Climate change impacts on water availability in the Murrumbidgee River catchment

A Thesis submitted by

Newton Muhury

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Abstract

Global climate signature has been rapidly changing since mid-last century following modern industrialisation. The changing climate has impacted various natural systems and processes namely hydrological cycle, crop cycles and life cycles. Climate change impacts on the hydrological cycle are important aspects as human need water for domestic, agriculture and industrial use. Climate change impacts on water resources of the tropical and subtropical countries.

The effects of climate changes have been observed in the Murray-Darling Basin (MDB), which is one seventh of the total land area of Australia. This is the largest and most important agricultural production area in Australia. It produces more than $34 billion of agricultural products annually and accounts for about 46% of Australia's total agricultural production. Since Australia's economy largely depends on its natural resources, climate change impacts the economy in various ways.

According to the Intergovernmental Panel on Climate Change fifth assessment report (IPCC, AR5), the adaptive capacity and adaptation processes have increased in Australia. Australia has implemented policy and management changes in both rural and urban water systems to adapt to future drought, drier conditions and other climatic changes.

The main three rivers of the Murray Darling Basin, i.e. the River Murray, the Darling River and the Murrumbidgee River, capture most of the basin’s runoff. The objective of this study is to quantify future trend in water flows within the Murrumbidgee catchment under various climate scenarios. Better understanding of the impact of the climate change on river flows will assist in water resource planning in the MDB.

Future river flows have been estimated using the hydrological model, Simplified Hydrolog (SIMHYD), which is integrated with data from three different general climate models and emission scenarios. In this study, two different representative concentration pathway (RCP) emission scenarios RCP 4.5 and RCP 8.5 were selected to obtain downscaled future precipitation and potential evapotranspiration data from government agencies for the period of 2016 to 2100. Data from the two emission scenarios show an anticipated warmer and drier climate for the Murrumbidgee catchment. Runoff in the Murrumbidgee catchment is controlled by various dams and weirs, which yields positive results in runoff even when monthly rainfall trend was negative. The overall runoff simulations indicated that impact of climate change is short and intense.

The result of the Simplified Hydrolog (SIMHYD) modelling tool used in this study under RCP 4.5 scenario for the 2016 to 2045 period indicates a significant future impact from climate change on the volumes of runoff in the Murrumbidgee River catchment. The climate change prediction for the 2016 to 2045 period indicates a decrease in total annual rainfall by

9% to 19%. This reduction in rainfall translates to a 33% to 43% decrease in river runoff over the projected periods, although there is less confidence in the estimation of this prediction. This study shows potential runoff trends are higher in the downstream catchments (eastern part of Wagga Wagga), there can be opportunity to build irrigation dams for dry seasons irrigation.

Certification of Thesis

This Thesis is entirely the work of Newton Muhury except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Principal Supervisor: Professor Joachim Ribbe

Associate Supervisor: Associate Professor Shahbaz Mushtaq

Student and supervisors' signatures of endorsement are held at the University.

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CHAPTER ONE: INTRODUCTION

1.0 Background of the study

Hydrology is the study of the movement, distribution and circulation of water and their chemical and physical properties and their reaction with the environment including their relation to living things (Linsley et al. 1975). Rainfall is a key part of the water cycle as it contributes to surface run off and streamflow, soil moisture and aquifer recharge, and most importantly, it dictates the amount of water available for humans and our environment. The availability of water has been rapidly decreasing in many parts of the world because of exponential population and economic growth with large demands on water in industries such as irrigation (Chartres & Varma 2010). Since 1945, the world population has increased almost three times, and industrial production has increased almost 50 times (Karamouz et al. 2011). This means water demand has been steadily increasing leading to depletion of good quality water across urban, agriculture and industrial uses (Karamouz et al. 2011).

Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization (IPCC 2014).

Since the being of industrialisation, human made pollution directly influences the climate and this anthropogenically driving change occurs faster than natural changes (IPCC 2013). The changes which directly impacted on climate components are precipitation, average temperature, humidity, evapotranspiration rate, etc. The IPCC AR5 on climate change shows water scarcity will increase due to local precipitation and temperature change (Tan et al. 2017). Therefore, it is necessary to evaluate future water availability due to climate change to develop policies that ensure efficient use of water and water management system.

Global warming due to climate change can potentially lead to changes in future rainfall and runoff that could significantly impact on regional hydrology and future water resources availability (Vaze et al. 2011). There is a high-pressure area called the subtropical ridge (STR), sits over the Australian continent. The intensification of this area is estimated to account for roughly 80% of the recent decline in rainfall in southeast Australia. This effect may lead this area into prolonged drought (Timbal & Drowdowsky 2012). In addition, projections of climate changes also suggest that southeast Australia will continue to be drier in the future (IPCC 2014; Whetton et al. 2012).

The Murrumbidgee River and its tributaries have undergone a decrease in flows over the past 100 years due to climate change (Bren 1988; Kingsford & Thomas 2002; 2004). Using data from General Circulation Models (GCMs) in simulation of a hydrological basin is regarded as one of the most reliable methods to evaluate stream flow changes (Xu 1999). Researchers have used multiple GCMs to project future stream flows and have found it to be uncertain in hydro-climatic studies (Tan et al. 2014; Sellami et al. 2016). The IPCC (2014) has released four new greenhouse gas emission scenarios in its fifth Assessment Report (AR5), which are referred to as Representative Concentration Pathways (RCPs) 2.5, 4.5, 6, and 8.5. These scenarios were named based on their possible range of radiative forcing values (Wm^{-2}) by the end of 21st century (Tan et al. 2017). Many hydro-climatic studies have been carried out using the GCMs and RCPs as future climate scenarios (e.g. Tan et al. 2014; Zhang et al. 2016). Coupled Model Intercomparison Project Phase 5 (CMIP5) is the most current standard experimental framework for studying the output of coupled atmosphere-ocean general circulation. According to AR5 report CMIP5 uses Representation Concentration Pathway scenarios (RCPs). In this study data from Coupled Model Intercomparison Project Phase 5 (CMIP5) were applied in order to project future runoff using a hydrological model Simplified Hydrolog (SIMHYD) and two different emission scenarios (RCPs).

The MDB area covers 1.06 million square kilometres of inland south-eastern Australia (Figure 1). Although this area is only 14% of the continent, it represents 75% of Australia’s total irrigation which, generates nearly $6 billion worth of irrigated crops (Biswas 2014). Water also has been diverted for industrial and domestic purposes from the basin’s streams and rivers. The three main rivers, i.e. the Upper Murray, Murrumbidgee and Goulburn, account for over 45 % of the basin’s runoff (Norris et al. 2001). These rivers normally recharge from the annual rain in these regions. But several studies show that there is notable change in climate variables such as rainfall and evapotranspiration in this region which impact recharge and water flows (Connor et al. 2009; Goesch et al. 2009; Adamson et al. 2009).

Climate change modelling constantly indicates that many of the world’s major river basins will face severe droughts and floods (Turral 2011). Research studies suggest that rainfall patterns are likely to change across the MDB in future with rainfall projected to decrease by about 15% to 20% in the MDB (Climate Change in Australia 2018; CSIRO & BoM 2007). This reduction in rainfall will directly impact the river-flow in south-east Australia.

According to Australian Bureau of Statistics (2011) data, the Murrumbidgee River basin, one of the largest sub-basins within MDB, has a population of over 550,000 and accounts for 22% of the MDB’s surface water diverted for irrigation and urban use. It contributes 25% of fruit and vegetable production, 42% of grapes in New South Wales; and half of Australia's rice production. Agricultural production within the Murrumbidgee is valued at over AUD1.9 billion annually or 0.2% of Australia's GDP (Kandasamy et al. 2014).

1.1 Problem statement

During the millennium drought (2001 – 2009) (Van Dijk et al. 2013), the Murrumbidgee catchment (Figure 1) was severely affected by lack of water, reducing its main crop, rice, to almost zero production (Kirby et al. 2012). Furthermore, the Lowbidgee floodplain (near Balranald in Figure 2) which is one of Australia's key wetland coverings around 217000 ha, was significantly reduced in size due to low water flow (Kandasamy et al. 2014).

Many hydrological modelling studies (e.g. Chiew et al. 2008; Wen et al. 2011a; Wen et al. 2011b; Kandasamy et al. 2014) have been conducted to understand the hydrology of the Murrumbidgee River. These found that major water savings could be realised by reducing non-beneficial water usage in the catchment (Khan et al. 2005). However, no hydrological modelling studies were reported considering the processes (identifying water uses apart from domestic and industrial use) in the sub-catchments such as the Yass River (Saha et al. 2013). Considering the importance of the Murrumbidgee River catchment for the MDB system, review suggests that more rainfall-runoff based modelling studies of this river system are essential in understanding how future climate changes would impact on catchment flows.

This research seeks to estimate the impacts of global climate variability downscaled to the Murrumbidgee River catchment. A hydrologic modelling framework is used to estimate the effects of climate variability and evaluate future water flow under different emission scenarios RCP 4.5 and RCP 8.5. The modelling framework used in this research consists of applying climate change models and a hydrological model. The hydrological model used the SIMHYD, which has been widely used in Australia for rainfall runoff modelling. Based on the historical data, the SIMHYD model was calibrated and validated and then was used to analyse the impacts on the catchments water flow due to the different climate change scenarios.

1.2 Aims and objectives

The aim of this study is to identify the potential impact of climate change on the water availability in the Murrumbidgee River catchment under future climate projections. To do so, future river flows were simulated using the hydrological model Simplified Hydrolog (SIMHYD). A series of computational experiments were conducted using historical runoff, as well as future rainfall and potential evapotranspiration data from several climate general circulation modelling studies using two future greenhouse gas representative concentration pathways.

1.2.1 Specific Objectives

The specific objectives of the research documented in the thesis include the following:

1. Identify the impacts of climate change on the rainfall pattern in the Murrumbidgee river catchment area under various climate change scenarios,
2. Develop an integrated hydrologic-climate model approach to assess the impacts of future runoff in the Murrumbidgee River catchment,
3. Investigate the sensitivity of water availability in the Murrumbidgee River under various climate change scenarios, and
4. Project future water availability in the Murrumbidgee River using a hydrologic model and historic flow data.

1.3 Research Area

1.3.1 Location

The Murrumbidgee Catchment covers 8% of the MDB (Figure 1), which consists of 6749 km of streams and the catchment covers an area of over 84,000 km² (Norris et al. 2001). The Murrumbidgee River (1485 km) is the main channel within this catchment.

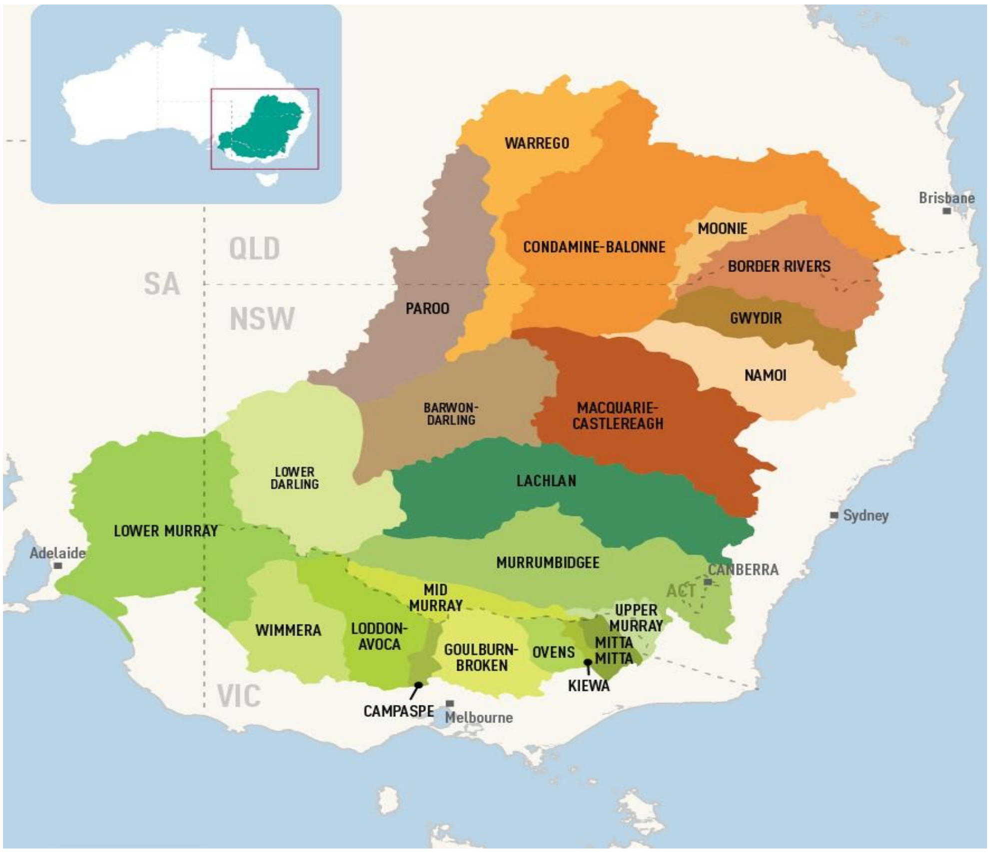


Figure 1: Murray Darling Basin Catchments (Source: MDBA website, viewed on 10 June 2017 from <https://www.mdba.gov.au/>)

The Murrumbidgee River starts in the Fiery Range of the Snowy Mountains (Figure 2), 1600 m above sea level (ASL), and flows through the undulating terrain through to Wagga Wagga in New South Wales. The catchment's land gradient decreases in the downstream of Wagga Wagga and floodplain width increases between 5 and 20 km. The Murrumbidgee River enters the Riverine Plain in Narrandera near Griffith.

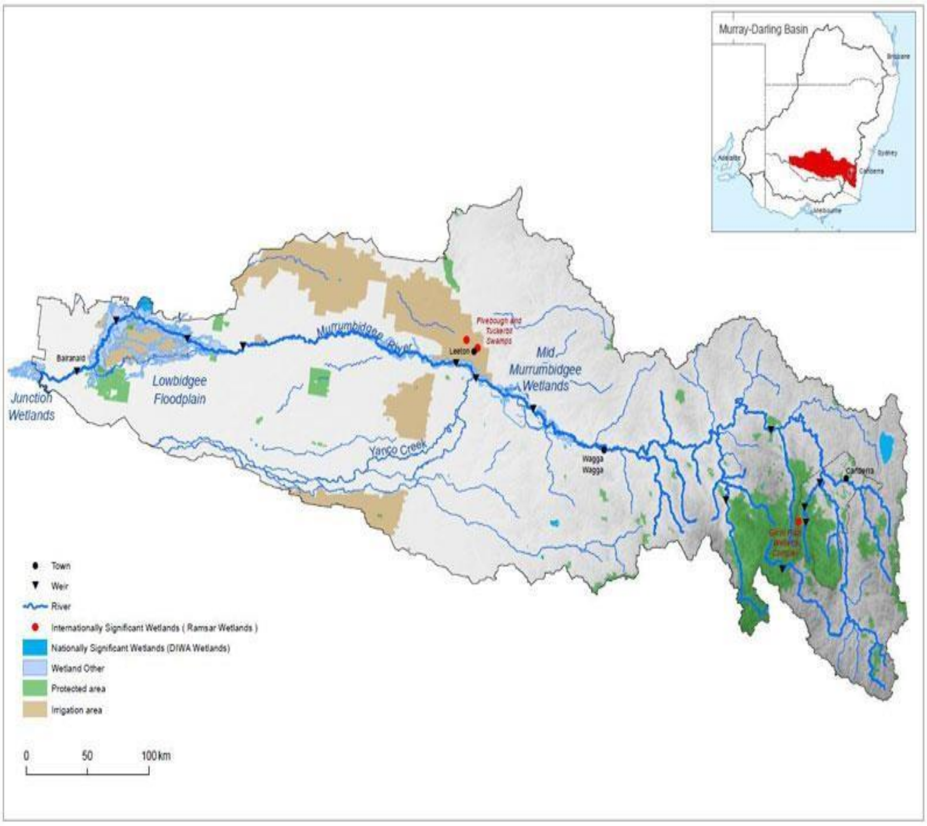


Figure 2: Murrumbidgee River catchment area (Source: NSW Office of Water website, viewed on 10 June 2017 from <https://www.water.nsw.gov.au/>)

1.3.2 Climate of the Murrumbidgee catchment

The climate of the Murrumbidgee River catchment is one of the most diverse climates in New South Wales (NSW), which varies from the cooler high alpine in the east to the hot and dry plains of the west (Wen et al. 2011). Its annual rainfall varies from more than 1500 mm in the high alpine to less than 400 mm on the western plains. The average monthly rainfall is higher in the upper catchment (the eastern part of Wagga Wagga e.g. the Yass River catchment) and lower in the lower catchment (the western part of Wagga Wagga e.g. at Balranald) area (Figure 3). The potential evapotranspiration varies from 1000 mm to over 1800 mm annually, respectively, for the same regions (Green et al. 2011). During average climatic conditions about 24% of the rainfall in the 28,000 km^2 river catchment upstream of Wagga Wagga (Figure 2) appears as runoff, contributing to most of the river flow (Saha et al. 2013). Downstream of Wagga Wagga, the runoff coefficient (the amount of runoff to the amount of precipitation received) is less than 2% (Khan 2008).

