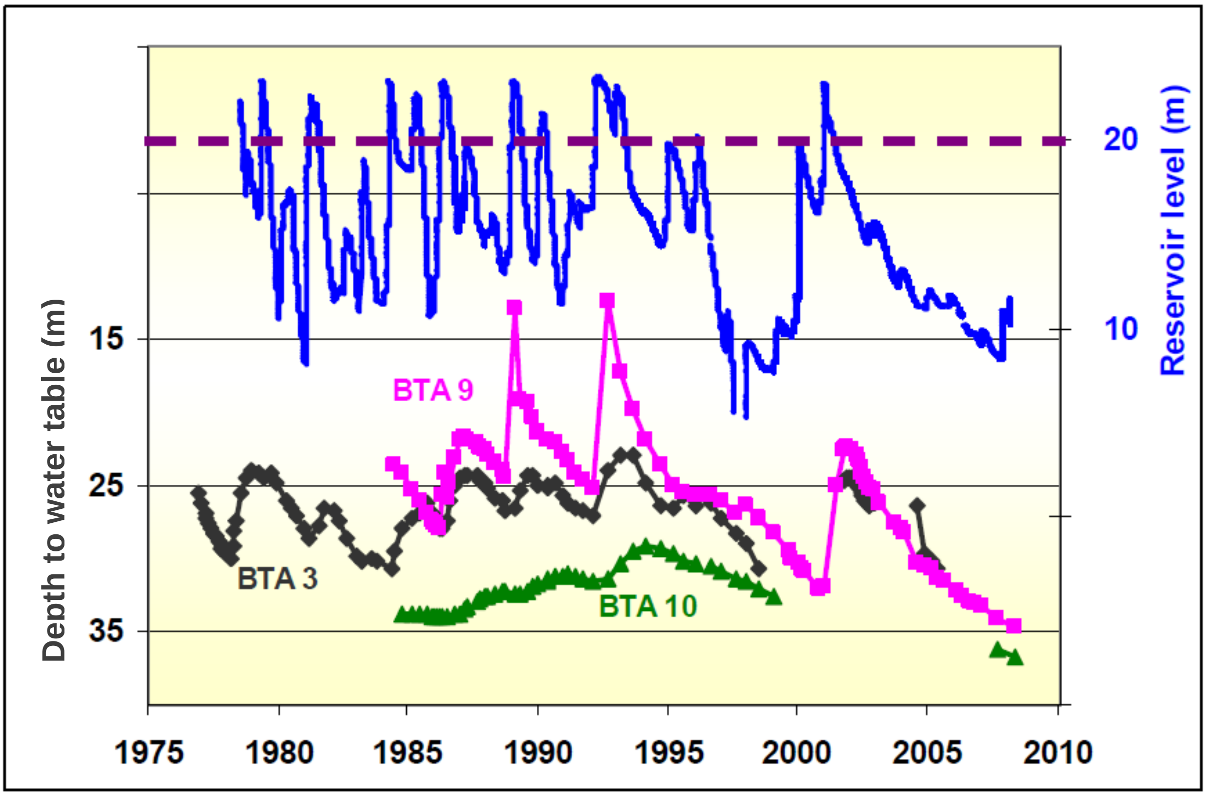


Figure 24. Groundwater levels in Baroota PWRA, showing fluctuations in response overflow events from Baroota Reservoir (taken from Barnett, 2009)

For these reasons, LEACHM models for simulating recharge were not constructed for Baroota. Rather, the outputs of surface water models of Baroota Reservoir were analysed to see how often the critical level (which leads to overflow of the reservoir and groundwater recharge) is reached under future climate scenarios. Therefore, the potential impacts of climate change on groundwater resources in Baroota are not reported as a change in recharge in mm/y or in volume, but rather as a change in the frequency of significant recharge events.

4. MODEL RESULTS

4.1. CLARE VALLEY PWRA

4.1.1. CLARE VALLEY 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 Hill River rainfall station in the Clare Valley (A21025) as an example, Figure 23 shows the percent changes in average annual rainfall for the four GCMs under the A2 and B1 emission scenarios. At first glance, it appears that the NCAR GCM predicts the lowest reduction in rainfall, while the CSIRO Mk 3.5 GCM predicts the greatest. However Figure 26 shows the percent change in average winter rainfall (taken from June to August, when monthly rainfall generally exceeds monthly PET), which is generally more important in generating groundwater recharge and surface water run-off. As can be seen, the LASG-IAP GCM predicts the least reduction in winter rainfall, while the CSIRO Mk 3.5 GCM still predicts the greatest reduction.

Figure 27 shows the annual change in PET, with the CSIRO Mk 3.5 GCM again predicting the greatest change, followed closely by the NACR GCM. However the NCAR GCM predicts the greatest increase in winter PET (Figure 28), which is potentially more significant than the annual change, considering the influence of winter PET on recharge/runoff. The MRI GCM shows the lowest increase in winter PET, however it displayed the second highest decrease in winter rainfall.

Generally, both A2 and B1 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, 2007). However a greater discrepancy is observed for 2050 and 2070, with a greater reduction in rainfall and increase in PET observed for the A2 story line, which predicts greater emissions than the B1 story line after 2030.

The graphs in Figures 25 to 28 illustrate the rainfall and PET projections of the individual GCMs for the Clare Valley under various scenarios. The GCM projections are derived from the CSIRO's Ozclim climate scenario generator, which uses a relationship between the projected global temperature change and the local variable (rainfall or PET) change, to produce the trend projected for a given year. This method allows a trend to be identified, without natural climate variability obscuring the relationship. However, this also means that only the average projected change in the variable is produced, without the error or uncertainty around the projection provided by the GCM. Hence, the graphs in figures 25 to 28 do not show uncertainty bounds for the projected changes.

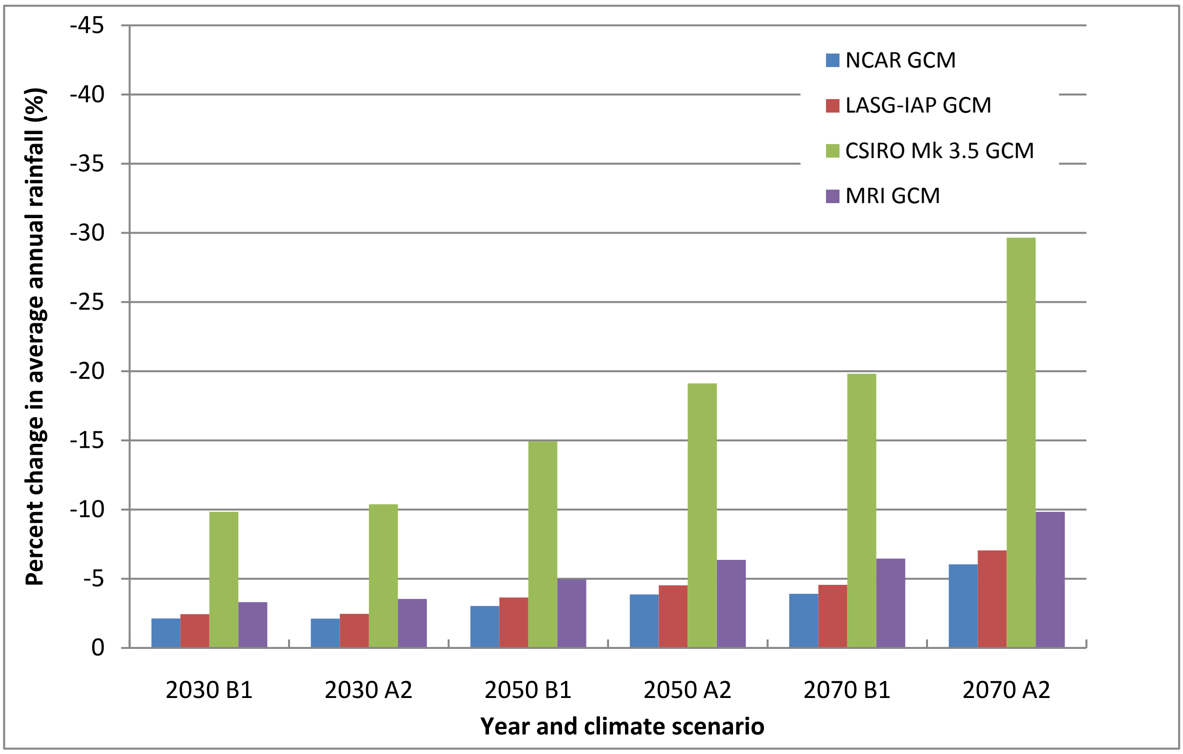


Figure 25. Percent reduction in average annual rainfall produced by the four different GCMs under the A2 and B1 emissions scenarios (based on historic rainfall data taken from the Hill River weather station)

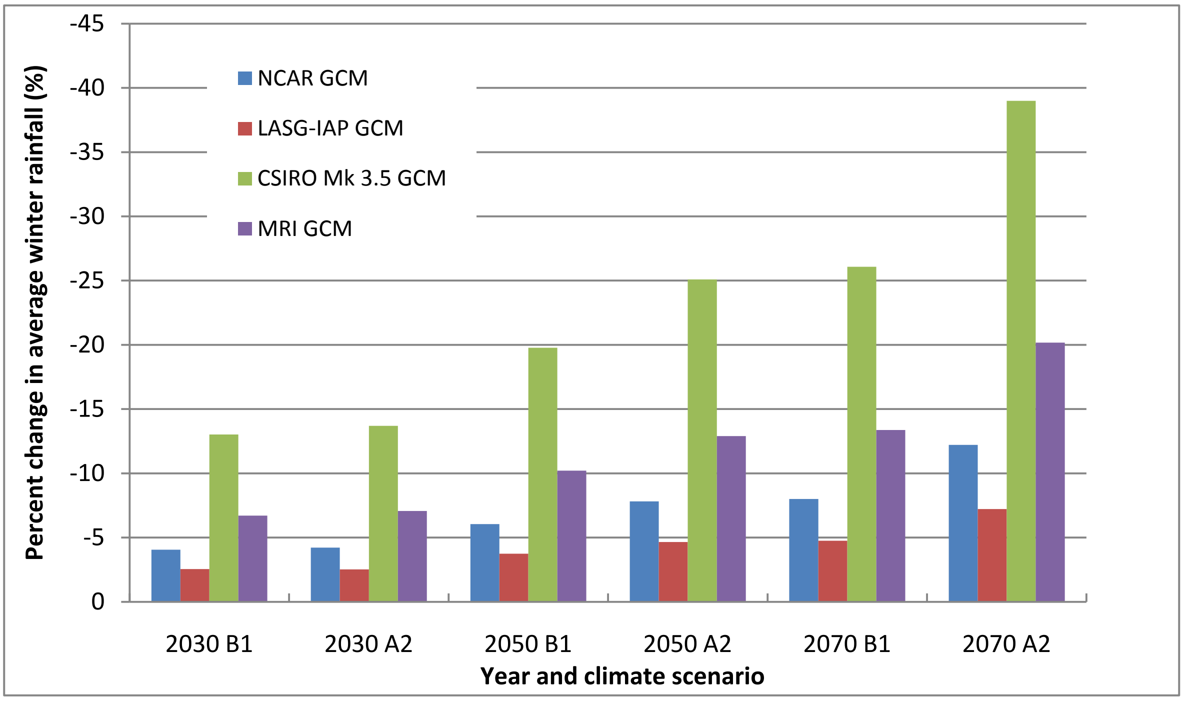


Figure 26. Percent reduction in average winter (June to August) rainfall produced by the four different GCMs under the A2 and B1 emissions scenarios (based on historic rainfall data taken from the Hill River weather station)

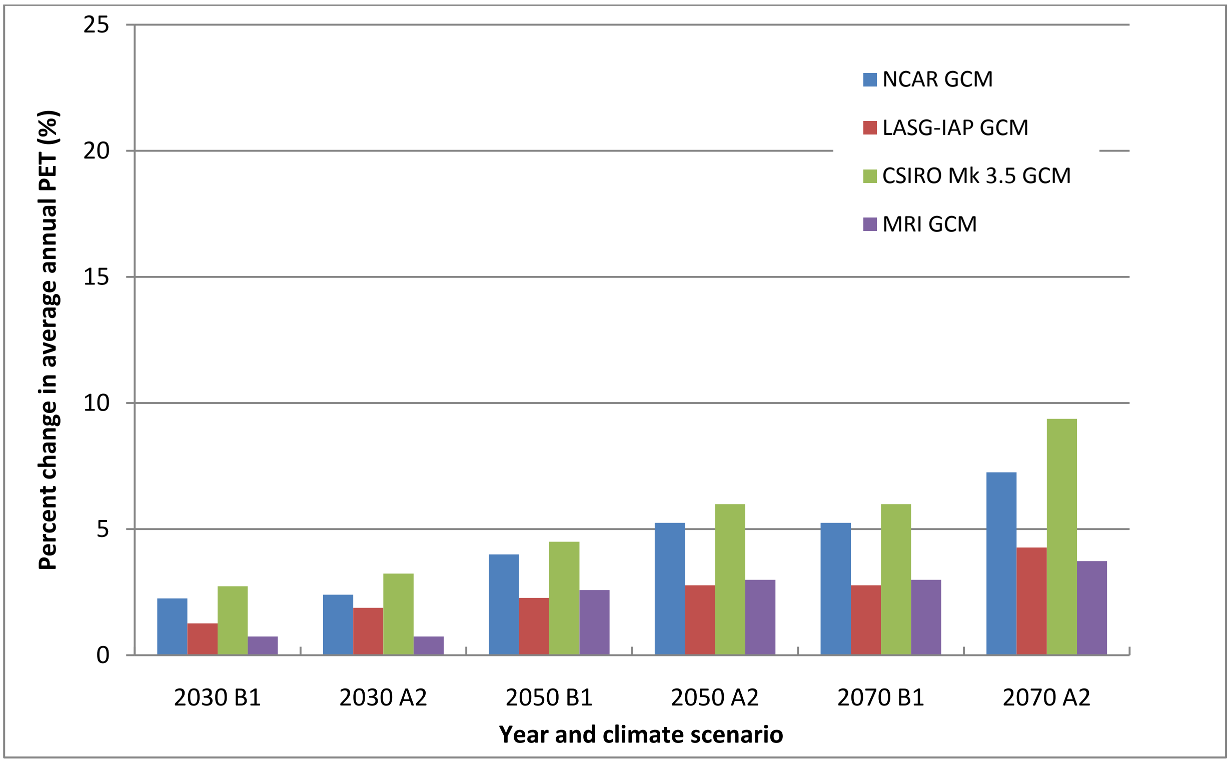


Figure 27. Percent increase in average annual PET produced by the four different GCMs under the A2 and B1 emissions scenarios (based on historic rainfall data taken from the Hill River weather station)

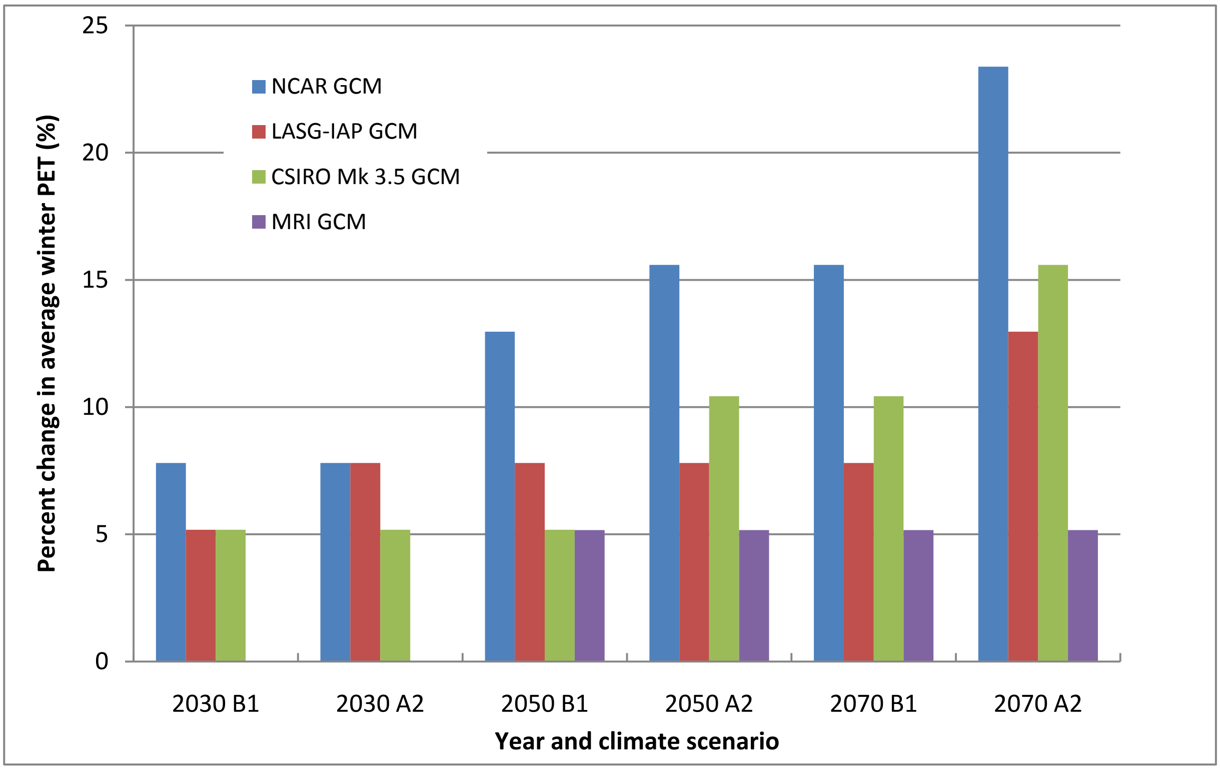


Figure 28. Percent increase in average winter (June to August) PET produced by the four different GCMs under the A2 and B1 emissions scenarios (based on historic rainfall data taken from the Hill River weather station)

4.1.2. SURFACE WATER RUNOFF MODELS – WAKEFIELD AND HUTT RIVERS

The results from the surface water modelling are summarised in Figure 29 for Hutt River and Figure 30 for Wakefield River. The general trend is similar across the catchments, with the percent reduction in runoff increasing into the future and greater reductions for the higher emission case of A2 compared to the lower case emissions case of B1.

The effect of the extreme rainfall projections provided by the CSIRO Mk 3.5 GCM (Figure 25 and Figure 26) is evident, with the resulting decrease in runoff close to double that simulated based on the other three GCMs for the cases considered up to 2070. The remaining three GCMs, NCAR-CCSM3, LASG-IAP and MRI are relatively consistent across the different scenarios for the both catchments, with the change in median runoff from each GCM projection within 15% change in median annual runoff for all time horizons and emission cases. For these catchments the projected change in rainfall has a greater impact on the resulting change in runoff compared to the changes in PET, hence the GCMs are more consistent for the runoff results compared to the recharge results, further outlined in the section 4.1.3.

For a given future time horizon and emission scenario, the climate change impacts were found to be slightly greater for the Hutt River (Figure 29) compared to the Wakefield River (Figure 30). This is due to the Hutt River being a smaller catchment typically experiencing very quick flow events, generally occurring for only a number of days and only after large rainfall events, and hence more susceptible to changes in amount of rainfall.

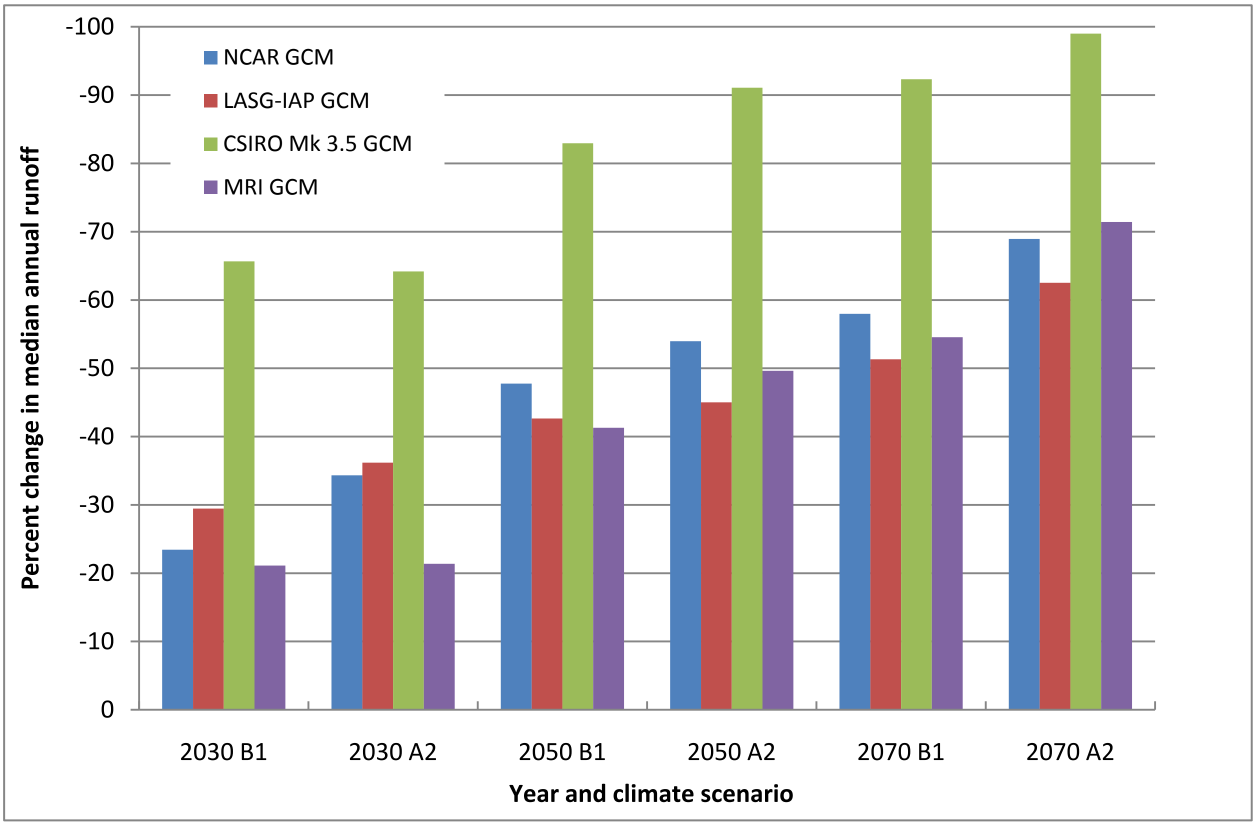


Figure 29. Estimated changes in average annual runoff for Hutt River

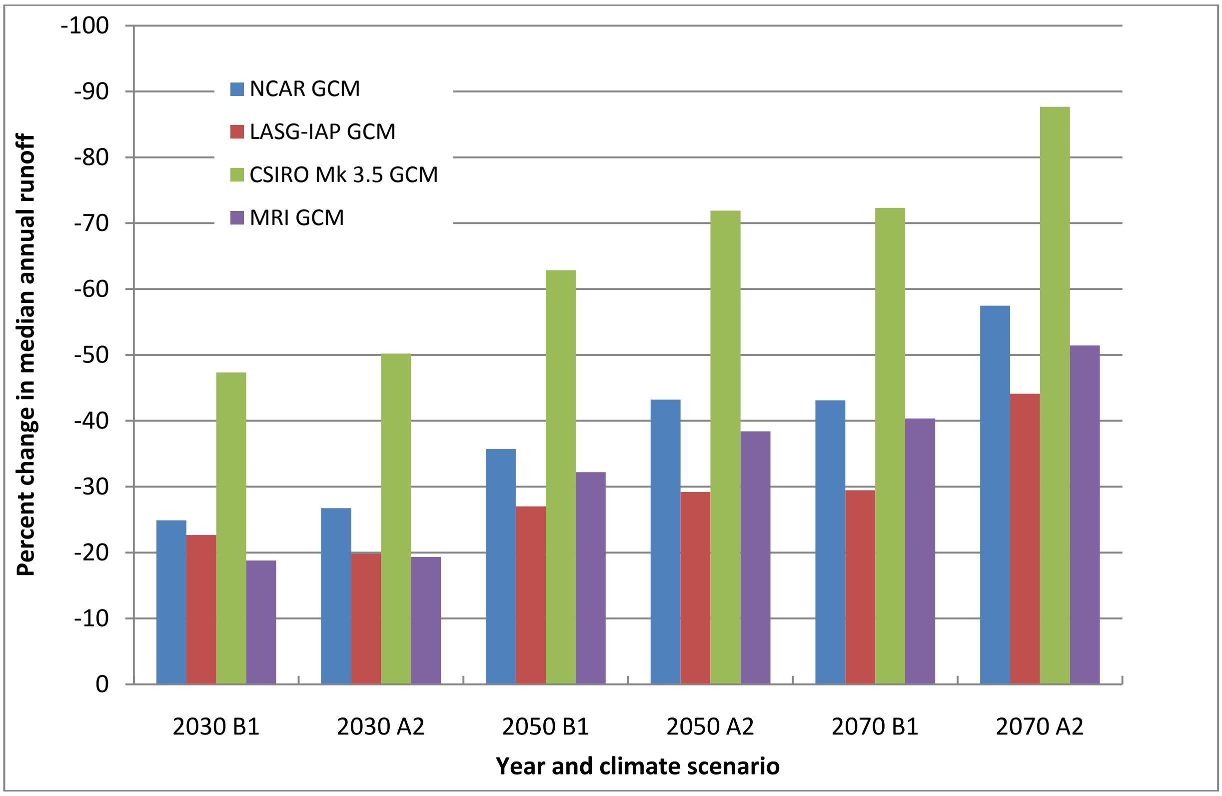


Figure 30. Estimated changes in average annual runoff for Wakefield River

Values for the change in median runoff for Wakefield River (as presented in Figure 29 and Figure 30) can be seen in Table 7 to Table 10 for each GCM, as well as the change in average rainfall and PET projected by each GCM that produced that change in runoff. Similar results are obtained for the Hutt River catchment and corresponding tables are provided in Appendix B. Median, rather than average, runoff has been presented, as the distribution of flow is positively skewed, resulting in larger average values biased by high flow years. Rainfall and PET data are much more evenly distributed, where the median and average values are typically very similar.

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. For each GCM, the historic 20th and 80th percentile annual flows is presented in the 1990 column, and 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.

It can be seen from Table 7 to Table 10 that for all cases it is not only the median flow that is decreasing, but the whole flow distribution that is changing. With each increasing time horizon or emission case the number of flow events below the historic low flow level is increasing and the number of years above the high flow level continually decreasing. Again, the CSIRO Mk 3.5 can be seen to be much more extreme than the other three GCMs selected. For the 2070 A2 scenario 43 of the 50 years simulated are below the historic 20th percentile flow and the high 80th percentile flow for the future case equal to approximately 30% of the historic median flow.

Table 7. Changes in climate and runoff simulated for Wakefield River using input data generated using the LASG-IAP GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	558	546	545	539	534	534	521
Average Winter Rainfall (mm)	207	203	203	200	198	198	193
Average Annual PET (mm)	1264	1287	1289	1295	1299	1301	1325
Average Winter PET (mm)	128	137	137	137	137	137	146
Median Annual Runoff (ML)	6270	4850	5026	4576	4439	4423	3505
Change in Annual Rainfall (%)		-2	-2	-3	-4	-4	-7
Change in Winter Rainfall (%)		-2	-2	-3	-5	-4	-7
Change in Annual PET (%)		2	2	2	3	3	5
Change in Winter PET (%)		7	7	7	7	7	14
Change in Median Runoff (%)		-23	-20	-27	-29	-29	-44
Low Events							
20th Percentile Runoff (ML)	2752	2140	2244	1962	1940	1827	1447
Years Below 1990 20th %	10	12	12	13	14	14	18
High Events							
80th Percentile Runoff (ML)	14308	12329	12000	11675	11168	10890	8838
Years Above 1990 80th %	10	7	7	7	6	6	6

Table 8. Changes in climate and runoff simulated for Wakefield River using input data generated using the NCAR-CCSM3 GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	558	546	545	541	536	535	524
Average Winter Rainfall (mm)	207	200	199	195	192	192	183
Average Annual PET (mm)	1264	1293	1295	1313	1328	1328	1360
Average Winter PET (mm)	128	137	137	143	146	146	157
Median Annual Runoff (ML)	6270	4709	4594	4029	3561	3567	2666
Change in Annual Rainfall (%)		-2	-2	-3	-4	-4	-6
Change in Winter Rainfall (%)		-4	-4	-6	-8	-8	-12
Change in Annual PET (%)		2	2	4	5	5	8
Change in Winter PET (%)		7	7	12	14	14	23
Change in Median Runoff (%)		-25	-27	-36	-43	-43	-57
Low Events							
20th Percentile Runoff (ML)	2752	2539	2497	1913	1824	1634	1355
Years Below 1990 20th %	10	12	12	17	17	17	26
High Events							
80th Percentile Runoff (ML)	14308	13474	12761	10262	9475	9169	7763
Years Above 1990 80th %	10	9	8	6	6	6	6

Table 9. Changes in climate and runoff simulated for Wakefield River using input data generated using the MRI GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	558	541	539	532	524	523	506
Average Winter Rainfall (mm)	207	194	193	187	181	181	167
Average Annual PET (mm)	1264	1273	1276	1297	1301	1301	1310
Average Winter PET (mm)	128	128	128	134	134	134	134
Median Annual Runoff (ML)	992	805	800	673	611	592	481
Change in Annual Rainfall (%)		-3	-3	-5	-6	-6	-9
Change in Winter Rainfall (%)		-7	-7	-10	-13	-13	-19
Change in Annual PET (%)		1	1	3	3	3	4
Change in Winter PET (%)		0	0	5	5	5	5
Change in Median Runoff (%)		-19	-19	-32	-38	-40	-51
Low Events							
20th Percentile Runoff (ML)	469	393	372	331	295	304	244
Years Below 1990 20th %	10	12	12	15	17	18	24
High Events							
80th Percentile Runoff (ML)	2215	2134	2162	1899	1755	1643	1332
Years Above 1990 80th %	10	8	8	6	6	6	5

Table 10. Changes in climate and runoff simulated for Wakefield River 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)	558	505	501	477	454	451	398
Average Winter Rainfall (mm)	207	182	180	168	158	155	130
Average Annual PET (mm)	1264	1304	1304	1325	1337	1339	1388
Average Winter PET (mm)	128	134	134	137	140	140	146
Median Annual Runoff (ML)	6270	3301	3123	2328	1762	1735	773
Change in Annual Rainfall (%)		-10	-10	-15	-19	-19	-29
Change in Winter Rainfall (%)		-12	-13	-19	-24	-25	-37
Change in Annual PET (%)		3	3	5	6	6	10
Change in Winter PET (%)		5	5	7	10	10	14
Change in Median Runoff (%)		-47	-50	-63	-72	-72	-88
Low Events							
20th Percentile Runoff (ML)	2752	1623	1516	1129	913	905	273
Years Below 1990 20th %	10	20	21	29	35	36	43
High Events							
80th Percentile Runoff (ML)	14308	8084	7860	5745	4291	4193	1825
Years Above 1990 80th %	10	6	6	3	1	1	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 medium projection for the change in winter rainfall, with the MRI and LASG-IAP GCMs generally a smaller change in runoff and the CSIRO Mk 3.5 GCM much higher. The historic scenario is presented in Figure 31, followed by each time horizon and emission case considered in Figure 32 to Figure 37. Similar results are obtained for the Hutt River catchment, with the results presented in Appendix C.

The impact of the downscaling technique having the ability to change the rainfall intensity for different rainfall amounts can be seen from the figures, for example the annual runoff for the fourth year is actually higher for the 2030 B1 case (Figure 32), compared to the historic case in Figure 31, even though the median runoff over the whole period is less in the 2030 B1 scenario. In this case, the NCAR-CCSM3 GCM projects that the extreme rainfall events will increase, even though there is an overall decrease in the annual rainfall, which then translates into the simulated runoff.

On each plot, the 1990 median and 20th percentile flows are indicated by horizontal lines and then for each future case, the projected median runoff is represented by a purple horizontal line to illustrate the projected decrease in runoff compared to the historic case. It can be seen from Figure 37 that for the 2070 A2 scenario, the median runoff is projected to be slightly less than the 1990 20th percentile runoff, highlighting the significant reduction in water resources available in the region under this scenario. The implication of this is that annual flows that are considered 'low flow' years in the historic record are higher than the mean annual runoff year in the 2070 A2 scenario.

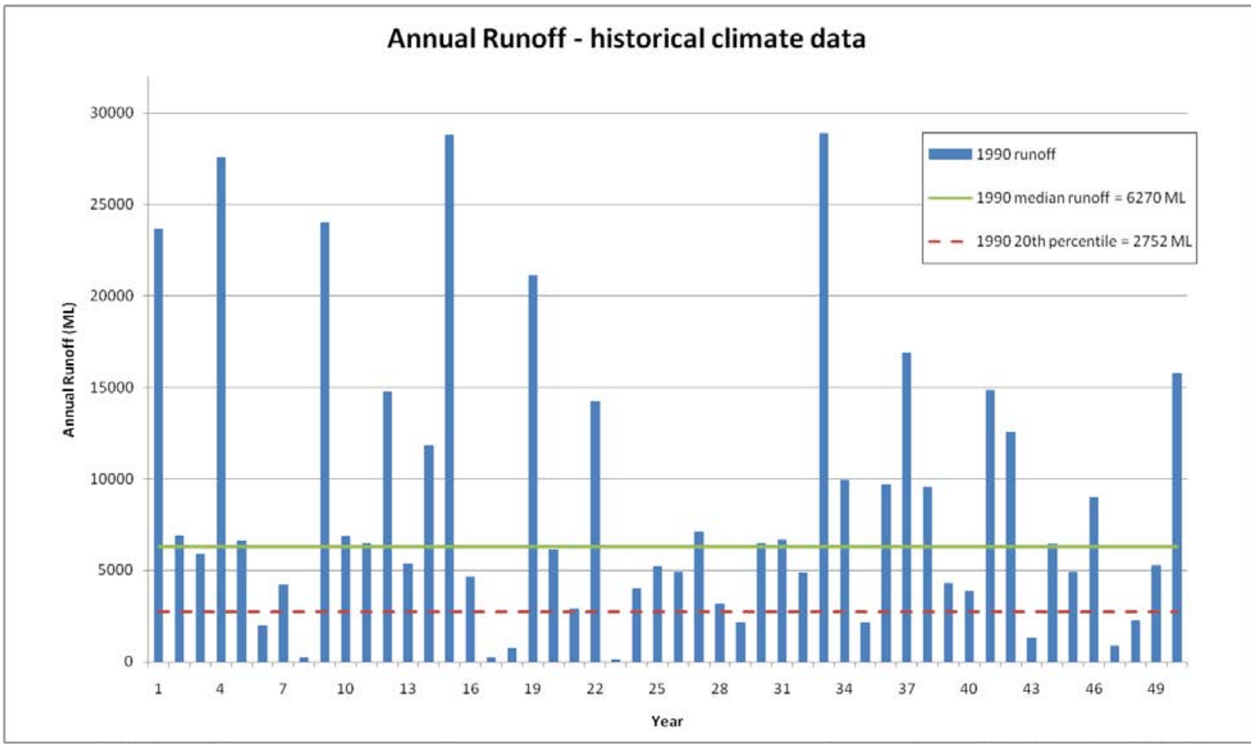


Figure 31. Annual runoff simulated for the Wakefield River, based on historically measured rainfall and PET data. Year 1 on the x axis represents 1961, and year 50 represents 2010.

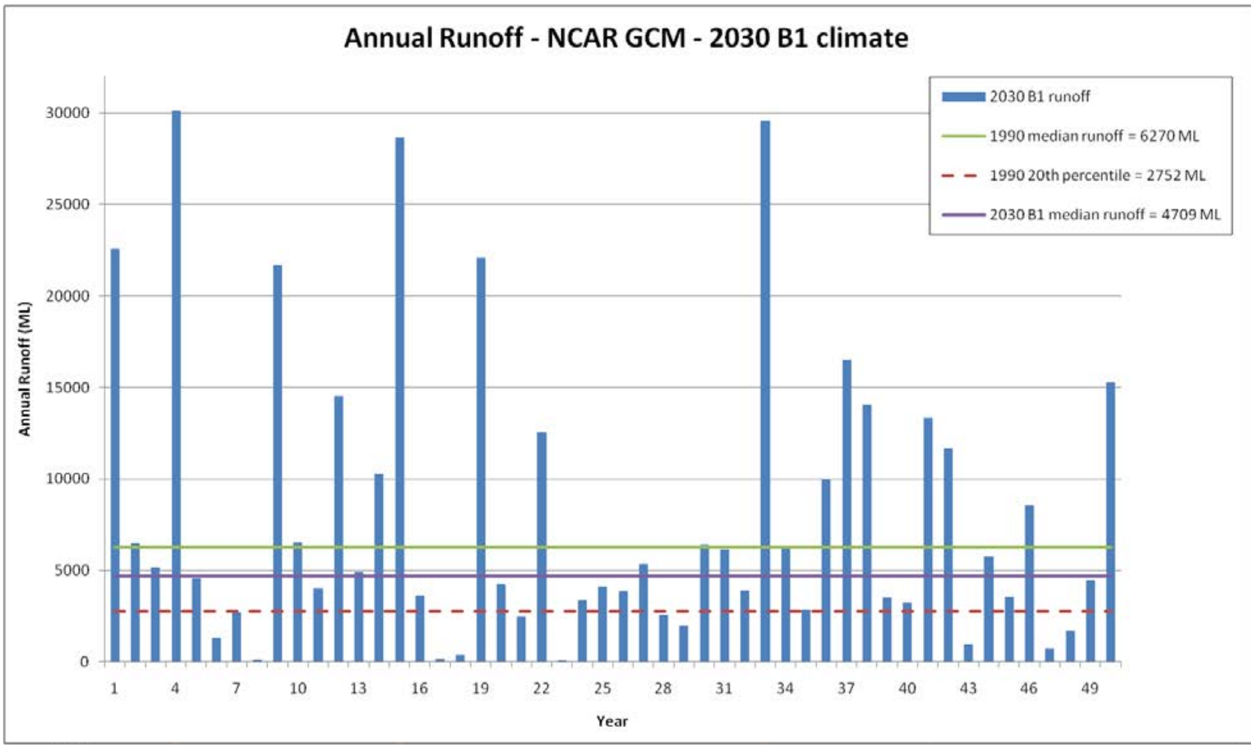


Figure 32. Annual runoff simulated for the Wakefield River, based on rainfall and PET input data generated by the NCAR GCM for a 2030 climate and B1 emissions

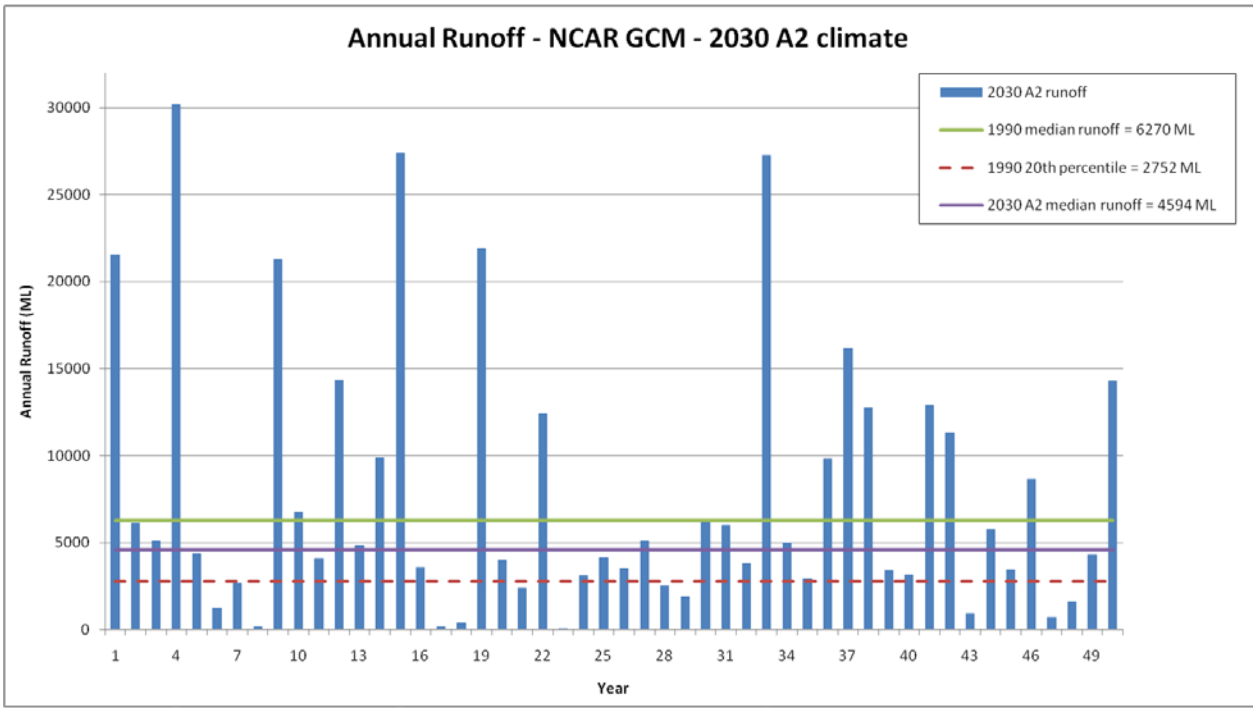


Figure 33. Annual runoff simulated for the Wakefield River, based on rainfall and PET input data generated by the NCAR GCM for a 2030 climate and A2 emissions

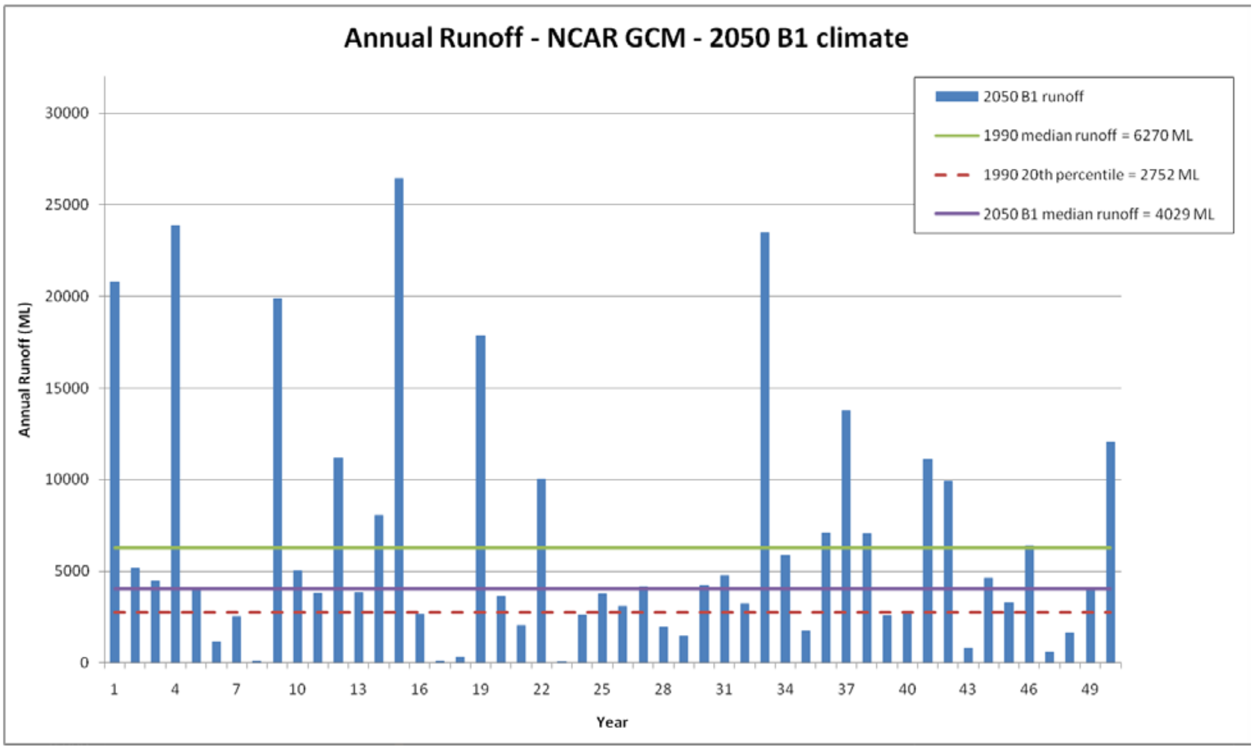


Figure 34. Annual runoff simulated for the Wakefield River, based on rainfall and PET input data generated by the NCAR GCM for a 2050 climate and B1 emissions

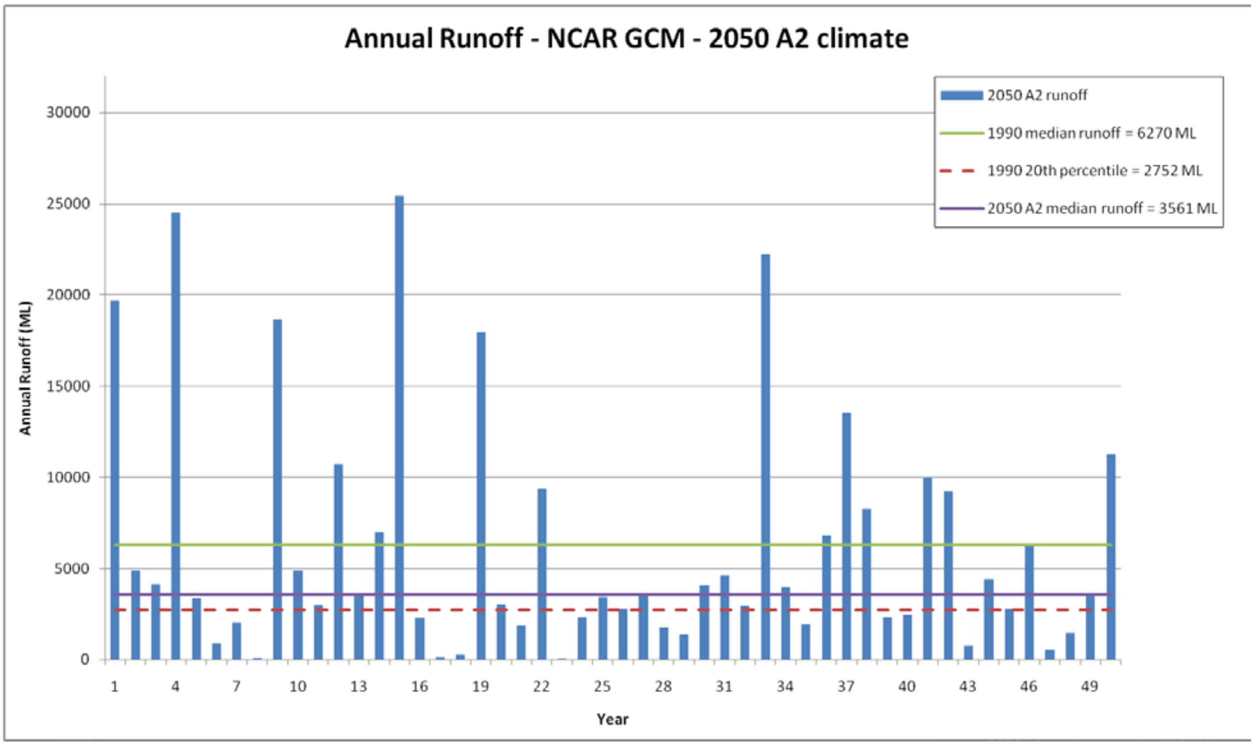


Figure 35. Annual runoff simulated for the Wakefield River, based on rainfall and PET input data generated by the NCAR GCM for a 2050 climate and A2 emissions

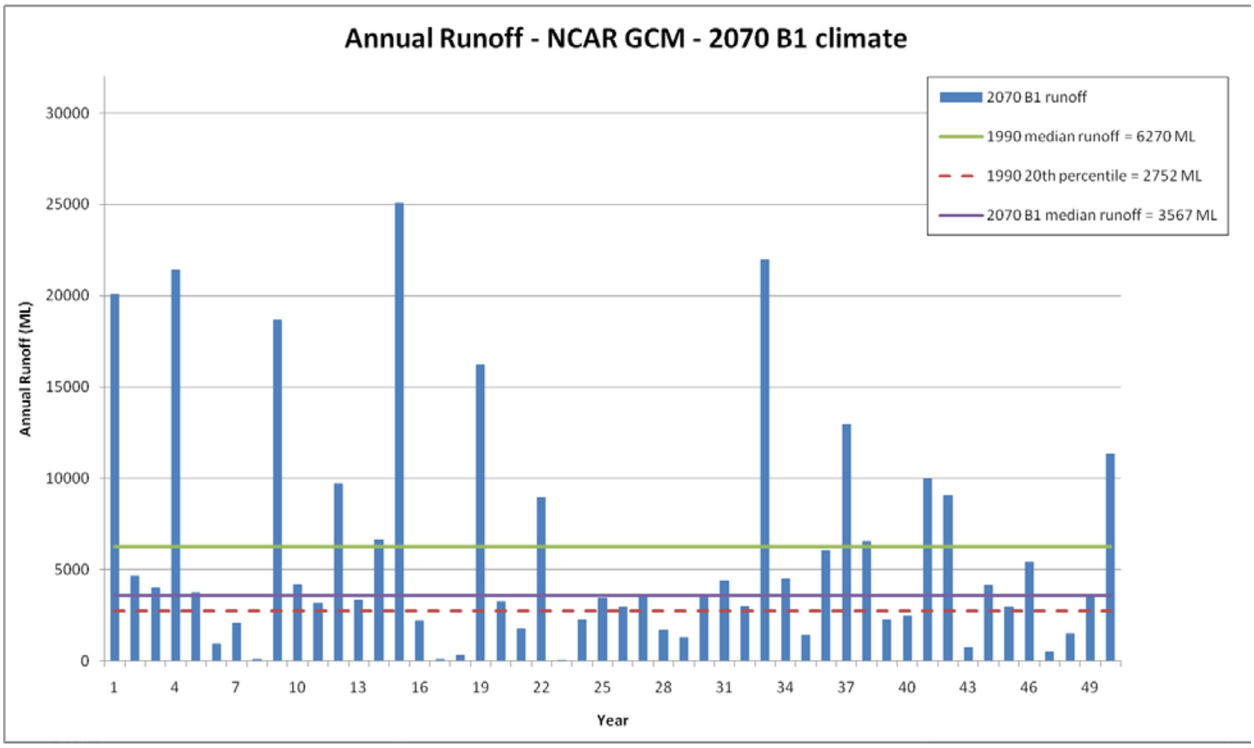


Figure 36. Annual runoff simulated for the Wakefield River, based on rainfall and PET input data generated by the NCAR GCM for a 2070 climate and B1 emissions

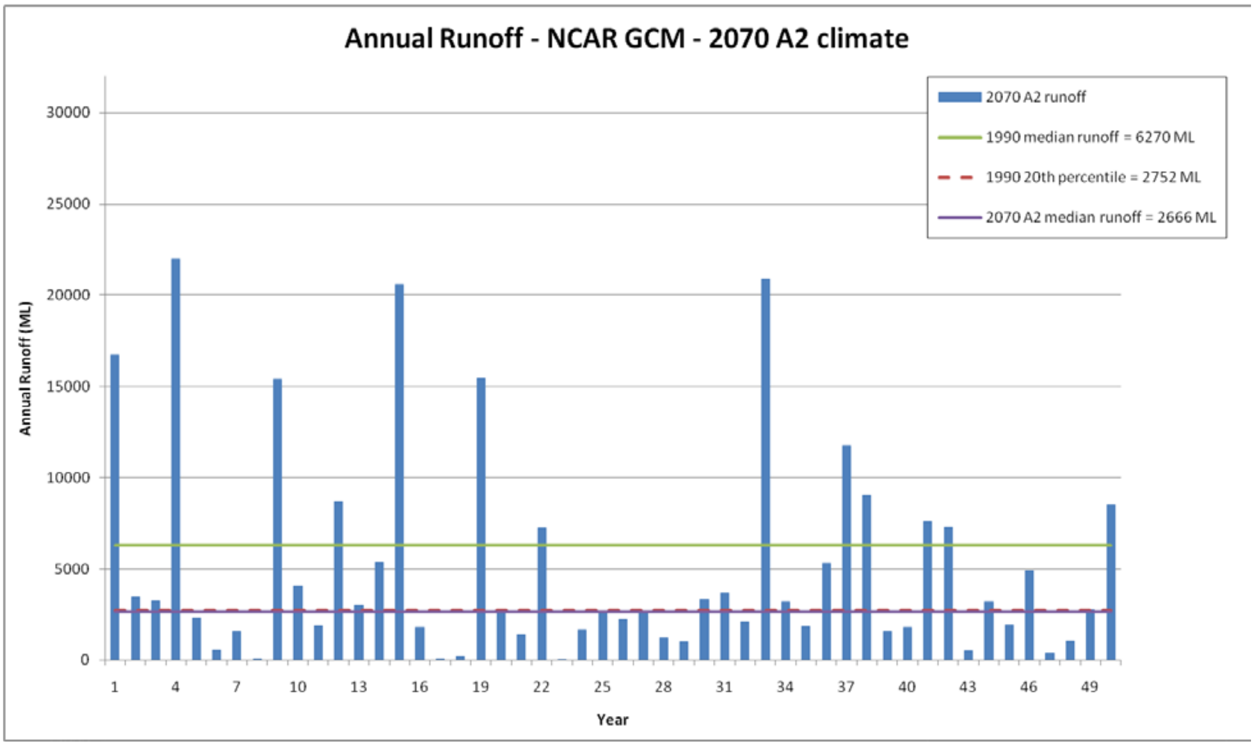


Figure 37. Annual runoff simulated for the Wakefield River, based on rainfall and PET input data generated by the NCAR GCM for a 2070 climate and A2 emissions

The results presented thus far are specific to the assumed emission scenarios and the impact of the scenario as projected by the different climate models for each time horizon. To generalise the impacts of a change in the climate on the simulated runoff, the change in runoff corresponding to each projected change in winter rainfall is presented in Figure 38 for the Wakefield River and Figure 39 for the Hutt River.

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 climate change impact results. The resulting equations are PR = 0.9 tanh(7.55 PW) for Wakefield River, and PR = 0.78 tanh(6.30 PW) for Hutt River, where PR is the percentage change in median annual runoff and PW is the percentage change in average winter rainfall.

The dashed lines on Figure 38 and Figure 39 represent 95% confidence limits, assuming normally distributed variation of the simulated results around the trend line. The 95% confidence intervals have been computed by:

$$CI_{95} = Q_T \pm 1.96 \sqrt{\frac{s_{Y|X}}{n}} \qquad \text{Equation 3}$$

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 = 24. The computed error bounds correspond to ±18% from the trend line for Wakefield River, and ±26% for the Hutt River.

The relationships derived allow the expected change in runoff to be estimated for any given change in winter rainfall to allow other projections or scenarios to be approximated based on the results presented in this work. 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 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, as well as the change in the rainfall intensity introduced by the downscaling method according to the daily GCM rainfall projections.

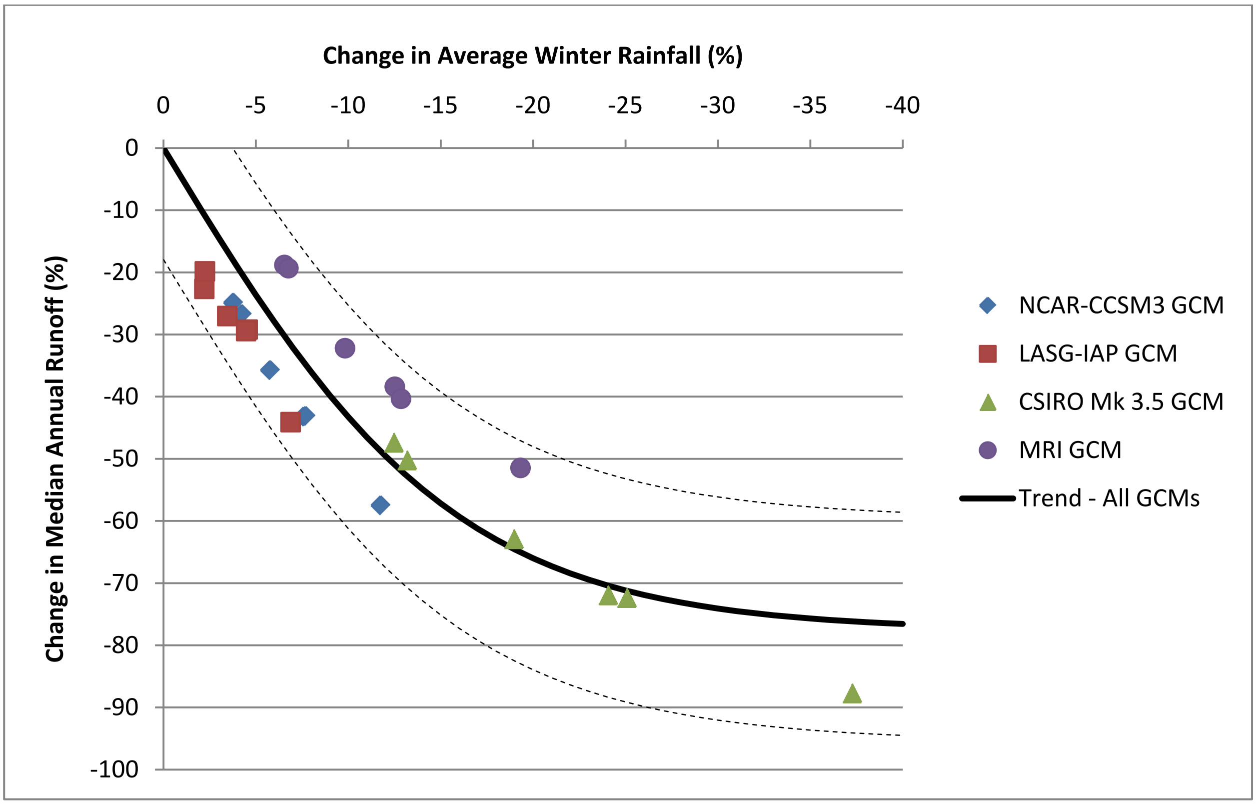


Figure 38. Percent changes in average winter rainfall versus changes in median annual runoff for the Wakefield River. Trend line is a tanh relationship, dashed line shows the upper and lower 95% bounds.

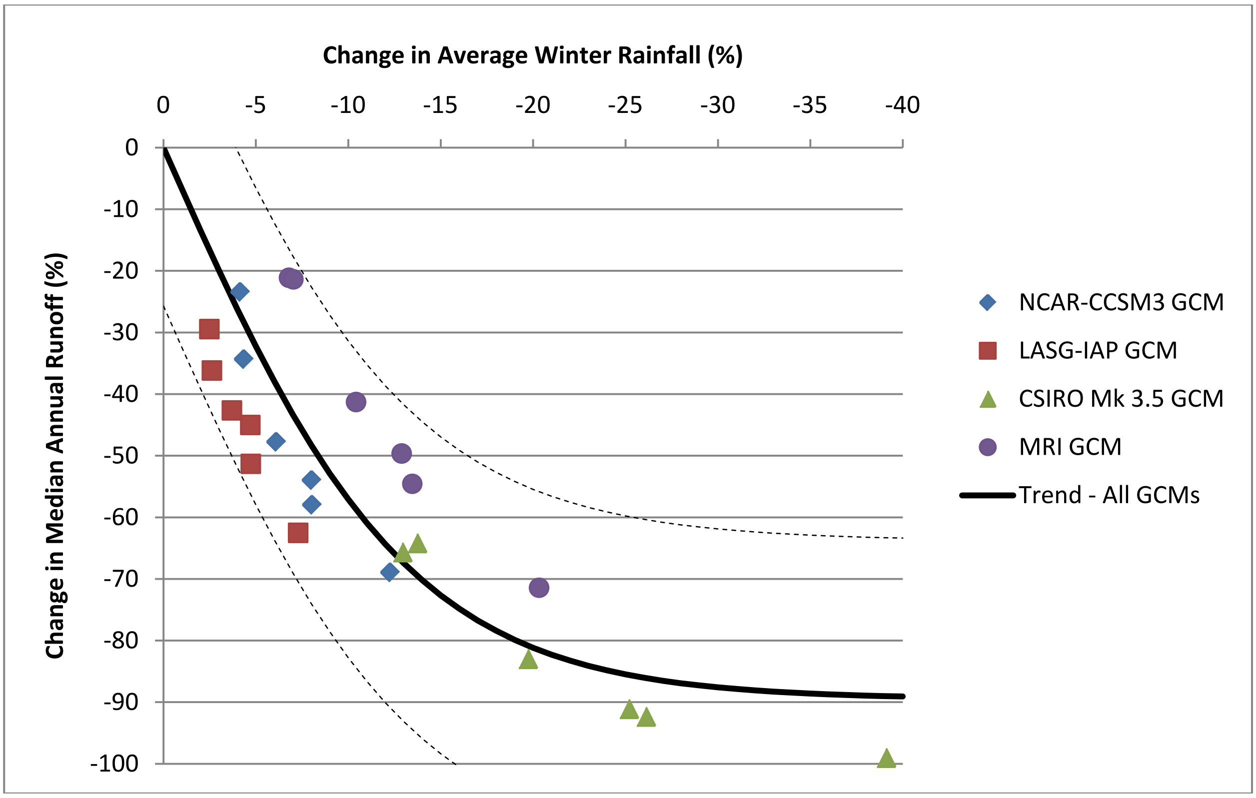


Figure 39. Percent changes in average winter rainfall versus changes in median annual runoff for the Hutt River. Trend line is a tanh relationship, dashed line shows the upper and lower 95% bounds.

4.1.3. GROUNDWATER RECHARGE MODELS – CLARE VALLEY PWRA

The results of the spatially distributed LEACHM-GIS modelling for the Clare Valley PWRA are summarised in Figure 38.

Water balances of the model outputs were found to be consistent, with water balance errors consistently less than one percent. As the LEACHG framework runs a large number of individual models to represent the variation across the study area (200 models were run for each of the 24 climate scenarios), it is impractical to provide water balances for all of the models in this report. However, example water balances are tabulated in Appendix D.

The percent reductions in average annual recharge represent the area-weighted averages for the PWRA, based on the results of the LEACHG model. The reductions are compared to the average annual recharge rate determined using historical climate data (1961 - 2010), which gave an annual, area weighted average recharge rate of 43mm/y, in agreement with estimates from previous studies of 30 – 75 mm/y. As can be seen, the projected reductions in recharge vary 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 approximately -20% at 2030 to -40% at 2070, while data from the CSIRO Mk 3.5 GCM produces the greatest reduction in recharge, from approximately -45% at 2030 to -100% (zero mean recharge) by 2070.

The reductions in recharge predicted under the NCAR GCM scenarios are surprisingly high when compared to the relatively moderate rainfall reductions projected by this GCM (Figure 25 and Figure 26). However, the NCAR GCM projects the greatest increase in winter PET of all the four GCMs applied here. These results show the importance of both rainfall and PET and their seasonal changes in influencing groundwater recharge.

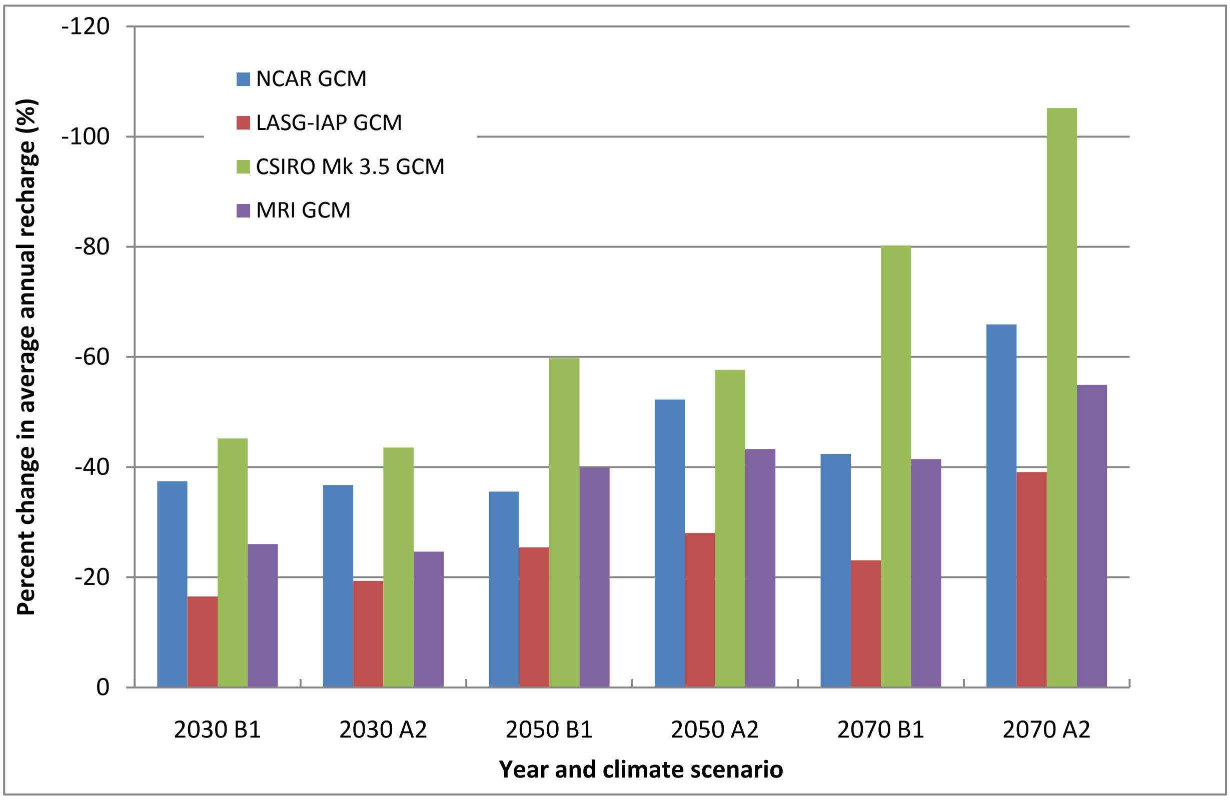


Figure 40. Modelled changes in average annual recharge for the Clare Valley for the different GCMs, emissions scenarios and time horizons considered, as estimated by the LEACHG models

Tables 11 to 14 summarise the results from the LEACHM-GIS models for future climate scenarios from all four GCMs.

As well as the changes to median 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 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 flow.
For example, in Table 15 the historic baseline (1990) low (20th percentile) and high (80th percentile) annual recharge amounts are 16 mm and 61 mm respectively. In the results from models run with NCAR GCM climate projections for the 2050 B1 scenario, the 20th and 80th percentile recharge fluxes are reduced to 6 mm and 44 mm respectively. The number of years that would have historically been considered low recharge years (less than 1990 20th percentile recharge) increases 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 to 4 in a 50-year sequence.

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 and the NCAR and MRI GCMs project a median change.