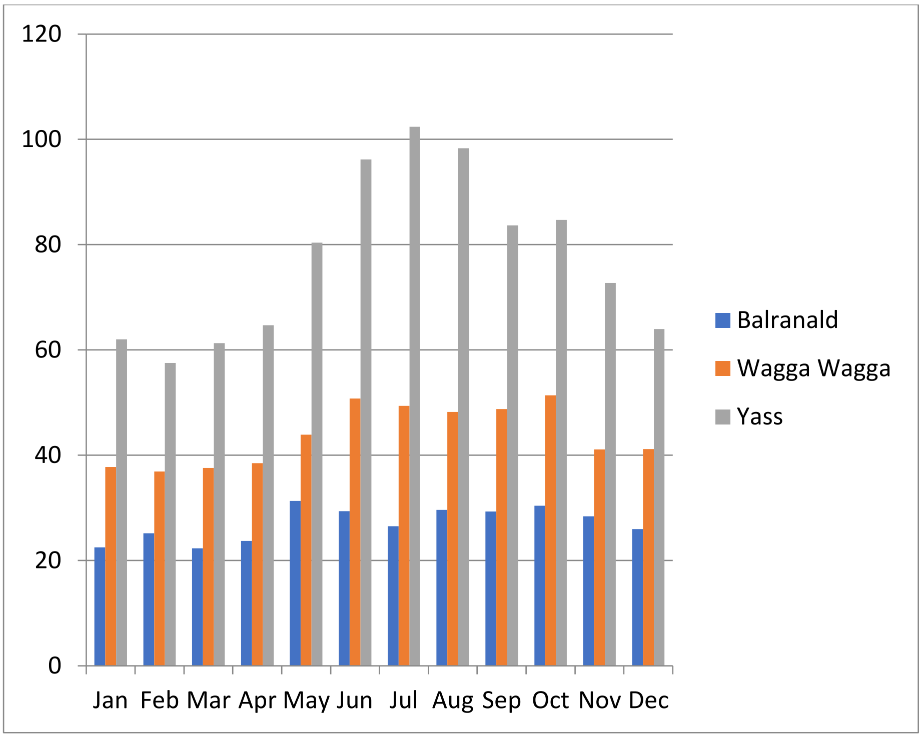


Figure 3: Mean monthly rainfall pattern in the Murrumbidgee catchment for past 100 years for three (Balranald, Wagga Wagga and Yass) rain gauge stations (Source: Bureau of Meteorology (BoM) 2018, from <http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObs

The Murrumbidgee River flow is a highly-regulated due to 14 dams and 8 large weirs along its main course. The largest dams include Burrinjuck Dam near Yass, with a capacity of 1.026 million mega litres, and Blowering Dam near Tumut, holding 1.628 million mega litres (CSIRO 2006). These dams control water for the Murrumbidgee Irrigation Area and the Coleambally Irrigation Area situated in the lower Murrumbidgee Catchment.

The Murrumbidgee River basin has seen the development of infrastructure to support expansion of irrigated agriculture, such as dams and weirs (Kandasamy et al. 2014). These man-made structures have altered the river flow dynamics that normally result from external climatic drivers, such as rainfall. This has caused the diversion of excess water to irrigation areas that would have otherwise flowed down the river network to the ocean and periodically inundated precious wetlands and riparian areas.

1.3.2 Climate change of the catchment

Climate change has been increasingly influenced the river flows in the Murray Darling Basin due to decreased annual precipitation, increased in annual temperature and low runoff in this area. The cycle in which water evaporates from the oceans and the land surface, is carried over the Earth in atmospheric circulation as water vapour, condenses to form clouds, precipitates again as rain or snow, is intercepted by trees and vegetation, provides runoff on the land surface, infiltrates into soils, recharges groundwater, and/or discharges into streams and flows out into the oceans, and ultimately evaporates again from the oceans or land surface. The various systems involved in the hydrological cycle are usually referred to as hydrological systems (IPCC 2012). During this runoff, some water passing through the land and store as soil moisture and groundwater.

The Murray-Darling Basin (MDB) region bestrides Queensland, southern New South Wales, northern Victoria, south-eastern South Australia and Australian Capital Territory and represents 14 percent of the total area of the Murray-Darling Basin (MDB). The Murray–Darling Basin is situated on a flat and shallow region (Williams 2011). The region is based around the Darling River, the River Murray and the Murrumbidgee and extends the full length of the Murray River to the Southern Ocean. The Basin receives inflows from the Barwon-Darling, Murrumbidgee, Ovens, Goulburn-Broken, Campaspe and Loddon-Avoca regions (Connell & Grafton 2011).

CHAPTER TWO: LITERATURE REVIEW

2.0 Introduction

An extensive literature has been reviewed on climate change and its influence on the stream flow of the Murrumbidgee River to explore the changing trend in the water flows due to change in climate variables. The desktop analysis included a structure review using SCOPUS, Science Direct, Google Scholar etc. and keyword search to identify the change in climatic variables for the Murrumbidgee River catchment and its sub-catchments.

Previous research by e.g. Qureshi & Whitten (2014), Kirby et al. (2013) & Adamson et al. (2009) applied different climate scenarios and hydrologic models to project the impact of climate change on different catchments within the MDB. Zhu et al. (2017) conducted hydrological modelling to estimate ground water recharge in the Murrumbidgee catchment. Frazier et al. (2005) applied daily estimation hydrological model to find the effect of flow regulation on the Murrumbidgee River. Similar hydrological modelling studies have been completed in the Murrumbidgee River catchment area to find climate change effect and adaptation options (Qureshi & Whitten 2014; Reinfelds et al. 2014; Ren & Kingsford 2014; Dyer et al. 2014). In this research Coupled Model Intercomparison Project

(CMIP) Phase 5 climate model data used for hydrological modelling which is slightly different from previous studies.

Recent Australian rainfall trends are investigated since the decrease of south-eastern Australia rainfall led to unprecedented low runoff for the region. Rainfall projections from Global Climate Models (GCMs) are examined and implemented downscaling methods to check the possibility of improving resolution of these projections that will be useful on a regional scale. Different hydrological methods will be examined to determine an appropriate method to improve runoff projections for the Murrumbidgee River catchment.

2.1 Aspects of Climate Change

Climate change can directly and indirectly affect the environment, culture, economy and health. Climate change effects have been observed globally, regionally and catchment scale due to increasing greenhouse gases in the atmosphere. These changes include variation in distribution and timing of precipitation, ocean and air temperature, wind patterns, aspects of intense rainfall and unexpected drought and fires (IPCC 2007).

2.2 Water resources in the Murray-Darling Basin

Human activity over the past 150 years has exacerbated geological, hydrological and ecological processes driven by a history of changing and highly variable climate through time and across the Basin (Williams & Goss 2002). These intensified ecological processes occurred against a backdrop of a changing climate which, has given us a severe, nine-year drought (2001-2009) and extensive floods in 2011 and 2012. These extreme climatic conditions characterise the Basin of the recent past and they can be expected to be an increasing part of future climate change (Francis & Hengeveld 1998; Min et al. 2011; Pall et al. 2011).

Inflows to the Darling River in the north of the Basin (Figure 4) are derived from highly variable episodic summer rainfall, often driven by monsoon depressions. The Murray River and its tributaries have their sources in the Australian Alps and receive most of their intake inflows from rain and snow in winter and spring (Murray-Darling Basin Authority 2015). This steep decline in rainfall features a complementary increase in evaporation. Most of the Basin in the western part of Wagga Wagga city in Dubbo has an annual water deficit, however, in the eastern part, which is roughly 15% of the Basin, witnesses a winter surplus, which drives the Basin’s water flow (Crabb 1997).

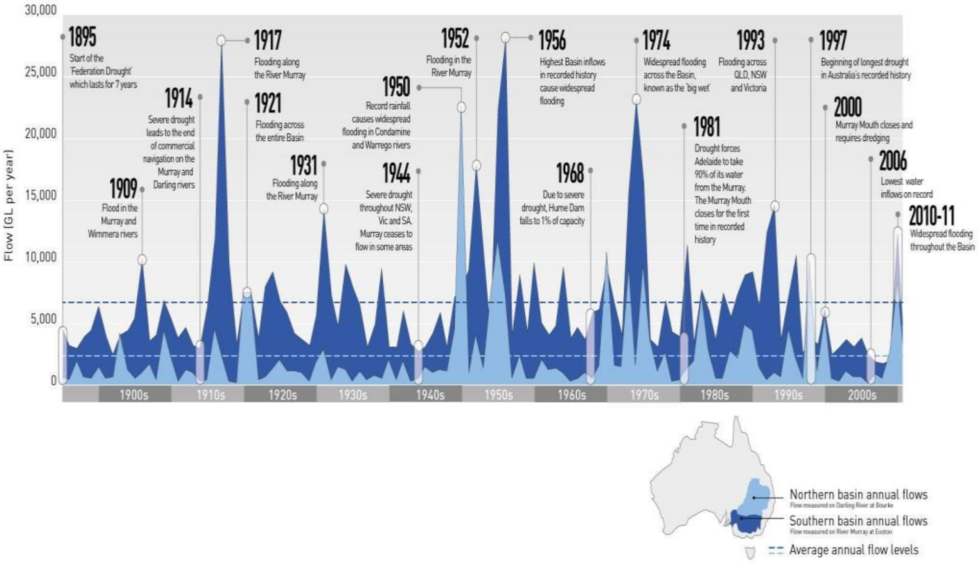


Figure 4: Surface water inflows into the Basin (Source: Murray-Darling Basin Authority 2017, viewed on 10 June 2017 from < https://www.mdba.gov.au/>)

The Murray Darling Basin contributes more than 40% of agricultural production in Australia (Beare & Heaney 2002) and provides domestic water supplies to more than 10% of the Australian population and support a range of industries.

2.4 Climate change in Australia

Under the current climate change projections, the finer resolution modelling shows the average temperature in Australia could rise between 0.6°C and 1.5°C by 2030 and it could rise to 1.1°C and 2.5°C by

2070 (IPCC 2014). Global warming will intensify the global water cycle, exacerbate extreme rainfall and hydrological events, and lead to a global redistribution of water resources at multiple temporal and spatial scales (Chen et al. 2017). The rainfall-runoff modelling also indicates decrease in rainfall in the southern part of the Murray-Darling Basin (MDB) (Figure 5) especially during winter and spring, which is traditionally the time of the highest precipitation (Bureau of Meteorology 2010).

The future rainfall reduction between 10% and 20% by 2030 for the southern catchments is a trend consistent with a southward shift in the Southern Annular Mode (Meneghini et al. 2007). Southern Annular Mode is a dominant driver of climate variability at high southern latitudes. When this mode is in its positive phase, there will be weaker westerly winds in southern Australia and stronger westerly winds at high latitudes (CSIRO & BoM 2007). The central and northern river systems are expected to have smaller reductions, particularly where summer rainfall is the main source of flow.

It is also expected that ocean-warming associated with La Nina in the northern Basin is likely to increase Summer rainfall and contribute to large flooding events across the Basin (Connell & Grafton 2011). Even in the south, where the mean is expected to decrease, the distribution of rainfall around that mean is less certain and could indicate an increase in extremes of both severe droughts and immense floods (Min et al. 2011; Pall et al. 2011).

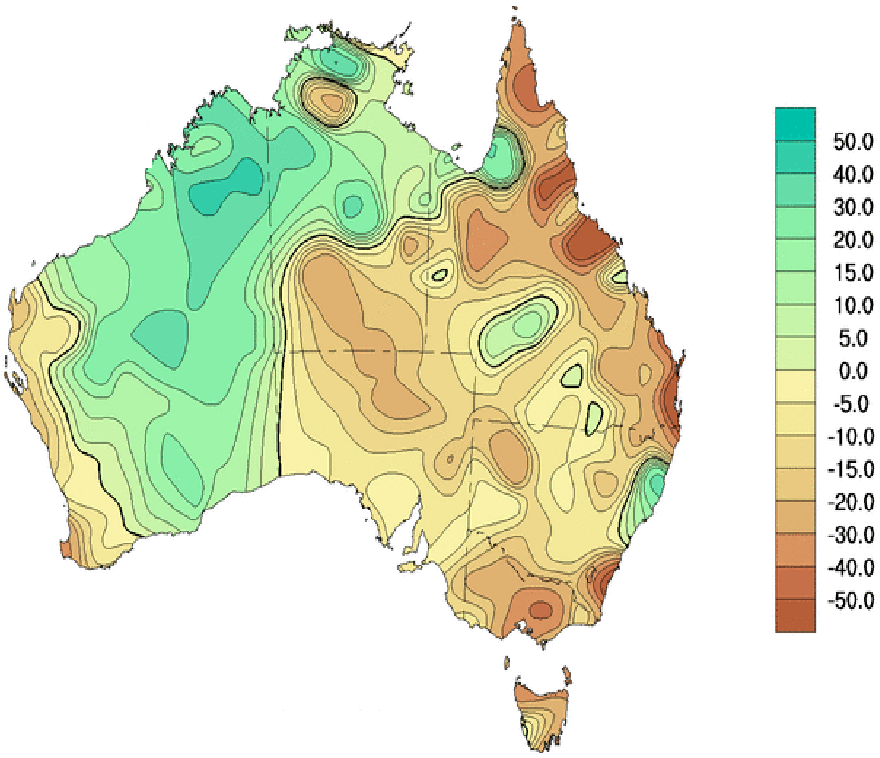


Figure 5: Monthly rainfall pattern in Australia (Source: Bureau of Meteorology 2017, Viewed on 14 June 2017, from < http://www.bom.gov.au/climate/>)

2.5 Climate change impact on Murray Darling Basin water resources

The main source of water flow of the Australian rivers is precipitation and any changes in precipitation are the main cause of change of water availability of both surface and ground water resources. In a balanced water rainfall-runoff model, the volume of water available as surface water and ground water resources are the excess of precipitation over evapotranspiration (Beare & Heaney 2002). Evapotranspiration can be influenced by climatic factors like temperature, solar radiation, wind and humidity. Types and area of vegetation also influence the evapotranspiration. Annual grasses help to reduce runoff whereas perennial trees increase evapotranspiration by returning more water through its surface. However, the influence of vegetation cover on transpiration increases with higher precipitation which moderates the direct impacts of climate change (Zhang, Walker & Dawes 1999). Change in climatic conditions may have an impact on ground cover and evapotranspiration. The increase in vegetation impact increases atmospheric carbon dioxide, and higher level of carbon dioxide increases water use efficiency, which causes less transpiration. On the other hand, climate variables such as higher temperatures, changes in rainfall pattern and soil moisture could either enhance or negate the benefit of higher carbon dioxide concentrations on plant physiology (Swann et al. 2016).

The amount of water that comes as precipitation is either transported as surface water runoff or infiltrates into the soil as ground water recharge. This amount of water that enters the ground water system depends on the rate of infiltration. This infiltration rate is influenced by several factors like the gradient of the land, the size, texture and soil particles of the land. On a steep slope the land infiltration rate is less than on a flat land, and sandy soil has a higher infiltration rate than clay soil.

2.6 Water demand

Agriculture is the main demand for surface water in the Murray-Darling Basin. In the Murray-Darling Basin region, the total volume of irrigation water applied is 5.9 million ML (Australian Bureau of Statistics 2013), which is 72% of the total irrigated water in Australia.

Each year, approximately 10,000 giga litres of surface water is diverted for irrigation from the Murray-Darling Basin (Murray-Darling Basin Authority 2002). As a result of climate change, the availability of irrigation water may decrease because of reduced precipitation and increased evapotranspiration (Beare & Heaney 2002). More research is needed on the use of rainfall-runoff water model to identify the change in water flow in the Murrumbidgee River. Hatch et al. (1999) showed that irrigation requirements were estimated to decrease by as much as 30 % for corn in the south-east US. If there is a possibility to change pattern for agricultural crop production in the south-east part of Australia, then possibility of water shortage impact on livelihood will be less.

2.7 Hydrological modelling

Potter et al. (2009) demonstrated the severity of climate change using rainfall-runoff model in the Murray-Darling Basin, by calculating the data from rainfall-runoff modelling across the Murray-Darling Basin applying the Simplified Hydrolog (SIMHYD) rainfall-runoff model with Muskingum routing (Chiew et al. 2002; Chiew & Siriwardena 2005a). There is a significant reduction in observed low rainfall and runoff during the dry period in the Murray-Darling Basin. McMahon et al. (2007) compared this high variability with similar river system around the world. Fu et al. (2013) successfully used Simplified Hydrolog (SIMHYD) as a modelling tool with statistically downscaled data and gridded catchment rainfall series. They used SILO *Data Drill* which provides 0.05° gridded daily rainfall in the MDB area.

2.7.1 Review of hydrological methods currently used

The rainfall runoff modelling can be categorised into two main groups including stochastic and deterministic models (Gayathri et al. 2015). Deterministic model will give same output for a single set of input values whereas in stochastic models, different values of output can be produced for a single set of inputs. Deterministic model can be divided into conceptual and process model (Gayathri et al. 2015).

The main classifications of the hydrological models are empirical model, conceptual models and physically based models.

2.7.1.1 Empirical models

These are observation oriented models which take only the information from the existing data without considering the features and processes of hydrological system and hence these models are also called data driven models (Gayathri et al. 2015). Regression type analyses are examples of empirical models which have been used for a long time in this field.

2.7.1.2 Average Runoff Coefficient Method

The Average Annual Runoff Coefficient Method recommended by Burton (1965), which is a simplified empirical technique to relate rainfall to runoff with a certain probability. The rainfall runoff relation can be expressed by equation 1.

$$Q = P - AET \pm \Delta S \qquad \text{(equation 1)}$$

Q = the Runoff (mm)

P = the Rainfall (mm)

AET = the actual evapotranspiration loses (mm)

ΔS = the change in soil moisture storage

2.7.1.3 Rainfall Runoff Correlation (Probabilistic Method)

Correlation and regression technique can be applied to determine the functional relationship between rainfall and runoff for a catchment. The relationships obtained by the correlation coefficient, standard deviation, confidence limits and tests of significance (Tokar & Johnson 1999). If long term rainfall data are available and the parameters of rainfall runoff correlation can be determined for the catchment then this method is valuable for ungauged catchments.

2.7.1.4 The Stochastic Approach (Monte Carlo Model)

This approach is designed to extend hydrologic forecasts and improve decision making ability. In many hydrological models require long period of rainfall and stream flow data and if these data are not available then may be extended using stochastic models (Aronica & Candela 2007). Using the value of μ, σ, and ρ (population mean, standard deviation and lag-one serial correlation determined from the historical data) with a selected random generator, the stream flow for the future period can be estimated.

2.7.1.5 Conceptual methods

This model describes all hydrological component processes with a few interconnected reservoirs which represents the physical elements of the catchment in which they are recharged by rainfall, infiltration and percolation and are emptied by evaporation, runoff etc. Many conceptual models have been developed with varying degree of complexity. Stanford Watershed Model IV (SWM) is the first major conceptual model developed by Crawford & Linsley (1966) with 16 to 20 parameters.

2.7.1.6 Stanford Watershed Model

The Stanford Watershed Model (Crawford & Linsley 1966) utilises hourly rainfall and daily potential evapotranspiration as input to produce the runoff hydrographs as well as other data on simulated catchment behaviour. This model requires hourly rainfall and runoff data for simulation.

2.7.1.7 Physically based model

This method is mathematically representation of the real catchment scenarios. These are also called mechanistic models that include the principles of physical processes. It uses state variables which are measurable and both functions of time and space. Physical model can overcome many defects of the other models because of the use of parameters having physical interpretation. It can provide large amount of information even outside the boundary and can applied for a wide range of situations. SHE/ MIKE SHE model is an example of physically based model (Abbott et al. 1986a).

2.7.1.8 SWAT Model (Soil and Water Assessment Tool)

SWAT model is a complex physically based model and was designed to test and forecast the water and sediment circulation and agricultural production with chemicals in ungauged basins. The model breaks the entire catchment in to sub-catchments which are further divided into hydrologic response units (HRU), land use, vegetation and soil characteristics (Gayathri et al. 2015). The model uses the following water balance equation 2 in the catchment.

$$SW_t = SW_o + \sum_{i=1}^{t} (R_v - Q_s - W_{seepage} - E_t \;\; Q_{gw}) \qquad \text{(equation 2)}$$

Where SWt is the final soil water content (mm H_2O), SWo is the initial soil water content on day i (mm H_2O), t is the time (days), Rv is the amount of precipitation on day i (mm H_2O), Qs is the amount of surface runoff on day i (mm H_2O), *Et* is the amount of evapotranspiration on day i (mm H_2O), *Wseepage* is the amount of water entering the vadose zone from the soil profile on day i (mm H_2O), and *Qgw* is the amount of return flow on day i (mm H_2O).

2.7.1.9 HBV Model (Hydrologiska Byrans Vattenavdelning model)

This model is an example of semi distributed conceptual model (Bergstrom 1976). The entire catchment is divided into sub catchments, which are further divided into different elevation and vegetation zones. It runs on daily and monthly rainfall data, air temperature and evaporation. Air temperature data are used for calculating snow accumulation. The general water balance equation used is

$$P - E - Q = \frac{d}{dt}(SP + SM + UZ + LZ + lakes) \qquad \text{(equation 3)}$$

The above equation shows ground water recharge is equilibrium to the functions of actual water storage. Where P is precipitation (mm/day), E is evaporation (mm/day), Q is runoff (mm/day), SP is the snow pack (mm), SM is the soil moisture (mm), UZ (mm) and LZ (mm) are the upper and lower ground water zone, lakes represent the volume of lake (m^{-3}) and$^{d}/_{dt}$Is the derivative over time.

2.7.1.10 TOP MODEL

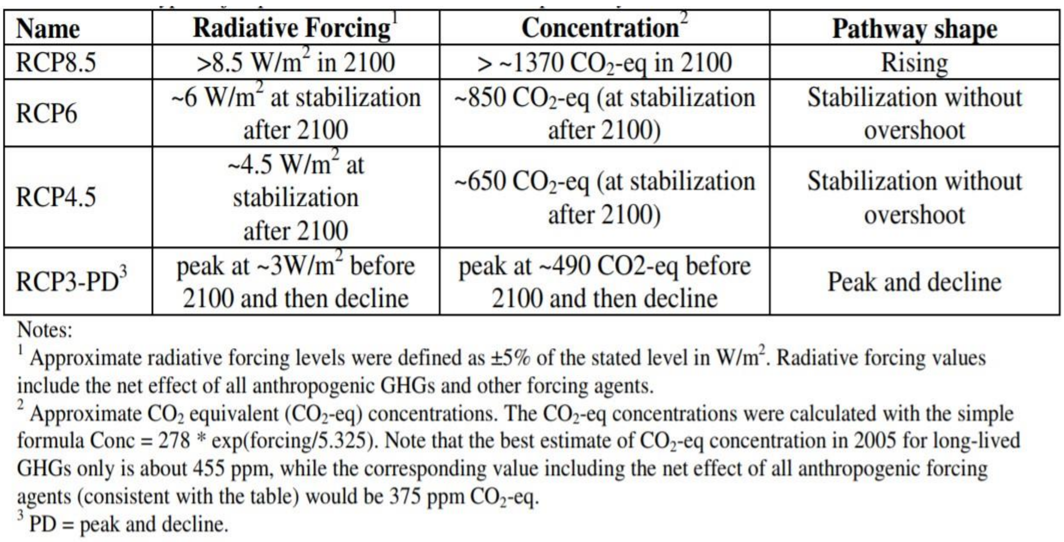
It is a semi distributed conceptual rainfall runoff model that takes the advantage of topographic information related to runoff generation. But according to Beven & Kirby (1979), the TOPMODEL is considered as a physically based model as model parameters can be theoretically measured. The major factors considered in this model are the catchment topography and soil transmissivity. The model uses exponential Green-Ampt method of Beven et al. (1984) for runoff calculation and reduces the use of parameters. The output will be in the form of area maps or simulated hydrographs.

2.8 Review of Climate Models

Climate models attempt to simulate the interaction of the physical processes which define the climate. Models, which simulate the entire Earth’s climate, are called global climate models. These have coarse spatial resolutions (up to 300km grids spacing, which translates to one theoretical value per 300km by 300km grid cell) and range from simple one-dimensional to complex three-dimensional models known as general circulation models (GCMs). GCMs can further be divided into oceanic GCMs (OGCM) and atmospheric GCMs (AGCM) (Abiodun & Abedoyin 2016). These two models can be coupled to interactively simulate the oceans, atmosphere and land surface. These are called atmospheric-ocean GCMs (AOGCMs).

The multi-model data archive of Coupled Model Intercomparison Project (CMIP) Phase 5 (CMIP5) has been released in preparation of the IPCC AR5 under which a series of experiments including the 20th century historical simulation and 21st century climate projections (Taylor et al. 2012). There were four different representative concentration pathways (RCP) performed using various coupled general circulation models (CGCMs) developed by a number of international climate modelling groups from around the world (Sharmila et al. 2015). Compared to CMIP3, the CMIP5 models are better in terms of representing model physics, vertical resolution and the inclusion of atmospheric aerosols (Sperber et al. 2013; Taylor et al. 2012).

Recent studies have already investigated the overall future changes in global monsoon precipitation using multi-model ensemble and selected CMIP5 models under different range of RCP scenarios (Figure 6) (Wang et al. 2014; Kitoh et al. 2013; Lee & Wang 2014), that suggest notable increase in global monsoon precipitation during 21st century due to global warming. However, by comparing the future projections between RCP4.5 (moderate) and RCP8.5 (strongest) scenarios, Kitoh et al. (2013) suggested that the global monsoon response to atmospheric warming is larger and more robust in a warmer RCP8.5 world among the models.



Name	Radiative Forcing[1]	Concentration[2]	Pathway shape
RCP8.5	>8.5 W/m^2 in 2100	> ~1370 CO_2-eq in 2100	Rising
RCP6	~6 W/m^2 at stabilization after 2100	~850 CO_2-eq (at stabilization after 2100)	Stabilization without overshoot
RCP4.5	~4.5 W/m^2 at stabilization after 2100	~650 CO_2-eq (at stabilization after 2100)	Stabilization without overshoot
RCP3-PD[3]	peak at ~3W/m^2 before 2100 and then decline	peak at ~490 CO2-eq before 2100 and then decline	Peak and decline

Notes:

[1] Approximate radiative forcing levels were defined as ±5% of the stated level in W/m^2. Radiative forcing values include the net effect of all anthropogenic GHGs and other forcing agents.

[2] Approximate CO_2 equivalent (CO_2-eq) concentrations. The CO_2-eq concentrations were calculated with the simple formula Conc = 278 * exp(forcing/5.325). Note that the best estimate of CO_2-eq concentration in 2005 for long-lived GHGs only is about 455 ppm, while the corresponding value including the net effect of all anthropogenic forcing agents (consistent with the table) would be 375 ppm CO_2-eq.

[3] PD = peak and decline.

Figure 6: Types of Representative Concentration Pathways (Source: IPCC 2014, Viewed on 10 June 2017, from <https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf>)

GCMs have been used to predict future changes in climate until the end of the 21st century by various institutions specialising in climate research. More information on these institutions, their models and analyses data can be obtained from the IPCC Data Distribution Centre at <http://www.ipcc-data.org>.

According to Hewitson et al. (2005) AOGCMs are the ideal tools for current and future climate simulation. These tools have low spatial resolutions and require to be downscaled to use in regional climate impact studies, which require higher resolutions ranging from 10km to 100km.

The following three main techniques applied to downscaling described by Mearns et al. (2003).

2.8.1 Variable resolution time-scale GCM experiments

Simulation of climate at higher grid resolutions ranging in the order of 100km globally and 50km locally is feasible over shorter time scales of several decades. The ‘time-slices’ of interest are identified and modelled in finer spatial detail.

2.8.2 Nested regional climate models

This modelling approach uses a high resolution regional climate model (RCM) within the lower resolution GCM. This is known as ‘nesting’ the RCM within the GCM. The input to the nested RCM is the output from the GCM at its nesting boundary. These models are also known as limited area models (LAMs).

2.8.3 Empirical / statistical interpolation

Statistical downscaling involves modelling the relationship between the large-scale variables from GCMs (predictors) to the regional or local variables (predicants). Thereafter, the GCM predictors are input into the statistical model to estimate the corresponding local or regional predicants.

2.9 Summary

Previous study shows that the future impact of climate change in the southeast of Australia is considerable and requires better water management in this region to store winter rainfall for use during the dry seasons. In this region as well as Australia's water resources are highly vulnerable to climate change scenarios (Preston & Jones 2006). Rapidly increasing surface temperatures, increasing rate of evaporation and longer droughts reduce stream flow more significantly than reductions in rainfall. Having reliable and robust rainfall projections are important when planning water management strategies that will adapt to changes in the region rainfall regime. Statistical downscaled data obtained from Australian government agencies to provide rainfall projections on a sub-catchment scale for the Murrumbidgee River catchment. Whilst dynamical downscaling methods do provide more robust rainfall simulations, the expertise and computer power required for these methods is beyond the scope of this analysis.

CHAPTER THREE: RESEARCH METHODOLOGY

3.0 Introduction

Daily time series rainfall and evapotranspiration data were used as input for the SIMHYD hydrological rainfall and runoff model. I have used historical rainfall, evapotranspiration and stream flow data for SIMHYD model calibration and validation. These calibration results have been used for future simulations using future projected rainfall and runoff. According to three different GCMs projected rainfall increases in winter season and decreases in summer season. Rainfall will be linked with runoff on daily basis. Applying historical rainfall and runoff data in the hydrological model will enhance historical simulations of the catchment. This will be the baseline runoff simulation for future catchment runoff modelling.

3.1 Data

The Murrumbidgee river catchment covers 84,000 km^2 and located in southeast of Australia with latitude and longitude ranging from 33°S to 37°S & 143°E to 150°E respectively. The Murrumbidgee River catchment is in the higher runoff generation areas (Vaze et al. 2011) in the southeast Australia. The lowest flow observed 30 ML/Day in September 2009 and the highest flow was recorded 31,224 ML/Day in November 2016 (BoM 2017). The annual runoff coefficient varies from 0.06 to 0.36.

Daily observed flow data of the Murrumbidgee River obtained from the New South Wales (NSW) government of water (NSW Office of Water Information website <http://waterinfo.nsw.gov.au/>) for five different points. The historical (AWRA-L model simulated) daily data on rainfall, temperature and potential evaporation were collected from Bureau of Meteorology (<http://www.bom.gov.au/climate/data) and projected CMIP5 climate data for emission scenarios RCP 4.5 & RCP 8.5 based on different climate models obtained from CSIRO Melbourne office and some partial data were obtained from Climate Change in Australia (<https://www.climatechangeinaustralia.gov.au/en/>). The obtained historical data were pre-processed using AWRA model for 0.05° x 0.05° gridded area by the agency. The climate of the study area varies considerably across the region.

Table 1: Data obtained for different gauging stations

Station ID	Site Name	Latitude	Longitude
074127	Murrumbidgee River at Wagga Wagga	-35.086	147.33
049002	Murrumbidgee River at Balranald	-34.63	143.53
410026	Murrumbidgee River at Yass	-34.82	148.91
070083	Murrumbidgee River at Tharwa	-35.51	149.06
410047	Murrumbidgee River Borambola	-35.11	147.63

The main inputs for SIMHYD model are daily rainfall and daily potential evapotranspiration. The total number of five different sub-catchments from the Murrumbidgee River catchment were identified which have sufficient historical data with appropriate characteristics that will need for modelling purposes.

Historical rainfall, Potential Evapotranspiration and runoff data obtained from Bureau of Meteorology.

3.1.2 Historical Rainfall

The average annual rainfall of the Murrumbidgee river catchment is about 533 mm (mean annual long-term rainfall data from Balranald, Wagga Wagga and Yass). This annual rainfall pattern varies 714 mm to 359 mm from high elevated area Yass and in the downstream area at Balranald. Most of the rainfall occurs in winter (May – October) in Wagga Wagga and Yass whereas at Balranald rainfall drops in the month of Jun and July. In comparison long term average rainfall (1879-2017) with last sixteen years (2001-2016) of average record shows autumn rainfall has increased in February by 70% at Balranald (Figure 7), 51% at Wagga Wagga (Figure 8), 49% at Yass (Figure 9), 58% at Borambola (Figure 10), 47% at Tharwa (Figure 11). The rainfall comparison pattern shows higher trend in Yass and lower trend in downstream of Wagga Wagga (Figure 12).