Table 11. Changes in climate and recharge simulated by the LEACHM modelling using input data generated using the LASG-IAP GCM

LASG-IAP GCM, rainfall station A21025	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	636	620	620	612	607	607	591
Average Winter Rainfall (mm)	247	240	240	237	235	235	229
Average Annual PET (mm)	1215	1230	1238	1242	1248	1248	1267
Average Winter PET (mm)	118	124	127	127	127	127	133
Average Annual Recharge (mm)	43	36	34	32	31	33	26
Change in Annual Rainfall (%)		-2	-2	-4	-5	-5	-7
Change in Winter Rainfall (%)		-3	-3	-4	-5	-5	-7
Change in Annual PET (%)		1	2	2	3	3	4
Change in Winter PET (%)		5	8	8	8	8	13
Change in average recharge (%)		-17	-19	-25	-28	-23	-39
Low Events							
20th Percentile Recharge (mm)	16	12	11	10	9	10	6
Years Below 1990 20th %	10	13	14	15	17	15	21
High Events							
80th Percentile Recharge (mm)	61	54	53	50	49	51	43
Years Above 1990 80th %	10	8	8	8	8	8	4

Table 12. Changes in climate and recharge simulated by the LEACHM modelling using input data generated using the NCAR GCM

NCAR GCM, rainfall station A21025	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	636	622	622	616	611	611	597
Average Winter Rainfall (mm)	247	236	236	232	227	227	216
Average Annual PET (mm)	1215	1242	1244	1263	1278	1278	1303
Average Winter PET (mm)	118	127	127	133	137	137	146
Average Annual Recharge (mm)	43	27	27	27	20	25	15
Change in Annual Rainfall (%)		-2	-2	-3	-4	-4	-6
Change in Winter Rainfall (%)		-4	-4	-6	-8	-8	-12
Change in Annual PET (%)		2	2	4	5	5	7
Change in Winter PET (%)		8	8	13	16	16	23
Change in average recharge (%)		-37	-37	-36	-52	-42	-66
Low Events							
20th Percentile Recharge (mm)	16	7	7	6	2	5	-1
Years Below 1990 20th %	10	22	21	19	25	25	32
High Events							
80th Percentile Recharge (mm)	61	44	44	44	37	41	30
Years Above 1990 80th %	10	6	6	4	2	4	1

Table 13. Changes in climate and recharge simulated by the LEACHM modelling using input data generated using the MRI GCM

MRI GCM, rainfall station A21025	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	635	614	613	604	595	594	573
Average Winter Rainfall (mm)	247	230	229	221	215	214	197
Average Annual PET (mm)	1215	1224	1224	1246	1251	1251	1260
Average Winter PET (mm)	118	118	118	124	124	124	124
Average Annual Recharge (mm)	43	32	32	26	24	25	19
Change in Annual Rainfall (%)		-3	-4	-5	-6	-6	-10
Change in Winter Rainfall (%)		-7	-7	-10	-13	-13	-20
Change in Annual PET (%)		1	1	3	3	3	4
Change in Winter PET (%)		0	0	5	5	5	5
Change in average recharge (%)		-26	-26	-40	-43	-41	-55
Low Events							
20th Percentile Recharge (mm)	16	11	10	7	5	6	2.4
Years Below 1990 20th %	10	15	15	24	25	25	27
High Events							
80th Percentile Recharge (mm)	61	51	52	44	42	43	35
Years Above 1990 80th %	10	8	8	6	4	5	2

Table 14. Changes in climate and recharge simulated by the LEACHM modelling using input data generated using the CSIRO Mk 3.5 GCM

CSIRO Mk 3.5 GCM, rainfall station A21025	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	636	573	570	541	514	510	447
Average Winter Rainfall (mm)	247	214	213	198	185	182	150
Average Annual PET (mm)	1215	1248	1254	1269	1288	1288	1329
Average Winter PET (mm)	118	124	124	124	130	130	137
Average Annual Recharge (mm)	43	23	24	17	18	8	-2
Change in Annual Rainfall (%)		-10	-10	-15	-19	-20	-30
Change in Winter Rainfall (%)		-13	-14	-20	-25	-26	-39
Change in Annual PET (%)		3	3	5	6	6	9
Change in Winter PET (%)		5	5	5	10	10	16
Change in average recharge (%)		-45	-44	-60	-58	-80	-105
Low Events							
20th Percentile Recharge (mm)	16	5	4	0	0	-6	-11
Years Below 1990 20th %	10	25	24	27	27	36	47
High Events							
80th Percentile Recharge (mm)	61	39	40	31	33	22	8
Years Above 1990 80th %	10	4	3	2	3	1	0

It should be noted that a reduction in average annual recharge of greater than 100%, as given by the CSIRO Mk 3.5 GCM 2070 A2 results in Table 14, suggests a change to a small net discharge of groundwater when averaged across the study area. This is partly a result of the assumption of an unchanged water table depth in the models for all climate scenarios. In reality, the large reduction in recharge occurring under some of the more extreme climate scenarios would result in significant groundwater level decline, creating more preferable recharge conditions in the unsaturated zone as the depth to groundwater increases. This would tend to counteract some of the effects of the change in climate and reduce the reduction in recharge. However, the areas of shallow water table depth where this effect is significant are limited in the Clare Valley study area (refer Figure 22). The result for the CSIRO Mk3.5 2070 A2 scenario could reasonably be interpreted as a condition approaching zero annual average recharge, rather than a change to a net groundwater discharge state.

Figure 41 to Figure 47 show the area weighted recharge rates from each year of the 50-year LEACHG model simulations, using baseline historic climate data (Figure 41) and climate data scaled according to the projections of the NCAR GCM. In these results, mean annual recharge rates generally decrease with increasing time, with the greatest decrease observed under A2 emissions scenarios. However there are some exceptions. For example, under the B1 emission scenario, an increase in mean annual recharge is observed between 2030 and 2050. This is thought to be caused by an increase in the extreme events for the 2050 scenario as determined by the GCM projections: within the 50-year sequence the most extreme rainfall events were increased by a greater amount for the 2050 case compared to the 2030 case, resulting in a higher mean annual rainfall for this case.

With reference to Table 12, the mean annual recharge rate does not appear to reduce between 2030 and 2050 climates from the NCAR GCM with the B1 emissions scenario. However there is a change in the frequency of 'high recharge' years (ie. above the 1990 80th percentile) and 'low recharge' years (below the 1990 20th percentile). This trend is not seen in the results from the LASG-IAP GCM with the B1 emission scenario (Table 11), in which the number of 'high' recharge years remains constant from

2030 to 2070. These varying effects of the different GCMs and emissions scenarios highlight the need to consider results the projections from more than one GCM.

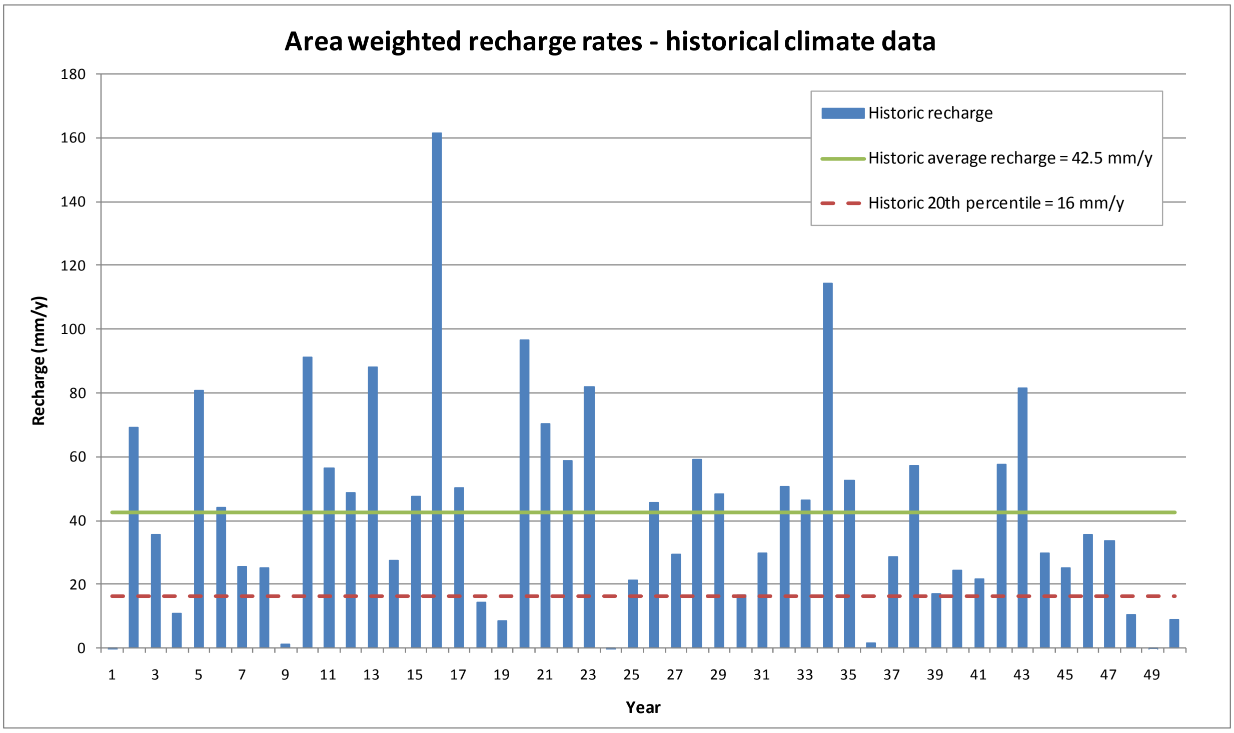


Figure 41. Annual area-weighted recharge rates produced by the LEACHG model for the Clare Valley, using historical measured rainfall and PET data. Year 1 on the x axis represents 1961, and year 50 represents 2010.

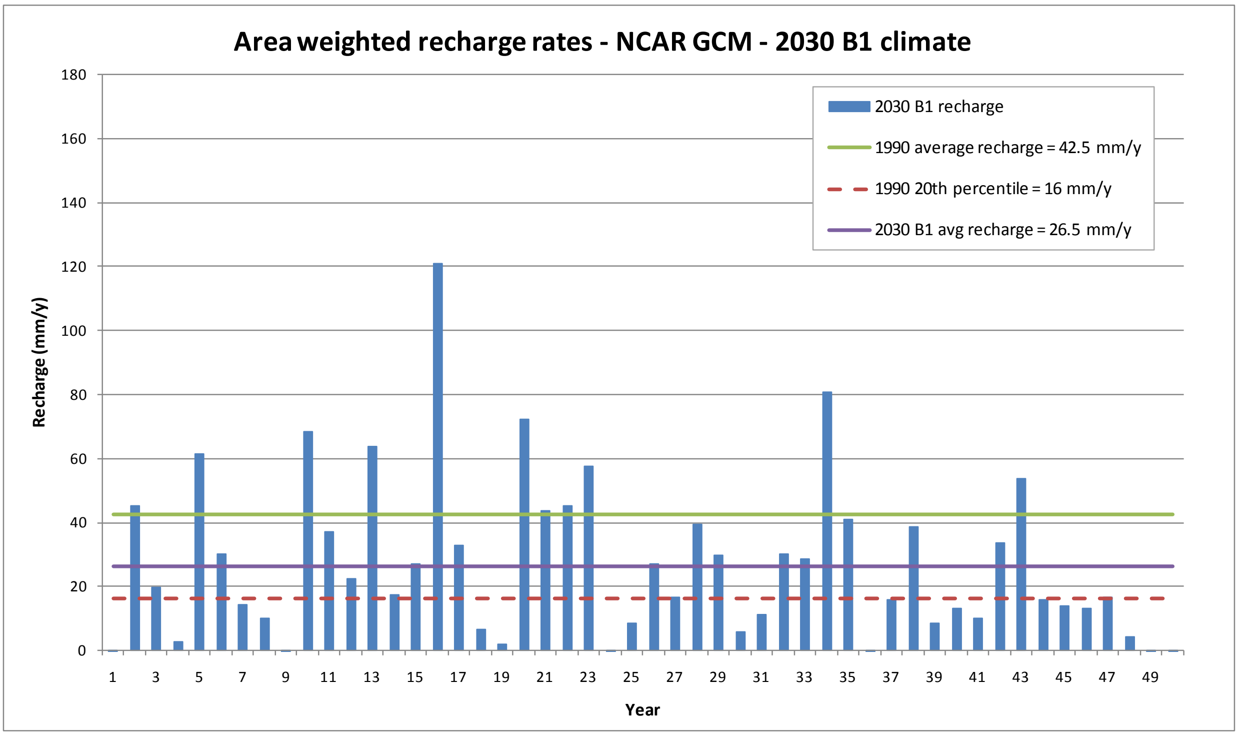


Figure 42. Annual area-weighted recharge rates produced by the LEACHG model for the Clare Valley, using rainfall and PET input data generated by the NCAR GCM for a 2030 climate and B1 emissions

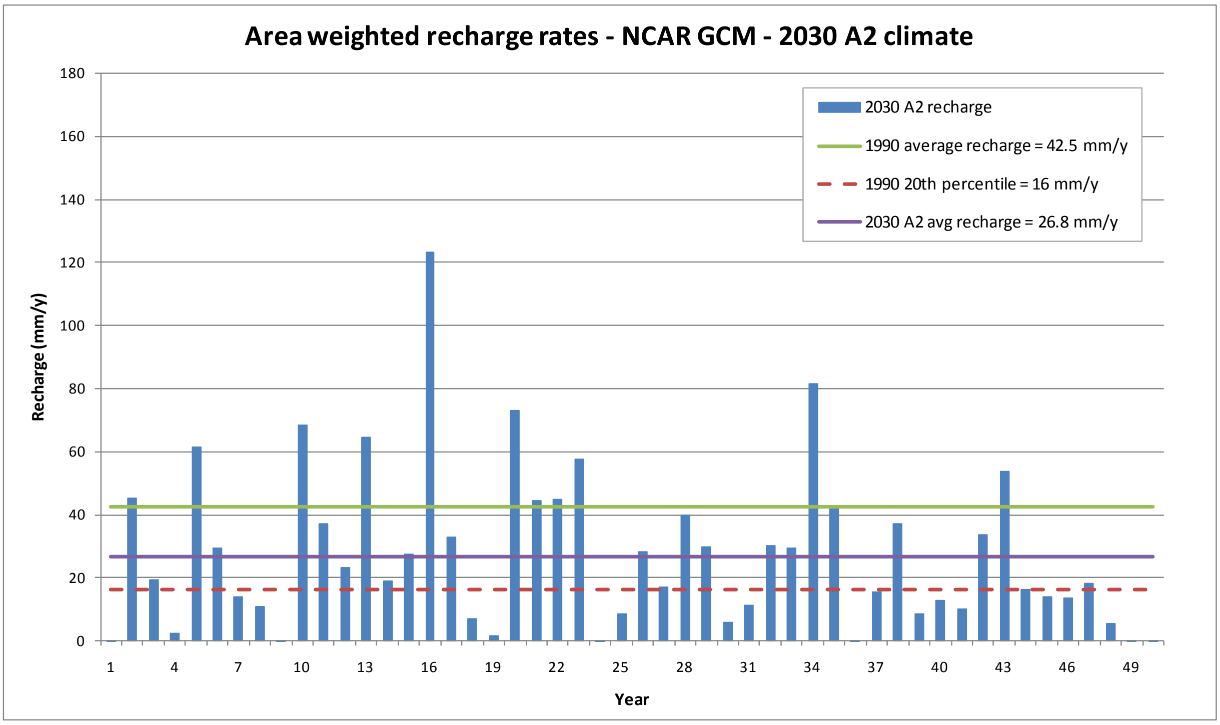


Figure 43. Annual area-weighted recharge rates produced by the LEACHG model for the Clare Valley, using rainfall and PET input data generated by the NCAR GCM for a 2030 climate and A2 emissions

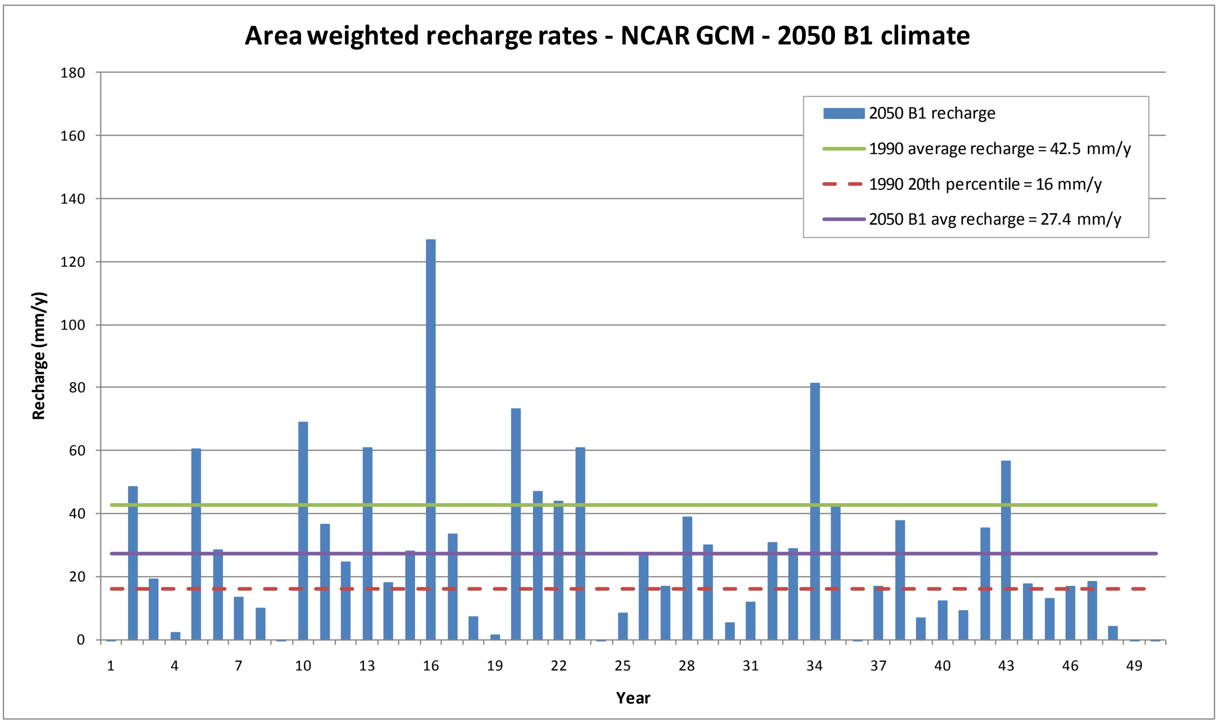


Figure 44. Annual area-weighted recharge rates produced by the LEACHG model for the Clare Valley, using rainfall and PET input data generated by the NCAR GCM for a 2050 climate and B1 emissions

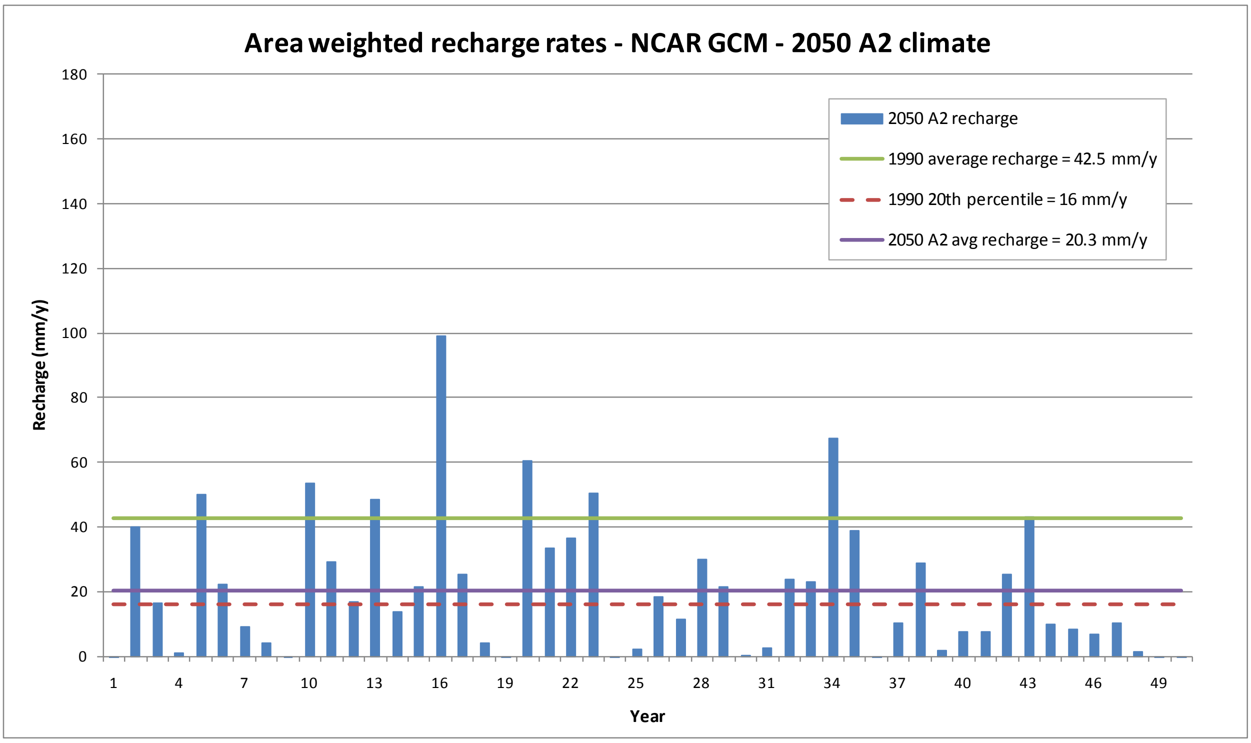


Figure 45. Annual area-weighted recharge rates produced by the LEACHG model for the Clare Valley, using rainfall and PET input data generated by the NCAR GCM for a 2050 climate and A2 emissions

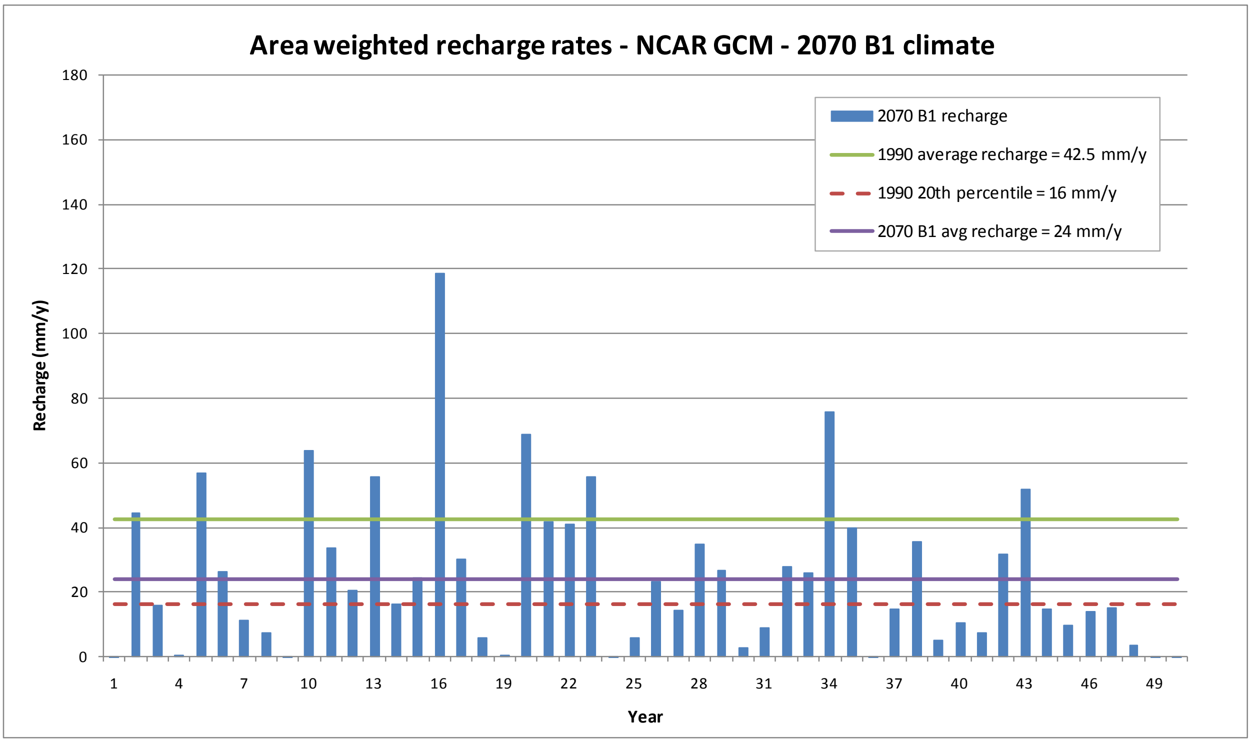


Figure 46. Annual area-weighted recharge rates produced by the LEACHG model for the Clare Valley, using rainfall and PET input data generated by the NCAR GCM for a 2070 climate and B1 emissions

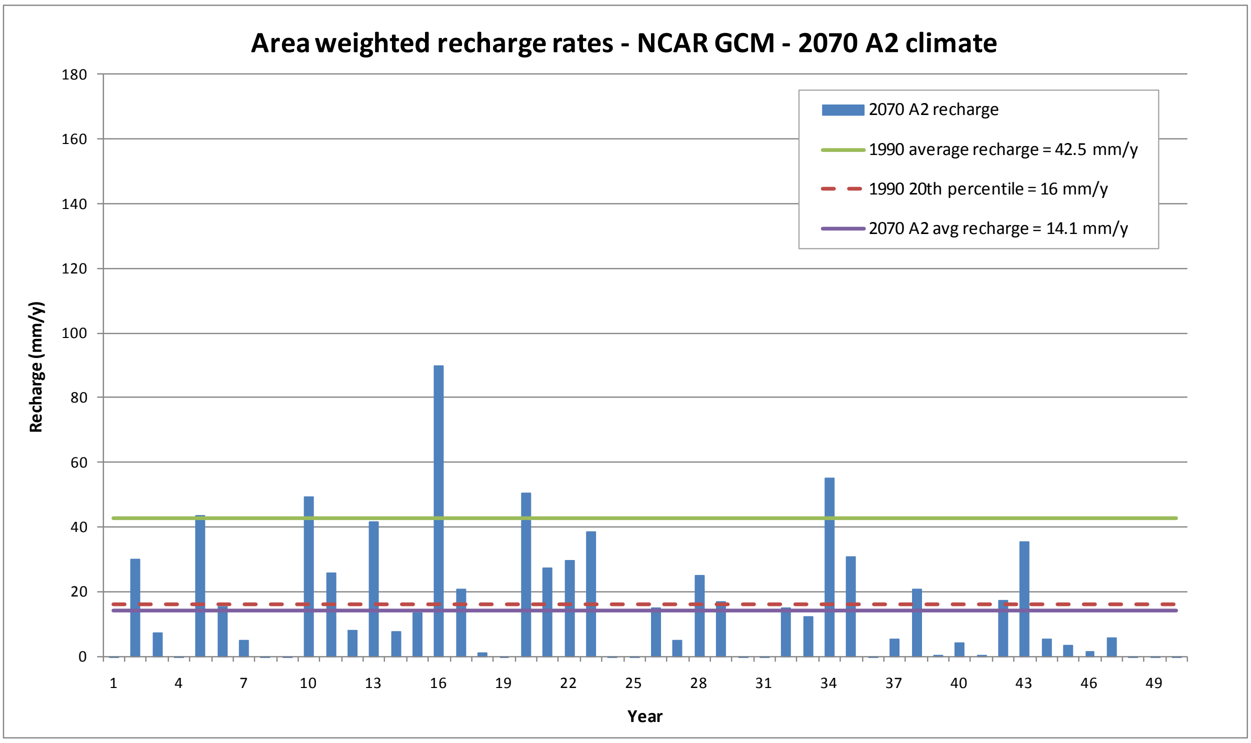


Figure 47. Annual area-weighted recharge rates produced by the LEACHG model for the Clare Valley, using rainfall and PET input data generated by the NCAR GCM for a 2070 climate and A2 emissions

In all scenarios, the annual recharge totals are more closely correlated with winter rainfall than with any other seasonal climate variable. 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 winter rainfall is presented in Figure 48.

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 48 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 (section 4.1.2).

The relationship derived allows the expected change in recharge to be estimated for any given change in winter rainfall. Thus, rainfall changes reported by other climate change projection summaries (such as the Regional Climate Change Projections, Northern and Yorke (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 winter rainfall is due to a number of factors, including the change in rainfall projected for the other seasons of the year and the corresponding change in PET projected by the GCM. The change in the rainfall intensity introduced by the downscaling method, according to the daily GCM rainfall projections, also plays a part.

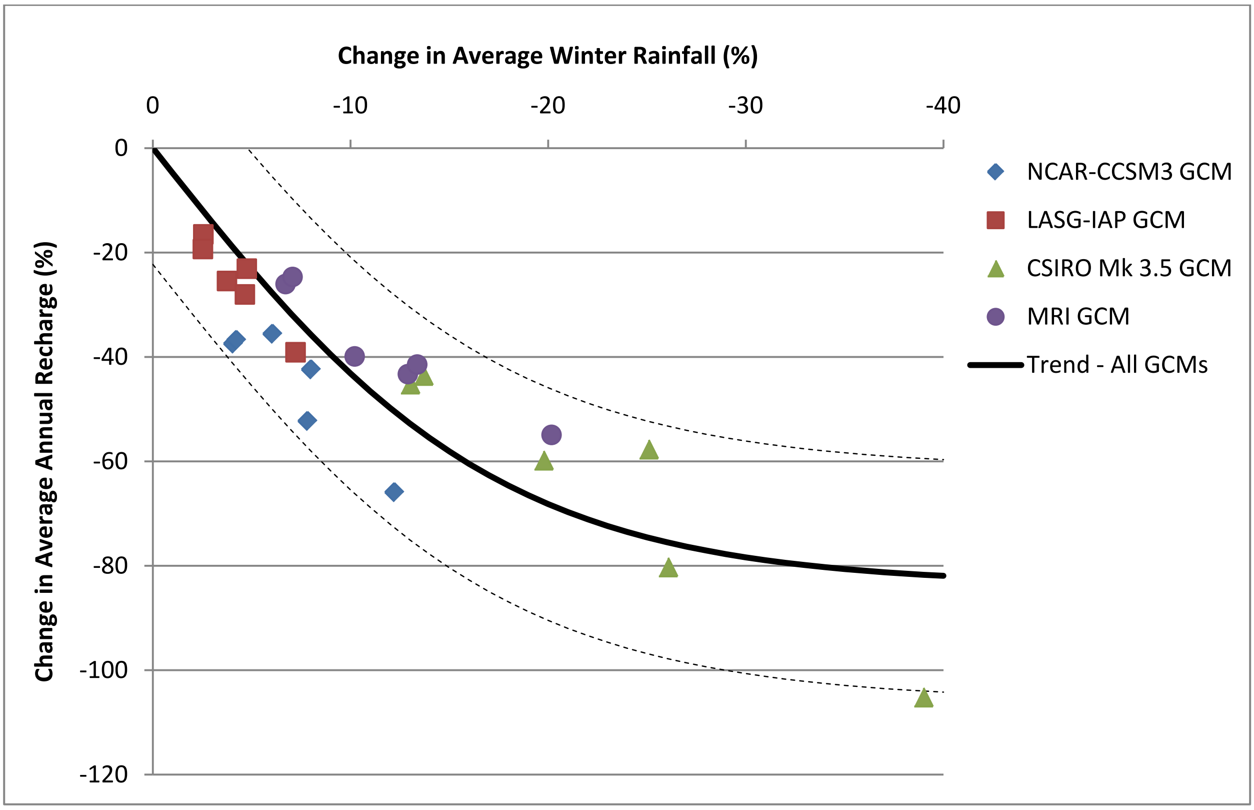


Figure 48. Percent changes in average winter rainfall versus changes in average annual recharge for the Clare Valley. Trend line is a tanh relationship, dashed line shows the upper and lower 95% bounds.

The relationship presented in Figure 48 is the basis of the projections presented for Clare Valley PWRA recharge changes in the 'Water Resource Impact Summary' in Chapter 5 of this report.

4.2. BAROOTA PWRA

4.2.1. BAROOTA CLIMATE CHANGE SCENARIOS

GCM simulations operate on a cell size in the order of hundreds of kilometres by hundreds of kilometres. Hence, all of the sites considered for the Clare PWRA models fell within the same GCM cell, and therefore the same projections were applied to all sites. The Baroota PWRA is approximately 120 km to the North and East of the Clare PWRA and hence, slightly different projections are appropriate for this location. The site considered for the Baroota reservoir model was the BoM site located at the reservoir (weather station # 19102). The resulting change in annual and winter rainfall, as well as annual and winter PET, can be seen in Figure 49 to Figure 52.

While a different rainfall site has been used for the Baroota PWRA modelling, as well as the GCM outputs from a different simulation cell, the projections are largely the same as those outlined in Section 4.1.1. This is expected, as the GCM projections are adjacent to each other and the GCM simulation results are generally highly correlated in space.