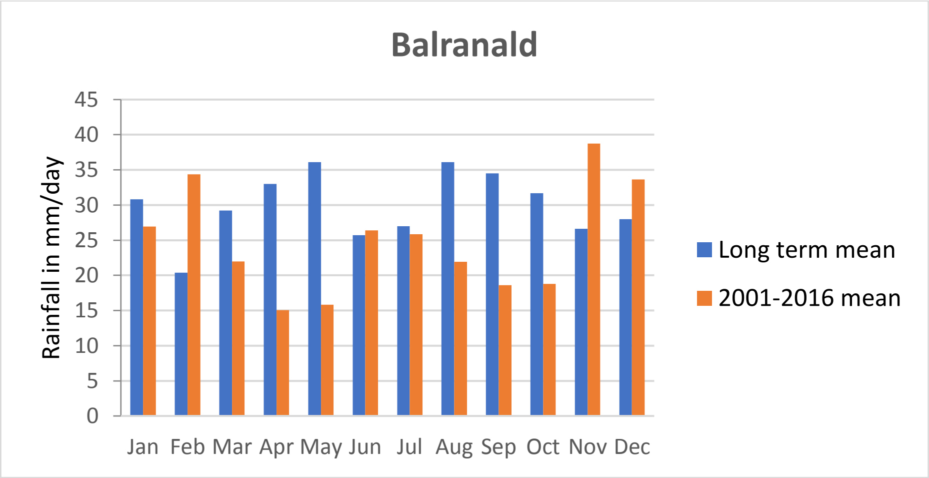


Figure 7: Long term mean (1879-2017) monthly rainfall (mm/day) and 2001-2016 mean monthly rainfall (mm/day) comparison at Balranald

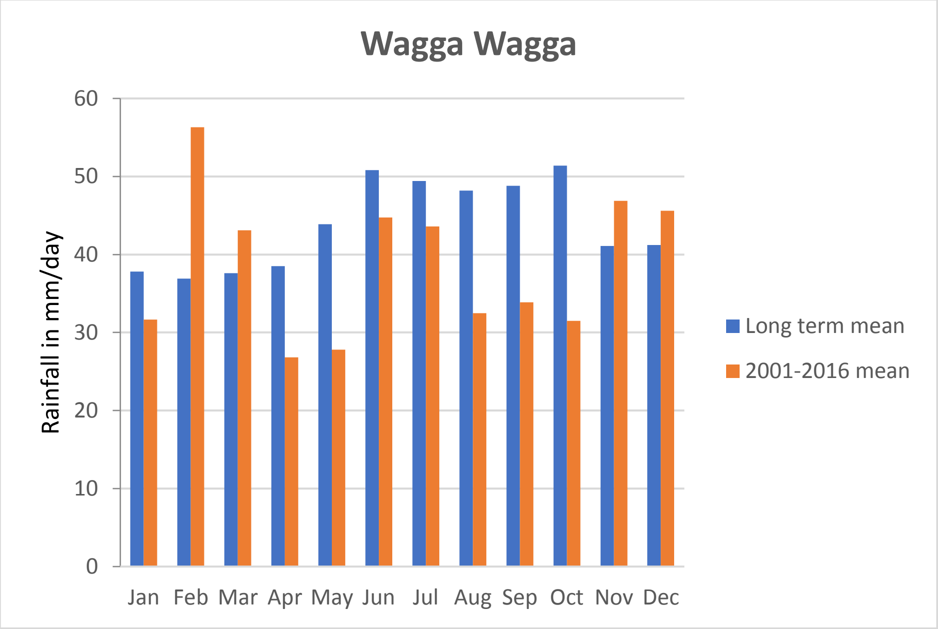


Figure 8: Long term mean (1879-2017) monthly rainfall (mm/day) and 2001-2016 mean monthly rainfall (mm/day) comparison at Wagga Wagga

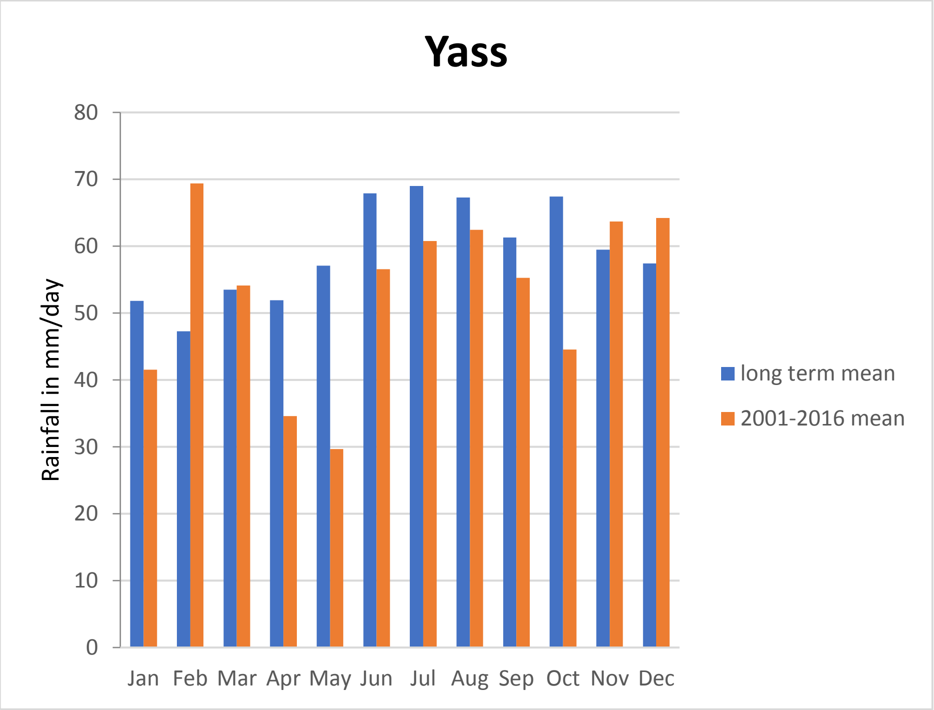


Figure 9: Long term mean (1879-2017) monthly rainfall (mm/day) and 2001-2016 mean monthly rainfall (mm/day) comparison at Yass.

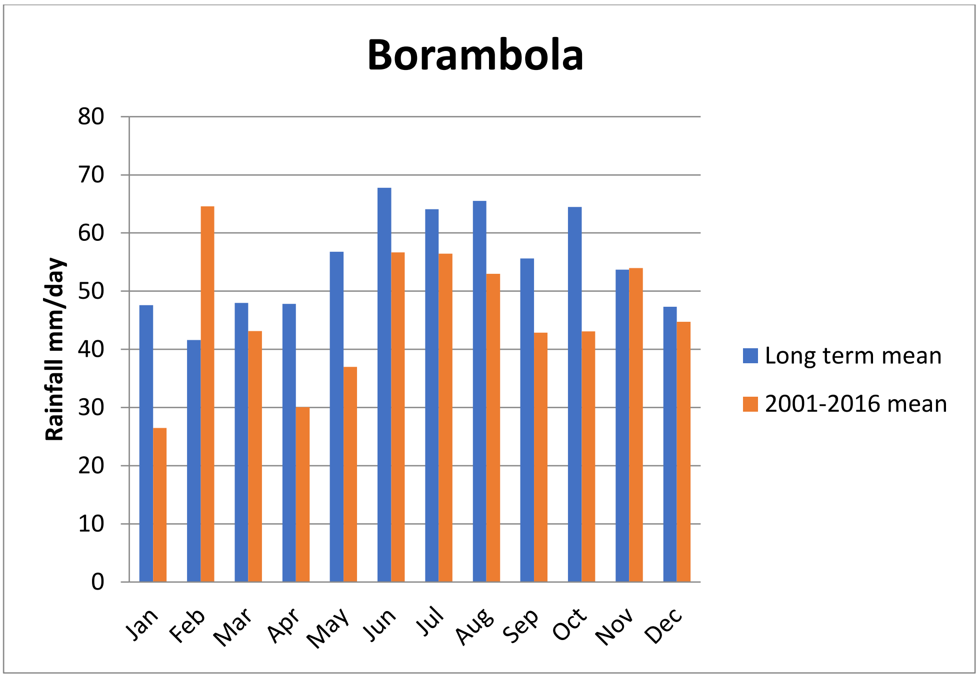


Figure 10: Long term mean (1879-2017) monthly rainfall (mm/day) and 2001-2016 mean monthly rainfall (mm/day) comparison at Borambola.

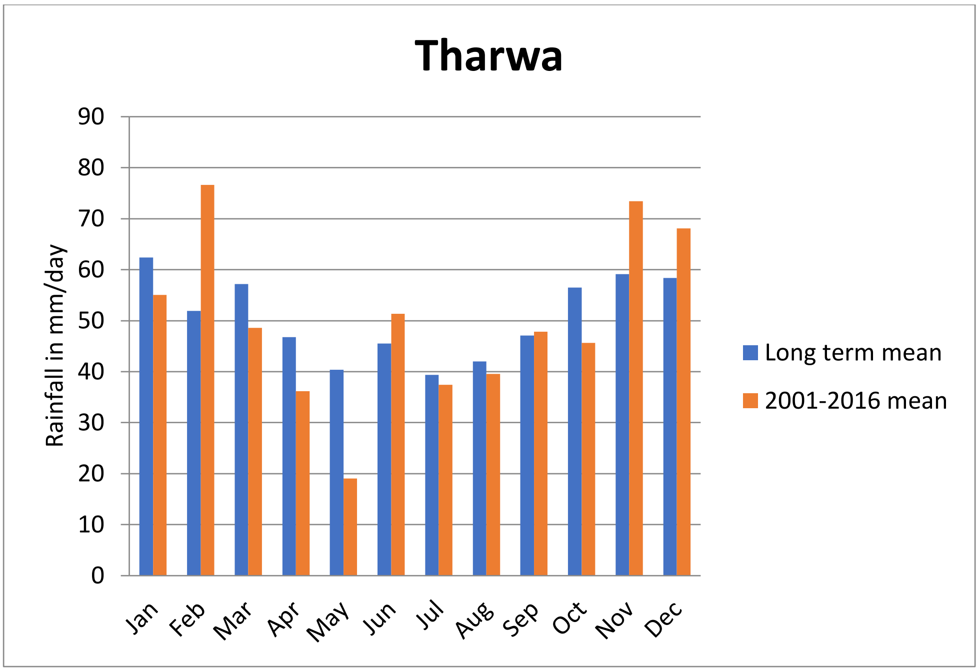


Figure 11: Long term mean (1879-2017) monthly rainfall (mm/day) and 2001-2016 mean monthly rainfall (mm/day) comparison at Tharwa.

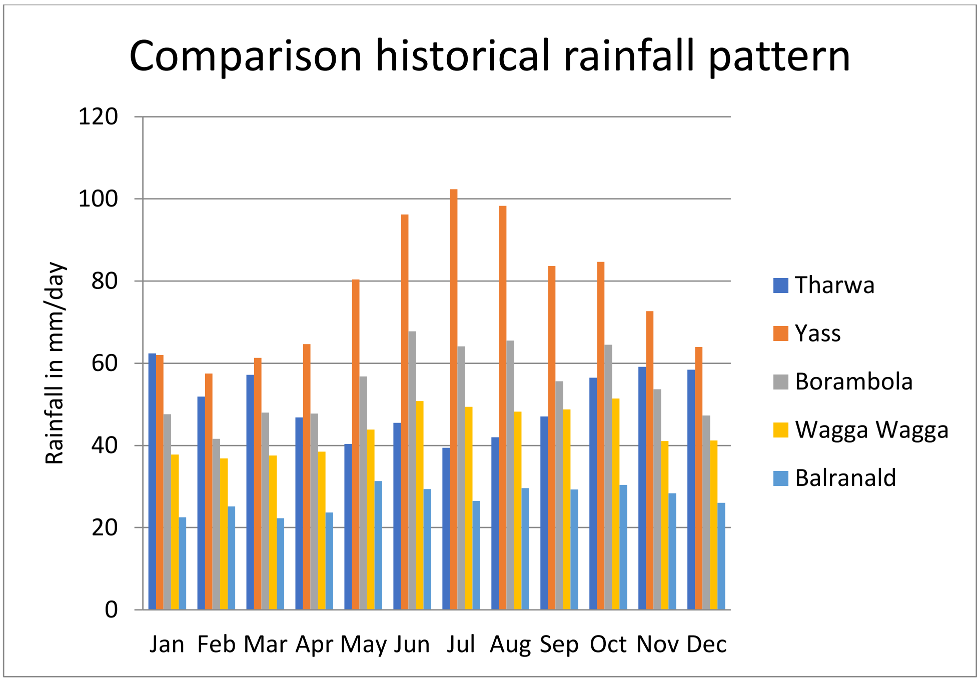


Figure 12: Long term mean (1879-2017) monthly rainfall (mm/day) comparison for five different sub-catchments.

3.1.2 Historical Runoff

The annual surface water availability in the Murrumbidgee River catchment is 4270 GL (Chiew et al. 2008a). This flow rate is low in the alpine region for Tharwa and higher in the downstream of the Murrumbidgee River area at Balranald (west of the catchment). The historical runoff data (1979 – 2017) have been compared with last seventeen years of data (2001 -2017) which shows in the figures 13a, 13b, 13c, 13d & 13e. It is evident that the average runoff is decreasing in all the five sub-catchments.

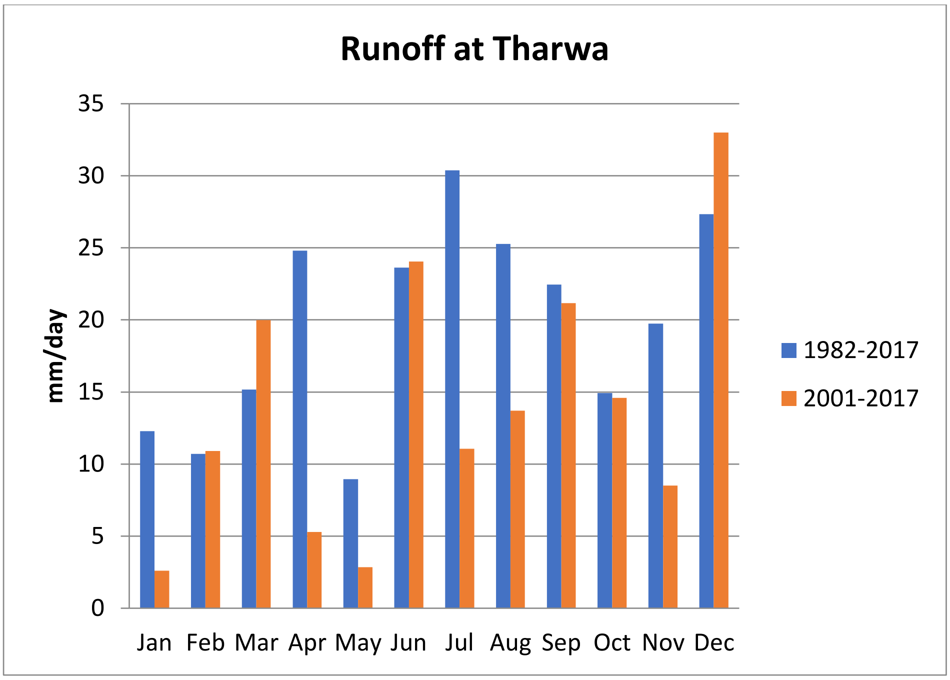


Figure 13a: Historical runoff (1982-2017) comparison (2001-2017) at Tharwa (BoM 2017)

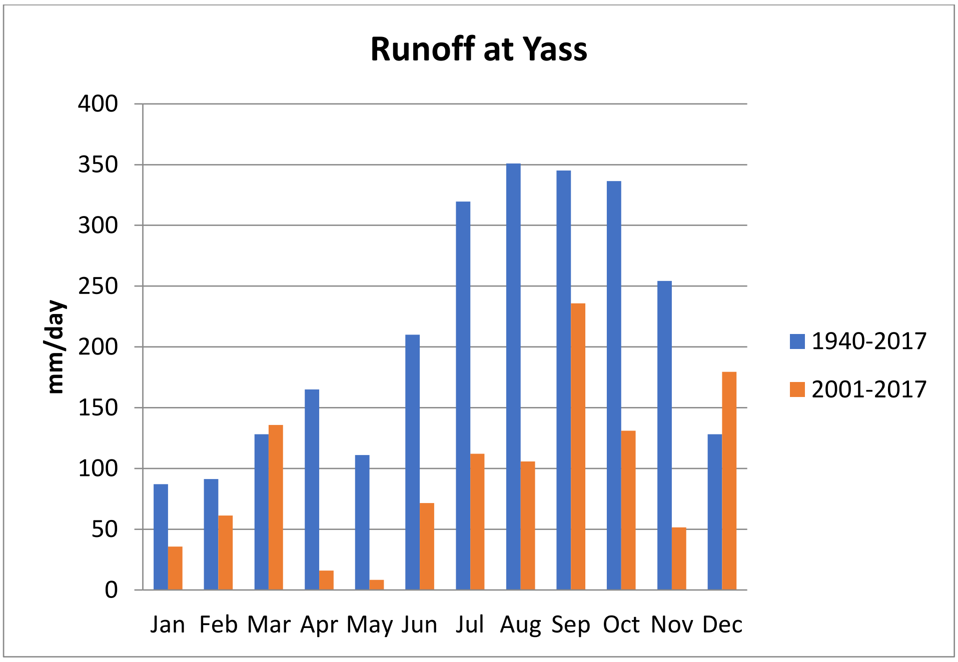


Figure 13b: Historical runoff (1940-2017) comparison (2001-2017) at Yass (BoM 2017)

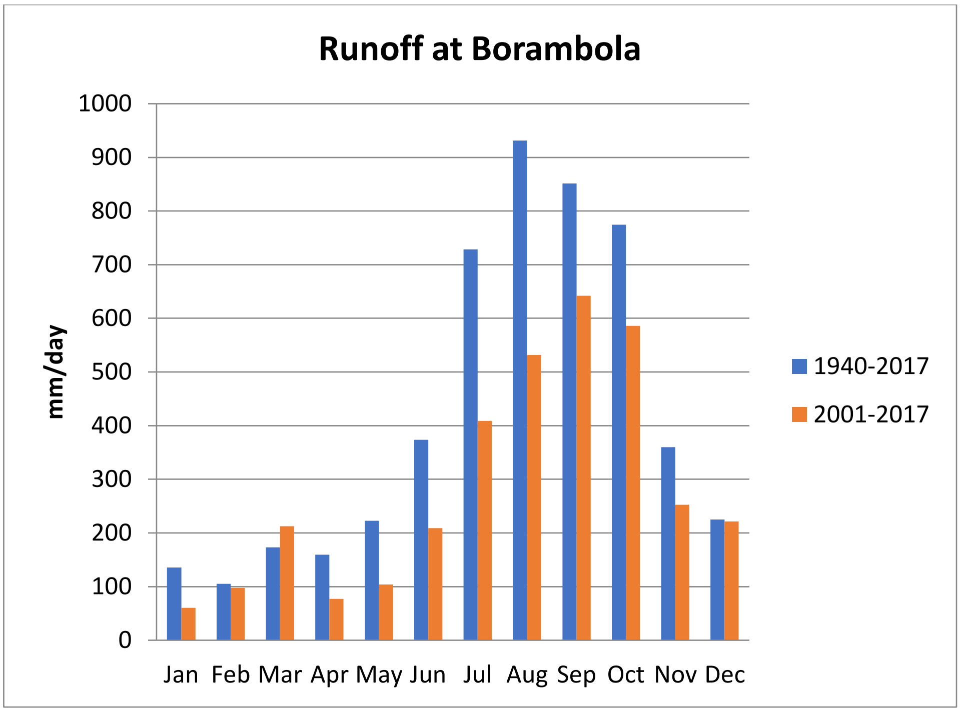


Figure 13c: Historical runoff (1940-2017) comparison (2001-2017) at Borambola (BoM 2017)

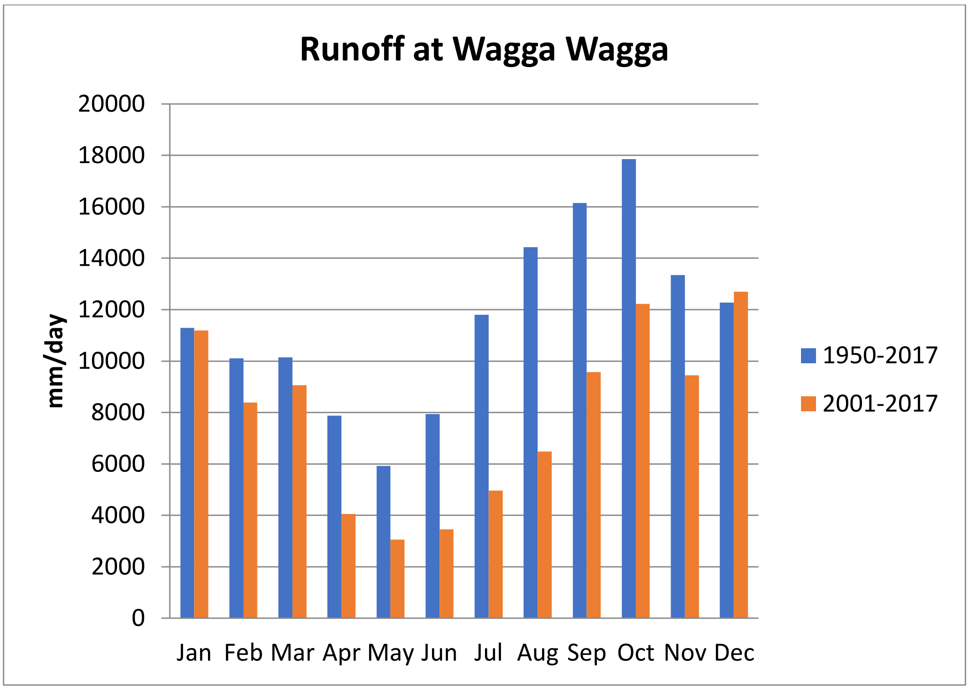


Figure 13d: Historical runoff (1950-2017) comparison (2001-2017) at Wagga Wagga (BoM 2017)

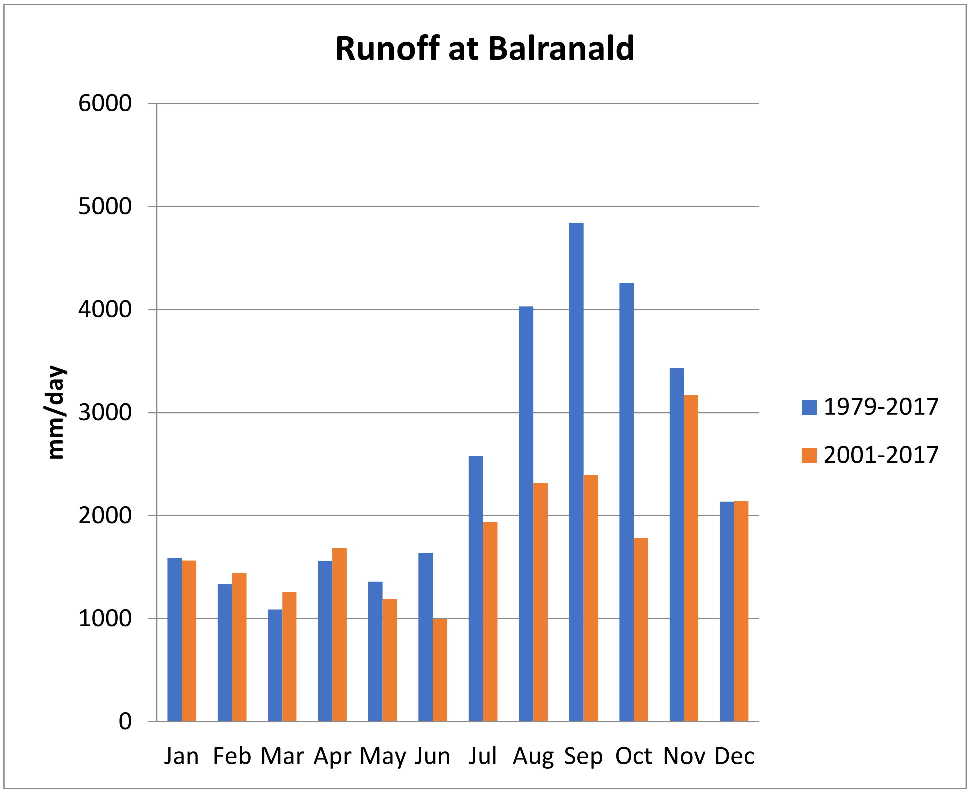


Figure 13e: Historical runoff (1979-2017) comparison (2001-2017) at Balranald (BoM 2017)

3.1.3 Climate Models

There are three climate models used in this project to simulate historical and projected climate variable data for precipitation, potential evapotranspiration and runoff. Historical precipitation, potential evapotranspiration and runoff data downloaded from the Bureau of Meteorology website. In this study, I have used ACCESS1.0, GFDL-ESM2M and MIROC5 climate models to predict future climate data under the emission scenario of RCP 4.5 and RCP 8.5. These models have been selected as best case, worst case and maximum consensus scenarios. Best case scenario model MIROC5 was selected for predicting least increase (greatest decrease) in evapotranspiration and greatest increase in precipitation. For worst case scenario GFDL-ESM2M model was selected as this model projects greatest increase in evapotranspiration and greatest decrease in precipitation. ACCESS1.0 has been used as maximum consensus scenario model. Maximum Consensus defined as the climate future populated by the greatest number of models, where that number must be at least one third of the total available GCMs and must be at least 10% greater than the next most populous climate future.

Table 2: Climate models used for future projections-based RCP scenarios

Model Name	Group	Country	Atmospheric Resolution (longitude X latitude)
Australian Community Climate and Earth System Simulator (ACCESS1.0)	ACCESS1.0	Australia	1.25 x 1.875
NOAA Geophysical Fluid Dynamics Laboratory – Earth System Model	GFDL-ESM2M	US	2.0225X 2.5
Model for Interdisciplinary Research on Climate	MIROC5	Japan	1.4008 X 1.40625

3.1.4 Climate Scenario

The following two scenarios will be assessed for the four future periods of 2016-2035, 2035 -2055, 2055-2075 and 2075-2100. These scenarios are defined by daily time series of climate data based on historical rainfall, temperature and evapotranspiration 1985 to 2015.

- Scenario 1: Representative Concentration Pathway (RCP) 4.5 – 2016–2035, 2035–2055, 2055–2075, 2075-2100.
- Scenario 2: Representative Concentration Pathway (RCP) 8.5 – 2016–2035, 2035–2055, 2055 –2075, 2075-2100.

3.1.5 Hydrological Model Selection

Model selection depends on various objectives and the hydrologic system and element being modelled; e.g. hydrological forecasting or climate change impact assessment, type of catchment, daily average discharge, monthly average discharge etc.

In Australia, mostly conceptual rainfall-runoff models have been widely used for hydrological modelling. Because they are relatively easy to calibrate and these models give a good estimation of flow in gauged and ungauged catchments. SIMHYD is one of the mostly used conceptual models in Australia. The input data into the model are daily rainfall, potential evapotranspiration, and daily runoff for the catchment area to be modelled.

According to previous study south eastern Australia has the extreme variability in climate change (Saha et al. 2013). Water adds to the catchment through the rainfall and snowfall, and drains in the process of evapotranspiration and runoff. In a climate change condition rainfall and evapotranspiration are the most vulnerable for catchment hydrology.

SIMHYD model requires only seven parameters and doesn’t require high resolution spatial data layers. This model has ability to implement multiple runs for automated calibration. Most likely previous calibrated models are available for the catchment.

SIMHYD has been used successfully for the estimation of climate change impact on runoff (Potter & Chiew 2009; Chiew & McMahan 2002) and also in various regionalisation studies (Chiew et al. 2010; Zhang & Chiew 2009).

In SIMHYD model there are two constraints used in the calibration: the total modelled runoff must be within 5% of the total recorded runoff; and the quick flow ratio (surface runoff divided by total runoff) in the modelled runoff must be within 20% of the quick flow ratio in the recorded runoff. In most catchments SIMHYD simulates little to no infiltration excess runoff and therefore optimisation of maximum infiltration loss (COEFF default value is 200) and infiltration loss exponent (SQ default value is 1.5) is not required in most catchments except for tropical catchments. The calibration against monthly runoff with two constraints and five parameters increase the optimised parameters taking meaningful values (Chiew & Siriwardena 2005a).

3.2 Research Method

Modelling strategy for evaluating climate change impact on the Murrumbidgee River catchment is presented in Figure 14.

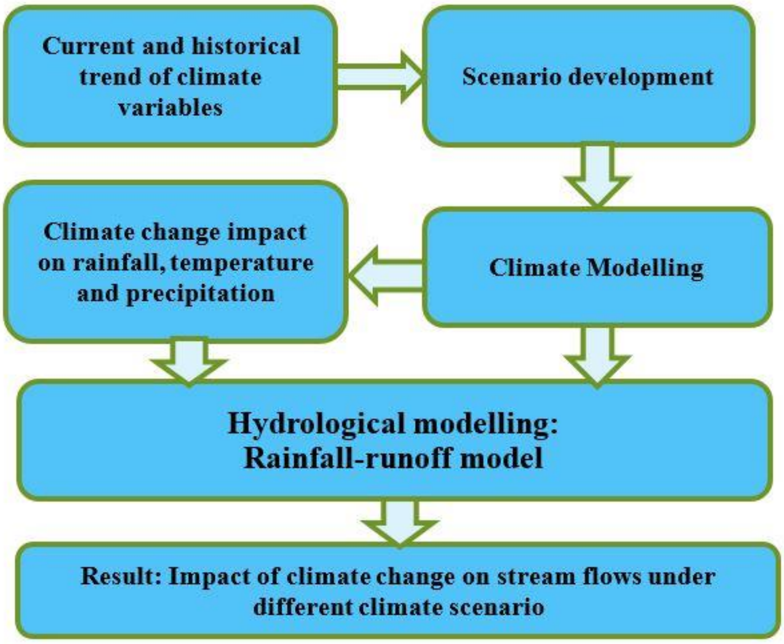


Figure 14: Modelling strategy for evaluating climate change impact on the Murrumbidgee River catchment

The long term historical simulations and future climate projections from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) used for this study as these are better representation of earth’s physical processes (Pattnayak et al. 2017). The highest emission scenario RCP 8.5 is the priority and moderate emission scenario RCP4.5 is the second priority. The data were obtained from Bureau of Meteorology, included for the period of 1911 to 2100. These data have been divided into historical climate period (1961 to 2015) and projected climate period (2016 to 2099). The rainfall data will be compared with multiple datasets of observed gridded rainfall such as Climatic Research Unit (CRU) to evaluate the model simulations. Areal potential evapotranspiration (APET) and monthly streamflow data from five stations across the Murumbidgee catchment have also used for this study.

3.2.1 SIMHYD Hydrological Model

The rainfall-runoff model, SIMHYD has been used in this study as it is a simplified version of the daily conceptual rainfall-runoff model HYDROLOG which requires less parameter and has significant advantages of accuracy, flexibility, and ease of use (Peel et al. 2000).

The structure of SIMHYD is shown in Figure 15 with its seven parameters highlighted in bold.

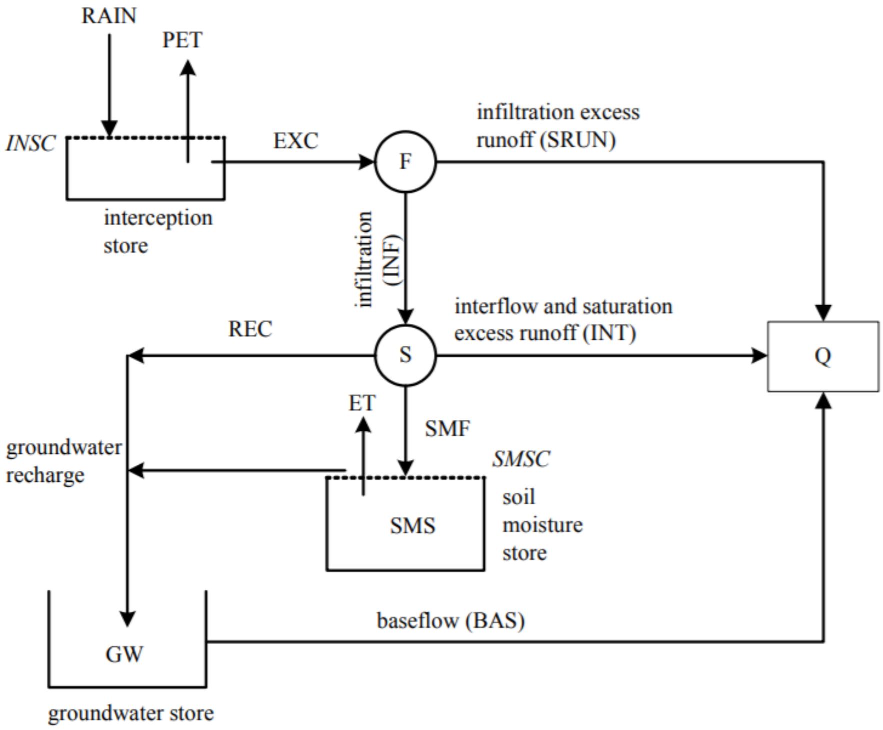


Figure 15: Structure of the daily lumped conceptual rainfall-runoff model SIMHYD (Source: Chiew & Siriwardena 2005a)

The model therefore estimates runoff simulation from three sources (Podger 2004)

a) Infiltration excess runoff (SRUN)

b) Interflow (saturation excess runoff) (INT) and

c) Base flow (BAS)

The fundamental equations of the model are;

Equation 1: EXC = RAIN - ***INSC,*** EXC > 0

Equation 2: $\mathrm{INF} = \min\{\boldsymbol{COEFF}^{(-\boldsymbol{SQ}*\frac{\boldsymbol{SMS}}{\boldsymbol{SMSC}})}, \mathrm{EXC}\}$

Equation 3: SRUN = EXC - INF

Equation 4: $\mathrm{INT} = \frac{\mathrm{SUB} * \mathrm{SMS} * \mathrm{INF}}{\boldsymbol{SMSC}}$

Equation 5: $\mathrm{REC} = \boldsymbol{CRAK} \; \mathrm{X} \frac{SMS}{\boldsymbol{SMSC}} \mathrm{X} \; (\mathrm{INF} - \mathrm{INT})$

Equation 6: SMF = INF – (INT – REC)

Equation 7: $\mathrm{ET} = \min\{ 10 * \left(\frac{SMS}{SMSC}\right), PET\}$

Equation 8: BAS = ***K*** X GW

The parameters used in these equations are described below.

INSC = Interception store capacity (mm)

COEFF = Maximum infiltration loss (mm)

SQ = Infiltration loss exponent

SMSC = Soil moisture store capacity (mm)

SUB = Constant of proportionality in interflow equation

CRAK = Constant of proportionality in groundwater recharge equation

K = Baseflow linear recession parameter

EXC= Throughfall

INF = Infiltration

SMS = Soil Moisture Store

Q = Total Runoff

SMF = Soil Input

PET = Potential Evapotranspiration

ET = Evapotranspiration

In SIMHYD, daily rainfall first fills the interception storage, which is emptied each day by evaporation. The excess rainfall is then subjected to an infiltration function that determines the infiltration capacity. The excess rainfall that exceeds the infiltration capacity becomes infiltration excess runoff. Moisture that infiltrates is subjected to a soil moisture function that diverts the water to the stream (interflow), groundwater storage (recharge) and soil moisture store. Interflow is first estimated as a linear function of the soil wetness (soil moisture level divided by soil moisture capacity).