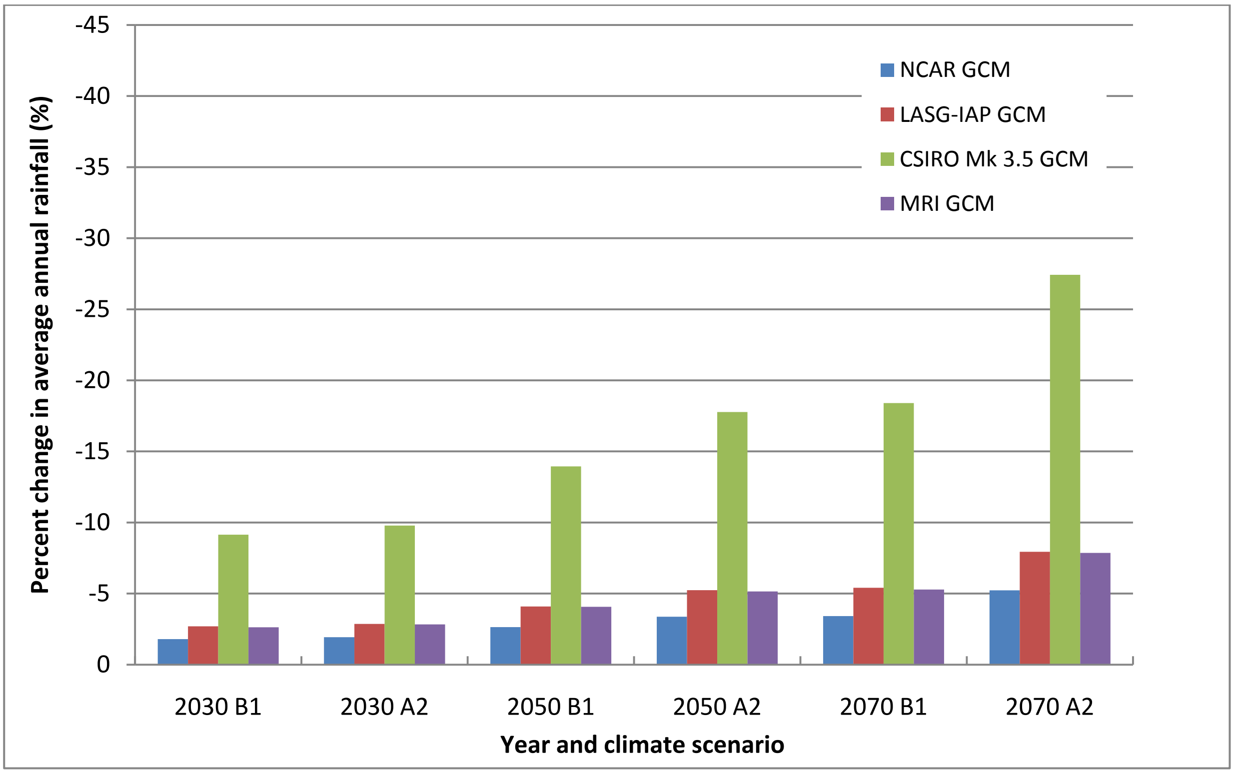


Figure 49. Percent reduction in average annual rainfall produced by the four different GCMs under the A2 and B1 emissions scenarios (based on historic rainfall data taken from the Baroota weather station)

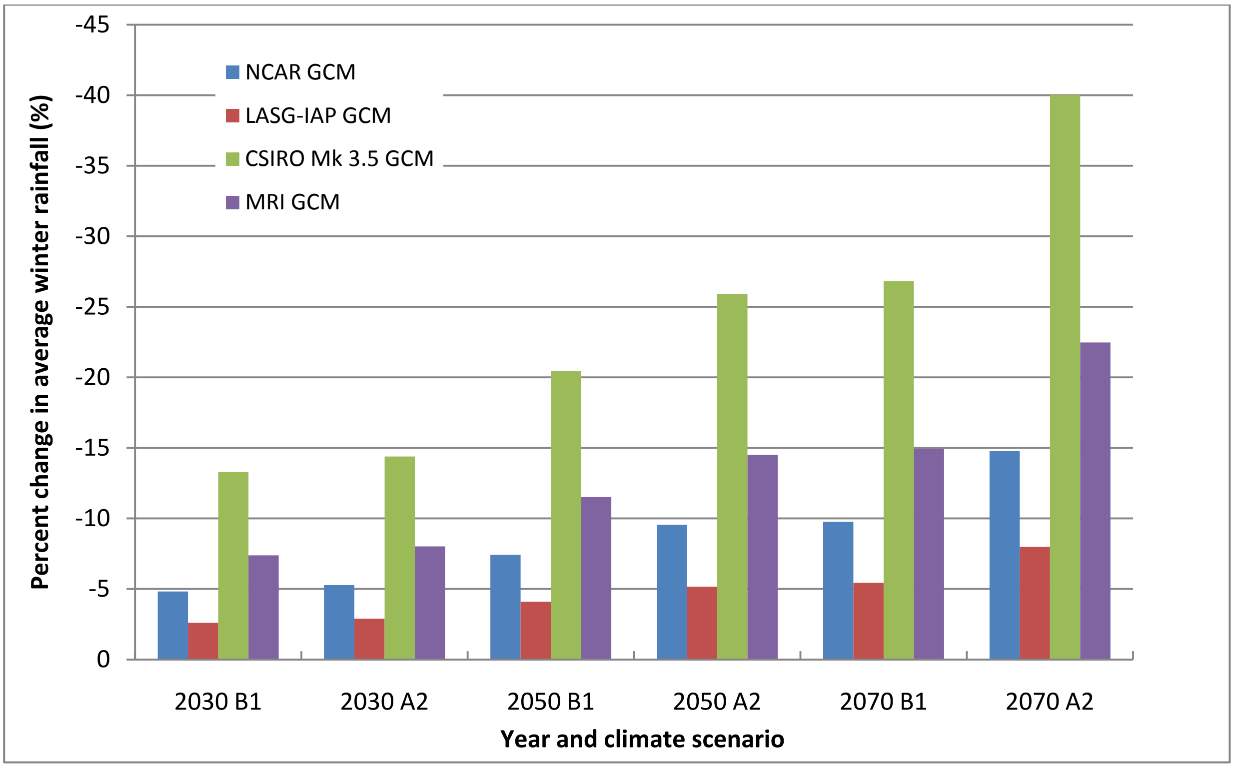


Figure 50. Percent reduction in average winter (June to August) rainfall produced by the four different GCMs under the A2 and B1 emissions scenarios (based on historic rainfall data taken from the Baroota weather station)

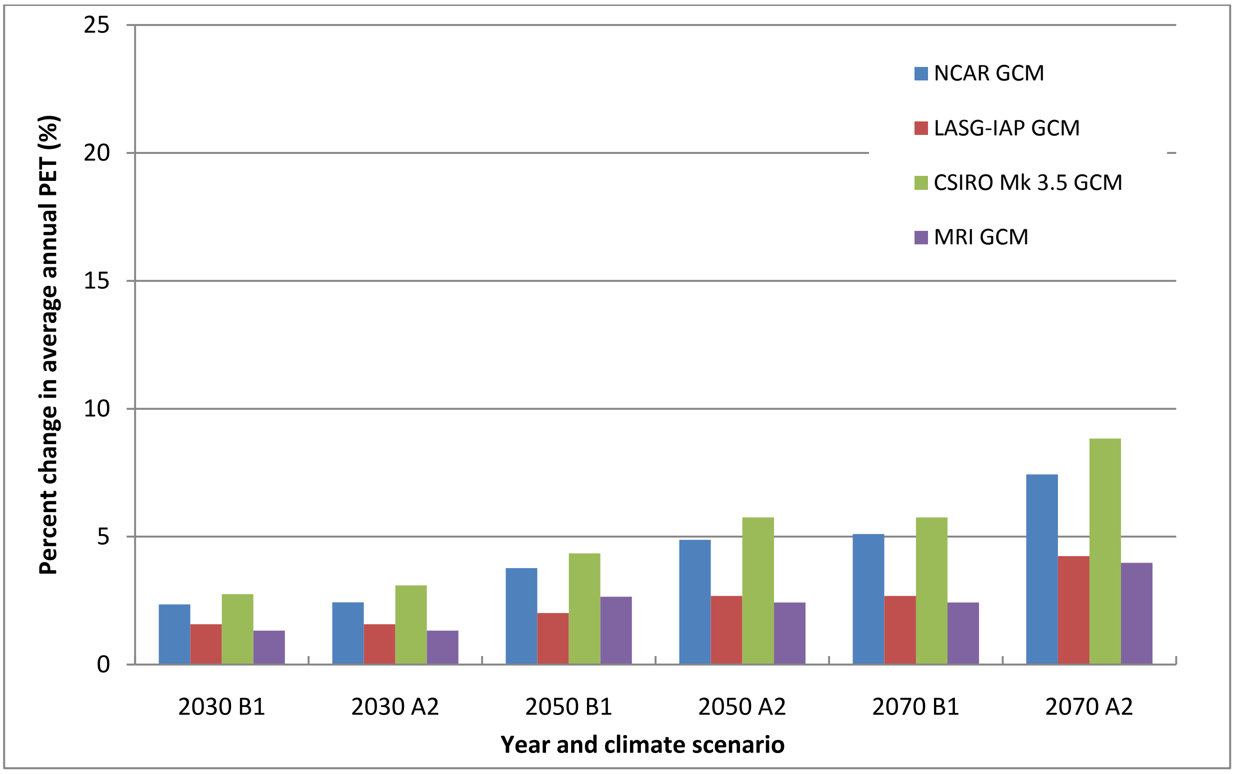


Figure 51. Percent reduction in average annual PET produced by the four different GCMs under the A2 and B1 emissions scenarios (based on historic PET data taken from the Baroota Reservoir weather station)

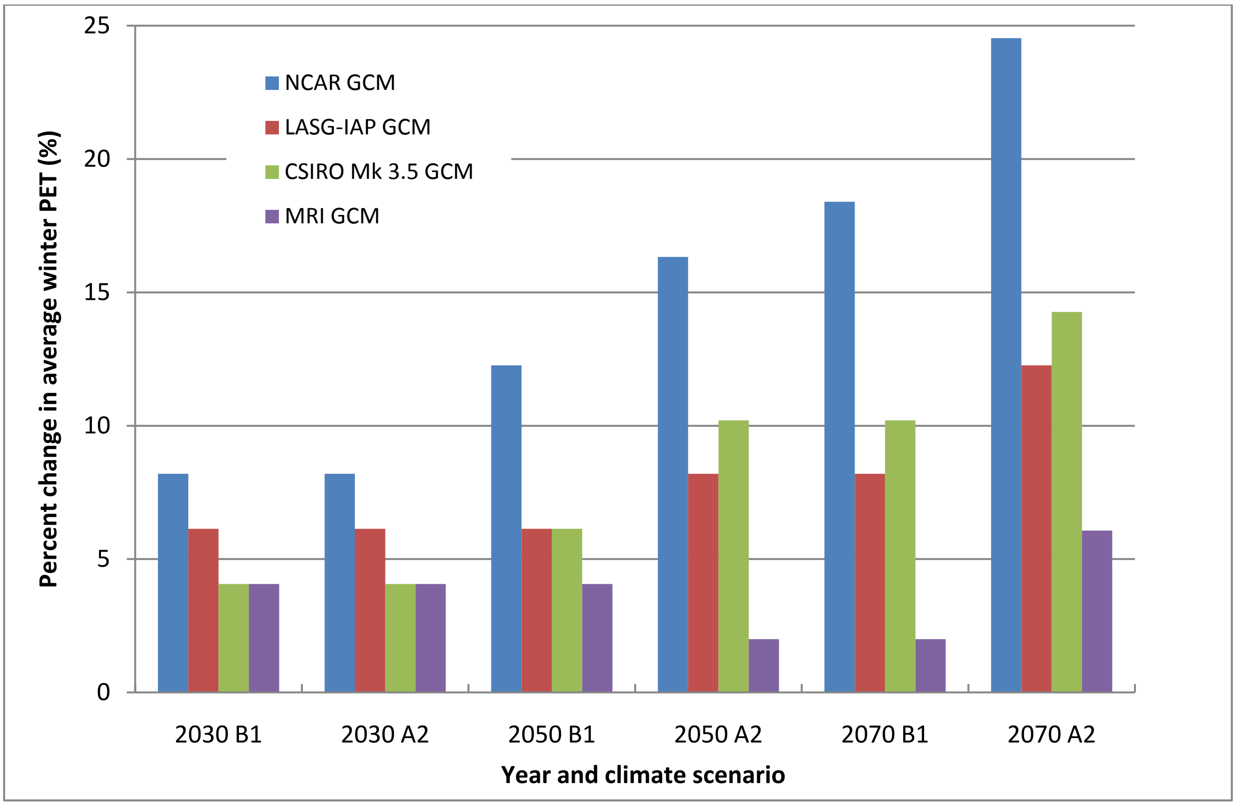


Figure 52. Percent reduction in average winter (June to August) PET produced by the four different GCMs under the A2 and B1 emissions scenarios (based on historic PET data taken from the Baroota weather station)

4.2.2. SURFACE WATER RUNOFF MODELS – BAROOTA RESERVOIR CATCHMENT

The results from the surface water modelling are summarised in Figure 53 for the Baroota Reservoir Catchment. As expected based on the greenhouse gas emission projections for each scenario, the percentage reduction in median annual runoff can be seen to increase as the time horizon into the future increases. Similar to the Clare Valley results, the percent changes in runoff are within 15% of each other or a given time horizon and emission case for the NCAR-CCSM3, LASG-IAP and MRI GCMs, with the projections provided by the CSRIO Mk 3.5 GCM resulting in approximately double the reduction in runoff compared to the other GCMs considered.

Values for the change in median runoff for Baroota Reservoir catchment (as presented in Figure 53) can be seen in Table 15 to Table 18, as well as the change in rainfall and PET projected by each GCM. The corresponding change in high (80th percentile) and low (20th percentile) events are also presented and as with the Clare Valley water resources, a consistent decrease in the number of high events and corresponding increase in the low events is projected to occur over time.

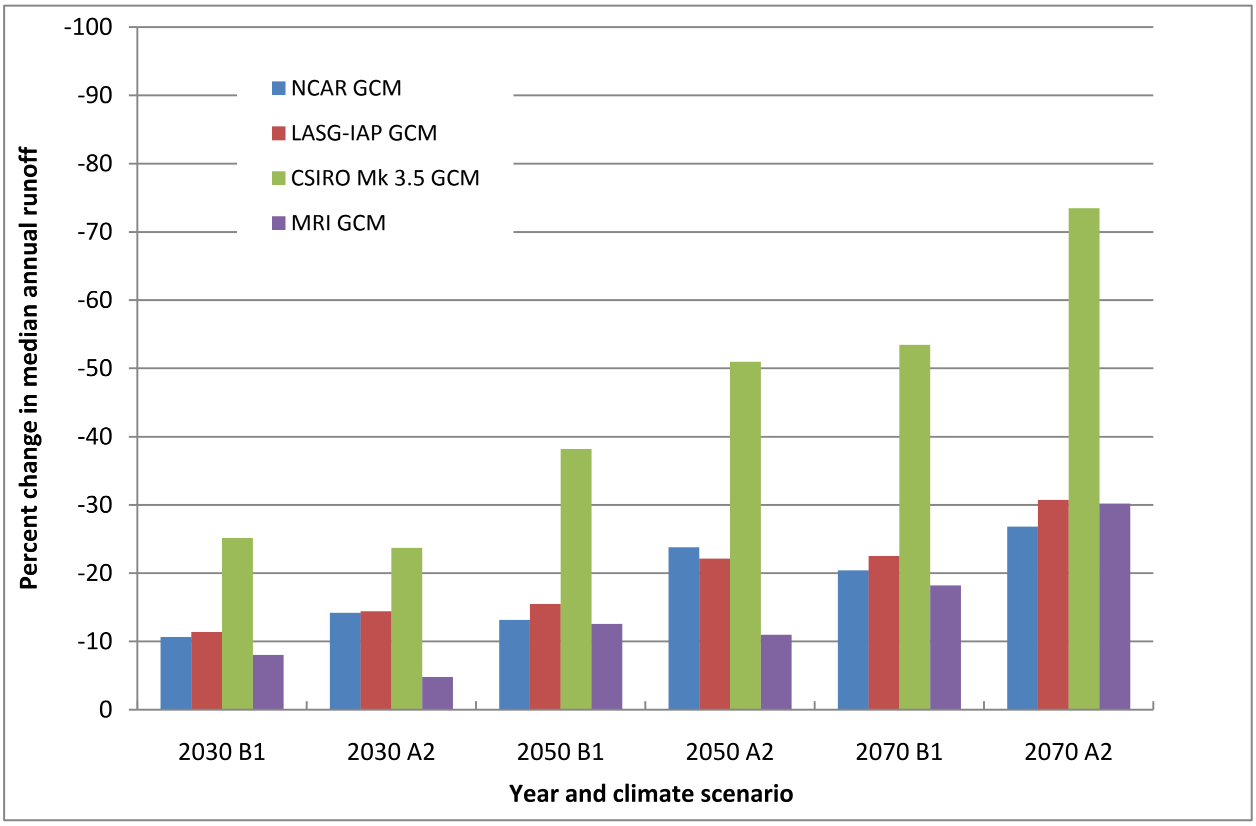


Figure 53. Estimated changes in median annual runoff for Baroota Reservoir Catchment

The impact of PET is much more pronounced for the Baroota reservoir catchment compared to the Clare Valley sites. For example, for the MRI GCM and 2050, the B1 scenario results in less runoff because it has a higher change in PET, even though it has more rainfall compared to the 2050 A2 emission scenario. However, the difference between both rainfall and PET is only 3 - 4 mm per year on average (Table 17), which is within the uncertainty around GCM projections. The greater impact of the PET changes on the resulting runoff volume is largely due to a much lower annual rainfall for this site of only 401mm, compared to 456mm and 558mm for Wakefield River and Hutt River, respectively, as well as a much higher annual PET of 1372 mm, compared to 1264 mm and 1283 mm for Wakefield River and Hutt River, respectively.

Table 15. Changes in climate and runoff simulated for Baroota Reservoir Catchment using input data generated using the LASG-IAP GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	401	390	389	384	380	379	369
Average Winter Rainfall (mm)	131	128	127	126	124	124	121
Average Annual PET (mm)	1372	1393	1393	1399	1409	1409	1430
Average Winter PET (mm)	150	159	159	159	162	162	168
Median Annual Runoff (ML)	2944	2609	2519	2489	2292	2281	2039
Change in Annual Rainfall (%)		-3	-3	-4	-5	-5	-8
Change in Winter Rainfall (%)		-3	-3	-4	-5	-5	-8
Change in Annual PET (%)		2	2	2	3	3	4
Change in Winter PET (%)		6	6	6	8	8	12
Change in Median Runoff (%)		-11	-14	-15	-22	-23	-31
Low Events							
20th Percentile Runoff (ML)	1159	974	961	938	902	846	763
Years Below 1990 20th %	10	12	12	12	12	12	15
High Events							
80th Percentile Runoff (ML)	6275	5527	5524	5270	5017	4899	4401
Years Above 1990 80th %	10	8	8	7	6	6	5

Table 16. Changes in climate and runoff simulated for Baroota Reservoir Catchment using input data generated using the NCAR-CCSM3 GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	401	394	393	390	387	387	380
Average Winter Rainfall (mm)	131	125	124	121	119	118	112
Average Annual PET (mm)	1372	1404	1405	1424	1439	1442	1474
Average Winter PET (mm)	150	162	162	168	175	178	187
Median Annual Runoff (ML)	2944	2631	2526	2557	2244	2343	2154
Change in Annual Rainfall (%)		-2	-2	-3	-3	-3	-5
Change in Winter Rainfall (%)		-5	-5	-7	-10	-10	-15
Change in Annual PET (%)		2	2	4	5	5	7
Change in Winter PET (%)		8	8	12	16	18	25
Change in Median Runoff (%)		-11	-14	-13	-24	-20	-27
Low Events							
20th Percentile Runoff (ML)	1159	1048	1001	904	757	756	505
Years Below 1990 20th %	10	12	12	13	13	14	16
High Events							
80th Percentile Runoff (ML)	6275	5477	5502	5088	4695	4500	3878
Years Above 1990 80th %	10	8	8	7	5	5	4

Table 17. Changes in climate and runoff simulated for Baroota Reservoir Catchment using input data generated using the MRI GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	401	390	389	384	380	380	369
Average Winter Rainfall (mm)	131	121	121	116	112	112	102
Average Annual PET (mm)	1372	1390	1390	1408	1405	1405	1426
Average Winter PET (mm)	150	156	156	156	153	153	159
Median Annual Runoff (ML)	2944	2708	2803	2574	2620	2408	2055
Change in Annual Rainfall (%)		-3	-3	-4	-5	-5	-8
Change in Winter Rainfall (%)		-7	-8	-12	-15	-15	-22
Change in Annual PET (%)		1	1	3	2	2	4
Change in Winter PET (%)		4	4	4	2	2	6
Change in Median Runoff (%)		-8	-5	-13	-11	-18	-30
Low Events							
20th Percentile Runoff (ML)	1159	1011	1026	956	944	905	641
Years Below 1990 20th %	10	12	12	13	13	14	15
High Events							
80th Percentile Runoff (ML)	6275	5368	5430	4989	4836	4672	4028
Years Above 1990 80th %	10	8	8	6	6	6	5

Table 18. Changes in climate and runoff simulated for Baroota Reservoir Catchment 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)	401	364	361	345	329	327	291
Average Winter Rainfall (mm)	131	114	112	104	97	96	79
Average Annual PET (mm)	1372	1410	1414	1431	1451	1451	1493
Average Winter PET (mm)	150	156	156	159	165	165	171
Median Annual Runoff (ML)	2944	2203	2246	1820	1443	1370	781
Change in Annual Rainfall (%)		-9	-10	-14	-18	-18	-27
Change in Winter Rainfall (%)		-13	-14	-20	-26	-27	-40
Change in Annual PET (%)		3	3	4	6	6	9
Change in Winter PET (%)		4	4	6	10	10	14
Change in Median Runoff (%)		-25	-24	-38	-51	-53	-73
Low Events							
20th Percentile Runoff (ML)	1159	681	600	404	287	278	172
Years Below 1990 20th %	10	14	14	18	21	21	37
High Events							
80th Percentile Runoff (ML)	6275	4210	4031	3365	2852	2731	1817
Years Above 1990 80th %	10	5	5	3	3	3	1

This lower average annual rainfall at the Baroota Reservoir compared to the Clare Valley catchments is also likely to be the reason that the percent change in runoff for the Baroota reservoir catchment for a given time horizon and emission case (Figure 53) is generally much less than that found for the Hutt River (Figure 29) or Wakefield River (Figure 30). As the annual rainfall for this site is lower, so is the magnitude of the change in rainfall, based on a percentage reduction. For example, comparing the historic (1990) case with the projected 2070 A2 case for the CSIRO Mk 3.5 GCM, for the Baroota Reservoir catchment the reduction in annual rainfall is projected to be 110 mm and winter rainfall 52 mm (Table 18), compared to the Wakefield River catchment with a projected reduction in annual rainfall of 160 mm and winter rainfall 77 mm (Table 10). This larger change in rainfall amount is coupled with a higher sensitivity of the runoff at for the Wakefield catchment to the amount of rainfall compared to the Baroota reservoir. This sensitivity can be estimated by calculating the elasticity of the annual runoff to the annual rainfall (Chiew, 2006) and the Wakefield catchment has a much higher elasticity of 2.71 compared to 1.96 for the Baroota catchment and therefore, a higher sensitivity of the amount of runoff to a similar change in rainfall. This greater sensitivity of the runoff from the Wakefield River catchment, coupled with a greater reduction in the magnitude of rainfall for the Clare Valley catchments, results in a larger reduction in the total runoff compared to the Baroota Reservoir catchment.

The difference in the climate change impacts for the different regions can also be explained by the characteristics of the catchments considered. The presence of farm dams in the Clare Valley catchments produces a slight increase in the impacts of climate changes for these catchments compared to the Baroota reservoir catchment, which does not include farm dams. A fraction of the flow passing each of the farm dams in the model is diverted out of the system, which is then not available for other purposes downstream. For the Hutt River catchment under historic conditions, 16% of the total runoff generated from the catchments was diverted to farm dams. As a comparison, this increased to 22% for the 2070 A2 emissions scenario based on NCAR-CCSM3 projections, or 38% for the same case based on CSIRO Mk 3.5 projections. Similar results are obtained for the Wakefield River catchment, with 10% of the runoff generated from the catchments diverted to farm dams under historic conditions, increasing to 13% for the 2070 A2 emission scenario based on NCAR-CCSM3 projections and 19% based on CSRIO Mk 3.5 projections. This is based on an already reduced runoff from the catchment for the future cases, hence larger reductions in the runoff are simulated for the Clare Valley catchments that include farm dams.

Also, the Baroota reservoir catchment requires less total rainfall for flow to commence for a season compared to the Clare Valley catchments. This can be seen in Figure 54, presenting the simulated annual runoff for each year of the 50 year simulation under historic conditions for each catchment, against the corresponding annual rainfall. The annual rainfall required for runoff to occur for the Wakefield River catchment is approximately 400 mm, hence 72% of the average rainfall of 568 mm is required for flow to commence. Due to the steeper catchment of the Baroota reservoir, only approximately 200 mm of rainfall is required for flow to commence in a given year, half of the average annual rainfall of 401 mm. Hence, over the 50 year simulation period there are fewer years that result in no, or very low, flow and the percentage reduction in annual rainfall is also less.

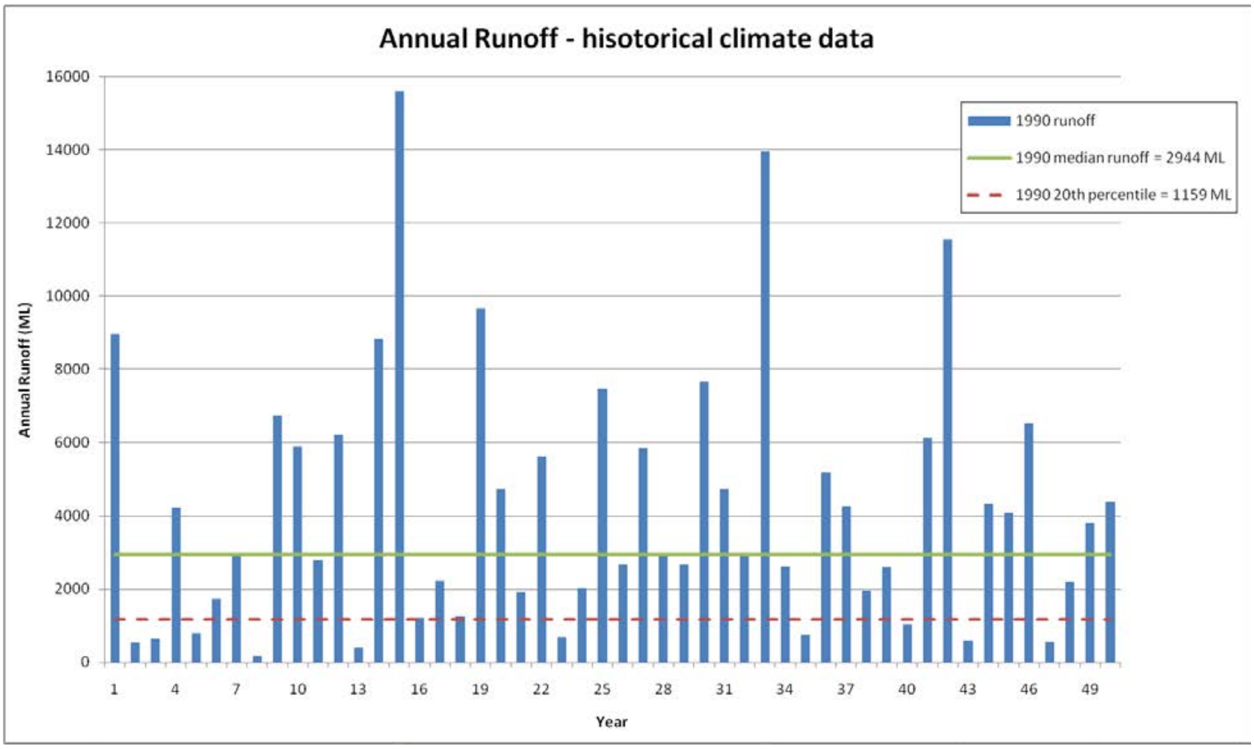


Figure 54. Annual runoff simulated for the Baroota reservoir catchment, based on historically measured rainfall and PET data. Year 1 on the x axis represents 1961, and year 50 represents 2010.

This result can also be seen in Figure 57 to Figure 62, where the simulated yield each year from the Baroota reservoir catchment for each scenario considered is presented (based on the NCAR-CCSM3 GCM projections only). As with the Clare Valley PWRA area results, the projections from this GCM has been selected as they are generally a middle case, less than the CSIRO Mk 3.5 GCM projections and generally a greater change than that projected by the MRI or LASG-IAP GCMs. Again, the 1990 median and 20th percentile flows are indicated by horizontal lines on each plot and then for each future case the projected median runoff is represented by a purple horizontal line to illustrate the projected decrease in runoff compared to the historic case.

It can be seen that the changes in runoff are projected to be much less for the Baroota reservoir. Even for the most extreme cases considered (2070 conditions and A2 emission scenario) the simulated median runoff is reduced, but is still higher than the 20th percentile runoff. This can be compared to the results for the Wakefield River (Figure 37), where the median runoff was projected to be slightly less than the 20th percentile runoff.

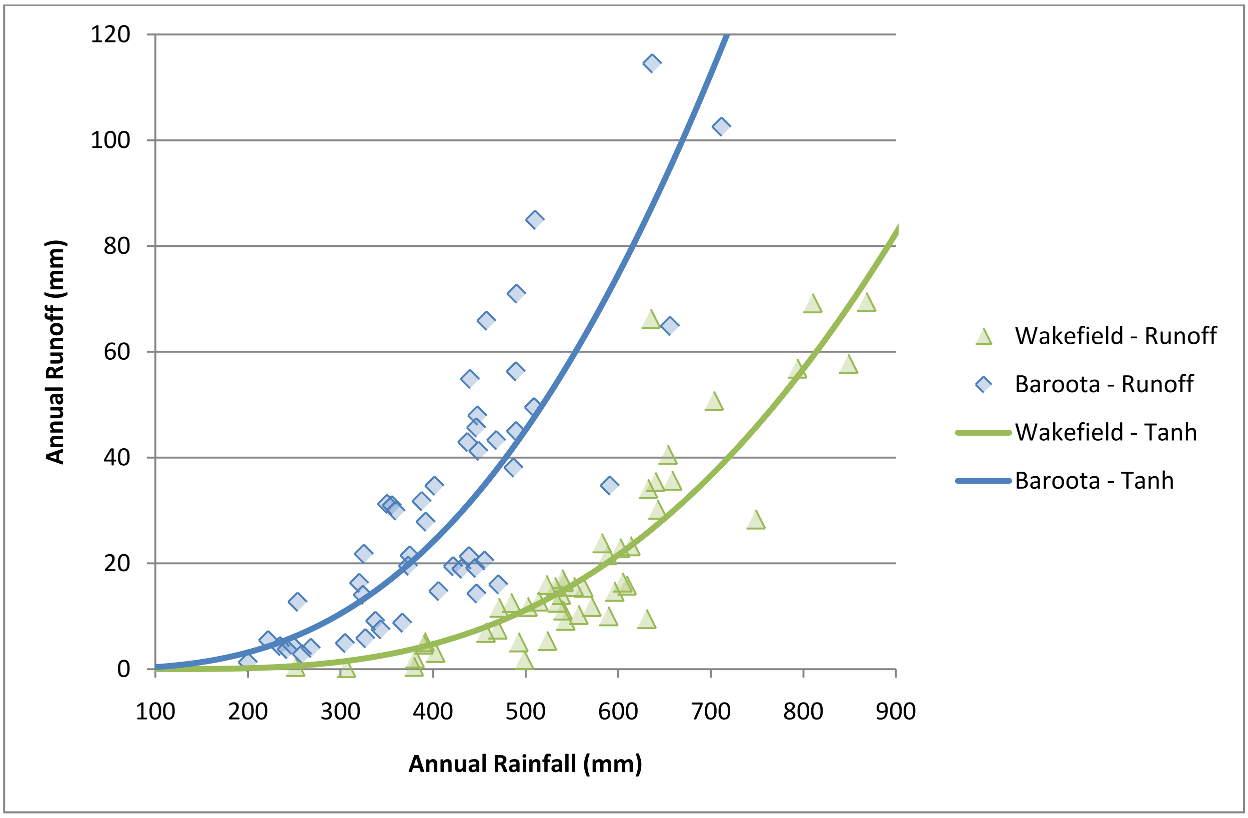


Figure 55. Simulated rainfall – runoff relationships for the Baroota Reservoir and Wakefield River catchments

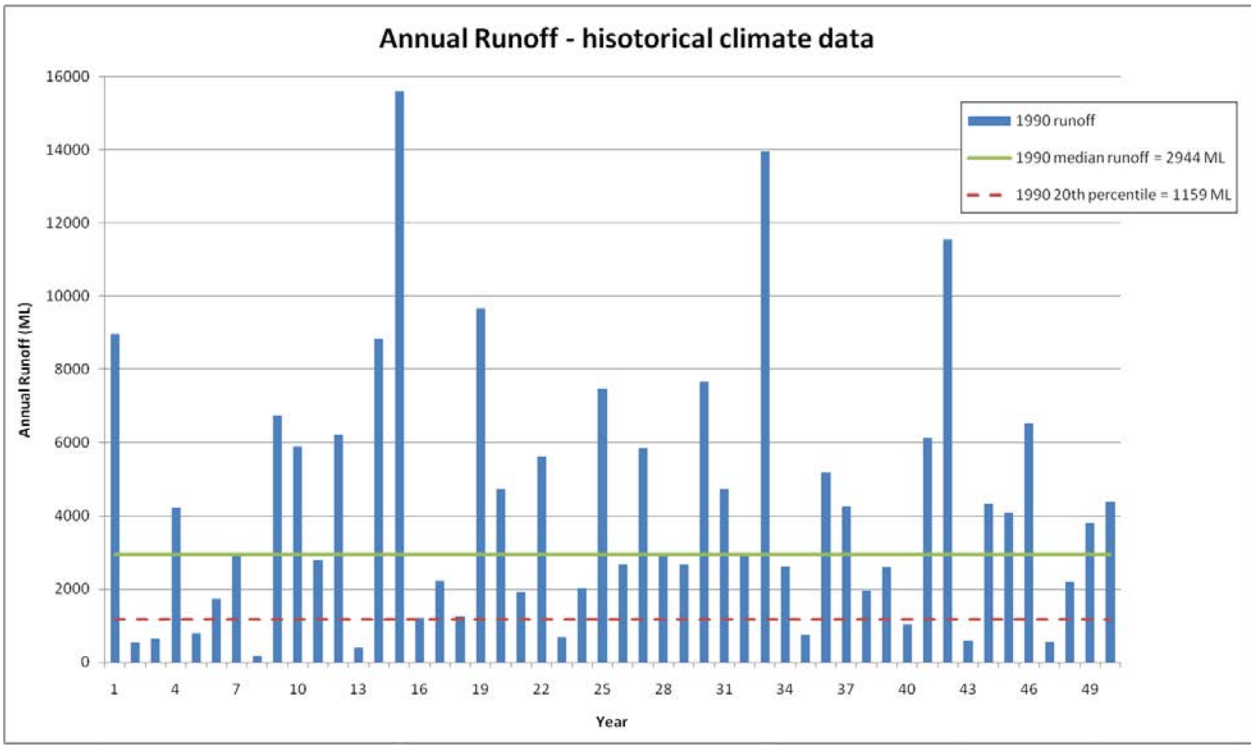


Figure 56. Annual runoff simulated for the Baroota Reservoir Catchment, based on historically measured rainfall and PET data. Year 1 on the x axis represents 1961, and year 50 represents 2010.

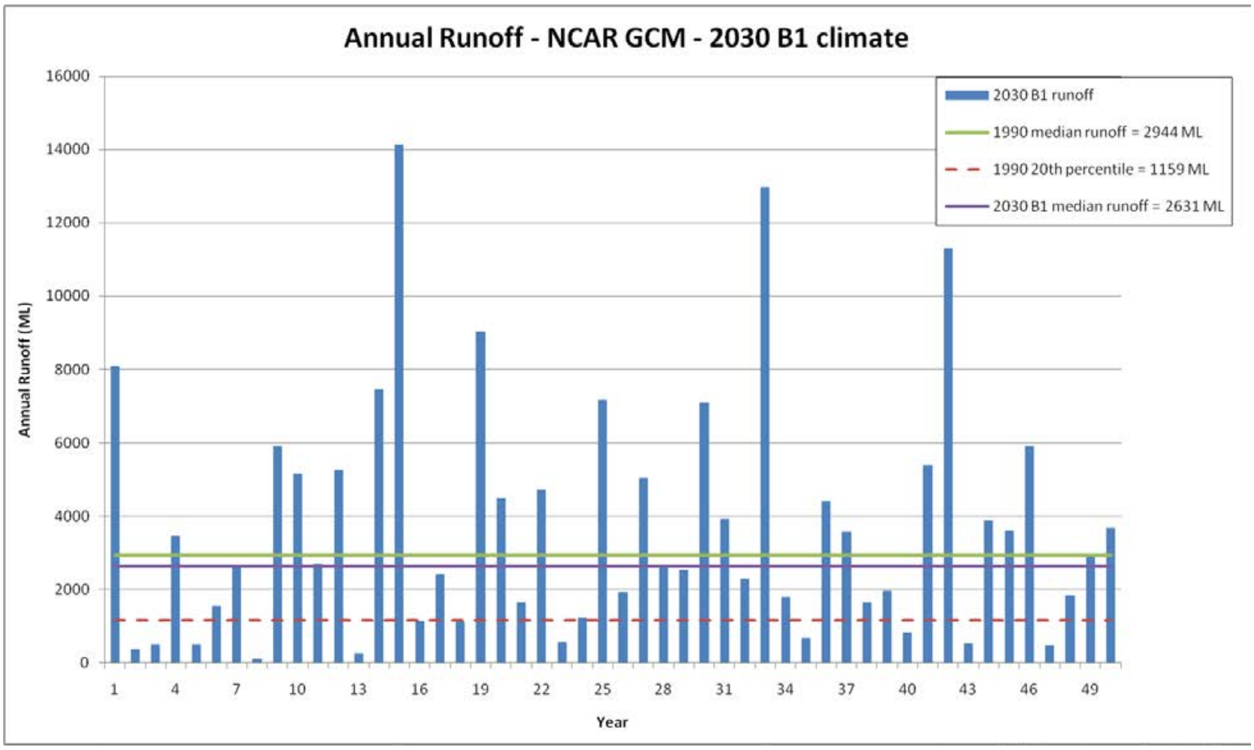


Figure 57. Annual runoff simulated for the Baroota Reservoir Catchment, based on rainfall and PET input data generated by the NCAR GCM for a 2030 climate and B1 emissions

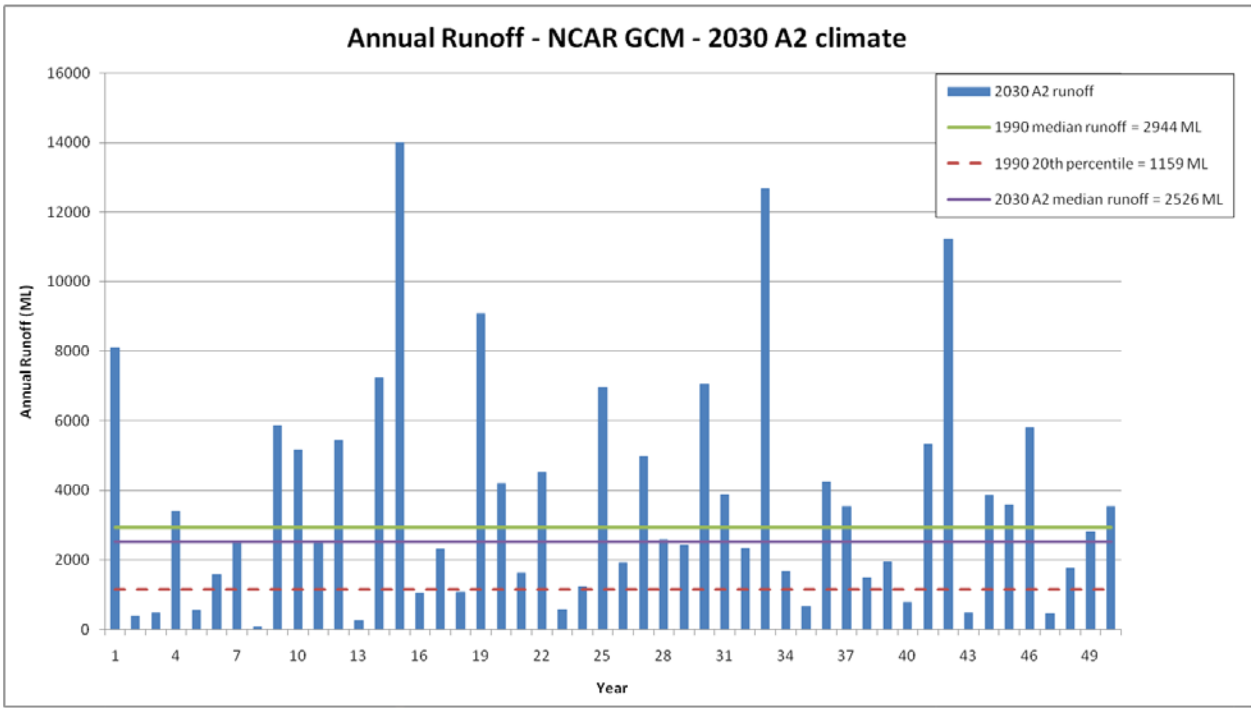


Figure 58. Annual runoff simulated for the Baroota Reservoir Catchment, based on rainfall and PET input data generated by the NCAR GCM for a 2030 climate and A2 emissions

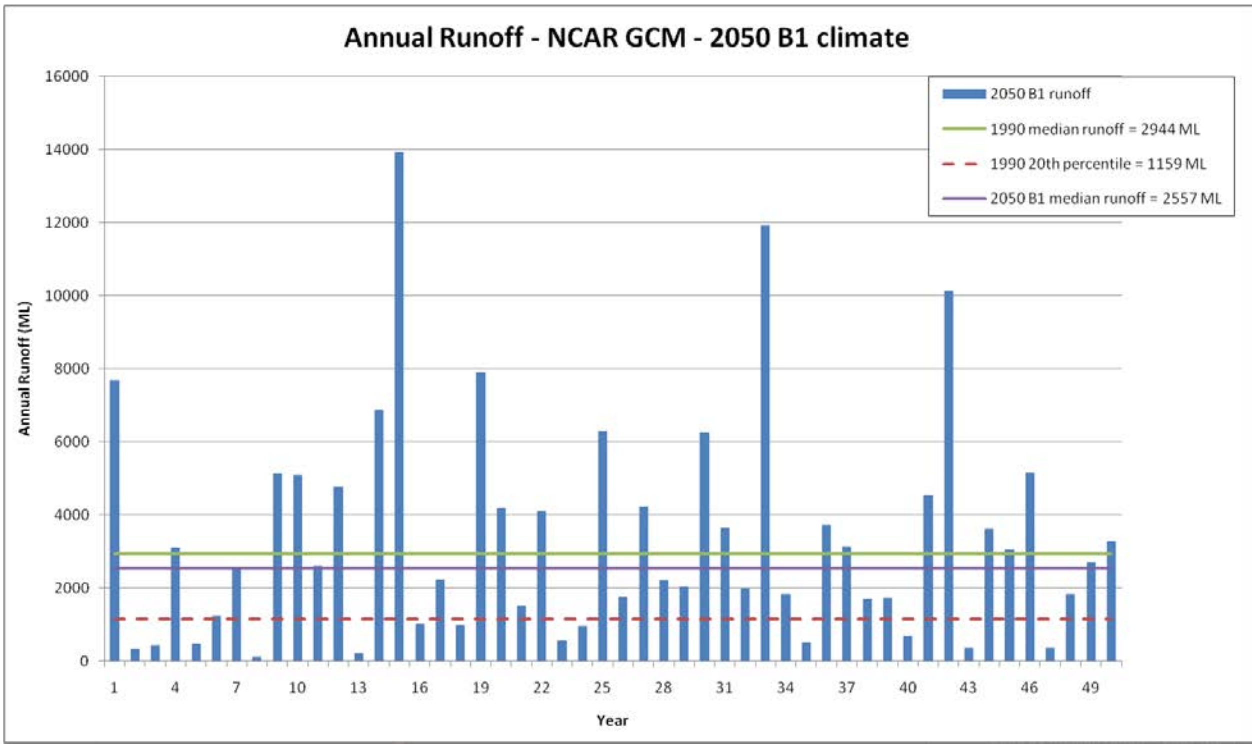


Figure 59. Annual runoff simulated for the Baroota Reservoir Catchment, based on rainfall and PET input data generated by the NCAR GCM for a 2050 climate and B1 emissions

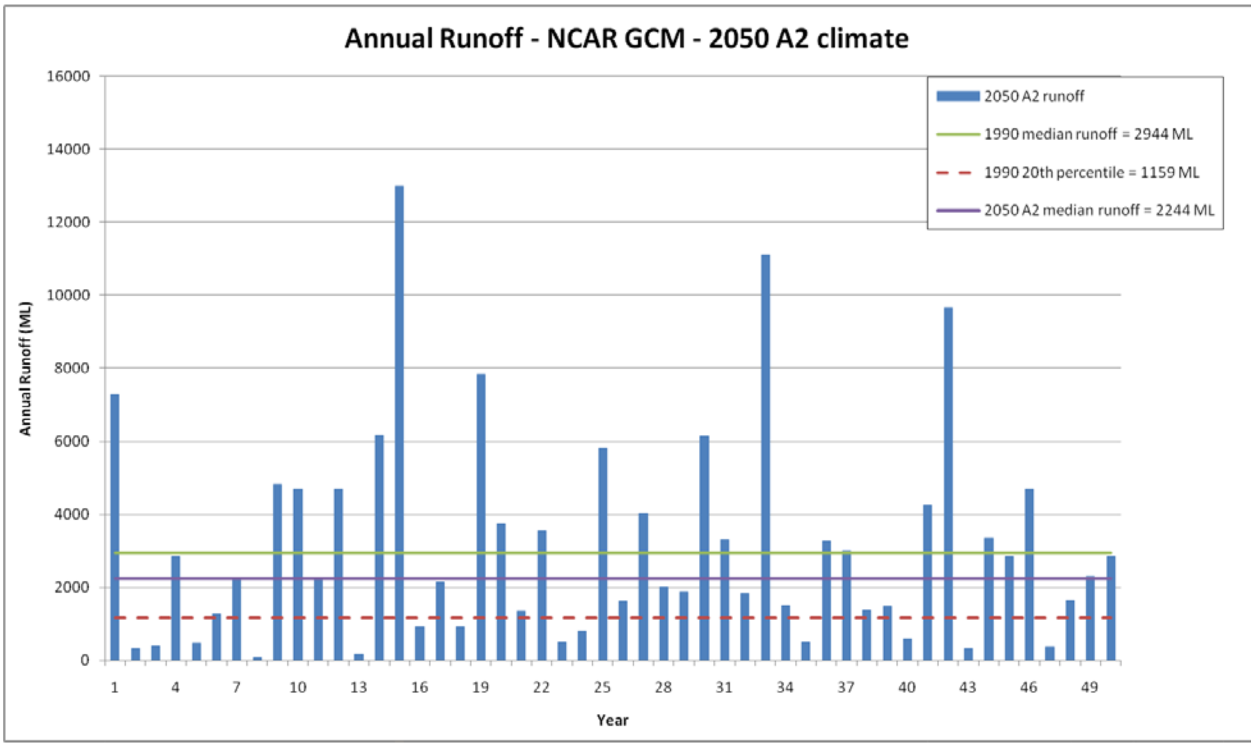


Figure 60. Annual runoff simulated for the Baroota Reservoir Catchment, based on rainfall and PET input data generated by the NCAR GCM for a 2050 climate and A2 emissions

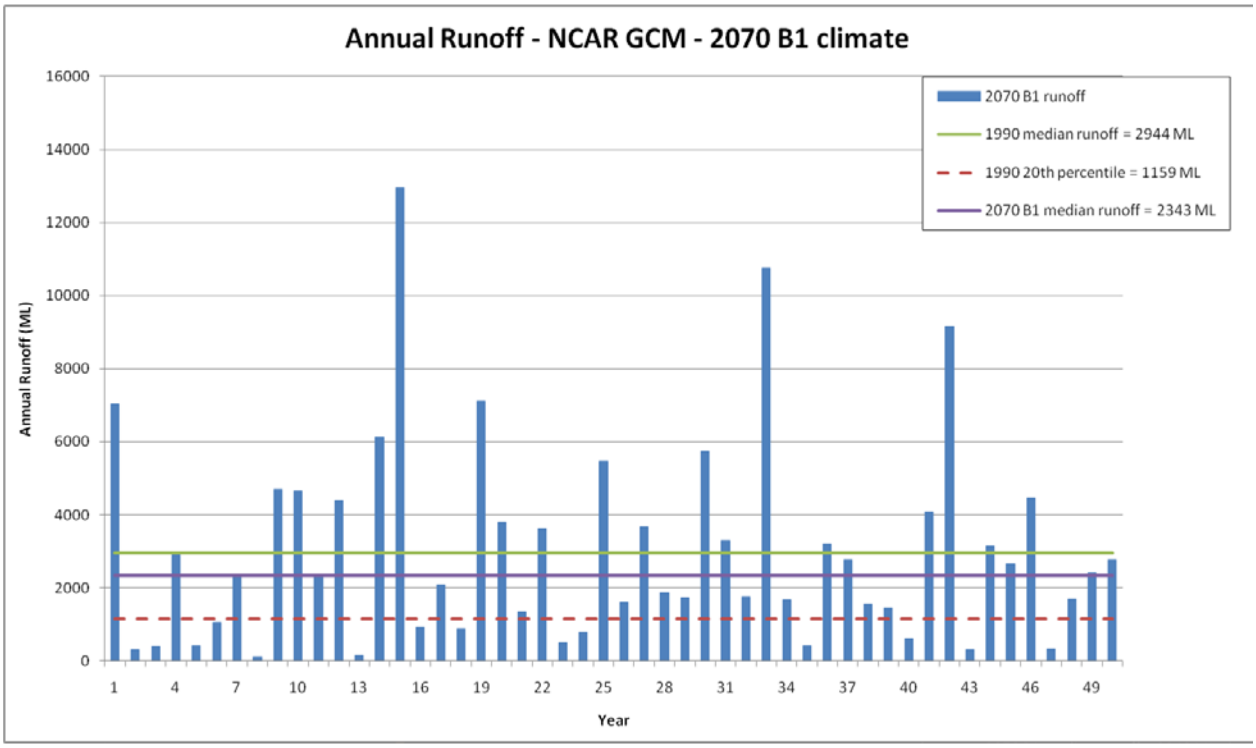


Figure 61. Annual runoff simulated for the Baroota Reservoir Catchment, based on rainfall and PET input data generated by the NCAR GCM for a 2070 climate and B1 emissions

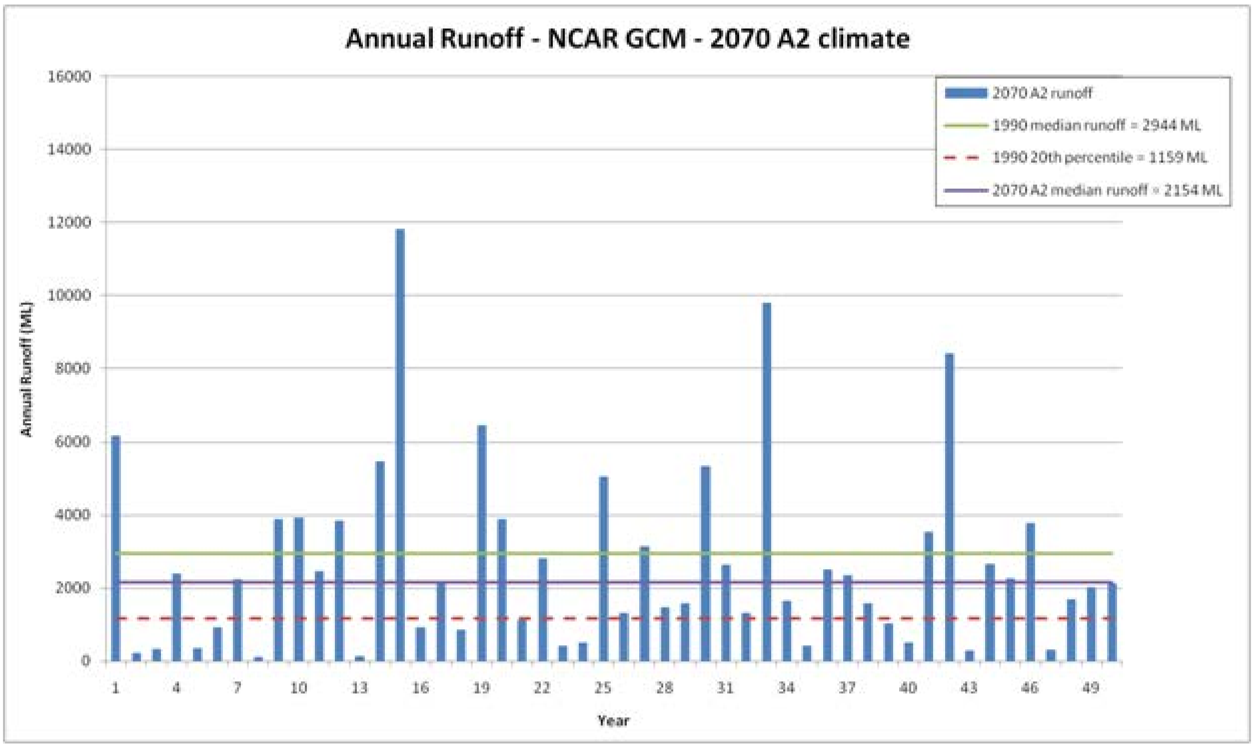


Figure 62. Annual runoff simulated for the Baroota Reservoir Catchment, based on rainfall and PET input data generated by the NCAR GCM for a 2070 climate and A2 emissions

To allow the results presented for the Baroota reservoir catchment to be applied to scenarios other than only the GCMs, emission cases and time horizons presented, a relationship between the change in winter rainfall and resulting change in median runoff has also been developed for this catchment. The data points of a projected change in winter rainfall and corresponding change in median runoff can be seen in Figure 63, with the tanh function fitted to all data points. 95% confidence bounds have also been determined, using the method outlined in Section 4.1.2. The resulting relationship was PR = 2.74 tanh(0.67 PW) ± 16%, where PR is the percentage change in median annual runoff and PW is the percentage change in average winter rainfall.

The relationship presented in Figure 63 is much more linear than that found for the Clare Valley catchments, indicating that a given change in winter rainfall will result in double that change in the corresponding runoff obtained. For example, from Figure 63 a 10% reduction in average winter rainfall is expected to lead to 20% reduction in median annual runoff, with 95% confidence bounds of ±16%, or between a 4% reduction and a 36% reduction. The linear relationship can be explained to some extent by the relationship between rainfall and runoff seen in Figure 55. A 25% reduction in rainfall corresponds in a reduction of the average rainfall from 401mm to 300mm and from Figure 63 the tanh curve fitted to the Baroota Reservoir catchment results (blue line) is relatively linear over this range. The results are not directly transferrable, as one is based on annual rainfall and the other winter rainfall, but provides an insight into the expected runoff behaviour for this catchment.

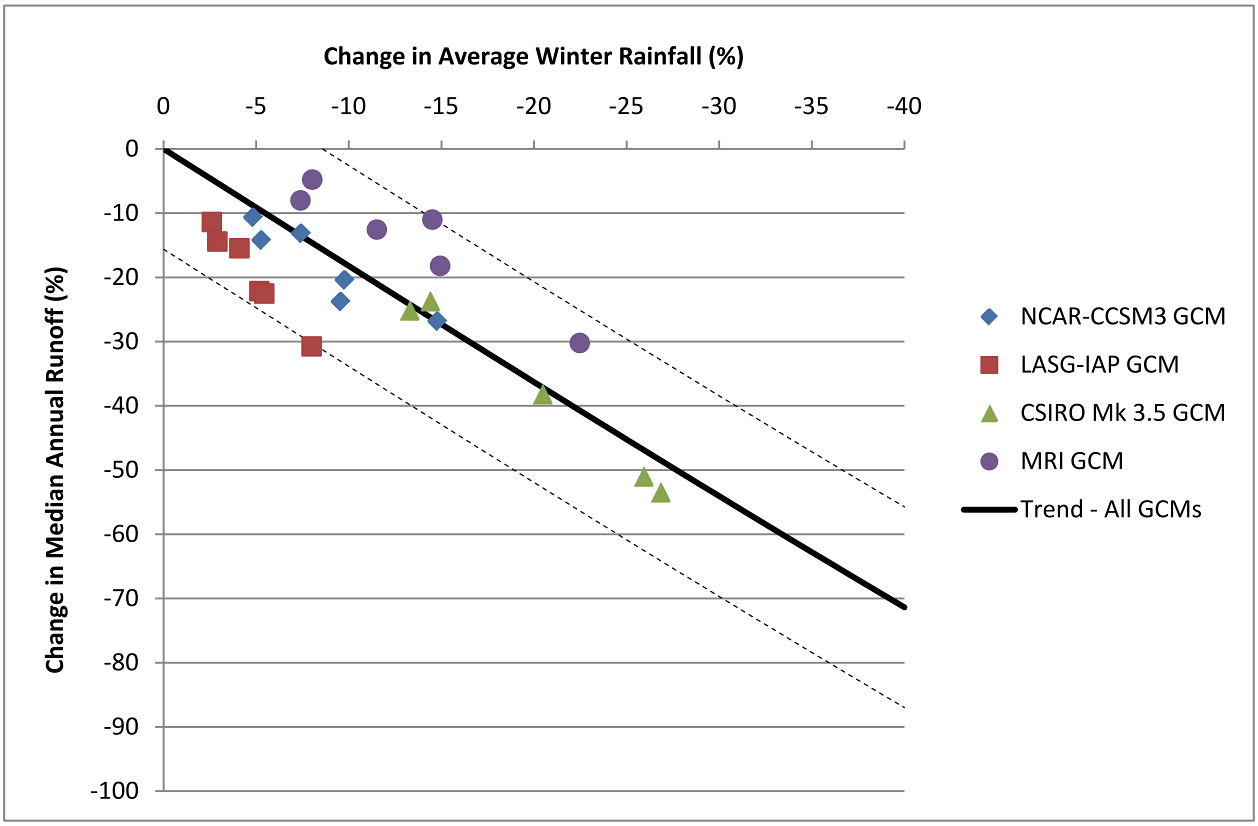


Figure 63. Percent changes in average winter rainfall vs changes in median annual runoff for the Baroota Reservoir Catchment. Trend line is a linear relationship, dashed line shows the upper and lower 95% bounds.

4.2.3. GROUNDWATER RECHARGE IN THE BAROOTA PWRA

The surface water model for Baroota Reservoir was used to determine the number of years (out of the 50 years simulation) in which the reservoir level reached 20m (the level at which overflow and significant groundwater recharge has occurred in the past). Results for the percent change in the number of years in which this level is reached are presented in Figure 64. As can be seen, the greatest reduction in 'potential recharge' is observed for scenarios using input data generated by the CSIRO Mk 3.5 GCM, followed by the NCAR GCM. These results are similar to those seen in the Clare Valley recharge modelling results and reflect the overall large reductions in rainfall predicted by the CSIRO Mk 3.5 GCM and the large increases in winter PET predicted by the NCAR GCM. While the exact relationship between surface water level and recharge cannot be quantified, these results at least give an indication of how climate change will impact upon significant recharge events in the Baroota PWRA.

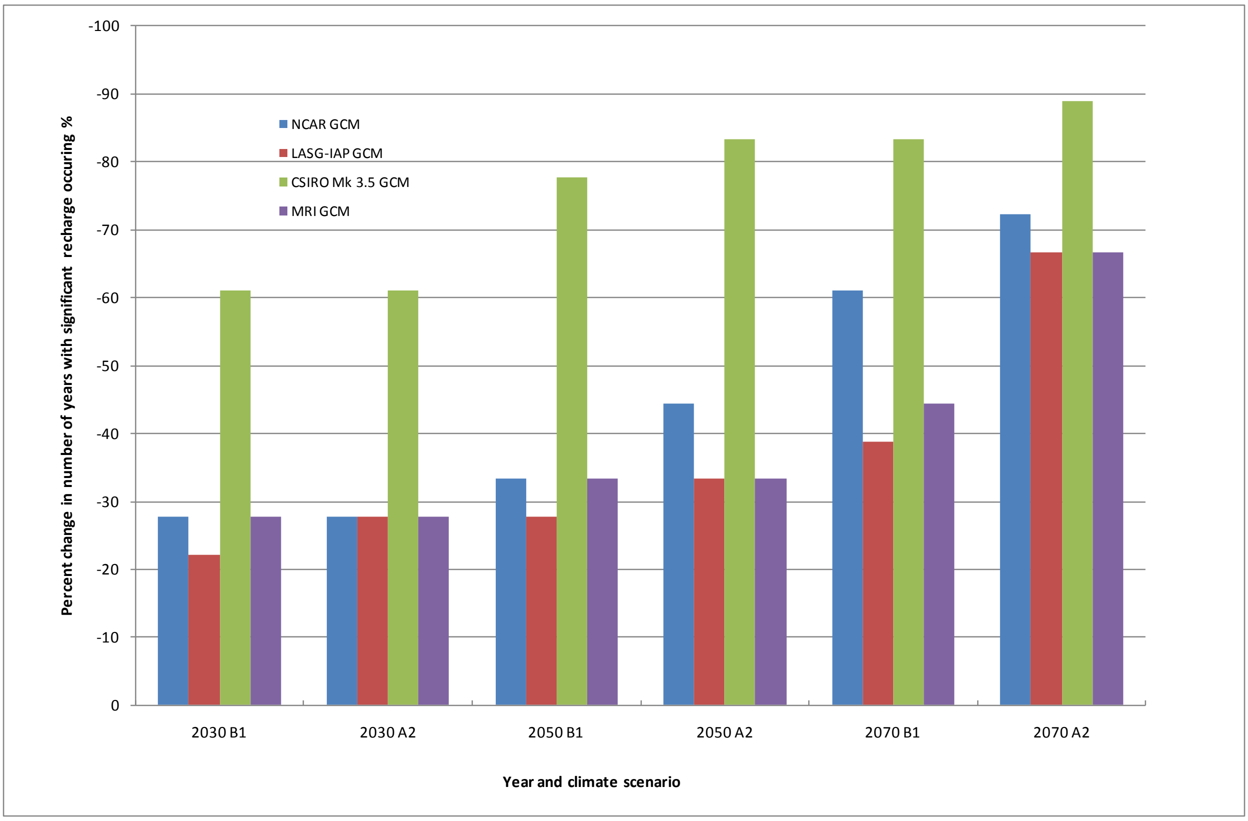


Figure 64. Results from the Baroota Reservoir model displaying the percent change in years in which the reservoir overflows (and hence significant recharge is likely to occur), for the different GCMs, emissions scenarios and time horizons considered

Table 19 to Table 22 summarise the results derived from the Baroota reservoir model for future climate scenarios from all four GCMs. As well as the changes to median 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.

Table 19. Changes in climate and significant recharge events simulated by the Baroota surface water modelling using input data generated using the LASG-IAP GCM

LASG-IAP	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	401	390	389	384	380	379	369
Average Winter Rainfall (mm)	131	128	127	126	124	124	121
Average Annual PET (mm)	1372	1393	1393	1399	1409	1409	1430
Average Winter PET (mm)	150	159	159	159	162	162	168
Years with Recharge (in 50)	18	14	13	13	12	11	6
Change in Annual Rainfall (%)		-3	-3	-4	-5	-5	-8
Change in Winter Rainfall (%)		-3	-3	-4	-5	-5	-8
Change in Annual PET (%)		2	2	2	3	3	4
Change in Winter PET (%)		6	6	6	8	8	12
Change in Recharge Events (%)		-22	-28	-28	-33	-39	-67

Table 20. Changes in climate and significant recharge events simulated by the Baroota surface water modelling using input data generated using the NCAR GCM

NCAR GCM	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	401	394	393	390	387	387	380
Average Winter Rainfall (mm)	131	125	124	121	119	118	112
Average Annual PET (mm)	1372	1404	1405	1424	1439	1442	1474
Average Winter PET (mm)	150	162	162	168	175	178	187
Years with Recharge (in 50)	18	13	13	12	10	7	5
Change in Annual Rainfall (%)		-2	-2	-3	-3	-3	-5
Change in Winter Rainfall (%)		-5	-5	-7	-10	-10	-15
Change in Annual PET (%)		2	2	4	5	5	7
Change in Winter PET (%)		8	8	12	16	18	25
Change in Recharge Events (%)		-28	-28	-33	-44	-61	-72

Table 21. Changes in climate and significant recharge events simulated by the Baroota surface water modelling using input data generated using the MRI GCM

MRI GCM	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	401	390	389	384	380	380	369
Average Winter Rainfall (mm)	131	121	121	116	112	112	102
Average Annual PET (mm)	1372	1390	1390	1408	1405	1405	1426
Average Winter PET (mm)	150	156	156	156	153	153	159
Years with Recharge (in 50)	18	13	13	12	12	10	6
Change in Annual Rainfall (%)		-3	-3	-4	-5	-5	-8
Change in Winter Rainfall (%)		-7	-8	-12	-15	-15	-22
Change in Annual PET (%)		1	1	3	2	2	4
Change in Winter PET (%)		4	4	4	2	2	6
Change in Recharge Events (%)		-28	-28	-33	-33	-44	-67

Table 22. Changes in climate and significant recharge events simulated by the Baroota surface water modelling using input data generated using the CSIRO Mk 3.5 GCM

CSIRO Mk 3.5 GCM	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	401	364	361	345	329	327	291
Average Winter Rainfall (mm)	131	114	112	104	97	96	79
Average Annual PET (mm)	1372	1410	1414	1431	1451	1451	1493
Average Winter PET (mm)	150	156	156	159	165	165	171
Years with Recharge (in 50)	18	7	7	4	3	3	2
Change in Annual Rainfall (%)		-9	-10	-14	-18	-18	-27
Change in Winter Rainfall (%)		-13	-14	-20	-26	-27	-40
Change in Annual PET (%)		3	3	4	6	6	9
Change in Winter PET (%)		4	4	6	10	10	14
Change in Recharge Events (%)		-61	-61	-78	-83	-83	-89

The results from all model runs plotted against the percent change in average winter rainfall are shown in Figure 65. Again, the trend of these results is represented with a tanh curve, which can be seen to provide a suitable representation of the trend of climate change impacts on the number of years in which recharge is likely to occur. The dashed lines in Figure 65 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 (section 4.1.2).

The relationship depicted in this graph allows the expected change in the number of years in which recharge is likely to occur to be estimated for any given change in winter rainfall, such as those reported for the NYNRM Region (DENR 2010). This relationship is presented in the 'Water Resource Impact Summary' section of the report (section 5.3.2). 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 change in the number of significant recharge years 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.

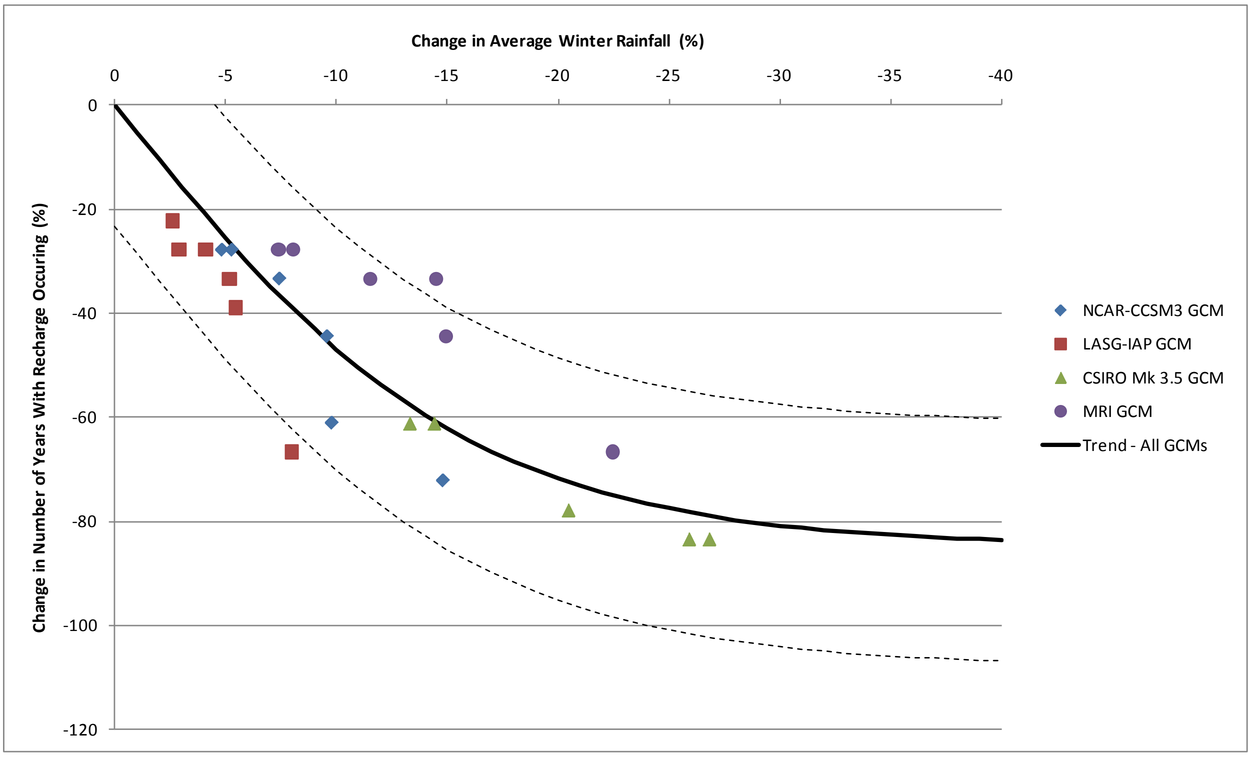


Figure 65. Percent changes in average winter rainfall versus changes in the number of years in which significant recharge is likely to occur in the Baroota PWRA. Trend line is a tanh relationship, dashed lines show the upper and lower 95% confidence bounds.

4.3. UNCERTAINTIES AND LIMITATIONS

There are two primary sources of the 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 atmospheric and oceanic process, 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 from the different models. The differences are more marked in variables that are influenced by a 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 weather station scale, each with different advantages and disadvantages and with different outputs representing the future climate. 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 Swart, 2000) that are widely adopted for use 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 the accepted emissions scenarios. The authors make no recommendations on which of the eight climate scenarios applied to the hydrological models herein is more likely to eventuate.

When projected changes in climate are applied to hydrological models, the uncertainty in the climate projections is compounded with the uncertainty in the hydrological models. Sensitivity analysis and calibration of the hydrological models developed in this study has ensured that 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 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 all of the GCMs that are deemed appropriate for South Australia (refer ICCWR Project Phase 2 report, 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 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 illustrate the complexity involved in modelling the potential impacts of climate change on water resources and highlighted the need to consider a number of factors in assessing potential impacts, such as the variation in results of multiple global climate models (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.

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 work, to assess a number of possible scenarios, selected according to their suitability for representing the South Australian climate. The projections used in this work, which can be seen in Sections 4.1.1 and 4.2.1, vary significantly depending on the year 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 (refer ICCWR Project Phase 2 report, 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 66 to 69.

5.1. CLIMATE CHANGE PROJECTIONS FOR THE NORTHERN AND YORKE REGION

The national climate projections presented in the 2007 CSIRO-BoM Climate Change in Australia report (CSIRO-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 Northern and Yorke NRM 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 NYNRM Region. The median projected changes in winter rainfall in the NYNRM Region under high, low and medium emissions scenarios for 2030, 2050 and 2070 are shown in Table 23.

In the recharge and runoff modelling results described in Section 4 of this report, projected changes in winter 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 winter rainfall change have therefore been used within this section as climate change reference points against which the winter rainfall / water resource impact relationships are compared in figures 66 to 69 and in the corresponding tables 24 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 winter rainfall / water resource impact relationships were developed, the reader should refer to sections 3 and 4 of this report.