The equation used to simulate interflow therefore attempts to mimic both the interflow and saturation excess runoff processes (with the soil wetness used to reflect parts of the catchment that are saturated from which saturation excess runoff can occur). Groundwater recharge is then estimated, also as a linear function of the soil wetness. The remaining moisture flows into the soil moisture storage (USQ 2009).

Evapotranspiration from the soil moisture store is estimated as a linear function of the soil wetness but cannot exceed the atmospherically controlled rate of areal potential evapotranspiration. The soil moisture store has a finite capacity and overflows into the groundwater storage. Base flow from the groundwater storage is simulated as a linear recession from the store.

SIMHYD tool used in this study is a part of RRL tool which has been downloaded from eWater (<www.ewater.org.au>). The RRL is configured with a set of default values for SIMHYD model parameter. These default values specify the initial parameter value and the upper and lower boundary values. The default values that have used for SIMHYD model lists below.

Table 3: SIMHYD model parameters and their boundary values

Parameter	Default value	Minimum	Maximum
Baseflow Coefficient	0.3	0.0	1.0
Impervious Threshold	1	0	5
Infiltration Coefficient	200	0	400
Infiltration Shape	3	0	10
Interflow Coefficient	0.1	0.0	1.0
Pervious faction	0.9	0.0	1.0
Rainfall Interception Store Capacity	1.5	0.0	5.0
Recharge Coefficient	0.2	0.0	1.0
Soil Moisture Store Capacity	320	1	500

In the model calibration, the six parameters in SIMHYD are optimised to maximise an objective function that incorporates the Nash-Sutcliffe efficiency (Nash & Sutcliffe, 1970) of monthly runoff and daily flow duration curve. The resulting optimised model parameters are therefore identical for all cells within a calibrated catchment.

3.2.2 Model Calibration and Validation

Calibration and validation gives a way to assess the robustness of the model use for the catchment. There are different methods of model calibration and among them suitably long period of runoff record is the preferred method. This method helps to verify the model behaviour outside the calibration period.

It is important to select calibration period carefully to cover both wet and dry extremes and has an average annual flow similar to the average annual flow for the whole period of record. The SIMHYD was calibrated against the daily runoff data (Figure 16). The calibration period selected for 1985 to 2015 which covers both extreme wet and dry flows. Climate models simulate climate variables at the annual and seasonal time scales where downscaling required linking information from large scales to local scale climate information, allowing generation of regional climate change (USQ 2009). The following prime method and data were used:

- Precipitation and temperature data under IPCC Fifth Assessment (AR5) were downloaded from the site https://www.climatechangeinaustralia.gov.au/en/ for all selected models. Precipitation data were used for rainfall while temperature and other climate data were used to calculate Potential evapotranspiration (PET). PET was calculated using ETo calculator from Penman Monteith method (Allen et al. 1998).

- The rainfall and potential evapotranspiration data were then processed to long term monthly historical data (Harrold & Jones 2003) and then further processed to daily values. These daily data were used as an input to the hydrological model applied for the Murrumbidgee River catchment.

- A period of 16 years (1995 -2010) including one year of warmup was selected for calibration and 5 years (2011-2015) for validation with daily streamflow and climate data from the Balranald station.

- The modelling was carried out for 0.05° X 0.05° grid cells to allow a better representation of the spatial patterns and gradient in rainfall. The same set of parameter values were used for all 0.05° X 0.05° grid cells for Balranald station. The model was calibrated to optimise the Nash-Sutcliffe efficiency (Nash & Sutcliffe 1970) of daily runoff.

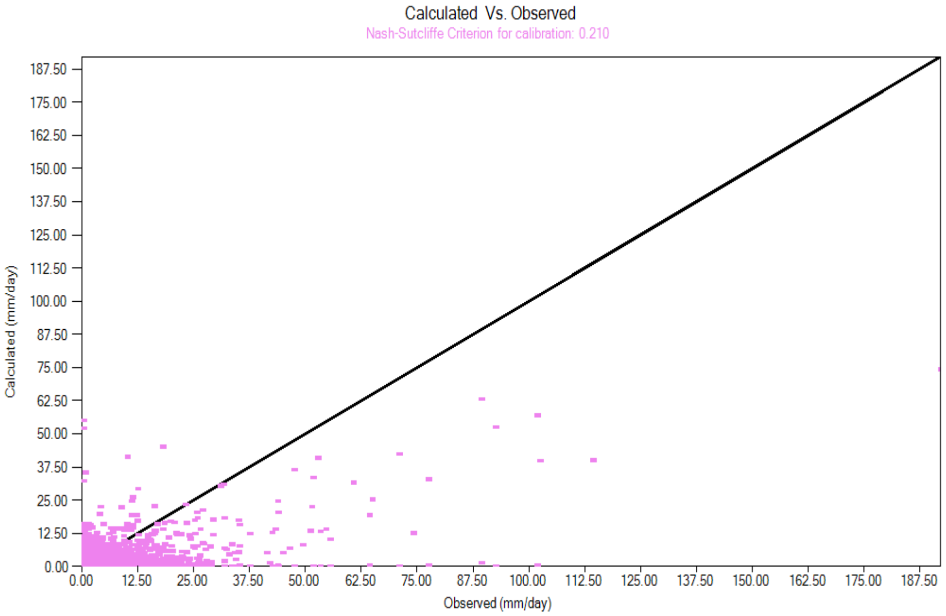


Figure 16: Calibration result from SIMHYD hydrological model

Penman-Monteith equation 4 (Allen et al., 1998), as follows:

$ET_o = 0.408\ \Delta\ (R_n - G) + y\ 900\ T + 273\ U_2\ (e_s - e_a)\ \Delta + y(1 + 0.34\ U_2)$ (equation 4)

Where ET_o is crop reference ET (mm/day), $R_n$is net radiation at the crop surface (MJ m²/day), G is soil heat flux density (MJ m²/day), T is air temperature at 2 m height (°C), U_2 is the wind speed at 2 m height (m/s), e_s is station vapor pressure (kPa), e_a is actual vapor pressure (kPa), $e_s - e_a$ is saturation vapor pressure deficit (kPa), Δ is slope vapor pressure curve (kPa/°C) and y is the phychrometric constant (kPa/°C).

3.2.3 Model Performance Criteria

The value of the objective function for the calibration of parameters can be used as the model performance statistics. I used Nash-Sutcliffe efficiency (NSE) as the objective function (Nash & Sutcliffe 1970) which can be described as equation 5:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs},i - Q_{sim},i)^2}{\sum_{i=1}^{n}\left(Q_{obs},i - \overline{Q_{obs}}\right)^2} \qquad \text{(equation 5)}$$

Where *n* is the number of time steps, $Q_{obs,i}$ is the observed flow at time step *i* (daily here), $\overline{Q_{obs}}$ is the mean of the observed flow and $Q_{sim,i}$ is the simulated flow. The range of NSE is $[-\infty, 1\,]$ where 1 represents perfect match between observed and simulated flow.

3.3 Contribution to the research field

Since 1950 the average temperature in the Murrumbidgee River catchment area has increased around 0.8°C and rainfall has declined around 30 mm per decade. The future climate of the Murrumbidgee Catchment is likely to be warmer and drier. These changes are likely to lead to reduce water flow in the Murrumbidgee catchment area (CSIRO 2006). In this study, I applied integrated climate, especially new generation of GCMs in hydrological modelling to more accurately quantifying the impact of climate change on Murrumbidgee catchment. The impact assessment of the catchment will contribute for better water resource management policies in the Murrumbidgee catchment area.

CHAPTER FOUR: RESULTS

4.0 Introduction

The rainfalls projections from three different GCM are compared with historical data are presented under integrated rainfall-runoff modelling section. The runoff results for the emission scenario RCP 4.5 are presented in sections 4.3 and 4.4 respectively. The mean annual climate variability changes for the Murrumbidgee River catchment discussed in the section 4.5. The monthly rainfall and runoff detail analysed results are presented in Table 17 & Table 18.

4.1 Runoff Model Performance

SIMHYD model was calibrated and validated using historical streamflow data from three different catchments. These catchments were selected for model calibration because of data consistency for at least 30 years.

The longer term historical data required to capture the variability in streamflow.

SIMHYD model runs on daily time series of data and it is calibrated against daily runoff data. Model performance can be measured by Nash Sutcliffe Coefficient of efficiency (NSE). The NSE value 1 indicates modelled runoff is the same as the recorded runoff. The NSE value describes the agreement between the calibrated and recorded daily runoffs. In practically NSE values greater than 0.6 suggest a reasonable modelling of runoff and E values greater than 0.8 means a good modelling of runoff for catchment (Peel et al. 2000).

The daily flow duration curve (Figure 17a & Figure 17b) compares the daily modelled and observed runoff for the Murrumbidgee River at Tharwa. The result shows SIMHYD model can generate acceptable observed daily runoff series. The calibration and verification results range from NSE 0.30 to NSE 0.85.

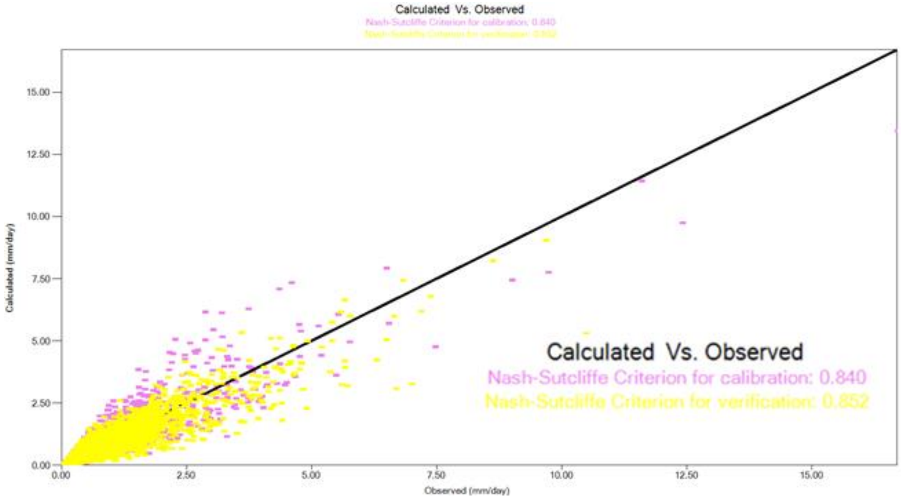


Figure 17a: Calculated Vs historical (monthly) calibration and validation at Tharwa using SIMHYD Model

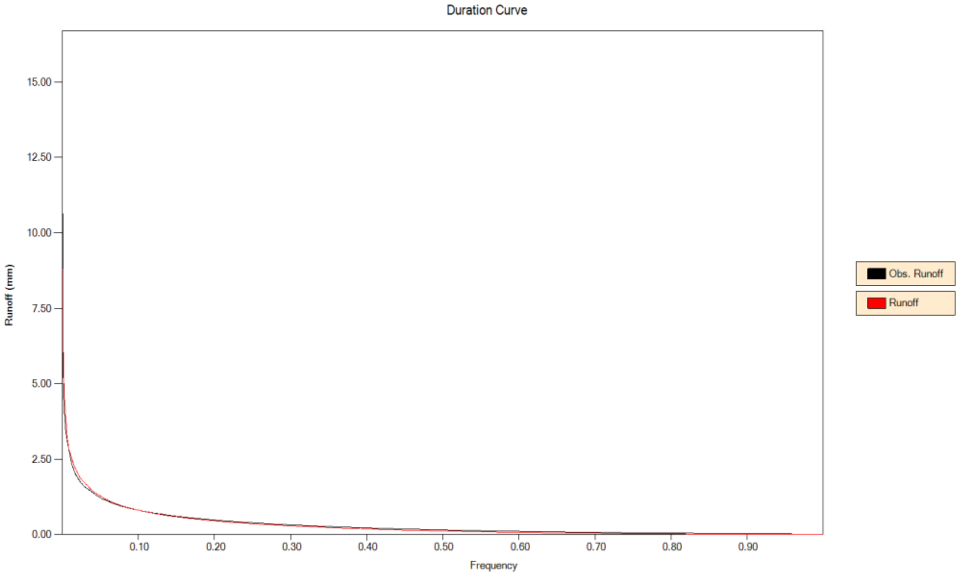


Figure 17b: Historical and calculated flow duration curve for the Murrumbidgee River at Tharwa using SIMHYD Model

4.2 Climate Impacts: Changes in the rainfall

The projected rainfall analysis for the Murrumbidgee River catchment at five different sub-catchments compared to the period of 1985-2015 (mean) for emission scenarios RCP 4.5 & RCP 8.5. The analysis shows rainfall trends are higher in the months of May and June for all three

GCMs at Tharwa (Figure 18a). Applying same emission scenario rainfall increases in the month of May at Yass according to three climate model's projections (Figure 18b). At Balranald, there is a significant increase in rainfall projected by ACCESS1 GCM (Figure 18c) and for the rest of months rainfall trend remains close to the historical trend. Summer rainfall trend is below the historical level, whereas winter rainfall in May will increase according to three GCMs projections at Wagga Wagga (Figure 18d). Rainfall increases in both summer and winter at Balranald (Figure 18e).

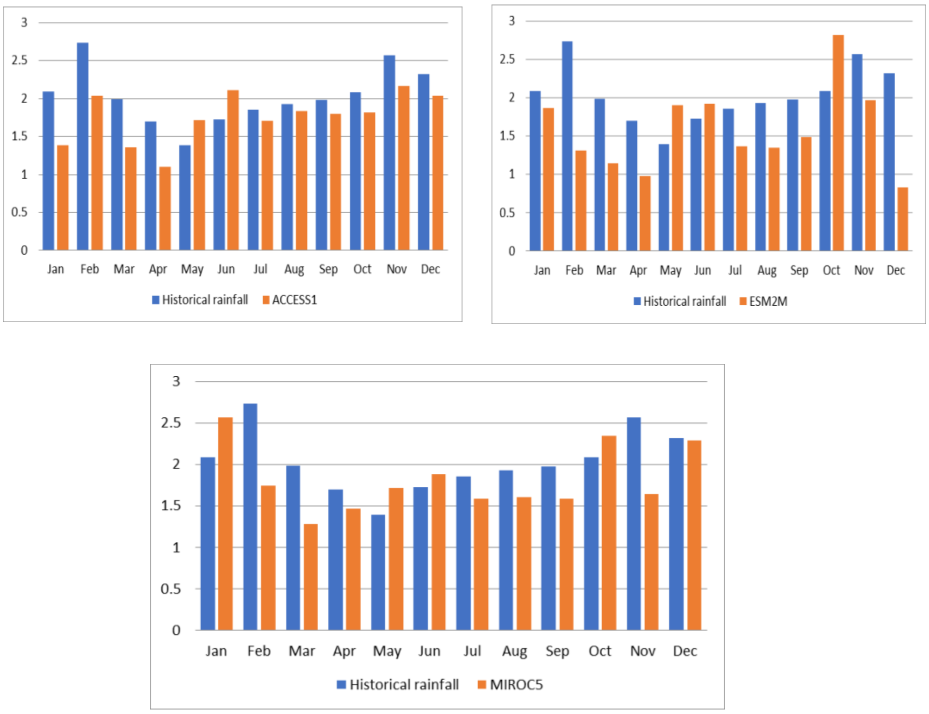


Figure 18a: Rainfall trend at Tharwa under emission scenario RCP4.5 for the period of 2016-2045

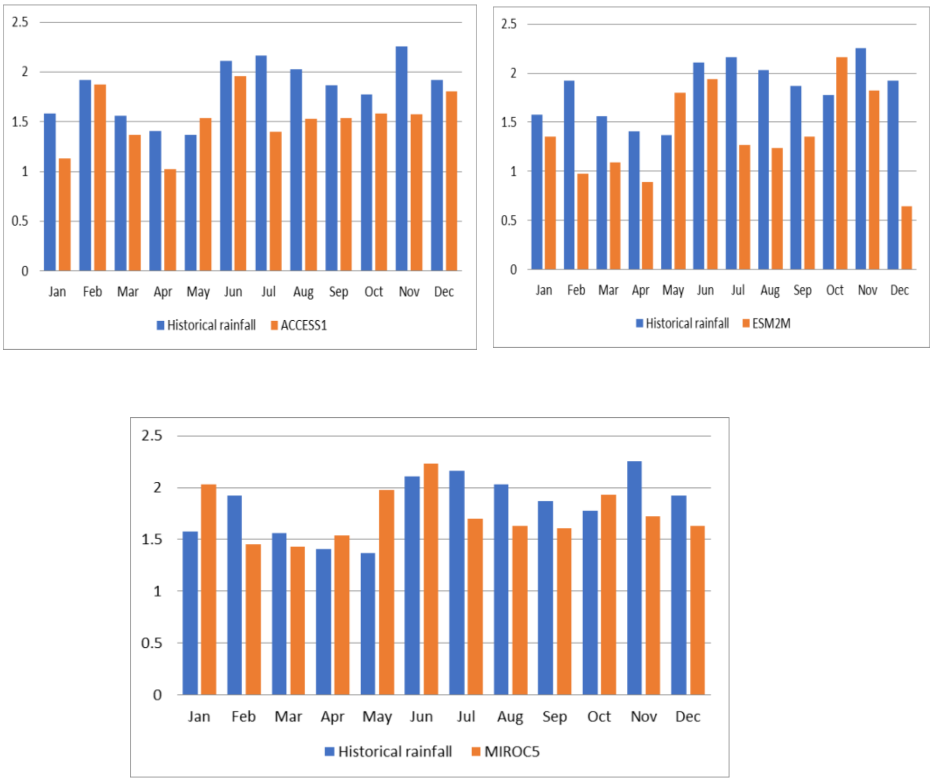


Figure 18b: Rainfall trend at Yass under emission scenario RCP4.5 for the period of 2016-2045