Table 23. Median projections of percentage change in average winter rainfall for NYNRM Region, based on an ensemble of 13 GCMs suitable for the South Australian Climate, as reported by DENR (2010) and CSIRO-BoM (2007)

Time horizon	2030			2050			2070		
Emissions scenario	Low	Med	High	Low	Med	High	Low	Med	High
Change in average winter rainfall (%)	-5	-6.5	-6.5	-7.5	-10	-13	-9	-15	-15

5.2. IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES IN THE CLARE VALLEY PWRA

5.2.1. SURFACE WATER RUNOFF

Two catchments were used to assess the potential impacts of climate change on runoff in the Clare Valley PWRA, the Hutt River (a tributary of the Broughton River) and the Wakefield River. The models were calibrated to represent runoff under the historic climate, based on the observed flow record available. 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 results for the different climate projections considered was found to have the strongest relationship with the projected winter rainfall. Hence, relationships were developed to show the change in runoff compared to projected changes in winter rainfall, with the results shown in Figure 38 for Wakefield River, and Figure 39 for Hutt River. These relationships are represented by tanh curves in Figure 66, together with a combined relationship fitted to the results from both catchments. The latter represents the average response of the catchments considered in the Clare Valley PWRA. The dashed lines represent the 95% confidence intervals for the combined relationship representing both the Hutt River and Wakefield River catchments.

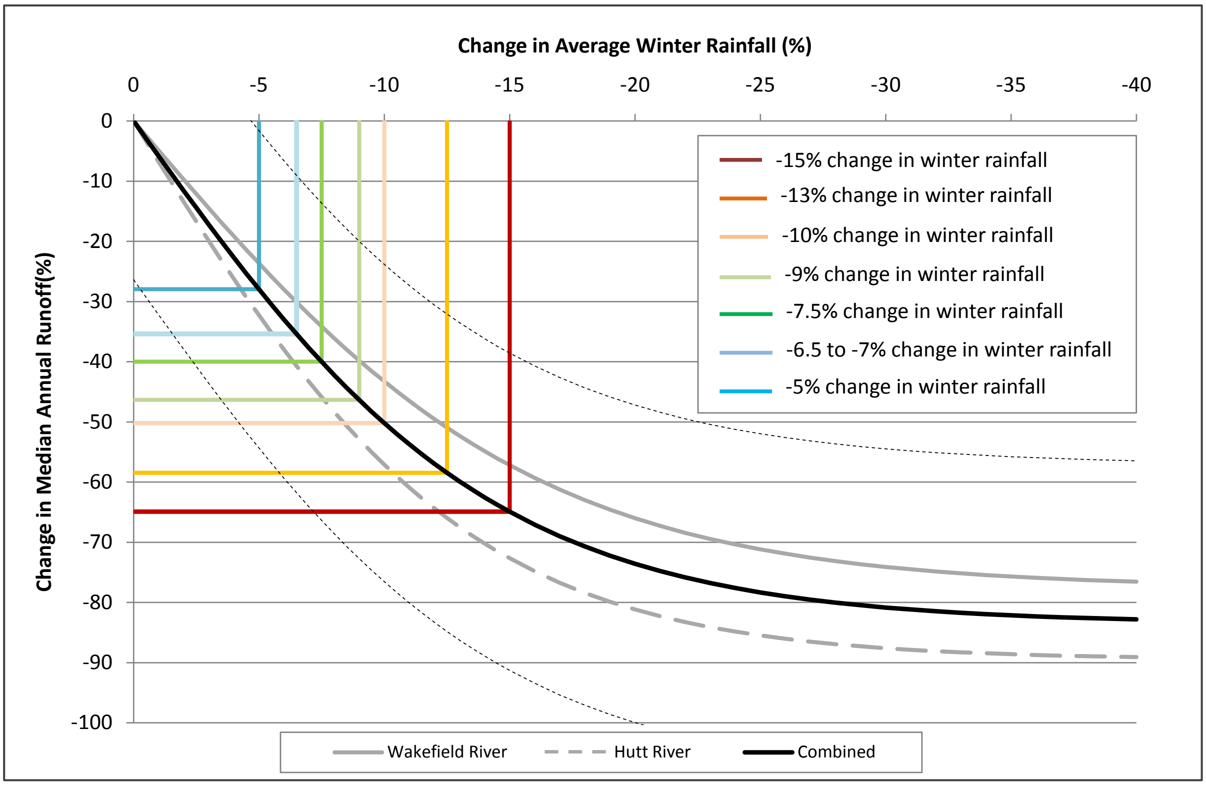


Figure 66. Percent change in median annual runoff for a given percent change in average winter rainfall, for Hutt and Wakefield river catchments and a combination of both catchments. Dashed lines represent 95% confidence bounds for the combined relationship . Coloured lines indicate the winter rainfall projections reported by DENR (2010) and CSIRO-BoM (2007) for the Northern and Yorke NRM Region.

The coloured lines in Figure 66 represent the median projected changes in winter rainfall, as reported by DENR (2010) and CSIRO-BoM (2007). The corresponding changes to the simulated median annual runoff are also presented in Table 24.

Table 24. Summary of percent changes in median annual runoff for the Clare Valley PWRA for the projected changes in winter rainfall for the Northern and Yorke NRM Region. The colours of each box in the table correspond to the colours shown in Figure 66 (winter rainfall projections from DENR (2010) and CSIRO-BoM (2007)).

Time horizon	**2030**			**2050**			**2070**		
Emissions scenario	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Change in average winter rainfall (%)	-5	-6.5	-6.5	-7.5	-10	-13	-9	-15	-15
Change in median annual runoff (%)	-28	-35	-35	-40	-50	-58	-46	-65	-65

These results indicate that runoff in the Clare Valley PWRA region is highly sensitive to projected climate changes, with the impact on runoff approximately 4.7 times greater than the change in winter rainfall that produced the change. For example, for the 2050 high emission scenario, a 13% reduction in winter rainfall leads to a 58% reduction in runoff. This high sensitivity to potential climate changes is most likely due to the runoff response of these catchments, which generally occurs for only a number of days after large rainfall events making it more susceptible to changes in the amount of rainfall in each rainfall event.

5.2.2. GROUNDWATER RECHARGE

The LEACHM modelling code was used to model the potential impacts of climate change on groundwater recharge in the Clare Valley PWRA. A number of models were constructed to represent the different soil types and land covers in the region and these were spatially aggregated in a GIS platform to give area-weighted average recharge rates for the Clare Valley PWRA. The models were calibrated to observed data where possible. Recharge under current climate conditions was simulated using measured rainfall and PET data from 1961 – 2010 as inputs to the model. The potential impacts of climate change on recharge were then simulated for six future climate scenarios, based on time horizons of 2030, 2050, and 2070, with high and low emissions scenarios. Four different GCMs were used to generate future rainfall and PET data for each of 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 Clare Valley. Figure 67 shows the relationship between modelled changes in recharge and related changes in winter 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 winter rainfall.

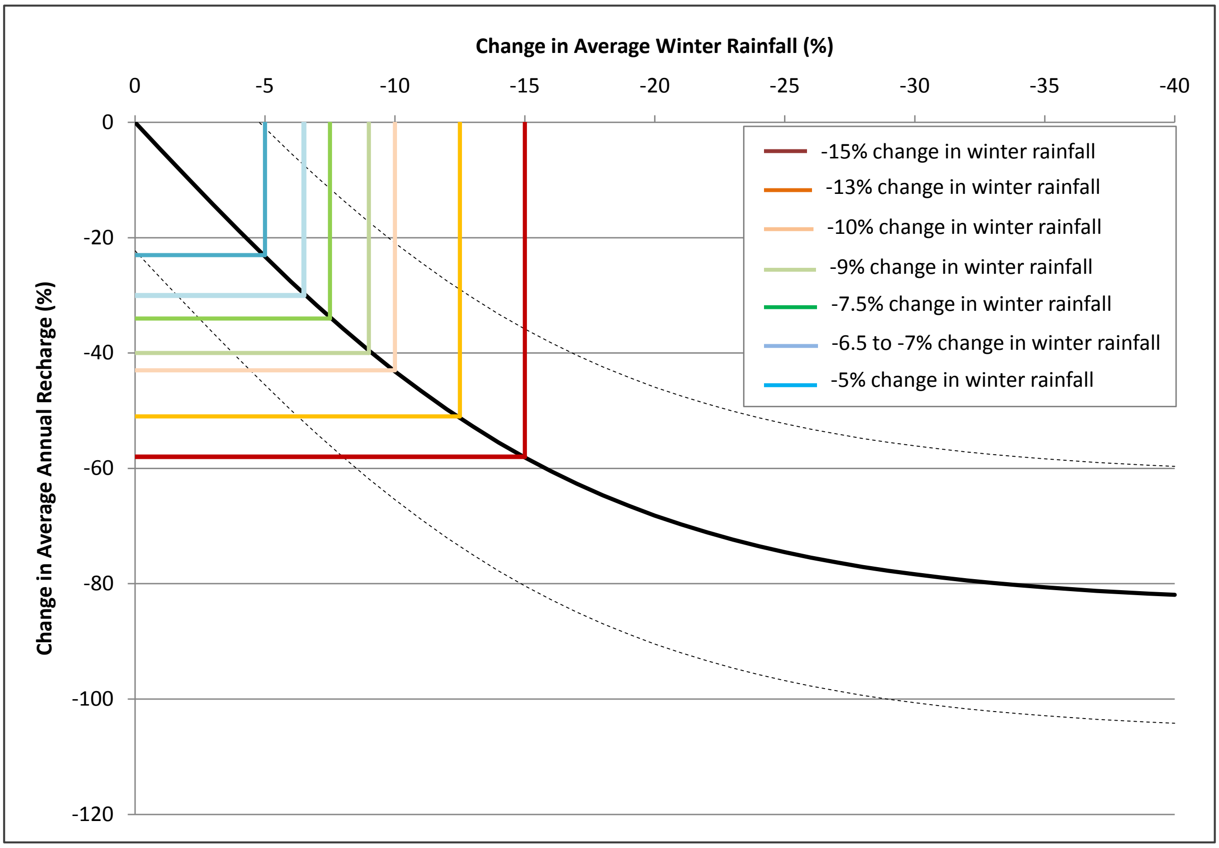


Figure 67. Percent change in average annual recharge for a given percent change in average winter rainfall in the Clare Valley prescribed Water Resources Area. Dashed lines indicate the 95% confidence bounds. Coloured lines indicate the winter rainfall projections reported by DENR (2010) and CSIRO-BoM (2007) for the Northern and Yorke NRM Region.

The coloured lines in Figure 67 represent the median projected changes in winter rainfall, as reported by DENR (2010) and CSIRO-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 percent changes in average annual recharge to the Clare Valley groundwater resources for the projected changes in winter rainfall in the Northern and Yorke NRM Region. The colours of each box in the table correspond to the colours shown in Figure 67 (winter rainfall projections from DENR (2010) and CSIRO-BoM (2007)).

Time horizon	**2030**			**2050**			**2070**		
Emissions scenario	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Change in average winter rainfall (%)	-5	-6.5	-6.5	-7.5	-10	-13	-9	-15	-15
Change in average annual recharge (%)	-23	-30	-30	-34	-43	-51	-40	-58	-58

These results indicate that groundwater recharge in the Clare Valley region is highly sensitive to changes in rainfall and runoff. This sensitivity is due to a combination of the soil types, land cover types, land slope variations and climate, which determine how much of area's water balance goes to evapotranspiration, runoff, or recharge. The average annual recharge across the area under the historic climate is only approximately 6 – 12% of the average annual rainfall, with the remainder going to runoff and evapotranspiration. Hence the combination of a reduction in winter rainfall and a corresponding increase in potential evapotranspiration under a future climate scenario tends to increase the proportion of the water balance that goes to evapotranspiration. As this is the largest component of the water balance in this region, the result is a percentage change in recharge that is significantly larger than the percentage change in rainfall.

5.3. IMPACTS OF CLIMATE CHANGE ON THE BAROOTA PWRA

5.3.1. SURFACE WATER RUNOFF

A one node rainfall – runoff model was used to represent the yield from the local catchment along Baroota Creek to the Baroota reservoir. Each of the 24 GCM, time horizon and emission scenario combinations were applied to the calibrated model to estimate the impact of the projected changes in the future climate on the resulting runoff.

Based on these simulations a relationship between average winter rainfall and median annual runoff follows a linear trend, as shown in Figure 68. The uncertainty in the results, represented by the dashed 95% confidence interval lines in Figure 68, is due to a number of factors including the annual variations in non-winter rainfall, the corresponding variations in evapotranspiration and the variations in the intensity of the daily rainfall amounts implemented in the climate downscaling method. The coloured lines indicate the median projected changes in winter rainfall as reported by DENR (2010) and CSIRO-BoM (2007).

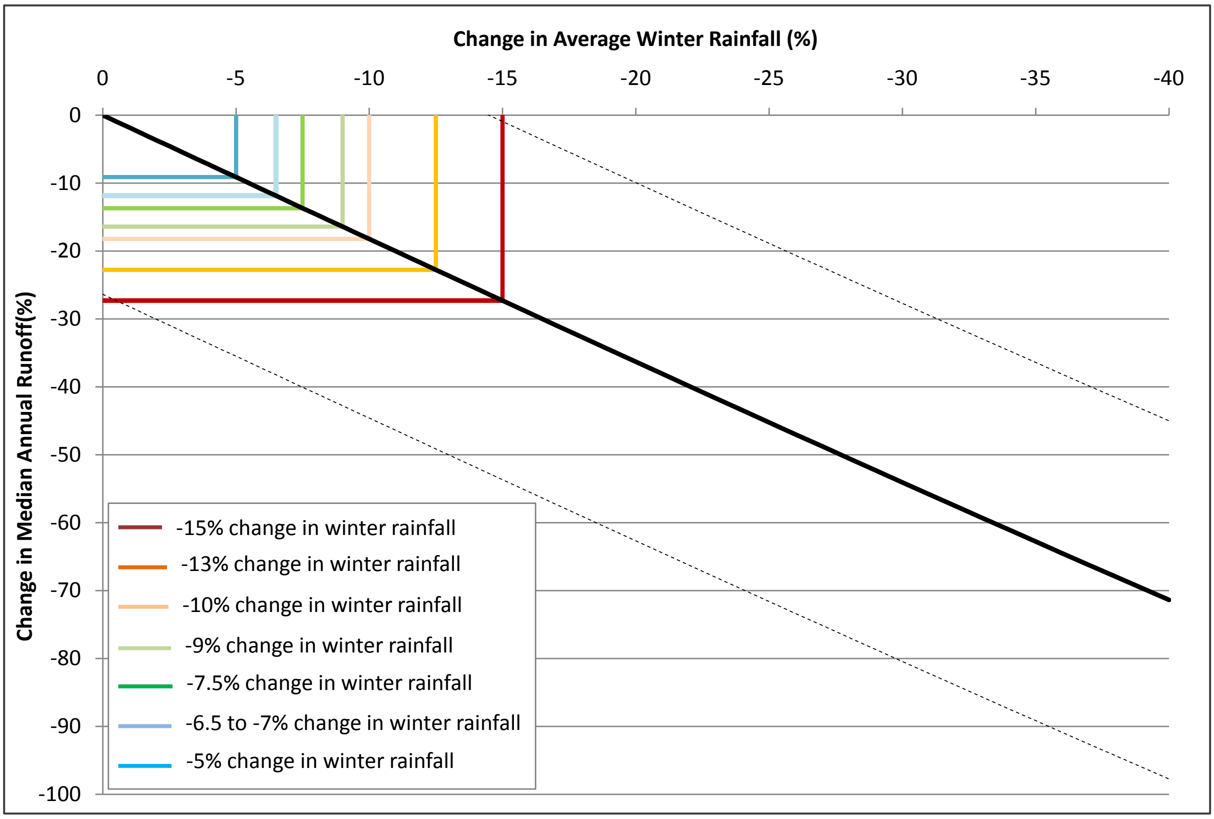


Figure 68. Percent change in median annual runoff for a given percent change in average winter rainfall for the Baroota reservoir catchment. Dashed lines represent 95% confidence intervals. Coloured lines indicate the winter rainfall projections reported by DENR (2010) and CSIRO (2007)) for the Northern and Yorke NRM Region

The corresponding changes in median annual runoff for the winter rainfall change projections are presented in Table 26. The projected changes in runoff in the Baroota catchment can be seen to be much less severe compared to those expected in the Clare Valley catchments. For the Baroota catchment, the impact on runoff is approximately 1.8 times greater than the corresponding change in winter rainfall. For example, for the 2050 medium emissions scenario, the projected 10% reduction in winter rainfall is expected to result in an 18% reduction in the median annual runoff. This is a relatively low sensitivity to projected climate changes and is most likely due to the steep slopes in this catchment generating runoff most years. For example, from the rainfall – runoff relationship presented in Figure 55 (Section 4.2.2), some runoff is expected to be generated even for a very dry year with an annual rainfall of little more than 200 mm, whereas over 400 mm of rainfall is required for an equivalent runoff depth from the Wakefield catchment.

Table 26. Percent change in median annual runoff into the Baroota Reservoir for the projected changes in winter rainfall for the Northern and Yorke NRM Region. The colours of each box in the table correspond to the colours shown in Figure 68 (winter rainfall projections from DENR (2010) and CSIRO-BoM (2007)).

Time horizon	**2030**			**2050**			**2070**		
Emissions scenario	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Change in average winter rainfall (%)	-5	-6.5	-6.5	-7.5	-10	-13	-9	-15	-15
Change in median annual runoff (%)	-9	-12	-12	-14	-18	-23	-16	-27	-27

5.3.2. GROUNDWATER RECHARGE

The limited knowledge on groundwater recharge processes in Baroota and the lack of available data with which to estimate recharge rates meant that detailed LEACHM models were not constructed as they were for the Clare Valley PWRA. Instead, a relationship between reservoir overflows and the occurrence of recharge events in Baroota Reservoir catchment was developed and applied to results from a surface water model of the reservoir to provide an indication of the reduction in the number of years in which recharge is likely to occur. Current climate conditions were simulated using measured rainfall and PET data from 1960 – 2010 as input to the model. The potential impacts of climate change on recharge were then simulated for six future climate scenarios, based on time horizons of 2030, 2050, and 2070, with high and low emissions scenarios. Four different GCMs were used to generate future rainfall and PET data for each of 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 Baroota PWRA. Figure 69 shows the relationship between the modelled changes in the frequency of reservoir overflow events and the related changes in winter rainfall. The trend of this relationship is represented by a tanh curve. This provides an indication of the potential reduction in groundwater recharge resulting from projected changes in winter rainfall under future climate scenarios.

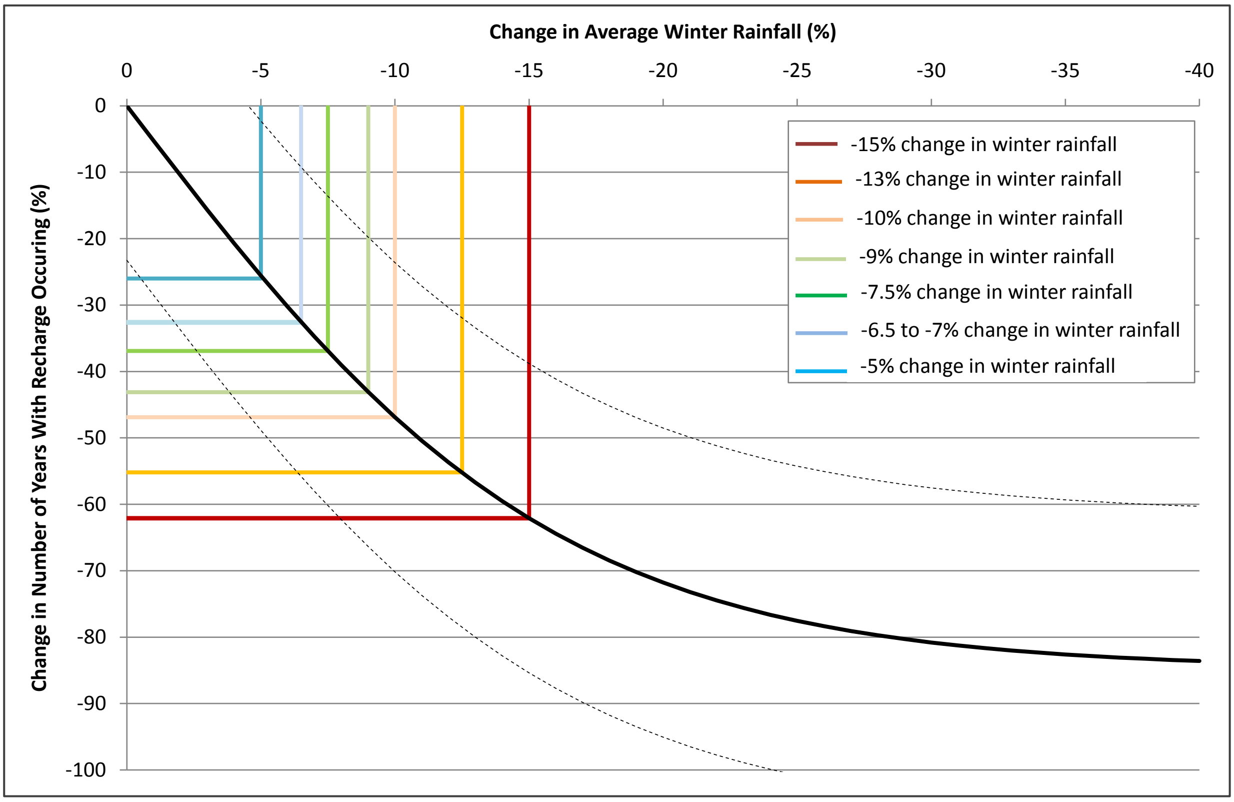


Figure 69. Percent change in the number of years in which significant recharge may occur in the Baroota PWRA for a given percent change in average winter rainfall. Dashed lines indicate the 95% confidence bounds. Coloured lines show the winter rainfall projections reported by DENR (2010) and CSIRO (2007) for the Northern and Yorke NRM Region.

The coloured lines in Figure 69 represent the median projected changes in winter rainfall, as reported by DENR (2010) and CSIRO-BoM (2007). The changes in frequency of significant recharge events corresponding to the median climate change projections are also presented in Table 27. These are derived from the trend of change in frequency of significant recharge events described by the tanh curve in Figure 69, above.

Table27. Summary of percent changes in the frequency which significant recharge may occur in the Baroota PWRA (based on modelled levels in Baroota Reservoir), for the projected changes in winter rainfall in the Northern and Yorke NRM Region. The colours of each box in the table correspond to the colours shown in Figure 69 (winter rainfall projection from DENR (2010) and CSIRO (2007)).

Time horizon	2030			2050			2070		
Emissions scenario	Low	Med	High	Low	Med	High	Low	Med	High
Change in average winter rainfall (%)	-5	-6.5	-6.5	-7.5	-10	-13	-9	-15	-15
Change in number of recharge events (%)	-26	-33	-33	-37	-47	-55	-43	-62	-62

The percentage changes in the number of recharge events in the Baroota Reservoir catchment shown in Figure 69 and Table 27 are considerably greater than the percentage changes in surface runoff projected for this catchment under the same climate scenarios (Figure 68 and Table 26). The relatively moderate projected changes in runoff into the reservoir have a significant effect on the frequency with which the reservoir overflows. For example, under a medium emissions scenario 2030 climate with a 7% reduction in average winter rainfall, the runoff in the Baroota catchment reduces by 12%, however this reduction in runoff translates into a 33% reduction in the frequency of reservoir overflow events.

The groundwater level data for the Baroota catchment suggests that the frequency of reservoir overflow events is a reasonable proxy for the frequency of recharge events. There is likely to continue to be a high variability in the size of recharge events and any change in this variability under future climates is not incorporated in the projected percentage changes in recharge indicated in Figure 69 and Table 27. However, for resource planning purposes the projected percentage changes shown here should be taken to be a reasonable estimate of the change to recharge in the Baroota PWRA under future climate scenarios.

6. CONCLUSIONS AND RECOMMENDATIONS

The focus of this study was the impacts of climate change on groundwater recharge and surface water runoff in the Clare Valley and Baroota PWRAs of the NYNRM 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.

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 winter 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.

The changes in surface water runoff and groundwater recharge projected in this study represent large percentages of the capacity of the water resources in these prescribed areas. Reductions of up to 62% of historic annual groundwater recharge and 65% of annual runoff are projected from median (DENR, 2010) climate change projections with a medium range emissions scenario. Also notable are the projected changes to the frequency of years with low and high runoff or recharge, characterised by annual amounts below the 20^{th} percentile and above the 80^{th} percentile of annual runoff and recharge in the historic baseline period. In many cases there are significant reductions in the number of years of high recharge and runoff and increases in the frequency of years with low recharge and runoff. In several 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 this region and for the viability of current agricultural and horticultural practices, unless mitigated by alternative water sources and/or water demand reduction strategies. It is recommended that natural resource and water resource 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 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, it is likely that the changes required to diversion and extraction limits under future climate scenarios will be approximately proportional to reductions in surface runoff and groundwater recharge.

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 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 NYNRM 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 NYNRM Region. The most up-to-date data have been used to provide a best estimate of these impacts, 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 LEACHM MODELS

Soil type A6: Gradational calcareous clay loam
Location: Clare Valley PWRA (weather data from Hill River weather station)

Outputs from the LEACHM model for soil type A6 were compared to watertable fluctuations in Obswell CLR042, a well located on the same dominant soil type located approximately 5km north-west from the Hill River weather station. Figure 70 shows the groundwater level trend in CLR042 from 1991 – 2010. An irrigated vines land use was implemented.

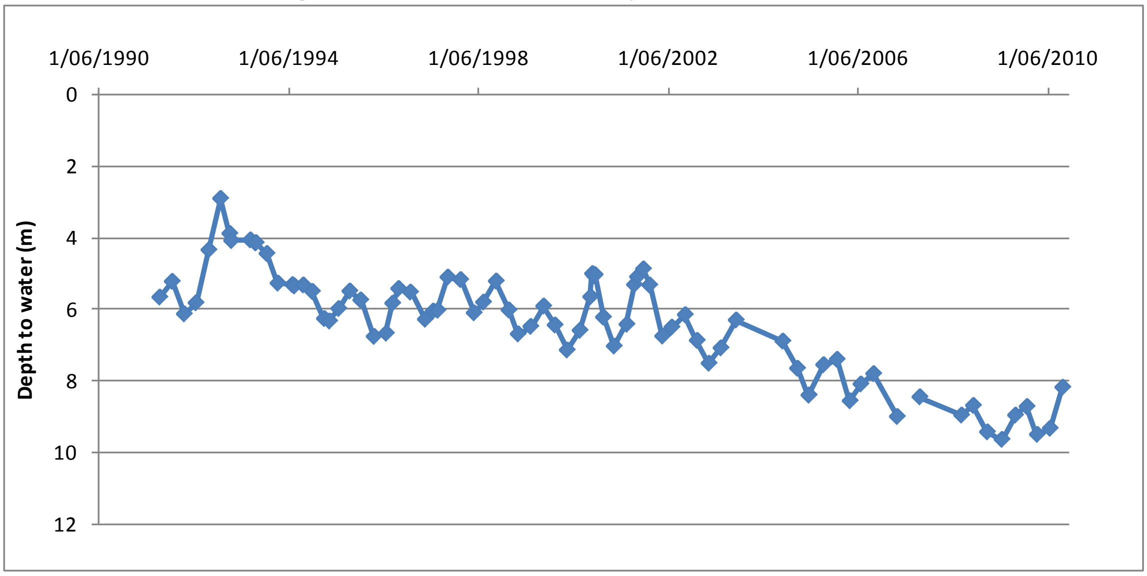


Figure 70. Observed groundwater levels in Obswell CLR042

Figure 71 shows the relationship between estimated recharge and LEACHM modelled recharge for soil type A6 and CLR042. A reasonably good fit is achieved between the two data sets. Figure 72 shows the year to year variation in modelled and measured recharge. Again, average modelled and average estimated recharge are in fairly good agreement.

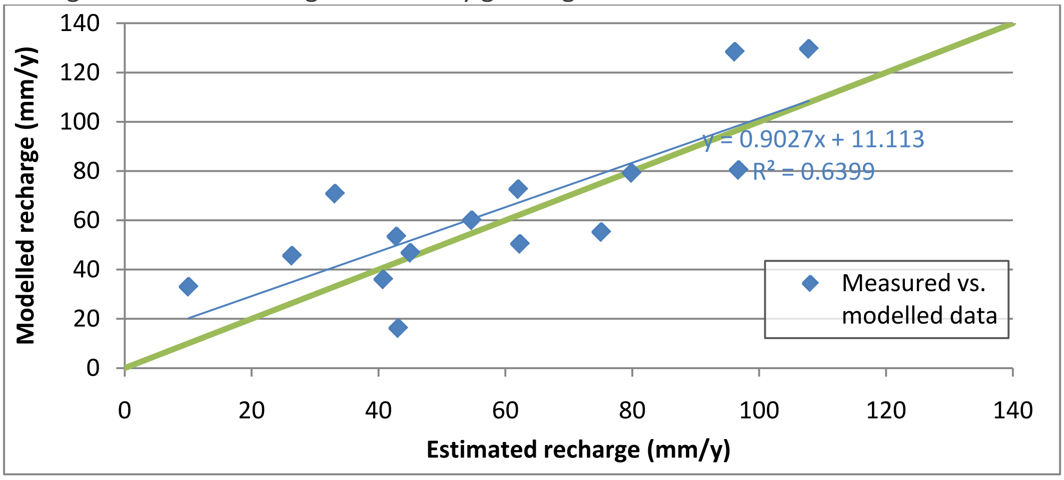


Figure 71. LEACHM modelled recharge versus estimated recharge for CLR042

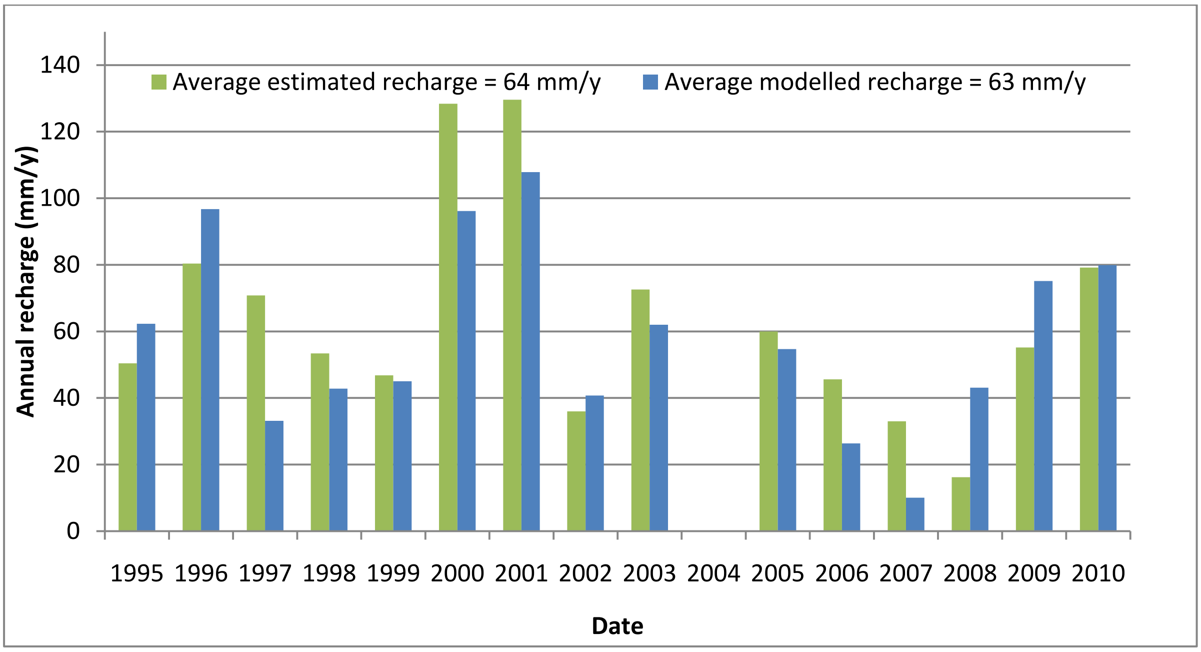


Figure 72. Modelled vs. estimated recharge from year to year (years where no recharge is registered relate to gaps in the monitoring record, not low rainfall/recharge)

Figure 73 plots deviation from average values of winter rainfall and of measured and modelled recharge. As can be seen, the LEACHM model replicates the pattern of changes in recharge with changes in rainfall reasonably well. Given that there is some uncertainty in the annual estimated recharge rates, the LEACHM model can be considered to model changes in recharge in repsonse to changes in rainfall reasonably well, and is therefore a useful tool to assess the impacts of climate change on recharge at this location.

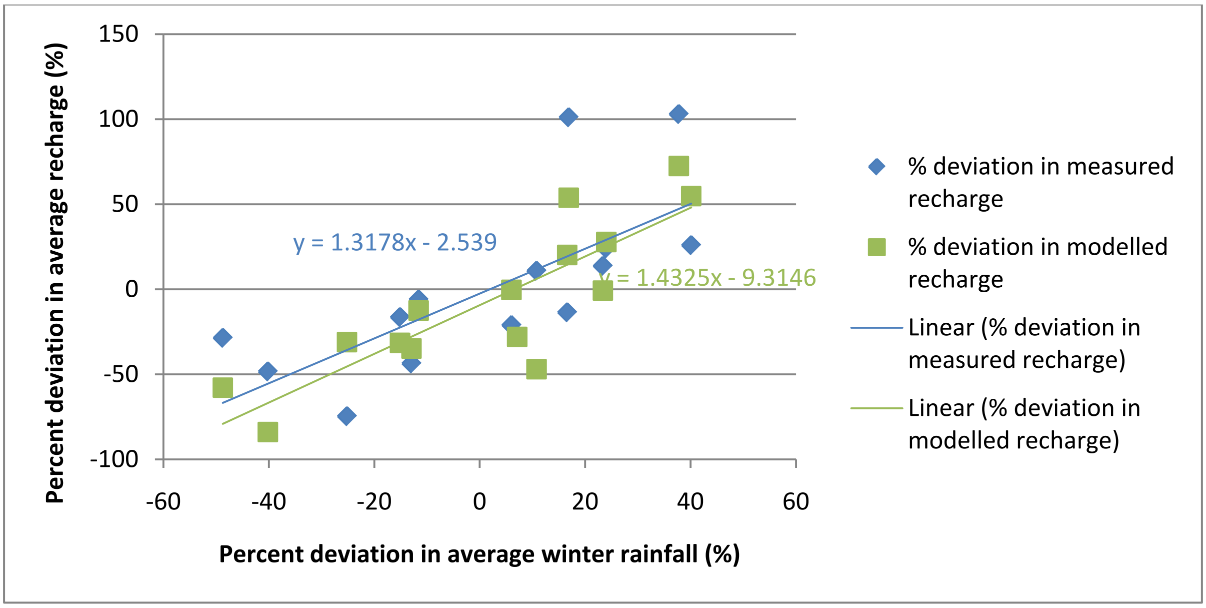


Figure 73. Modelled versus estimated percentage deviations in rainfall and recharge

Soil type D2: Loam over red clay
Location: Clare Valley PWRA (weather data from Calcannia weather station)

Outputs from the LEACHM model for soil type D2 were compared to watertable fluctuations in Obswell MLN007, a well located on the same dominant soil type located approximately 4.5km south of the Calcannia weather station. Figure 74 shows the groundwater level trend in MLN007 from 1991 – 2010. An irrigated vines land use was used.