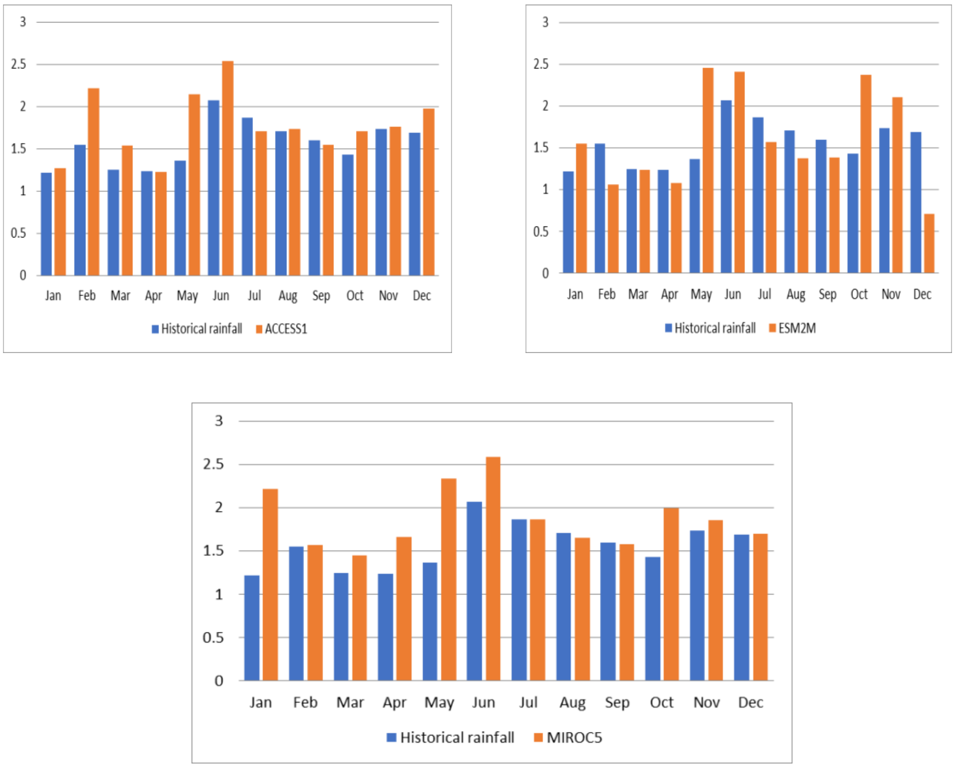


Figure 18c: Rainfall trend at Borambola under emission scenario RCP4.5 for the period of 2016-2045

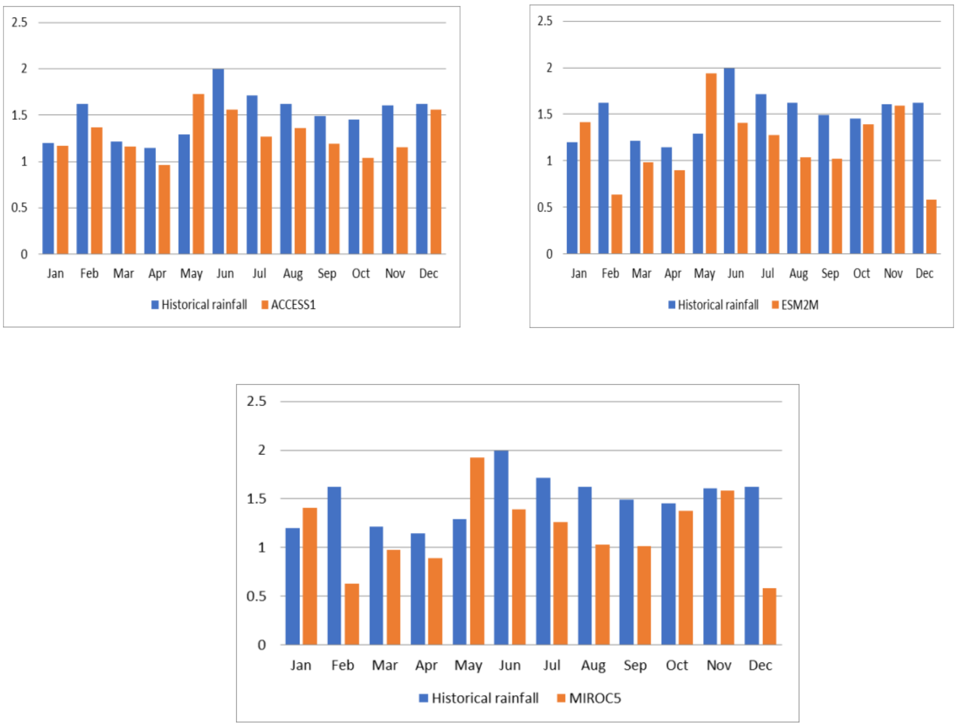


Figure 18d: Rainfall trend at Wagga Wagga under emission scenario RCP4.5 for the period of 2016-2045

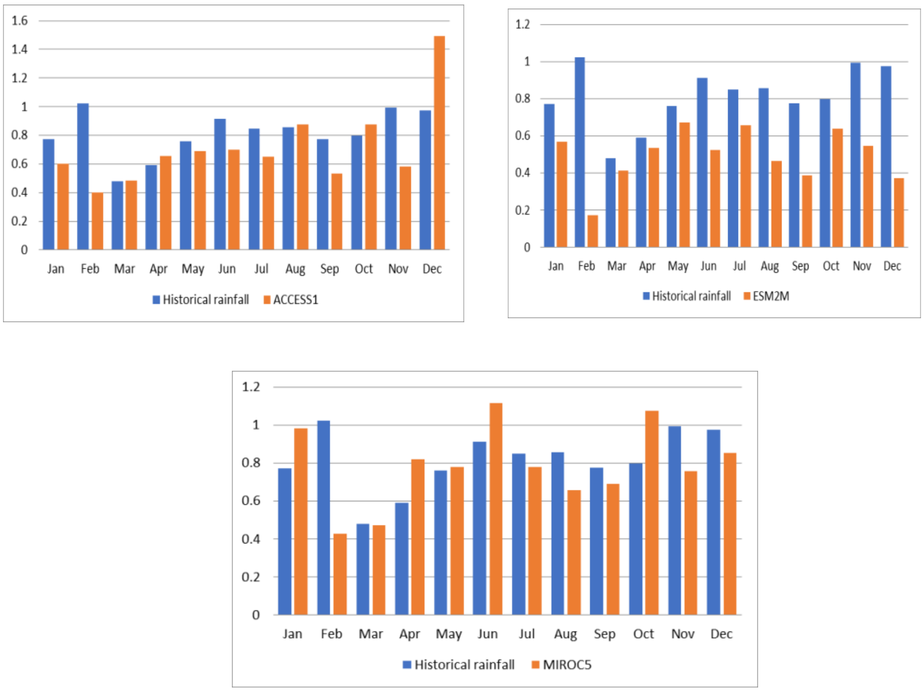


Figure 18e: Rainfall trend at Balranald under emission scenario RCP4.5 for the period of 2016-2045

4.4 Integrated Rainfall-Runoff Modelling

According to GCM model ACCESS1 projected rainfall is decreasing when compare to historical rainfall except for the months of May and June (Table 4). SIMHYD simulated runoff trend is also decreases for all the year in comparison with historical runoff (Table 4). Rainfall is declined dramatically for the month of December and increasing for May, June and October respectively under the projection of ESM2M model (Table 4). According to MIROC5 model projected rainfall is increasing in the month of January, May, June and October whereas runoff resides below the historical flow level (Table 4).

Table 4: GCMs projected rainfall and SIMHYD predicted runoff for RCP 4.5 at Tharwa

ACCESS1												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	66%	74%	68%	64%	124%	122%	92%	95%	91%	87%	84%	88%
Runoff	42%	57%	41%	35%	71%	90%	81%	85%	81%	70%	78%	65%
ESM2M												
Rainfall	89%	48%	58%	58%	138%	112%	74%	70%	76%	135%	77%	36%
Runoff	55%	34%	30%	29%	79%	90%	59%	53%	53%	103%	78%	26%
MIROC5												
Rainfall	123%	64%	65%	86%	124%	109%	86%	84%	81%	113%	64%	99%
Runoff	108%	57%	43%	55%	83%	93%	75%	74%	64%	88%	61%	78%

Future projected rainfall is below the historical level according to ACCESS1 model at Yass catchment (Table 5). Historical rainfall data were calculated for the period of 1985-2015 and compared with GCM modelled future rainfall under the emission scenario at RCP 4.5. According to ESM2M model projected rainfall increases for the month of May and October and dramatically decreases for the month of December (Table 5). According to MIROC5 model rainfall increase for the month of January, April, May, June and October (Table 5).

Table 5: GCMs projected rainfall and SIMHYD predicted runoff for RCP 4.5 at Yass

ACCESS1												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	72%	98%	88%	73%	112%	93%	65%	75%	82%	89%	70%	94%
Runoff	44%	70%	50%	43%	67%	78%	55%	60%	70%	60%	55%	70%
ESM2M												
Rainfall	86%	51%	70%	63%	131%	92%	59%	61%	72%	122%	81%	34%
Runoff	44%	30%	30%	29%	67%	67%	36%	40%	50%	80%	73%	20%
MIROC5												
Rainfall	128%	76%	92%	109%	144%	106%	78%	80%	86%	109%	77%	85%
Runoff	89%	60%	60%	71%	100%	100%	73%	90%	90%	90%	73%	70%

GCM models predict higher rainfall for almost over the year when comparing with historical rainfall for the period 1985-2015 under the emission scenario at RCP 4.5 at Borambola. According to ACCESS1 rainfall is much higher in the month of February, May and June (Table 6) whereas ESM2M projects higher rainfall in May, June, October and November (Table 6). According to MIROC5 predictions, rainfall and runoff are above the historical level for each month.

Table 6: GCMs projected rainfall and SIMHYD predicted runoff for RCP 4.5 at Borambola

ACCESS1												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	105%	143%	123%	99%	157%	122%	91%	101%	97%	120%	102%	117%
Runoff	200%	367%	175%	200%	450%	320%	217%	280%	220%	225%	300%	200%
ESM2M												
Rainfall	128%	68%	99%	88%	181%	116%	84%	80%	87%	167%	121%	92%
Runoff	250%	100%	75%	150%	450%	280%	200%	200%	180%	325%	467%	125%
MIROC5												
Rainfall	183%	101%	117%	135%	172%	125%	100%	96%	99%	141%	108%	131%
Runoff	550%	233%	150%	300%	550%	380%	283%	320%	260%	325%	400%	275%

At Balranald catchment, ACCESS1 refers rainfall and runoff projections are below from the historical level (Table 7). Rainfall trend shows a continuous decrease for all the year with ESM2M projections but SIMHYD prediction shows a significant increase in runoff from September to November (Table 7). MIROC5 projects higher rainfall in January, April, June, October & December (Table 7). Similarly, SIMHYD simulates increased runoff for the same months of the year (Table 7).

Table 7: GCMs projected rainfall and SIMHYD predicted runoff for RCP 4.5 at Balranald

<table>
<tr><td colspan="13">ACCESS1</td></tr>
<tr><td>Month</td><td>Jan</td><td>Feb</td><td>Mar</td><td>Apr</td><td>May</td><td>Jun</td><td>Jul</td><td>Aug</td><td>Sep</td><td>Oct</td><td>Nov</td><td>Dec</td></tr>
<tr><td>Rainfall</td><td>78%</td><td>39%</td><td>102%</td><td>112%</td><td>91%</td><td>77%</td><td>76%</td><td>102%</td><td>68%</td><td>110%</td><td>59%</td><td>78%</td></tr>
<tr><td>Runoff</td><td>28%</td><td>5%</td><td>39%</td><td>42%</td><td>61%</td><td>68%</td><td>111%</td><td>160%</td><td>93%</td><td>97%</td><td>29%</td><td>169%</td></tr>
<tr><td colspan="13">ESM2M</td></tr>
<tr><td>Rainfall</td><td>74%</td><td>17%</td><td>85%</td><td>92%</td><td>88%</td><td>57%</td><td>78%</td><td>54%</td><td>50%</td><td>80%</td><td>56%</td><td>74%</td></tr>
<tr><td>Runoff</td><td>53%</td><td>8%</td><td>35%</td><td>59%</td><td>142%</td><td>142%</td><td>287%</td><td>223%</td><td>275%</td><td>409%</td><td>270%</td><td>104%</td></tr>
<tr><td colspan="13">MIROC5</td></tr>
<tr><td>Rainfall</td><td>127%</td><td>42%</td><td>98%</td><td>139%</td><td>103%</td><td>122%</td><td>92%</td><td>78%</td><td>88%</td><td>135%</td><td>77%</td><td>127%</td></tr>
<tr><td>Runoff</td><td>121%</td><td>10%</td><td>103%</td><td>116%</td><td>136%</td><td>430%</td><td>361%</td><td>219%</td><td>277%</td><td>257%</td><td>103%</td><td>130%</td></tr>
</table>

According to ACCESS1, ESM2M and MIROC5 rainfall will increase only in January & May and decreases for rest of the months (Table 8). SIMHYD simulations show runoff trends are above the historical level with a significant increase in May (Table 8). These catchments are controlled by several weirs and dams which impact actual runoff calculation from catchment rainfall.

Table 8: GCMs projected rainfall and SIMHYD predicted runoff for RCP 4.5 at Wagga Wagga

ACCESS1												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	98%	85%	96%	84%	133%	78%	74%	84%	80%	72%	72%	96%
Runoff	268%	232%	83%	116%	340%	147%	98%	108%	106%	88%	134%	123%
ESM2M												
Rainfall	118%	39%	81%	78%	150%	70%	74%	64%	68%	95%	99%	36%
Runoff	280%	89%	40%	83%	332%	117%	94%	82%	82%	119%	237%	51%
MIROC5												
Rainfall	118%	39%	80%	78%	149%	70%	74%	63%	68%	94%	99%	36%
Runoff	558%	202%	66%	102%	422%	177%	123%	120%	118%	112%	207%	117%

4.4.1 Monthly changes for RCP 4.5 & RCP 8.5

The SIMHYD projected runoff results have been analysed under the emission scenarios RCP 4.5 & RCP 8.5 for five sub-catchments and compared to the historical period of 1985-2015 (mean). These historical years have been selected to accommodate both extreme wet and dry scenarios in the Murrumbidgee catchment area. SIMHYD predicted runoff results show decreasing trends at Tharwa and Yass catchments for all the year using three GCMs' projected data (Table 9 & Table 10). Runoff is higher in winter months such as May, June, July & August at Balranald catchment (Table 11). Runoff trends are above the historical level both at Wagga Wagga and Borambola catchments (Table 12 & Table 13).

Table 9: Simulated runoff under RCP 4.5 & 8.5 at Tharwa for the period of 2016-2045

ACCESS1												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	44%	58%	42%	38%	72%	90%	81%	84%	79%	70%	79%	65%
RCP 8.5	74%	54%	35%	46%	70%	75%	56%	54%	51%	61%	98%	80%
ESM2M												
RCP 4.5	56%	33%	30%	29%	77%	88%	59%	53%	51%	103%	79%	25%
RCP 8.5	53%	50%	54%	31%	63%	101%	61%	58%	74%	106%	93%	50%
MIROC5												
RCP 4.5	108%	57%	42%	55%	83%	91%	75%	72%	63%	87%	60%	76%
RCP 8.5	118%	40%	40%	49%	68%	67%	63%	77%	56%	60%	50%	67%

Table 10: Simulated runoff under RCP 4.5 & 8.5 at Yass for the period of 2016-2045

ACCESS1												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	44%	70%	56%	44%	60%	77%	56%	66%	71%	60%	57%	63%
RCP 8.5	85%	73%	48%	71%	77%	75%	48%	44%	46%	65%	121%	73%
ESM2M												
RCP 4.5	42%	27%	29%	27%	60%	61%	42%	45%	51%	80%	76%	20%
RCP 8.5	55%	59%	79%	34%	82%	99%	47%	57%	94%	111%	96%	44%
MIROC5												
RCP 4.5	95%	64%	59%	74%	97%	98%	80%	92%	92%	94%	76%	64%
RCP 8.5	137%	50%	64%	69%	78%	68%	53%	74%	61%	62%	53%	72%

Table 11: Simulated runoff under RCP 4.5 & 8.5 at Balranald for the period of 2016-2045

ACCESS1												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	28%	5%	39%	42%	61%	68%	111%	160%	93%	97%	29%	169%
RCP 8.5	474%	60%	48%	756%	691%	53%	114%	97%	116%	114%	101%	142%
ESM2M												
RCP 4.5	53%	8%	35%	59%	142%	142%	287%	223%	276%	409%	270%	104%
RCP 8.5	411%	33%	87%	188%	415%	53%	65%	87%	139%	95%	107%	63%
MIROC5												
RCP 4.5	121%	10%	103%	116%	136%	430%	361%	219%	277%	257%	103%	130%
RCP 8.5	756%	46%	61%	421%	679%	130%	162%	133%	112%	105%	62%	78%

Table 12: Simulated runoff under RCP 4.5 & 8.5 at Wagga Wagga for the period of 2016-2045

ACCESS1												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	268%	232%	83%	116%	340%	147%	98%	108%	106%	88%	134%	123%
RCP 8.5	437%	260%	75%	181%	357%	140%	90%	72%	71%	80%	360%	175%
ESM2M												
RCP 4.5	280%	89%	40%	83%	332%	117%	94%	82%	82%	119%	237%	51%
RCP 8.5	342%	177%	98%	98%	305%	114%	75%	78%	113%	148%	376%	115%
MIROC5												
RCP 4.5	558%	202%	66%	102%	422%	177%	123%	120%	118%	112%	207%	117%
RCP 8.5	719%	219%	79%	134%	338%	110%	102%	109%	105%	98%	199%	126%

Table 13: Simulated runoff under RCP 4.5 & 8.5 at Borambola for the period of 2016-2045

ACCESS1												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5	199%	324%	162%	158%	321%	294%	221%	255%	207%	238%	253%	179%
RCP 8.5	300%	184%	34%	144%	216%	110%	28%	14%	-7%	105%	400%	97%
ESM2M												
RCP 4.5	207%	82%	70%	90%	307%	251%	192%	186%	159%	319%	377%	57%
RCP 8.5	165%	101%	101%	16%	225%	135%	24%	41%	90%	247%	309%	24%
MIROC5												
RCP 4.5	465%	207%	134%	213%	392%	331%	280%	285%	233%	323%	323%	175%
RCP 8.5	552%	81%	71%	121%	224%	77%	49%	86%	35%	106%	125%	86%

4.4.2 Seasonal changes for RCP 4.5 & RCP 8.5

For the summer period a review of the results (Table 14 & Table 15) where aforementioned models provided varying degrees of capability in various months and seasons under emission scenario suggest potential for general decrease in rainfall through December-February for four sub-catchments (Tharwa, Yass, Balranald & Wagga Wagga) (rainfall range decrease 5% to 57% for RCP 4.5 and 2% to 35% for RCP 8.5) and an increasing trend at Borambola catchment for both RCP 4.5 and RCP 8.5. For the autumn months, most months show a tendency for a decrease in rainfall (decrease of 9%-16% for RCP 4.5 and 3% to 19% for RCP 8.5) in the upstream of Wagga Wagga (Tharwa & Yass) and a potential increase rainfall ranges 1% to 41% for RCP 4.5 and 7% to 34% in the downstream (Wagga Wagga, Borambola & Balranald).

For the winter period, a decreasing trend in rainfall (decrease of 3% to 37% for RCP 4.5 and 1% to 34% for RCP 8.5) for all five catchments. However, further analyses suggest the period, generally from May through to October, as mostly a period of potentially reduced rainfall.

For the spring months, while October continues the generally decreasing potential of the winter period for four catchments (Tharwa, Yass, Wagga Wagga & Balranald), there is an increase in rainfall for Borambola station.

Table 14: Rainfall and runoff seasonal changes under emission scenario RCP 4.5 for the period of 2016-2035

RCP 4.5	Model	Summer		Autumn		Winter		Spring	
		Rainfall	Runoff	Rainfall	Runoff	Rainfall	Runoff	Rainfall	Runoff
Tharwa	ACCESS1	-24%	-44%	-14%	-49%	3%	-15%	-13%	-24%
	ESM2M	-42%	-62%	-16%	-55%	-15%	-33%	-4%	-23%
	MIROC5	-5%	-67%	-9%	-24%	-7%	-30%	-14%	-26%
Yass	ACCESS1	-12%	-41%	-9%	-47%	-22%	-34%	-20%	-38%
	ESM2M	-43%	-70%	-12%	-62%	-30%	-51%	-8%	-31%
	MIROC5	-4%	-26%	15%	-23%	-12%	-10%	-10%	-12%
Balranald	ACCESS1	-10%	-33%	1%	-53%	-15%	13%	-21%	-27%
	ESM2M	-57%	-60%	-12%	-5%	-37%	120%	-38%	70%
	MIROC5	-14%	-13%	13%	18%	-3%	237%	0%	112%
Wagga Wagga	ACCESS1	-7%	-79%	5%	-82%	-21%	-88%	-25%	-89%
	ESM2M	-36%	-86%	3%	-85%	-30%	-90%	-12%	-85%
	MIROC5	-36%	-67%	2%	-79%	-31%	-85%	-13%	-84%
Borambola	ACCESS1	21%	134%	27%	114%	5%	157%	6%	132%
	ESM2M	-21%	15%	22%	56%	-6%	110%	25%	185%
	MIROC5	28%	182%	41%	146%	7%	198%	15%	193%

Table 15: Rainfall and runoff seasonal changes under emission scenario RCP 8.5 for the period of 2016-2035

RCP 8.5	Model	Summer		Autumn		Winter		Spring	
		Rainfall	Runoff	Rainfall	Runoff	Rainfall	Runoff	Rainfall	Runoff
Tharwa	ACCESS1	-18%	-31%	-18%	-50%	-18%	-38%	-10%	-30%
	ESM2M	-33%	-49%	-19%	-51%	-8%	-26%	3%	-9%
	MIROC5	-9%	-25%	-15%	-47%	-9%	-31%	-27%	-45%

Yass	ACCESS1	-14%	-23%	-7%	-35%	-30%	-44%	-11%	-23%
	ESM2M	-34%	-48%	-10%	-35%	-25%	-32%	5%	0%
	MIROC5	-7%	-14%	-3%	-29%	-21%	-35%	-27%	-41%
Balranald	ACCESS1	-4%	125%	19%	398%	-21%	-12%	7%	11%
	ESM2M	-35%	69%	-6%	130%	-34%	-32%	8%	14%
	MIROC5	-10%	193%	10%	287%	-1%	42%	-9%	-7%
Wagga Wagga	ACCESS1	-2%	191%	15%	104%	-27%	1%	-8%	70%
	ESM2M	-23%	112%	7%	67%	-27%	-11%	6%	112%
	MIROC5	8%	255%	10%	84%	-17%	7%	-22%	34%
Borambola	ACCESS1	21%	194%	30%	131%	-6%	51%	24%	166%
	ESM2M	-9%	97%	25%	114%	-1%	67%	43%	215%
	MIROC5	31%	240%	34%	138%	7%	71%	-1%	89%

4.4.3 Annual changes for RCP 4.5 & RCP 8.5

The following provide yearly assessments for each of the GCM systems applied for two different emission scenarios RCP 4.5 and RCP 8.5 at five different sub-catchments. Table 16 provides output for each model with SIMHYD hydrological model applied for these periods for five sub-catchments under RCP 4.5.

Time series depicted in the following series provide an indication of extension of these model runs out to 2104. These results are shown in the table below for each GCM output. Noteworthy results are that all models suggest a decreasing overall trend for four sub-catchments over these longer periods. ACCESS1, ESM2M and MIROC5 model do not display such a major longer-term decline at Borambola sub-catchment, an upward trend in rainfall and runoff for all these time periods. However, it should be noted that all the three models continue to provide a downward overall trend in yearly rainfall under the emission scenarios RCP 4.5 and RCP 8.5 and model selected provided here suggest a downward overall trend in runoff for four sub-catchments (Table 16 & Table 17).

Table 16: Rainfall and runoff annual changes under emission scenario RCP 4.5

RCP 4.5	Model	2016 – 2035		2035 -2055		2056- 2074		2075 - 2100	
		Rainfall	Runoff	Rainfall	Runoff	Rainfall	Runoff	Rainfall	Runoff
Tharwa	ACCESS1	-12%	-33%	-13%	-30%	-13%	-30%	-20%	-41%
	ESM2M	-19%	-43%	-16%	-35%	-31%	-48%	-21%	-42%
	MIROC5	-9%	-37%	-14%	-31%	-6%	-20%	-18%	-39%
Yass	ACCESS1	-16%	-40%	-12%	-28%	-8%	-25%	-17%	-41%
	ESM2M	-23%	-53%	-19%	-37%	-34%	-67%	-25%	-52%
	MIROC5	-2%	-18%	-13%	-34%	-5%	-20%	-17%	-42%
Balranald	ACCESS1	-11%	-25%	-4%	107%	-5%	104%	-1%	82%
	ESM2M	-36%	31%	-25%	30%	-43%	17%	-23%	13%
	MIROC5	-1%	89%	9%	160%	17%	105%	-1%	79%
Wagga Wagga	ACCESS1	-12%	54%	-6%	-38%	-2%	34%	-10%	-45%
	ESM2M	-19%	-13%	-15%	-49%	-31%	-68%	17%	-7%
	MIROC5	-20%	32%	-1%	-32%	4%	-28%	-6%	-42%
Borambola	ACCESS1	15%	134%	22%	57%	29%	86%	14%	-8%
	ESM2M	5%	91%	10%	49%	-11%	11%	3%	37%
	MIROC5	23%	180%	20%	97%	30%	187%	14%	87%

Table 17: Rainfall and runoff annual changes under emission scenario RCP 8.5

RCP 8.5	Model	2016 – 2035		2035 -2055		2056- 2074		2075 – 2100	
		Rainfall	Runoff	Rainfall	Runoff	Rainfall	Runoff	Rainfall	Runoff
Tharwa	ACCESS1	-16%	-37%	-9%	-26%	-15%	-36%	-25%	-50%
	ESM2M	-14%	-34%	-25%	-48%	-28%	-54%	-40%	-67%
	MIROC5	-15%	-37%	-18%	-41%	-13%	-34%	-4%	-20%
Yass	ACCESS1	-15%	-31%	-9%	-17%	-16%	-28%	-25%	42%
	ESM2M	-16%	-29%	-31%	-47%	-30%	-48%	-42%	-60%
	MIROC5	-15%	-30%	-16%	-35%	-2%	-13%	-1%	-8%
Balranald	ACCESS1	0%	131%	-9%	116%	-11%	122%	-20%	67%
	ESM2M	-17%	45%	-32%	23%	-39%	-3%	-50%	-31%
	MIROC5	-2%	129%	4%	186%	14%	216%	23%	239%
Wagga Wagga	ACCESS1	-6%	91%	-3%	97%	-12%	61%	-21%	30%
	ESM2M	-9%	70%	-25%	21%	-25%	12%	-38%	-17%
	MIROC5	-5%	95%	-5%	85%	0%	103%	15%	177%
Borambola	ACCESS1	17%	135%	25%	164%	14%	128%	2%	86%
	ESM2M	15%	123%	-6%	60%	-5%	63%	-21%	24%
	MIROC5	18%	134%	16%	119%	22%	138%	40%	203%

4.5 Rainfall and Runoff changes at the Murrumbidgee River catchment

The percentage change in the mean annual rainfall and the percentage change mean annual runoff compared with the historical (1985-2015) rainfall and runoff data are presented in Table 18. The result indicates that the potential impact of climate change on catchment runoff is significant. The climate models show a decrease in annual rainfall by -9% to -19%. These changing trends in rainfall data used in the SIMHYD hydrological model, which simulated considerable runoff reduction (between 33% and 43%) over the projected periods though there is less confidence in the estimation of projections. I have calculated average annual rainfall and runoff for three different Global Climate Models applied to each sub catchments in the Murrumbidgee River catchment. The calculated result presented in the Table 18 below.

Table 18: Percentage change in mean annual rainfall and runoff compared with historical period (1985-2015) for the Murrumbidgee River catchment for RCP 4.5 and RCP 8.5

RCP 4.5	**2016-2035**	
GCM	**Rainfall**	**SIMHYD**
ACCESS1.0	92.8%	118%
ESM2M	81.6%	119.2%
MIROC5	98.2%	167.2%
RCP 8.5	**2016-2035**	
GCM	**Rainfall**	**SIMHYD**
ACCESS1.0	96%	157.8%
ESM2M	92.8%	135%
MIROC5	96.2%	158.2%

CHAPTER FIVE: DISCUSSION

5.0 Introduction

The results will be discussed in terms of current literature and in how these outcomes answered the research question posed. In this section I would also like to mention about the limitations of the work and what areas of further research are important in providing runoff projections to best utilise future water resources for the Murray Darling Basin.

5.1 Discussion

In the result chapter, section 4.4 shows three GCMs that indicate a decrease in mean annual, summer and winter runoff at Tharwa and Yass which are similar to Chiew et al. (2008). The results indicate that the potential changes in runoff because of climate variability can be very significant. At Tharwa, using MIROC5 projected data in SIMHYD, the winter runoff decreases by 30% whereas the summer runoff decreases by 67%. In the same sub-catchment runoff increases in October by 3% for ESM2M model's projection but a decrease for rest of the months by 10% to 100%.

Similarly, simulated results show decreases in runoff at Yass and Wagga Wagga in March and April even rainfall increases for these months. The result indicates a small hydrological drought signal identified at Wagga Wagga (Wen et al. 2011a) was likely primarily due to increased flows provided by the Snowy Mountains Scheme, balanced against the increased impacts of water diversions upstream, principally to Australian Capital Territory.

At Yass catchment rainfall increases in the month of October and November by 31% & 22% according to ACCESS1 and with these data input SIMHYD simulated runoff shows increase by 53% & 49%. Model simulation also shows runoff increases for each month at Balranald even though rainfall decreases for February, September, November and December. Three GCMs show an increase in rainfall in the month of May at Wagga Wagga by 42%, 47% & 62% and SIMHYD simulation shows runoff increases in the month of May by 9%, 13% & 61% respectively. According to ACCESS1 predicted rainfall increases in the month of October and November by 86% & 88% at Borambola, whereas runoff increases only by 15% and 105% respectively.

According to Wen et al. (2011a) the standardised flow index identified considerable increased drying at Balranald, downstream of the Lowbidgee floodplain, particularly after the 1960. It is also important to acknowledge that while this research has considerable simplicity, there are challenges in that many different processes affect river flows, besides climate change, including the clearing of trees and upstream catchment processes and river regulation. In addition, there are complex climate and storage effects extending over a series of years (Chiew et al. 2014). Modelling was unlikely to fully capture these processes and effects on flow, but the model provided a reasonably good assessment of gross changes in flow. Also, this modelling approach is probably not so well equipped to predict future conditions (i.e. data streams not yet experienced). However, increasing current data streams can still be used to model a changing river’s behaviour.

5.2 Does output data answer the research question?

The research question and motivation for this research was to find the future water flow trend in the Murrumbidgee River catchment. Applying three different model’s climate projection shows rainfall decreases dramatically in this region. These projected rainfall and evapotranspiration data used as input in the SIMHYD hydrological model and found overall runoff decrease in the simulations.

There was a significant dry period from 2000 to 2010 which influenced model during calibration. As a result, we can find the future trend in runoff is decreased for five different sub-catchments within the Murrumbidgee River catchment.

The autumn that has been marked by excessive runoff could damage local infrastructure and properties. According to this research future projections of annual runoff for the Murrumbidgee region may be accurate which can be used for urban planning to reduce the damages.

CHAPTER SIX: SUMMARY AND CONCLUSION

The Murrumbidgee River catchment is in the south-east region of the MDB. It covers an area of 84,000 square km and supports over 540,000 people including Australian Capital Territory and NSW inland city Wagga Wagga. The Murrumbidgee catchment accounts for 22% of the surface water diversion for irrigation and urban use though it represents only 8% of total land mass of the MDB. In terms of economy, it contributes 25% of NSW state's fruit and vegetable production, 42% of state's grapes and half of Australia's rice production.

There are several dams and weirs built in the Murrumbidgee catchment for irrigation and the generation of hydropower. The irrigation schemes and associated infrastructure has vastly modified the natural river basin characteristics. The human-induced structures have altered the flow dynamics that normally result from external climatic drivers such as precipitation, evapotranspiration, percolation and runoff.

The trends in the data of water use, agricultural production, and environmental flows are reflections of the history of human settlements, agricultural development, government policy & investment, social issues, and environmental conditions within the Murrumbidgee Catchment. Because of post European settlements and landscape changes that happened in the Murrumbidgee catchment, it is important to understand the flow behaviour of its most important river under changing climatic conditions. Two emission scenarios namely, RCP 4.5 and RCP 8.5, were used to project future precipitation and potential evapotranspiration for the period of 2016 to 2100. Both the scenarios showed a future warmer and drier climate for this catchment.

The result of the SYMHYD model predictions for 2016-2045 under RCP 4.5 scenario indicates a big impact of climate change on the Murrumbidgee catchment runoff volumes. With climate change prediction for 2016-2045, a decrease in annual rainfall by 9% to 19% was forecasted. The average reduction in rainfall equates to 33% to 43% reduction in runoff over the projected periods though there is less confidence in the estimation of projections.

The results of this climate change impact on the Murrumbidgee stream flow will provide good evidence to government policy makers to develop a water policy that will save the river, irrigators and farmers.

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