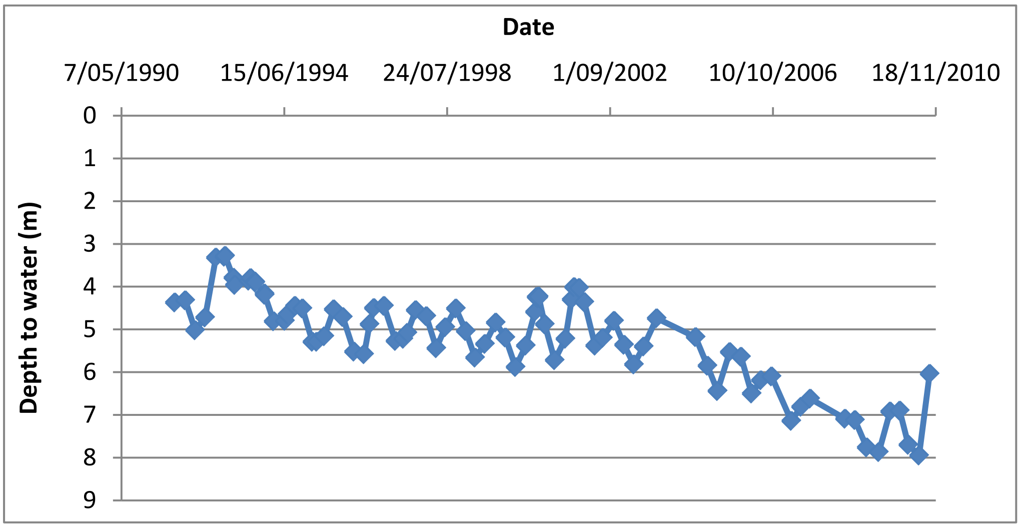


Figure 74. Observed groundwater levels in Obswell MLN007

Figure 75 shows the relationship between estimated recharge and LEACHM modelled recharge for soil type D2 and MLN007. As can be seen, a reasonably good fit is achieved between the two data sets, however there is some scatter observed in higher recharge events, with the model inconsistently over-predicting and under-predicting recharge when estimated recharge is >60mm. This is likely due to inconsistencies in the monitoring data. Figure 76 shows the year to year variation in modelled and measured recharge. A reasonably good correlation is observed, with average modelled and average estimated recharge in good agreement.

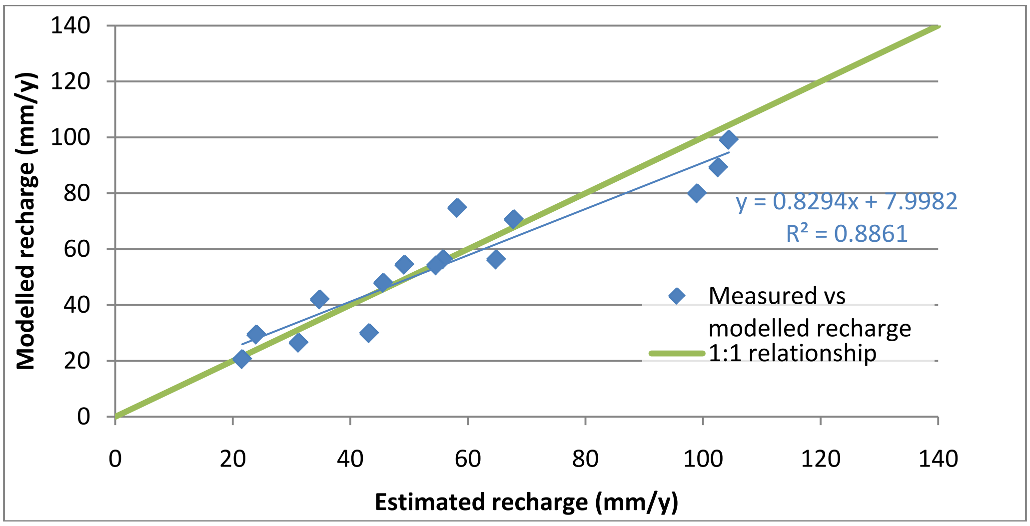


Figure 75. LEACHM modelled recharge vs. estimated recharge for MLN007 and soil D2

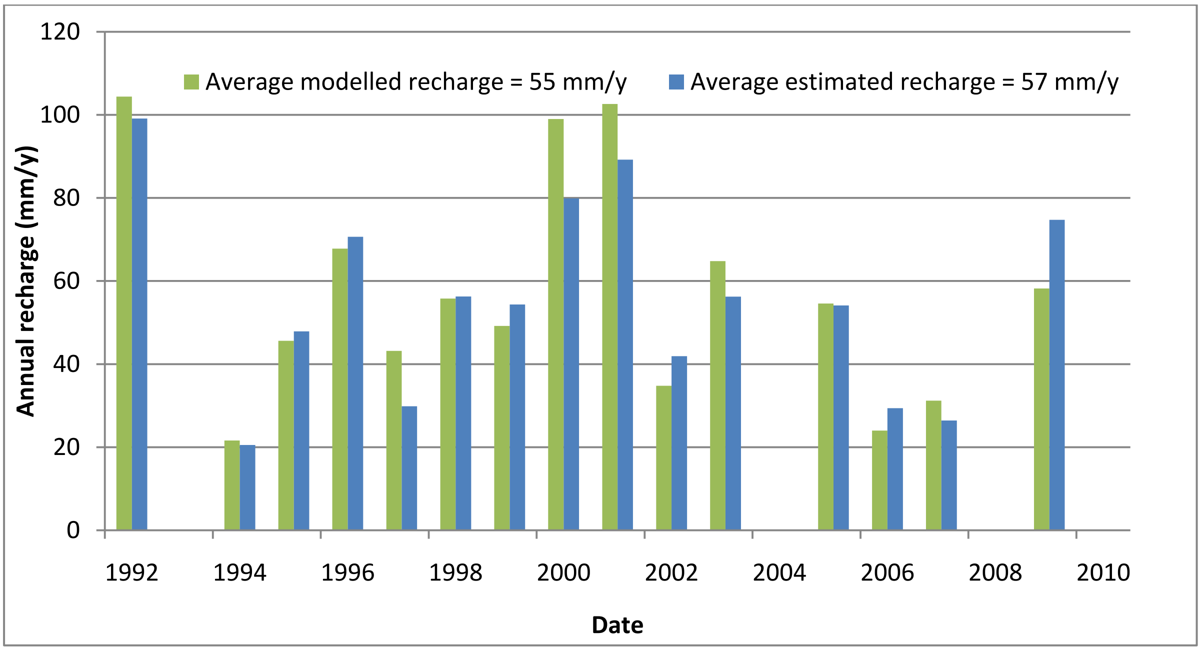


Figure 76. Modelled versus estimated recharge from year to year (years where no recharge is registered relate to gaps in the monitoring record, not low rainfall/recharge)

Figure 77 plots deviation from average values of winter rainfall and of measured and modelled recharge. As can be seen, the LEACHM model replicates the pattern of changes in recharge with changes in rainfall reasonably well. Given that there is some uncertainty in the annual estimated recharge rates, and the previously mentioned inconcsistencies in monitoring data the LEACHM model can be considered to model changes in recharge in repsonse to changes in rainfall reasonably well, and is therefore a useful tool to assess the impacts of climate change on recharge at this location.

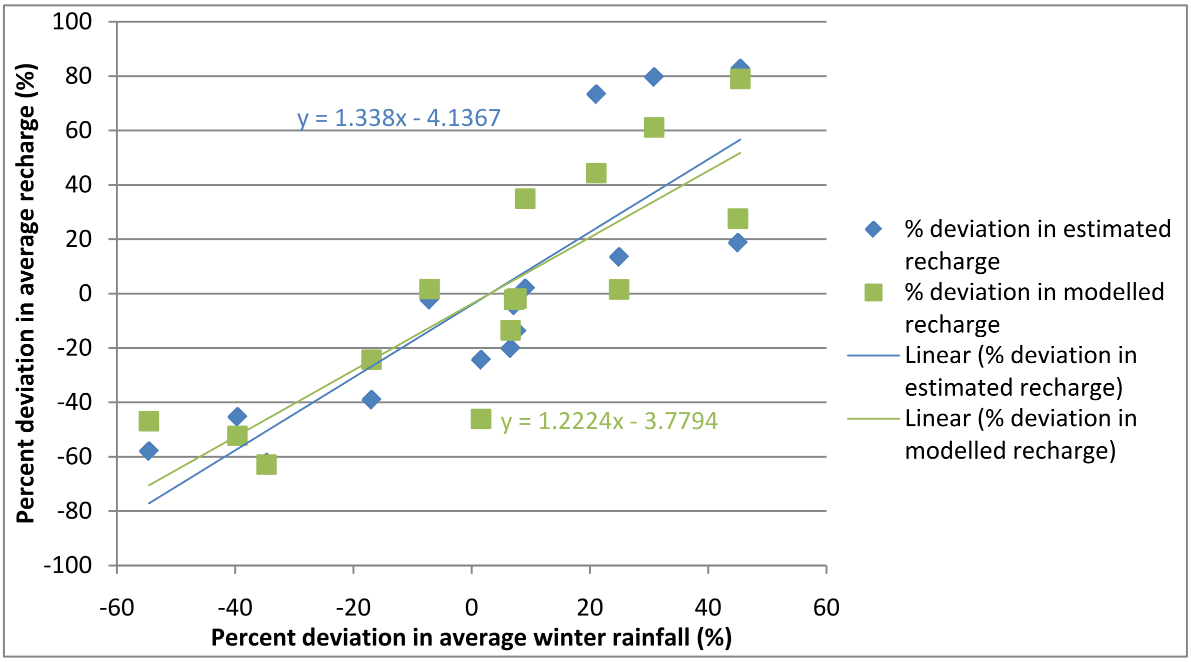


Figure 77. Modelled versus estimated percentage deviations in rainfall and recharge

<u>Soil type D1: Loam over clay on rock</u>
<u>Location: Clare Valley PWRA (weather data from Hill River weather station)</u>

Outputs from the LEACHM model for soil type D1 were compared to watertable fluctuations in Obswell CLR101, a well located on the same dominant soil type located approximately 4km east of the Hill River weather station. Figure 78 shows the groundwater level trend in CLR101 from 1991 – 2010. An irrigated vines land use was used.

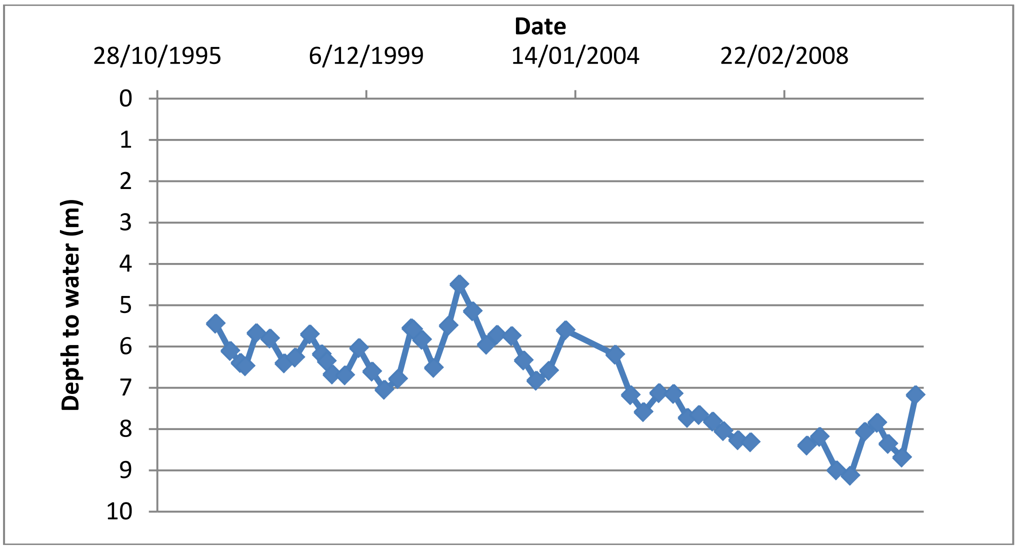


Figure 78. Observed groundwater levels in Obswell CLR101

Figure 79 shows the relationship between estimated recharge and LEACHM modelled recharge for soil type D1 and CLR101. As can be seen, a reasonably good fit is achieved between the two data sets. Figure 80 shows the year to year variation in modelled and measured recharge. A reasonably good correlation is observed, with average modelled and average estimated recharge in good agreement.

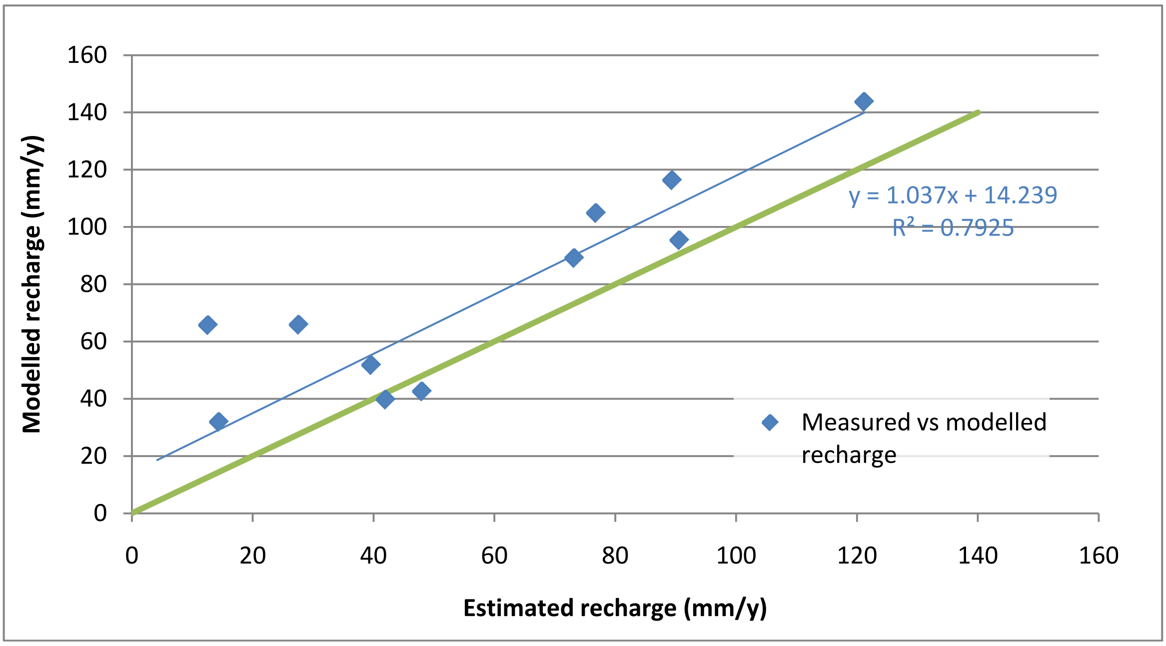


Figure 79. LEACHM modelled recharge versus estimated recharge for CLR101 and soil D1

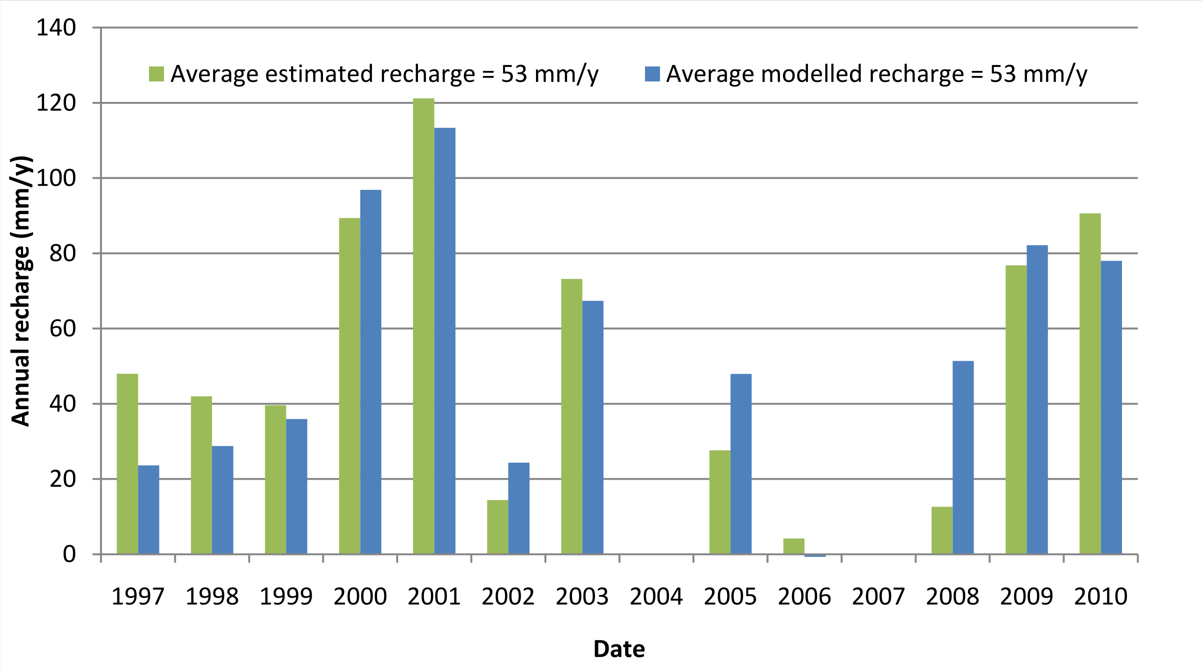


Figure 80. Modelled versus estimated recharge from year to year (years where no recharge is registered relate to gaps in the monitoring record, not low rainfall/recharge)

Figure 81 plots deviation from average values of winter rainfall and of measured and modelled recharge. As can be seen, the LEACHM model replicates the pattern of changes in recharge with changes in rainfall reasonably well. Given that there is some uncertainty in the annual estimated recharge rates, the LEACHM model can be considered to model changes in recharge in repsonse to changes in rainfall reasonably well, and is therefore a useful tool to assess the impacts of climate change on recharge at this location.

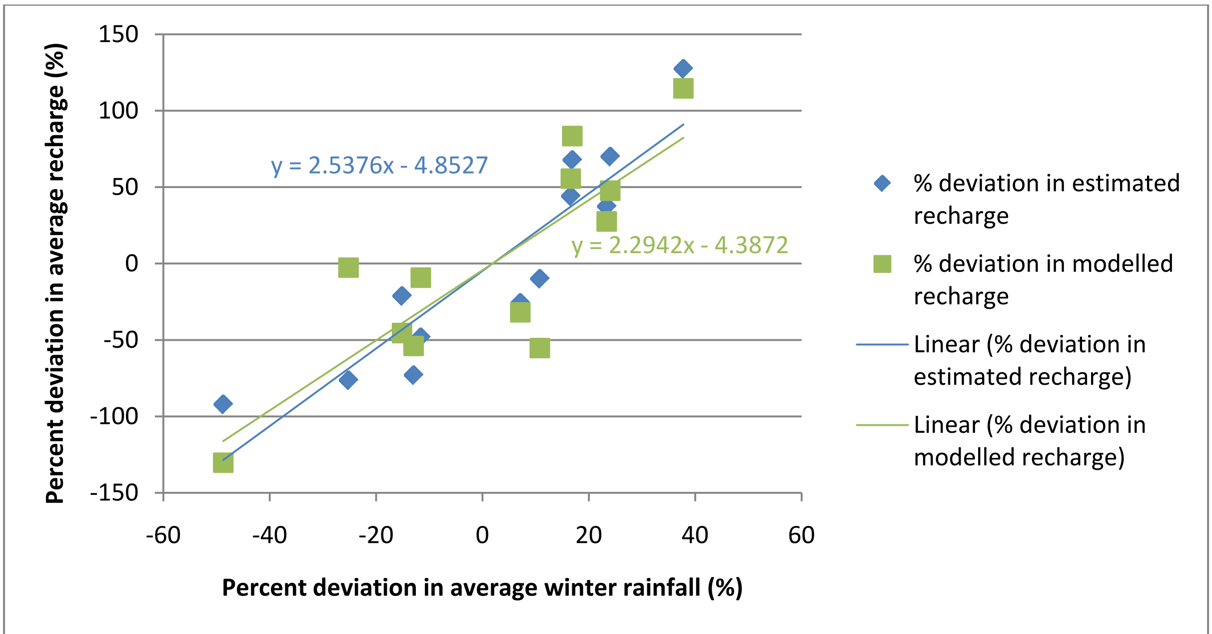


Figure 81. Modelled versus estimated percentage deviations in rainfall and recharge

Soil type D3: Loam over poorly structured red clay

An Obswell was identified to calibrate soil type D3 to (CLR154), however it only had five years of data, and only four seasonal fluctuations to calibrate to. It was decided that this was insufficient data to calibrate this soil to, and a more general approach was taken with this soil type. Initial soil parameters based on previous soil models from other parts of the State, then altered using parameters from calibrated soil models. A grazing modified pasture crop type was used, and rainfall and PET data was taken from the Calcannia weather station.

Running the model with these parameters gave an average annual recharge rate of 45 mm/y (see Figure 82). This falls within the ranges reported by Love et al. (2002), and is therefore considered representative.

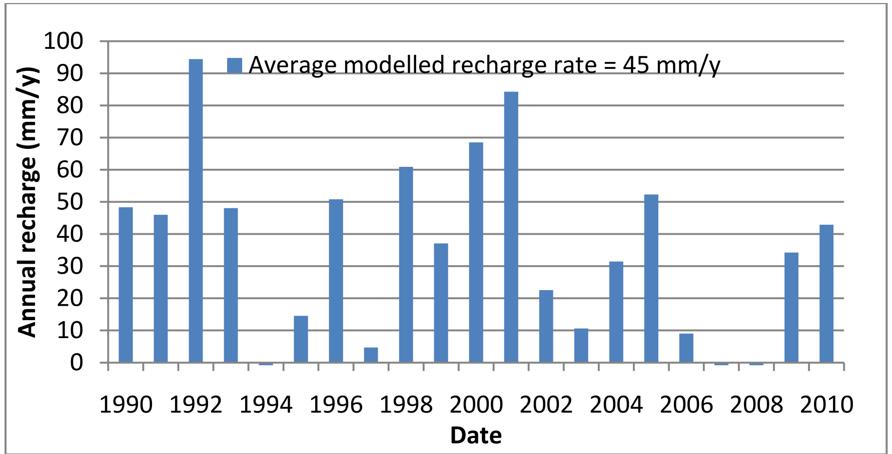


Figure 82. Modelled recharge rates for the D3 soil type

A plot of percent deviation in average winter rainfall against percent deviation in average modelled recharge (Figure 83) gives a slope of 1.05, which is in the same range as the calibrated models (slopes between 1 and 2), therefore the model for soil type D3 is considered representative for conditions in the Clare Valley. The few data points that were available from Obswell CLR154 are also included on this plot, and as can be seen there is a good match. If more data on soil parameters or recharge rates under this soil type become available in the future, then this model may be re-visited.

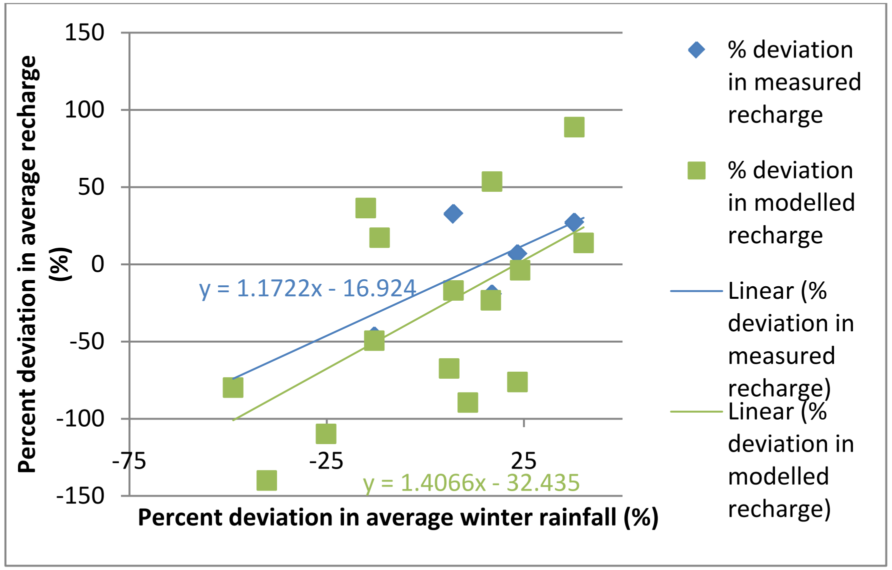


Figure 83. Percent deviation in average winter rainfall and average modelled recharge for soil type D3

Soil type C2: Gradational loam on rock

A suitable observation well record was not available to calibrate the C2 soil to. To test the suitability of the model, it was run with initial soil parameters based on previous soil models from other parts of the State, then altered using parameters from calibrated soil models (primarily A6 and D2). A grazing modified pasture crop type was used, and rainfall and PET data was taken from the Hill River weather station. Running the model with these parameters gave an average annual recharge rate of 45 mm/y (see Figure 84Figur). This falls within the ranges reported by Love et al. (2002), and is therefore considered representative.

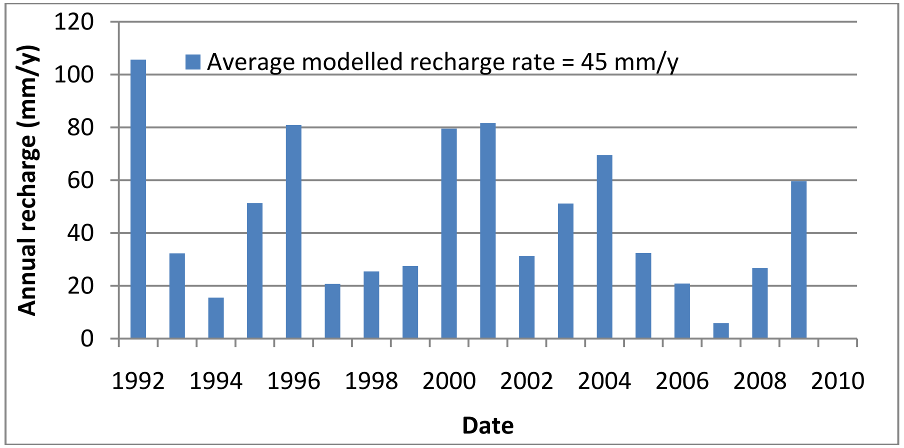


Figure 84. Modelled recharge rates for the C2 soil type

A plot of percent deviation in average winter rainfall against percent deviation in average modelled recharge (Figure 85) gives a slope of 1.88, which is similar to the calibrated models (slopes between 1 and 2), therefore the model for soil type C2 is considered representative for conditions in the Clare Valley. If more data on soil parameters or recharge rates under this soil type become available in the future, then this model may be re-visited.

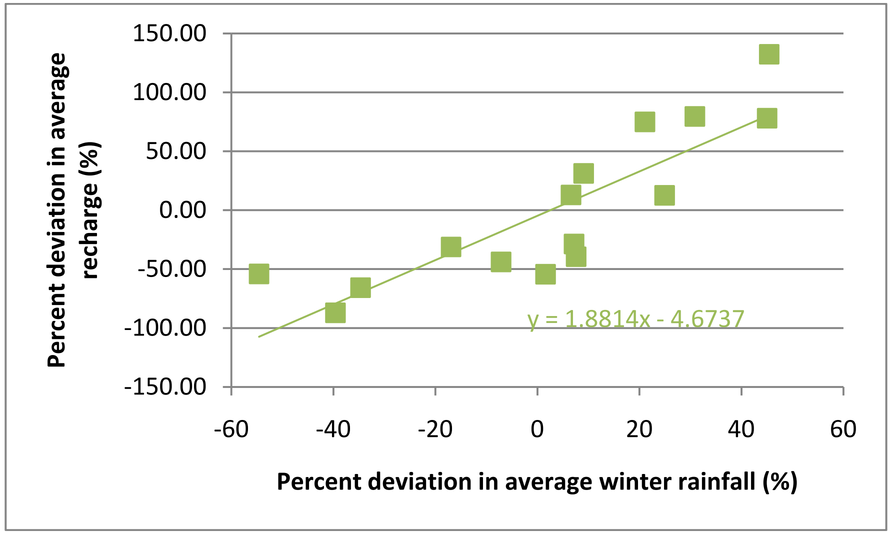


Figure 85. Percent deviation in average winter rainfall and average modelled recharge for soil type C2

Soil type B4: Shallow red loam on limestone

A suitable observation well record was not available to calibrate the B4 soil to. To test the suitability of the model, it was run with initial soil parameters based on previous soil models from other parts of the State, then altered slightly. A grazing modified pasture crop type was used, and rainfall and PET data was taken from the Hill River weather station.
Running the model with these parameters gave an average annual recharge rate of 53 mm/y (see Figure 86). This falls within the ranges reported by Love et al. (2002), and is therefore considered representative.

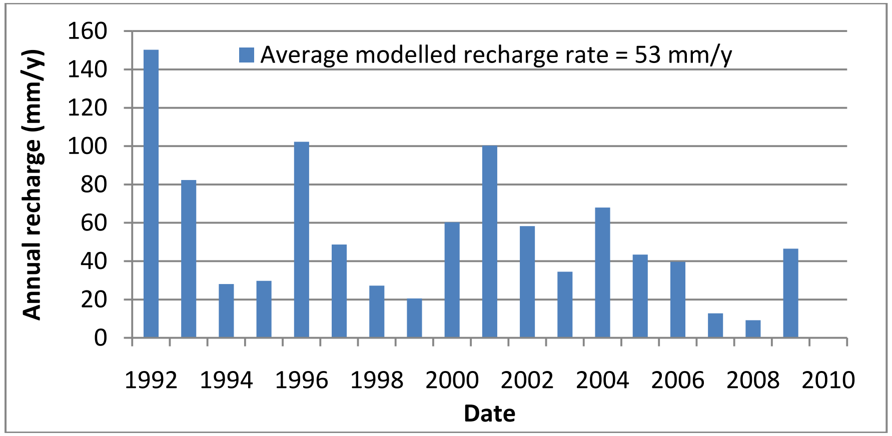


Figure 86. Modelled recharge rates for the B4 soil type

A plot of percent deviation in average winter rainfall against percent deviation in average modelled recharge (Figure 87) gives a slope of 1.67, which is similar to the calibrated models (slopes between 1 and 2), therefore the model for soil type B4 is considered representative for conditions in the Clare Valley. If more data on soil parameters or recharge rates under this soil type become available in the future, then this model may be re-visited.

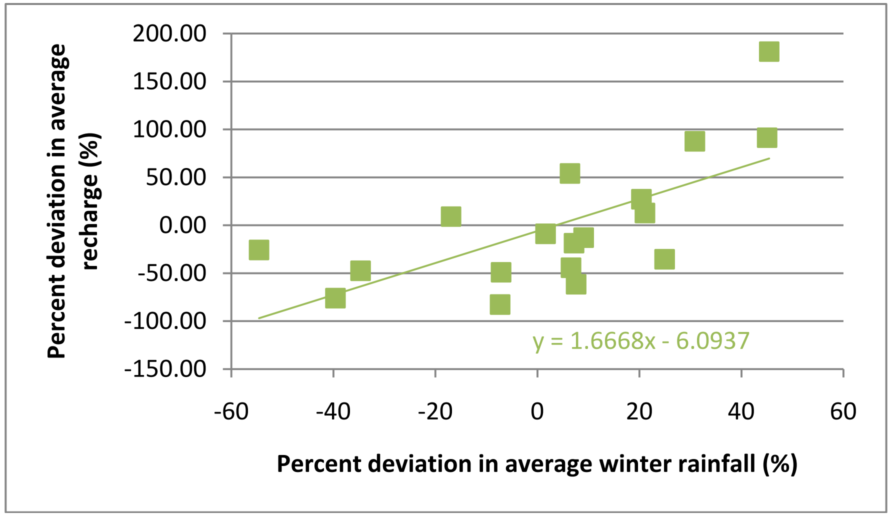


Figure 87. Percent deviation in average winter rainfall and average modelled recharge for soil type B4

Soil type L1: Shallow soil on rock

A suitable observation well record was not available to calibrate the L1 soil to. To test the suitability of the model, it was run with initial soil parameters based on previous soil models from other parts of the State, then using parameters from calibrated models that had a shallow soil overlying rock (eg. the models for D1 and C2). A grazing modified pasture crop type was used, and rainfall and PET data was taken from the Hill River weather station.

Running the model with these parameters gave an average annual recharge rate of 58 mm/y (see Figure 88). This falls within the ranges reported by Love et al. (2002), and is therefore considered representative.

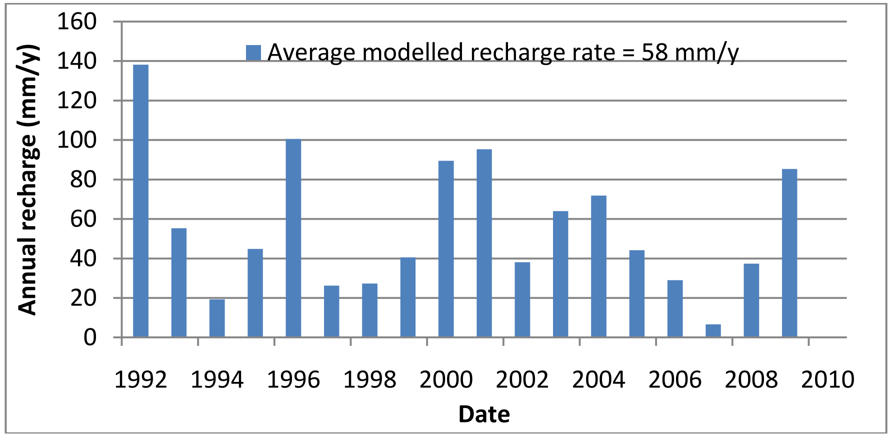


Figure 88. Modelled recharge rates for the L1 soil type

A plot of percent deviation in average winter rainfall against percent deviation in average modelled recharge (Figure 89) gives a slope of 1.88, which is similar to the calibrated models (slopes between 1 and 2), and the same as a similar soil type (type C2 – a gradational loam on rock). Therefore the model for soil type L1 is considered representative for conditions in the Clare Valley. If more data on soil parameters or recharge rates under this soil type become available in the future, then this model may be re-visited.

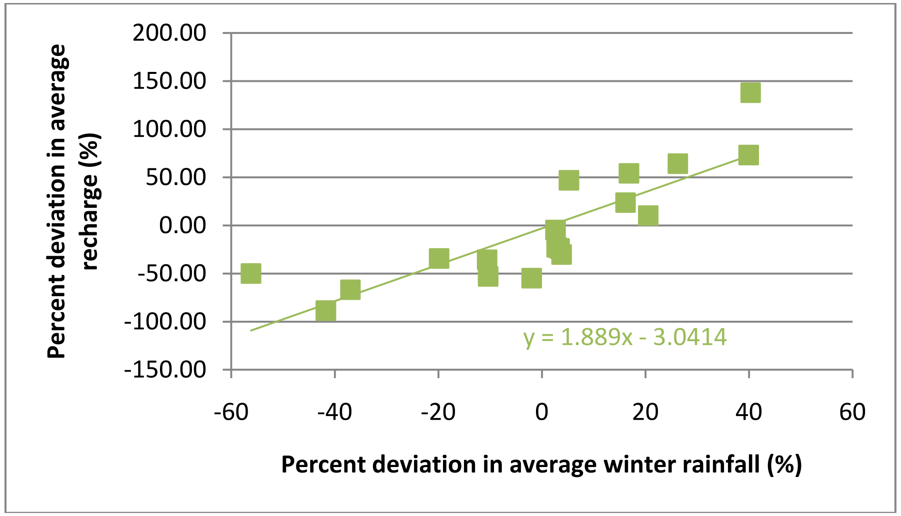


Figure 89. Percent deviation in average winter rainfall and average modelled recharge for soil type L1

B. HUTT RIVER RUNOFF SUMMARY RESULTS

Table 28. Changes in climate and runoff simulated for Hutt River using input data generated using the LASG-IAP GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	456	445	444	439	435	435	424
Average Winter Rainfall (mm)	174	170	170	168	166	166	162
Average Annual PET (mm)	1283	1298	1306	1310	1317	1317	1335
Average Winter PET (mm)	130	136	139	139	139	139	145
Median Annual Runoff (ML)	3292	2322	2101	1888	1810	1603	1234
Change in Annual Rainfall (%)		-2	-3	-4	-5	-5	-7
Change in Winter Rainfall (%)		-2	-3	-4	-5	-5	-7
Change in Annual PET (%)		1	2	2	3	3	4
Change in Winter PET (%)		5	7	7	7	7	12
Change in Median Runoff (%)		-29	-36	-43	-45	-51	-63
Low Events							
20th Percentile Runoff (ML)	503	349	316	277	276	221	169
Years Below 1990 20th %	10	12	12	13	14	14	17
High Events							
80th Percentile Runoff (ML)	10804	8625	8435	7620	7607	6562	5896
Years Above 1990 80th %	10	9	9	9	9	9	5

Table 29. Changes in climate and runoff simulated for Hutt River using input data generated using the NCAR-CCSM3 GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	456	446	446	442	438	438	429
Average Winter Rainfall (mm)	174	167	167	164	160	160	153
Average Annual PET (mm)	1283	1310	1312	1331	1347	1347	1371
Average Winter PET (mm)	130	139	139	145	148	148	158
Median Annual Runoff (ML)	3292	2521	2162	1720	1515	1383	1022
Change in Annual Rainfall (%)		-2	-2	-3	-4	-4	-6
Change in Winter Rainfall (%)		-4	-4	-6	-8	-8	-12
Change in Annual PET (%)		2	2	4	5	5	7
Change in Winter PET (%)		7	7	12	14	14	21
Change in Median Runoff (%)		-23	-34	-48	-54	-58	-69
Low Events							
20th Percentile Runoff (ML)	503	506	490	249	240	165	127
Years Below 1990 20th %	10	10	11	15	18	17	24
High Events							
80th Percentile Runoff (ML)	10804	10928	10465	7442	7250	6788	6359
Years Above 1990 80th %	10	10	10	7	6	6	4

Table 30. Changes in climate and runoff simulated for Hutt River using input data generated using the MRI GCM

	1990	2030		2050		2070	
		B1	A2	B1	A2	B1	A2
Average Annual Rainfall (mm)	456	441	440	433	427	426	411
Average Winter Rainfall (mm)	174	162	162	156	152	151	139
Average Annual PET (mm)	1283	1292	1292	1314	1319	1319	1328
Average Winter PET (mm)	130	130	130	136	136	136	136
Median Annual Runoff (ML)	3292	2597	2588	1933	1658	1496	940
Change in Annual Rainfall (%)		-3	-3	-5	-6	-6	-10
Change in Winter Rainfall (%)		-7	-7	-10	-13	-13	-20
Change in Annual PET (%)		1	1	2	3	3	4
Change in Winter PET (%)		0	0	5	5	5	5
Change in Median Runoff (%)		-21	-21	-41	-50	-55	-71
Low Events							
20th Percentile Runoff (ML)	503	520	476	318	236	228	113
Years Below 1990 20th %	10	10	11	16	18	18	21
High Events							
80th Percentile Runoff (ML)	10804	9976	9899	7780	6992	6324	4427
Years Above 1990 80th %	10	9	9	7	7	6	3

Table 31. Changes in climate and runoff simulated for Hutt River 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)	456	412	408	388	369	366	322
Average Winter Rainfall (mm)	174	152	150	140	130	129	106
Average Annual PET (mm)	1283	1316	1322	1338	1356	1356	1397
Average Winter PET (mm)	130	136	136	136	142	142	148
Median Annual Runoff (ML)	3292	1131	1179	561	294	253	33
Change in Annual Rainfall (%)		-10	-10	-15	-19	-20	-29
Change in Winter Rainfall (%)		-13	-14	-20	-25	-26	-39
Change in Annual PET (%)		3	3	4	6	6	9
Change in Winter PET (%)		5	5	5	9	9	14
Change in Median Runoff (%)		-66	-64	-83	-91	-92	-99
Low Events							
20th Percentile Runoff (ML)	503	227	156	114	48	46	1
Years Below 1990 20th %	10	19	19	23	28	29	39
High Events							
80th Percentile Runoff (ML)	10804	6479	5493	3743	2238	2635	779
Years Above 1990 80th %	10	5	4	2	1	2	0

C. HUTT RIVER NCAR – CCSM3 ANNUAL RUNOFF RESULTS

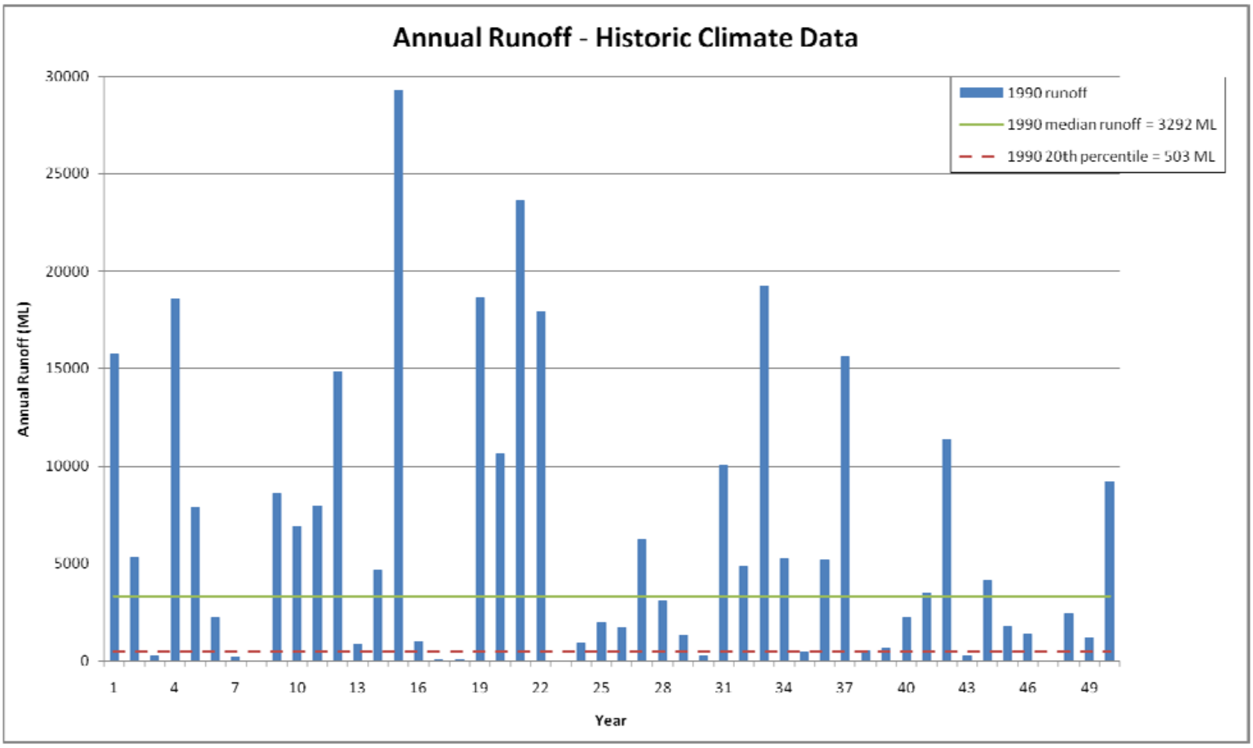


Figure 90. Annual runoff simulated for the Hutt River, based on historically measured rainfall and PET data. Year 1 on the x axis represents 1961, and year 50 represents 2010.

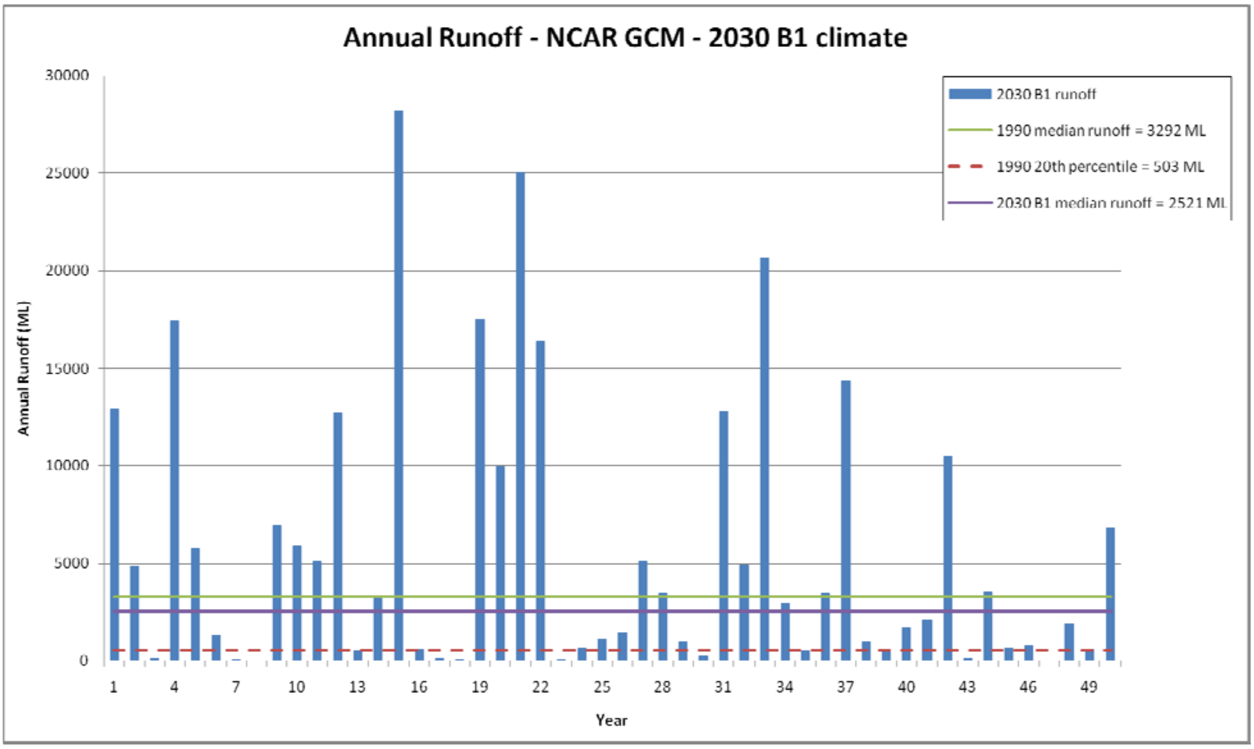


Figure 91. Annual runoff simulated for the Hutt River, based on rainfall and PET input data generated by the NCAR GCM for a 2030 climate and B1 emissions

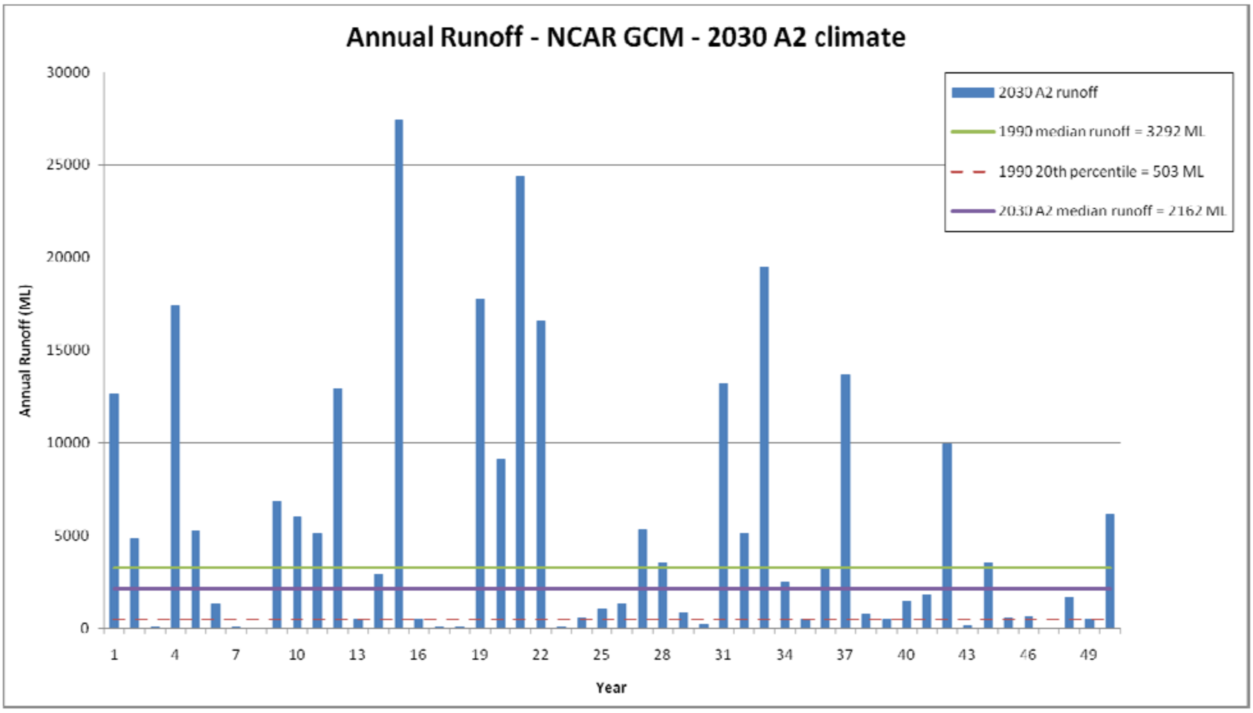


Figure 92. Annual runoff simulated for the Hutt River, based on rainfall and PET input data generated by the NCAR GCM for a 2030 climate and A2 emissions

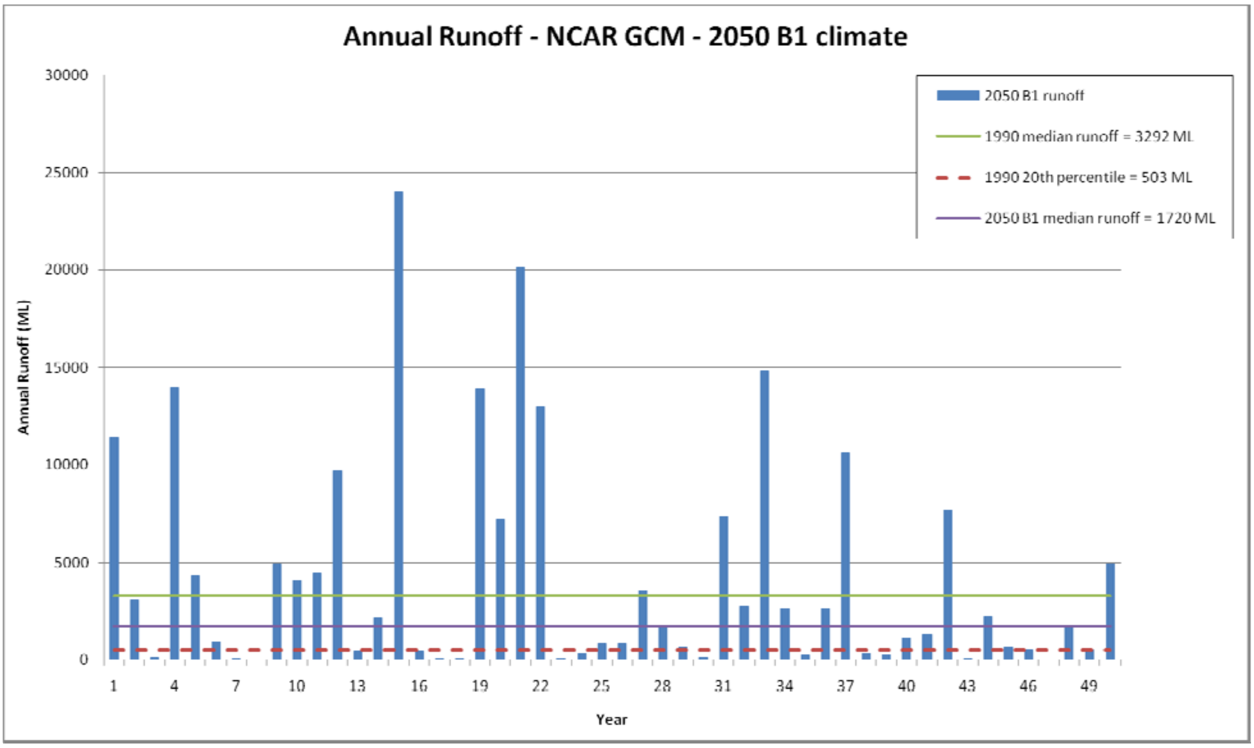


Figure 93. Annual runoff simulated for the Hutt River, based on rainfall and PET input data generated by the NCAR GCM for a 2050 climate and B1 emissions

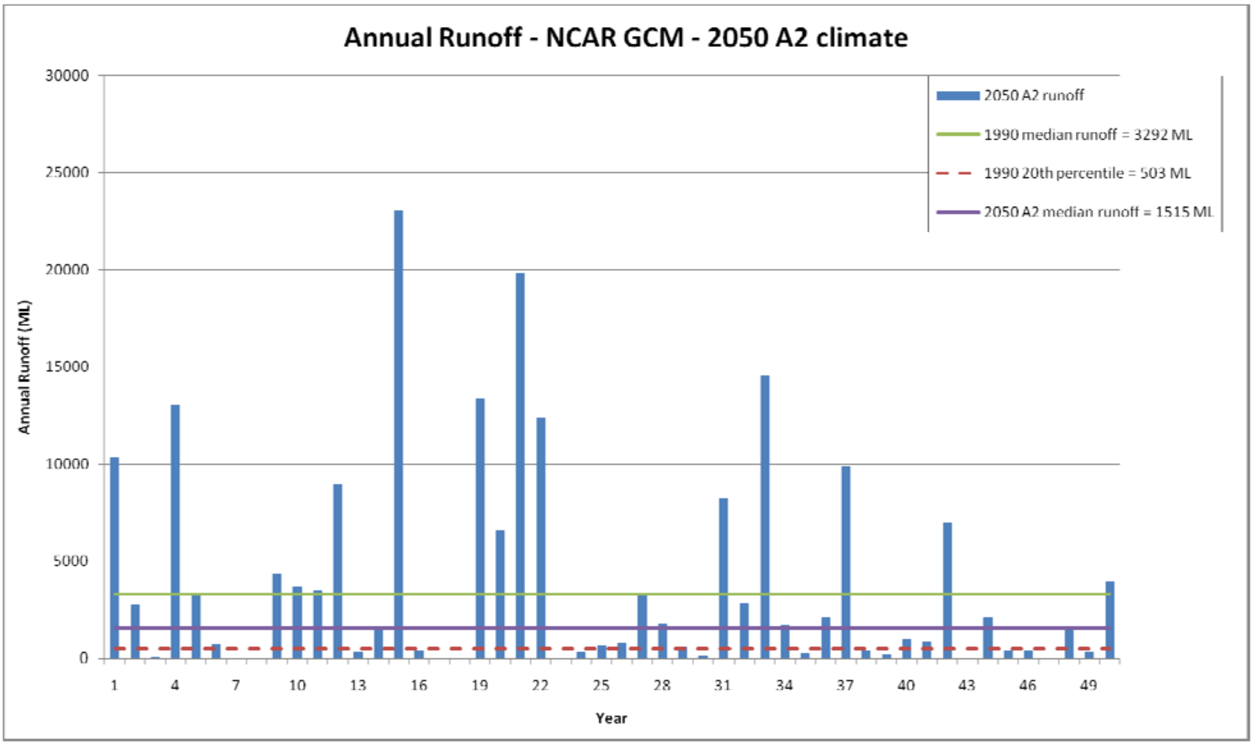


Figure 94. Annual runoff simulated for the Hutt River, based on rainfall and PET input data generated by the NCAR GCM for a 2050 climate and A2 emissions

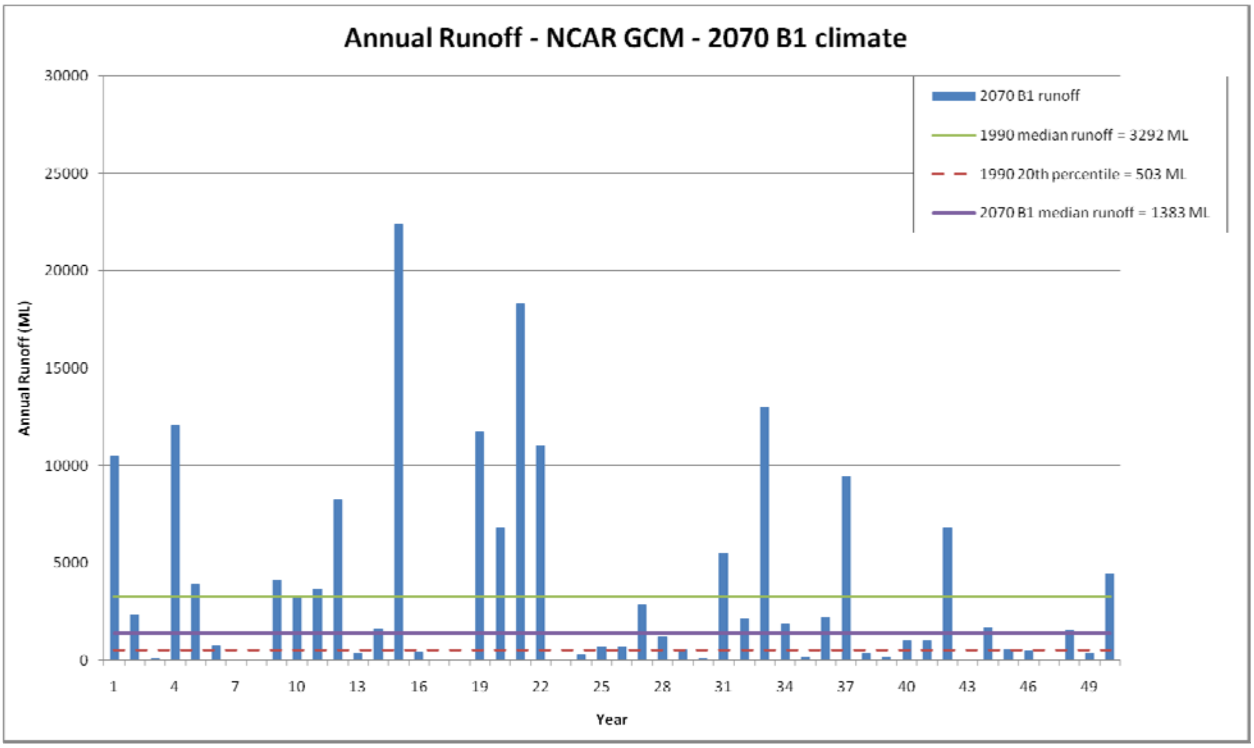


Figure 95. Annual runoff simulated for the Hutt River, based on rainfall and PET input data generated by the NCAR GCM for a 2070 climate and B1 emissions

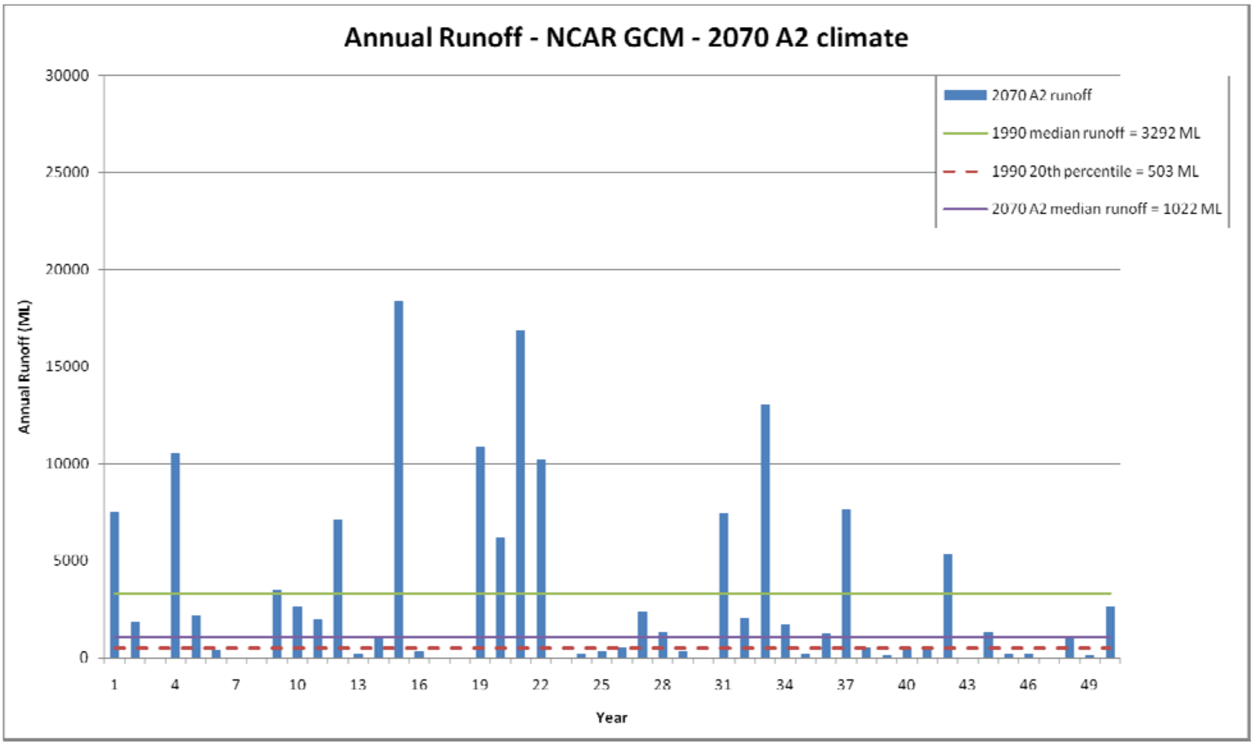


Figure 96. Annual runoff simulated for the Hutt River, based on rainfall and PET input data generated by the NCAR GCM for a 2070 climate and A2 emissions

D. EXAMPLE WATER BALANCES FROM LEACHM RECHARGE MODELS

Table and Table give example water balances from various scenarios for soil type 5 (loam over clay on rock), under different land uses (irrigated and un-irrigated) in the two different rainfall zones. In both cases there is an insignificant discrepancy in the water balance. In the irrigated example, where rainfall is higher, evaporation is the dominant output (likely a result of increased water availability in the top of the soil profile), and the overall change in soil water storage is consistently positive. In the un-irrigated example however, with lower rainfall (and higher PET), evaporation is less and transpiration becomes the dominant output. The overall change in soil storage in this second example is consistently negative, representing a net loss of water from the unsaturated zone.

Soil 5, irrigated vines, Hill River weather data, slope 2	Average annual Inputs (ML)		Average annual Outputs (ML)				Average annual Change in storage (ML)	Average annual Difference in Water Balance (ML)
	Rainfall	Irrigation	Evaporation	Transpiration	Drainage	Runoff	Soil water storage difference	Inputs - outputs + change in storage
1990	1593	1103	1006	907	379	401	2.2	1.0
2030 A2 - LASG-IAP	1183	1121	1021	928	352	371	2.2	1.0
2050 B1 – NCAR	1171	1143	1033	950	327	374	2.2	0.9
2050 A2 – MRI	1109	1177	1030	937	315	382	2.2	1.0
2070 B1 - CSIRO Mk 3.5	1011	1256	1057	961	246	266	2.0	0.9

Table 32. Water balance examples for soil type 5, with an irrigated vines land use, relatively high rainfall (based on Hill River weather station data) and a slope class of 2

Soil 5, grazing, Calcannia weather data, slope 4	Average annual Inputs (ML)		Average annual Outputs (ML)				Average annual Change in storage (ML)	Average annual Difference in Water Balance (ML)
	Rainfall	Irrigation	Evaporation	Transpiration	Drainage	Runoff	Soil water storage difference	Inputs - outputs + change in storage
1990	1178	0	61	1048	69	216	-0.9	1.2
2030 A2 - LASG-IAP	1166	0	60	1056	50	194	-1.0	1.2
2050 B1 - NCAR	1161	0	60	1069	32	190	-1.0	1.2
2050 A2 - MRI	1110	0	57	1026	27	195	-1.0	1.2
2070 B1 - CSIRO Mk 3.5	1000	0	49	961	-9	117	-1.3	1.2

Table 33. Water balance examples for soil type 5, with grazing (un-irrigated) land use, relatively low rainfall (based on Calcannia weather station data) and a slope class of 4

UNITS OF MEASUREMENT

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

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

Shortened forms

~ approximately equal to

bgs below ground surface

K hydraulic conductivity (m/d)

GLOSSARY

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

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'

DFW — Department for Water (Government of South Australia)

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

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

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

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

NYNRM — Northern and Yorke 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

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

REFERENCES

Allen, R. G., Pereira, L.A., Raes, D., Smith, M. (1998). Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, Food and Agriculture Organisation of the United Nations, Rome, Italy.

Armstrong, D.W. and Narayan, K.A., (1998), *Using groundwater responses to infer recharge in Studies in Catchment Hydrology,* The Basics of Recharge and Discharge. CSIRO Australia 1998.

Barnett, S, (2009), *Groundwater Resource Assessment of the Baroota Prescribed Water Resource Area,* DWLBC Technical Note 2009/27

BoM, (2010), NRM Enhanced Meteorological data sets (SILO) website (http://www.longpaddock.qld.gov.au/silo/) Website accessed December 2010

Clark, R and Cresswell, D, (2009) *WaterCress User Manual*. Unpublished.

Clarke, D.K., (1990) *Groundwater and irrigation in the Baroota Area, Southern Pirie-Torrens Basin.* South Australia. Department of Mines and Energy, Report Book 90/39.

Chiew, FHS, (2006) *Estimation of rainfall elasticity of streamflow in Australia*, Hydrological Sciences Journal, 51(4), 613 – 625.

Chiew FHS, Cai W, Smith IN (2009) 'Advice on defining climate scenarios for use in Murray-Darling Basin Authority Basin Plan modelling, CSIRO report for the Murray-Darling Basin Authority.' MDBA Technical Report Series: Basin Plan: BP01. (Canberra)

Cook, PG, (2003), *A Guide to Regional Groundwater Flow in Fractured Rock Aquifers,* Seaview Press, Henley Beach (South Australia), 108pp.

Cresswell D., (2000), Broughton River scientific panel assessment of environmental flow: hydrology. Unpublished report to the Department for Environment and Heritage, South Australia.

CSIRO-BoM, (2007) *Climate Change in Australia*, K. Pearce, P. Holper, M. Hopkins, W. Bouma, P. Whetton, K. Hennessy and S. Power (Eds.), CSIRO Technical Report, 148 pp.

Department of Environment and Natural Resources (DENR), (1996) *Catchment Yield Analyses for South Australian reservoirs, Volume 1*.Water Information Unit, Water Resources Group.

Department of Environment and Natural Resources (DENR) (2010) *Regional Climate Change Projections: Northern and Yorke*, South Australia

Department for Water, Land and Biodiversity Conservation (DWLBC), (2007), *Land and Soil Spatial Data – GIS format,* CD-ROM, Government of South Australia

Evans, S, (2004), *Baroota Groundwater Resource – Monitoring Review and Augmentation,* DWLBC Report 2004/56

REFERENCES

Favier, D, Rixon, S, and Scholz, G, (2000) *A River Management Plan for the Wakefield Catchment,* Special Projects Group, Evaluation Branch, Environment Protection Agency, South Australia.

Favier, D, Scholz, G, VanLaarhoven, J, Bradley, J, and Phipps, L, (2004) *A River Management Plan for the Broughton Catchment.* Department of Water, Land and Biodiversity Conservation, Technical Report DWLBC 2004/16.

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

Green, G, (2010), *Point and regional scale modelling of vadose zone water and salt fluxes in an area of intensive horticulture,* PhD Thesis, Flinders University South Australia, 187 pp.

Hutson, J. L. (2003). Leaching Estimation and Chemistry Model, Version 4. Research Series R03-1, March 2003, Department of Crop and Soil Science, Cornell University, Ithaca, New York.

Hutson, J.L., Waganet, R.J. and Niederhofer, M.E. (1997). LEACHM, Leaching Estimation and Chemistry Model. A process-based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone. Versions LEACHF and LEACHG. Research Series No. R97-1, January 1997. Department of Soil, Crop and Atmospheric Sciences, Cornell University, Ithaca, New York.

Jeffrey, S.J., Carter, J.O., Moodie, K.B., Beswick, A.R. (2001). Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling & Software, 16, 309–330

Love, AJ, Cook, PG, Harrington, GA, and Simmons, CT, (2002), *Groundwater flow in the Clare Valley,* Department for Water Resources, Special Report DWR02.03.0002

Nakicenovic, N., and Stewart, R. (2000) IPCC Special Report on Emissions Scenarios. Cambridge University Press, Cambridge, UK, 570 pp.

Stewart, S, (2010), *Groundwater Status Report Clare Valley PWRA 2008/09,* Department for Water Technical Report 2010/, Government of South Australia

Wood, C, and Green, G, (2011), *Impacts of Climate Change on Water Resources Phase 1: First Order Assessment and Prioritisation*, Department for Water Technical Report 2011/01